Annual DOE

active solar heating and cooling contractors' review meeting

Premeeting Proceedings and Project Summaries

September 1981
Washington, D.C.

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Office of Solar Heat Technologies

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FOREWORD

The annual Active Solar Heating and Cooling Contractors' Review Meeting is sponsored by the Department of Energy under the Office of the Assistant Secretary for Conservation and Renewable Energy. This meeting serves as a forum for an exchange of technical information and an updating of program strategy and policy for both the participating contractors and the field management offices.

The active solar heating and cooling development programs are directed by the Active Heating and Cooling Division of the Office of Solar Heat Technology. DOE uses the following resources in the management and implementation of this program:

- DOE Operations Offices
- DOE National Laboratories
- National Aeronautics and Space Administration (NASA)
- Solar Energy Research Institute
- Contractors

Currently, major emphasis is being placed on the development of reliable, cost effective, publicly acceptable solar heating and cooling systems. Work is also continuing in the area of advanced components, subsystems, and materials. For convenience, the papers contained herein are organized according to the Active Heating and Cooling Division program management structure which includes the following seven program elements and five program technology groups:

Program Elements	Technology Groups
Rankine Solar Cooling Systems	Solar Collector Technology
Absorption Solar Cooling Systems	Solar Storage Technology
Desiccant Solar Cooling Systems	Solar Controls Technology
Solar Heat Pump Systems	Solar Analysis Technology
Solar Hot Water Systems	Solar Materials Technology
Special Projects	
Administrative/Management Support	

Due to the practical limitation of the time period for this meeting, only selected papers will be presented. However, the general progress and status of other active contracts have been summarized in the overview papers presented by the session chairmen. These overviews are printed at the beginning of each section of the Proceedings and are followed by papers in alphabetical order by name of the contract organization.

Finally, it is expected that the public release and dissemination of the subject proceedings will lead to a better understanding of the status and progress of the DOE Active Solar Heating and Cooling Program. Through the exchange of such information, it is anticipated that the widespread application of Active Solar Energy Technology will be significantly expedited.

D. Robert Jordan, Acting Director
Active Heating & Cooling Division
Office of Solar Heat Technologies
Conservation and Renewable Energy

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SECTION 12: SOLAR MATERIALS GROUP

Section 1: RANKINE SOLAR COOLING SYSTEMS

1

Overview of Active Solar Absorption/Rankine Cooling Program¶

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Michael Wahlig, Al Heitz*, Harry Angerman*, Ron Glas, Mashuri Warren

OBJECTIVE

The overall objective of the DOE active solar cooling program is to develop the basic solar cooling technology that industry can draw upon to engineer and produce solar cooling systems that will compete favorably with conventional cooling systems. By taking responsibility for the high-risk early research and development stages that private industry cannot yet justify undertaking, DOE will lay the foundation for technically sound solar cooling systems that the private sector can commercialize when market conditions are suitable.

BACKGROUND

A number of specific major objectives have been identified as necessary to achieve the overall objective. To meet these major objectives, a number of projects are being supported in both the absorption and the Rankine cooling areas. The correspondence between the individual projects and the major objectives is shown in Figure 1 for the absorption program and in Figure 2 for the Rankine program. Brief descriptions of the technical content of each project are given below in the Technical Accomplishments section. This paper is an update of the review of project activities that was reported at the Mach 1980 Annual DOE Active Solar Heating and Cooling Contractors Review Meeting[1]. This information covers the period March 1980 to May 1981.

Figure 1. Absorption Cooling Program

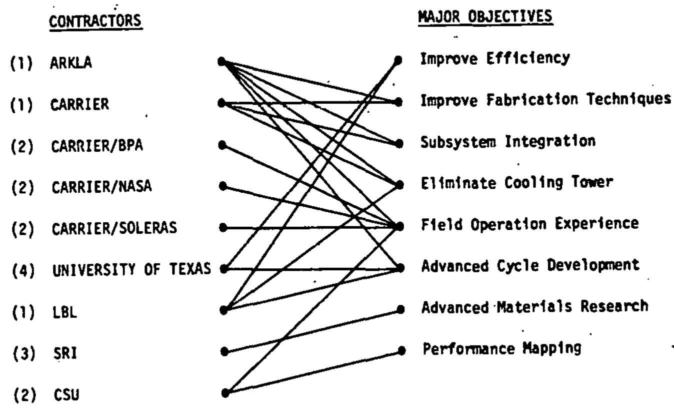
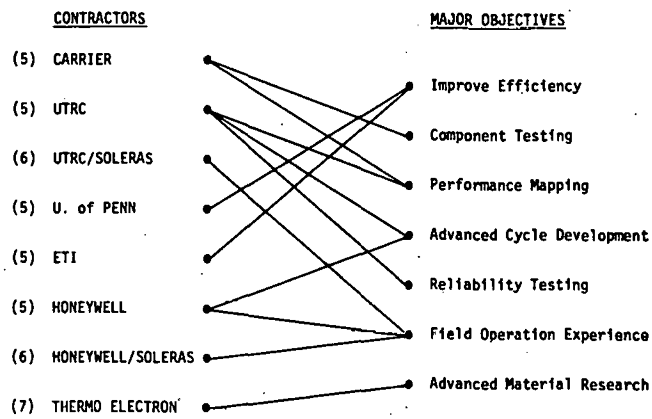


Figure 2. Rankine Cooling Program



SUMMARY

The tasks being performed in the absorption and Rankine program areas run the gamut from basic work on fluids to development of chillers and chiller components, to field and reliability testing of complete prototype cooling systems. In the absorption program there are three active component development projects (1), four systems field test projects (2), one advanced fluid study project (3), and one advanced cycle study project (4) currently funded by DOE. In the Rankine program, there are five active component development projects (5), two system field test projects (6), and one advanced fluid study project (7). (The numbers in parentheses are keyed to the contractors listed in Figures 1 and 2.)

Several of the solar cooling projects are managed by NASA/MSFC (Marshall Space Flight Center, Huntsville, Alabama): the Carrier/NASA absorption projects and the Honeywell Rankine project. The

¶ This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.
* Employees of Keller & Gannon, a subsidiary of Lester B. Knight Associates, Inc.

Honeywell project is a continuation of the earlier NASA/MSFC "404" program; two other 404 projects, by AiResearch and General Electric, have now been completed.

Some of the DOE solar cooling projects reported in last year's Overview[1] have also been completed since then, and several others are in the final report stage. Those completed are: an earlier ARKLA absorption project (Contract No. AC03-76SF-10507, Development of Third-Generation Three Ton Lithium Bromide-Water Absorption Chiller), the Brookhaven National Laboratory project (Contract No. C-02-0016, Development and Use of a Simulator to Test Solar Cooling Subsystems), and the EIC Corporation project (Contract No. AC03-77CS-34537, Design of a Solar Air Conditioner Using Solid Phase Absorbent-Chemical Heat Pump). The projects in the final report phase are those by Southern Research Institute (Contract No. AC03-77CS-31586, Analysis of Advanced Conceptual Absorption Chiller Designs) and the Institute of Gas Technology (Contract No. AC03-77CS-31439, Development of New Fluids for Solar Absorption Cooling). None of these projects will be included in the detailed descriptions given in the following section.

Three new projects have been started during the past year and will be reported on here: Determination of Properties of Fluids for Solar Applications, by SRI International; Fabrication and Installation at Field Test Sites of 120-ton and 75-ton Absorption Chillers, by Carrier Corporation (NASA/MSFC contracts); and Determination of the Thermal Stability of Organic Working Fluids Used in Rankine Cycle Systems, by Thermo Electron. In addition, much of the ongoing systems test work at Colorado State University is an integral part of the active solar cooling program and that effort will be reported here also.

A joint US/Saudi Arabian effort has contributed to the development of Rankine and absorption solar cooling systems. Four projects have been funded by this (SOLERAS) activity, all to be installed and operated in Phoenix, Arizona. Each manufacturer has contributed some private money in addition to the 50/50 share by the U.S. and Saudi Arabia. Table 1 summarizes these projects.

Table 1

U.S./SAUDI ARABIAN PROJECTS (SOLERAS PROGRAM)

CONTRACTOR	TYPE SYSTEM CYCLE/COLLECTORS	COOLING CAPACITY (TONS)
UTRC	RANKINE/TROUGH TRACKING	18
HONEYWELL	RANKINE/EVACUATED TUBE	25
CARRIER	ABSORPTION (WATER COOLED)/TROUGH TRACKING	15
CARRIER	ABSORPTION (AIR COOLED)/FRESNEL DUAL TRACKING	10

Some technical highlights of the program are presented in Table 2.

Table 2

TECHNICAL HIGHLIGHTS

CONTRACTORS	ACCOMPLISHMENTS
• HONEYWELL (RANKINE)	Continued successful field operation in Lawrence, Kansas and other locations.
• UTRC (RANKINE)	Prototype unit converted to air cooled operation, with successful start-up in Phoenix SOLERAS test project.
• U. of TEXAS (ABSORPTION)	Identification of potential for substantial technical performance improvements through development and use of computer models of double-effect absorption chillers.

TECHNICAL ACCOMPLISHMENTS

The individual absorption and Rankine projects are identified in this section, along with the main features and accomplishments/status of each.

ABSORPTION PROJECTS

Contractor: ARKLA

Contract No.: AC03-77CS-34593

Project: Develop and test unitary 3-ton and 25-ton LiBr/H_2O absorption cooling systems. Develop and test double effect, gas fired auxiliary absorption unit.

Features: Unitary package; fuel aux; manufacturing study; application and maintenance manuals; tooling improvements; lab reliability testing. Gas fired double effect absorption unit provides highly efficient COP (1.0) on non-solar operation.

Accomplishments:

- Two field test installations have been completed and performance predictions verified.
- 25-ton unitized packaged chiller has been lab tested and prepared for field installation scheduled for Building 71 at Lawrence Berkeley Laboratory.
- Tooling has been developed to produce absorber and condenser heat exchangers at reduced cost.

Future Plans:

- Complete design of double effect gas fired auxiliary absorption unit; fabricate and test.
- Assist in field test of 3-ton system at CSU and 25-ton system at LBL.
- Complete laboratory reliability testing of 3rd generation 3-ton units.

Contractor: Carrier Corporation

Contract No.: AC03-77CS-51587

Project: Development of air cooled absorption chillers.

Features: Air cooled; 120° C - 130° C input temperature; falling film approach using additives; manufacturing study and market evaluation.

Accomplishments:

- Prototype #1, a 10KW air cooled unitized package chiller has been fabricated; performance testing is in progress.

Future Plans:

- Improve design of 10KW absorption chiller; fabricate and test three 10KW units.
- Design, fabricate and test a 70 KW absorption chiller.

Contractor: Carrier Corporation/BPA

Contract No.: AC79-79BP-10467

Project: Fabricate two 15-ton unitized absorption chillers and install them at two field sites: Dalles, Oregon and Tyler, Texas.

Features: Water cooled, LiBr chillers; packaged; on-site testing; personnel training.

Accomplishments:

- Tyler, Texas and Dalles, Oregon installations have been successfully operated for a full cooling season.

Future Plans:

- The Tyler, Texas installation will continue to be operated during the summer of 1981 to obtain additional data on field test performance.

Contractor: Carrier Corporation/NASA

Contract No.: DEN 8-000005 & DEN 8-000015

Project: Fabricate one 120-ton absorption unit to be installed at Frenchman's Reef, V.I. and two 75-ton absorption units to be installed at Houston and Las Vegas sites. Field test systems at each site.

Features: Water cooled; LiBr chillers; packaged; on-site testing; personnel training.

Accomplishments:

- Frenchmen's Reef chiller has been fabricated and shipped to the site for installation.

Future Plans:

- Las Vegas and Houston installations are planned for completion in 1982.

Contractor: Carrier Corporation/SOLERAS

Contract No.: DE-FC03-80ET 20643

Project: Design, fabricate, install, and field test two active solar cooling systems using absorption chillers.

Features: System #1, 15-ton water-cooled absorption chiller and trough tracking collectors (Acurex).

System #2, 10-ton air-cooled absorption chiller and Fresnel dual tracking collectors (E-Systems).

Accomplishments

- The 15-ton water cooled system has been installed and operated at Phoenix test site. Debugging is presently underway.
- The 10-ton air cooled system is complete except for final placement of the chiller. The absorption unit is undergoing extensive lab tests at the Carrier facility in Syracuse, N.Y.

Future Plans:

- Both systems will be field tested and the data will be used in the active solar cooling program.

Contractor: University of Texas at Austin

Contract No.: DE-AC03-79SF 10540

Project: Analysis of double effect absorption cooling system

Features: Determine performance as a function of many parameters, including inlet water, cooling water and chilled water temperatures, location and size of heat exchangers; $LiBr/H_2O$ pair.

Accomplishments:

- Computer model has been successfully developed to simulate operating performance of double-effect absorption cycles.
- Final report has been completed.

Future Plans

- Apply the computer model developed for double-effect absorption chillers to investigate control schemes, parasitic power requirements, and heat exchanger optimization relative to system performance.

- Assist industry in using computer model.

Contractor: Lawrence Berkeley Laboratory

Contract No.: W-7405-ENG-48

Project: Development of advanced-cycle absorption chillers.

Features: Air-cooled; internally powered solution pump; tube-in-tube heat exchangers; single-effect chiller with 3-ton capacity at 218°F using NH_3/H_2O; advanced cycles with COP increasing with temperature; heat pump operation also.

Accomplishments:

- Early testing of single effect chiller verified the condenser, generator, preheater and recuperative solution pump are operating according to design.
- Design drawings have been completed and fabrication is underway for the double-effect regenerative absorption chiller.

Future Plans:

- Detailed testing will conclude on the single-effect chiller.
- Fabrication will be completed, followed by testing of the double-effect regenerative absorption chiller.
- Cycle analysis of the single-effect regenerative absorption chiller will incorporate the results of the SRI measurements of fluids' properties.

Contractor: SRI International

Contract No.: DE-AC03-80CS 30221

Project: Determine pressure-volume-temperature (P-V-T) data and calorimetric data for organic refrigerant and absorbent fluids and their binary mixtures.

Features: Conduct a critical survey of thermodynamic data on absorption fluids and fluid pairs and measure properties of selected fluids and their mixtures.

Accomplishments:

- Literature search has been completed and findings documented.
- Experimental measurements of the properties of the fluids are underway.

Future Plans:

- In-depth experiments will be conducted and the data will be analyzed on selected absorption fluids and fluid pairs.

Contractor: Colorado State University

Contract No.: DE-AC03-81CS 30569

Project: Test and evaluate complete solar cooling systems incorporating absorption chillers, both air and liquid cooled, using CSU Solar Houses I and III.

Features: The CSU Solar Houses contain collectors, storage, chillers, pumps, piping and controls, all fully instrumented for collecting test data. The test systems are scheduled to operate with an ARKLA evaporatively cooled 3-ton chiller and a Carrier air cooled 3-ton chiller.

Accomplishments:

- Instrumentation is in place and programmable controllers are being installed in the Solar Houses.
- Philips Mark I heat pipe evacuated tube collectors have been installed and operated on Solar House I.
- The ARKLA 3rd generation unit was installed in Solar House I and operated briefly at the end of the 1980 cooling season.

Future Plans:

- Extensive testing will be done on the ARKLA 3rd generation chiller using Solar House I during summer 1981.
- Evacuated tube collectors will be selected and installed on Solar House III during 1981.
- The Carrier air cooled 3-ton absorption chiller will be installed in Solar House III and operated during the summer of 1982.

Contractor: University of Maryland

Contract No.: DE AC03-79CS 30204

Project: Technical program support and special studies.

Features: General program support activities; optimization studies and parametric analysis.

Accomplishments:

- Report on refrigerant/absorbent pairs completed.
- Transient simulation of absorption cycles completed and compared favorably to experimental data.

Project: Development of a superheated steam Rankine turbine.

Features: Solar-boiled water at 300°F; fuel-superheated to 1000°F; 4 stage, 75,000 RPM radial outflow turbine; nominal 30 ton.

Accomplishments:

- Laboratory testing of turbine has been completed successfully.
- Final report has been completed.

Future Plans:

- Project completed.

Contractor: Honeywell

Contract No.: NAS8-32093

Project: Development of Rankine cycle chillers and field installation for testing.

Features: 3-ton and 25-ton Rankine chiller design; water-cooled; R-113 power cycle loop; R-12 refrigerant cycle loop; radial inflow turbine, 40,000 RPM; double reduction gear box to 1200 RPM; reciprocating compressor (centrifugal compressor optional); motor/generator auxiliary.

Accomplishments:

- Field test sites continue to be operated successfully and monitored.
- High temperature Rankine unit fabricated and installed at NASA/MSFC.

Future Plans:

- Further technology development to improve efficiency of chiller and cooling system.
- Continued monitoring of operational test sites.

Contractor: Honeywell/SOLERAS

Contract No.: DF-FE02-80ET 20645

Project: Design, fabricate, install and field test 25-ton Rankine cycle cooling system.

Features: Air-cooled; 300°F; R-113 power cycle loop, R-12 refrigerant cycle loop; radial inflow turbine, 40,000 RPM; double reduction gearbox to 1200 RPM; reciprocating compressor; motor/generator auxiliary.

Accomplishments:

- Components have been fabricated and system installed at Phoenix site. Operating tests are presently underway.

Future Plans:

- Continue field operating tests for two cooling seasons.

Contractor: Thermo Electron Corporation

Contract No.: DE-AC03-80CS 30220

Project: Conduct thermal stability tests on fluids used in Rankine cycle systems.

Features: Five identical dynamic test loop to be constructed to test decomposition of organic working fluids as a function of temperature and the materials in contact with the fluid.

Accomplishments:

- Loop designs are completed and construction underway.
- R-11 and R-113 selected as fluids to be tested in four of the loops.

Future Plans:

- Carry out dynamic thermal stability tests of fluids in 5 loops.
- Conduct supplemental capsule tests.

Contractor: Hittman Associates, Inc. (HAI)

Contract No.: DE-AC03-79CS 30202

Project: Technical program support and special studies.

Features: General program support activities; special system, component and economic analyses.

Accomplishments:

- Thermal storage for solar Rankine and absorption cooling systems report completed.
- Performance test plans completed for Rankine and desiccant cooling equipment.
- Hybrid solar/fossil Rankine cooling conceptual study completed and report written.
- High temperature solar cooling topical report completed.
- Preliminary plan for testing of cooling system control strategies was developed.

- Simplified cooling design charts developed on a regional basis, and compared to detailed simulation.

- Parametric studies of PV/T systems have identified performance sensitivities to collector area, storage capacity and other parameters.

Future Plans

- Technical support activities will continue.

- The cooling design charts and PVT analysis will be completed during the next year.

RANKINE PROJECTS

Contractor: Carrier Corporation

Contract No.: DE-AC03-77CS 31590

Project: Development of 25-ton Rankine chiller.

Features: Air-cooled; R-113 in both loops; 290°F; 20,000 RPM turbine directly driving compressor; electric motor shares the load.

Accomplisments:

- Turbo-compressor assembly has passed the air test and is under R-113 test on prototype.

- Two stage boiler feed pump has been fabricated and successfully tested.

Future Plans:

- Operate T/C assembly to design conditions and determine performance map of the chiller.

- Continue development of chiller to include air cooled condensing coils and microprocessor based control system.

Contractor: United Technologies Research Center (UTRC)

Contract No.:DE-AC03-77CS 34510

Project: Development of 18-ton Rankine heat pump.

Features: Air Cooled; R-11 in both loops; 290°F; 45,000 RPM turbo compressor; fossil fuel auxiliary; both heating and cooling operation.

Accomplishments:

- Endurance testing and component assessment has been completed.

- Advanced heat pump design has been completed to improve operating efficiency and reduce fabrication cost.

Future Plans:

- Fabrication and testing of advanced heat pump design.

Contractor: United Technologies Research Center/SOLERAS

Contract No.: DE-FC02-80ET 20642

Project: Design, fabricate, install and field test a Rankine cycle solar cooling system.

Features: 18-ton Rankine cycle heat pump; air-cooled; R-11 in both loops; 290°F; 45,000 RPM turbo-compressor; fossil fuel auxiliary; trough tracking collectors.

Accomplishments:

- Prototype unit converted to air-cooled operation with successful start-up in Phoenix SOLERAS test project.

Future Plans:

- Field testing of SOLERAS system through two cooling seasons.

Contractor: University of Pennsylvania

Contract No.: AC03-78ET-20110

Project: Development of 20-ton superheated steam Rankine chiller.

Features: Solar-boiled water at 260°F; fuel-superheated to 1100°F; 5 stage, 15,000 RPM radial outflow turbine and rotary expander design; stored water flashes to steam.

Accomplishments:

- Fabrication of turbine assembly is being completed and test loop is under construction.

Future Plans:

- Performance map of turbine will be measured using the steam power loop.

Contractor: Energy Technology, Inc. (ETI)

Contract No.: AC03-80CS-30214

Future Plans:

- Technical support activities and special studies will continue.

SYSTEM ANALYSIS PROJECTS

Contractor: Science Applications, Inc. (SAI)

Contract No.: XB-0-9145-1

Project: Performance and economic analyses of absorption and Rankine cooling systems.

Features: Develop computer programs to evaluate system performance and economics for residential and commercial active solar cooling systems; selected cities used.

Accomplishments:

- Completed detailed system modeling of 25-ton absorption and Rankine chillers.
- Annual system simulations and economic analyses completed for four cities.

Future Plans:

- Continued system evaluation for additional locations and system configurations.

In addition to the activities in the above contracts, extensive planning efforts are underway for long-range development efforts in the active solar cooling program. An important function for this planning effort was the active solar cooling workshop attended by representatives from the solar and HVAC industry, utilities and local government, financial and marketing organizations, and the architecture and engineering fields. The workshop concentrated on four major topics: (1) technical, (2) financial, (3) codes and standards, and (4) marketing aspects of active solar cooling. The response from the 28 attendees provided a data base for follow-on presentations that will further contribute to DOE's planning efforts.

FUTURE ACTIVITIES

From a technical point of view, the Rankine and absorption projects have progressed from the very early design and development stage to operating prototypes undergoing performance evaluations. Operation of many of the early prototypes have identified key areas of concerns for Rankine units such as optimized system control, bearing design and cooling schemes, back-up system alternatives, and heat exchanger designs. For the absorption systems, concerns are fluid flow design in the absorber section, heat exchanger optimization, control functions, and parasitic power reduction. Common concerns for both systems are cost reduction, collector and storage selection criteria, and fluid stability at high tempertures. The future activities of the active solar cooling program will address these key concerns.

In the past year, substantial progress has been made identifying quantitative program goals. A method of system analysis has been developed to provide values of cost and performance goals, using computer simulation models and results of market analysis. This effort is continuing.

It is expected that further development in the absorption and Rankine cooling technologies will ensue as a result of competitive solicitations for advanced cooling systems and components. In addition, it is planned to conduct systems engineering of developed components leading to design and application manuals that will be available for use by A&E firms and the HVAC industry.

REFERENCES

[1] Michael Wahlig, Al. Heitz, and Barbara Boyce, "Overview - Absorption/Rankine Solar Cooling Program," Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26-28, 1980.

DEVELOPMENT OF A HIGH TEMPERATURE SOLAR POWERED WATER CHILLER

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

RICHARD A. ENGLISH

DE-AC-3-77CS31590

OBJECTIVE

The objectives of this program are: to develop a high temperature solar powered air cooled 25 ton chiller utilizing 250 to 300°F solar hot water suitable for commercial and multi-family applications; to study, design and build a prototype Rankine powered vapor compression cycle; and to demonstrate and evaluate performance through steady state and dynamic laboratory testing.

DESCRIPTION OF WORK

The design concept chosen as a result of Phase I work is a dual loop Rankine power cycle driving a Rankine vapor compression cycle. A single working fluid, R-113, is used and both loops are connected to a common condenser (Figure 1). The prime mover is a high speed turbo compressor being developed under subcontract by Mechanical Technology Inc. This hermetic machine consists of a single stage centrifugal compressor driven by a radial inflow turbine. An auxiliary motor is mounted on the shaft between the turbine and compressor and will be powered by a variable frequency inverter. The shaft assembly is supported on gas film bearings to eliminate oil from the system (Figure 2).

The chiller will be an air cooled outdoor packaged unit similar to conventional rooftop air conditioning equipment. Under design conditions of 45°F leaving chilled water, 95°F entering condenser air and 290°F entering solar water, the chiller will produce 25 tons of cooling at a COP predicted to be above 0.70 with low parasitic power.

Under Phase II, the detailed design of all of the components and the final assembly was completed; preliminary thermal stability tests on R-113 were carried out successfully. The project is now in Phase III. The chiller has been built in a water cooled configuration for initial turbo machine testing, and has been installed and instrumented in a special test facility. The turbo machine was built and successfully tested on air at MTI. The air tests verified the dynamic stability of the rotor running on the gas bearings at all speeds up to the design speed of 24,000 rpm. Initial spin testing now underway with R-113 in the solar chiller is directed at reproducing the air tests and confirming the rotor dynamics predicted for R-113 (Figure 3). Another aspect of this testing is to verify motor/bearing cooling gas flow and the resulting cooling effectiveness. At the same time, experience with the boiler feed pump and its piping design is being gained (Figure 4).

When these initial qualification tests are completed satisfactorily, performance mapping of the turbine and compressor will be undertaken. At the same time, a performance evaluation of the major heat transfer components and the overall cycle can be accomplished. Control strategies will also be explored and evaluated.

The air cooled configuration will then be built, controls will be finalized, and tests will be run to verify performance of the final chiller concept.

ACCOMPLISHMENTS

- Cycle studies and preliminary turbo machine studies were completed under Phase I establishing the final conceptual approach and anticipated cost/performance.
- The evaluation of the working fluid thermal stability has satisfactorily shown that R-113 has excellent life potential in an oil-free steel boiler at the maximum expected temperature, 320°F, for this application.
- The detailed design of the turbo machine and the chiller has been completed.
- The turbomachine has been completed and has successfully passed its qualification tests on air.
- The chiller has been built in the water cooled configuration, has been installed in a test facility, instrumented and charged.
- A two stage boiler feed pump has been developed and successfully tested on R-113 in a separate loop.

FUTURE ACTIVITIES

- Initial qualification tests of the turbo machine are underway in the chiller test loop to evaluate the dynamic behavior of the turbo machine.
- After dynamic testing, the turbo machine performance will be mapped over the expected operating range and evaluated.
- The chiller performance will be mapped over the expected operating range and evaluated.
- The chiller will be converted to the final air cooled configuration and performance testing will be undertaken to complete the scope of work of the original contract.

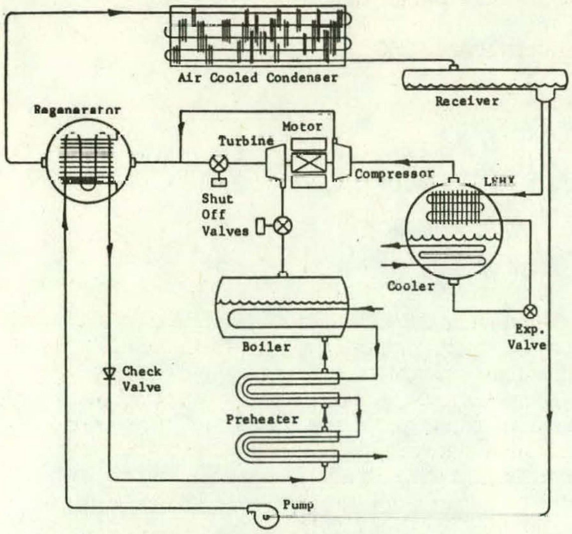


FIGURE 1. Air cooled Dual Loop Rankine Driven Vapor Compression Cycle.

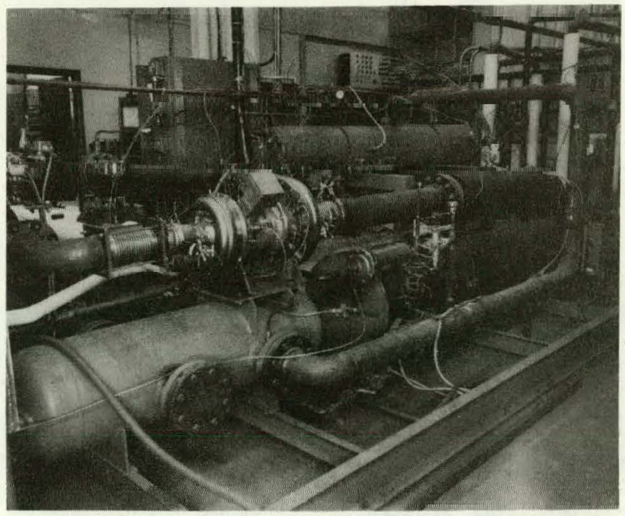


FIGURE 3. Carrier Solar Chiller Water Cooled Test Bed.

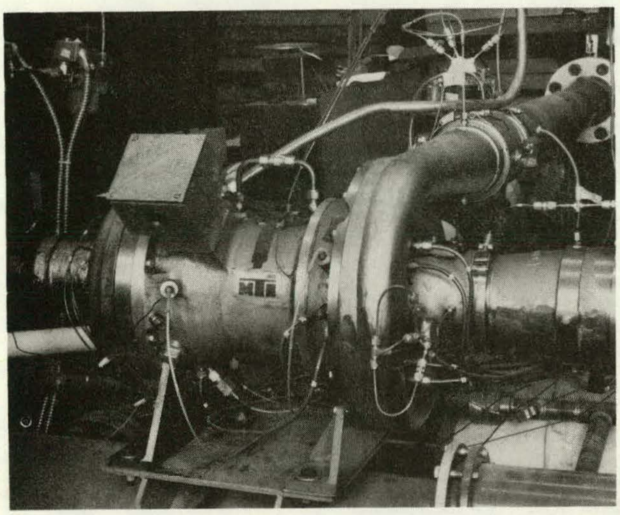


FIGURE 2. Carrier/MTI Solar Powered Water Chiller Turbo Machine Instrumented for Test.

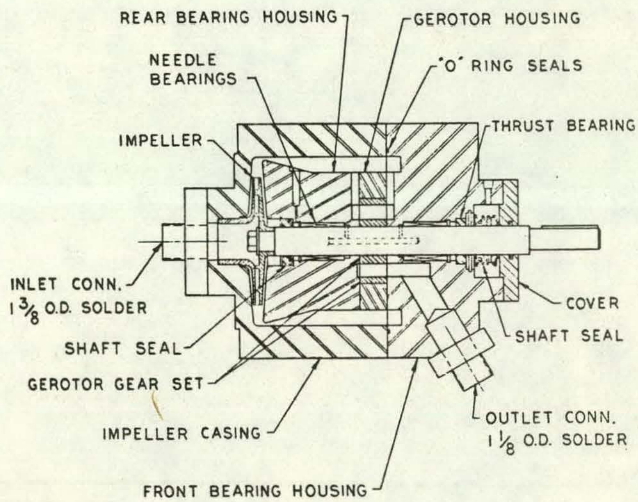


FIGURE 4. Cross Section of Prototype Boiler Feed Pump.

PUBLICATIONS/REPORTS

1. Development of a High Temperature Solar Powered Water Chiller, Phase I Technical Progress Report for Period September 1977 to June 1978. Volumes I, II, III, and IV. R. A. English, SAN-1590-1/314 (1978).

2. Development of a High Temperature Solar Powered Water Chiller, Phase II Technical Progress Report for Period June 1978 to March 1979. Volumes I and II. R. A. English.

3. Development of a High Temperature Solar Powered Water Chiller, Phase III, Technical Progress Report for Period April 1979 to September 1979, Volume I, R. A. English.

4. Development of a High Temperature Solar Powered Water Chiller, Proceedings of DOE Active Solar Heating and Cooling Contractors' Meeting, March 26-28, 1980, R. A. English, CONF 800340

CONTRACT INFORMATION

START DATE October 1977 END DATE August 1981 CONTRACT VALUE $1,842,000

MILESTONES

Item:		Due date:
1.	Phase I	May 1979
2.	Phase II	January 1980
3.	Phase III - Point "A"	August 1981
4.		
5.		

SOLAR HEATING AND COOLING SYSTEMS

HONEYWELL, INCORPORATED; 1700 WEST HIGHWAY; ROSEVILLE, MINNESOTA 55113

STEVE SCARBOROUGH

NAS8-32093

The NASA Marshall Space Flight Center, working in support of the U.S. Department of Energy to develop solar heating and cooling systems for residential and commercial application, entered into a contract in June 1976, with Honeywell, Inc., of Minneapolis, Minnesota, to design and develop solar systems having high performance, low cost, modular application, and marketability. Acting as the prime contractor responsible for the solar system design, Honeywell teamed with Barber-Nichols of Denver, Colorado, and Lennox Industries of Dallas, Texas.

In keeping with the objectives of the solar energy development effort, Honeywell was given the task of providing solar heating systems for residential use and solar heating and cooling systems for residential, multi-family, and commercial application. This responsibility includes the full range of system design, fabrication, installation, maintenance, and evaluation.

The major outgrowth of the team design effort was two solar energy systems which utilize flat plate collectors and are capable of both heating and cooling. Similar in operation, the systems differ principally in their size and energy output. The smaller system, designed for home use, is capable of heating and producing 3 tons of cooling, while the system designed for commercial application provides cooling in 25-ton increments in addition to providing heat. Further development effort resulted in a higher efficiency high-temperature version of the 25-ton chiller for concentrating collector application and a power generation module. The power generation module, based on the 25-ton chiller power unit, is capable of producing up to 13 KVA. During the course of the development effort, other major accomplishments included: full qualification of the Lennox collector to the Interim Performance Criteria; the development of a residential energy transport module; the development of a high-performance, low-cost heat exchanger; and the development of a low-cost collector support structure and headers. Further work was done in the definition and testing of several system improvements (including an improved centrifugal compressor, gear box, and purge system) and the study of power generation.

As the prime contractor, Honeywell was responsible for the solar system design, overall program management, and subcontractor coordination. Barber-Nichols developed the Rankine-cycle engine used in the 3-ton Rankine-engine-assisted direct expansion air conditioner and 25-ton Rankine-engine-assisted water chiller. Lennox Industries supplied the HVAC products, purge units, collectors and packaged the 3-ton Rankine-assisted air conditioner. Currently, four 3-ton residential systems, two 25-ton multi-family or commercial systems, and two 50-ton commercial systems are operating in the field. Installation of both the 25-ton high-temperature system and the power generation module are currently underway.

The 3-ton and 25-ton solar heating and cooling systems are basically similar and include the following subsystems:

Collection Subsystem which consists of 600—840 square feet (3-ton) or 4,500—5,000 square feet (25-ton) of water-glycol cooled flat-plate collectors. A purge coil unit with fin-tube coil and blower is used to dissipate excess or unused heat energy from the collectors.

Storage Subsystem which utilizes 1,000 gallon (3-ton) or 3,000--8,000 gallon (25-ton) insulated steel tanks.

Space-Heating Subsystem which employs solar heated water through a water-to-air fin-tube coil in a conventional hot air furnace, air handler or fin coil blower.

Domestic Hot Water Preheat Subsystem.

Energy Transport Subsystem (Residential) which contains the pumps, valves, heat exchanger and hydronic specialities in a sturdy and attractive steel cabinet (32H x 42L x 26W, 550 lbs.).

Control Subsystem which consists of the solar control panel, building thermostat, temperature sensors and valves. Early systems use control panels utilizing relay logic and later systems use microprocessor-based programmable controllers that also provide diagnostics. Small status panels mounted on the controller door and near the thermostat provide a visual indication of system mode and malfunctions.

Rankine-Cycle Air Conditioner System which employs a vapor compression chiller driven by a solar-powered Rankine cycle engine. The Rankine-cycle engine couples to the chiller compressor through a double-shafted electric motor that furnishes power for cooling when there is insufficient solar energy and also serves as an electrical generator when there is more solar energy than that needed for the cooling requirements.

The general system schematic is shown in the attached figure. The Rankine engine cycle is similar to the vapor compression cycle, with the Rankine being the reverse of the vapor compression. Both cycles use halogenated refrigerants for working fluid; R-113 for the Rankine cycle and R-12 for the chiller cycle.

Operation of the Rankine engine can be traced by referring to the turnoff valve in the schematic. Leaving the valve, the high pressure, high-temperature working fluid enters the turbine as a vapor. There it expands through the turbine wheel where the fluid energy is given up to the high-speed wheel. This energy, in turn, is transmitted through the gear box to reduce the speed to that suitable for the electric motor and the chiller compressor. The vaporized working fluid exhausted from the turbine rotor, still containing excess energy, is directed into a heat exchanger called the regenerator. The other side of the regenerator contains the liquid working fluid going to the boiler. The regenerator simply passes energy from one part of the cycle to another, improving the efficiency of the cycle. After the vapor has given up some energy in the regenerator, it passes to the condenser where it is cooled and converted to a liquid. This is accomplished by giving up heat to the cooling water furnished by a cooling tower or evaporative condenser. The saturated liquid leaves the condenser where it is pumped to the liquid side of the regenerator, where it receives the energy from the turbine exhaust. It then enters the boiler where it receives heat from the solar fluid. This energy converts it to a high-pressure, high-temperature fluid ready to go into the turbine.

The control system for the unit permits it to provide the maximum energy output under varying conditions. Full rated power is reached by the Rankine-cycle turbine power unit when 195^{o}F. solar-heated water is available. However, the unit will deliver lesser amounts of power down to an input temperature of 150^{o}. With 195^{o} F. solar-heated water available, the unit will provide the power to drive the air-conditioning compressor to full output. The electric motor/generator will provide whatever additional power is required when the inlet temperature is less than 195^{o} F. if full compressor output is required.

During periods of ample solar insolation and diminished cooling requirements, the excess turbine power can be used to overdrive the electric motor, thus generating electricity. If no cooling requirement is present during periods of adequate solar energy, the electromagnetic clutch between the motor/generator and the compressor can be disengaged to permit direct electrical power generation. The generating mode requires line voltage and frequency excitation, thus assuring a safe condition if there is a general power outage. Without the air-conditioning compressor engaged, the commercial size unit can produce up to 12.8 KW while the residential unit can produce up to 1.5 KW, less pump and control power.

During the program, ten solar heating and cooling systems were designed, fabricated, installed and put into operation at ten different sites in nine states.

Eight sites were equipped with site data acquisition system. In addition, two heating-only systems were installed at New Castle, Pennsylvania, and William O'Brien, Minnesota. Table 1 is a summary of the site characteristics.

William O'Brien, Minnesota - SFR Heating Site

This system utilizes 33 collectors (600 square feet) to provide solar assisted heating to a gas-fired hot air heating system. The space heat energy requirements during the test period amounted to 73 x 10^6 Btu. Over the year, 60 million Btu's were collected, 47 million Btu's were delivered to storage, 32 million Btu's went to space heating, and 7.4 million Btu's were contributed to domestic hot water heating. During the best month (August), 6.8 million Btu's were collected. Analysis of daily data indicates that the system is functioning satisfactorily with a maximum collector rate of 83,000 Btu's per hour and a peak efficiency of 49 percent.

New Castle, Pennsylvania - SFR Heating Site

This system utilizes 28 roof-mounted collectors (500 square feet) to provide solar assisted heating in a conventional heat pump and resistive heating system through a water-to-air coil mounted in the air handling unit. This system also provides solar preheated DHW. A total of 15 x 10^6 Btu was collected over the 5-month test period with an average of 35 percent efficiency, with total energy load and available energy slightly lower than expected. The solar contribution towards meeting the load was 12 x 10^6 Btu. This was 36 percent of the load, slightly lower than the predicted 40 percent.

Duffield, Virginia - SFR Heating and Cooling Site

This system utilizes 36-roof-mounted collectors (650 square feet) to provide solar assisted heating and cooling to an electric forced air system. The operational test period started November 1, 1979, and ended October 31, 1980. The system performed well throughout the 12-month test period, keeping the house very comfortable. Final processing of the data is in progress. Preliminary data for September 1980 indicates an average operational collector efficiency of 36 percent. The system collected 6.4 x 10^6 Btu during September, of which 1.6 x 10^6 Btu were used for solar cooling. The balance of the collected energy was used to heat domestic hot water and generate electricity and some was lost. Of the space cooling load, 43 percent was supplied by solar energy during September 1980.

Newnan, Georgia - SFRH Heating and Cooling Site

This system utilizes 39 roof-mounted collectors (700 square feet) to provide solar assisted heating and cooling to a natural gas-fired forced air system. This site is equipped with the microprocessor controller. System installation was completed in October 1980 and the system has been operational since that time. During January 1981, the system collected 7.1 x 10^6 Btu with an operational collector efficiency of 34 percent, and 75 percent of the heating load of 6.8 x 10^6 Btu was met by solar energy. The solar heating fraction was higher during February.

The Rankine-cycle air conditioner was made operational in mid-April and has been generating power and cooling the house since then.

Lawrenceburg, Tennessee - SFR Heating and Cooling Site

This system utilized 30 roof-mounted Daystar collectors (630 square feet) to provide solar-assisted heating and cooling to an electric forced air system. The system became operational in August 1979. The system operates satisfactorily but is not instrumented with a Site Data Acquisition System for data collector.

Allaire State Park, New Jersey - SFR Heating and Cooling Site

This system utilizes 40 ground-supported Daystar collectors (840 square feet) to provide solar assisted heating and cooling to an oil-fired forced air system. This system is equipped with the programmable microprocessor controller. The system became operational in mid-November 1980. The system has operated well in the heating mode and will be operated in the cooling mode for the first time this summer. This system does not have a Site Data Acquisition System.

University of Kansas, Lawrence, Kansas - 25-Ton MFR Heating and Cooling (Multi-Family)

This system utilizes 252 ground-mounted collectors (4,700 square feet) to provide solar assisted heating and cooling through a hydronic loop to air handlers in twelve apartments. This system also has an 8,000 gallon storage tank. The system functioned well during the heating and cooling seasons. Over the 12-month period (December 1978 to December 1979), 489 million Btu's were collected. Of this total, 112 million Btu's were delivered to space heating, 88 million Btu's were supplied to domestic hot water and 152 million Btu's were delivered to the Rankine engine. The Rankine-engine driven air conditioner supplied 25 million Btu's solar cooling and the Rankine-driven generator supplied 275 kWhr. Honeywell has analyzed information from the SDAS to prepare a performance report. On November 10, 1979, a day chosen for heating season analysis, solar energy supplied 2.7 MMBtu's of space heating, with 78 percent of the solar space heating coming from storage and 22 percent from direct heating from the collector array. The majority of the heating load is seen at night when the system is in the heating from storage mode. The natural gas savings on this day was 3.9 MMBtu's. During a selected cooling season day, July 26, 1979, solar energy supplied 24 percent of the cooling load over the entire day. At peak solar conditions, the Rankine engine supplied all of the chiller shaft input power and generated 7.3 kWh.

Ocmulgee, Georgia - 25-Ton Commercial Heating and Cooling Site

This system utilizes 280 ground-mounted collectors (4,900 square feet) to provide solar-assisted cooling and heating through hydronic air handlers and air units in the Visitor Center at the Ocmulgee National Monument, Macon, Georgia. This system has a 4,000 gallon storage tank and provides DHW preheat. The system at this site has been fully operational since March 25, 1981. Data is being received and is currently being analyzed.

Carrollton, Texas - 50-Ton Commercial Heating and Cooling Site

This system utilizes 432 ground-mounted collectors (7,800 square feet) to provide solar assisted cooling and heating through hydronic air handlers in the Lennox Industries Research Laboratory in Carrollton, Texas. This system has a 6,000 gallon storage tank. The 50-ton capacity is obtained by operating two 25-ton units, either in parallel or independently. Analysis of the site data is underway. The system provided space cooling and generated electricity, although there was no heating load during the year-long test period.

Phoenix, Arizona - 50-Ton Commercial Heating and Cooling Site

This system uses 456 roof-mounted collectors (8,200 square feet) to provide solar assisted heating and cooling for a Salt River Project electric power company maintenance and warehouse building near Phoenix, Arizona. This system has a 2,500 gallon storage tank. A Honeywell designed and built microprocessor-based tailorable controller was installed to provide the control logic and diagnostics. This installation is the last of the solar operational test sites and incorporates all of the technical developments, innovations, and experience acquired from the previous sites. System startup occurred on April 30, 1981. Site data is presently being analyzed. The data indicates the system is operating within the design parameters.

Other hardware produced includes:

13 KVA Power Generation Module

The 13 KVA power generation module has been designed, fabricated, and tested. This unit used the "25-Ton" Organic Rankine engine and a generator to feed solar-produced air conditioned power into the grid. This unit will soon be installed at the University of New Mexico in Albuquerque using a field of both flat plate and evacuated tube collectors. Operation of this system is expected to start in late summer 1981.

High-Temperature Rankine-Assisted Chiller

The high-temperature, 25-ton Rankine-assisted water chiller represents an extension of the work that Honeywell, Barber-Nichols Engineering, and Lennox have completed on low-temperature, 25-ton units and on the company funded high-temperature, 100-ton chiller units used in the General Offices system at Honeywell Plaza in Minneapolis. This program involved primarily a Barber-Nichols' design, fabrication, test and delivery of one high-temperature, 25-ton Rankine-assisted chiller. The unit has been delivered and is being installed at the Medical Center at NASA Marshall Space Flight Center, near Huntsville, Alabama.

Of particular interest is the study completed in December 1980 of solar power generation. The report documents a study of light commercial solar heating systems with and without solar power generation via a Rankine-cycle engine. Generally, solar energy costs and system payback periods were reduced for mass-produced solar energy systems by the addition of solar power generation to systems with larger collector array areas (3,000 to 7,000 ft.^{2}). The precise collector area for which this holds was found to be a function of site location and collector type. Overall, flat plate solar energy systems were found to be more cost effective than evacuated tube system.

All the development team members, Honeywell, Lennox, and Barber-Nichols, continue to monitor the marketplace for opportunities to commercialize the hardware, subsystems, and systems developed on the program. At this time, the flat plate collectors are in mass production at Lennox and are being sold in support of HVAC systems nationwide. The solar domestic hot water heating system is a production product with full marketing sales distribution. The basic solar residential heating system and its design application are included in the Lennox product offering. The site application and component selection are now being accomplished by Lennox distributors.

The heating and cooling systems involve the more sophisticated Rankine-driven subsystem and are not yet in sufficient demand to expand marketing and production efforts. However, the team members have stated their intentions to pursue additional opportunities for the developed hardware to increase the size of the market, thus increasing the sales potential needed to establish production tooling and fabrication.

CONTRACT INFORMATION

START DATE 7/76 END DATE 9/81 CONTRACT VALUE Prior Years - $7.1M; FY 81 - $500,000

MILESTONES

Item: Due date:

1.

2.

3.

4.

5.

1810-79

GENERAL SYSTEM SCHEMATIC FOR RANKINE-CYCLE AIR-CONDITIONING SYSTEM

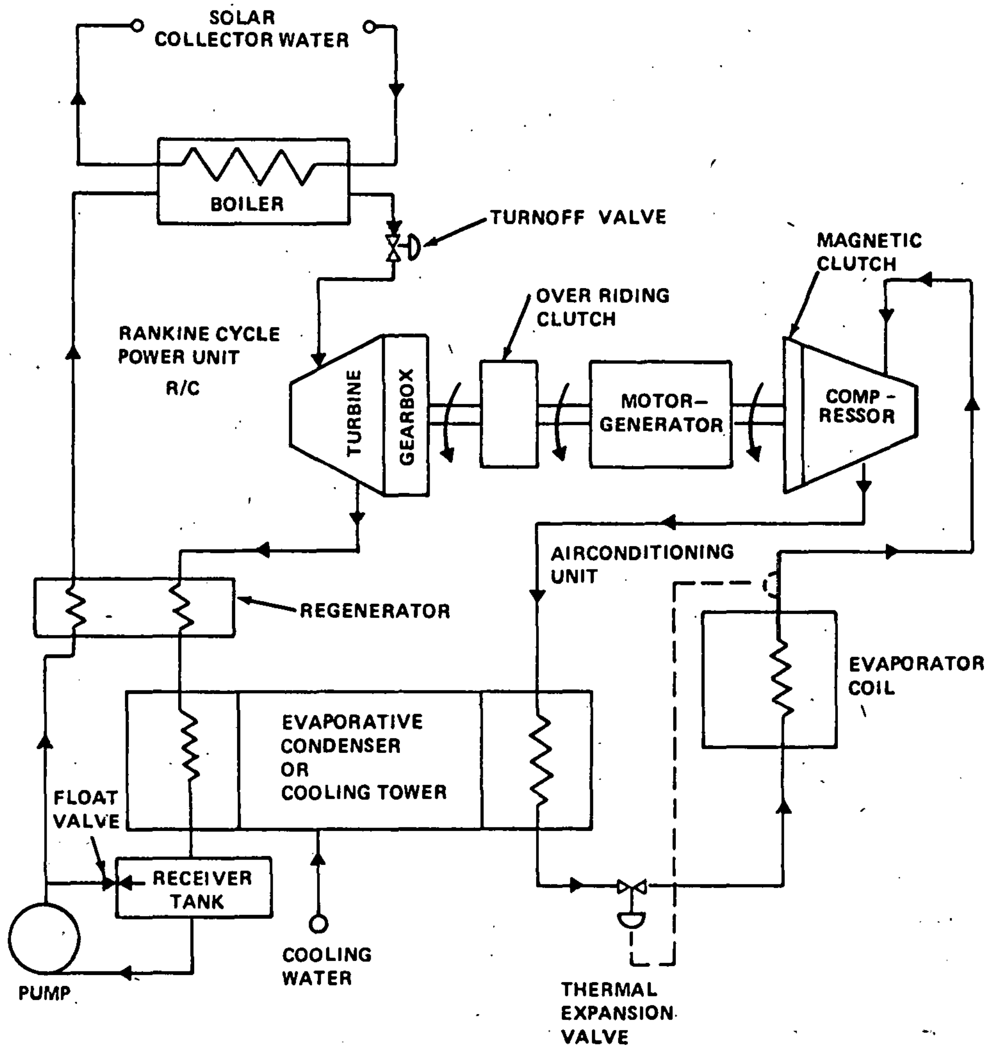


FIGURE 1

SITE	LOCATION	TYPE (SEE LEGEND)	FIELD SIZE (SQUARE FEET)	A/C SIZE (TONS)
RESIDENCE	WM. O'BRIEN PARK, MN	H/DHW	600	--
RESIDENCE	NEW CASTLE, PA	H/HDW	500	--
RESIDENCE	DUFFIELD, VA	H/C/DHW	650	3
RESIDENCE	LAWRENCEBURG, TN	H/C/DHW	630	3
STUDENT RESIDENCE	KANSAS U, KS	H/C/DHW	4700	25
VISITOR CENTER	OCMULGEE NATIONAL MONUMENT, GA	H/C/DHW	4900	25
LENNOX RESEARCH CENTER	CARROLLTON, TX	H/C	7800	50
RESIDENCE	NEWNAN, GA	H/C/DHW	700	3
RESIDENCE	ALLAIRE PARK, NJ	H/C/DHW	840	3
SALT RIVER PROJECT	PHOENIX, AZ	H/C	8200	50

LEGEND: H = HEATING
C = COOLING
DHW = DOMESTIC HOT WATER

TABLE 1 - SITE CHARACTERISTICS

DETERMINATION OF THE THERMAL STABILITY OF
ORGANIC WORKING FLUIDS USED IN RANKINE CYCLE SYSTEMS

Thermo Electron Corporation

Dr. Dean T. Morgan

DE-AC03-80CS30220

OBJECTIVE

The determination of the rate of decomposition of organic working fluids due to either pyrolytic or chemical reaction phenomenon, or both, as a function of temperature and the materials in contact with the fluid, under dynamic conditions simulating the use of the fluid in Rankine engines for solar cooling applications.

DESCRIPTION OF WORK

Several prototype systems for active solar cooling have been constructed, based on solar-heated Rankine cycle engines utilizing organic working fluids to drive air-conditioning equipment. These prototype systems use refrigerants, specifically R-11 and R-113, as working fluids in the Rankine engine. In future developments, other working fluids, particularly those with a higher thermal stability than the refrigerants, may be used in these systems.

A program objective is the achievement of high performance by operating at design temperatures that approach the thermal stability limit of the organic working fluids. Achievement of high performance is of particular importance for solar Rankine cooling in order to reduce the solar collector cost and maximize the economic potential of these systems. At the same time, it is also essential that the systems have a long life with minimum maintenance requirements for practical and economic commercial usage.

For the most part, thermal stability properties of the organic working fluids have been obtained from prior work as reported in the existing literature, based primarily on static capsule testing supplemented in some cases by limited capsule testing by the prototype system developers. Now that prototypes of several of these Rankine systems have been constructed, it is imperative that the long-term thermal stabilities of the working fluids be demonstrated. For the results to be meaningful, the fluids must be tested dynamically for extended periods of time; the dynamic loop must reasonably simulate conditions experienced in real Rankine systems; and the fluids must be exposed to the same materials that will be encountered in practice.

In this program, five identical dynamic loops will be constructed and used for the long-term testing of organic working fluids, of interest for solar Rankine cooling, under carefully controlled test conditions. The loop-flow-schematic is illustrated in Figure 1 and includes all components in an actual Rankine engine with the exception of the expander which is replaced

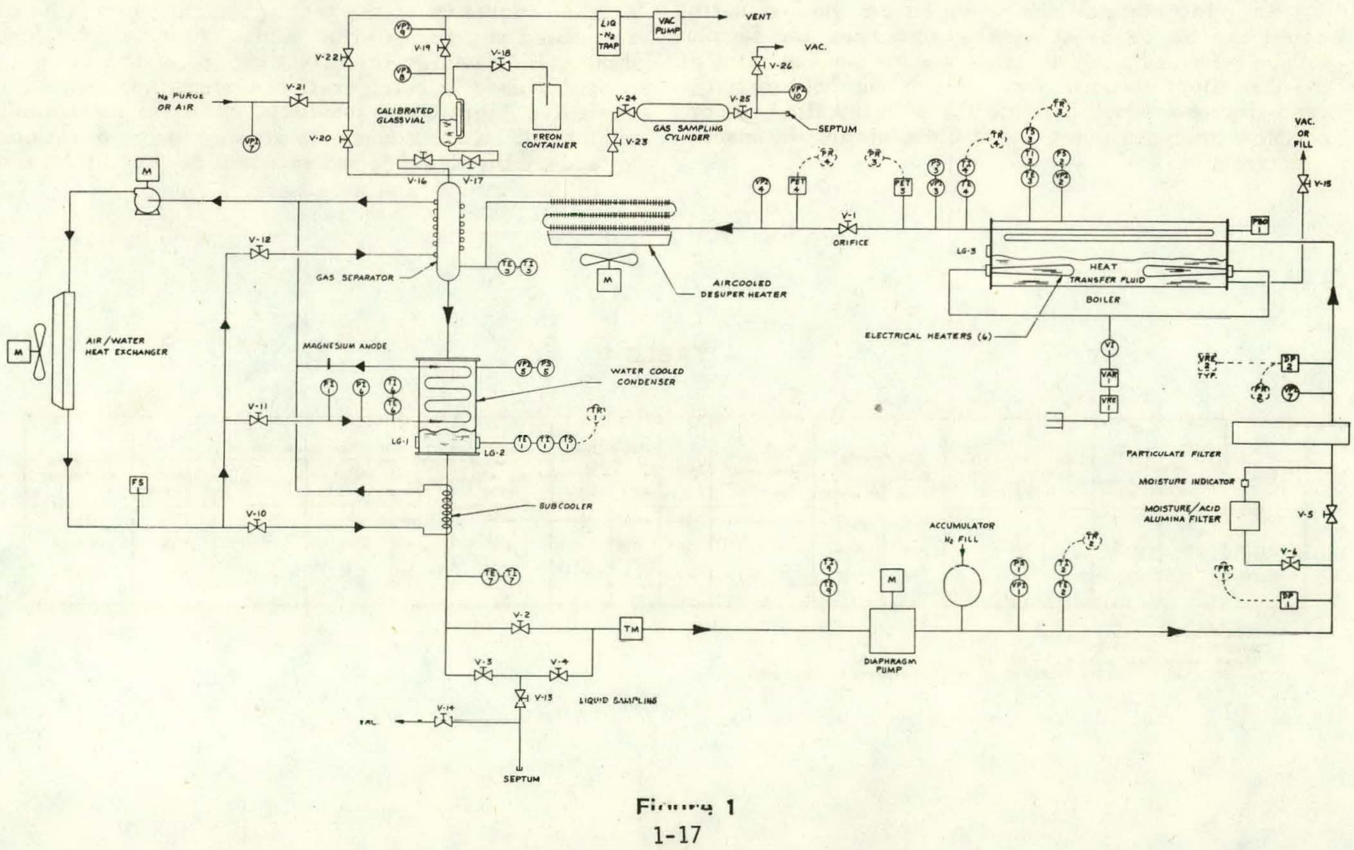


Figure 1

by a variable orifice pressure let-down valve to reduce the boiler pressure to the condenser pressure. The main considerations in the loop design have been:

- High reliability and leak-tightness
- Loop control for long-term stable operation with a minimum of attention
- Key temperature and pressure measurements
- Materials of construction and loop inventory/surface area ratios within the range of actual hardware

An additional design consideration has been capability for future testing of high-temperature working fluids (up to 750°F boiler outlet temperature) at boiler pressures up to 1150 psia, even though the initial testing is to be concentrated on low-temperature working fluids.

A key component for long-term operation is the pump. Because of its reputation for high reliability, as well as the need for a hermetic pump, a LEWA Diaphragm Metering Pump (Teflon/carbon diaphragm) with maximum flow capability of 17 gph was selected. The boiler is electrically heated and used vapor-phase heat transfer to the boiler tube carrying the test fluid (FC-77 heat transfer fluid for the low-temperature testing). The boiler tube bundle is 44 feet of 0.50 inch o.d. carbon steel tubing arranged in a serpentine fashion in the vapor space. The primary material of construction used throughout the loop is carbon steel. An aluminum tube downstream of the pressure let-down valve is used to simulate the aluminum construction expected in the turbine for commercial systems using low-temperature fluids. The condenser is water cooled and a liquid reservoir is provided to provide fluid inventory for liquid sampling throughout a test.

Sampling stations are provided for the circulating liquid and for vapor above the condenser and samples will be taken at periodic intervals for measurement of the fluid degradation. Dr. Vernon Reinhold of Harvard University will provide the primary fluid/vapor chemical analyses using a gas chromatography/mass spectrometer.

Following discussion with the major system developers, the following recommendations were made for the fluids to be tested in the five loops:

Loop No.	Test Fluid	Lubricant?	Initial Boilei Outlet Test Temperature °F
1	R-11	No	275
2	R-11	Yes	250
3	R-113	No	275
4	R-113	Yes	250
5	R-114 (tentative)	No	300

R-11 and R-113 are the fluids used by the major system developers. R-114 was recommended as a fluid with higher thermal stability than either R-11 or R-113. Loop design point conditions for each fluid are summarized in Table 1. The estimated loop internal volume and fluid inventory are summarized in Table 2 and other pertinent operating characteristics summarized in Table 3.

The fluid degradation rate for each test condition will be determined for at least three boiler outlet temperatures. The test program will evaluate the penalty on temperature limit resulting from use of a lubricant in the system. Within the limits of the available test time, the effect of trace quantities of O_2 and H_2O on the temperature limit will also be evaluated. The loop testing will be supplemented as required with selected capsule tests to aid in interpretation of the loop results.

An additional goal of the program will be to provide guidance to the system developers on the effects on the loop of fluid decomposition, in particular formation of noncondensable gases, formation of corrosive degradation products, and modification of fluid properties (particularly the lubricating oil if used). At the conclusion of the testing, each loop will be disassembled and the internal surfaces inspected. Also, during the testing, the effectiveness of the dryer normally used in refrigeration systems in removing corrosive degradation products will be experimentally evaluated. While a complete answer to the question of an acceptable degradation rate will not result from the

TABLE 1

Fluid	Nominal Boiler Outlet		Vapor Temp. After Let-Down Valve (°F)	Condensing		Liquid Subcooled To: (°F)***	lb/hr	Liquid Flow Rate		Boiler Electrical Power Input (kWe)	Heat Loads, Btu/hr				Ideal Pump Horsepower
	T (°F)	P (psia)		T (°F)	P (psia)			GPH	cc/min		Boiler	Vapor Subcooling	Condensing	Liquid Subcooling	
R-11*	300	300.21	230	110	27.75	70	173.9	14.0	885	5.12	17,460	3180	12,920	1450	0.037
R-113*	300	175.6	270	136	20.0	70	118.8	9.06	572	3.41	11,620	2544	7,335	1743	0.014
R-114**	350	304	320	94	41.8	70	187	15.7	991	5.64	19,240	8135	10,008	1097	0.040

*Saturated vapor cycle
**Superheated vapor cycle
***Liquid subcooling to provide 14.5 psi NPSH
****Let-down valve orifice area approximately same for all fluids at design point

current program, an objective is to provide a rational and technical basis for use by the system developers in selecting an acceptable decomposition rate and operating temperature for their particular system.

TABLE 2

Component	Internal Volume (cm^3)	Fluid Mass (grams) R-11	R-113	R-114
Pump	7	11	11	10
Accumulator	100	149	157	143
Line - Pump to Boiler (5-ft length)	143	213	225	205
Particulate Strainer	7	11	11	10
Boiler Tube (44-ft length)	1260	470 liquid 109 vapor	495 liquid 80 vapor	450 liquid 139 vapor
Line - Boiler to Let-Down Valve (1-ft length)	29	3.4	2.4	3.4
Line - Let-Down Valve to Desuperheater (1-ft length)	29	0.3	0.2	0.4
Desuperheater	260	2.6	2.2	4.3
Gas Separator	150	1.6	1.5	3.1
Condenser Vapor Liquid (Initial)	 700 600	 7.5 894	 7.1 942	 14.7 858
Line - Condenser to Pump Including Subcooler (7-ft length)	200	298	314	286
TOTALS	3485	2170	2248	2127

Commercial Dryer - ∿20 cm^3 liquid volume (packed with 30 $in.^3$ of Activated Alumina, Zeolite)

TABLE 3

	R-11	R-113	R-114
Inventory Fraction in Vapor Generator	0.27	0.26	0.28
Inventory Fraction as High Temperature Vapor	0.052	0.037	0.067
Average Boiler Heat Flux, Btu/hr-ft^2	3530	2350	3890
Average Refrigerant Liquid Volume/Boiler Internal Surface Area, cm^3/ft^2	294	290	300

TECHNICAL ACCOMPLISHMENTS

- Discussions with the major system developers were held and recommendations for the test program developed.
- The loop design has been completed and the construction of the first loop is in progress.

FUTURE ACTIVITIES

Contract Activities

The first loop should be assembled by early May for checkout and startup. Early operation of this loop will permit any required design modifications to be incorporated in the remaining four loops prior to their construction. The schedule for startup of the remaining four loops is:

Loop No.	Planned Startup
2	September 1, 1981
3	October 1, 1981
4	October 1, 1981
5	November 1, 1981

Post-Contract Activities

An appropriate use of the dynamic loops following the current contract would be testing of higher-temperature organic working fluids than the refrigerants as well as resolution of any remaining questions on the low-temperature fluids.

PUBLICATIONS/REPORTS/REFERENCES

No publications on the program have been issued at present.

CONTRACT INFORMATION

START DATE Sept. 30, 1980 END DATE Sept. 30, 1982 CONTRACT VALUE $418,244

MILESTONES

Item:	Due date:
1. Detailed Test Plan	January 1981 (m)
2. Summary Reports on Test Results for Each Fluid	Within 30 Days After Completion of Tests on That Fluid (p)
3. Final Report	September 30, 1982 or Within 30 Days of Completion of Experimental Program (p)
4.	
5.	

DESIGN, DEVELOPMENT AND TESTING OF A SOLAR-POWERED TURBOCOMPRESSOR HEAT PUMP SYSTEM

RESEARCH CENTER AND HAMILTON STANDARD DIVISION OF UNITED TECHNOLOGIES

UTRC: F. R. BIANCARDI, G. MELIKIAN; HSD: J. W. SITLER

DE-AC03-77CS34510

OBJECTIVE

United Technologies is currently designing, building and conducting laboratory and field tests of unique solar-powered heat pumps and solar cooling systems sized for multifamily residential and light commercial applications. The heat pumps and solar chillers are specifically designed to operate at moderate peak temperatures and to permit efficient air cooling. The basic design data has been developed under prior NSF/ERDA, and DOE-sponsored programs in which UTRC demonstrated the operational feasibility and performance advantages of Rankine-cycle solar heating and cooling systems.

TURBOCOMPRESSOR CONCEPT

The UTC heat pump (HP) system, shown in Fig. 1, incorporates a Rankine-cycle power loop in which a centrifugal turbine is used to drive a centrifugal compressor in a vapor compression refrigeration loop. The thermal energy to the power loop is provided at temperatures up to 300 F (149 C) by a medium-concentration solar collector array. Auxiliary energy for cooling is provided by a fossil-fuel-fired furnace. Heating can be provided by direct solar, direct furnace, or furnace-driven heat pumping (Fig. 1) of low-temperature solar energy in combination with power loop heat recovery. The HP is rated at 18 tons for cooling and approximately 500,000 Btu/hr for heating. It utilizes low-maintenance air-cooled condensers for heat rejection and conventional HVAC design heat exchangers and controls. Refrigerant 11, a common fluorocarbon is used as the working fluid in both the power and cooling loops.

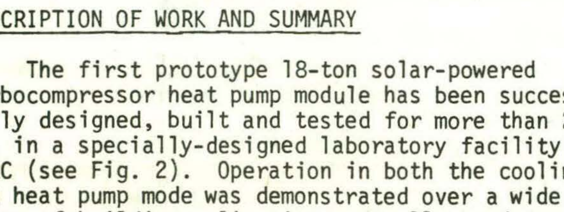


Fig. 1. Heat pump system in heat pump mode.

DESCRIPTION OF WORK AND SUMMARY

The first prototype 18-ton solar-powered turbocompressor heat pump module has been successfully designed, built and tested for more than 250 hr. in a specially-designed laboratory facility at UTRC (see Fig. 2). Operation in both the cooling and heat pump mode was demonstrated over a wide range of building, climatic, and collector/storage conditions. The design point performance of the heat pump in both the cooling and heat pump modes has been confirmed, and performance mapping of the module completed. The heat pump demonstrated the wide operating range possible (using 200 to 300 F hot water) and high heat pump mode performance levels, such as a COP of 1.4 to 2.5 and 500,000 Btu/hr capacity. In cooling, a COP of 0.5 to 0.75 and up to 20 tons was demonstrated. In a simulation of operation in an actual building, the heat pump smoothly and accurately followed the building load for a full day.

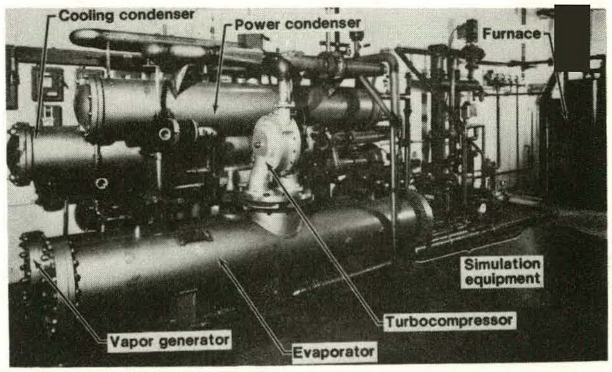


Fig. 2 Heat pump module in UTRC simulation laboratory.

A detailed assessment of the individual module components was completed and performance, cost and reliability improvements were identified. No evidence of R11 decomposition or component wear or corrosion was found.

The first UTRC heat pump module was modified and installed in a complete UTRC-designed (SOLERAS) solar cooling system for field tests in a Phoenix, AZ office building. The system installation and initial test results are briefly described herein.

A second, advanced, higher performance heat pump module has been designed and is currently being fabricated at UTRC. This heat pump incorporates numerous operating and reliability improvements identified during the laboratory and field tests. Still higher performance configurations have been designed and are under evaluation.

TECHNICAL ACCOMPLISHMENTS

● PERFORMANCE MAPPING. A primary objective of the 1980 efforts was to conduct extended testing of the unit to establish performance over the entire operating range in both the cooling and heat pump modes. Utilizing the automatic data acquisition facility in the UTRC heat pump laboratory, data was recorded for over 2000 data slices taken at 400 sets of water inlet conditions, simulating various collector/storage tank output, ambient air and building load conditions. The mapping was conducted over vapor generator water inlet temperatures from 200 F to 300 F, evaporator temperatures from 55 F to 125 F, and condenser inlet temperatures from 80 F to 125 F.

Figure 3 shows the measured heat pump mode performance and the extremely wide range of output capacities provided by the heat pump. Good agreement between test and predicted values of performance and capacity was found for both the cooling and heat pump operating modes.

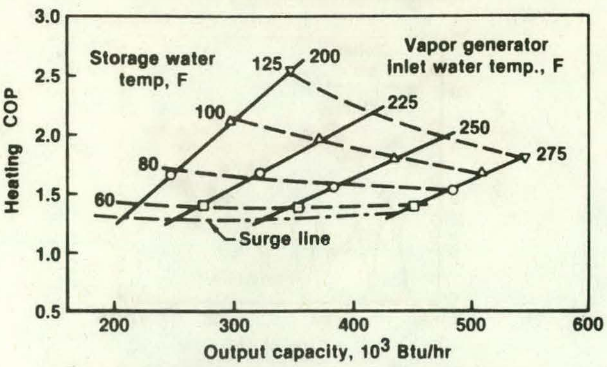


Fig. 3. Measured heat pump mode performance.

● FULL-DAY SIMULATIONS. The heat pump was also run over a range of conditions to simulate operation in an actual building. The boundary conditions for operating the system in the solar cooling mode for an office building located in New York were provided by the UTRC-modified TRNSYS computer program. The hot water storage tank temperature was varied from 275 F to 220 F representing the continual extraction of energy from hot storage. Ambient temperature for the day followed a typical pattern with a night low of approximately 75 F and a mid-day peak of 89 F. Typical results of the full-day simulation tests are shown in Fig. 4 where the solar cooling mode output profile is compared with the TRNSYS predicted building loads. Cooling produced ranged from 4 to 17 tons and a peak COP of of 0.75 was attained. During morning operation at lower ambient temperatures, the module output exceeded the instantaneous demand. Therefore, solar cooling was turned off as room temperature was allowed to increase into the allowable range. The integrated water-side cooling output was 96 percent of that required by the building. The pertinent results are summarized below.

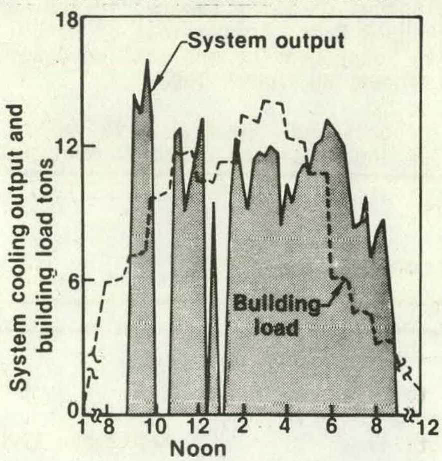


Fig. 4. Typical full day system operation.

● ENDURANCE TESTING AND COMPONENT ASSESSMENTS. Sufficient instrumentation was incorporated in the heat pump components so that detailed assessments of component performance, wear, and durability could be made continuously. In addition, the major module components, i.e., heat exchangers, turbocompressor and valving were disassembled and inspected after the endurance testing was completed. After 250 hrs of testing, the turbocompressor condition was essentially as "new" (Fig. 5). All of the major components were found to be in extremely good condition, except for the water-cooled condensers which experienced water-side fouling due to the use of untreated city-water. Chemical tests and visual inspection of the R11 working fluid showed no sign of decomposition even though much of the testing was at elevated temperatures (280-290 F). This can be attributed to careful material selection and elimination of oil from the power loop. The data gathered during this testing was used as input for the design and fabrication of the advanced heat pump module.

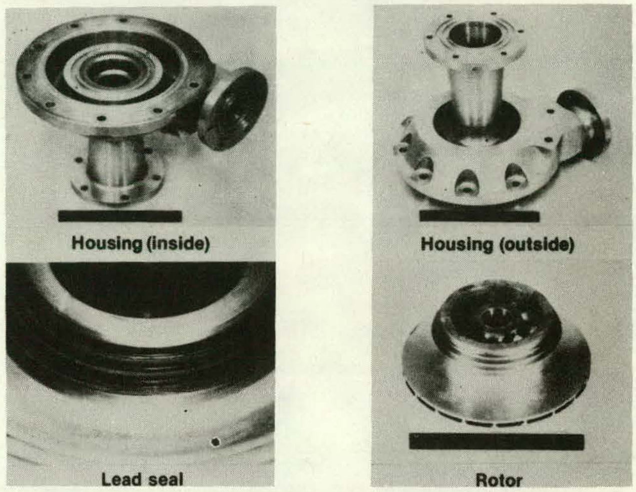


Fig. 5. Turbine elements after testing.

● SOLERAS SYSTEM. The first UTRC heat pump module was modified for the joint DOE/Saudi Arabian SOLERAS solar cooling field test program, in which SERI is the operating agent. These modifications included replacement of the water-cooled condensers with R11-to-air condensers, addition of a purge unit and unique microprocessor control and data acquisition systems.

In the SOLERAS program, the UTRC solar turbocompressor chiller module provides approximately 75 percent of the cooling in the headquarters office building of the Hamilton Test Systems, located in Phoenix, Arizona.

● Design and Analysis. Extensive modeling of the building load, ambient conditions, and system components such as the chiller, collectors, storage tanks and building fan-coils was used in the design of the SOLERAS solar cooling system. Tradeoff analyses (Fig. 6) were used to optimize the collector array size (1316 ft^2 net area or 75 ft^2/ton of cooling). Similar analyses were used to optimize the cold tank (2000 gal) and hot tank (1500 gal) capacities.

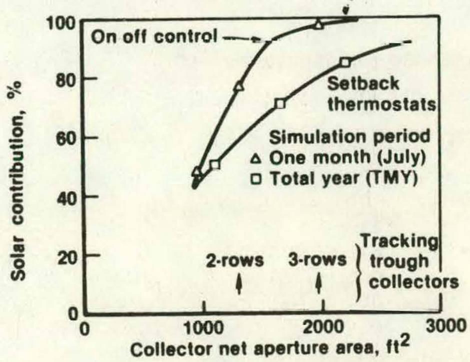


Fig. 6. Collector area optimization.

● Fabrication & Installation. The installation of the parabolic trough collectors on a carport at the rear of the HTS headquarters is shown in Fig. 7. The chiller is located in a separate equipment room in the carport and hot and cold tanks are buried. Chilled water is delivered to three ceiling-mounted fan-coils. Installation was initiated in December 1980 and the entire system installation was completed by the end of February, 1981.

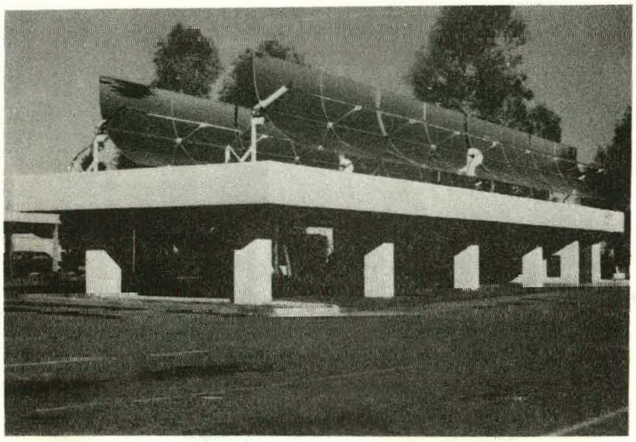


Fig. 7. UTRC solar cooling installation.

● Checkout and Acceptance Tests. Highly successful component and system checkout tests were begun in March and the system was delivering up to 20 tons of cooling in April 1981. Typical results obtained during the acceptance tests are shown in Fig. 8 over the course of a day. Early in the day when tank water levels are about 300 F, the UTC system provides about 18 to 21 tons of cooling, about half of which is stored in the cold tank and the remainder delivered to the building fan coils. Although the collector continuously collects about 15 tons (200,000 Btu/hr) of energy, the hot water temperature and thus, chiller output falls off during the day. The system COP has varied from 0.55 to about 0.75.

● ADVANCED HEAT PUMP DESIGN COMPLETED. UTRC and HSD are currently fabricating and assembling an advanced solar-powered heat pump module with higher cooling mode performance capability and lower cost features which were identified as a result of laboratory and field testing. Another unitary heat pump configuration with a cooling mode design point COP of 0.8 is also under evaluation and optimization.

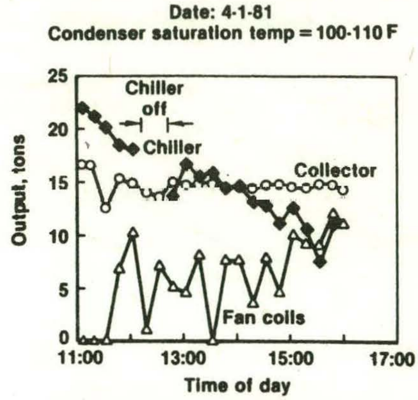


Fig. 8. Solar cooling system test performance.

FUTURE ACTIVITIES

● Contract Activities. Module design and assembly of the advanced heat pump is continuing under the current program prior to subsequent laboratory testing in the UTRC facility. Field testing of the SOLERAS system will continue for two and, possibly, three complete cooling seasons.

● Post Contract Activities. Additional field test sites and adaptations of the system concept to other sizes and applications are being explored.

ACKNOWLEDGMENTS

Technical effort under this program was provided by Messrs. M. D. Meader, C. E. Kepler, A. M. Landerman, B. W. Rhodes, T. N. Obee, M. D. Krosney, H. E. Khalifa and T. J. Anderson of UTRC. Their assistance is greatly appreciated.

PUBLICATIONS/REPORTS/REFERENCES

1. Development of Solar Powered 18-ton Rankine Cycle Heat Pump, Proceedings of Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 1980.

Various reports and papers are available. See IECEC, DOE and prior contractors' meetings.

CONTRACT INFORMATION

START DATE Sept. 1, 1977 END DATE Sept 30, 1982 CONTRACT VALUE $1,672,550

MILESTONES

Item:	Due date:
1. Extended Testing Complete	September 1980 (m)
2. Component Specification for MOD 2	January 1981 (m)
3. T/C Manufacture and Assembly	September 1981 (p)
4. Assemble Advanced HP Module	October 1981 (p)
5. Interim Report	December 1981

Section 2: ABSORPTION SOLAR COOLING SYSTEMS

2

Overview of Active Solar Absorption/Rankine Cooling Program¶

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Michael Wahlig, Al Heitz*, Harry Angerman*, Ron Glas, Mashuri Warren

OBJECTIVE

The overall objective of the DOE active solar cooling program is to develop the basic solar cooling technology that industry can draw upon to engineer and produce solar cooling systems that will compete favorably with conventional cooling systems. By taking responsibility for the high-risk early research and development stages that private industry cannot yet justify undertaking, DOE will lay the foundation for technically sound solar cooling systems that the private sector can commercialize when market conditions are suitable.

BACKGROUND

A number of specific major objectives have been identified as necessary to achieve the overall objective. To meet these major objectives, a number of projects are being supported in both the absorption and the Rankine cooling areas. The correspondence between the individual projects and the major objectives is shown in Figure 1 for the absorption program and in Figure 2 for the Rankine program. Brief descriptions of the technical content of each project are given below in the Technical Accomplishments section. This paper is an update of the review of project activities that was reported at the Mach 1980 Annual DOE Active Solar Heating and Cooling Contractors Review Meeting[1]. This information covers the period March 1980 to May 1981.

Figure 1. Absorption Cooling Program

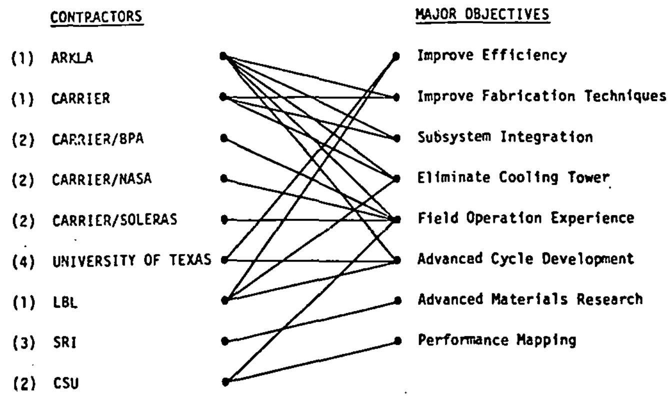
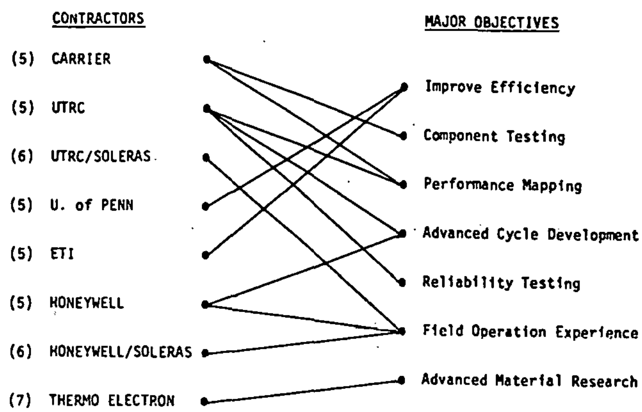


Figure 2. Rankine Cooling Program



SUMMARY

The tasks being performed in the absorption and Rankine program areas run the gamut from basic work on fluids to development of chillers and chiller components, to field and reliability testing of complete prototype cooling systems. In the absorption program there are three active component development projects (1), four systems field test projects (2), one advanced fluid study project (3), and one advanced cycle study project (4) currently funded by DOE. In the Rankine program, there are five active component development projects (5), two system field test projects (6), and one advanced fluid study project (7). (The numbers in parentheses are keyed to the contractors listed in Figures 1 and 2.)

Several of the solar cooling projects are managed by NASA/MSFC (Marshall Space Flight Center, Huntsville, Alabama): the Carrier/NASA absorption projects and the Honeywell Rankine project. The

¶ This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.
* Employees of Keller & Gannon, a subsidiary of Lester B. Knight Associates, Inc.

Honeywell project is a continuation of the earlier NASA/MSFC "404" program; two other 404 projects, by AiResearch and General Electric, have now been completed.

Some of the DOE solar cooling projects reported in last year's Overview[1] have also been completed since then, and several others are in the final report stage. Those completed are: an earlier ARKLA absorption project (Contract No. AC03-76SF-10507, Development of Third-Generation Three Ton Lithium Bromide-Water Absorption Chiller), the Brookhaven National Laboratory project (Contract No. C-02-0016, Development and Use of a Simulator to Test Solar Cooling Subsystems), and the EIC Corporation project (Contract No. AC03-77CS-34537, Design of a Solar Air Conditioner Using Solid Phase Absorbent-Chemical Heat Pump). The projects in the final report phase are those by Southern Research Institute (Contract No. AC03-77CS-31586, Analysis of Advanced Conceptual Absorption Chiller Designs) and the Institute of Gas Technology (Contract No. AC03-77CS-31439, Development of New Fluids for Solar Absorption Cooling). None of these projects will be included in the detailed descriptions given in the following section.

Three new projects have been started during the past year and will be reported on here: Determination of Properties of Fluids for Solar Applications, by SRI International; Fabrication and Installation at Field Test Sites of 120-ton and 75-ton Absorption Chillers, by Carrier Corporation (NASA/MSFC contracts); and Determination of the Thermal Stability of Organic Working Fluids Used in Rankine Cycle Systems, by Thermo Electron. In addition, much of the ongoing systems test work at Colorado State University is an integral part of the active solar cooling program and that effort will be reported here also.

A joint US/Saudi Arabian effort has contributed to the development of Rankine and absorption solar cooling systems. Four projects have been funded by this (SOLERAS) activity, all to be installed and operated in Phoenix, Arizona. Each manufacturer has contributed some private money in addition to the 50/50 share by the U.S. and Saudi Arabia. Table 1 summarizes these projects.

Table 1

U.S./SAUDI ARABIAN PROJECTS (SOLERAS PROGRAM)

CONTRACTOR	TYPE SYSTEM CYCLE/COLLECTORS	COOLING CAPACITY (TONS)
UTRC	RANKINE/TROUGH TRACKING	18
HONEYWELL	RANKINE/EVACUATED TUBE	25
CARRIER	ABSORPTION (WATER COOLED)/TROUGH TRACKING	15
CARRIER	ABSORPTION (AIR COOLED)/FRESNEL DUAL TRACKING	10

Some technical highlights of the program are presented in Table 2.

Table 2

TECHNICAL HIGHLIGHTS

CONTRACTORS	ACCOMPLISHMENTS
• HONEYWELL (RANKINE)	Continued successful field operation in Lawrence, Kansas and other locations.
• UTRC (RANKINE)	Prototype unit converted to air cooled operation, with successful start-up in Phoenix SOLERAS test project.
• U. of TEXAS (ABSORPTION)	Identification of potential for substantial technical performance improvements through development and use of computer models of double-effect absorption chillers.

TECHNICAL ACCOMPLISHMENTS

The individual absorption and Rankine projects are identified in this section, along with the main features and accomplishments/status of each.

ABSORPTION PROJECTS

Contractor: ARKLA

Contract No.: AC03-77CS-34593

Project: Develop and test unitary 3-ton and 25-ton LiBr/H_2O absorption cooling systems. Develop and test double effect, gas fired auxiliary absorption unit.

Features: Unitary package; fuel aux; manufacturing study; application and maintenance manuals; tooling improvements; lab reliability testing. Gas fired double effect absorption unit provides highly efficient COP (1.0) on non-solar operation.

Accomplishments:

- Two field test installations have been completed and performance predictions verified.
- 25-ton unitized packaged chiller has been lab tested and prepared for field installation scheduled for Building 71 at Lawrence Berkeley Laboratory.
- Tooling has been developed to produce absorber and condenser heat exchangers at reduced cost.

Future Plans:

- Complete design of double effect gas fired auxiliary absorption unit; fabricate and test.
- Assist in field test of 3-ton system at CSU and 25-ton system at LBL.
- Complete laboratory reliability testing of 3rd generation 3-ton units.

Contractor: Carrier Corporation

Contract No.: AC03-77CS-51587

Project: Development of air cooled absorption chillers.

Features: Air cooled; 120^{o} C - 130^{o} C input temperature; falling film approach using additives; manufacturing study and market evaluation.

Accomplishments:

- Prototype #1, a 10KW air cooled unitized package chiller has been fabricated; performance testing is in progress.

Future Plans:

- Improve design of 10KW absorption chiller; fabricate and test three 10KW units.
- Design, fabricate and test a 70 KW absorption chiller.

Contractor: Carrier Corporation/BPA

Contract No.: AC79-79BP-10467

Project: Fabricate two 15-ton unitized absorption chillers and install them at two field sites: Dalles, Oregon and Tyler, Texas.

Features: Water cooled, LiBr chillers; packaged; on-site testing; personnel training.

Accomplishments:

- Tyler, Texas and Dalles, Oregon installations have been successfully operated for a full cooling season.

Future Plans:

- The Tyler, Texas installation will continue to be operated during the summer of 1981 to obtain additional data on field test performance.

Contractor: Carrier Corporation/NASA

Contract No.: DEN 8-000005 & DEN 8-000015

Project: Fabricate one 120-ton absorption unit to be installed at Frenchman's Reef, V.I. and two 75-ton absorption units to be installed at Houston and Las Vegas sites. Field test systems at each site.

Features: Water cooled; LiBr chillers; packaged; on-site testing; personnel training.

Accomplishments:

- Frenchmen's Reef chiller has been fabricated and shipped to the site for installation.

Future Plans:

- Las Vegas and Houston installations are planned for completion in 1982.

Contractor: Carrier Corporation/SOLERAS

Contract No.: DE-FC03-80ET 20643

Project: Design, fabricate, install, and field test two active solar cooling systems using absorption chillers.

Features: System #1, 15-ton water-cooled absorption chiller and trough tracking collectors (Acurex).

System #2, 10-ton air-cooled absorption chiller and Fresnel dual tracking collectors (E-Systems).

Accomplishments

- The 15-ton water cooled system has been installed and operated at Phoenix test site. Debugging is presently underway.
- The 10-ton air cooled system is complete except for final placement of the chiller. The absorption unit is undergoing extensive lab tests at the Carrier facility in Syracuse, N.Y.

Future Plans:

- Both systems will be field tested and the data will be used in the active solar cooling program.

Contractor: University of Texas at Austin

Contract No.: DE-AC03-79SF 10540

Project: Analysis of double effect absorption cooling system

Features: Determine performance as a function of many parameters, including inlet water, cooling water and chilled water temperatures, location and size of heat exchangers; $LiBr/H_2O$ pair.

Accomplishments:

- Computer model has been successfully developed to simulate operating performance of double-effect absorption cycles.
- Final report has been completed.

Future Plans

- Apply the computer model developed for double-effect absorption chillers to investigate control schemes, parasitic power requirements, and heat exchanger optimization relative to system performance.

- Assist industry in using computer model.

Contractor: Lawrence Berkeley Laboratory

Contract No.: W-7405-ENG-48

Project: Development of advanced-cycle absorption chillers.

Features: Air-cooled; internally powered solution pump; tube-in-tube heat exchangers; single-effect chiller with 3-ton capacity at 218°F using NH_3/H_2O; advanced cycles with COP increasing with temperature; heat pump operation also.

Accomplishments:

- Early testing of single effect chiller verified the condenser, generator, preheater and recuperative solution pump are operating according to design.
- Design drawings have been completed and fabrication is underway for the double-effect regenerative absorption chiller.

Future Plans:

- Detailed testing will conclude on the single-effect chiller.
- Fabrication will be completed, followed by testing of the double-effect regenerative absorption chiller.
- Cycle analysis of the single-effect regenerative absorption chiller will incorporate the results of the SRI measurements of fluids' properties.

Contractor: SRI International

Contract No.: DE-AC03-80CS 30221

Project: Determine pressure-volume-temperature (P-V-T) data and calorimetric data for organic refrigerant and absorbent fluids and their binary mixtures.

Features: Conduct a critical survey of thermodynamic data on absorption fluids and fluid pairs and measure properties of selected fluids and their mixtures.

Accomplishments:

- Literature search has been completed and findings documented.
- Experimental measurements of the properties of the fluids are underway.

Future Plans:

- In-depth experiments will be conducted and the data will be analyzed on selected absorption fluids and fluid pairs.

Contractor: Colorado State University

Contract No.: DE-AC03-81CS 30569

Project: Test and evaluate complete solar cooling systems incorporating absorption chillers, both air and liquid cooled, using CSU Solar Houses I and III.

Features: The CSU Solar Houses contain collectors, storage, chillers, pumps, piping and controls, all fully instrumented for collecting test data. The test systems are scheduled to operate with an ARKLA evaporatively cooled 3-ton chiller and a Carrier air cooled 3-ton chiller.

Accomplishments:

- Instrumentation is in place and programmable controllers are being installed in the Solar Houses.
- Philips Mark I heat pipe evacuated tube collectors have been installed and operated on Solar House I.
- The ARKLA 3rd generation unit was installed in Solar House I and operated briefly at the end of the 1980 cooling season.

Future Plans:

- Extensive testing will be done on the ARKLA 3rd generation chiller using Solar House I during summer 1981.
- Evacuated tube collectors will be selected and installed on Solar House III during 1981.
- The Carrier air cooled 3-ton absorption chiller will be installed in Solar House III and operated during the summer of 1982.

Contractor: University of Maryland

Contract No.: DE AC03-79CS 30204

Project: Technical program support and special studies.

Features: General program support activities; optimization studies and parametric analysis.

Accomplishments:

- Report on refrigerant/absorbent pairs completed.
- Transient simulation of absorption cycles completed and compared favorably to experimental data.

Project: Development of a superheated steam Rankine turbine.

Features: Solar-boiled water at 300°F; fuel-superheated to 1000°F; 4 stage, 75,000 RPM radial outflow turbine; nominal 30 ton.

Accomplishments:

- Laboratory testing of turbine has been completed successfully.
- Final report has been completed.

Future Plans:

- Project completed.

Contractor: Honeywell

Contract No.: NAS8-32093

Project: Development of Rankine cycle chillers and field installation for testing.

Features: 3-ton and 25-ton Rankine chiller design; water-cooled; R-113 power cycle loop; R-12 refrigerant cycle loop; radial inflow turbine, 40,000 RPM; double reduction gear box to 1200 RPM; reciprocating compressor (centrifugal compressor optional); motor/generator auxiliary.

Accomplishments:

- Field test sites continue to be operated successfully and monitored.
- High temperature Rankine unit fabricated and installed at NASA/MSFC.

Future Plans:

- Further technology development to improve efficiency of chiller and cooling system.
- Continued monitoring of operational test sites.

Contractor: Honeywell/SOLERAS

Contract No.: DF-FE02-80ET 20645

Project: Design, fabricate, install and field test 25-ton Rankine cycle cooling system.

Features: Air-cooled; 300°F; R-113 power cycle loop, R-12 refrigerant cycle loop; radial inflow turbine, 40,000 RPM; double reduction gearbox to 1200 RPM; reciprocating compressor; motor/generator auxiliary.

Accomplishments:

- Components have been fabricated and system installed at Phoenix site. Operating tests are presently underway.

Future Plans:

- Continue field operating tests for two cooling seasons.

Contractor: Thermo Electron Corporation

Contract No.: DE-AC03-80CS 30220

Project: Conduct thermal stability tests on fluids used in Rankine cycle systems.

Features: Five identical dynamic test loop to be constructed to test decomposition of organic working fluids as a function of temperature and the materials in contact with the fluid.

Accomplishments:

- Loop designs are completed and construction underway.
- R-11 and R-113 selected as fluids to be tested in four of the loops.

Future Plans:

- Carry out dynamic thermal stability tests of fluids in 5 loops.
- Conduct supplemental capsule tests.

Contractor: Hittman Associates, Inc. (HAI)

Contract No.: DE-AC03-79CS 30202

Project: Technical program support and special studies.

Features: General program support activities; special system, component and economic analyses.

Accomplishments:

- Thermal storage for solar Rankine and absorption cooling systems report completed.
- Performance test plans completed for Rankine and desiccant cooling equipment.
- Hybrid solar/fossil Rankine cooling conceptual study completed and report written.
- High temperature solar cooling topical report completed.
- Preliminary plan for testing of cooling system control strategies was developed.

- Simplified cooling design charts developed on a regional basis, and compared to detailed simulation.

- Parametric studies of PV/T systems have identified performance sensitivities to collector area, storage capacity and other parameters.

Future Plans

- Technical support activities will continue.

- The cooling design charts and PVT analysis will be completed during the next year.

RANKINE PROJECTS

Contractor: Carrier Corporation

Contract No.: DE-AC03-77CS 31590

Project: Development of 25-ton Rankine chiller.

Features: Air-cooled; R-113 in both loops; 290°F; 20,000 RPM turbine directly driving compressor; electric motor shares the load.

Accomplisments:

- Turbo-compressor assembly has passed the air test and is under R-113 test on prototype.

- Two stage boiler feed pump has been fabricated and successfully tested.

Future Plans:

- Operate T/C assembly to design conditions and determine performance map of the chiller.

- Continue development of chiller to include air cooled condensing coils and microprocessor based control system.

Contractor: United Technologies Research Center (UTRC)

Contract No.:DE-AC03-77CS 34510

Project: Development of 18-ton Rankine heat pump.

Features: Air Cooled; R-11 in both loops; 290°F; 45,000 RPM turbo compressor; fossil fuel auxiliary; both heating and cooling operation.

Accomplishments:

- Endurance testing and component assessment has been completed.

- Advanced heat pump design has been completed to improve operating efficiency and reduce fabrication cost.

Future Plans:

- Fabrication and testing of advanced heat pump design.

Contractor: United Technologies Research Center/SOLERAS

Contract No.: DE-FC02-80ET 20642

Project: Design, fabricate, install and field test a Rankine cycle solar cooling system.

Features: 18-ton Rankine cycle heat pump; air-cooled; R-11 in both loops; 290°F; 45,000 RPM turbo-compressor; fossil fuel auxiliary; trough tracking collectors.

Accomplishments:

- Prototype unit converted to air-cooled operation with successful start-up in Phoenix SOLERAS test project.

Future Plans:

- Field testing of SOLERAS system through two cooling seasons.

Contractor: University of Pennsylvania

Contract No.: AC03-78ET-20110

Project: Development of 20-ton superheated steam Rankine chiller.

Features: Solar-boiled water at 260°F; fuel-superheated to 1100°F; 5 stage, 15,000 RPM radial outflow turbine and rotary expander design; stored water flashes to steam.

Accomplishments:

- Fabrication of turbine assembly is being completed and test loop is under construction.

Future Plans:

- Performance map of turbine will be measured using the steam power loop.

Contractor: Energy Technology, Inc. (ETI)

Contract No.: AC03-80CS-30214

Future Plans:

- Technical support activities and special studies will continue.

SYSTEM ANALYSIS PROJECTS

Contractor: Science Applications, Inc. (SAI)

Contract No.: XB-0-9145-1

Project: Performance and economic analyses of absorption and Rankine cooling systems.

Features: Develop computer programs to evaluate system performance and economics for residential and commercial active solar cooling systems; selected cities used.

Accomplishments:

- Completed detailed system modeling of 25-ton absorption and Rankine chillers.
- Annual system simulations and economic analyses completed for four cities.

Future Plans:

- Continued system evaluation for additional locations and system configurations.

In addition to the activities in the above contracts, extensive planning efforts are underway for long-range development efforts in the active solar cooling program. An important function for this planning effort was the active solar cooling workshop attended by representatives from the solar and HVAC industry, utilities and local government, financial and marketing organizations, and the architecture and engineering fields. The workshop concentrated on four major topics: (1) technical, (2) financial, (3) codes and standards, and (4) marketing aspects of active solar cooling. The response from the 28 attendees provided a data base for follow-on presentations that will further contribute to DOE's planning efforts.

FUTURE ACTIVITIES

From a technical point of view, the Rankine and absorption projects have progressed from the very early design and development stage to operating prototypes undergoing performance evaluations. Operation of many of the early prototypes have identified key areas of concerns for Rankine units such as optimized system control, bearing design and cooling schemes, back-up system alternatives, and heat exchanger designs. For the absorption systems, concerns are fluid flow design in the absorber section, heat exchanger optimization, control functions, and parasitic power reduction. Common concerns for both systems are cost reduction, collector and storage selection criteria, and fluid stability at high tempertures. The future activities of the active solar cooling program will address these key concerns.

In the past year, substantial progress has been made identifying quantitative program goals. A method of system analysis has been developed to provide values of cost and performance goals, using computer simulation models and results of market analysis. This effort is continuing.

It is expected that further development in the absorption and Rankine cooling technologies will ensue as a result of competitive solicitations for advanced cooling systems and components. In addition, it is planned to conduct systems engineering of developed components leading to design and application manuals that will be available for use by A&E firms and the HVAC industry.

REFERENCES

[1] Michael Wahlig, Al. Heitz, and Barbara Boyce, "Overview - Absorption/Rankine Solar Cooling Program," Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26-28, 1980.

UNITARY SOLAR HEATING/COOLING SYSTEM PACKAGE DEVELOPMENT

ARKLA INDUSTRIES INC.

RICHARD H. MERRICK

DE-AC03-77CS-34593

OBJECTIVE

To develop 3 ton residential and 25 ton commercial unitary solar heating and cooling system hardware and software; to develop an evaporatively cooled 3 ton lithium bromide water absorption chiller and establish its reliability and manufacturability; to add a double effect, gas fired auxiliary mode of operation to the evaporatively cooled chiller creating a dual solar/gas unit.

DESCRIPTION OF WORK

Applying the unitary system approach to solar heating and cooling will reduce hardware installed cost and maximize reliability and efficiency. Sizing and installation software keyed to specific hardware is more accurate and easier to use in the field.

The evaporatively cooled chiller concept is an advance over conventional tower cooled equipment. Elimination of the separate cooling tower reduces first cost, installation cost and parasitic power. Water scaling and freezing will be managed to achieve a maintenance level approaching that of air cooled systems.

The double effect, gas fired auxiliary mode will provide high efficiency (fuel based COP $\geq$ 1) during non-solar operation. Solar cooling equipment that matches conventional cooling equipment in the non-solar mode can credit all its solar operation to energy savings. This feature increases in importance as the solar fraction reduces.

TECHNICAL ACCOMPLISHMENTS

- Commercialization of a 3 ton solar package has been achieved. Two of these systems are operating in Evansville, a retrofit home for 2 years and a new home for 3 years. Operation has led to system improvements and cost reductions of this product.

- An application manual has been prepared covering all aspects of a complete solar system for heating, cooling and domestic hot water as well as collector array sizing and orientation for the PWF-36 unitized package.

- As a result of operating the collection systems at the two houses, a predictive model for the amount of actually delivered solar energy has evolved, Figure 1.

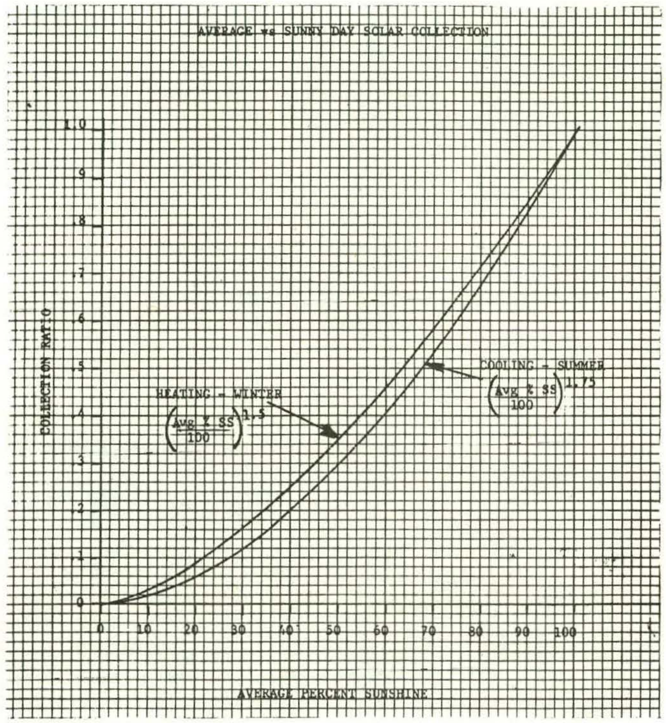


Figure 1 Deliverable Solar Energy

- A 25 ton unitized packaged, Figure 2, has been developed and successfully tested. This system will be slightly modified prior to field testing at the LBL on year-round conditioning duty.

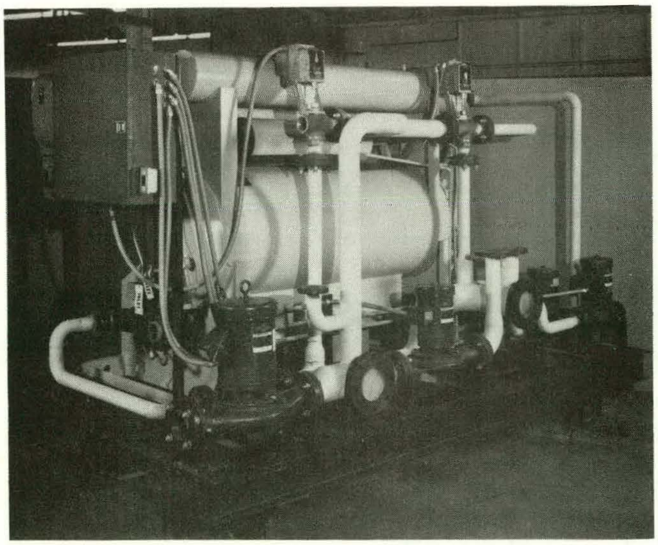


Figure 2 25 Ton Unitized Package

- Two evaporatively cooled units have been installed at field sites. One unit has been operational at the retrofit house as part of the PWF-36 unitary package. The other unit was installed late last summer (1980) at Colorado State University at Fort Collins to gain field experience in a low wet bulb climate. Figure 3 is a comparison of the 3 ton evaporatively cooled unit and the WF-36 chiller with its required cooling tower and pump.

- A reliable vendor developed permanent magnet drive solution pump has been undergoing life test and actual operational evaluation as a part of the evaporatively cooled field units plus two life/scale test chillers in the Arkla lab.

- A detailed production study has verified the manufacturability of the evaporatively cooled unit.

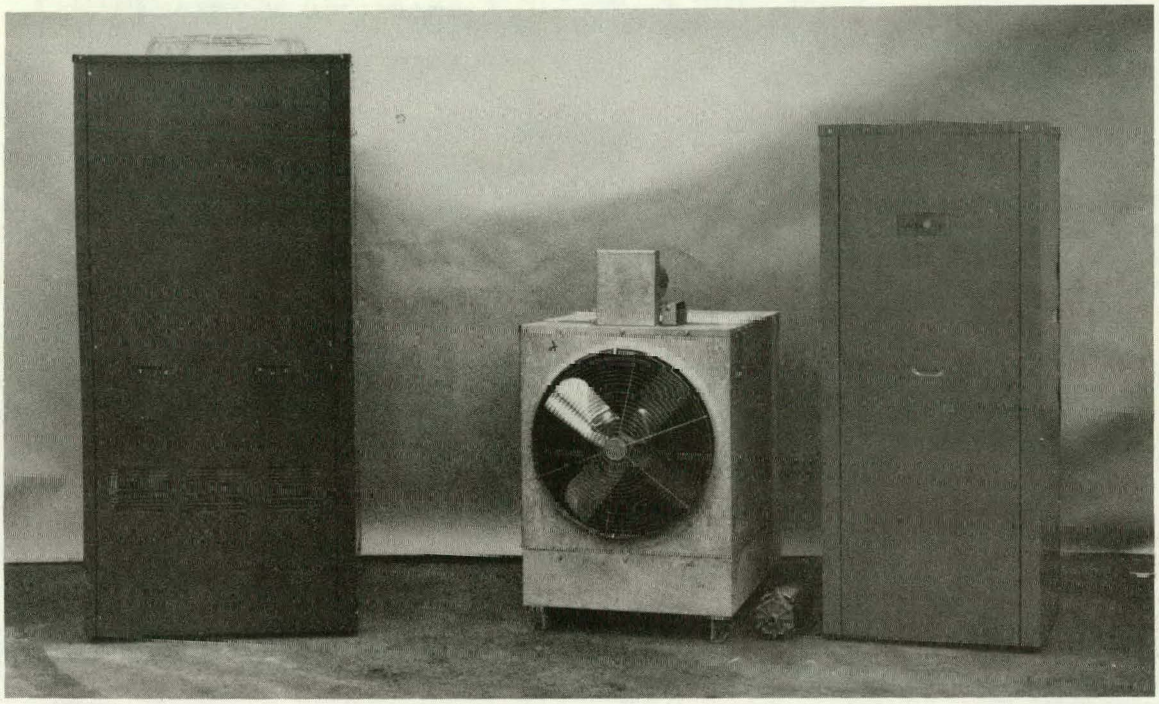


Figure 3 Three Ton Evaporative Chiller vs Tower Cooled WF36 Chiller

The base area of the evaporatively cooled unit is 9.75 ft^2. The base area of the WF-36 plus the cooling tower is 15.5 ft^2. Fewer field pipe connections are required. Parasitic power consumption of the evap. cooled unit is 450 watts vs about 1000 for the WF-36 with a cooling tower. The parasitic power of a double effect chiller should be less than a single due to less heat rejection although a larger solution pump motor is required.

- Operation of the two residential system's chillers has led to improvements in the commercial product chiller, WF36, especially controls, seasonal COP and, potentially, instantaneous COP at reduced firing temperatures through parallel condensing water flow without increasing system parasitic power.

- The 1250 gallon underground storage tank at the retrofit house has not shown any insulation deterioration over the 2 years of operation. The actual losses from an in-residence tank, such as a basement location, can add substantial load to the chiller equivalent to an hour of operating time each day, even in mild weather.

- Temporary tooling from the barrel industry has been developed, built, and successfully used to produce 7 different corrugated heat transfer shells for the evaporatively cooled unit. Figure 4 shows this equipment set up at Arkla.

Figure 4 Corrugating Equipment

- A thermal analysis of an evaporatively cooled double effect cycle has been completed. This analysis shows a COP $\geq$ 1 on a fuel basis can be achieved without compromising the .72 COP operating in the solar mode, see Figure 5.

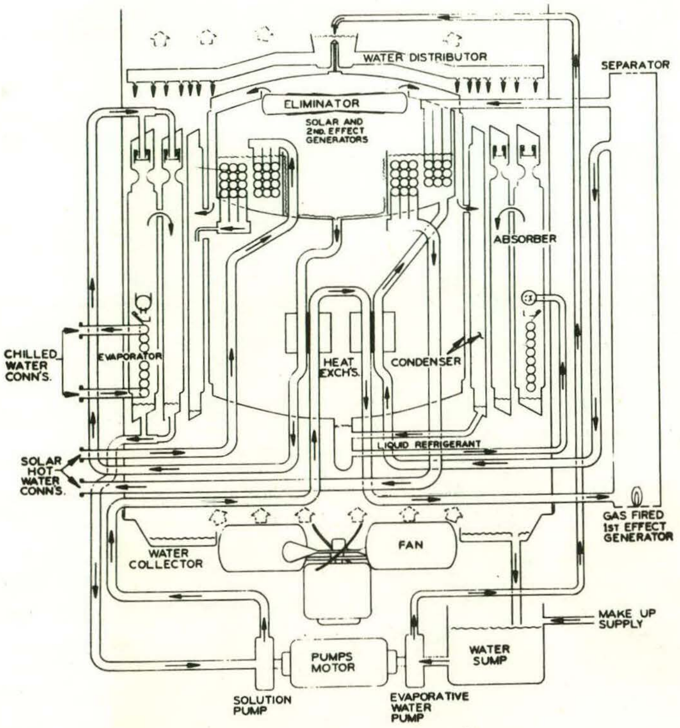


Figure 5 Solar/Gas Chiller Schematic

- Concepts have been evaluated and the actual design phase of breadboard components is in process. The prototype high temperature solution heat exchanger is being tested. Fabrication of the combination solar generator/2nd effect generator/1st effect condenser is underway.

FUTURE ACTIVITIES

Marketing the 25 ton commercial package is a possibility pending successful results with the LBL field test.

Assuming favorable results from the preliminary work funded for the double effect solar/gas chiller, we are proposing additional funding to complete this development. Continuing with life and field testing of the existing single effect units would also be part of this work. Specifically, more work must be done to develop a satisfactory protective coating. Some of the existing materials have failed and others are marginal. Although galvanizing can be effective, it is relatively expensive.

PUBLICATIONS/REPORTS/REFERENCES

Merrick, Richard H., "Unitary Solar Heating/Cooling System Package Development" proceedings of 3rd annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Washington D. C., September 24 - 27, 1978 p 271 - 275.

Merrick, Richard H., "Unitary Solar Heating/Cooling System Package Development" proceedings of the annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26 - 28, 1980, p. 2 - 5 to 2 - 8.

CONTRACT INFORMATION

START DATE 06/77 END DATE 12/81 CONTRACT VALUE $1,304,488

MILESTONES

Item:	Due date:
1. 3 Ton Unitary Package for Solar Heating/Cooling/DHW (with natural gas back-up)	November, 1977 (completed)
2. Complete Application Manual (Residential)	March, 1979 (completed)
3. 25 Ton Packaged System	May, 1980 (completed)
4. Two Chillers "Off" temporary mfg. eqmt.	March, 1981 (1 unit completed)
5. Operational Breadboard Double Effect/Solar Unit	December, 1981

AIR COOLED ABSORPTION CHILLERS FOR SOLAR COOLING APPLICATIONS

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

DR. WENDELL J. BIERMANN, ROBERT REIMANN

EG-77-C-03-1587

OBJECTIVES

The purpose of this program is to identify the chemical composition of a "best" absorption-refrigerant system, capable of being air cooled to determine those properties of the system necessary to design hot water operated, air cooled chilling equipment and to design and operate air cooled chillers from single family residential sizes into the commercial rooftop size range.

DESCRIPTION OF WORK

At previous Contractors' meetings we have discussed the considerations which led us to the selection of a mixture of lithium bromide and ethylene glycol as an absorbent, coupled with water as a refrigerant.

Figure 1 shows the pressure-temperature relationship of this system in the form of a Duhring plot. Superimposed on this plot is a parallelogram showing the approximate limits covered by an air cooled absorption cycle at the design point of 35°C (95°F) air. The absorbent ratio of LiBr:glycol was selected as 4.5, roughly optimized for the various considerations of vapor pressure, cycle pumping rate and heat transfer properties. It will be noted that the crystallization line, shown as a dashed line, is comfortably removed from the region occupied by the cycle. By contrast, the crystallization line for lithium bromide cuts very close to the working area, inviting a solidified system should there be a sudden perturbation of the operating conditions or should there be some minor errors in the information.

This system is useful only if it can be operated near the equilibrium conditions. Our major chemical innovation has been the identification of a chemical additive, 1-nonylamine, which lowers subcooling in the absorber to about 1°C from the 15°C range of the simple refrigerant-absorbent combination. Without this additive the gain in crystallization is obviously lost in increased subcooling.

For convenience we have coined the term "Carrol" to describe a system comprising an absorbent of lithium bromide and ethylene glycol in a weight ratio of 4.5:1, with water as refrigerant and 1-nonylamine as an additive.

MACHINERY DEVELOPMENT

At the present writing three chillers have been constructed and two of them operated under test conditions. The first of these, a "breadboard" type construction, produced about 7 kW (2 t) of cooling at the design point of 110°C (230°F) hot

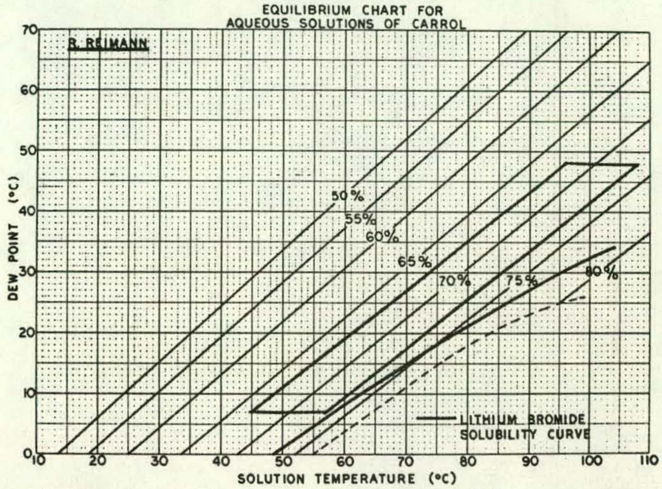


FIGURE 1. Equilibrium Chart for Aqueous Solutions of Carrol. For reference purposes, the crystallization line for lithium bromide-water has been superimposed as well as a typical cooling cycle path.

water entering the generator, 35°C ambient air and 7.2°C (45°F) chilled water to the load at a thermal COP of 0.74. The schematic representation of the breadboard and subsequent models is shown in Figure 2. This served to vindicate the basic design concepts and refined some of the heat transfer coefficient data.

A second piece of equipment, a first prototype single family residential unit, was designed from the breadboard data with a projected cooling capacity of 10 kW (3 tons). This unit is shown, with the sheet metal case removed, in Figure 3. When placed in operation in a laboratory facility designed and built especially for the purpose, the initial cooling capacity at design conditions was about 8.7 kW at a thermal COP of 0.71, sustained for about ten days. Unfortunately the performance of this equipment soon deteriorated to about 6 kW at design conditions as a result of heat transfer surface contamination, due at least in great part to air leakage. After a series of unsuccessful attempts to resuscitate the prototype, the decision was made to abandon the machine and move on to the next program step. The first prototype experience emphasized to us the importance of designing all components with ease of leak detection and leak repair a major design consideration.

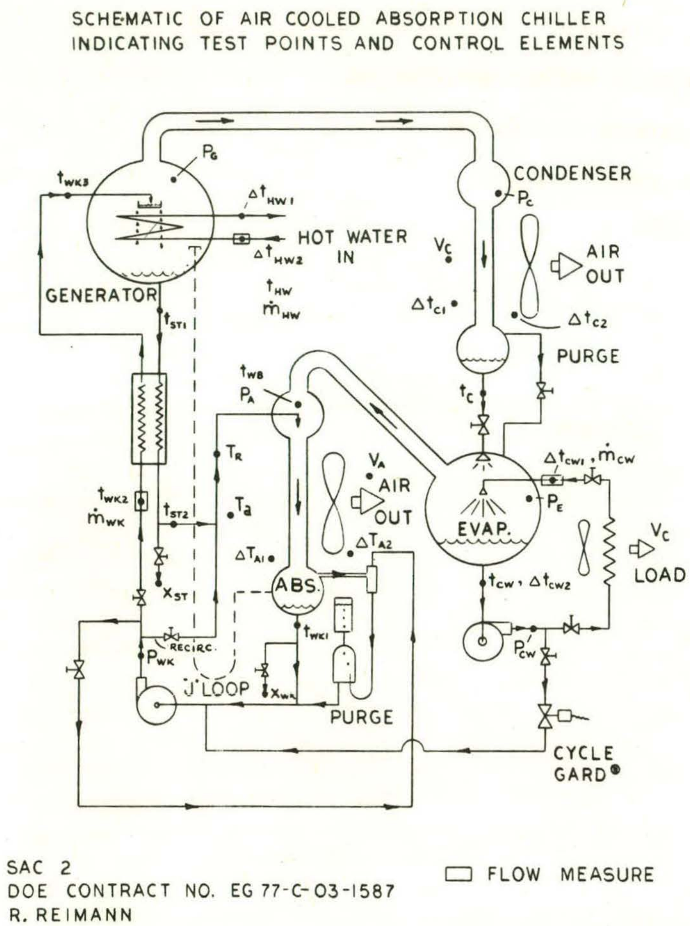


FIGURE 2. Schematic Diagram of Air Cooled Absorption Chiller.

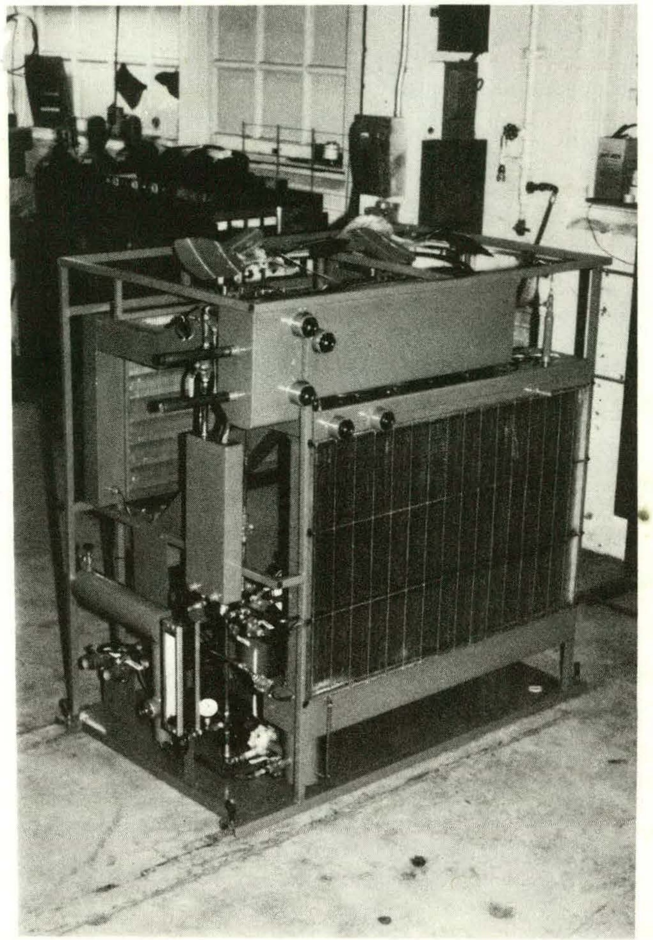


FIGURE 3. First 10 kW (3 ton) Prototype Air Cooled Solar Absorption Chiller.

The next program step selected was not an immediate redesign of the 10 kW prototype but rather a move to a larger rooftop solar package built around a 35 kW (10 ton) air cooled chiller. Funding for this particular step has been supplied through the SOLERAS program administered by the Solar Energy Research Institute (Contract DE-FC02-80-ET20643). Figure 4 shows the 35 kW rooftop package which integrates the solar system pumps, controls and some data retrieval functions.

Selection of the larger equipment as the successor step to the first residential 10 kW prototype was based primarily on the belief that the larger size was, in some ways, less of a deviation from established designs. These considerations will be included in the following consideration of the major components of the chiller designs.

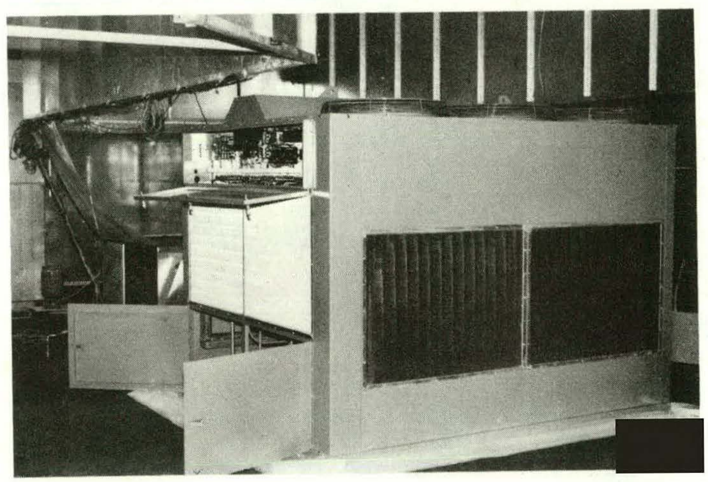


FIGURE 4. View of the 35 kW (10 Ton) Air Cooled Solar Absorption Chiller Package

Generator

In all cases a falling film generator is used, based on the very successful application of this design in our parallel development of water cooled chillers for low temperature application. The falling film generator is preferred over the submerged tube bundle because it permits counter-current heat transfer, eliminates submergence losses, minimizes the need for superheat to induce nucleate boiling and greatly reduces cycling losses by eliminating the large quantity of hot solution stored in the generator.

Distribution of the solution over the tube bundles in the 10 kW design was by means of a series of weirs which overflowed onto the exterior of the generator tubes through capillary drippers. In the larger 35 kW package there is sufficient room to use spray headers, which has been the basis of all our previous experience with the falling film generator.

Absorber and Condenser

Both are plate fin coils with one inch copper tubes and ten mil aluminum fins, 14 per inch. Since the last Contractors' conference report was written, the coil parameters were measured by the Carrier Research Division and a computer analysis made of this application. As a result, the condenser coil was redimensioned and recircuited and the air velocity through both condenser and absorber reduced. This will significantly reduce fan power from that required in earlier designs.

Evaporator

It has been most convenient thus far to work with a flash evaporator, in which return chilled water is flashed through a nozzle in a chamber communicating with the absorber. With the 35 kW rooftop package, however, we will return to the more conventional tube and shell chiller which will lessen the likelihood of leaks and will simplify the problem of freeze-proofing the units.

It is conceptually possible that the ethylene glycol component could evaporate in the generator and concentrate in the refrigerant loop. This does not happen and a steady state concentration of glycol in refrigerant of about 5% has regularly been observed.

Fans

Based on the new requirements for the redesigned coils, the Carrier Corporate fan selection program was used to make an optimum selection of fan motor and blades. The 35 kW rooftop unit will use six fans with about 215 watts per ton capacity, compared to about 300 watts per ton in the previous designs.

Solution Heat Exchanger

The solution heat exchanger is a major consideration in getting good thermal efficiency. Very little head is available on the strong solution side, a situation not helpful in achieving a high effectiveness ($\eta \cong 0.8$). Our flat plate design, constructed of a stack of simple shapes easily punched from sheet metal, has worked out well.

Purge

A small version of the jet purge that Carrier uses on its commercial 16JB absorption chiller series has given us effective purging of gases from leaks and corrosion. The maximum pump head in the 35 kW chiller is sufficiently high to permit emptying the purge storage tank by pump discharge pressure.

Controls

A low refrigerant level sensor protects the liquid lubricated refrigerant pump by turning it off when refrigerant stores on the solution side. In the breadboard and 10 kW prototype versions the refrigerant pump served to couple the flash evaporator to the external load. This design has been replaced by a conventional tube and shell chiller in which the evaporator pump is used only for internal refrigerant pumping from sump to spray header.

Should overconcentration of the Carrol threaten solidification, this is detected by a high refrigerant level sensor which activates a Cycle-Guard^R solenoid valve which feeds refrigerant into the solution pump suction. To maintain constant load capacity as ambient temperatures increase, it is necessary to increase generator temperature by two degrees for each degree increase in ambient above the design point of 35°C.

A second solenoid valve will also be introduced into the 35 kW package and subsequent machines which will permit the output of the solution pump to be introduced into the suction side of the refrigerant pump as a means of preventing the refrigerant from freezing during winter shutdown. In conjunction with an additional level sensor in the refrigerant sump, it can also be used to extend machine operation to lower ambient temperatures, with minor losses in thermal COP.

TECHNICAL ACCOMPLISHMENTS

A survey of possible air cooled absorbent-refrigerant combinations has identified a lithium bromide-ethylene glycol-water system, with 1-nonylamine as an additive, which was a "best" system with respect to cost, chemical stability, flammability, toxicity and projected development time.

All necessary engineering design information-vapor pressure, enthalpy, heat transfer coefficients, etc., has been measured.

Component designs have been tested in 10 kW (3 ton) breadboard and first prototype configurations.

A 35 kW (10 ton) rooftop solar package has been designed and built.

A test facility for running small air cooled absorption chillers over a variety of controlled conditions has been designed and built.

FUTURE ACTIVITIES

The equipment resulting from this program are intended as prototypes of products aimed at a market still in process of development. With this in mind, our Commercial Products Division prepared a Fabrication Cost Estimate for a 10 kW (3 ton) product based on the first prototype design. A run of 1000 units would have a fabrication cost of $2,400 each.

Our corporate experience with similar products has closely followed an 80% experience curve in projecting cost reductions. Table I shows a possible future cost scenario which would be consistent with our previous experience in developing very similar new products for emerging markets. Cost to the consumer will be higher by distribution, profit and other business costs.

TABLE I

Average Fabrication Cost Projection
3-Ton Absorption Machine (Air Cooled)

Year	Annual Production	Cumulative Production	20% Initial Cost Reduction Average Fab. Cost/Unit 1980 Dollars
1	100	100	$1,916
2	500	600	1,886
3	2,000	2,600	1,782
4	6,000	8,600	1,561
5	12,000	20,600	1,299
6	13,200	33,800	1,111
7	14,500	48,300	992
8	16,000	64,300	905
9	17,600	81,900	838
10	19,300	101,200	783

CONTRACT INFORMATION

Starting Date: September 30, 1977
End Date: September 1982

Total Face Value of Contract: $1,232,880

Major Deliverables

1. Survey of absorption-refrigerant combinations and selection of "best" combination. Report 6/79.

2. Properties of "best" absorbent-refrigerant combination and machine component designs. Report 5/81.

3. First Prototype 10 kW Absorption Chiller 6/80.

4. Second Prototype 10 kW Absorption Chiller (three units), Complete 9/15/81.

5. 70 kW Absorption Chiller, Complete 12/15/81.

PUBLICATIONS AND REPORTS

"Candidate Chemical Systems for Air Cooled Solar Powered Absorption Air Conditioner Design." Part I - Organic Absorbent Systems; Part II - Solid Absorbents, High Latent Heat Refrigerants; Part III - Lithium Salts with Antifreeze Additives; Wendell J. Biermann (1978). Parts I and II are available from NTIS, Part III release expected shortly.

"Properties of the Carrol System and a Machine Designed for Solar Powered, Air-Cooled, Absorption Space Cooling," Revised Report May 1981.

WATER COOLED ABSORPTION CHILLERS FOR SOLAR COOLING APPLICATIONS

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

DR. WENDELL J. BIERMANN, ROBERT C. REIMANN

OBJECTIVES

The long term objective of the program which has been implemented by the contracts enumerated below, was the development of a broad line of absorption chillers designed to operate with hot fluids at as low a temperature as practical while rejecting heat to a stream of water.

A second objective was to develop a packaging concept for solar application in which controls, pumps, valves and other system components could be factory assembled into a unitary solar module.

DESCRIPTION OF WORK

Energy Systems Division, Carrier Corporation, has been conducting programs in solar cooling with various agencies all of which have been tied together with a common group of assumptions and goals. One of these assumptions was that of the various methods of solar cooling possible, absorption cooling was the only technology which could become commercial on a relatively short time frame. Absorption cooling with heat rejection to a water stream, as might couple to a cooling tower, appeared to warrant the highest priority because of the large background of developed technology. This program is the subject of the present paper. A second program, development of a line of air cooled absorption chillers over the residential and smaller commercial sizes, appeared to be somewhat longer in term and our contributions in that area are described in a second paper in this Conference Proceedings.

A design point was selected on the basis of what might reasonably be expected from a system using good quality flat plate solar collectors. Specifically we chose:

Rating Conditions:

Hot water 82°C (180°F) and 0.060 l s^{-1}/kW capacity (3.33 gpm/ton (c))
Cooling water 29°C (85°F) and 0.126 l s^{-1}/kW (c) (7.00 gpm/ton (c))
Chilled water 7.2°C (45°F) and 0.043 l s^{-1}/kW (c) (2.40 gpm/ton (c))

Size Range:

50 - 500 kW (c) (15 - 150 tons)
Smaller Units to be Contained in Preassembled Solar Packages.

In addition we wanted a basic design which would retain a large fraction of design capacity when the hot water temperature dropped to 65°C (150°F), other quantities remaining at the rating condition, and which would have minimum losses due to cycling.

The primary approach which was to be used was to increase surface in a fairly conventional tube bundle for evaporator, absorber and condenser design, but to increase the number of passes in the evaporator and absorber so as to approximate counterflow rather than cross flow heat transfer. Instead of the submerged tube bundle generator normally employed, we elected to use a falling film type generator which would reduce approach temperatures by permitting counterflow rather than cross flow heat transfer and avoid superheating effects associated with nucleate boiling and hydrostatic head. By eliminating the storage of the mass of solution required to cover the generator tube bundle, the heat losses on interrupted operation were very greatly reduced.

Table 1, on the following page, summarizes in tabular form the contracts and the several agencies which have made it possible to carry out the individual steps in the overall program. In each case, a brief note gives the specific objective of that portion of the program and the current status.

Typical performance data and illustrations of the 50 kW (15 ton) solar absorption chillers have been given at previous Contractor's meetings and in the publication list appended.

By way of update, three figures are included. Figure 1 shows the latest packaged version of the 50 kW chiller, presently installed at the BDP Distribution Center, Phoenix, Arizona, as part of the SOLERAS program. This package includes pumps for solar collector, chilled water distribution and for induced draft cooling tower, necessary control sensors and valves plus all needed control logic devices.

The second figure shows the largest unit thus far built in this series, a solar absorption chiller designed to produce about 130 tons of cooling at the program rating point, and was developed under sponsorship of Marshall Space Flight Center (NASA). This machine is semi-commercial in that it was produced down the same assembly line as the standard Carrier absorption chillers. To become fully commercial, it requires only enough volume to justify certain special tooling and setting in place a complete manufacturing plan.

Major Task Number	Technical Task	Status or Schedule
1	Design, build, factory test, field install in solar system with evacuated tube collectors and monitor for one year; a 50 kW (15 ton) solar absorption chiller.	Installation completed, Ross Control House (Vancouver, WA) March 1978. Currently operating. Preliminary Final Report submitted January 1980. Bonneville Power Administration to issue final final report about May 1981. Funding: Bonneville Power Administration. 14-03-6280N $848,959
2	Select new solution and refrigerant pumps for 50 kW (15 ton) package developed in task #1. Develop solar package for steam as auxiliary energy. Install with flat plate collectors and operate for one year.	Installation completed, Carrier factory in Tyler, Texas, October 1979. Operation monitored to October 1980. Presently inoperative due to collector problem. Funding: Bonneville Power Administration/ DOE DE-AC79-79BP 14067 $375,000
3	Operate Tyler, Texas installation for cooling season, 1981.	Contract anticipated May 1981. To be followed by preliminary final report to Bonneville Power Administration November 1981. Funding: SERI Contract Pending $15,250
4	Using the modified 50 kW (15 ton) solar absorption chiller of Task 2, develop package using electric driven heat pump for auxiliary. Install, using drainable, evacuated tube collectors, at Big Eddy Control House, The Dalles, Oregon.	Installation completed April 1980. Year's operation completed April 1981. Preliminary Final Report, June 1981. Funding: Bonneville Power Administration/ DOE DE-AC79-79BP 14067 $375,000
5	Using absorption chiller design proven in Tasks 2 and 4, develop improved packages. Install, using tracking concentrating trough collector, BDP Distribution Center, Phoenix, Arizona. Operate through two cooling seasons.	Installation completed April 1981. Preliminary Final Report November 1982. Funding: SOLERAS, Managed by SERI DE-FC02-80ET 20643 $815,000 (including a second installation)
6	Scale up the 50 kW (15 ton) design to meet needs of Frenchman's Reef Holiday Inn, American Virgin Islands. Under selected rating conditions, this would be about 450 kW (130 tons). Design will produce over 700 kW (200 tons) at higher temperatures.	Construction completed March 1981. Laboratory tested April 1981. Shipped April 1981. Installation and field testing will be contracted by NASA, scheduled about June 1981. Funding: NASA DEN 8-000007 $266,318
7	Using same design as Task 6, design, construct and laboratory test two solar absorption chillers of 260 kW (75 ton) capacity at design conditions.	Construction completed March 1982. Will be installed and field tested under separate NASA contract in 1982 at University of Houston and University of Nevada (Las Vegas). Funding: NASA DEN-8-000015 $227,900
8	Do cost reduction study of design in 50 kW (15 tons) to 150 kW (40 tons) range. Build and test one unit to prove cost reduced design.	Desirable to improved commercial value.
9	Using design concepts proven in past program, design a solar chiller with two stage generator to increase COP. Design hot water temperature to be not in excess of 115°C (240°F).	Logical step for technological advance of solar cooling.

TABLE 1. Summary of Contracts Constituting the Water Cooled Absorption Chiller Program of Energy Systems Division, Carrier Corporation.

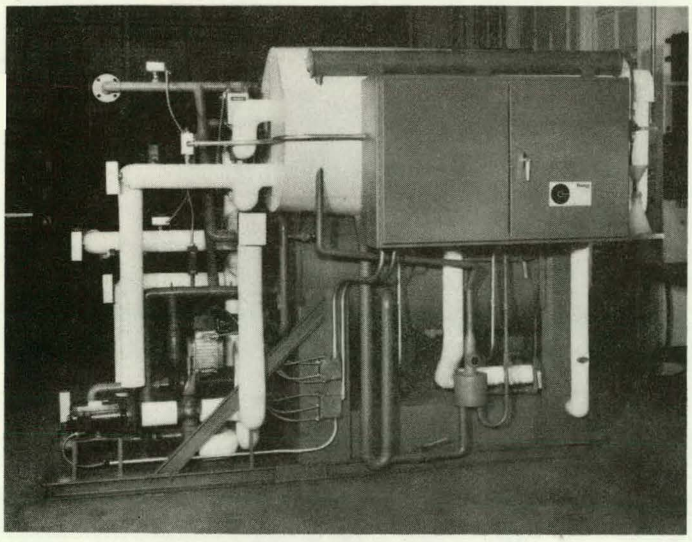


FIGURE 1. Solar Unitary Package, BDP Distribution Center, Phoenix, Arizona

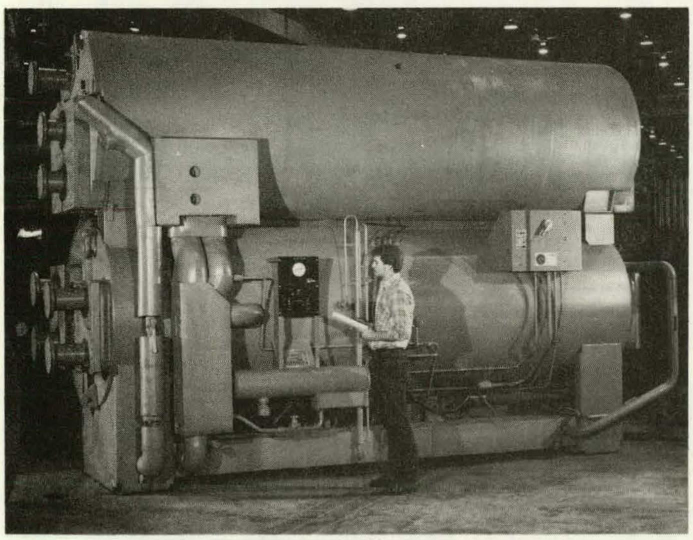


FIGURE 2. Scaled Up Solar Absorption Chiller, Frenchman's Reef Holiday Inn, American Virgin Islands

Figure 3 shows the performance of the large absorption chiller over a range of hot water temperatures. These data result from performance testing done in the Engineering Test Laboratory, Machinery and Systems Division, Carrier Corporation.

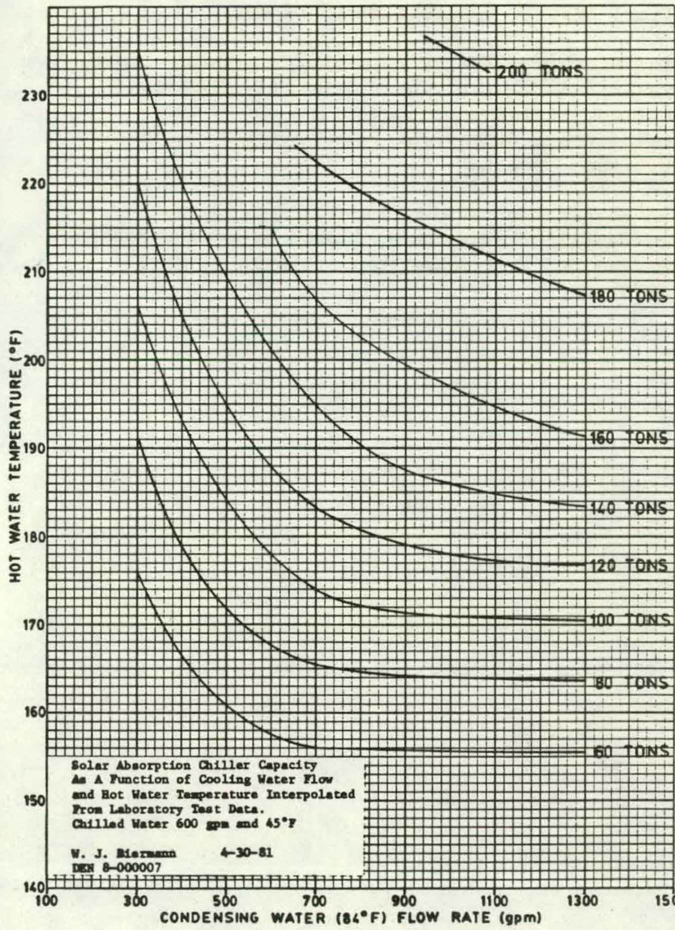


FIGURE 3. Capacity of Large Solar Absorption Chiller Over a Range of Hot Water Temperatures

TECHNICAL ACCOMPLISHMENTS

A low temperature absorption chiller has been designed, laboratory tested and field tested. It is suitable for solar, geothermal or energy recovery applications.

The manufacturability of the low temperature chiller has been demonstrated on a commercial production line.

The low temperature chiller design includes 15 tons, 75 tons and 130 tons.

Packaging of the 15 ton size chiller into a simple unitary solar package has been done.

FUTURE ACTIVITIES

Absorption chillers of this improved design are salable items. They are being offered for sale, potential customers have expressed interest but no actual private sales have been consummated. Cost is a serious obstacle -- capital investment is needed to reduce manufacturing cost (tooling, fixtures and procedures) but the volume of production needed to amortize the investment cannot be identified, at least not presently for the single stage machine.

PUBLICATIONS

"Evaluation Report Prototype Energy Retrieval System," Submitted to Bonneville Power Administration January 1980 (Final Report, Contract 14-03-6280N)

"The Prototype Energy Retrieval and Solar (PERS) System," April 1981, by Bob Guddat, Mechanical Section, Division of Substation and Control Engineering, Bonneville Power Administration, Portland, Oregon

"An Absorption Machine for Solar Cooling," Dr. Wendell J. Biermann, ASHRAE Symposium Paper PH-79-3 No. 2, ASHRAE Transactions 85, Part I (1979)

CONTRACT INFORMATION

START DATE__________ END DATE__________ CONTRACT VALUE__________

MILESTONES

Item: Due date:

1.

2.

3.

4.

5.

DEVELOPMENT OF SOLAR-DRIVEN ABSORPTION AIR-CONDITIONERS

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

Kim Dao, Michael Wahlig, Joseph Rasson
Contract No. W-7405-ENG-48

OBJECTIVE

The objective of this project is to develop absorption-cycle refrigeration systems that achieve significantly higher seasonal conversion efficiencies than is possible using other cooling approaches. A secondary objective is to avoid the necessity for water cooling towers by using air-cooled condensers and absorbers.

The quest for higher conversion efficiencies is one of the approaches leading toward eventual achievement of cost-effective solar cooling systems by the solar industry. The major cost component of a solar cooling system is the collectors; the collector area required to satisfy a given load can be reduced (lowering costs) as the efficiency of the chiller component is increased.

DESCRIPTION OF WORK

A phased plan has been devised to develop an advanced high-efficiency absorption chiller that is considerably beyond today's state-of-the-art. This is to be achieved through the design, fabrication, testing and evaluation of a series of incrementally improved absorption chillers.

The first phase of this project consisted of the partial reconstruction for solar-powered operation of a conventional gas-fired ammonia/water absorption chiller. This phase was successfully completed some time ago,[1] and it demonstrated the capability of our analysis techniques to predict accurately the performance of single-effect, absorption-cycle chillers under operating conditions appropriate for solar-powered operation.

The second phase includes the design and fabrication of a single-effect ammonia/water absorption chiller that incorporates several unique design features: tube-in-tube heat exchangers for high effectiveness at reasonable cost, an internally powered solution pump for reduced parasitic power use, and a rectification path for the hot vapor generated that also effectively recuperates the heat of the vapor. The laboratory test unit has a capacity of three tons. This chiller, which represents the starting point for the development of the higher efficiency units in subsequent phases, is currently in the test and evaluation stage.

The third phase of the project is the development of an advanced higher efficiency cycle, a double-effect regenerative cycle (which we call cycle 2R) that adds a unique second stage to the chiller developed in phase two. With the addition of this second stage, the overall chiller efficiency increases continuously as a function of the inlet temperature from the solar collectors. The basic concept of this 2R cycle was described some time ago,[2] and is shown schematically in Figure 1. Since then the design has been completed, and fabrication has started.

The fourth phase takes advantage of the experience gained in previous phases to develop a still higher efficiency chiller, yet one with less hardware and thus with the potential for lower cost. This chiller is based on a single-effect regenerative cycle (which we call cycle 1R). Although the basic concept has been described by our group previously,[3] this chiller is still in an early design stage. The success of the cycle 1R chiller depends on our experience gained from developing the cycle 2R chiller and on locating a refrigerant/absorbent fluid pair with suitable properties at the higher boiling temperatures where ammonia/water performance drops off.

An absorption-cycle air conditioner is essentially a heat pump and, accordingly, can be used for heating as well as cooling as long as the refrigerant fluid does not freeze in the outdoor coil during heating applications. Thus these technology improvements will also lead to more efficient thermally driven heat pumps.

TECHNICAL ACCOMPLISHMENTS

Single Effect Absorption Chiller

- The testing, modification, and evaluation of the single-effect ammonia/water chiller is in progress. Initial results show that the condenser, generator, preheater, and the recuperative solution pump perform up to expectation. Uneven fluid distribution in the absorber's parallel coils and excessive pressure drop across the evaporator are problems that still need correction. After the necessary modifications to decrease the absorber temperature and the evaporator pressure drop, the COP of the chiller should be in the range of 0.65 - 0.70 at design conditions.

- We have had mixed success in developing the two internally powered piston circulation pumps; much effort has been expended on them. The recuperative pump powered by the returned weak aqua-ammonia solution has been successfully developed; it pumps 1.45 gpm of strong solution. The make-up pump powered by high pressure ammonia vapor did not work reliably because of vapor absorption by the liquid ever present in the pump switching lines. At present the make-up pump has been replaced by a make-up electric piston pump having an output of 0.85 gpm, for a total circulation of 2.3 gpm of strong solution.

Cycle 2R Absorption Chiller

- The detailed design and drawings for the components of the 2R chiller have been completed.
- Fabrication of some components has been completed, including the boiler, the preheater, the recuperator, the generator, the rectifier, and the multi-stage pump.
- All components of the experimental 2R chiller are being made of stainless steel to avoid rust problems that may occur during periods of cutting open the chiller for necessary modifications.

Cycle 1R Absorption Chiller

- Work on the cycle 1R chiller during FY 1980 has consisted of computer modeling the cycle for design and fluid selection purposes, and devising a method for the calculation of the properties of the promising pairs from a basic set of experimental data.
- A number of candidate fluid pairs have been selected. The basic set of experimental data needed to determine the mixture properties of these fluids has been specified. After review of proposals received, in response to a competitive solicitation, DOE negotiated a contract with SRI International for the collection of the basic set of data through a literature search followed up with measurement of the as yet unmeasured parameters.

FUTURE ACTIVITIES

The testing of the single-effect chiller will continue. Further improvement of the vapor pump will not be pursued; the chiller will be operated using the electric make-up pump for the remaining chiller tests. The testing is expected to be completed and the results published during FY 1981.

The design and fabrication of the absorber and evaporator of the cycle 2R chiller will proceed following analysis of the final results of the testing of the single-effect unit; this test information is needed to finalize the design of these components. Testing of the multi-stage pump is planned to begin late in FY 1981. The fabrication of the 2R chiller should be completed early in FY 1982, followed by testing and evaluation throughout the remainder of FY 1982.

The cycle analysis work on the cycle 1R chiller will continue during FY 1982 as we continue to reduce the theoretical cycle to a practical design. The required measurements of the properties of candidate fluids for the 1R cycle should be completed by SRI International by the end of FY 1981; we will work closely with them to insure the maximum utilization of the data measured during that project. The final 1R design and working drawings are expected to follow during FY 1983.

REFERENCES

1. K. Dao, M. Simmons, R. Wolgast, M. Wahlig, Performance of an Experimental Solar-Driven Absorption Air Conditioner, Lawrence Berkeley Laboratory report LBL-5911, January 1977.
2. K. Dao, Conceptual Design of an Advanced Absorption Cycle: The Double-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory report LBL-8405, September 1978.
3. K. Dao, A New Absorption Cycle: The Single-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory report LBL-6879, February 1978.

SCHEMATIC DIAGRAM OF 2R CHILLER

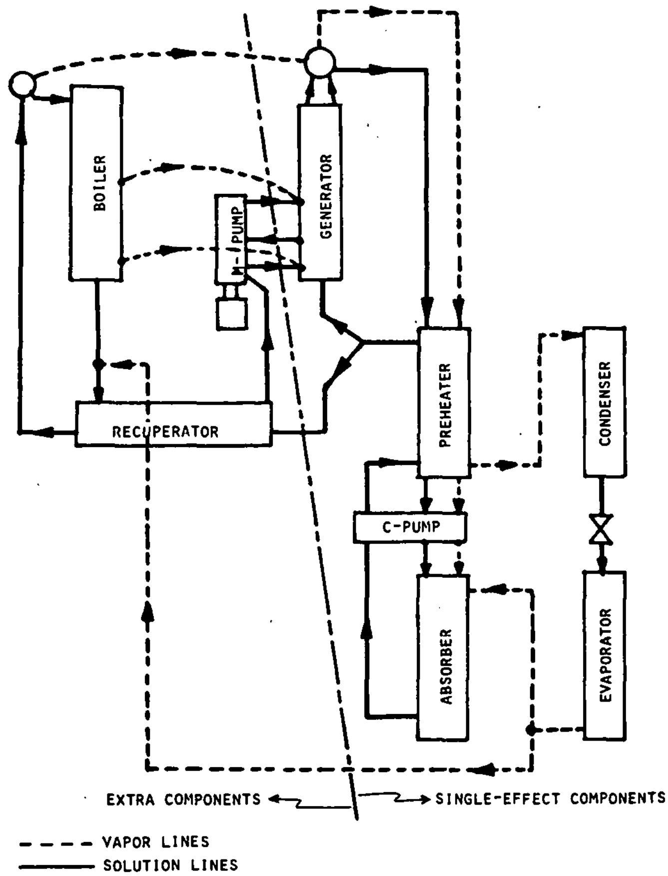


Figure 1. Schematic Diagram of the Double Effect Regenerative Absorption Air Conditioner.

CONTRACT INFORMATION		
START DATE 7/74	END DATE Cont.	CONTRACT VALUE $1372 K

MILESTONES

Item:	Due date:
1. Single-effect chiller: complete testing and issue report	12/81
2. Double-effect regenerative chiller: fabrication completed	10/81
3. Double-effect regenerative chiller: complete testing and issue report	11/84
4. Single-effect regenerative chiller: design completed	3/85
5. Single-effect regenerative chiller: complete fabrication, start testing	9/86

DETERMINATION OF PROPERTIES OF FLUIDS FOR SOLAR COOLING APPLICATIONS

SRI INTERNATIONAL

RICHARD THOMAS PODOLL

CONTRACT NO. DE-AC03-80CS30221

OBJECTIVES

The objectives of this project are to determine pressure-volume-temperature (P-V-T) data and calorimetric data for organic refrigerant and absorbent fluids and their binary mixtures that are accurate enough to be used for the design of solar-powered cooling engines.

DESCRIPTION OF WORK

The Lawrence Berkeley Laboratory has developed a concept of a solar-activated advanced absorption cycle called the Single Effect Regenerative Absorption Refrigeration Cycle (Report LBL-6879). The coefficient of performance (COP) of this cycle improves with increasing input temperatures up to a limit imposed by the thermodynamic properties of the working fluid refrigerant/absorbent pair. The COP increases up to an input temperature of 280°F, for example, for the working fluid pair ammonia/water. Pairs other than ammonia/water are needed to take advantage of the potential increase in COP with an increase in input temperature above 280°F. The purpose of this project is to conduct an initial comparative study of a number of refrigerant/absorbent pairs that show promise of fulfilling this potential.

The fluids to be tested are the following.

Refrigerants	Absorbents
Ammonia	Ethylene glycol
Methylamine	1,4-butanediol
Ethylamine	Diethylene glycol dimethyl ether
Dichlorofluoromethane	N,N-dimethylacetamide
Difluorochloromethane	N,N-dimethylhexanamide
	N,N-dimethyldecanamide

The thermodynamic properties to be determined are the following.

Pure Fluids

- P-V-T data: critical properties, vapor pressures, vapor and liquid densities
- Calorimetric data: specific heats of vapor and liquid, enthalpy of vaporization

Fluid Mixtures (14 binary pairs)

- P-V-T data: saturation temperatures
- Calorimetric data: enthalpy of mixing, specific heats

The work is divided into two tasks. The first task is a critical literature survey of thermodynamic data on the fluid pairs listed above. The second task is to measure those properties of the pure fluids and their mixtures that have not previously been measured to the required accuracy.

These data will be used by LBL (Contract No. W-7405-ENG-48) together with thermal stability data to determine the most promising pairs for the advanced absorption cycle.

TECHNICAL ACCOMPLISHMENTS

- Most of the thermodynamic data on the pure refrigerants was found to the required accuracy in the literature. Very litte experimental data was found for the absorbents and no experimental data was found for any of the mixtures. Estimation techniques were used to calculate pure fluid properties of the absorbents but these values are very uncertain because of the high polarity and/or high molecular weight of the test absorbent fluids. Reported and estimated data are discussed and tabulated in the Literature Survey [1].
- Experimental work has begun on the pure fluids. Because of thermal decomposition at 300°C (572°F) or less, the critical properties of none of the absorbents may be measured, and the remaining properties will be determined up to the onset of thermal decomposition (in the absence of oxygen).

Future Activities

- The experimental work on the pure fluids and their mixtures will be finished
- The literature and experimental data will be tablulated in a Final Report

References

1. Podoll, R. Thomas "Literature Survey: Determination of Properties of Fluids for Solar Cooling Applications," February 1981. Prepared for the U.S. Department of Energy, San Francisco Operations Office

CONTRACT INFORMATION

START DATE 9/29/80 END DATE 9/30/81 CONTRACT VALUE $121,857

MILESTONES

Item:	Due date:
1. Literature Survey	31 January 1981
2. Complete experimental measurements	31 August 1981
3. Final Report	30 September 1981
4.	

DESIGN OF A SOLAR ENERGY COOLING SYSTEM

SUNMASTER CORPORATION, 35 WEST WILLIAM STREET, CORNING, NEW YORK 14830

JOSEPH R. FRISSORA

CONTRACT DEN8-000005

The objective of this project was to design and develop a large scale, industrial sized solar system which would supply hot water to a large modified Carrier Corporation 16JB018 absorption chiller.

The second objective was to demonstrate the feasibility and capabilities of drainable evacuated glass tube solar collectors in a large industrial application.

The Sunmaster Corporation, Corning, New York, entered into a contract with NASA Marshall Space Flight Center in January 1979 to design a solar system which would provide hot water for the operation of an existing Carrier 16JB018 absorption chiller installed in the Frenchman's Reef Holiday Inn Hotel, St. Thomas, U.S. Virgin Islands.

The Hotel uses two Carrier 16JB018 absorption chillers to generate chilled water which is used to cool the air in the restaurants, shops, bars, and public areas of the Hotel, and additionally, to cool fresh desalinated potable water. One chiller, designated Chiller No. 1, has been modified to be powered by hot water, and the water can be heated by the solar system and/or by a steam heated heat exchanger. The other chiller, designated Chiller No. 2, is powered by steam. The chillers can be utilized separately or together to generate the chill water required by the air conditioning loads.

The solar energy collection system was based on the Sunmaster^{tm} drainable evacuated glass tube solar collector. The Sunmaster^{tm} collector consists of eight 4-feet long evacuated glass tube collectors attached to an insulated supply and drain manifold, and mounted to a frame that incorporates the unique double cusp reflectors designed by the Argonne National Laboratories. When mounted with the tubes oriented on a north-south line and inclined perpendicular to the sun's incident rays, the Argonne reflectors concentrate the solar radient energy on the inner tubes' absorber coating throughout the solar day.

The design of the solar array was based on the orientation of the Hotel, the available roof space, and the local annual insolation as calculated from data acquired in San Juan, Puerto Rico, latitude 18^{o} North. The solar array consists of 956 Sunmaster^{tm} collectors for a total of 13,384 effective square feet collection area.

When operating, water in the solar collectors is heated to a maximum of 240^{o} F. and then piped to the first of two 2,500 gallon tanks. The first, or upper tank, is designed to maintain an 8-inch deep level of water, and water exceeding that level flows through a connecting line to the second and lower 2,500 gallon tank. Water in the lower tank is then pumped back and recirculated through the collectors. The 8-inch deep water in the upper tank serves as a reservoir from which solar heated water is pumped to Chiller No. 1. Return water from Chiller No. 1 is pumped back to the upper tank where a baffle prevents the return water from mixing with the solar heated water before it flows to the lower tank and then to collectors.

An Andover Controls Corporation Sunlogger^{tm} Solar Controller is used to control the solar system and acquire operating data. Temperature is sensed in the collectors, tanks, and hot water lines to and from the Chiller No. 1 along with flow rates, and insolation measurements. The microprocessor scans the data and executes systems controls which activates pumps and valves, thus causing the system to operate to and within a set of preselected and programmed parameters. The Sunlogger^{tm} can also print out real-time data, time-phased historical data, and integrated data such as Btu/hour and efficiencies. The Sunlogger^{tm} system also provides for remote monitoring through telephone coupling.

The Sunmaster^{tm} collector system employs a unique drain-back feature whereby all the water in the collectors will drain back to the two 2,500 gallon tanks if there is a power failure or when there is insufficient insolation to merit continued operation as at night or on rainy days. This drain-back feature precludes thermal losses due to radiation at night or excessive temperatures and pressures in the collectors when water is trapped in the collectors when power and pumps fail. Both tanks are heavily insulated to minimize heat losses.

During the initial phase of work in 1979, the contract was modified to provide for the installation of a pilot collector array which would confirm the feasibility of the design and provide a level of experience useful in fabricating and installing the full scale system. This prototype or pilot array was completed in June 1979 and consisted of 34 Sunmaster^{tm} collectors with 476 square feet of collection area, a pump, a 250 gallon storage tank, and a liquid-to-air heat exchanger, all controlled by the Sunlogger^{tm} Solar Controller. With the exception of the heat exchanger, all components were assimilated into the final system.

Tests were performed on the completed system in March 1980. The all day insolation in the plane of the collector was 1,852 Btu/square foot, 37.9 percent of the available insolation was collected, and 84 percent of collected heat was delivered to the chiller.

Except for repairs to the chiller and associated equipment and maintenance to the solar system, the system has been operating since installation completion in November 1979 and providing solar heated water to the Chiller No. 1.

CONTRACT INFORMATION

START DATE 1/3/79 END DATE 6/30/81 CONTRACT VALUE $1,042,879

MILESTONES

Item:		Due date:
1.	Final Design Review	June 1979
2.	System Installation Complete	November 1979
3.	Complete Maintenance	July 1981
4.		
5.		

MULTIPLE-EFFECT ABSORPTION CYCLE SOLAR COOLING

THE UNIVERSITY OF TEXAS AT AUSTIN: CTR. FOR ENERGY STUDIES/DEPT. OF MECH. ENGINEERING

GARY C. VLIET

CONTRACT: DE AC03-79SF10540

OBJECTIVE

The purposes of this investigation were: to develop a dynamic computer model of the water-lithium bromide double-effect absorption cooling cycle; to use the code to assess the effect on performance of variations in the cycle's several design and operating parameters; and to briefly assess the cost of double-effect absorption cooling per unit of capacity for varying capacity. The work accomplished under this contract is documented in the contract final report [1].

DESCRIPTION OF WORK

The absorption cycle is one of the alternatives for solar cooling, and the double-effect absorption cycle is a competitor to proposed Rankine cycle solar cooling systems. While the Rankine cycle has the specific advantage of mechanical/electrical output, the double-effect absorption cycle appears to have a potentially better COP when operating purely in the cooling mode. The double-effect cycle has been available for several years, although there has not been significant interest in it for application to solar cooling systems.

Auh [2] provides an excellent overview of absorption cooling. A preliminary assessment of the potential of double-effect water-lithium bromide absorption systems is presented in [3]. The first prototype double-effect unit was developed by Southwest Research Institute in 1956-58 under funding from the American Gas Association [4,5]. Later, the Iron Fireman Company of Cleveland, Ohio, purchased the manufacturing rights and began production of the "Iron Fireman" unit in 1963, a nominal 15-ton, gas-fired unit with a gross COP of 0.9 to 1.0 and a net COP of 1.2 to 1.3 near design capacity. Only a few units were manufactured and sold, and it is no longer in production. In 1973, the Trane Company introduced a line of steam-fired double-effect absorption units with capacities between 385 and 1,060 tons, and COPs in the range of 0.9 to 1.0 near design capacity. The Sanyo Company of Japan previously built a line of double-effect units; however, the line has been discontinued. Yazaki, also of Japan, has announced the introduction of a gas-fired 20-ton unit. Although double-effect units have been and still are available, they do not appear to have reached their performance potential, possibly because they were designed during the availability of cheap energy.

The major objectives of this project were to develop a fairly comprehensive dynamic computer code of the (water-lithium bromide) double-effect absorption cooling cycle, and to use the code to investigate the influence of the several design and operational variables on the cycle performance (coefficient of performance and capacity). Ultimately, it is hoped these results and/or the computer model would be used by manufacturers for optimizing the design of future systems.

TECHNICAL ACCOMPLISHMENTS

- A physical model of the (water-lithium bromide) double-effect absorption cooling system was defined as shown in Figure 1. It includes seven (7) heat exchangers in all--including the two recovery heat exchangers, two regenerators, condenser, evaporator, and absorber--as well as a solution pump. The model allowed for either an orifice (pressure-driven flow) or a float (refrigerant vapor trap) in the refrigerant condensate stream between the second generator and condenser.

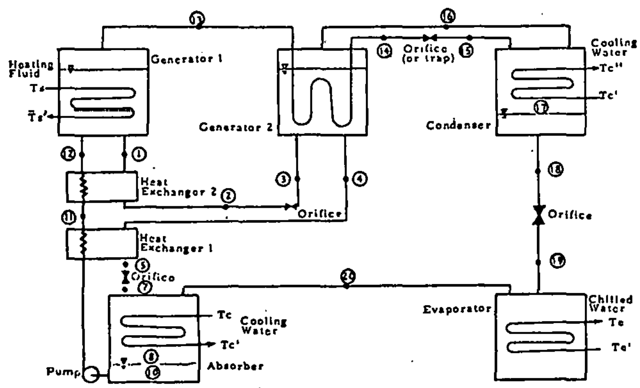


Figure 1. Schematic of Physical Model

- A dynamic computer code was developed around the above physical model. It includes mass, species, and energy balances as well as fluid flow, heat transfer, and mass transfer specifications for the various components and thermophysical property data for the water-lithium bromide system. The computer code has been used successfully to simulate cycle performance over ranges of the several individual design and operational parameters.

- The effects on cycle performance (COP and capacity) were determined for each of the design and operational variables, some of which are discussed briefly below. Most of the results wer developed assuming a constant capacity solutio.. pump and a refrigerant vapor trap (or float) between the second generator and condenser. A "nominal" design condition was selected (after several investigative runs) which resulted in reasonably optimal sizes for the various components at the nominal condition. The nominal condition for a 10-ton system is summarized in Table 1. Each of the parameters was then varied individually as all others were held at their nominal values. Table 1 also includes the ranges over which each of the parameters was varied.

Table 1. Nominal Conditions and Parametric Ranges

	Investigated Condition	Nominal Condition*	Range
T_s	Source hot water temperature	280°F	220-320°F
T_c	Cooling water temperature	85°F	50-100°F
T_{ch}	Chilled water temperature	44°F	34-74°F
m_s	Source hot water flow rate	5,000 lb/hr	2,000-10,000 lb/hr
m_c	Cooling water flow rate	18,000 lb/hr	8,000-28,000 lb/hr
m_{ch}	Chilled water flow rate	10,000 lb/hr	5,000-15,000 lb/hr
m(10)	Solution flow rate	900 lb/hr	500-1,500 lb/hr
A_{G1}	Area of first generator	35 ft^2	5-105 ft^2
A_{G2}	Area of second generator	20 ft^2	5-105 ft^2
A_C	Area of condenser	20 ft^2	5-105 ft^2
A_E	Area of evaporator	55 ft^2	5-105 ft^2
A_A	Area of absorber	60 ft^2	5-105 ft^2
A_{HX1}	Area of first heat exchanger	5 ft^2	0-20 ft^2
A_{HX2}	Area of second heat exchanger	5 ft^2	0-20 ft^2
c	Pressure drop coefficient between the evaporator and the absorber	0.5×10^{-6}	$0\text{-}5 \times 10^{-6}$
	Orifice flow control (varying T_s)		220-320°F
	Centrifugal pump I (varying T_s)		220-320°F
	Centrifugal pump II (varying T_s)		220-320°F
	Orifice flow control with centrifugal pump I (varying T_s)		220-320°F
	Orifice flow control with centrifugal pump II (varying T_s)		220-320°F

*The nominal condition corresponds to a cooling capacity of approximately 10 tons.

--Figure 2 compares the relative effects on performance of float (trap) control and orifice control over a range of source hot water temperatures (and constant capacity solution pump). It is seen that use of a vapor trap maintains the COP (in particular) at a high level over a wider range of source temperatures and also enhances capacity (but to a lesser degree) compared to the orifice flow design.

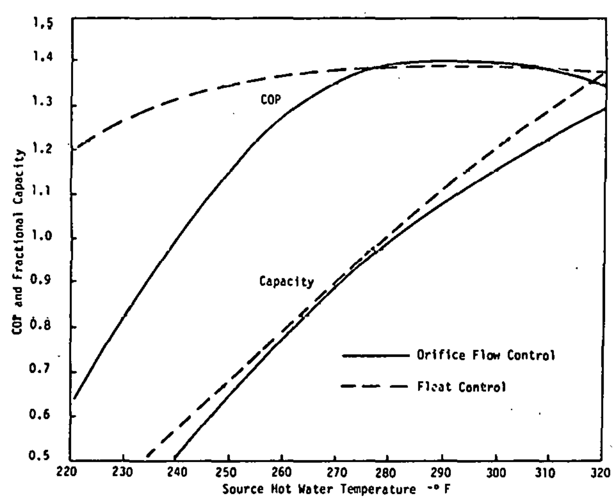


Figure 2. Effect of Source Hot Water on Performance: Comparison of Orifice and Float Control

--Figure 3 shows the combined effects of refrigerant flow control and type of pump characteristics on performance. The use of a centrifugal pump somewhat further degrades the cycle performance, but principally at higher source temperatures. The reason is that for a centrifugal pump with its varying capacity (due to pressure head), the solution circulation rate is reduced at higher source temperatures.

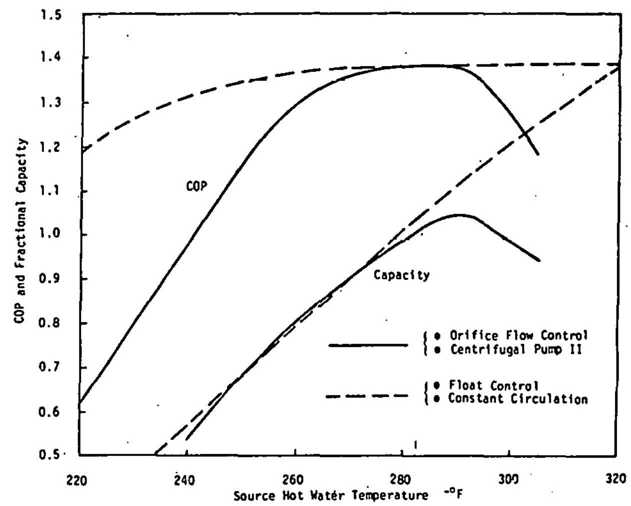


Figure 3. Effect of Centrifugal Pump (Varying Circulation Rate) and Orifice Control on Performance

--Figure 4 shows the effect on performance of the two regenerator heat exchanger areas. Note that the capacity is affected somewhat more by the area of the first generator than by the second, and that COP is not markedly affected by either.

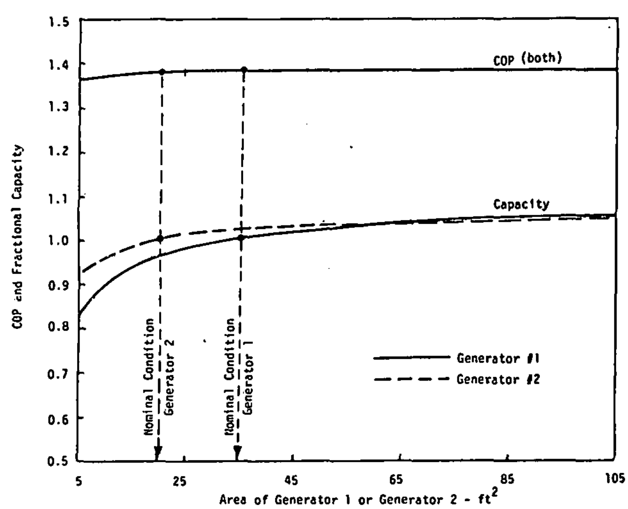


Figure 4. Effect of Each Generator Area on Performance

Sensitivity data were also obtained for varying condenser, evaporator, and absorber areas (not presented). Figure 5 shows the effect on performance of the two recovery heat exchangers. The capacity is seen to be little affected for either heat exchanger; however, the COP is significantly affected, and about equally by each.

--Figure 6 shows typical curves for performance (COP and capacity) for a specified 50°F exit chilled water temperature and varying source and

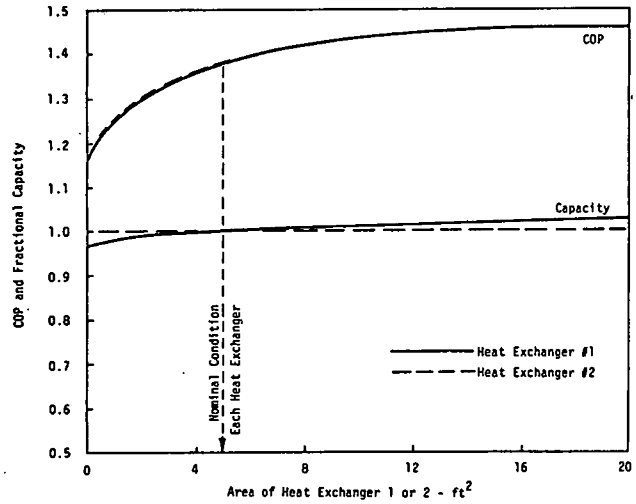


Figure 5. Effect of Each Recovery Heat Exchanger Area on Performance

cooling water temperatures. These data are for constant solution circulation and float (trap) control. The locus of the crystallization condition is indicated.

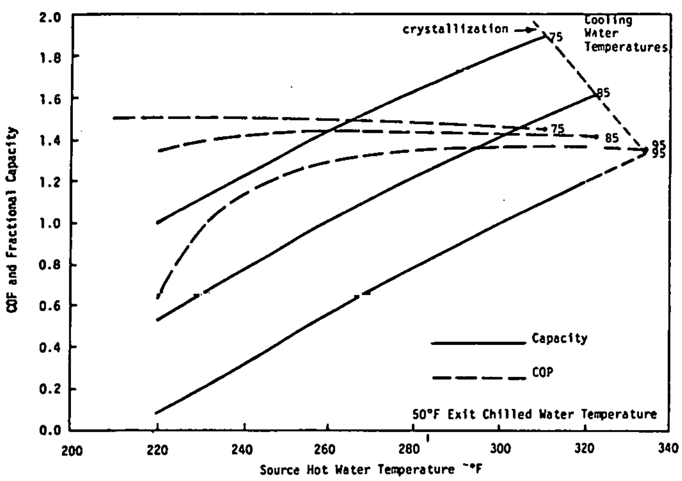


Figure 6. Cycle Performance for 50°F Exiting Chilled Water Temperature

- Some specific conclusions about optimal system design evolve from these results. (a) The trap or float control is much preferred to the orifice flow design in terms of maintaining high performance over a wide range of source temperatures. This capability is particularly important for a solar-driven system, where the source temperatures will vary considerably. (b) The solution pump characteristic is important, particularly at high source temperatures, with one approaching constant displacement preferred. (c) The relative allocation of heat exchanger area to the seven heat exchangers is very important to cycle performance and cost, since a large portion of the cost of absorption systems is in heat exchange surface.

- A secondary objective of the study was to assess the cost of absorption cycle cooling per unit of design capacity. Figure 7 shows a summary of data for single- and double-effect units. The cost of small tonnage (single-effect systems)

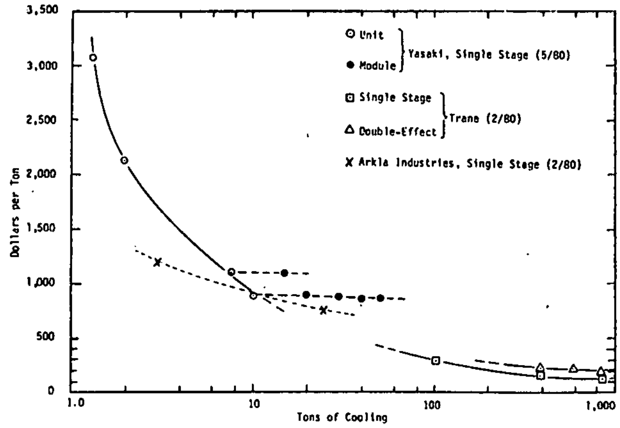


Figure 7. Unit Capacity Cost Versus Capacity of Water-Lithium Bromide Absorption Systems

appears excessive, but it would appear that there is merit in considering intermediate capacity double-effect systems in the range of 20 to 100 tons. Modularizing, as done by Yazaki, has merit in flexibility, but unit cost is high. A comparison of the Trane single- and double-effect large capacity units is interesting. Their relative costs are about equal to their relative COPs. Since the increased capital costs of the double-effect units (over single) are probably considerably less than the incremental collector cost for solar systems or life-cycle fuel costs for conventional systems, it would appear that the double-effect cycle is a viable choice.

FUTURE ACTIVITIES

The availability of this dynamic computer code for the (water-lithium bromide) absorption cooling cycle provides a tool for manufacturing and systems analysts to develop more optimal designs.

It has been proposed that some additional effort be put into the computer code to ensure that it has the most current thermophysical property data, to provide an improved physical model for the absorber, and to better document the code. In addition, a more in-depth assessment of the allocation of heat transfer area to the different components should be made, and a direct comparison between the model's predictions and the performance of commercially available unit(s) is needed. It is also proposed that the model, results, and advice on using or modifying the model be made available to interested manufacturing firms.

PUBLICATIONS/REPORTS/REFERENCES

1. Vliet, Gary C.; Lawson, Michael B.; and Lithgow, Rudolfo A., Water-Lithium Bromide Double-Effect Absorption Cooling Analysis Final Report on DOE Contract DE AC03-79SF10540, (Austin: The University of Texas at Austin Center for Energy Studies, December 1980).

2. Auh, Paul C., A Survey of Absorption Cooling Technology in Solar Applications, Report Number BNL50704 (Upton, New York: Brookhaven National Laboratory, July 1977).

3. Vliet, Gary C., and Saiidi, Mohammad J., "Double Effect Absorption Cooling with Solar Energy," Proceedings of the Third Workshop on

the Use of Solar Energy for Cooling of Buildings, 1978.

4. Whitlow, E. P., and Swearingen, E. P., "An Improved Absorption Refrigerant Cycle," J. Gas Age, October 1958.

5. Versagi, Frank J., Technical Conversations in Air Conditioning and Refrigeration (Detroit: Business News Publishing Company, 1962).

CONTRACT INFORMATION

START DATE Sept. 1, 1979 END DATE Nov. 30, 1980 CONTRACT VALUE $51,032

MILESTONES

Item:	Due date:
1. Final Report	11-30-80
2. Computer Program	11-30-80
3.	
4.	
5.	

Section 3: DESSICANT SOLAR COOLING SYSTEMS

3

NATIONAL SOLAR DESICCANT COOLING PROGRAM

Dennis R. Schlepp
Solar Energy Research Institute
Golden, Colorado

ABSTRACT

This paper presents a brief overview of the activities and accomplishments of contractors in the Solar Desiccant Cooling Program. The progress of SERI's desiccant cooling research program is also discussed.

BACKGROUND

Research and development efforts in the Solar Desiccant Cooling Program are going on in four categories: open-cycle solid desiccant adsorption systems, open-cycle liquid desiccant adsorption systems, open-cycle absorption refrigeration systems and closed-cycle solid desiccant adsorption systems.

Most of the activity in the past has centered on developing the open-cycle solid desiccant adsorption systems for residential applications. The process used is dehumidification and evaporative cooling to provide comfortable air with solar heated air used for regeneration of the desiccant for reuse. Both the Institute of Gas Technology and Garrett AiResearch have been involved in designing, building and testing solid desiccant chillers with capacities in the range of 1.5 tons. The Illinois Institute of Technology has built a cross-cooled desiccant chiller that is presently being tested. The University of Wisconsin has provided analytical support to this portion of the program through the use of a TRNSYS computer simulation of desiccant chillers, and through a cooperative agreement with the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, they will be performing laboratory experiments with rotary dehumidifiers and heat exchangers.

Interest and activity has increased in investigating open-cycle absorption refrigeration systems for commercial applications. Open-cycle absorption units are similar to conventional closed-cycle absorption units, but they use water as the refrigerant and reject water vapor to the atmosphere in open-flow collectors, eliminating the need for a condenser. Colorado State University has been studying the regeneration of lithium chloride solutions in packed concentrating towers to determine applicability of the process to hot air collector systems. Lockheed Missiles and Space Co. and Arizona State University will determine the heat and mass transfer rates of lithium chloride regeneration on open-flow collectors for hot humid climates and hot, dry climates, respectively. All of the studies will aid in design of an absorption refrigeration chiller in the future.

Open-cycle liquid desiccant adsorption systems operate on the same principles as the solid desiccant systems, but use liquid desiccant sprays for dehumidification. The University of South Carolina is installing such a chiller in a residence to demonstrate the viability of this solar cooling system.

The closed-cycle solid desiccant adsorption process has been developed by The Zeopower Company for use as a combined heating and cooling unit. This system, using natural zeolites sealed in vacuum-tight collectors, is able to provide a residence with air conditioning in summer and heat in the winter by using the closed adsorption cycle.

SERI's in-house research efforts have supported activities in all areas of the program. Computer simulation models of both solid desiccant and liquid desiccant systems have been valuable in determining areas for performance improvements in the open-cycle systems. The desiccant cooling research laboratory is providing data on the adsorption properties of different desiccants and on different desiccant bed configurations. Assistance to the contractors in the program in technical matters has been provided throughout.

SUMMARY

Some of the most significant accomplishments of the Solar Desiccant Cooling Program have come in the area of the residential open-cycle solid desiccant chillers. Both the IGT and AiResearch machines have been successfully tested in the last year, with encouraging performance results. Both systems have operated above the predicted levels of performance at their rated capacities, with solar coefficients of performance (COP's) in the range of 0.5 to 0.6. These tests have demonstrated the technical viability of the concept and point toward further development efforts and field testing of the machines.

Results obtained from the research in the area of open-cycle absorption refrigeration systems also show great promise for future development. Tests on prototype regenerators have proven that the regeneration process takes place according to theoretical predictions. With the potential for very low cost regenerators, these systems have a bright future in commercial applications.

TECHNICAL ACCOMPLISHMENTS

Institute of Gas Technology

- IGT's SOLAR-MEC III solar cooling systems has been successfully tested in the laboratory. Test data from the machine have shown COP's in the range of 0.5 to 0.6 at design conditions, with a capacity of 1.67 tons of cooling.

- The seasonal simulation model developed by IGT as a design tool for the SOLAR-MEC has been verified by the experimental results and can be used for prediction of system performance at off-design conditions.

Garrett AiResearch Mfg. Co.

- Design point performance was exceeded by the AiResearch chiller (SODAC) in the recirculated mode, with an average COP of 0.59 at a capacity of 1.35 tons of cooling, compared with a predicted COP of 0.52. Off-design (half-flow) performance was also higher than predicted, with an actual COP of 0.56 as compared to the predicted value of 0.46.
- Economic analyses were performed using the performance data collected in the testing and showed that SODAC would have positive present value benefits in conjunction with a solar heating system.

Illinois Institute of Technology

- A mathematical model for laminar flow through an isothermal dehumidifier was developed and fitted to experimental data.
- A complete one-ton cooling system using two cross-cooled dehumidifiers has been installed in a test house with air collectors and is currently being tested.

University of Wisconsin/CSIRO

- System studies by the University of Wisconsin have covered many areas of solar desiccant cooling. The subjects of these studies have included: desiccant property analysis, dehumidifier modeling and design, the effects of transient and nonuniform inlet conditions on dehumidifier and heat exchanger performance. These studies have established performance goals and practical limits for solar desiccant cooling systems.
- Experimental component testing at CSIRO in Australia has been performed on rotary heat exchangers and will begin soon on rotary packed-bed silica gel dehumidifiers. The results will be used to improve system designs and verify the computer models.

Colorado State University

- Experimental work has demonstrated the feasibility of regenerating lithium chloride solutions in packed towers. Values for the heat and mass transfer coefficients have confirmed theoretical values established in earlier work. These results will aid in design of open-cycle absorption chillers for air collector systems.

Lockheed Missiles and Space Co.

Preliminary results of regeneration of lithium chloride solutions on open-flow collectors have been obtained using a small prototype collector, and have shown the regeneration to occur as predicted by a model developed at SERI. The full size (50 ft x 50 ft) collector will be finished in time for experimental work during the summer cooling season.

Arizona State University

- Tests of flow distribution over the fluid film collector have been made to establish final regenerator design criteria. The collector will be operative for the summer testing period.

University of South Carolina

- U of SC has installed a liquid desiccant chiller with open-flow glazed regenerators on a residence at Pawley's Island, SC. The system using calcium chloride solutions as the desiccant, will be operational by June 1 for testing through the summer.

The Zeopower Company

- The integrated zeolite collector has been installed and tested in three sites around the country: Natick, MA; Golden, CO; and Tucson, AZ. The collectors have been performing up to the design levels under most conditions. Problems with vacuum integity of the collector appear to have been solved by design changes.

SERI

- A computer simulation model of a solid desiccant chiller has been developed and verified by experimental data from SERI's desiccant research laboratory. This model is able to predict the performance of desiccant systems in both cylcical and once-through configurations, making it a flexible tool for analysis of candidate systems.
- The desiccant research laboratory is evaluating the dehumidification performance of packed beds of silica gel. Other desiccants and desiccant bed geometries will be tested in coming months.
- A model of the performance of open-cycle absorption refrigeration systems has predicted the ability of such a system to provide heating as well as cooling, making an integrated system possible for commercial applications.

FUTURE ACTIVITIES

In the area of open-cycle desiccant systems, current plans call for work to develop control strategies and equipment, followed by field testing of prototype units. Research will continue for performance improvements through better system designs, new or improved desiccant materials and components such as high efficiency heat exchangers and evaporative coolers. It is anticipated that these efforts will increase system COP's and lower system costs.

As mentioned earlier, researchers in the area of liquid desiccants will be working during the summer months of 1981 to gather data on regeneration of the liquid desiccant solutions. The results of this work will determine the direction of future research and development efforts. Current plans call for construction and testing of prototype cooling systems to address the operational problems that are anticipated.

DEVELOPMENT OF A SOLAR DESICCANT DEHUMIDIFIER

AIRESEARCH MANUFACTURING COMPANY

JEAN ROUSSEAU

CONTRACT NO. EG-77-C-03-1591

OBJECTIVE

The objective of this program is to design and develop a 1-1/2-ton solar desiccant air conditioner (SODAC) for residential application.

DESCRIPTION OF WORK

Concept

A schematic of the system is shown in Figure 1; the arrangement of the desiccant bed and regenerator is depicted in Figure 2. The system, compared with competing desiccant system approaches, incorporates three important features:

(1) Granular silica gel is used as the desiccant.

(2) Outside air precools the bed before it enters the adsorbing zone; heat removed from this portion of the bed is used to preheat the bed as it enters the desorbing zone, thus reducing the solar heat required for desorption.

(3) The silica gel bed and regenerator are packaged in thin cylindrical drums; this arrangement provides large flow areas and minimum bed depth resulting in a small pressure drop.

The schematic shown in Figure 1 depicts the recirculated mode configuration whereby air from the conditioned space is processed in the SODAC and returned to that space. This configuration was found to be more effective over a broader range of operating conditions and was selected as baseline. Also part of the baseline concept is the use of two-speed indoor and outdoor fans; operation at half-design flow rates was found to offer significant advantages at reduced loads.

Scope of Work

The first phase of the program (completed in September 1980) covered a three-year period and was concerned with the design, fabrication, and development testing of the SODAC. The Phase I test program included (1) configuration development, (2) design point optimization, and (3) limited off-design performance characterization.

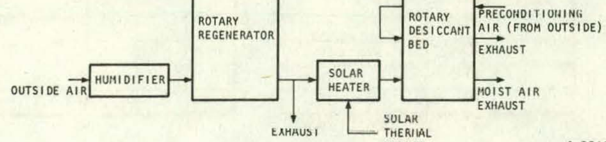


Figure 1. System Schematic

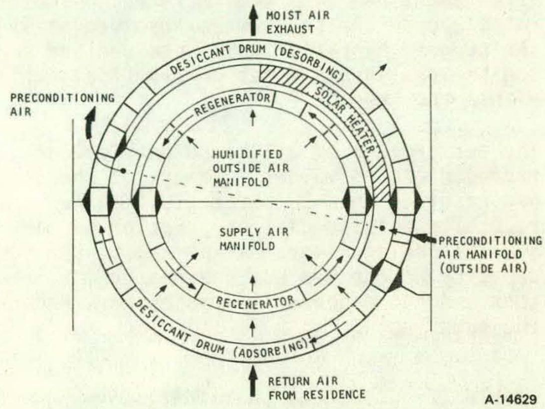


Figure 2. Dehumidifier Cross Section

The current second phase constitutes a continuation of the test program and will result in complete performance characterization in the recirculated mode at full-flow and half-flow conditions. The test program also will include performance testing in the alternate ventilated mode, in which outside air is processed in the SODAC and used for cooling the conditioned space.

TECHNICAL ACCOMPLISHMENTS

Technical accomplishments are listed below for both phases of the program. Details can be found in the publications listed at the end of this paper.

- The SODAC design has been completed. A photograph of the unit is shown in Figure 3. The

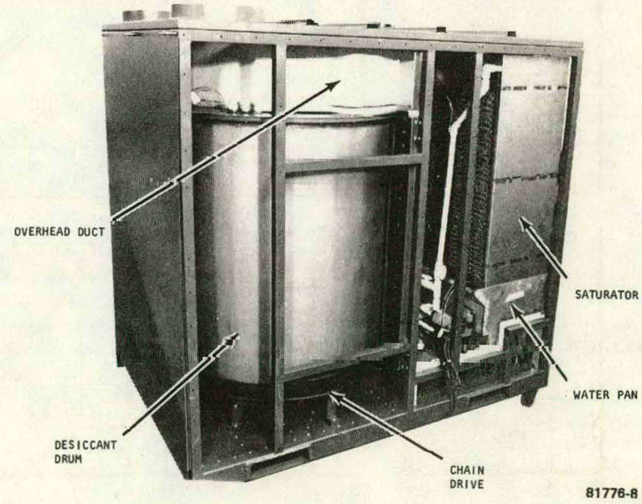


Figure 3. SODAC Package

unit was designed for maximum COP within the constraints of size and parasitic power usage. A summary of the component characteristics is presented in Table 1.

- Preliminary testing has been accomplished. The system was instrumented and installed in a controlled atmosphere chamber at the Dunham-Bush Harrisonburg facility. Preliminary performance runs verified selection of airflow rates and drum speeds.

- The basic configuration of the bed and sealing arrangement has been demonstrated. High leakage rates around the seals were resolved early in the program by partitioning the bed and modifying the seals to overlap the vertical partitions within the beds.

- The performance of all components met or exceeded design values. Rework of the desiccant bed resulted in a 10 percent silica gel charge reduction because of incorporation of partitions and stiffening rings. As a result, the nominal capacity of the bed was reduced from 1.5 to 1.35 tons and the process flow rates were reduced by the same ratio.

Table 1. Component Characteristics Summary

Desiccant Bed	Regenerator
8 to 10 mesh silica gel	24 x 24 x 0.014 in. steel screen
Bed inside diameter: 31.3 in.	Matrix inside diameter: 19.0 in.
Bed active height: 34.7 in.	Matrix active height: 34.5 in.
Bed thickness: 1.25 in.	Matrix thickness: 1.13 in.
Bed weight (dry): 110 lb	Matrix weight: 165 lb
Rotating speed: 5 rph	Rotating speed: 20 rpm
Working capacity: 3.1 percent	Effectiveness: 90 percent
Pressure drop: 0.63 in. H_2O	Pressure drop: 0.19 in. H_2O
Airflow Rates	**Solar Heater**
Residence airstream: 850 scfm	Effectiveness: 85 percent
Preconditioning airstream: 120 scfm	Arc: 86.6 deg
Outside airstream (without preconditioning air): 830 scfm	Heating rate: 35,000 Btu/hr
	Water flow rate: 3600 lb/hr
Solar heater airstream: 455 scfm	Air pressure drop: 0.04 in. H_2O
Preconditioning Air	**Mechanical Drive**
Manifold arc: 22.5 deg	Power requirement: 0.1 kw (max.)

Cooling capacity: 1-1/2 tons (18,000 Btu/hr) nominal

- The design-point performance was exceeded. The capacity of the machine in the test configuration was predicted to be 16,200 Btu/hr. Table 2 summarizes the experimental data obtained; predicted data are shown for comparison. Figure 4 shows design point performance obtained on test.

- Off-design performance has been obtained. The off-design performance of the SODAC was obtained over a range of interface conditions defined by (1) indoor wet- and dry-bulb temperatures, (2) outdoor wet- and dry-bulb temperatures, and (3) water (solar heat input) temperature. These data are shown in Figure 5 for design air flows and also for half-flow conditions.

Table 2. Test Performance in Recirculated Mode

	Full Flow	Half Flow
Experimental Data		
Capacity, Btu/hr	16,200	7,400
Coefficient of performance	0.59	0.56
Conditioned space air flow, scfm	760	380
Outdoor air flow, scfm	925	490
Water usage, gal/hr	3.9	2.0
Parasitic power (fans, pumps, and drive), kw	0.8	0.24
Predicted Data		
Capacity, Btu/hr	16,200	8,000
Coefficient of performance	0.52	0.46
Parasitic power, kw	0.75	

Indoor temperatures: 80°F dry bulb, 67°F wet bulb
Outdoor temperatures: 95°F dry bulb, 75°F wet bulb
Water source temperature: 200°F

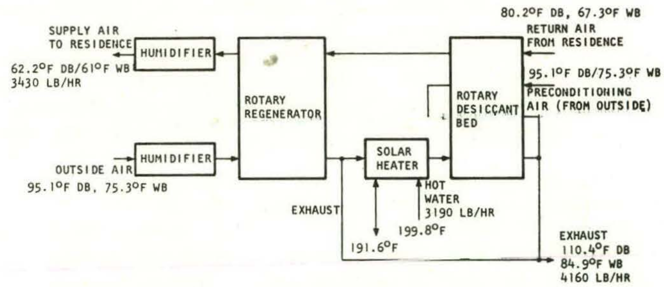


Figure 4. Design Point Performance A-9102

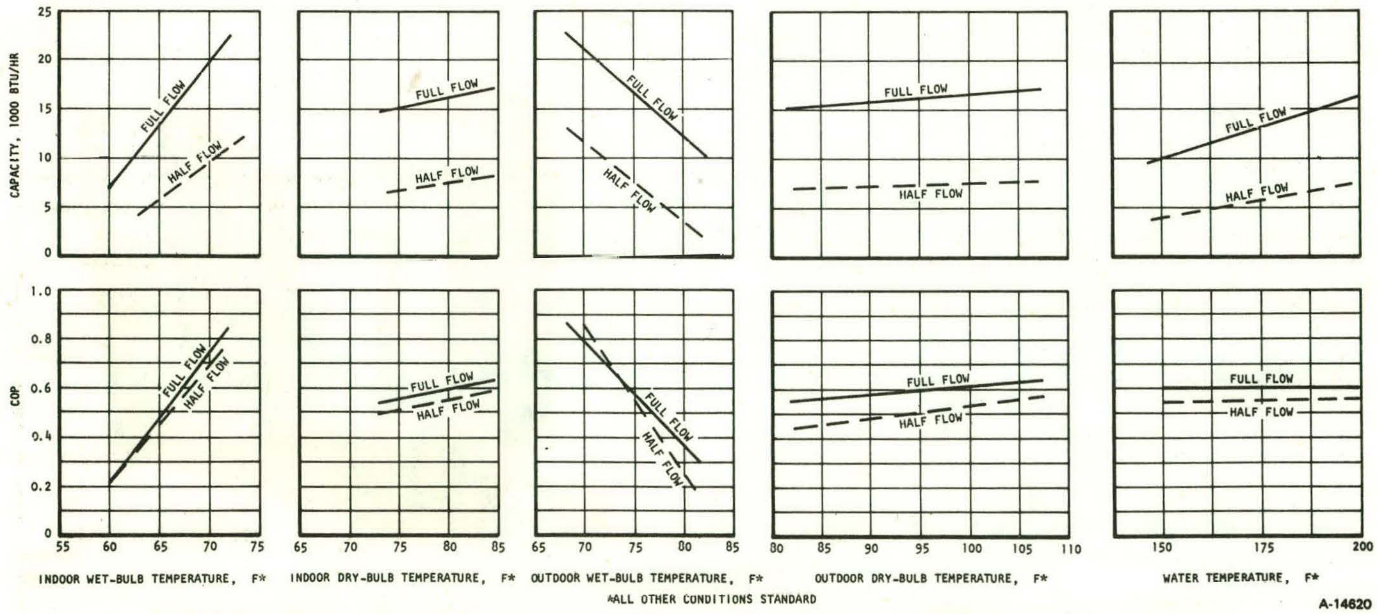


Figure 5. Test Performance

- Correlation of test and computer data is excellent. This is especially so at the full-flow conditions (see Figure 6). In general, the capacity of the SODAC is as predicted, while the COP is higher by about 15 percent.

- The economic feasibility of the concept has been demonstrated. Economic analyses show that the SODAC, when used in conjunction with a solar heating system, will result in present value benefits over the life of the system. These conclusions were reached using realistic data for collector and energy cost.

CONCLUSIONS

- SODAC performance and potential first cost compares favorably with other solar air conditioning concepts for residential applications.

- Test data validate the basis for the studies conducted earlier, showing that SODAC is a viable economic option.

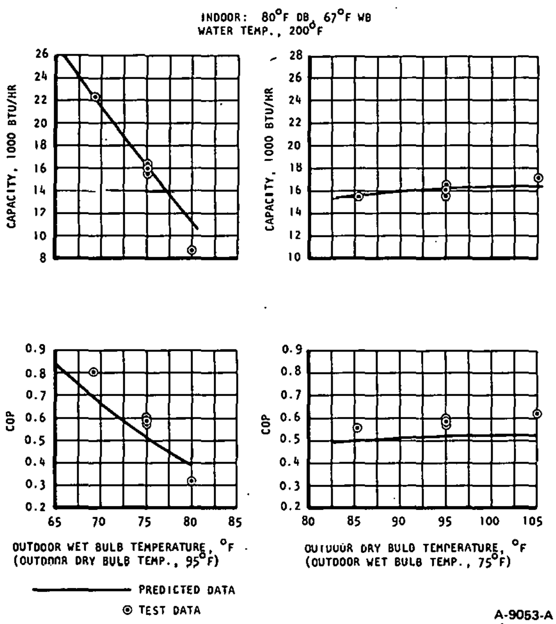


Figure 6. Test Performance Compared with Computer Prediction

FUTURE ACTIVITIES

A second series of tests is in progress to characterize the SODAC in the ventilated mode configuration at full-flow and half-flow rates. Concurrently, analyses are being conducted in an effort to increase capacity and COP by moving the partitions within the SODAC, thus increasing the portion of the bed exposed to the adsorbing airflow.

PUBLICATIONS

First Technical Progress Report, Development of a Solar Desiccant Dehumidifier, March 31, 1978, SAN-1591-1.

Second Technical Progress Report, Development of a Solar Desiccant Dehumidifier, November 10, 1978, SAN-1591-2.

Third Technical Progress Report, Development of a Solar Desiccant Dehumidifier, June 12, 1979, SAN-1591-3.

Phase I Final Summary Report, Development of a Solar Desiccant Dehumidifier, September 1980 (awaiting DOE approval).

Phase II Technical Progress Report, Development of a Solar Desiccant Dehumidifier, March 1981 (awaiting DOE approval).

Rousseau, J., and K. C. Hwang, Preliminary Design of a Solar Desiccant Air Conditioner, paper presented at the Third Workshop on the Use of Solar Energy for the Cooling of Buildings, San Francisco, February 1978.

Gunderson, M., Development of a Solar Desiccant Dehumidifier, paper presented at the Third Annual Solar Heating and Cooling Contractors Meeting, Washington, D.C., September 1978.

Rousseau, J., Development of a Solar Desiccant Dehumidifier, paper presented at the annual DOE Active Solar Heating and Cooling Contractors Review Meeting, Lake Tahoe, March 1980.

CONTRACT INFORMATION

START DATE September 1, 1977 END DATE September 1, 1981 CONTRACT VALUE $814,329

MILESTONES

Item:	Due date:
1. Baseline system test	April 30, 1981
2. SODAC modification	May 30, 1981
3. Updated configuration test	July 30, 1981
4. Final report	October 1, 1981
5.	

HEAT AND MASS TRANSFER CHARACTERISTICS OF LIQUID DESICCANT OPEN FLOW COLLECTORS

Arizona State University

Byard D. Wood

SERI XE-0-9179-2

OBJECTIVE

The goal of this project is to evaluate the technical and economic viability of open flow liquid desiccant collectors for use in conjunction with solar cooling/dehumidification applications. The specific objective is to determine the heat and mass transfer characteristics for a prototype collector in a hot arid climate.

DESCRIPTION OF WORK

Open cycle absorption refrigeration is a method of using solar energy for cooling that may prove to be economically viable. A key component of such a system is the collector/regenerator. The collector/regenerator is an open, flat plate solar collector over which the absorbent flows in a thin film. The solution starts at the top of the plate as a weak absorbent and water vapor is driven out of the solution as it flows over the collector. This regenerates the solution so that a strong solution flows off the bottom of the collector. This strong solution (desiccant) can then be used to absorb water vapor in the absorber, when the water vapor comes from the evaporation of water in the evaporator. The cooling effect comes from this evaporation.

The scope of work for this project includes the design, construction and testing of a 10.7 x 10.7 meter prototype collector/regenerator. Heat transfer and mass transfer rates are to be measured for at least one month during the Phoenix cooling season. Initial tests for the unglazed open flow collector will be for a 45 wt % LiCl-Water solution at flow rates of up to 0.60 kg/s. Salinity and temperature measurements will be made at 1.5 m intervals in the flow direction and 3m intervals in the transverse direction. The heat and mass transfer data will be correlated with the solar/meteorological variables such as ambient wind speed and direction, ambient wet and dry bulb temperature and insolation.

TECHNICAL ACCOMPLISHMENTS

- Scale model test apparatus has provided preliminary data on flow distribution and surface effects.
- Final design of prototype collector/regenerator has been completed with construction basically on schedule.
- Instrumentation and data analysis has been determined.

FUTURE ACTIVITIES

Preliminary data and analysis suggest that the collector/regenerator will work. Further development is anticipated to optimize (performance/cost ratio) collector surface and inlet flow geometry. This work is important in the synthesis of open cycle solar absorption cooling.

PARTICIPANTS

M. Breslauer, G. Buck, D. Siebe, B. Wood

CONTRACT INFORMATION

START DATE Aug. 15, 1980 END DATE Sept. 30, 1981 CONTRACT VALUE $114,953

MILESTONES

Item:		Due date:
1.	Collector/Regenerator Design Specifications	March 1981
2.	Construction of Prototype Collector	June 1981
3.	Testing of Prototype Collector	August 1981
4.	Data Analyses and Evaluation	September 1981
5.		

OPEN CYCLE LITHIUM CHLORIDE (SOLAR) COOLING

COLORADO STATE UNIVERSITY

GEORGE O. G. LOF

DE-AC03-79CS30206

OBJECTIVE

The objective of the investigation is the experimental determination of evaporation rates and the coefficients of heat transfer and mass transfer in a packed column designed for use in an open cycle lithium chloride absorption cooling system operated by solar heated air.

INTRODUCTION

The concept of an open cycle LiCl absorption air conditioner has been examined as a possible solution to the need for a cooling system which can be combined with and operated by a solar air heating system. Soviet researchers have built and operated a 10-ton cooling system based on this principle in an apartment building near Ashkabad in the USSR [1]. In constrast with conventional absorption refrigeration systems in which both the absorbent and refrigerant circulate in a closed cycle, only the absorbent, a lithium chloride solution, is recirculated in this open cycle. Water, the refrigerant, is continually evaporated to the atmosphere, and must therefore be continuously added to the cycle. The condenser and generator normally used in a conventional closed cycle system are not necessary, so there is a substantial reduction in equipment requirements.

The reconcentration of the lithium chloride solution in the Russian air conditioner is accomplished by trickling it across a gently sloping black roof which is directly exposed to solar radiation. The absorbed solar energy, and a hot, low humidity atmosphere, permit adequate reconcentration of the solution for return to the absorber. In the absorber, water vapor from the evaporator is again absorbed, and the cycle continues. The refrigeration effect is obtained by low temperature (less than 5°C) evaporation of the added water.

This system has been successfully operating for more than 5 years. As designed and operated, it has several limitations which prohibit the design from being utilized in more humid locations. Rainfall and high relative humidities cannot be tolerated since dilution of the solution and inadequate reconcentration would prevent satisfactory operation.

In order to broaden the application of the open cycle system to less arid locations, the possibility of reconcentrating the absorbent solution in a packed bed (stripping column) by means of solar heated air was investigated in a theoretical study by Leboeuf and Löf [2] at Colorado State University. Figure 1 is a schematic diagram of the USSR system as modified for use with solar heated air. The roof used for reconcentrating the LiCl solution in the USSR installation has been replaced (theoretically) by a packed column through which the LiCl solution trickles counter current to a rising stream of solar heated air.

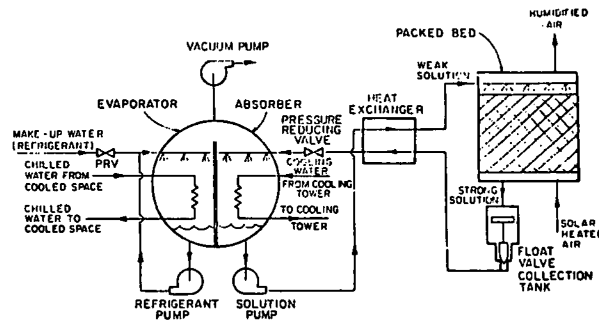


Figure 1. Schematic of the Open Cycle Absorption Air Conditioning System

On the basis of not fully adequate mass transfer data in the literature, it was found in the theoretical analysis that a packed column of convenient size should be suitable for reconcentrating LiCl solutions by means of air heated to temperatures of 70°C to 90°C. Packed heights of less than one meter and column diameters of about one-half meter were estimated to be sufficient for evaporating about 15 kg of water per hour (roughly equivalent to 3 tons of refrigeration) from LiCl solutions with air at temperatures conveniently available from an efficient flat plate solar air collector.

To substantiate the theoretical analysis, and specifically, to verify the mass transfer and heat transfer coefficients assumed in that analysis, the present experimental investigation of evaporation rates from LiCl solutions in a packed column was undertaken. Only by experimental measurement of mass and heat transfer rates in a well instrumented system could the necessary confidence be placed in the capability of such equipment to accomplish the reconcentrating function. Finally, reliable sizing of a packed column for use in a complete solar cooling system of the open cycle LiCl type requires mass transfer data of an accuracy obtainable only by measurements under conditions comparable to those involved in practical operation.

EXPERIMENTAL APPARATUS

Figure 2 shows the experimental system for measurement of heat and mass transfer rates under various conditions of operation. The main component is a packed column shop-fabricated from copper sheets. It is 50 cm in diameter and 1.8 m high. The column is provided with piping

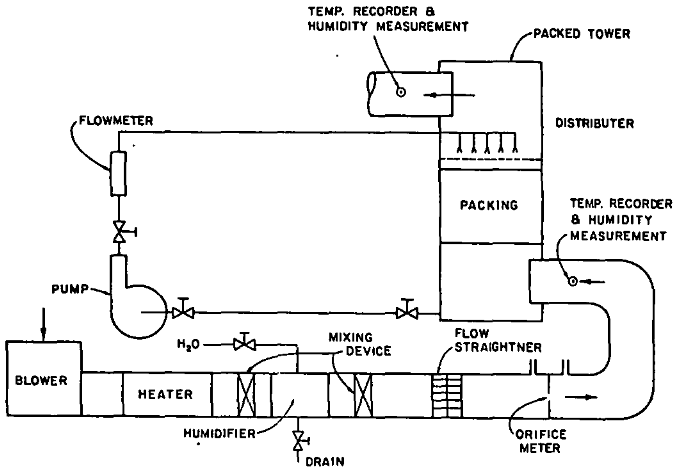


Figure 2. Experimental Apparatus for Measurement of Rates of Heat Transfer and Water Vapor Transfer in A Stripping Column in Which a Lithium Chloride Solution is Being Contacted with Heated Air.

connections for supplying liquid to the top of the column and withdrawing liquid from the bottom section. Air is introduced at the bottom through a 30 cm duct. A perforated base plate has been provided at the bottom to support the packing of 1-inch ceramic Raschig rings. The solution is distributed uniformly over the packing by means of a perforated copper plate located just below the liquid entrance in the upper section of the column. (Spray nozzles first used for liquid supply were found unsatisfactory for uniform distribution of the solution over the packing). The packed bed height can be varied up to a maximum of 75 cm.

The column is supported on an elevated platform so the solution can drain by gravity into the pump suction connections.

Air is supplied to the packed column at variable rates, temperatures, and humidities from a system consisting of a centrifugal blower, a propane gas air heater, a humidifier, and flow meter. The belt driven blower has the capacity to deliver air at rates up to 2.83 m^3/min (800 cfm). The combination of a damper near the column inlet, a vent following the blower, and several motor/blower speed ratios provides adequate air flow variation and control. The propane gas heater has the capacity to heat air up to 110°C (230°F) by varying the fuel flow to the burner by a pressure regulator. Air can be humidified to the desired inlet conditions by the combination of moisture from propane combustion and by direct water spray into the air supply duct.

The local velocity of the airstream at the center of the entrance duct is measured by use of a pitot tube and micromanometer readable to 0.0025 cm water gage. This measurement is made at a point about 1 m before the entrance to the column. The orifice meter was calibrated against the pitot tube and used as the operating control meter for air flow uniformity. Air temperatures and humidity are measured at the column entrance and exit. Copper-constantan thermocouples and a multi-point strip chart recorder are used, and humidity measurements are made by means of a recording dew point hygrometer. The air sampling tubes to the hygrometer are electrically heated to prevent condensation of moisture in the sampling lines.

The desiccant solution flow rate is measured by visual reading of a calibrated rotameter. Temperatures of solutions entering and leaving the column are measured by copper constantan thermocouples and strip chart recorder. The concentration of LiCl in solution is determined by measuring the specific gravity of samples to within 0.0001 by use of a picnometer.

EXPERIMENTAL PROCEDURE

Experimental runs were performed with air inlet temperatures of 60°C to 105°C (140°F to 220°F), lithium chloride concentration from 9% to 35%, and air flow rates from 1.06 to 1.77 m^3/min (300 to 500 cfm). The liquid flow rate was 5.67 liters/min (1.5 gallons per minute). The packed bed consists of a 23 cm height of 2.54 cm (1-inch) Raschig rings.

After the fan, propane burner, and solution pump were started, the air flow rate was brought to the desired value by adjustment of damper and vent openings. Liquid flow was observed by rotameter position and regulated by control valve. Air temperature was then brought to the proper level by adjusting the fuel pressure to the burner. Inlet humidity was found to be in a suitable range, partly by the moisture from gas combustion, so no additional increased water spray was required.

The lithium chloride solution was neither heated nor cooled, but allowed to reach equilibrium temperatures in the liquid circulation loop. The strip chart record of liquid and air temperatures and air humidities was continuously monitored, usually for about half an hour, until all values had stabilized at essentially constant levels. A sample of the solution was then drawn for subsequent specific gravity measurement, and the final chart readings were used in the calculation of heat and mass transfer coefficients.

RESULTS AND DISCUSSION

It was found difficult to create a complete adiabatic conditon in practice as assumed in theoretical study. There was a considerable loss of heat to the atmosphere in spite of insulation to the tower. Also it must be noted that experiments were conducted in windy weather and snowy conditions which increase heat losses. Rough estimations of heat loss were found to be on the order of 19% and corrections were made to the heat transfer coefficient for this loss.

A second possible reason for departure from theory is incomplete wetting of packing. It is generally difficult to check the degree of wetting. Studies have shown that the mass transfer coefficient is strongly affected by wetting.

The principal results of the investigation are shown in Table 1. Coefficients of heat transfer and water vapor transfer measured at two levels of air flow over a range of air temperatures and humdities are tabulated. Also listed are the computed values of the heat transfer coefficient based on the McAdams [2] empirical relationship:

$$h_G a_H = 1.78 G'^{0.7} L'^{0.07} e^{0.0023(t_f)} \qquad (1)$$

also used by Leboeuf and Löf [3] in the previous theoretical study of this process. In this equation,

$$t_f = t_L + (t_G + t_L)/2. \qquad (2)$$

Table 1.

Air Flow Rate (cfm)	Liquid Flow Rate gpm	Air Inlet Temp. °F	Air Outlet Temp. °F	Air Inlet Humidity lb H_2O/ lb air	Air Outlet Humidity lb H_2O/ lb air	Liquid Inlet Temp. °F	Liquid Outlet Temp. °F	Mean Liquid Concentration %	Interface Humidity lb H_2O/ lb air	Evaporation Rate lbs/hr	Heat Transfer Coefficient Btu/hr sq/ft°F	Theoretical Heat Transfer Coefficient Btu/hr sq ft°F	Mass Transfer Coefficient lb/hr ft^3
426	1.5	146	86	0.01268	0.02	79	80	9.5	0.0212	13.6	671	451	2232
426	1.5	228	126	0.016	0.0249	101	102	21.4	0.0294	16.6	455	517	1242
426	1.5	228	124	0.0167	0.0288	101	102	21.4	0.0339	22	478	517	1384
426	1.5	228	126	0.0175	0.027	100	100.5	22.4	0.0318	17.7	446	517	1243
342	1.5	186	112	0.0120	0.0237	96	97	17.8	0.0349	17.5	388	427	646
342	1.5	200	132	0.0083	0.0280	110	110	28.2	0.0321	29	316	448	1607
342	1.5	178	104	0.0116	0.0203	97	98	27.4	0.0260	13	467	623	844
342	1.5	176	108	0.0111	0.0174	102	102	27.6	0.0263	9	564	423	533
342	1.5	188	108	0.0120	0.0220	102	105	29.5	0.0238	14.9	659	435	1710
342	1.5	185	116	0.0164	0.0288	93	94	12	0.0358	18.5	320	425	930

Although the McAdams equation is based on experimental measurements with pure water in a column packed with 1-inch rings, the degree of agreement with the results of the present work with lithium chloride solutions is within expected limits.

The experimental set up is designed to evaporate about 11 lbs/hr of water which is equivalent to 1 ton refrigeration capacity. Results in table show that this evaporation rate can be practical in packed column.

TECHNICAL ACCOMPLISHMENTS

- o Coefficients of heat transfer and mass transfer in a packed column in which water is vaporized from a LiCl solution by heated air have been experimentally determined.
- o The influences of air flow rate, humidity, and temperature on the coefficients of heat transfer and mass transfer in a packed column in which water is vaporized from a LiCl solution by heated air have been experimentally determined.
- o Theoretical predictions of transfer coefficients and packed column sizes in an open cycle LiCl solar cooling system have been experimentally verified.
- o The feasibility of operating an open cycle cooling system in which LiCl solutions are concentrated in a packed column supplied with solar heated air has been established.

FUTURE ACTIVITIES

Having established the feasibility of concentrating LiCl solutions with air from a conventional solar air collector, the design and testing of a complete solar cooling system is required. Essential to the satisfactory operation of this system is the deaeration of the solution in the partial vacuum of the absorber-evaporator chamber. Continuous or intermittent removal of non condensible gas (air) by a vacuum pump is required. It is possible that a pre deaeration of the LiCl solution leaving the packed column will reduce the vacuum pumping requirements. In negotiation, therefore, is a contract between CSU and DOE to investigate the deaeration/vacuum requirements of this sytem, as well as a study of possible problems in accumulation of dissolved salts that are introduced to the system in the make up water supply.

PUBLICATIONS/REPORTS/REFERENCES

[1] Baum, V.A., Kakabayev, A., and Klyschayeve, C. "Technico-Economic Characteristics of Solar Units for Cooling Buildings", Third Soviet-American Seminar (1977).

[2] McAdams, W.G., Pohlenz, J.B. and St. John, R.C. "Transfer of Heat and Mass Between Air in a Packed Tower", Chem. Engr. Progress, Vol. 45, No. 4, pp. 241-252 (1949).

[3] Leboeuf, Cecile M. "Solar Driven LiCl Open Cycle Absorption Cooling With Packed Bed Absorbent Reconcentration", M.S. Thesis, Colorado State University, Fort Collins, CO. 1979.

CONTRACT INFORMATION

START DATE 15 Sept. 1979 END DATE 31 May 1981 CONTRACT VALUE $31,993

MILESTONES

Item:	Due date:
1. Monthly Reports	Met
2. Final Report	30 June 1981 (pending)
3. Technical Paper - Leboeuf and Löf, 1980 Meeting of AS/ISES	Met
4.	
5.	

TESTING OF A CROSS-COOLED SOLAR POWERED DESICCANT COOLING SYSTEM

ILLINOIS INSTITUTE OF TECHNOLOGY

ZALMAN LAVAN AND DIMITRI GIDASPOW

EG-77-C-01-4042

OBJECTIVE

To test a solar powered desiccant cooling system using two fixed bed cross-cooled silica gel dehumidifiers. The process stream channels are lined with silica gel sheets and the bed is cooled by air flowing in perpendicular channels. The dehumidifiers undergo adsorption, preheating, desorption and precooling in a cyclic fashion. The cooling capacity of the experimental system is one ton at ARI design conditions. The system has a high cooling capacity, high COP, low parasitic power consumption and requires low regeneration temperatures.

DESCRIPTION OF WORK

A solar powered cooling system which uses the concept of cross-cooling to lower the regeneration temperature was developed at IIT. The cross-cooled dehumidifier uses silica gel sheets developed at IIT (1). The equilibrium and sorption dynamics were studied and modeled (1-2). A cross-cooled dehumidifier model was tested and compared to analytical predictions (3, 4, 5 and 6). Using these results, a 1 ton prototype was built and the effect of several parameters was studied and is documented (7, 8). The present paper deals with a complete desiccant cooling system consisting of two heat exchangers, solar collectors, three evaporative coolers and two cross-cooled dehumidifiers. Figure 1 shows the two stack mounted dehumidifiers complete with electronic air filters, dampers and inlet and outlet fittings.

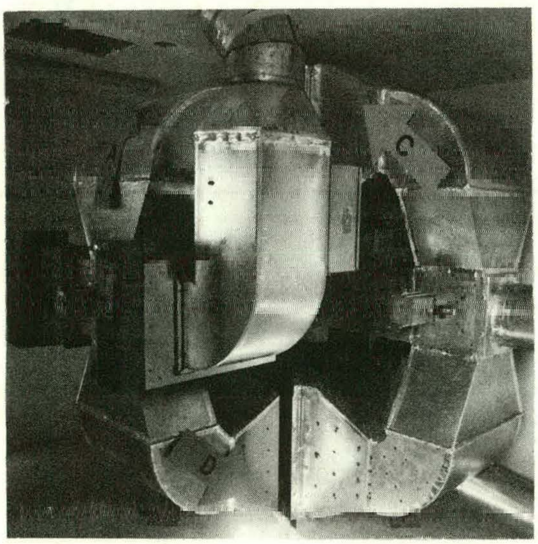


Figure 1. Dehumidifier Assembly

Each of the two dehumidifiers is cyclicly switched through four modes: Adsorption, preheating, desorption and precooling. Figure 2 shows the flow arrangement. Air from the solar house is first being dried in the adsorbing dehumidifier while a stream of humidified ambient air is passed in the cooling channels. The dehumidified air is further cooled towards the ambient wet-bulb temperature in a heat exchanger which consists of two pebble beds that are periodically cycled. Finally, the air is rehumidified as it is passed through the flutes of an evaporative cooler.

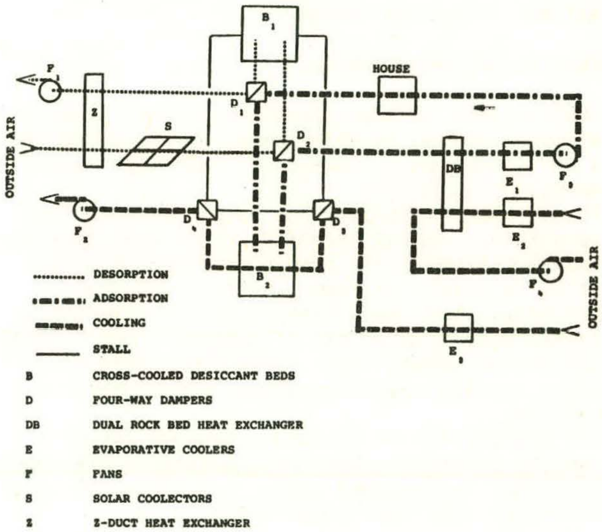


Figure 2. Sorption Mode Flow Schematic

A 21 m^2 air collector array has been installed to heat ambient air for regeneration of the desiccant. (An electric heater is also available to simulate the solar input when desired.) Sensible heat is recovered in a counterflow recuperator. During the purging periods (preheating and precooling), the cooling channels of the two units are connected in series and sensible heat from the dry hot unit is used to preheat the wet bed in preparation for the subsequent sorption period. Four 'four-way' dampers have been designed to implement the switching of the process and cross-cooling streams. The cross leaks between the air streams inside the dampers have been found to be less than 1%. The system instrumentation includes thermocouples, thermopiles, orifice plates and dew point hygrometers. A microprocessor based data acquisition system is used to collect, process and store data from the sensors.

Figure 3 shows the effect of regeneration humidity on COP. The three curves represent the experimental performance of a single dehumidifier prototype, the analytical prediction for the present configuration and the predicted performance for counterflow periodic operation. It can be seen that the performance is very sensitive to variations in ambient absolute humidity. The ambient stream absolute humidity has a similar effect on the cooling capacity as can be seen in Figure 4. These tests results show that at ARI conditions the unit will have a COP of 0.60 and a cooling capacity of 12.25 kJ/kg.

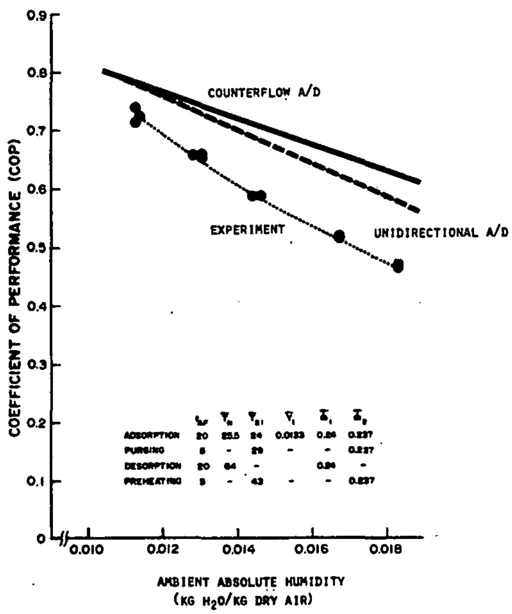


Figure 3. Effect of Ambient Absolute Humidity on COP

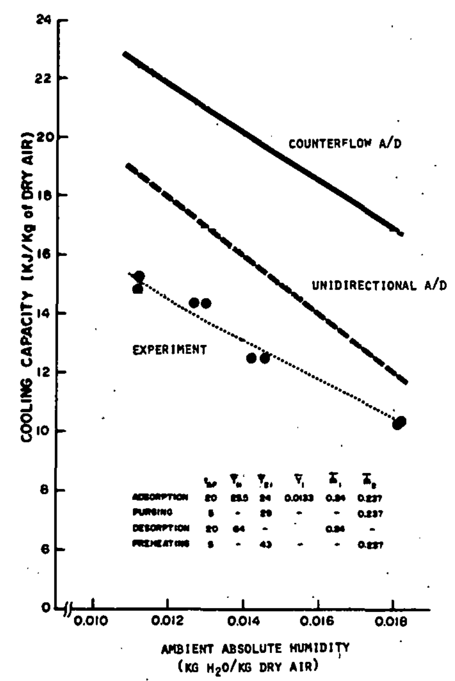


Figure 4. Effect of Ambient Absolute Humidity on Cooling Capacity

For optimum design of dehumidifiers, it is necessary to understand the dynamics of sorption. The dynamics was studied isothermally for three different desiccant sheet thicknesses; 0.076, 0.152 and 0.318 cm. Typical results at one dimensionless contact time, x, are shown in Figure 5, expressed as dimensionless mass transfer coefficients, called Nusselt numbers for the channel and for the sheets. The channel Nusselt numbers are close to the theoretically expected value of 1.345. The desiccant mass transfer coefficients are highly time dependent, casting doubt on the validity of standard models used in desiccant design. Figure 6 shows typical fluxes of water vapor at various dimensionless lengths, x. Note the expected motion of a humidity wave.

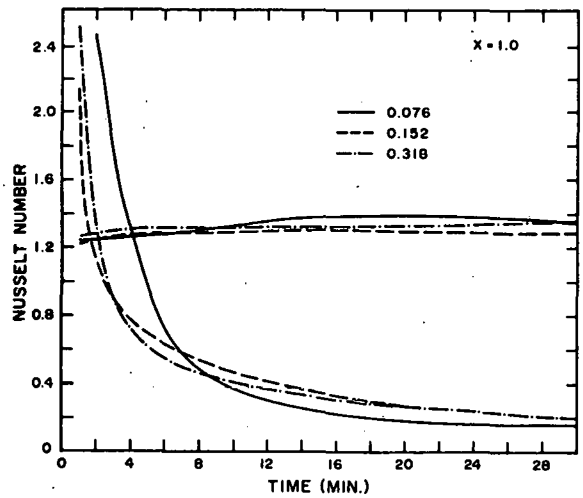


Figure 5. Mass Transfer Coefficient for Three Desiccant Sheets

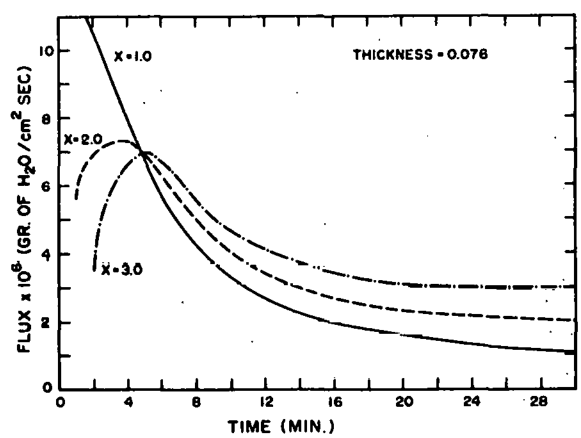


Figure 6. Humidity Sorption Rates

A second law analysis of open cycle desiccant cooling systems was carried out in order to determine their maximum possible cooling performance (9). It was found that the isentropic COP increases as the ambient absolute humidity decreases. At ARI conditions, this COP is higher than for closed cycle systems operating at the same dry bulb temperatures. Since cooled dehumidifier systems can be regenerated at lower temperatures than adiabatic systems the actual performance of cooled systems is closer to the isentropic limit.

TECHNICAL ACCOMPLISHMENTS

- A manufacturing process was developed to form silica gel material into paper-like sheets.
- A 15 x 15 x 15 cm cross-cooled silica gel dehumidifier model was designed, constructed and tested.
- Sorption isotherms of the silica gel sheets were determined in the range of 22-80°C for relative humidities between 5% and 95%.
- The cross-cooled dehumidifier was modeled and a complete cooling system using two fixed bed dehumidifiers was simulated.
- A 0.6 x 0.6 x 0.6 m cross-cooled dehumidifier prototype has been manufactured and extensively tested over a wide range of simulated operating conditions.
- A mathematical model for laminar flow through an isothermal dehumidifier considering macro-micro pore diffusion was developed. The model was fitted to transient experimental data.
- A complete one ton cooling system using two cross-cooled dehumidifiers and solar collectors has been built and is being tested. The number of dampers used to implement the switching of the dehumidifiers is four.
- A second law analysis was applied to open cycle desiccant cooling systems, revealing their potentials and theoretical limitations. The actual performance of cooled desiccant systems is closer to the isentropic limit than in the case of adiabatic systems.

ACTIVITIES

The outdoor cooling system is being tested and the performance will be simulated.

Post-contract activities. A two ton unit which will incorporate design modifications will be built and field tested. A two stage high COP (greater than unity) cooling system in which the condensing steam of the first stage activates the desorption of the second stage will be investigated.

ACKNOWLEDGEMENT

The support and interest of K. Collier and D. Schlepp from SERI is greatly appreciated.

PUBLICATIONS

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9. Lavan, Z., Worek, W.M. and Monnier, J-B., "Cooled Bed Solar-Powered Desiccant Air Conditioning," The 16th IECEC, 1981.

CONTRACT INFORMATION

START DATE Nov. 1, 1980 END DATE Oct. 31, 1981 CONTRACT VALUE $30,000.00

MILESTONES

Item:		Due date:
1.	Cooling System Set up and Instrumentation	m- 2/15/81
2.	Operation at Design Conditions	p- 7/31/81
3.	Operation Under Outdoor Conditions	p- 9/30/81
4.	Monthly and Final Progress Reports	p-10/31/81
5.		

SOLAR-MEC® DEVELOPMENT PROGRAM

INSTITUTE OF GAS TECHNOLOGY

Robert A. Macriss, Jaroslav Wurm, Thomas S. Zawacki and John A. Kinast

DE-AC03-77CS34495

OBJECTIVE

IGT is currently developing under contract to DOE laboratory performance data, and a seasonal performance model based on these data, with a redesigned SOLAR-MEC® (System III) residential-size solar heating/cooling unit, developed under an earlier phase of this DOE funded program. The purpose of this overall effort is to complete the laboratory development effort, including effective control strategy to maximize seasonal heating and cooling performance, as the first step towards potential commercialization of this improved and versatile solar-gas residential space conditioning system.

BACKGROUND

The SOLAR-MEC is a versatile solar- and solar-gas-powered space conditioning system that can provide an effective combination of environmental control services (space heating and cooling, ventilation, and humidification/dehumidification), under a wide range of climatic conditions and building types. As a result of over 10 years of analytical, experimental and field-testing experience with the SOLAR-MEC system, IGT has recently developed an improved solar- and solar-gas-powered unit (designated as System III) of 3-ton capacity, the culmination of a 3-year effort supported by the U.S. Department of Energy (DOE).

The specific characteristics of this improved SOLAR-MEC unit (System III) are:

- Advanced process design features that incorporate staged reactivation of the dryer wheel, and unbalanced flow design and operation of the sensible heat exchanger, to maximize seasonal performance factor (SPF) for cooling and to reduce "parasitic" power consumption.
- Improvement of the hardware and resultant performance and life, through component and unit assembly modifications such as exchanger wheel drives, air seals, heat exchanger wheel fabrication, burner and fans, and evaporator pad materials.
- Replacement of the desiccant asbestos substrate by a novel, non-asbestos matrix.

Brief laboratory tests with the "improved" SOLAR-MEC (System III) unit were performed, towards the end of the early DOE-funded phase of this program, and the performance obtained demonstrated the potential of this improved design. The results of these tests were presented at the March 1980 Annual Review Meeting of DOE's Active Solar Heating and Cooling Contractors in Lake Tahoe, Nevada. The objective of the current (on-going) phase of this program derives from these preliminary results.

SUMMARY

The specific accomplishments of the present phase of this program to date are:

1. Development of detailed laboratory performance data with the improved design (System III) unit under a variety of ambient and indoor dry and wet bulb temperatures, simulating several climatic conditions corresponding to a variety of cooling loads.
2. Development of laboratory data with the unit operating in the ventilating (conditioning outdoor supply air) and the recirculation (conditioning room return air) modes. Both solar-only and combined solar-gas reactivation of the desiccant wheel were tested under these conditions.
3. Development of a seasonal performance simulation model (based on the above data) that can be used to predict gas, solar and parasitic energy consumption of the improved unit (System III) under given demand load. The model can also be used to provide fundamental variations in the output of the unit (for heating and cooling) with changes in input weather conditions of temperature and humidity. Alternatively, and for fixed weather conditions and level of reactivation temperature, the model is capable of predicting delivered temperature and humidity of the supply air.

Details of the data and seasonal model are presented in the next section of this report.

TECHNICAL ACCOMPLISHMENTS

A schematic of the improved SOLAR-MEC (System III) unit is shown in Figure 1. The specific design improvements of this unit (as compared to the original SOLAR-MEC system configuration) are:

- Staged reactivation of the desiccant wheel to increase cooling coefficient of performance (COP)
- Unbalanced flow design and operation of the heat exchanger wheel to increase cooling capacity
- Non-asbestos desiccant wheel matrix, and
- Hardware improvements (seals, fans, drives, etc.) to reduce parasitic power requirements.

The System III unit underwent intensive laboratory testing and evaluation during the present phase of the program. For this purpose, IGT's SOLAR-MEC test facility was employed after modifications to enable firing the unit with 230°F (incoming temperature) pressurized water to simulate the output from advanced concentrated collectors. Tests with the unit were carried out under low- and high-temperature solar-only firing and with combined solar-gas firing. Performance data obtained relate to unit capacity, COP and Solar EER values with the unit operating in the "Ventilating" and "Recirculation" modes. Examples of the data obtained are presented which show the differential performance of the unit under these two operating modes and variable input conditions of indoor-outdoor temperature and humidity, simulating a range of cooling loads for the unit.

Tables 1 and 2 summarize the effect of outdoor dry-bulb temperature on unit performance, at constant ARI indoor conditions of 80°F dry-bulb and 67°F wet-bulb temperatures. Each of these tables also shows the effect of the operating mode (ventilation-recirculation) on performance under these conditions. Table 1 presents results with the unit operating under low-temperature solar input for desiccant wheel deactivation. This type of input corresponds to incoming water temperature of 180°F and equivalent average reactivation temperature of 160°F. The results of Table 1 show that under low temperature reactivation conditions, recirculation is the preferred mode of operation, resulting in average EER values at ARI outdoor conditions (95°F dry-bulb and 75°F wet-bulb or 14 parts per thousand moisture content of air) of about 18. The serious deterioration of the unit's performance (under ventilation mode) at high ambient dry-bulb temperature (105.6°F) is also noted in Table 1.

At high-temperature solar input (incoming water temperature of 230°F, equivalent average reactivation temperature of 205°F), as shown in Table 2, the recirculation mode is still favored although, under both modes, EER values over 20 have been achieved, at ARI outdoor conditions. Table 2 also shows that, under the higher temperature of reactivation, the reduction of performance at extreme ambient dry-bulb temperature is not as severe as in the previous case (Table 1).

Similar results are obtained for solar-gas input desiccant reactivation (incoming water temperature of 180°F and supplemental gas firing to result in mixed-cup reactivation temperature of 195°F), as shown by the results of Table 3. Table 4 summarizes the effect of indoor dry-bulb temperature on unit performance with high-temperature, solar input desiccant reactivation at constant ARI outdoor conditions. With regards to preferred operating mode, similar conclusions are drawn as with results of Tables 2 and 3, i.e., the recirculation mode is still favored but EER values over 20 are achievable when operating with either mode.

Another task of this phase of the program was the development of a model for seasonal performance simulation, based on the data obtained in the laboratory. For this purpose, the data obtained were aggregated in the manner presented in Tables 1 to 4, in order to provide trend-lines of the effect of one variable at a time on system performance.

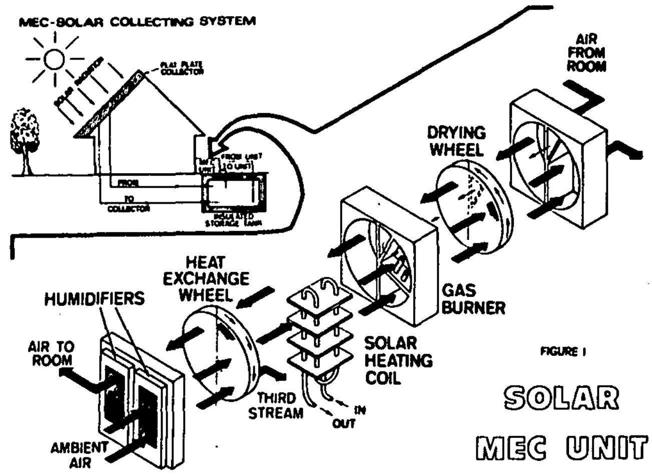

FIGURE I

SOLAR MEC UNIT

SYSTEM III

TEST NO.	OUTDOOR CONDITIONS DB,°F	PPT	INPUT BTU/HR	COOLING CAPACITY BTU/HR	COP	EER	MODE
36	75.3	14.3	40900	26900	0.66	24.2	RECIR
37	85.0	14.4	40500	23600	0.58	20.0	RECIR
46	94.6	14.0	38700	20000	0.52	17.7	RECIR
63	105.0	14.0	39000	17300	0.44	15.6	RECIR
13	74.8	13.9	41300	19800	0.48	16.6	VENT
60	84.9	14.0	36400	16600	0.46	14.6	VENT
48	94.8	14.2	34600	13000	0.38	11.1	VENT
10	105.6	14.3	35000	9900	0.28	8.3	VENT

TABLE 1. EFFECT OF OUTDOOR TEMPERATURE ON CAPACITY, COP AND EER WITH LOW-TEMPERATURE (180°F) SOLAR WATER FIRING (160°F MIXED-CUP EQUIVALENT REACTIVATION TEMPERATURE) AND ARI INDOOR CONDITIONS (80°F DRY-BULB, 67°F WET-BULB)

TEST NO.	OUTDOOR CONDITIONS DB,°F	PPT	INPUT BTU/HR	COOLING CAPACITY BTU/HR	COP	EER	MODE
26	75.3	14.2	70800	40800	0.58	33.4	RECIR
51	85.0	14.2	63900	35500	0.56	30.1	RECIR
28	95.4	13.9	71200	32500	0.46	27.5	RECIR
29	104.6	14.0	63700	29300	0.46	24.8	RECIR
52	75.0	14.2	56400	32900	0.58	28.6	VENT
50	85.3	14.2	61700	33200	0.54	28.4	VENT
54	95.0	14.0	50000	25500	0.51	22.0	VENT
55	104.9	14.0	45300	21700	0.48	17.8	VENT

TABLE 2. EFFECT OF OUTDOOR TEMPERATURE ON CAPACITY, COP AND EER WITH HIGH-TEMPERATURE (230°F) SOLAR WATER FIRING (205°F MIXED-CUP EQUIVALENT REACTIVATION TEMPERATURE) AND ARI INDOOR CONDITIONS (80°F DRY-BULB, 67°F WET-BULB)

TEST NO.	OUTDOOR CONDITIONS DB, °F	PPT	INPUT BTU/HR	COOLING CAPACITY BTU/HR	COP	EER	MODE
120	74.8	14.0	59300	33900	0.57	28.7	RECIR
130	85.0	14.1	58800	30500	0.52	26.1	RECIR
119	94.4	14.2	60300	28700	0.48	24.1	RECIR
129	105.2	14.2	59100	26100	0.44	22.3	RECIR
112	75.0	14.3	58200	29200	0.50	24.7	VENT
132	84.8	14.2	57100	27500	0.48	22.9	VENT
127	94.8	14.1	51800	25000	0.48	20.8	VENT
131	104.9	14.3	50200	21300	0.42	17.3	VENT

TABLE 3. EFFECT OF OUTDOOR TEMPERATURE ON CAPACITY, COP AND EER WITH LOW-TEMPERATURE SOLAR WATER FIRING COMBINED WITH GAS-FIRING TO RESULT IN EQUIVALENT REACTIVATION TEMPERATURE OF 195°F AND ARI INDOOR CONDITIONS (80°F DRY-BULB, 67°F WET-BULB)

Least-squares analysis was subsequently used to convert the resultant trend lines into polynomial forms for ease of manipulation together with weather solar, and structural load computer programs, to derive unit seasonal performance. Figures 2 and 3 show typical examples of the trend lines through the actual data. Figure 2 presents the variation of SOLAR-MEC (System III) unit's delivered air temperature with outdoor dry-bulb temperature, at two levels of outdoor humidity, with the unit operated in the ventilation mode at low-temperature solar input for desiccant reactivation. Equation 1, below,

$$T_d = 32.84 + 0.12\ T_o + 1.35\ H_o \qquad (1)$$

shows analytically the trend-line relationships of Figure 2 where —

T_d = Delivered Air Temperature, °F

T_o = Outdoor Air Temperature, °F

H_0 = Outdoor Air Humidity, ppt

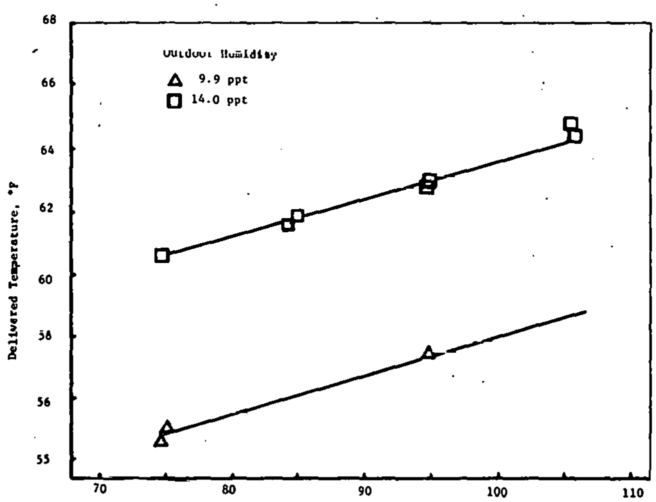

Figure 2.

COMPARISON OF TEST DATA TO MODEL PREDICTION, VENTILATION MODE, LOW TEMPERATURE, SOLAR WATER REGENERATION, AT ARI INDOOR CONDITIONS

TEST NO.	INDOOR CONDITIONS DB, °F	PPT	INPUT BTU/HR	COOLING CAPACITY BTU/HR	COP	EER	MODE
31	75.2	10.9	61600	27500	0.45	23.7	RECIR
28	80.0	11.0	71200	32500	0.46	27.5	RECIR
32	85.0	11.2	57000	34800	0.61	30.0	RECIR
23	75.1	10.9	54400	23800	0.44	20.5	VENT
54	79.7	11.0	50000	25500	0.51	22.0	VENT
20	84.7	11.0	55700	30200	0.54	27.7	VENT

TABLE 4. EFFECT OF INDOOR TEMPERATURE ON CAPACITY, COP AND EER WITH HIGH-TEMPERATURE (230°F) SOLAR WATER FIRING (205°F MIXED-CUP EQUIVALENT REACTIVATION TEMPERATURE) AND ARI OUTDOOR CONDITIONS (95°F DRY-BULB, 75°F WET-BULB)

Similarly, Figure 3 presents the variation of delivered air humidity with outdoor dry-bulb temperature at identical other conditions, as for Figure 2. Equation 2, below

$$H_d = 0.9 + 0.49\ H_o + (0.089 - 0.00089\ H_o + 0.00016\ H_o^2)\ \left(\frac{T_o - 32}{1.8}\right) \qquad (2)$$

shows analytically the trend-line relationships of Figure 3 where —

H_d = Delivered Air Humidity, ppt

H_o = Outdoor Air Humidity, ppt

Equations 1 and 2 are only valid for low-temperature solar input for desiccant reactivation, with the unit operating in the ventilating mode. Similar equations have been formulated for all other conditions encompassing the data developed in the laboratory.

FUTURE ACTIVITIES

- Completion of the laboratory testing of the SOLAR-MEC (System III) unit and use of the data to complete the seasonal performance model formulation
- Improvement of the unit's seasonal performance through the development of effective operating and control strategy.

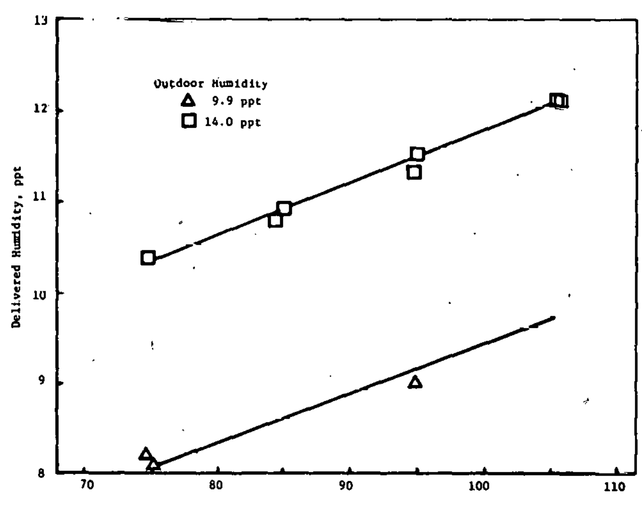

Figure 3.

COMPARISON OF TEST DATA TO MODEL PREDICTION, VENTILATION MODE, LOW TEMPERATURE, SOLAR WATER REGENERATION, AT ARI INDOOR CONDITIONS

CONTRACT INFORMATION

START DATE Sept. 1, 1977 END DATE Dec. 31, 1980 CONTRACT VALUE $663,955

MILESTONES

Item:	Due date:
1. Technical Report	July 1981
2.	
3.	
4.	
5.	

HEAT AND MASS TRANSFER CHARACTERISTICS OF LIQUID DESICCANT OPEN-FLOW SOLAR COLLECTORS

Lockheed-Huntsville Research & Engineering Center, Huntsville, Alabama 35807

Philomena G. Grodzka and Suzanne S. Rico

Contract SERI XE-0-9179-1

OBJECTIVE

The project objective is to accurately determine the heat and mass transfer rates of a lithium chloride salt solution flowing as a film across a solar-absorbing surface in a hot, humid climate. The goals to be accomplished in this project are to construct and equip with plumbing a 50 foot by 50 foot south-facing, slanted test structure; to surface this structure with a covering which will maintain a continuous, thin-flowing film of lithium chloride solution; to instrument the structure to provide temperature and concentration data at a number of locations on the structure as well as insolation, wind and humidity data; to obtain at least 30 days of data in the period June through July 1981; to analyze the test results and compare them with the results of an analytical model; and to improve the model as necessary.

DESCRIPTION OF WORK

Desiccants provide a means of storing solar energy as chemical energy. Such stored energy can be utilized for cooling or heating applications. Absorption refrigeration is an application that appears particularly promising. Various approaches to dehydrating liquid desiccant for absorption refrigeration have been pursued by a number of researchers. The open-cycle approach, although possessing a number of attractive features, has received relatively little study thus far. The present study was undertaken to provide performance data on an open-flow, liquid-desiccant desorber of a size sufficient to be relevant for applications assessment. The performance data collected will be compared with predictions of an analytical model constructed by R. K. Collier (Ref. 1).

A small scale version of the collector was built and tested to verify manifolding techniques and sample port design. Based on the data obtained during this test, a full scale test structure of the general features shown in Figure 1 was constructed. The surface covering is asphalt shingles. The manifold arrangement for distributing the liquid flow evenly at the top of the roof is shown in Figure 2. Presently 27 sampling ports for obtaining the liquid samples from the roof during a test have been equipped with thermocouples and installed into selected locations on the roof. The form of the ports is shown in Figure 3. The outputs of the temperature sensors, a wind velocimeter, insolation and ambient dew point temperature measuring equipment are recorded by a data logger.

Concentrations of the hot, concentrated lithium chloride samples are determined either by refractometry or density measurements.

ACCOMPLISHMENTS TO DATE

- The 50 foot by 50 foot open-flow collector structure was constructed, and initial tests indicate that the collector performs just as predicted. Standard construction techniques for houses using tongue-and-groove decking provided a sufficiently flat and level roof such that the asphalt shingle covering maintains a thin, continuous film flow. On a clean, dry roof, initial wetting by a concentrated lithium chloride solution is facilitated by first wetting the roof with water. If residual lithium chloride remains on the roof, i.e., as in the morning after the flow had been shut off the preceding evening, initial wetting is not required because the humidity in Alabama is high enough to keep the roof moist during the evening and early morning.
- Simple methods for determining the concentrations of concentrated lithium chloride solutions (refractometry and density) have been chosen. Although some further evaluations of these methods are in progress, they appear quite reliable.
- A computer model of the system has been constructed and results obtained with it compare quite well with preliminary experimental results obtained from both the small and full scale collectors.

FUTURE ACTIVITIES

The foreseen follow-on effort for the present study is to connect an absorption chiller to the open-flow, solar desorber, insulate the test structure building, and evaluate the performance of the system as a total absorption air-conditioning system. The possible use of the open-flow collector for space heating should also be evaluated. Upon successful completion of such an effort, a commercialization strategy should be implemented.

REFERENCE

1. Collier, R. K., "The Analysis and Simulation of an Open Cycle Absorption Refrigeration System," Solar Energy, Vol. 23, 1979, pp. 357-366.

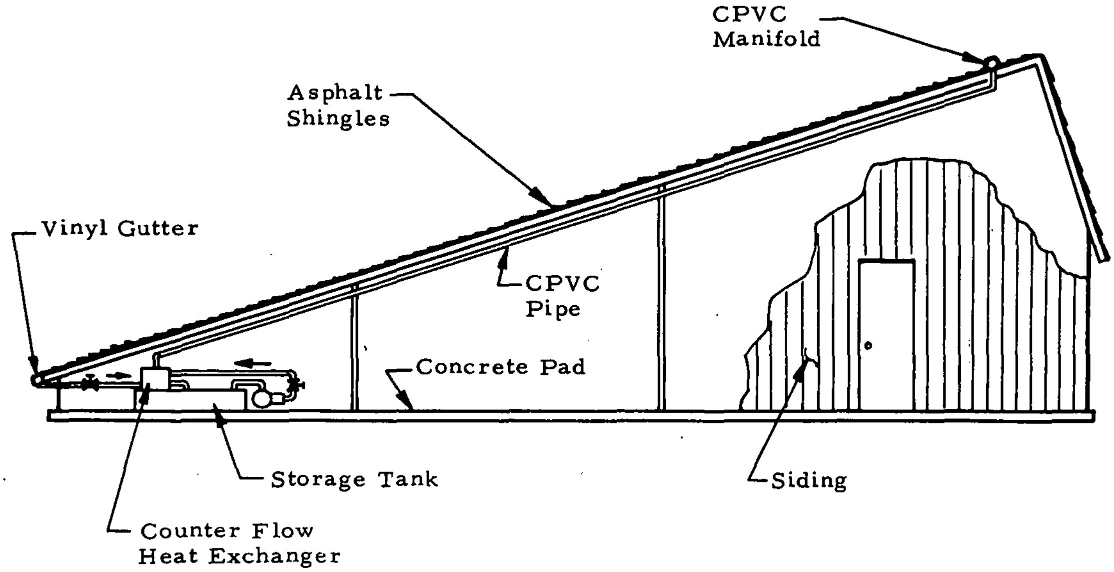

Fig. 1 - Solar Desorber Structure, East Elevation

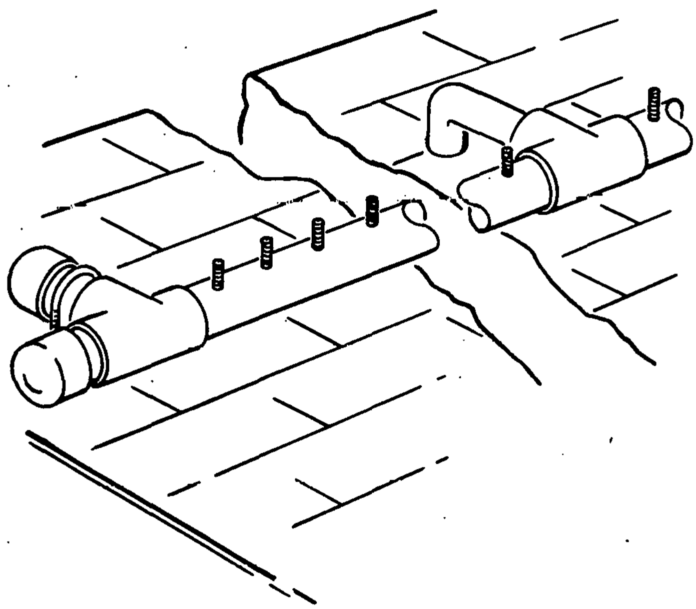

Fig. 2 - Manifold Arrangement

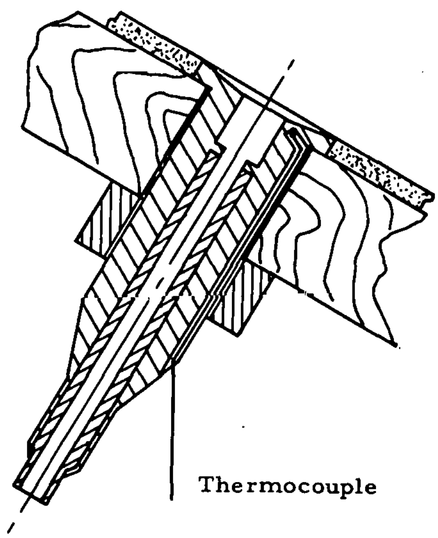

Fig. 3 - Sample Port Arrangement

CONTRACT INFORMATION

Start Date: 20 August 1980
End Date: 20 November 1980
Contract Value: $174,468

Deliverables: Draft Final Report and Final Report.

ANALYSIS OF SOLAR DESICCANT SYSTEMS AND CONCEPTS

Solar Energy Research Institute

Robert Barlow

EG-77-C-01-4042

OBJECTIVES

The long term goal of this research effort is to develop a general, versatile heat and mass transfer computer model to predict the performance of solid desiccant systems and to evaluate new concepts and new design strategies in solar desiccant cooling. Objectives of current work are: (1) to compare packed beds and parallel passage geometries and identify the most effective designs, (2) to investigate the effect of equilibrium sorption properties on system performance and identify desirable properties, and (3) to evaluate the potential performance of new desiccant materials and combinations of existing materials.

CONCEPT

The Solar Energy Research Institute's (SERI) desiccant simulation program (DESSIM) uses an entirely new approach to the modeling of the adiabatic adsorption/desorption process that greatly simplifies the mathematics of the analysis and facilitates a better understanding of physical behavior of desiccant systems. Previous nonlinear models [1,2,3] have used finite difference techniques to solve a set of coupled differential equations describing the adsorption process. In each case a transformation of variables was necessary to express the equations in a form convenient for numerical solution. These transformations have tended to obscure the physics of the problem, making it more difficult to develop an intuitive understanding of the behavior of desiccants. In contrast, the SERI model performs heat transfer and mass transfer calculations in an uncoupled manner using simple algebraic equations adapted from the theory of heat exchangers. No transformation of variables is required, and the model has proven to be accurate and relatively inexpensive to run.

Because the method is simple, the model can be adapted easily to look at different specific problems such as the effects of using different bed geometries, different desiccant properties, variable inlet air conditions, and various system design strategies. To further facilitate a full understanding of the behavior of desiccants, results of the simulation including temperature and loading profiles in the bed, as well as outlet air conditions, are displayed graphically.

TECHNICAL ACCOMPLISHMENTS

- A new and simple approach to modeling desiccant systems has been developed. Computer programs for predicting the performance silica gel beds in single-blow situations and in cyclically operating desiccant cooling systems have been written.
- The single-blow model has been validated and shows excellent agreement with experimental data from SERI's desiccant test lab. Graphs showing the measured and predicted conditions of adsorption process air leaving a packed bed of silica gel are given in the paper in these proceedings that describes SERI's desiccant lab. Figures 1, 2, and 3 show experimental data published by Koh [4] along with the corresponding prediction using DESSIM.

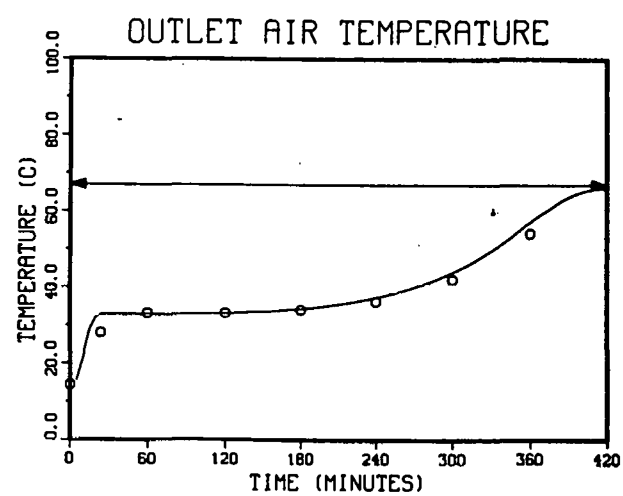

Figure 1. Measured (O) and Predicted (-) Outlet Air Temperature During Regeneration of Silica Gel.

- The cooling system simulation program has been used to evaluate the potential gains in cooling capacity and thermal COP that could be realized by using a nonhomogeneous desiccant bed composed of a series of hypothetical desiccants with different adsorption properties. This study [5] shows that the system cooling capacity could be increased by roughly 10% or that the bed thickness could be reduced by 37% if the silica gel were replaced by a staged bed with the properties shown in Fig. 4. Either strategy would result in a significant reduction in the parasitic power requirements of the system.

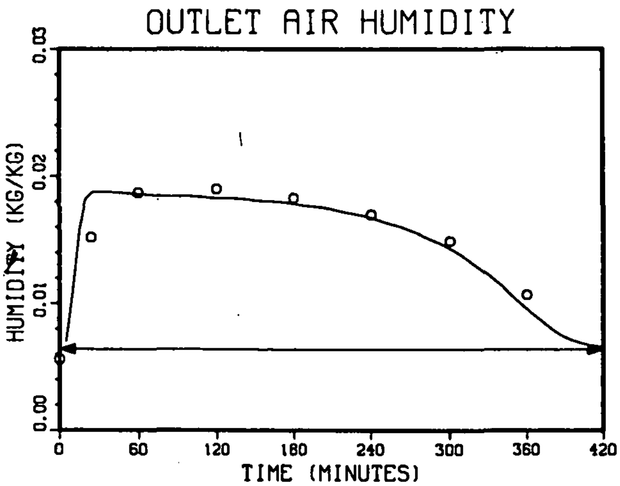

Figure 2. Measured (0) and Predicted (-) Outlet Air Humidity Ratio During Regeneration of Silica Gel

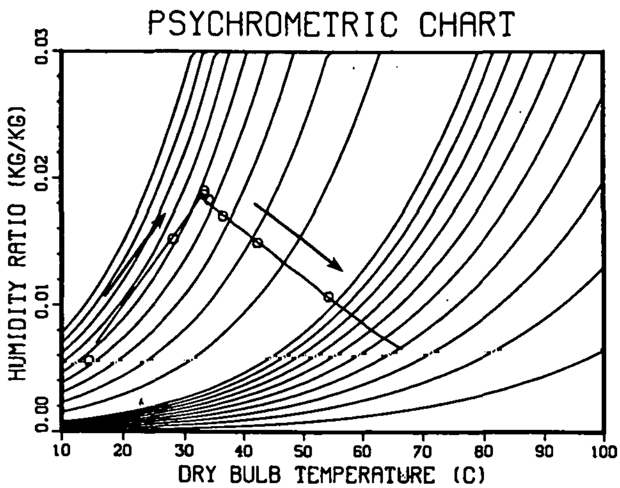

Figure 3. Measured (0) and Predicted (-) Psychrometric Process Lines During Regeneration

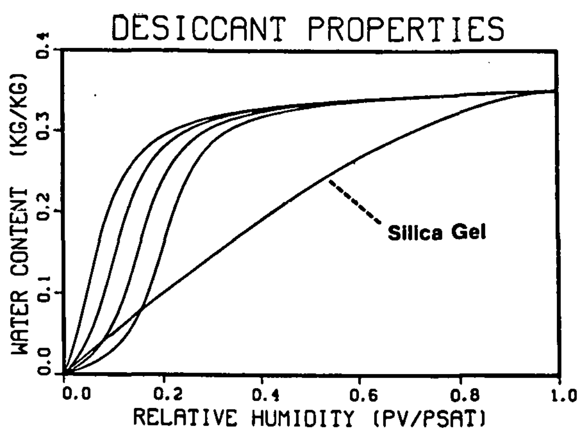

Figure 4. Equilibrium Adsorption Properties of Silica Gel and Four Hypothetical Desiccants for Staging

The physical phenomena that produce these results are displayed most effectively by Figs. 5 and 6. These are psychrometric charts showing the conditions of the process air leaving the two desiccant beds during cyclic operation. The process lines for the two beds trace almost exactly the same paths. During both adsorption and regeneration, the outlet air goes through a very rapid transient that lasts only about 40 seconds and runs along lines of nearly constant relative humidity. The trajectory of the process curve then changes, and outlet air conditions move slowly toward the conditions of the inlet air. The major difference between the staged bed and silica gel is that the progress of the outlet air toward the inlet

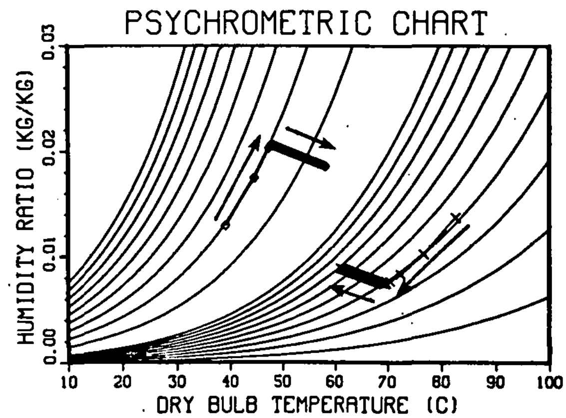

Figure 5. Conditions of Process Air Leaving the Silica Gel Bed (adsorption -(x), regeneration -(0), symbols at 12 second intervals).

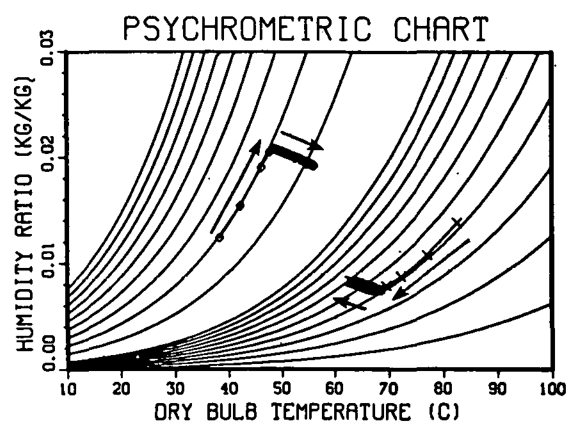

Figure 6. Conditions of Process Air Leaving the Staged Bed (symbols spaced at 12 second intervals)

condition is much slower. During adsorption the process line terminates at 7% relative humidity with silica gel, but reaches only 6% with the staged bed, even though the rotation period is twice as long. The same effect is seen during regeneration. The reason for this slowing of the breakthrough curve can only be that staging decreases the length of the effective MTZ (mass transfer zone). This is done by matching the properties of each desiccant stage to the range of relative humidities occurring in that section of the bed during cyclic operation. The result is that each desiccant is operating on the steep portion of its capacity curve, and this improves mass transfer.

FUTURE ACTIVITIES

- DESSIM will be used to evaluate new materials, new concepts, and new design strategies for solar desiccant cooling systems. Simulations will help to identify the most promising directions for research and development of advanced desiccant systems.
- Modeling efforts will be closely coordinated with SERI's experimental program. Laboratory data will determine the accuracy of the model over a wide range of conditions, and the model can help to identify the most informative experiments to be run.
- The capabilities of the cooling system simulation program will be expanded to include analysis of the purge process, experimentally determined transfer coefficients for parallel passage geometries, and sorption properties of molecular sieves and natural zeolites.

PUBLICATIONS/REPORTS/REFERENCES

1. AiResearch Manufacturing Company. 1980 (Sept.). Phase I Final Summary Report: Development of a Solar Desiccant Dehumidifier. Publication No. 80-17481.
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CONTRACT INFORMATION

START DATE ______ END DATE ______ CONTRACT VALUE ______

MILESTONES

Item:	Due date:
1. Chiller simulation model - Final Report	9/30/81
2.	
3.	
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INVESTIGATION OF LIQUID DESICCANT SOLAR COOLING SYSTEMS

Solar Energy Research Institute

Dennis R. Schlepp

EG-77-C-01-4042

Objective

The objectives of this project are to investigate the use of liquid desiccants in solar cooling systems; to evaluate the performance of such systems; and to establish design criteria and recommendations for construction of test apparatus.

Description of Work

The work to accomplish these objectives falls into two categories: computer simulation and experimental work. The experimental analyses to study the open-cycle regeneration of lithium chloride desiccant solutions and the resulting heat and mass transfer characteristics are being carried on at Lockheed Missile and Space Center in Huntsville, Alabama and at Arizona State Univesity in Tempe, Arizona, for hot, humid climates and hot, dry climates, respectively. Construction and testing of a residential liquid desiccant system using calcium chloride solution is being undertaken by the University of South Carolina at Pawley's Island, South Carolina. A study of lithium chloride regeneration in packed towers is being done at Colorado State University in Fort Collins, Colorado. Details on these projects and the accomplishments of each can be found in other technical papers in this summary.

The computer simulation work at SERI has concentrated on operation of the open-cycle absorption refrigeration (OCAR) system. Recent work has investigated the use of the OCAR system (Fig. 1) as a chemical heat pump for providing both heating and cooling. Successful application of the system year-round would encourage further development because the economics are more favorable.

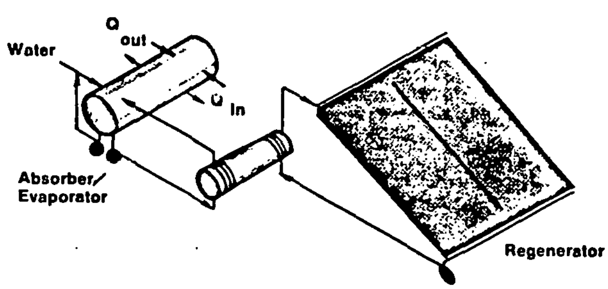

Figure 1. OCAR System

Technical Accomplishments

- A computer simulation code was written to model the operation of the OCAR system under all environmental conditons. This was accomplished by including correlations of lithium chloride solution physical properties over a wide range of temperatures.
- The OCAR system was found to operate effectively in winter climates in a heating mode, using waste heat sources as low as 20°C. Simulations using weather data in five U.S. cities showed that winter climates as severe as New York City and Albuquerque, New Mexico would still allow open regeneration of the desiccant solutions. Table 1 presents the solar COP's (heating output/solar input) for each of the five cities.

Table 1. OCAR System Performance for Five U.S. Cities

City	Solar COP
Phoenix	.186
Albuquerque	.161
Dallas	.127
Miami	.070
New York	.058

- A portion of the system's regenerator can be used as an open-flow trickle collector to provide the thermal energy necessary to make the system operate. This can be done, with a 50% cut in capacity, in the milder winter climates effectively.

This allows the system to be used as a complete heating and cooling unit for commercial applications.

Future Activities

Based on the results of the experimental efforts and the computer simulations, a complete open-cycle absorption system will be built and tested. This will allow investigation of the many operating problems that are anticipated, such as solution contamination and vacuum integrity. Research will also be extended into use of new or improved desiccant solutions.

Publications

1. Schlepp, D. and Collier, K., "The Use of An Open-Cycle Absorption System for Heating and Cooling". NTIS, SERI/TP-631-1159, Marc 1981. Proceedings of the AS/ISES Annua Conference May 1981.

SERI DESICCANT LABORATORY EXPERIMENTS

Solar Energy Research Institute

Charles F. Kutscher

EG-77-C-01-4042

OBJECTIVE

The objectives of the SERI Desiccant Laboratory are: to validate in-house adsorption computer models with experimental data; to test various concepts in desiccant bed design; and to test various desiccant materials.

DESCRIPTION OF WORK

The layout of the test apparatus has changed with time to improve the quality of data which can be taken. The current configuration is shown in Fig. 1.

The loop is designed so that either adsorption or regeneration of a test article can be performed. Two 2.24 kW (3 hp) centrifugal fans capable of supplying up to 40 kg/s (700 SCFM) in 30 m (12 in) circular duct are used, one for each direction. To perform adsorption, fan F-1 is turned on and butterfly dampers are used to obtain the proper flow rate. (A stepped cone pulley also allows fan speed to be adjusted.) Inlet room air is heated by a 6 kW duct heater to the desired dry bulb temperature--in a range of 27°-41°C (80°-105°F)--and steam from a 50 kW boiler is injected to achieve the desired humidity. The conditioned air is bypassed around the test article and exhausted to the outside, until proper conditions are met. At that time, several shutoff dampers are adjusted to initiate flow through the bed. Adsorption runs are ordinarily made until the bed is saturated, i.e., until outlet and inlet conditions are identical.

To perform regeneration, fan F-2 is used. Room air is heated to regeneration temperatures--up to 150°C (300°F)--by a 35 kW duct heater. The air is bypassed around the test article until proper air temperature and flow rate are obtained. Adjustment of shutoff dampers then initiates flow through the bed. Again, test runs are ordinarily made until outlet and inlet conditions converge.

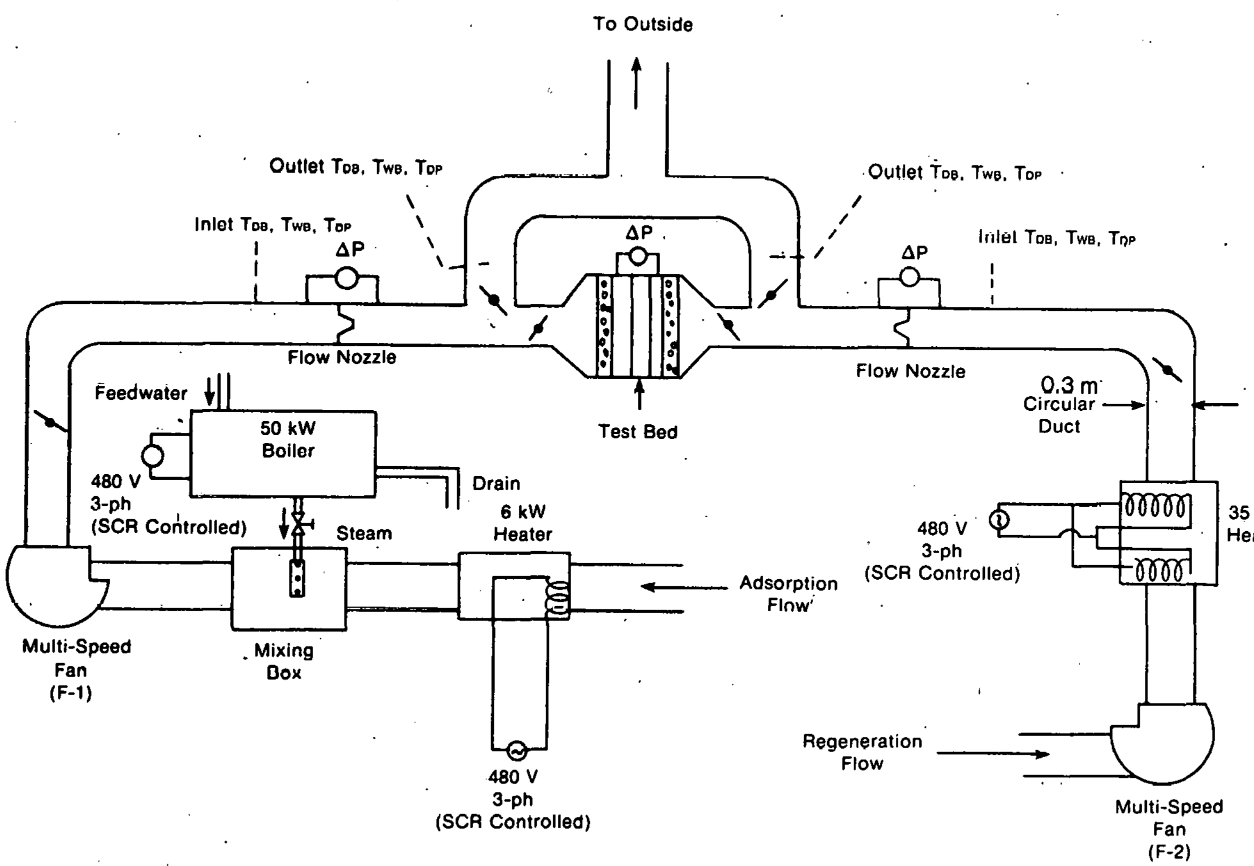

Figure 1. SERI Desiccant Test Loop

To better control temperatures, SCR controllers are used on the two duct heaters thus allowing the desired temperature to be "dialed in." An SCR controller is also used on the boiler heating elements to maintain a steady steam pressure.

Temperatures are measured throughout the system with exposed junction type T (copper/constantan) thermocouples. Humidity is measured via both wet bulb thermocouples and optical condensation dew point hygrometers. To ensure well mixed air in terms of both temperature and humidity, air mixers are used, one after the 35 kW heater and one on each side of the test article. Pressure drop across the test article is measured with a capacitance type transducer. Flow rates are measured with similar pressure readings taken across ASME flow nozzles.

Originally all of the sensor outputs were fed into a Kay Digistrip II data logger. Recently a Hewlett Packard data acquisition system consisting of an HP-85 desk top computer and an HP-3479 scanner/digital voltmeter has become operational. This system not only supplies test parameters in engineering units, but will do psychrometric conversions and supply graphics. Future plans are to also take advantage of this system's control potential to better control steam supply. [Currently inlet dew point varies ± .15°C (± 27°F).]

TECHNICAL ACCOMPLISHMENTS

After construction of the loop was completed, the equipment was operated in a shakedown phase. Numerous data runs were performed with a silica gel packed bed, and various changes were made to the loop to improve data quality. Although improvements will continue to be made, the test apparatus is now working well enough to be used to validate an in-house computer model, DESIM. (DESIM performs uncoupled heat and mass transfer calculations using simple equations adapted from heat exchanger theory. Published experimental data on silica gel properties and transfer coefficients are used in calculating the properties of a control volume of air as it moves through bed segments. See paper by R. Barlow presented at this conference.)

Figure 2 shows experimental results and computer prediction for the outlet humidity ratio versus time for a test run with the following conditions:

Inlet Dry Bulb Temperature:	35°C (95°F)
Inlet Dew Point Temperature:	20.8°C (69.4°F)
Flow Rate:	.23 ky/s (400 SCFM)
Bed Regeneration Temperature:	60°C (140°F)
Bed Diameter:	.64 m (25 in.)
Bed Width:	.032 m (1.25 in.)

This shows the so-called "breakthrough curve." Because the packed silica gel bed is thinner than the mass transfer zone (MTZ), some moisture begins to break through the downstream end of the bed from the start. As the run continues, the remaining bed capacity continues to drop, and the adsorption wave exits the bed, resulting in increasing humidity of the exit air. The experimental data points for outlet humidity ratio are derived from dew point measurements. Agreement

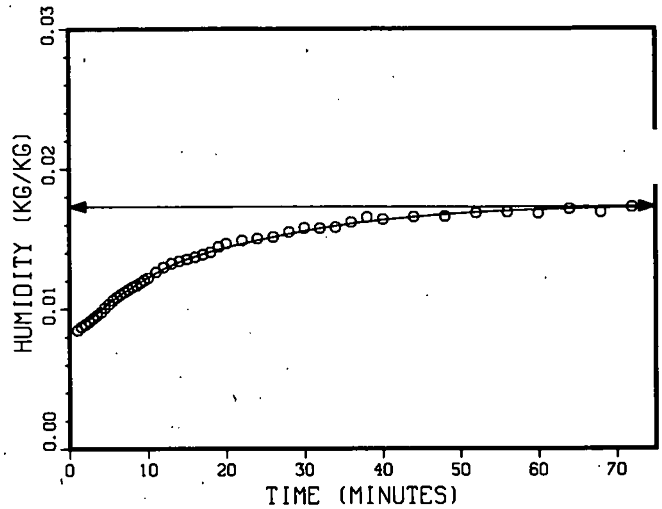

Figure 2. Outlet Humidity Ratio vs. Time

with the computer model prediction can be seen to be excellent.

The outlet air temperature versus time is shown in Fig. 3. The difference between predicted and experimental values at the beginning is due to the bed and duct being cool at the start of the run because of a delay between regeneration and adsorption. As the adsorption wave leaves the bed, less adsorption takes place meaning less heat of adsorption is released with a corresponding decay in outlet dry bulb temperature. Outlet dry bulb eventually reaches the inlet condition (35°C) once the bed capacity has been exhausted.

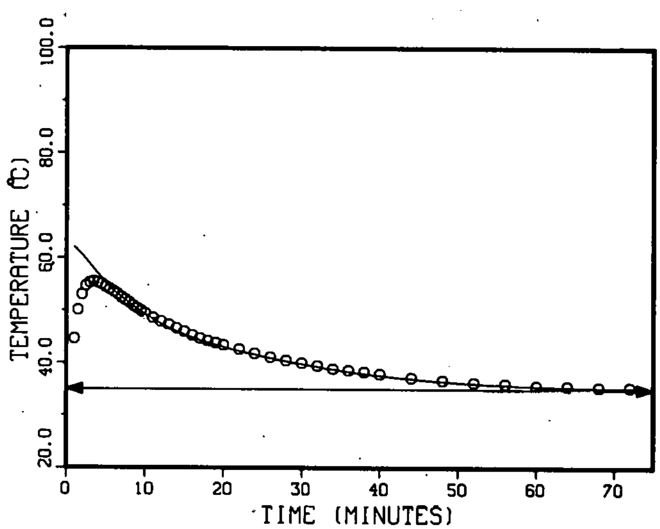

Figure 3. Outlet Air Dry Bulb Temperature vs. Time

Figure 4 shows the process line on a psychrometric chart (illustrating humidity ratio of the outlet air as a function of dry bulb temperature). Again the leading edge of the experimental curve results from the bed being cool at the start. The air is first heated by the heat of adsorption with some heat going into the bed and duct mass before an adiabatic process line is followed. The outlet air moves up the straight portion of the curve as it rises in moisture content.

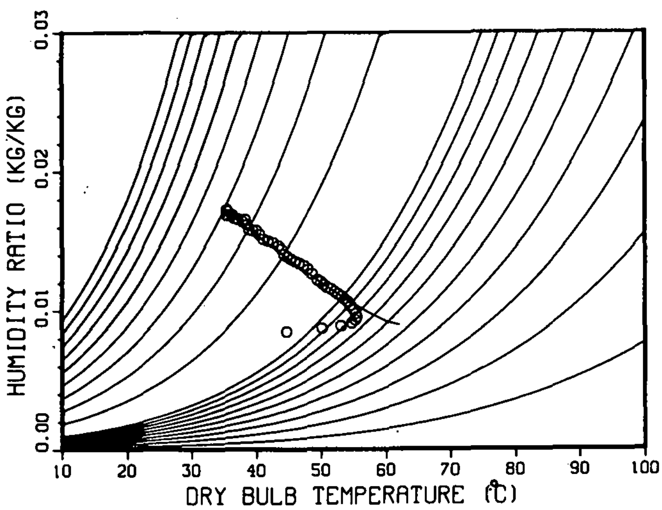

Figure 4. Process Line for Outlet Air on a Psychrometric Chart

This dehumidification line differs from a constant enthalpy line by the difference between heat of condensation and heat of adsorption. (Bed heat capacity also affects the slope of the line.) If one chooses any point on the line, the air flowing through the bed at that time can be considered to move down the dehumidification line to that point which would be the exit condition at that time. Figure 4 thus shows how the exit condition moves up the dehumidification line with time.

The close agreement between the DESIM model and the experimental data are encouraging and gives confidence that both can be useful tools in studying candidate desiccant beds.

FUTURE ACTIVITIES

The graphs shown in this report represent the first validation attempt of SERI's in-house adsorption computer model. Further experimental runs are being made with the current test article to extend the validation over a wide range of inlet (temperature/humidity) conditions. A number of variable length .30 m (12 in) diameter test sections have already been manufactured, and these will be installed to test length effects as well as better determine the in-situ pressure drop characteristics of the perforated plates which contain the silica gel. As testing of the variable length pack beds is performed, a channel flow bed will be built, and tests will be made to compare its heat and mass transfer and pressure drop characteristics with those of the packed beds.

Further improvements in the laboratory are also planned. These include: control of the steam supply valve with the HP-85 computer, and providing faster turnaround between regeneration and adsorption runs.

REFERENCES

Kreith, F. "An Overview of SERI Solar Thermal Research Facilities," Heat Transfer Engineering, Vol. 2: No. 2. Oct.-Dec. 1980.

CONTRACT INFORMATION

START DATE ________ END DATE ________ CONTRACT VALUE ________

MILESTONES

Item:	Due date:
1. Complete testing of packed bed geometry.	Sept. 30, 1981
2.	
3.	
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OPEN CYCLE CHEMICAL HEAT PUMP AND ENERGY STORAGE SYSTEM

COASTAL CAROLINA COLLEGE/UNIVERSITY OF SOUTH CAROLINA ENERGY LABORATORY

HARRY IRVING ROBISON

SUBCONTRACT NO. ZE-0-9185-1 UNDER PRIME CONTRACT NO. EG-77-C-01-4042

OBJECTIVE

The objective of this project is to speed the development of a marketable solar powered chemical heat pump that is a technically viable, environmentally acceptable, and economically competitive alternative to conventional space heating and cooling methods.

DESCRIPTION OF WORK

Introduction

The summer climate of the South Atlantic and Gulf Coast regions is hot and humid. The air conditioning load is principally one of dehumidification. As the cooling load exceeds the heating load, residential and commercial dehumidification and cooling are necessary during two-thirds of the year. Cooling and dehumidification are also needed throughout the Eastern seaboard and Great Lakes regions for a shorter period each year. Effective cooling equipment will allow solar collectors to be used throughout the year, thus reducing the pay-back period substantially.

Method

The Energy Laboratory of Coastal Carolina College of the University of South Carolina proposes to demonstrate over a 30-month period an open-cycle chemical heat pump that uses solar energy, well water, and a common salt solution to provide not only home heating and cooling, but also humidity control.

During the cooling cycle, the device uses well water and a salt solution made from water and calcium chloride to cool air to a temperature lower than that of the well water. During the heating cycle, the concentrated salt solution and well water are used to achieve an air temperature higher than the well water temperature. In both cooling and heating cycles, solar energy is used to concentrate the salt solution so that it can be used again. For continuous operation of the conditioner, a small, uninsulated tank stores the concentrated solution.

This liquid desiccant system, which can be powered by solar energy, waste heat, or off-peak electricity, which uses water as the refrigerant, and which uses no mechanical compressor, no vacuum or pressure system, no condenser, no gas-fired generator and no large insulated heat storage, will be used to heat and cool a 2800 foot^2 house. Actual operational data will be obtained with two different types of desiccant regeneration equipment, each operating under various environmental conditions and each under the influence of transient as well as steady state insolation conditions. Both regenerators use solar energy for power.

During the first year, the desiccant solution will be regenerated by direct solar radiation in the very inexpensive and simple trickle collector-regenerator. During the second year of operation, inexpensive plastic solar collectors and a modified off-the-shelf regenerator will be used for this operation. First costs should be competitive with conventional vapor-compressor heat pumps, and operational expenses should be negligible.

Use of a computer model to simulate operating conditions and a full year of operation with each regeneration system should allow the various parameters to be adjusted to achieve maximum performance with each system. As no new technology is required, immediate commercialization of the heat pump should be possible upon completion of the optimization process.

Background

The analyses of open cycle liquid desiccant cooling systems indicate the possibility of much-improved cost-effectiveness over presently proposed systems. One important aspect of this possible cost-effectiveness is the use of an open flow solar collector-regenerator.

A second advantage of a liquid desiccant system is the system's ability to store chemical energy in the form of a concentrated brine. This storage system can be in a small tank at ambient temperature. No insulation is needed.

A third advantage is the ability to heat as well as cool with a liquid desiccant system. True heat pump operation can be achieved by extracting heat from shallow-well water where this water is available. In other locations, heat can be extracted from passive storage walls even though their temperature is not high enough to heat room air directly.

This research is necessary to actually measure the thermodynamic performance of the open regenerator operating in conjunction with the desiccant conditioner/dehumidifier. Storage energy densities should be measured. Operation of an open cycle chemical heat pump under actual operating conditions has never been demonstrated.

TECHNICAL ACCOMPLISHMENTS

- A computer model of the roof collector/regenerator has been developed.
- Four 30 ft.^{2} roof sections have been built and used to collect data to verify the computer model as well as to obtain data to design the collector/regenerators which serve as the south-facing roof of the research house.

- Five separate collector systems have been constructed as an integral part of the research house.
- The conditioner and necessary plumbing and ductwork have been installed.

FUTURE ACTIVITIES

One integral part of the test house is an isothermal (81° F) passive collector/storage wall consisting of brick columns containing calcium chloride hexahydrate latent-heat storage rods. Both the regeneration air and the brine can be pre-heated in another rooftop system. Analysis of work just completed indicates that pre-heating should be advantageous. Recent work also indicates that the regenerator is more efficient during most times of the year when operating with laminar air flow than when operating with turbulent flow. The three different collector/regenerator sections will allow direct comparison of laminar flow and turbulent flow. The large brine storage tank already installed will allow evaluation of the possibility of seasonal energy storage as well as diurnal storage.

The research now under way has shown that the regenerator is very sensitive to the vapor pressure of the regeneration air. Direct comparison of operations using inside and outside air will be achieved. Variable fan and pump speeds will allow investigation of the effect of air flow rate, air flow velocity, solution flow rate and solution concentration. Additionally, the 60 ft^2 collector/regenerator roof section used during the past ten months of research will continue to be used to investigate the effect of the following: roof surface material, glazing material, and air slot dimensions.

In the southeastern states and particularly in Florida, more and more home owners are taking advantage of shallow-well water in water-to-air heat pumps. The open cycle chemical heat pump can also operate by using well water. A study of the availability of this source of energy will be undertaken by a co-investigator. Operational and environmental problems associated with use of ground water will be identified.

PUBLICATIONS

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CONTRACT INFORMATION

START DATE 7/2/80 END DATE 9/30/81 CONTRACT VALUE $98,488

MILESTONES

Item:	Due date:
1. Comprehensive report to SERI containing seasonal performance data and analysis of operation of open cycle liquid desiccant system.	10/31/81
2.	
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COMPONENT AND SYSTEM EVALUATION STUDY OF SOLAR DESICCANT COOLING

UNIVERSITY OF WISCONSIN-MADISON

JOHN A. DUFFIE AND JOHN W. MITCHELL

DE-AC03-79SF10548

OBJECTIVES

The objectives of this work are to develop reliable and useful models of the components of solar-desiccant air conditioning systems, to validate the model predictions against experimental results, and to use simulation methods to explore and evaluate systems.

DESCRIPTION OF WORK

The application of solar energy to space and water heating is well established, design techniques have been developed, and equipment is commercially available. The science of solar air conditioning is not as advanced, primarily due to the difficulty of using a low temperature solar heat source to drive a refrigeration cycle. Solar-desiccant air conditioning systems offer the potential of using the low temperature heat from a flat plate solar collector to provide cooling. The systems investigated in this study are constructed by arranging desiccant dehumidifiers, sensible heat exchangers, and evaporative coolers in various configurations. The limiting maximum performance of these systems is analyzed using thermodynamically ideal system components. The actual system performance is investigated using mathematical models of the "real" components by long-term computer simulation methods. The simulation methods allow evaluation of system performance in terms of component design, system configuration, load profile, and geographic location.

Thorough understanding of the system components is required to evaluate the potential of solar-desiccant air conditioning systems, and is gained from theoretical, numerical, and experimental analyses of the components, particularly the desiccant dehumidifier and sensible heat exchanger. Mathematical models are used to develop design criteria, assess the effect of off-design conditions, and determine limiting theoretical performance. A simplified desiccant dehumidifier model using an analogy with a sensible heat exchanger, is developed for use in long-term simulations. The mathematical models are verified by experimental tests on a rotary silica gel dehumidifier and a rotary sensible heat exchanger.

TECHNICAL ACCOMPLISHMENTS

- Desiccant Property Analysis

Analysis and optimization of desiccant cooling systems requires consideration of the thermodynamic properties of the desiccant employed. Two mathematical studies have been done in an effort to optimize system performance with desiccant properties. The first study used sorption isotherms of the five Brunauer classifications, with the heat of sorption equal to the heat of vaporization of water. Preliminary results indicated that the silica gel isotherm and the sigmoidal isotherm, corresponding to type 5 in the Brunauer classification, were most desirable for air conditioning applications. A more detailed investigation of six different sigmoidal isotherms showed that a silica gel dehumidifier will perform at least as well in a cooling system application as any of the other desiccants considered. A second study investigated the merits of staging different desiccants within the dehumidifier. Desiccants with sigmoidal isotherms were employed. The results indicate that, by staging desiccants in the dehumidifier, the process stream outlet humidity can be reduced to less than that obtained using a single component device composed of any of the staged materials alone. However, for the particular materials employed, the system results showed no particular advantage of the multicomponent dehumidifier over a single component silica gel device. Hence, silica gel has been employed as the desiccant in all following studies.

- Dehumidifier Modeling and Design (1,2)

Two different dehumidifier models have been developed. A detailed numerical model has been developed to describe the coupled and nonlinear exchange of heat and water vapor within the dehumidifier. The model assumes that the transfer resistance between air flow and matrix is represented by overall transfer coefficients, comprised of contributions from convective transfer resistance in the air and diffusional resistance in the solid. The latter contribution actually varies throughout the matrix at any time. However for heat transfer alone, a method by Hausen for determining an effective mean of this contribution gives accurate prediction of regenerator performance. A simplified linear method of dehumidifier analysis, the analogy method, has also been developed [1] which enables performance prediction from that of a similar exchanger transferring heat alone. The heat and vapor exchanger is represented by the superposition of two exchangers, each operating like a heat exchanger driven by a combined potential depending on air temperature and water vapor content. The application of the method gives significant understanding of exchanger operation. The method has also been extended to retain the essential nonlinearity of the heat and mass transfer process, which allows sufficient accuracy in dehumidifier modeling for system simulation. The analogy method as currently developed is found to satisfactorily predict performance for desiccants with well behaved properties such as silica gel. Curve fits to the relevant properties have been developed to facilitate performance evaluation. In system studies, the analogy method is the only method available for exploring system options, control strategies, and climate effects at reasonable computer cost.

Investigation of dehumidifier design has led to the conclusion that packed bed geometries are unfeasible. A solar-desiccant air conditioning system will be economically viable only if parasitic power requirements are minimized. Parallel flow geometries offer the only hope for minimal parasitic power consumption.

- Effects of Transient and Nonuniform Inlet Conditions on Dehumidifier and Heat Exchanger Performance (3)

The response of a rotary dehumidifier or heat exchanger exposed to either spatially nonuniform inlet conditions or a temporal step change in inlet conditions has been investigated. The analysis of a regenerator operating under steady state conditions exposed to nonuniform inlet conditions has led to two major conclusions. For a properly designed rotary heat exchanger, inlet condition nonuniformities have little effect on performance. However, for a properly designed dehumidifier, the nonuniformities can significantly affect performance, allowing improvement in dehumidifier design. Such nonuniformities are currently manifested in the form of purge cycles prior to absorption. A detailed numerical model has also been developed to describe the transient response of a rotary regenerator. Results show that the time for a dehumidifier to reach steady state conditions can be significant, often on the order of hours. Work is progressing to allow prediction of dehumidifier transient response using the analogy method.

- Experimental Component Testing

Experimental verification of heat exchanger and dehumidifier mathematical models have been performed in two stages. Experimental tests of rotary heat exchanger operating with either transient or nonuniform inlet conditions have been performed on an existing apparatus at CSIRO in Australia. The results of the tests show good agreement with predictions of the models and substantiate conclusions of the numerical analyses. Testing of dehumidifiers is being performed on a new apparatus, constructed specifically for this project. While the original plans anticipated that a modified total heat wheel manufactured by the Berner Company could be used for dehumidifier tests, further numerical and experimental tests showed the wheel to be unsatisfactory. A packed-bed silica gel dehumidifier has since been designed and constructed for testing purposes. While the computer controlled data acquisition system is being developed, preliminary tests have been performed using fixed psychrometer grids and multipoint recorders. These preliminary tests concur with numerical predictions that the effect of dehumidifier transients can be significant, on the order of 1-2 hours.

- Solar-Desiccant Air Conditioning System Simulation (3)

The system simulation study has been mainly concerned with the interaction of cycle configuration and climate, and the theoretical analysis of thermodynamically ideal systems. The three configurations studied in depth have been the ventilation, recirculation, and Dunkle cycles. The four climates were selected to represent a range of temperature and humidity combinations.

The results of the system simulations showed that it is essential to have high effectiveness system components. Sensible heat exchanger effectivenesses of 90% or greater are required, and a corresponding value is needed for the dehumidifier. With high performance components, cycle COPs of 1 to 1.6 were obtained, depending on climate. The higher COPs were obtained in the drier climates where the regenerative evaporative cooler capabilities could be utilized. Analyses of the thermodynamically ideal system performance have indicated maximum COPs on the order 2 to 4.

The comparison of the performance of the different system with high effectiveness components showed that the recirculation system performed poorest. The Dunkle cycle generally yields a higher COP and capacity than the ventilation cycle, but has the added complexity of another heat exchanger. It appears that the ventilation cycle may be the most promising cycle.

Simulations were performed to evaluate the ventilation and Dunkle cycles using solar energy only for regeneration. For all four climates, the system were found to meet a large fraction of the air conditioning load. The air temperatures obtained with flat-plate collectors are sufficient for desiccant regeneration.

The various ways in which desiccant and VAV systems for commercial buildings can be combined has been explored. One promising system uses a desiccant wheel for moisture removal and an indirect evaporative cooler plus vapor compression machine for sensible cooling. Heat rejection from the condenser is used to regenerate the desiccant. Using this arrangement, the chiller power can be reduced to 40%. The performance is almost linearly dependent on the ambient wet bulb temperature with the result that the power required over the season will be much lower than that at design conditions. These ideas will be explored via system simulations

FUTURE ACTIVITIES

Given the conclusion that packed-bed geometries are unsatisfactory for solar-desiccant air conditioning systems, future work will include design of a suitable parallel passage silica gel dehumidifier. The experimental apparatus will be used to test such dehumidifiers. Future component analyses will investigate extension of the analogy method to dehumidifier transient analysis. The feasibility of using large cooled desiccant beds for both dehumidification and energy storage will also be investigated. Future system simulation studies will include investigation of solar-desiccant systems in commercial applications.

PUBLICATIONS, REPORTS AND REFERENCES

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CONTRACT INFORMATION

START DATE 8/1/79 END DATE 7/31/81* CONTRACT VALUE $347,780.00
*Requested extension to 1/31/82

MILESTONES

Item:			Due date:
1.	Component models:	Rotary dehumidifier, fixed bed	7/31/80 (Completed 2/1/81)
2.	Desiccant properties:	Survey	7/31/80 (Completed 2/1/81)
3.	Component testing:	Rotary dehumidifier, evaporative cooler, fixed bed, comparison of tests and models	7/31/81
4.	System simulation:	System configuration and performance prediction, sensitivity and optimization, system model check	7/31/81
5.			

INTEGRATED SOLAR ZEOLITE COLLECTOR

THE ZEOPOWER COMPANY

DR. DIMITER IVANOV TCHERNEV

DE-AC03-78CS32117

OBJECTIVE

To design, construct and test an integrated solar zeolite collector, capable of providing hot water during the day and chilled water at night, which will act as one-for-one replacement for existing hot water solar collectors; to evaluate the performance of the integrated solar zeolite collector under different climatic conditions in different parts of the U.S.A.; to design, construct and test low cost zeolite collector; to produce a design for the integrated solar zeolite collector capable of reducing its cost when mass-produced to at least one-third of its present cost.

DESCRIPTION OF WORK

Zeolites provide a unique opportunity for solar solid-gas adsorption refrigeration systems because of their extremely nonlinear adsorption properties. By incorporating the zeolite in the solar collector, the overall efficiency of the adsorption system is increased considerably. Furthermore, all vacuum tight seals and tests are done in the factory thereby leaving only regular plumbing connections for the construction site. In the years preceding this project the feasibility of the concept and the high overall efficiency were demonstrated using small scale (1 sq.ft.) zeolite panels.

The work in this project began with the design of a full size zeolite collector suitable for mass production methods. The optimum zeolite loading was determined to be about 10 lb/ft^2, and the best natural zeolite for this purpose was determined to be chabazite from Bowie, Arizona. The evaporator/condenser was combined with the storage container and incorporated in the collector design. Two collectors of 16.4 ft^2 active area were then constructed and tested. The experimental performance agreed very closely with the performance predicted by a simplified computer simulation.

Next, the performance of the integrated solar zeolite collector was evaluated under different climatic conditions in different parts of the U.S.A. For this purpose a sufficient number of operating zeolite collectors were constructed and their performance tested first at the plant location. Afterwards a pair of collectors was installed at each of three different site locations: One pair at the research laboratory of the Anaconda Copper Company in Tucson, Arizona, another pair at the Solar Energy Research Institute in Golden, Colorado, and finally a pair at the Zeopower Company in Natick, Massachusetts. All three sites were instrumented and the input and output of the collectors was measured and recorded continuously.

Finally, during the last year of the project, the expected cost of the collector in mass production was analyzed in detail and separated into labor and material components. The design was then modified in order to permit the reduction of labor cost in mass production. The possibility of reduction of material cost was investigated and less expensive alternatives for copper were considered. Accelerated tests were performed on different methods to protect iron and aluminum from corrosion under operational conditions. The use of plastics for packaging and glazing was investigated and fiberglass-reinforced epoxy was selected as the container material to replace copper. Finally a low cost collector is being constructed and its performance will be tested under actual operating conditions.

TECHNICAL ACCOMPLISHMENTS

- The design of the full size integrated solar zeolite collector was completed on schedule in three months. The best natural zeolite for the purpose, chabazite from Bowie, Arizona, was selected and the optimum zeolite loading of 10 lb/ft^2 was established both experimentally and by computer simulation.
- The first full scale solar zeolite collectors with integrated condenser/evaporator were constructed on time. The active area of the collectors is 25" X 91" or 16.4 ft^2 and the size of the framed panel is 29" X 95". The collectors were vacuum tested and sealed successfully and then painted black and provided with double glazing and insulations.
- The integrated solar zeolite collectors were tested under actual operating conditions. For this purpose the panels were erected outdoors and completely instrumented. On two separate occasions data was taken manually, every fifteen minutes day and night over a period of three consecutive days. The manual data was analyzed and compared to the automatically recorded input and output data and all equipment was carefully calibrated. The actual experimental results were then compared to the theoretical predictions made by a computer simulation. This comparison is presented in Fig. 1

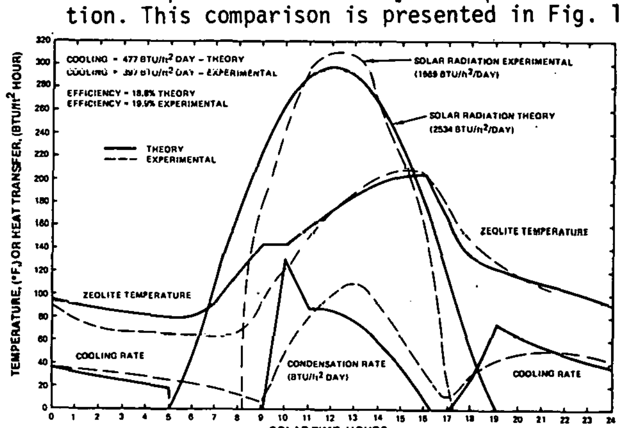

Fig. 1 Comparison of Theoretical and Experimental Collector Performance

and indicates a remarkable agreement between theory and experiment despite the simplifying assumptions which had to be made in the linearized computer model. The predicted cooling efficiency of 18.8% was easily surpassed and presently total daily efficiencies of 25 to 30% are common.

- A sufficient number of integrated solar zeolite collectors were constructed on schedule in order to be able to evaluate their performance under different climatic conditions in different parts of the U.S.A. The collectors were vacuum tested and sealed, then painted black and provided with double glazing, insulating and framing. The collectors were individually tested and their performance recorded with automated instrumentation designed to permit unattended operation for a period of one month.

- Two pairs of integrated zeolite collectors were delivered, installed and instrumented at each of the two selected sites: Tucson, Arizona and Golden, Colorado. A third pair was also installed and instrumented at the plant in Natick, Mass. The site installation and instrumentation was done on schedule and the two collectors at each site were provided with a liquid loop and temperature sensors. The instantaneous output of a solarimeter was recorded continuously on an integrating recorder together with the output of a Btu meter connected in the liquid loop.

- Data from the three test sites is being collected and analyzed continuously. The total overall heating and cooling efficiencies of the collectors on sunny days are between 25 and 30%. For example, the output vs. input heating curve for Tucson, Arizona derived from the February 1981 data is presented on Fig. 2. For inputs

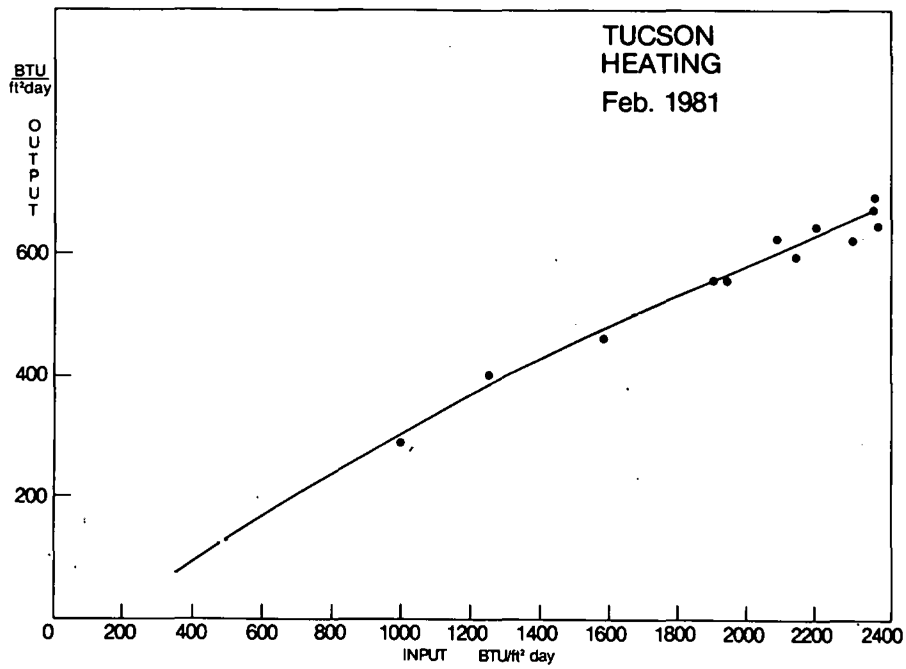

Fig. 2 Heating Output for Tucson, Arizona February 1981

above about 1000 Btu/ft^2 day all experimental paints fall on a straight line of about 30% of total daily collection efficiency.

- The thermal collection performance of the integrated zeolite collector was tested in a manner similar to ASHRAE Standard 93-77. The results, presented in Fig. 3 indicate a slope

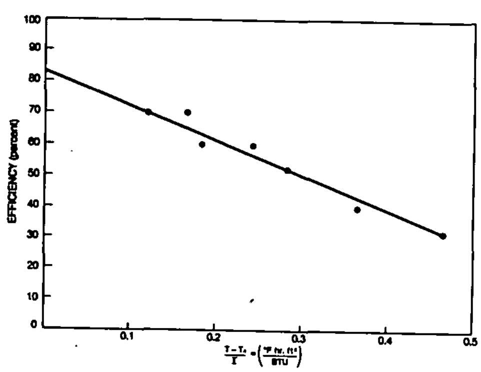

Fig. 3 Collector Thermal Performance per ASHRAE 93-77

F_R (U_L) of 1 Btu/°F ft^2hr and an intercept of 82%. This is an excellent performance by a double glazed collector with flat black paint. It indicates an absorptivity of 97% for the Nextel black velvet paint and a transmission of 92% for each layer of low-iron glass.

- A detailed cost analysis of the present design collector was completed on time. It indicated that material and labor costs were about equal and about 3 times higher than what is anticipated when the panel is mass-produced. The design was then modified to reduce labor costs under mass production.

- Design changes and studies were completed to reduce the material cost of the collector. Since the previous analysis has indicated the large quantity of copper used (5 lb/ft^2) to be a major contributor to the material cost, the effort was on replacing copper with aluminum, whenever good thermal conductivity is required and with iron whenever conductivity was not important. Since both aluminum and iron corrode under normal operational conditions, a new effort for corrosion protection was launched and is progressing very well.

- Samples of aluminum coated with HERESITE P-413 were successfully tested under accelerated conditions for over three months and exhibited excellent corrosion protection. The same is true for iron samples, electrolytically plated with 0.0003" to 0.0007" thick layers of copper.

- It was established that fiberglass-reinforced epoxy is satisfactory as packaging material. One collector was constructed utilizing this packaging technique. It is expected that this method of packaging will reduce the cost of the collector by almost $10/ft^2$.

FUTURE ACTIVITIES

The first full scale residential system utilizing the integrated solar zeolite collector is being built with private funds in Denver, Colorado. The residential building has over 4000 ft^2 of floor space and it will use 39 zeolite collectors of 640 ft^2 net collection area. The system is expected to be completed on time for performance testing during the cooling season - summer of 1981.

The office of the governor of the state of Arizona has offered to contribute $50,000 for the second full scale system in the U.S.A. which uses the zeolite collector. The system will consist of 60 integrated zeolite collectors with a total collection area of 984 ft^2 and will be installed on a residence with 4000 to 5000 ft^2 floor space. At this time final negotiations are being conducted with builders, intallers in the Phoenix, Arizona area and with the Salt River Water Authority, a local utility, to determine the exact location, ownership, etc. of the demonstration house.

The integrated solar zeolite collector will be presented to the public at the ISES Meeting in Philadelphia, PA at the end of May 1981. For this purpose, it will be displayed at the exhibit, together with the solar refrigerator, at the booth of The Zeopower Company. In addition, a paper describing the collector and its performance has been accepted and will be presented at the technical meeting at Philadelphia, PA.

Test and evaluation samples of the integrated zeolite collector have been purchased and delivered to places as far as Italy and Japan. Further orders for additional sample quantities have been received from the Middle East and African countries. It is expected that because of higher energy costs abroad, the overseas market for the zeolite collector will be at least as large as the U.S. market by 1985.

PUBLICATIONS/REPORTS

Integrated Solar Zeolite Collector, Annual DOE Contractors' Review Meeting, March 1980

The Use of Zeolites for Solar Cooling, Fifth International Conference on Zeolites, June 1980

Integrated Solar Zeolite Collector for Heating and Cooling, Annual Conference and Exposition of the International Solar Energy Society, May 1981

Final Report for Contract No. DE-AC03-78CS32117 for the period September 25, 1978 to September 24, 1980

CONTRACT INFORMATION

START DATE 9/25/78 END DATE 9/24/81 CONTRACT VALUE $519,035

MILESTONES

Item:	Due date:
1. Three pairs of collectors to sites in Arizona, Colorado and Massachusetts, delivered when due	August 1980
2. Final report for the first two years	May 1981
3. Final report for the third year	September 1981
4. Remaining four integrated zeolite collectors, to be delivered to SERI, Golden, Colorado	July 1981
5.	

Section 4: SOLAR HEAT PUMP SYSTEMS

4

THE DOE SOLAR ASSISTED HEAT PUMP PROGRAM: ITS EVOLUTION AND ITS POTENTIAL*

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ABSTRACT

Progress in the U.S. Department of Energy's (DOE) Solar Assisted Heat Pump (SAHP) program is described in terms of the progressive modification of original assumptions on the basis of accumulating experience. The ways in which these modifications have led to enhanced system potential are explained. A major impetus for progress has been the assimilation and reconciliation of divergent systems analysis results. Technical accomplishments in the program to date are described, and needed future activities are listed.

BACKGROUND

The SAHP program in the United States began in 1976 at the time of the formation of the United States Energy Research and Development Administration, forerunner of the present DOE. The fundamental idea of the SAHP system is to collect solar energy at temperatures too low for direct use in space heating, and to use this heat as a thermal source to the evaporator of a heat pump, which processes the heat to the load at a higher temperature. The intent of the concept is to improve the efficiencyof both the solar collector and the heat pump by operating in the 5 to 40 C temperature range, which is low for a solar collector (relative to collectors used for direct space heating) but high for a heat pump (relative to air-source heat pumps). The efficiency of a solar collector increases as its operating temperature is lowered, while for a heat pump the potential exists for increasing efficiency by raising the source temperature. The system concept envisioned at the program's inception rested on five fundamental premises. These were:

1) The special heat pump required for SAHP systems could be developed. The SAHP concept required the redesign of the heat pump to take advantage of these source temperatures, since currently available water-source heat pumps did not achieve the continuously rising coefficient of performance (COP) with rising source temperature that one would expect from the Second Law of Thermodynamics.

2) The special low-cost SAHP collectors could be developed, but collectors intended for higher-temperature applications were inherently more expensive because of the smaller thermal losses required.

3) The system would not require significant amounts of backup heat. It was thought that sufficient area of low-cost collectors could be provided to prevent the heat pump from becoming starved for heat from storage under normal operating conditions.

4) The performance of the system in the cooling mode would be enhanced. This performance improvement was projected on the use of parts of the solar system, such as storage, in cooling.

5) Utility interaction was not a significant concern for SAHP systems.

Only the first of these assumptions has been relatively unambiguously verified. The modifications which have been required in the remaining ones, as a result of work performed in the SAHP program, have led to systems with enhanced capabilities, but they have also led to significant changes in the system configurations, as explained below.

In the course of an investigation of solar collector requirements for SAHP systems, a low-cost collector was conceived which uses thin-film materials in both the absorber and glazing. Originally intended as a low-temperature collector for use as a heat pump source, it soon showed potential as a medium-temperature collector capable of direct space heating and even desiccant and absorption air conditioning applications. Such a development has to have an impact on system optimization. It rerequired a modification of the second assumption, but in a positive way not dreamed possible at the beginning of the program.

System simulation, both at Brookhaven National Laboratory (BNL) and elsewhere, showed that the third assumption (concerning backup heat requirements) was untenable. With a view to avoiding thermal starvation of the heat pump under conditions of high heating load and low insolation, an investigation of the ground as an alternative source of heat or storage element was begun. It soon became evident that such use of the ground, or "ground coupling" could exist on its own, without active solar input, and so the question became, not "Can ground coupling help a solar assisted heat pump system?", but "Can solar help a ground-coupled heat pump system?" Such a question, of course, implies economics as well as thermal considerations. Here too, a development with very favorable implications has forced a reevaluation of systems.

In the original system concept cooling was to be accomplished by rejection of air-conditioning waste heat to storage during the day, with subsequent cooling of storage by rejection to the cool nighttime ambient via a fan-coil unit. While it is possible that this concept may have merit in some climates, the emphasis on ground coupling has led to consideration of the ground as a heat sink for cooling as well as a heat source for heating. Ambient ground is cooler than ambient air in the summer time, but ground temperatures are driven up by continued rejection of heat into a restricted volume. Performance improvement does result if the ground coupling device is not too small. Another

*Work performed under the auspices of the Active Solar Heating and Cooling Division, U.S. Department of Energy, Contract No. DE-AC02-76CH00016.

possibility under investigation is that collectors can be used as rejectors to share the cooling load with the ground coupling device. In any case, the validity of the fourth assumption is highly dependent on system configuration.

The fifth assumption has been completely reversed and utility interaction is now considered to be of very high importance. Considerable work on the utility impact of ground coupled systems indicates that the use of ground coupling can improve a utility's load factor, whereas resistance backup degrades it. This is because with resistance backup the utility must stand ready to meet the design load of the building with electric heat at times when solar storage is depleted and the ambient temperature is low. The cost of this standby capacity - coupled with low electric energy sales to the solar residence because of its high efficiency under most conditions - results in a high unit price for electricity to the solar residence if it is not to be subsidized by other users.

With ground coupling, the heat pump can be sized to meet the design load of the building at the minimum ground source temperature. The point is that the ground temperature does not drop suddenly with the air temperature during periods of extreme cold but maintains a predictable minimum which is much warmer than the design minimum air temperature. Thus no backup is required and the maximum demand on the utility is the design load divided by the minimum heat pump coefficient of performance (COP).

Each of these developments has had its impact on systems thihking, with a resulting sifting of system configurations which has yet to run its course. The current outlook can however be stated. The solar/heat pump system configurations of greatest promise appear to be the following:

1) A modest amount of direct-gain passive meets about a quarter of the heating load, supplementing a ground-coupled heat pump which supplies the remainder of the heating load, the hot water, and cooling.

2) Active solar energy is combined with ground coupling, with long term in-ground storage of heat on the order of months up to annual, the ground serving to buffer the storage element against thermal starvation at times of high demand and low insolation. Examples of such systems are the Kaman Sciences buried-tank system, the FAFCO system with buried plastic plates and collector/rejectors, SAHP's using a swimming pool as the storage element, the BNL ground-coupled ice tank, multi-family ground coupled SAHP's with large-volume storage, and heat-pump-based solar ponds.

3) Active solar energy is used as input to a heat pump in systems which use some means other than ground coupling to avoid electric resistance backup. Examples of such systems are bivalent SAHP's (fossil fuel backup); gas-fired SAHP's; SAHP's for industrial process heat (year-round utilization); commercial building thermal loop SAHP's; and solar heat-pump-based community energy systems.

4) Photovoltaics are used to provide electric energy to operate the heat pump.

These options are listed in order from shortest to longest term potential.

SUMMARY

Activities in the program can be divided into the three major subsystem areas - heat pump, collector, and storage - and also activities encompassing the entire system. In the heat pump area, the potential for high heat pump COP's at solar source temperatures was demonstrated in the face of considerable initial skepticism; and a marketable prototype heat pump was fabricated which met the program goal of a COP of 6 at 90^{o}F entering water temperature. In the collector area, a low-cost collector design using thin-film polymeric materials in both the absorber and glazing was developed, fabricated, and tested. In the area of storage, four types of in-ground heat exchanger configurations were tested (horizontal pipe coil, vertical sealed well, buried tank, and buried plastic plate); and a TRNSYS-compatible computer model of in-ground heat flow was developed and validated against experimental data. In the system area, a plethora of SAHP system simulations were compared, analyzed and synthesized; system analyses of certain ground-coupled solar heat pump configurations were carried out; and cost/performance goals for solar and ground-coupled heat pump systems were veloped.

TECHNICAL ACCOMPLISHMENTS

- Demonstrated High COP Potential. Measurements carried out at BNL as well as at Northrup and Lennox have showed that electric powered vapor compression heat pumps can attain impressive COP's at high source temperatures. The keys to the attainment of high COP's in heat pumps are capacity control in the compressor(s), a condenser which is large relative to the compressor, and an expansion device capable of controlling superheat over a wide range of mass flow rates. Northrup pioneered the use of rotary compressors, which provide a COP edge over reciprocating compressors as well as motor unloading at high source temperatures.

- Fabricated High COP Heat Pumps. Northrup completed and delivered to BNL for testing a prototype dual-compressor heat pump. The characteristics of this heat pump and the test results are described in the accompanying paper on the BNL hardware simulator. Northrup retained a second prototype which is currently undergoing system tests. Lennox has fabricated a heat pump based on their two-speed compressor; this machine is currently undergoing testing at Lennox and should be on test at BNL by the time these proceedings are published. These are both residential-size machines. Dunham-Bush Incorporated is fabricating a multiple-slide screw compressor for commercial-size ($\sim$ 25 ton) applications with the possibility of later downsizing.

- Designed, Fabricated, and Tested Thin-Film Collector Prorotype. A collector concept utilizing thin-film polymeric materials in both the absorber and glazing, bonded to a bent metal frame, was developed at BNL. Central to the design is a lightweight, durable, long-life absorber using a laminate of aluminum foil and a thin-film polymer. A prototype tested at the Florida Solar Energy Center showed performance characteristics better than those of the average all-metal collector. Further work indicates the potential of the collector for applications up to the 150 to 200^{o}F temperature range, including desiccant and absorption air conditioning.

- Tested Four Types of In-Ground Heat Exchanger. Work under the program has been carried out at BNL (horizontal pipe coil, vertical sealed well, buried tank); E-Tech Incorporated (horizontal pipe coil); FAFCO Incorporated (horizontal pipe coil, buried plastic plate); Kaman Sciences Corporation (buried tank, buried plastic plate); and Oklahoma State University (horizontal pipe coil, vertical sealed well). Thermal performance and cost data were obtained which were generally consistent. Both wintertime heat extraction and summertime heat rejection were performed, and the appropriateness of various configurations for storage was investigated. Continuing liaison with European ground-coupling work has been maintained.

- Developed and Validated a TRNSYS-Compatible Ground Coupling Computer Model. The finite-element computer model GROCS was developed at BNL and later incorporated into a TRNSYS-compatible subroutine package. These programs have been run and compared with experimental data at BNL and at other ground-coupling sites such as Oklahoma State and FAFCO. In addition, approximately 35 copies of the card deck and user's manual have been sent upon request to laboratories around the world.

- Compared and Synthesized SAHP Systems Studies. Systems analyses performed by BNL, by SAHP contractors, and by other laboratories under contract to DOE gave apparently divergent results and stimulated lively debate. Two major areas of agreement have been reached which serve to clarify much of this controversy:

1) Electric resistance is a bad backup to SAHP systems and must be avoided;

2) Cost reduction from current standard solar technology, both in the collector and in the balance of system, is required and must be consistent with maintaining acceptable performance and system life.

These statements are equally applicable to active solar space heating systems which do not employ heat pumps.

- Analyzed Ground-Coupled Solar Heat Pump Systems. An analysis of ground coupled solar heat pump systems which use the ground as source and sink but not as storage was carried out at BNL. Analyses of the potential of the ground as an active storage element for solar energy have been performed at BNL, Oklahoma State, and Kaman Sciences. FAFCO is carrying out analyses of SAHP systems with emphasis on the potential for cooling performance enhancement. A set of cost/performance goals for solar and ground coupled heat pump systems was developed at BNL on the basis of payback, cash flow, and life-cycle costing.

FUTURE ACTIVITIES

The following activities have been identified as integral to the completion of the DOE SAHP program.

1) test prototype heat pumps developed by SAHP contractors;
2) explore means for further COP improvement;
3) evaluate fuel-fired and absorption heat pumps;
4) optimize preferred ground-coupled heat exchange devices;
5) advance design thin-film collector;
6) determine need for collector-rejector, and, if needed, perform advance design;
7) perform component field tests of heat pumps and collectors;
8) complete in-ground storage analysis;
9) complete assessment of cooling mode impact on SAHP system configuration;
10) optimize hot water production;
11) develop means for balance-of-system cost reduction;
12) assess non-technical barriers to SAHP system preliferation;
13) perform field tests of preferred systems;
14) develop system design guidelines and sizing tools.

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LOW COST SOLAR FLAT PLATE COLLECTOR DEVELOPMENT*

BROOKHAVEN NATIONAL LABORATORY

WILLIAM G. WILHELM

CONTRACT NO. DE-AC02-76CH00016

OBJECTIVE

The project objectives have been to identify cost goals for solar energy collectors consistent with competitive economic advantage for space heating systems and to develop solar collector designs consistent with these cost goals.

DESCRIPTION OF WORK

The initial part of the work performed over the last three years established the need for low-cost solar collectors as a critical factor in stimulating a solar industry and in promoting a solar space heating market in the interest of displacing fossil fuel usage. This early analysis placed a fairly severe constraint on collector and system cost based on considerations of payback and cash flow as well as life-cycle costing. Manufacturing costs for the collector of ~ $11/m^2$ ($1/ft^2$) and installed costs of ~ $55/m^2$ ($5/ft^2$) were indicated as necessary goals. We were unable to find commercial products with these characteristics. This led to an in-house effort to identify solar collector designs consistent with these goals.

The work performed over the last two years has demonstrated the potential for polymeric material in solar collectors. The advantages of these materials include very low cost, high performance, and durability sufficient to provide a life cycle value well in excess of initial cost.

The very low cost of these collectors is derived from a design which permits very thin material to be incorporated into the construction of the collector. This is assomplished through the use of laminate technilogy, high performance polymer film, and a non-pressurized liquid absorber. The mass production of this kind of collector is expected to yield a factory cost of $13/m^2$ and possibly less (see Table 1).

The most significant component of the design is the absorber heat exchanger (Figure 1). This unique component design differs from conventional absorbers by the dramatic reduction in material required and the method of liquid transport through it. Conventional absorbers are of heavy metal construction and require some pressurization to function. The laminate absorber illustrated is made with thin polymer film and aluminum foil for a strong water-tight envelope that requires no pressurization. The absorber functions in a flow-back mode. In operation, water is pumped to the upper portion of the absorber and is permitted to flow naturally back down through the absorber envelope and piping to storage.

Table 1
MANUFACTURING COST BREAKDOWN FOR FLUOROPLASTIC FILM SOLAR FLAT PLATE COLLECTOR PANEL WITH SINGLE WINDOW AND OPTICAL SELECTIVE ABSORBER (3 m^2 or 32 ft^2 PANEL)

FRAME (GALVANIZED STEEL) 26 GAUGE, 4' X 8' @ $0.10/ft	$ 2.40
WINDOW FILM - "TEDLAR PVF" (0.004 in.) @ $0.28/ft^2$	8.96
ABSORBER 2 - "TEFZEL" (0.001 in.) each @ $0.22/ft^2$)	14.08
2 - ALUMINUM FOIL (0.002 in.) each @ $0.028/ft^2$)	1.79
ABSORBER COATING (SELECTIVE PAINT) @ $0.02/ft^2$	0.64
LIQUID COUPLING 4 - @ $0.10	0.40
BONDING AND EXTRANEOUS HARDWARE (EST.)	0.50
INSULATION (HIGH TEMP. STRUCTURAL FOAM)	3.20
PRODUCTION AND LABOR	1.10
SUBTOTAL	$33.07
ADD 15% ADDITIONAL OVERHEAD FOR WASTE AND OTHER COSTS	4.96
TOTAL	$38.00
OR ($13/$m^2$)	$ 1.19/ft^2

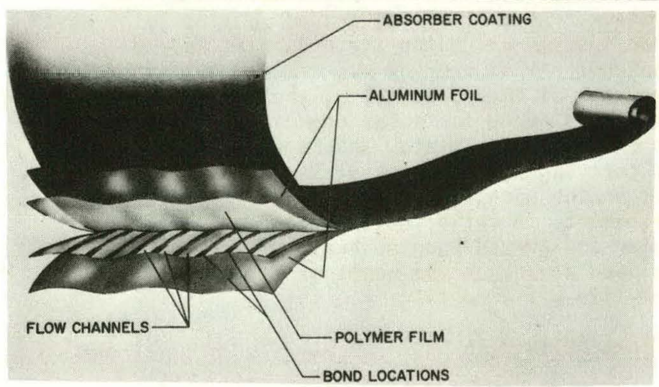

Figure 1. Solar Absorber, with Laminate Detail

The polymer film in the laminate absorber forms the flexible water barrier and the foil contributes structural stability and lateral heat transfer. The black surface that absorbs the sun's radiation can be printed onto the foil. The total thickness of the laminate absorber is 0.15 mm (0.006 in.) and can be manufactured for about $5/m^2$ ($0.50/ft^2$). The polymer film used in the absorber (Teflon PVF) is continuously tolerant to temperatures up to 400°F and has very high chemical stability for very long life.

Other design properties which contribute to low cost are the use of polymeric film in the collector window (Tedlar PVF); the use of monocoque contruction in which the absorber and glazing act as stressed "skins" which add structural strength to the frame; and the use of high speed manufacturing techniques. Figures 2 and 3 show some details of panel construction.

*Work performed under the auspices of the Active Solar Heating and Cooling Division, U.S. Department of Energy, Contract No. DE-AC02-76CH00016.

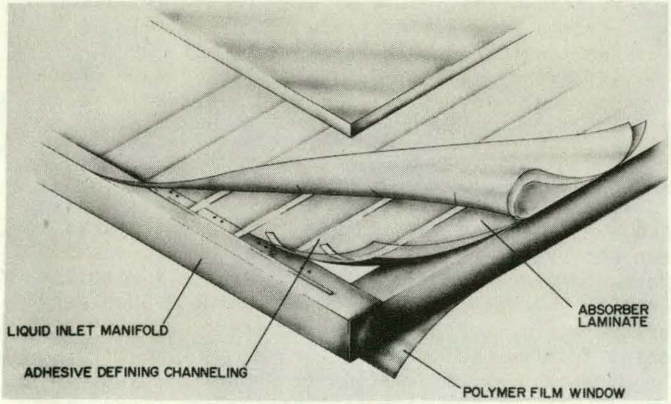

Figure 2. Collector Manifolding Detail

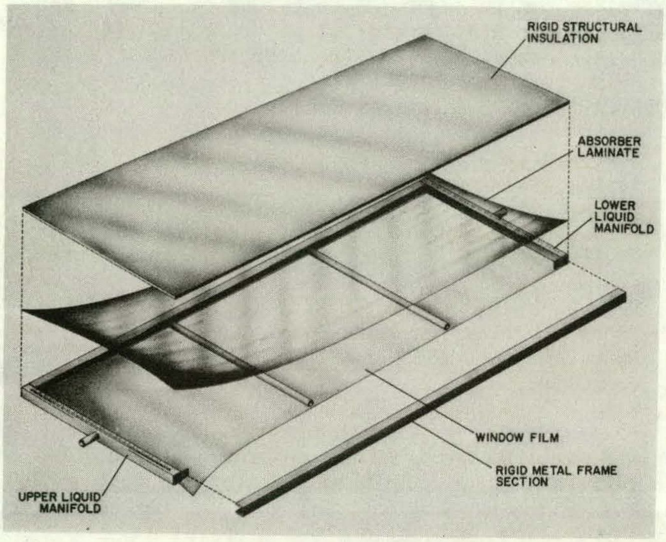

Figure 3. Exploded view of Panel Construction

The absorber is designed for rapid fabrication in volume using techniques common in the converting industry (Figure 4). Completed panels are sufficiently light in weight that 10 m^2 (100 ft^2) could be carried to the roof in a bundle and installed as a unit (Figure 5).

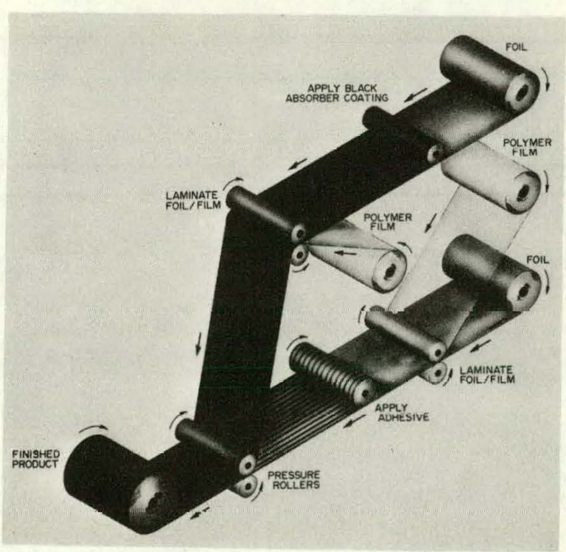

Figure 4. High Speed Production of Absorber

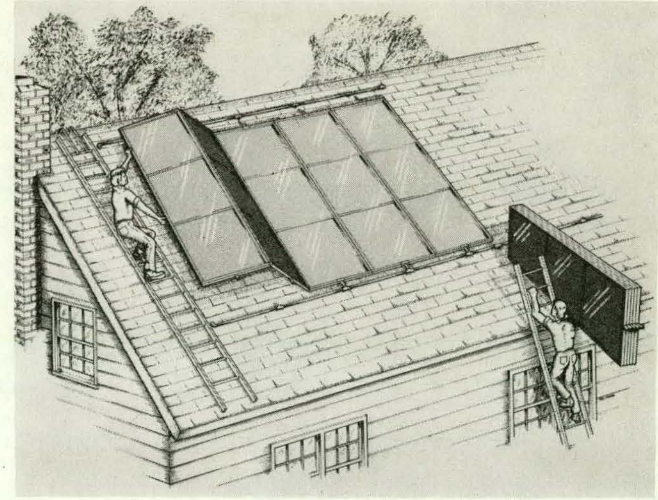
Figure 5. Installation of Five-Panel Units on Roof

TECHNICAL ACCOMPLISHMENTS

- Developed cost goals for the collector which led to the rejection of conventional approaches and to the exploration of thin-film technology. The approach taken in this analysis was to consider reasonable average values for collectable thermal energy, acceptable payback periods, and plausible fuel cost excalation rates. It was concluded that the incremental system cost should not exceed about ten times the first year's energy savings. This conclusion was supported by later consideration of cash flow and life-cycle costing.

- Invented a thin-film solar absorber suited for high-speed continuous-roll manufacture at low cost. The absorber comprises two sheets of aluminimum-foil/polymeric-material laminate bonded together at intervals to form channels. The two surfaces of polymeric material face each other, and the water which serves as the heat transfer fluid flows between them. The properties of the two materials complement one another. The aluminum foil provides good lateral heat transfer which maintains high efficiency even under incomplete wetting of the absorber and which serves to prevent localized hot spots under thermal stagnation. It also provides good dimensional stability. The polymeric film component provides good tear resistance and serves to protect the aluminum from contact with the water, thus preventing corrosion.

- Fabricated and tested several flat-plate panels, one of which was independently tested at the Florida Solar Energy Center (FSEC). The absorber is incorporated into a completed panel comprising a light metal frame, the absorber film, the glazing film, and rigid back insulation. The two films act as stressed skins which add structural strength to the frame. Several prototype panels have been constructed and tested at Brookhaven National Laboratory (BNL), and one has recently completed testing at the FSEC (Figures 6 and 7).

- Met performance goals. The following performance goals have been met:
  1. Stagnation tolerance to 200°C (400°F);
  2. Efficiency parameters in the FSEC test were vertical intercept $F'\tau\alpha$ equal to 0.75 and horizontal intercept $\tau\alpha/U_L$ = 0.66 °F-hr-ft^2/Btu

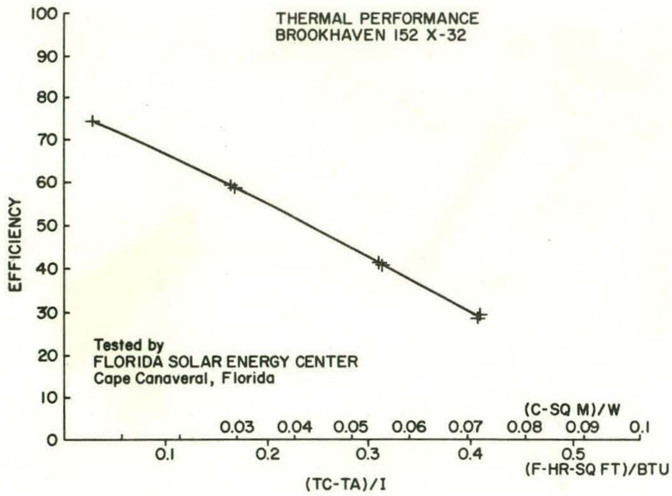

Figure 6. Collector Performance Test Results

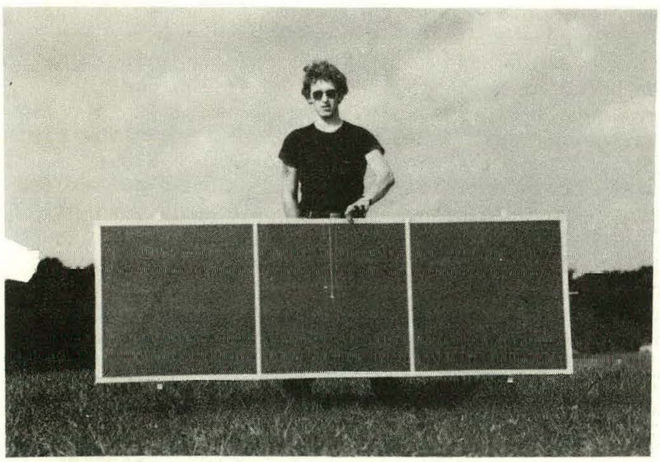

Figure 7. BNL Model "F" Solar Flat Plate Collector (This 20 ft^2 panel weighs 10 pounds.)

(0.12^oC-m^2/W). Some modules tested at BNL reached 0.80^oF-hr-ft^2/Btu (0.14^oC-m^2/W).

3. Panel weight 0.5 lb/ft^2 (2.4 kg/m^2).
4. Efficiency maintained at low liquid mass flow rates of ∿ 0.025 gal/min/ft^2 (0.017 kg/m^2-s).

FUTURE ACTIVITIES

The measured collector performance is highly encouraging. Good wetting and heat transfer have been observed. Collectors tested at BNL have shown thermal performance sufficient to be applied to absorption and desiccant air conditioning. Such performance is a strong function of the control of heat losses from the solar collector and is limited by the upper thermal stagnation temperature which can be tolerated by the materials in the absorber. The upper temperature limit of these materials has given encouragement that, with continued development, the collector can be a good match for space cooling as well as space heating and hot water applications. Such development activity has been proposed.

PUBLICATIONS/REPORTS

1. J.W. Andrews, "Heat Pump Impact Upon Solar Collector Design and Cost," Proc. 1979 ISES Int. Congr., Atlanta, GA, May 1979.
2. J.W. Andrews and W.G. Wilhelm, "Thin-Film Flat-Plate Solar Collectors for Low-Cost Manufacture and Installation, BNL 51124, March 1980.
3. W.G. Wilhelm, "Low-Cost Solar Collectors Using Thin-Film Plastics Absorbers and Glazings," Proc. Am Sect. ISES Ann. Mtg., Phoenix, AZ, June 1980.
4. W.G. Wilhelm, "Flat Plate Solar Collector Utilizing Polymeric Film for High Performance and Very Low Cost," to be presented at the 1981 ISES Int. Congr., Brighton, England, August 1981.
5. W.G. Wilhelm, "Low Cost Solar Energy Collection for Cooling Applications, in preparation.
6. W.G. Wilhelm, "Low Cost Solar Flat Plate Collector Development," Final Report, in preparation.

CONTRACT INFORMATION (FY 1981)

START DATE 10/1/80 END DATE 9/30/81 CONTRACT VALUE $55,000

MILESTONES

Item:		Due date:
1.	Collector Impact Study	5/79
2.	Collector Design Report	3/80
3.	Final Report	9/81
4.		
5.		

SOLAR HEAT PUMP SIMULATOR

BROOKHAVEN NATIONAL LABORATORY

MARK A. CATAN

CONTRACT NO. DE-AC02-76CH00016

OBJECTIVES

The solar assisted heat pump (SAHP) system's potential for energy conservation depends on the heat pump's ability to achieve the high coefficient of performance (COP) that is possible with the high source temperatures which can be supplied by solar energy.

The objectives of the solar heat pump hardware simulator project have been threefold:
1. To demonstrate the possibility of high heat pump COP's to an initially skeptical industry;
2. To explore practical means to realize and enhance this high performance potential;
3. To test prototype heat pumps produced by contractors under the SAHP program.

DESCRIPTION OF WORK

The Brookhaven National Laboratory (BNL) solar heat pump simulator project was begun in 1977 at the inception of the hardware development work by the SAHP contractors, Northrup Incorporated and Lennox Industries Incorproated. The simulator was utilized to provide controlled-temperature sources and sinks to an experimental water-to-water laboratory heat pump test bed. This combination was used to demonstrate and explore the potential of the vapor-compression cycle to deliver high COP's at SAHP source temperatures. Results from the simulator were used in computer simulations of complete systems performed by BNL, by the SAHP contractors, and by others. The Lennox 2-speed compressor was first tested at high source temperatures on the BNL simulator. In view of the decision by both contractors to construct water-to-air (rather than water-to-water) heat pumps, the BNL simulator was fitted with an air-side test loop. The Northrup prototype heat pump has been tested under steady-state conditions on the BNL simulator, with results reported below. Transient testing of the Norhtrup machine, and testing of the Lennox two-speed heat pump will follow. In addition to the heat pump testing, a concurrent exploration of means for further performance improvements is being pursued in concert with industry.

TECHNICAL ACCOMPLISHMENTS

- Constructed and Operated the Heat Pump Hardware Simulator. At the same time contracts for the development of SAHP's were awarded to Lennox Industries and Northrup Incorporated, construction of a SAHP simulator was undertaken at BNL. The purpose of the hardware simulator is to create a realistic environment for the fast and accurate testing of liquid source heat pumps. The simulator is capable of:
  - testing heat pumps of up to 8 ton capacity
  - testing liquid-to-water or liquid-to-air heat pumps
  - on line data reduction by digital computer
  - simulating source temperatures from -10 to 45 C (14 to 113 F) and load temperatures from 10 to 70 C (50 to 158 F)

The three subsystems of the SAHP simulator are depicted semischematically in Figure 1 as they are

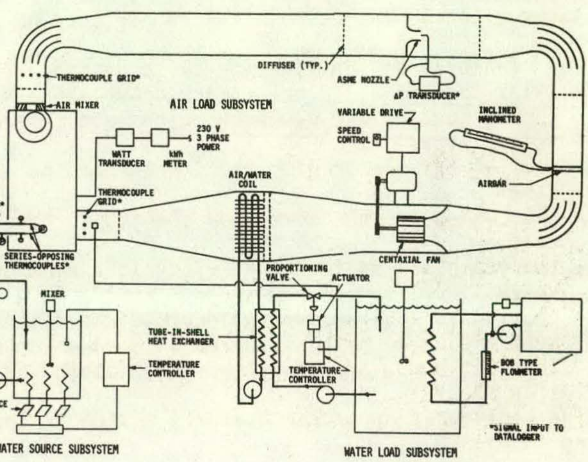

Figure 1. Solar Assisted Heat Pump Hardware Simulator

arranged for the testing of water-to-air heat pumps. The Water Source Subsystem and Water Load Subsystem alone comprise the simulator as it was used for testing an experimental water-to-water laboratory heat pump test bed. The capability for testing liquid-to-air heat pumps was added to the previously liquid based heat pump hardware simulator at BNL by the construction of an instrumented duct system called the Air Load Subsystem. The Air Load Subsystem provides for measurement, and control, of all conditions pertaining to the air side of the heat pump. In the water-to-air testing mode, the Water Load Subsystem is used by the Air Load Subsystem to withdraw heat from the heat pump's supply air via an air/water coil, at a rate which is controlled to keep the temperature of the air returned to the unit at a constant temperature (usually at residential space temperatures of 20 to 21 C (68 to 70 F). All instrumentation and procedures follow closely the recommendations of ASHRAE.[1]

- Demonstrated the Potential for High COP at Solar Source Temperatures. At the same time construction

*Work performed under the auspices of the Active Solar Heating and Cooling Division, U.S. Department of Energy, Contract No. DE-AC02-76CH00016.

of the simulator was begun, construction of a residential size experimental water-to-water solar heat pump was undertaken at BNL to be tested with the simulator to explore the details of the vapor compression cycle at high source temperatures and establish performance goals. The Laboratory Model Heat Pump employed components and controls which allowed it to operate effectively at high source temperatures. It used a variable speed compressor, heat exchangers that were large relative to the compressor, specially selected thermal expansion valves, and a receiver. The original open type Dunham-Bush compressor was later replaced with a Lennox 2-speed hermetic compressor to obtain performance results needed by Lennox Industries in their SAHP development effort. The tests of the Laboratory Heat Pump demonstrated that very high COP's are attainable, exceeding 9 at entering temperature (EWT) of 43 C (110 F), with motor unloading obtained at low speed.[2,3] All components behaved well and no detrimental effect to the compressors were noted.

- <u>Tested the Northrup Prototype Solar-Source Heat Pump.</u> A prototype SAHP has been delivered by Northrup Incorporated to BNL as part of a U.S. Department of Energy (DOE) sponsored SAHP development contract. The prototype has been tested on the BNL SAHP simulator with the recently installed Air Load Subsystem.

Features of the final Northrup design are:

- 1-1/2 ton and 2-1/2 ton rotary compressors with common suction and discharge lines and separate accumulators
- coaxial evaporator with refrigerant in the inner line
- the condenser is a three row slanted air-cooled coil
- the expansion device is an electric expansion valve
- Cooling is achieved via a separate water/air heat exchanger which receives chilled water from the heat pump, the condenser being cooled by outside air.

The configuration of the Northrup system is depicted in Figure 2.

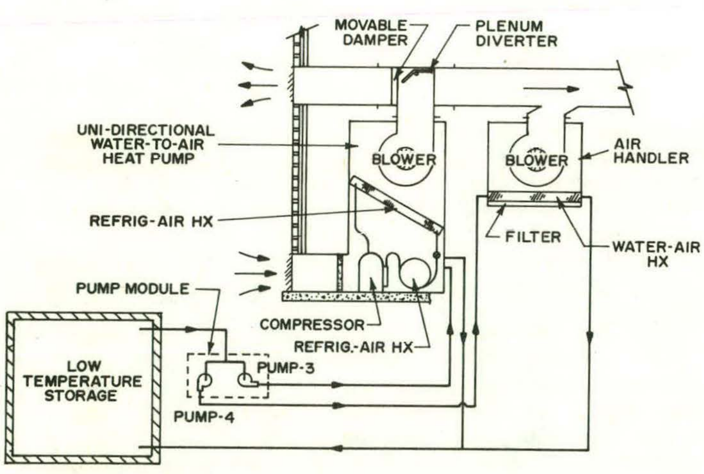

Figure 2. Northrup SAHP System

The conditions under which the heat pump was tested were staggered to minimize the appearance of extraneous trends in the data. Test conditions for which Northrup supplied data were duplicated. Steady state was ensured by allowing the unit to run for thirty minutes after target temperatures and flow rates were established.

Figures 3 and 4 show the Northrup test results and the BNL test results in superposition.[4] The

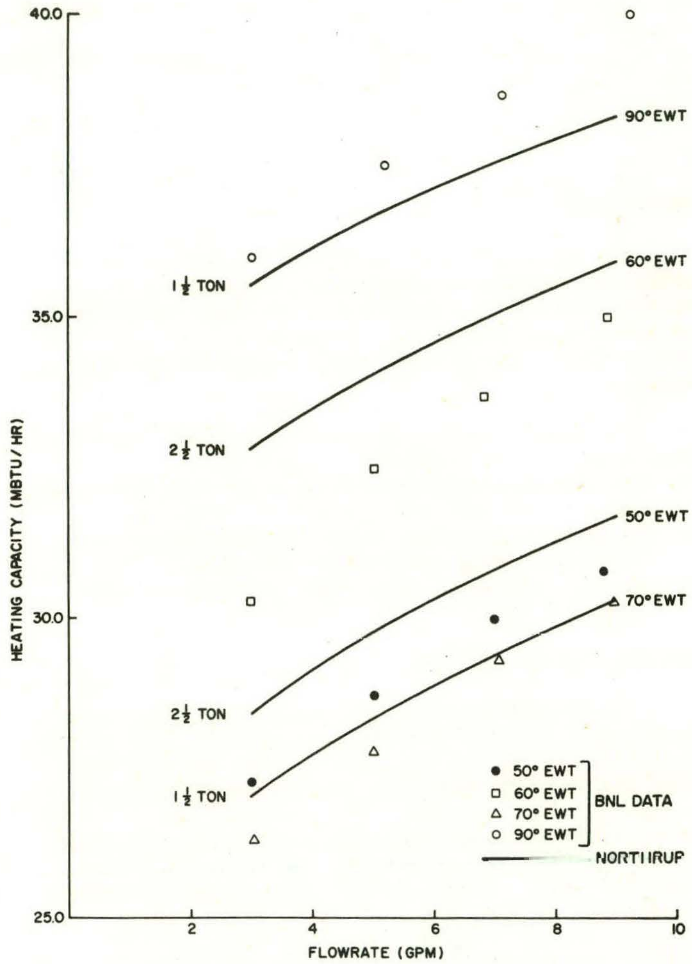

Figure 3. Heating Capacity vs Flowrate for Four Values of Entering Water Temperature (EWT) - Northrup and BNL Test Results

greatest discrepancy between the two heat capacity results amounts to less than 10%. The COP data are in excellent agreement. The contribution of the heat pump fan was not included in calculation of heating capacity and COP. Fan power requirement was approximately 300 watts, water pumping power requirement was approximately 150 watts at 30 L/m (8 gpm) (the latter from measured pressure drop and assumed 50% efficiency).

A nominal goal of a COP of 6 at 32 C (90 F) entering water temperature was set for the SAHP program contractors. Northrup claimed to have reached this goal. The results presented here show that this goal has been approximately attained with the prototype. Since the prototype is of a design which may be readily manufactured, these results are encouraging to the DOE program.

FUTURE ACTIVITIES

In order to predict the seasonal performance of the Northrup prototype SAHP the unsteady state behavior of the unit will be determined via further

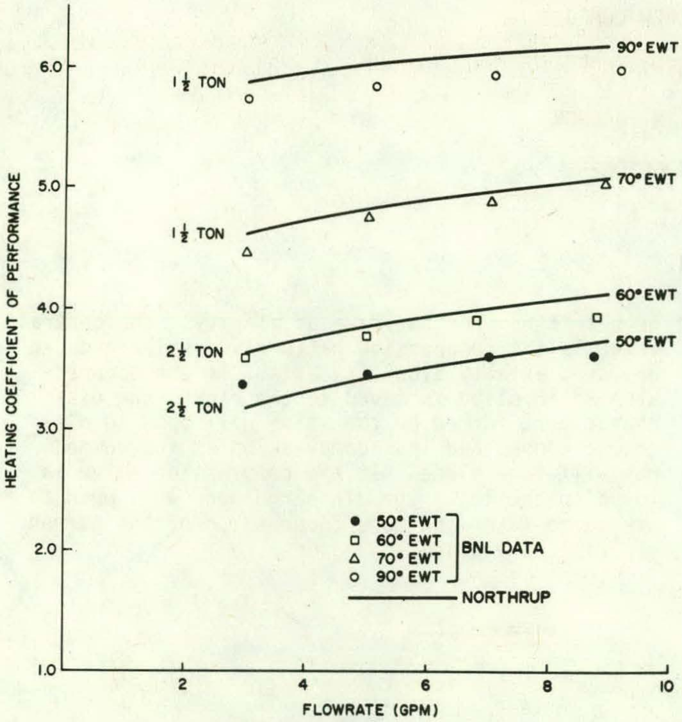

Figure 4. COP vs Flowrate for Four Values of Entering Water Temperature (EWT) - Northrup and BNL Test Results

tests on the simulator. The simulator will be modified so that room air will be drawn into the unit, supply air being cooled and vented into the test room. This will allow constant temperature air to be drawn into the unit during the start up period of the heat pump. The data acquisition system scanning rate will be increased to increase the temporal resolution of the performance data. The heat pump will be operated at various cycle rates and with various entering water temperatures. The benefit of allowing the heat pump fan to run longer than the compressor to distribute residual heat in the condenser will be assessed. The unsteady state test data will then be used in computer simulations to determine the performance potential of the Northrup SAHP.

The Lennox prototype SAHP will arrive in mid-1981. It will be tested in a fashion similar to that by which the Northrup was tested. The air load subsystem will not be a closed loop because unlike the Northrup unit cooling is done in the refrigerant/air coil of the unitary machine requiring air humidity pretreatment and measurement.

Several manufacturers have been invited to participate in a heat pump component optimization study whose objective is to identify heat pump components, particularly heat exchangers, which promise to make further performance improvements possible in practical water-source heat pumps. There will be two parallel paths to this effort. One will emanate from experimental and computer analytical studies and be directed toward the detailed characterization of total SAHP system performance. The other path will be a program of experimental heat pump component studies employing the simulator and the experimental laboratory heat pump to test existing and experimental components and control strategies. The two programs will share salient results, eventually leading to a clearer view of what SAHP systems are the most capable of exploiting the potential of the vapor compression cycle, and the heat pump configurations that are most suited to those systems. Eight manufacturers have demonstrated interest in this program. They represent a wide range of heat exchanger products and several novel approaches to linking the heat pump with the solar heat storage element have been suggested.

REFERENCES

1. ASHRAE Standard 37-38: Methods of Testing for Rating Unitary Air Conditioning and Heat Pump Equipment. Also ASHRAE Standards 41.1-74, 41.5-75, 41.7-78, 41.8-78.
2. Kush, E., "Experimental Study of a Series Solar Heat Pump," Proc. 4th Ann. Heat Pump Conf., Oklahoma State Univ., Stillwater, OK, April 1979.
3. Kush, E., "Performance of Heat Pumps at Evaporating Temperatures with Application to Solar Input," ASME J. of Solar Energy Engr., August 1980, pp. 203-210.
4. Catan, M. and Kush, E., "Results of Tests of a Prototype Solar Assisted Heat Pump," Proc. of 16th Ann. IECEC, Atlanta, GA, August 1981.

CONTRACT INFORMATION (FY 1981)

START DATE 10/1/80 END DATE 9/30/81 CONTRACT VALUE $175,000

MILESTONES

Item:		Due date:
1.	Determine High COP Potential	3/79
2.	Test 2-speed Compressor in SAHP	4/80
3.	Test Northrup Heat Pump	7/81
4.	Test SAHP Heat Exchangers	9/81
5.	Test Lennox Heat Pump	12/81

MULTIPLE SLIDE SCREW COMPRESSOR

DUNHAM-BUSH, INC.

JOSEPH A. L. N. GAGNON

DE-AC03-79CS30035

OBJECTIVE

The objective of this project is to develop the best possible compressor for use in Series Solar Heat Pump Systems. The compressor must be able to operate at extremely high efficiency levels from a compression ratio as low as 1.5 up to a compression ration as high as 6.5. The compressor must have the capability to efficiently adjust to the widely varying inlet flow requirements as dictated by the operating conditions of the Series Solar Heat Pump System.

DESCRIPTION OF WORK

In order to commercialize the solar assisted heat pump concept, it is necessary to develop high compression efficiencies over a wide range of operating conditions. The program is intended to demonstrate the potential of advanced concept helical screw compressors for that purpose up to a maximum of 25-ton heating capacity.

Presently, there are no compressors on the market that can obtain the performance level estimated herein for a two-speed, vapor-injected 25-ton helical screw compressor.

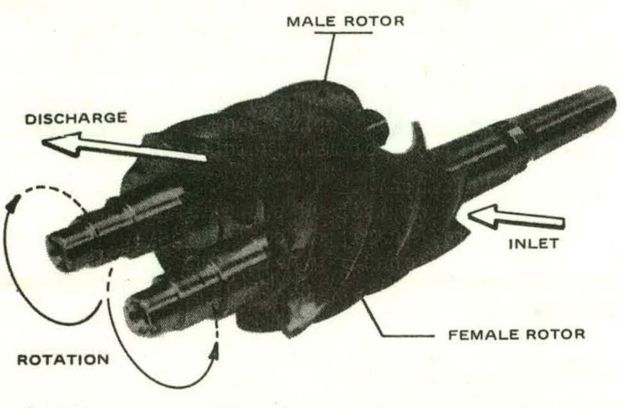

Figure 1. Helical Screw Rotor Set

Explanation of Fig. 1. In Fig. 1, compression of the vapor is started at the top rear of the diagram and high pressure discharge vapor exits as shown in the top front. The right hand rotor rotates in a counterclockwise fashion, whereas the left hand rotor rotates in a clockwise fashion as shown on the diagram.

Explanation of Fig. 2. To show in detail the discharge port and the suction bypass ports, Fig. 2 is shown in a different orientation than Fig. 1. In this figure, the inlet is at the top right while discharge is at the bottom left. The rotors have been left out for the sake of clarity. The central valve is the compression ratio slide valve and can be moved axially along its axis. If the compression ratio slide is moved to the right, the discharge port formed by the valve will open to discharge sooner and less compression of the pumped gas will take place. If the compression valve is moved to the left, the discharge port will open to discharge later and more compression of the pumped gas will take place.

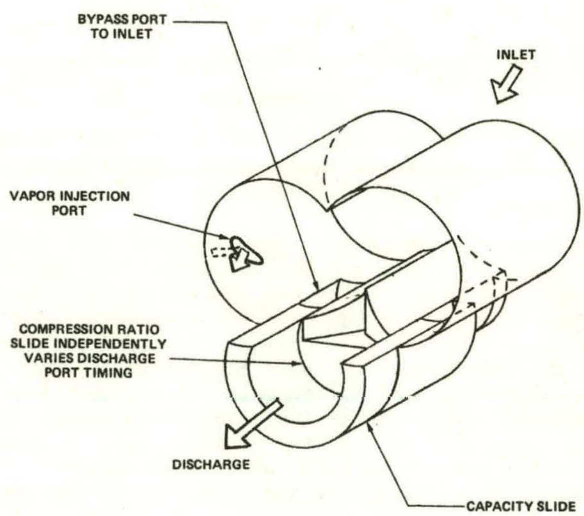

Figure 2. Potential Slide Valve Concept

Also shown in Fig. 2 is a capacity slide. The method demonstrated is called suction bypass. That is, during part load operation a portion of the gas taken in the inlet port is allowed to return back to the inlet before any appreciable work is expended on it. If the capacity slide is moved axially to the right, the bypass ports will be sealed and full capacity operation will result. As the slide moves to the left, the bypass ports progressively increase in size which progressively reduces the compressor capacity.

Also shown in Fig. 2 is a vapor injection port which will allow the near-ideal liquid expansion process as shown in Fig. 3. This port will also allow the compressor to accept vapor from an evaporator that is operating at a higher pressure level than that evaporator that is feeding the compressor suction. This means that the compressor has the ability to accept energy simultaneously from two different sources. An example of this would be a lower level ground source and a higher level solar source.

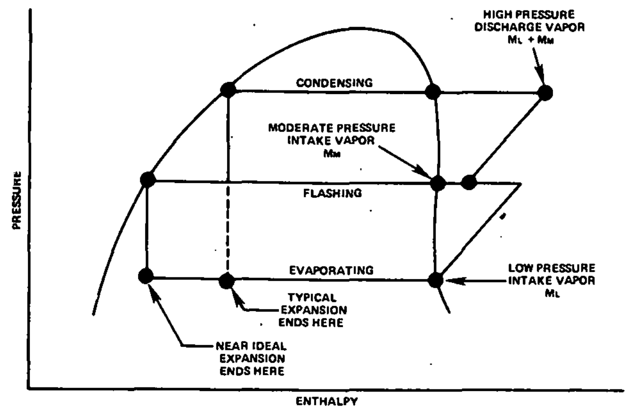

Figure 3. Pressure-Enthalpy-Diagram

Explanation of Fig. 3. Fig. 3 demonstrates one of the advantages of the injection port. In a typical pressure enthalpy diagram, condensing takes place as shown. In a conventional system, the condensed liquid then passes through some type of expansion device before entering the evaporator. The conventional process is constant enthalpy and therefore appears as first a solid and then a dashed line on the diagram. Obviously, a considerable amount of flash gas is generated during this expansion process and this flash gas must enter the evaporator and accomplishes no useful refrigeration effect. Yet, in the conventional process, this flash gas must be compressed all the way from the lower evaporating level up to the condensing level thus consuming compression energy with no useful benefit at all. With the injection port, we can allow a process as shown. The condensed liquid from the condenser, instead of being flashed all the way down to the evaporating level, is now flashed approximately half way down (considering temperature differential between condensing and evaporating). The flash vapor thus generated is separated and injected into the compressor by the injection slide at the appropriate point along the compression process. The temperature of the remaining liquid has now been reduced to the pressure corresponding to the flashing pressure. There are two ways to look at the thermodynamic cycle advantages of doing this. As can be seen from the diagram, a considerable increase in refrigeration effect is seen with the near-ideal expansion as compared to the typical expansion. This increase in refrigeration effect has been gained at no additional mass flow required by the compressor at its low pressure intake point. What has occurred is that a moderate amount of flash vapor has been generated at a moderate pressure as shown in the diagram. This flash vapor now enters the compressor after compression has already progressed significantly and therefore only has to be compressed part way up to the condensing level. This cycle as demonstrated is similar to the flash economizer cycle used in most two-stage centrifugal air conditioning systems. Another way of looking at the cycle from the vantage point of heating is as follows. A typical cycle would have compressed an amount M_L as shown all the way to condensing level. The heating effect would then be M_L times the enthalpy change occurring in the heating condenser. The coefficient of performance would be the heating effect divided by the compression energy requirement. With the near-ideal liquid expansion process, an increased mass flow now passes into the condenser. The new heating effect is now M_L plus M_M as shown. Obviously, the energy compression requirements for the additional mass M_M is less than the compression energy requirement per pound for M_L. Therefore, it can be seen that the heating energy delivered to the condenser compared to the compression energy required to deliver it is less if we consider the near-ideal liquid expansion process. This near-ideal liquid expansion process is one of the thermodynamic cycle advantages made possible by the utilization of the multislide screw compressor.

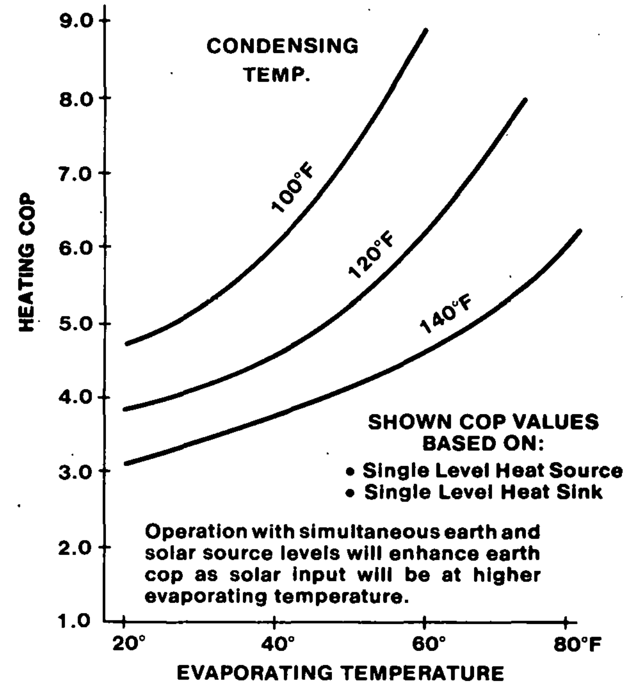

Figure 4. Estimated Heating COP

Explanation of Fig. 4. Fig. 4 is included to show the estimated heating coefficient of performance for evaporating levels from 20 F through 80^o F. and condensing levels from 100^{o}F through 140^{o}F.

The curve as drawn considers the suction bypass slide to be in the fully loaded position. However, the flexibility allowed by the compression ratio slide and the suction bypass slide will allow the part load COP to be quite close to the full load COP at the same evaporating and condensing levels.

Explanation of Fig. 5. Fig. 5 is included to show the part load 70 power. This is the power at part load shown as a percent of the power at full load. A two-speed motor is utilized as well as the suction bypass slide valve. There is no rebalance of system operating conditions considered in these curves. The evaporating and condensing temperatures at part load are considered to be identical with those at the full load condition.

The multi-slide screw compressor is a device capable of operating at various inlet flows and any desired compression ratio. The machine is inherently reliable; only two rotors are employed, both supported by anti-friction bearings. Oil injection is employed and near-isentropic compression levels are always enjoyed. In addition to this, a secondary or moderate pressure intake level is allowed thus allowing for the near-ideal liquid expansion process as explained, as well as allowing for an additional evaporating source level higher than the primary source level. This allows such items to be considered as simultaneous coupling with earth and solar sources. The earth source obviously would be developing vapor at the lower evaporating level, whereas the solar source would be developing vapor at the higher evaporating level. The actual mass flow involved in both streams could be approximately equal or could be widely varying as the demand and the sources allow. This simultaneous dual source capability would certainly allow the low side heat exchangers to be utilized most effectively and will avoid overpulling them. The potential capacity of such a compressor is significantly enhanced through utilization of the basic compressor displacement twice.

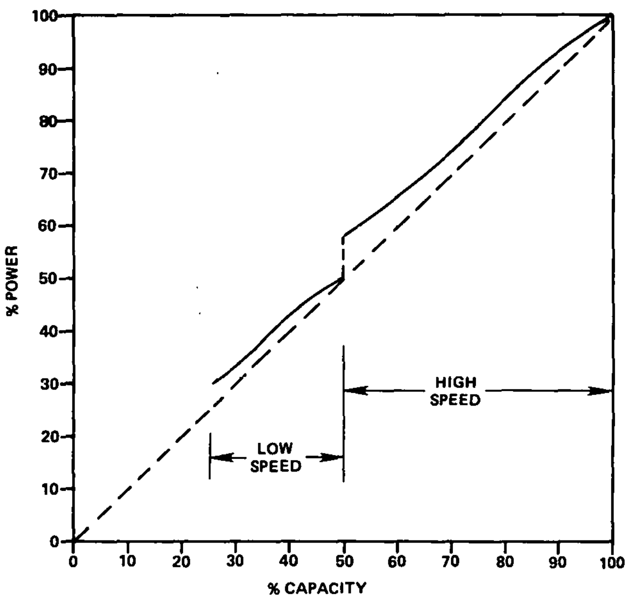

Figure 5. Part Load Performance

TECHNICAL ACCOMPLISHMENTS

Development of computer models to simplify compressor performance analysis.
Proving by actual test that the originally developed concept for compressor capacity control was not completely satisfactory from an energy reduction standpoint.
Development of alternate unloading concepts that still allow necessary independent variation of internal compression ratio. The new concept is shown in this paper.
Overall simplification of original compressor and system concepts, i.e., current approach favors a two-speed two-slide machine.
Generation of predicted performance maps for various configurations of compressors.
Prototype design has been completed yet some simplification redesign is now taking place.

FUTURE ACTIVITIES

It is expected that various performance estimates and experimental results can be used in order to provide a basis for synthesis of advanced solar systems. A fundamental key to Series Solar Heat Pump Systems of the future are the best possible compression concepts. It certainly is expected that this project will result in the proper development of these concepts. As such, commercialization of the various ideas should present no problem as the cost levels of the developed machines are not expected to be significantly above those of less capable production type compressors. It is expected that it will not be difficult to therefore identify the overall cost effectiveness of the enhanced performance of the developed machines as they relate to Series Solar and other Heat Pump Systems.

CONTRACT INFORMATION

START DATE Sept. 1979 END DATE Feb. 1982 CONTRACT VALUE $627,151.

MILESTONES

Item:	Due date:
1. Testing of existing research machine, data and analysis	Nov. 1980
2. Estimated performance map for 25-ton multislide compressors.	Apr. 1981
3. Detail design and drawings for 25-ton multislide compressors and test loop.	Apr. 1981
4. Procurement, fabrication and assembly of 25-ton multislide compressors and test loop.	Aug. 1981
5. Testing of 25-ton multislide compressors, data and analysis.	Feb. 1982

DEVELOPMENT AND ANALYSIS OF A GROUND COUPLED SOLAR ASSISTED HEAT PUMP SYSTEM FOR RESIDENTIAL APPLICATION

FAFCO, INCORPORATED

JONATHAN C. BACKLUND, PRINCIPAL INVESTIGATOR

CONTRACT NO. DE-AC03-80CS30224

OBJECTIVE

The object of this project is to research the technical and market feasibility of a novel ground coupled solar assisted heat pump system for residential space conditioning. Specific project goals are to experimentally investigate the heat rejection capability of several all polymer solar collector designs, to experimentally and analytically investigate the performance of a planar earth heat exchanger, to simulate the thermal performance of the space heating and cooling system, and to define a potentially viable market "niche" for such a system.

DESCRIPTION OF WORK

Combined solar heat pump systems, both series and parallel configurations, have been studied extensively.[1 2 3 4 5] Many researchers have concluded that such combined systems are not economically viable today in any form.

Ground coupling, the use of the earth as a source and sink for the heat pump, has also been the subject of study and experimentation.[6 7 8] When combined with solar heat pump systems, the earth provides energy source during periods of insufficient solar collection, avoiding electric resistance heat. During the cooling season, the earth can be a relatively cool heat sink, allowing more efficient cooling than conventional air conditioners or air to air heat pumps, which must reject heat to a warm ambient.

The FAFCO program goal is to accomplish space conditioning with a system that may eliminate some of the problems inherent in the systems analyzed and rejected by other researchers. A significant deviation from other studies is the emphasis on efficient cooling mode operation. Sun belt areas could be an attractive market, with much new construction, more available solar for heating, and the potential for reducing high cooling energy costs. A second novel feature is the use of inexpensive plastic solar collectors for heating, which can also operate effectively as nocturnal heat rejectors for cooling. A third feature is a unique ground coupling geometry to provide COP improvements in both heating and cooling. By using buried flat plates, rather than the more usual serpentine pipe coil or buried tank, large heat exchange areas can be realized with perhaps lower construction cost, less land area, and improved heat exchanger performance. It is noteworthy that all equipment is used in both heating and cooling operation. Figure 1 is a schematic representation of the FAFCO GCSAHP system.

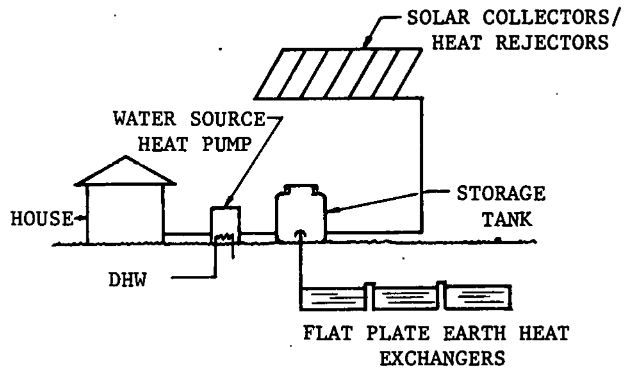

FIGURE 1: GROUND COUPLED SOLAR ASSISTED HEAT PUMP SYSTEM SCHEMATIC

TECHNICAL ACCOMPLISHMENTS

Collector/Rejector Research

A key element of the FAFCO GCSAHP system is an inexpensive solar collector which can also effectively reject energy at night. Three candidate collector/rejector prototypes have been built and tested. Two types of thermal experiments, daytime stagnation and nighttime heat rejection, were done to establish collector/rejector thermal performance.

The three designs are essentially single glazed flat plate solar collectors whose heat loss coefficient, U_L, is made to increase in the heat rejection mode. U_L is modulated in these collector/rejector designs by 1. varying the spacing between glazing and absorber plate (glazing spacing), 2. actively removing heated air from the space between glazing and absorber (forced convection), and 3. opening several transverse slots in the glazing to vent the space between glazing and absorber (natural convection).

The results of these collector/rejector performance experiments are shown in Figure 2. It was found that both daytime stagnation and nighttime heat rejection experiments yielded reasonable and consistent values of the heat loss coefficient, U_L. From these experiments, the following conclusions can be drawn:

1. The thermal performance of the air flow control design is best, the design is straight forward, but it requires electrical power and is not failsafe.

2. Glazing spacing control design gives satisfactory thermal performance, but it is very sensitive to small gaps and is a more diffi-

cult design to execute.

3. Heat removal by natural convection between absorber and glazing is only marginally effective.

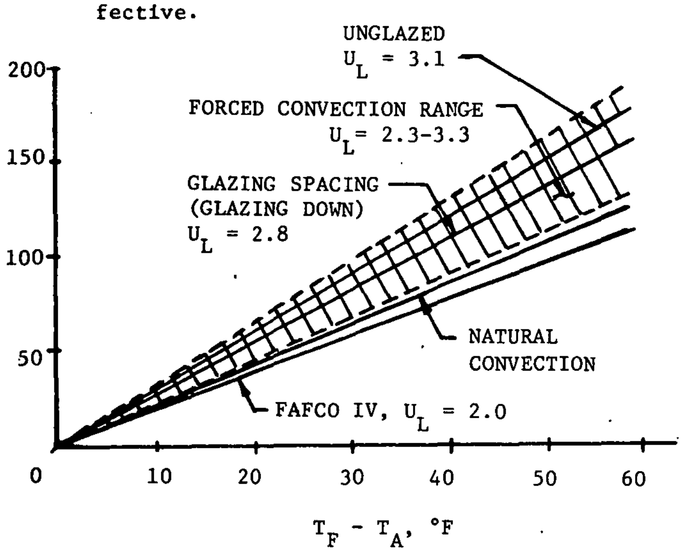

FIGURE 2: SUMMARY OF HEAT LOSS FACTORS FOR CANDIDATE COLLECTOR/REJECTOR DESIGNS

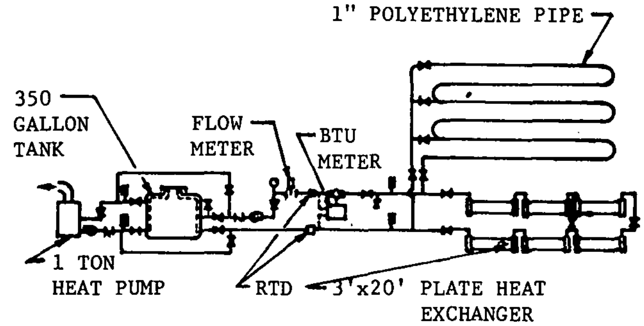

FIGURE 3: SCHEMATIC PIPING & INSTRUMENT DIAGRAM FOR GROUND COUPLING EXPERIMENTS

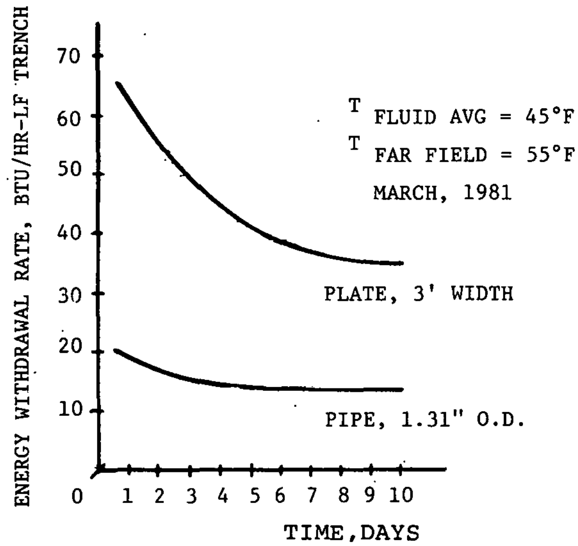

FIGURE 4: GROUND HEAT EXTRACTION AT CONSTANT FLUID SINK TEMPERATURE

GROUND COUPLING RESEARCH

An integral component of the space conditioning system is the earth heat exchanger, also known as ground coupling. In the heating mode, the earth is a back up source to the heat pump when solar input to storage is insufficient, avoiding resistance heat. In the cooling mode, the earth acts as a heat sink for some of the energy rejected by the heat pump to storage. Performance improvement over air/air heat pumps or air conditioners is possible, since the ground is usually cooler than ambient when there is a cooling load.

A common ground coupling geometry is a 1000' long 1-1/2" plastic pipe buried at a depth of 3 to 4 ft. An alternative method is to bury perhaps 200 to 300 ft. of 3 ft. wide flat plate heat exchanger at the same centerline depth. It may be possible to obtain substantially more transient and steady energy exchange per unit length of trench, due to the much greater surface area of the plate in contact with the soil. Reductions in installation cost and required land area may result. FAFCO has designed, constructed, and run a set of ground coupling experiments in which the heat exchanger performance of pipes and plates has been compared directly. Figure 3 is a schematic representation of the piping and instrumentation. Figure 4 shows experimental results of sequential constant temperatures heat extraction experiments. Other field experiments have been run to test system transient response to cyclic heat extraction and heat injection. A detailed finite element heat transfer model has been used to simulate the performance of both ground coupling geometries. Agreement with the field experiments is excellent.

System Thermal Analysis

The thermal performance of the GCSAHP system has been simulated in five areas (Fresno, Los Angeles, Fort Worth, Charleston S.C., and Washington D.C.) using the TRNSYS model. Other systems modeled were air/air heat pump, direct solar heating/electric cooling, and an earth/air dual source heat pump. Unique features of the TRNSYS modeling are the use of the GROCS subroutine for planar ground coupling arrays, nocturnal rejection via variable U_L solar collectors, and a high performance water source heat pump (solar optimized, rotary compressor) with a desuperheater for dhw heating.

Annual comparative results for Fresno are given in Table 1, below:

	SYS.A	SYS.B	SYS.C	SYS.D
HTG.LOAD	56.5	56.5	56.5	56.5
CLG.LOAD	48.6	48.6	48.6	48.6
HTG.ELEC.(INC.DHW)	39.4	19.3	22.3	21.4
CLG.ELEC.	19.3	18.5	13.5	15.0
FREE ENERGY %	0.44	0.64	0.66	0.65

(ALL UNITS IN 10^6 BTU)

System Sizing Notes:

A Air to Air Heat Pump: 3 ton Carrier system.
B Direct Solar-Electric Cool: 540 ft^2 Revere selective surface, Carrier A/C.
C Dual Source Heat Pump: Fedders Compression Furnace, 260 l.f. plate earth hx.
D GCSAHP System: Fedders Compression Furnace, 260 l.f. plate earth hx, 220 ft^2 unglazed collector, 500 gal. tank.
House (load): 2,400 ft^2 energy efficient, Ca. Title 24.

TABLE 1: TRNSYS SIMULATION RESULTS

The TRNSYS results have not as yet been thoroughly analyzed. However, preliminary conclusions are that, for the Fresno climate:

1. The dual source (earth/air) heat pump performance is similar to the GCSAHP system.

2. Unglazed collector/rejectors perform as well as the variable U_L collector/rejectors modeled (results not shown here).

3. A high COP heat pump is essential if significant energy savings over air to air units are to be realized.

4. Ground coupling is an essential element in the GCSAHP system, both as a minimum COP backup in heating, and as a heat sink in climates with high cooling loads.

5. It is difficult to meet the cooling load at all times in hot humid areas such as Fort Worth with a reasonably sized GCSAHP system.

COMMERCIALIZATION & MARKETING ANALYSIS

A possible "market niche" has been defined. The proposed GCSAHP system may be cost competitive with conventional systems in sunbelt areas where cooling and heating loads are about equal. Adequate cost effectiveness is computed using life cycle costing and the assumption that the buyer is interested in realizing a net positive cash flow as soon as possible.

Key features of the FAFCO marketing study are as follows:

1. A significant customer benefit can be seen with cash flow analysis, not necessarily payback.

2. Tax credits improve the economics substantially.

3. Heating and cooling loads of similar size allow reasonable system sizing, and allow the equipment to be fully utilized all year. The dhw load is also satisfied by this system. This leads to very good annual energy savings.

4. Low cost collectors, ground coupling, and an advanced heat pump are essential elements.

5. The heat pump is not included in the system cost, as this item would be purchased at a comparable price for central air conditioning in the new home in any case.

6. The GCSAHP system is most appropriately applied to new homes (not retrofit) larger (2400 ft^2) than average. A key result of the marketing analysis to date is that, in Fresno the proposed GCSAHP system would have a positive cash flow in less than five years.

FUTURE ACTIVITIES

Research will continue on the flat plate ground coupling concept and TRNSYS simulations. Given better defined technical input, market research will proceed.

REFERENCES

(1) Andrews, J.W., "Heat Pump Impact Upon Solar Collector Design and Cost", BNL-26217.

(2) Hughes, P.J., et al., "Comparison of Solar Heat Pump Systems to Conventional Methods for Residential Htg., Clg., and Water Htg.", SAI, McLean, VA., Volume II, Final Report, April 1980.

(3) Freeman, T.L. et al., "Performance of Combined Solar Heat Pump Systems", Solar Energy 22, (1979).

(4) Jaster, H., et al., "SAHP For the Htg. and Clg. of Bldgs.", G.E. Co., Six Month Tech. Report, Contract No. EG-78-C-03-1719, May 1979.

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(6) Metz, P.D., "Experimental Results From the First Year of Operation of the Solar Ground Coupling Research Facility at Brookhaven National Laboratory" BNL-27137.

(7) Bose, J.E., et al., Earth Coupled and SAHP Systems, Pres. at the 5th Annual Heat Pump Tech. Conf. at OK. State Univ., April 14-15, 1980.

(8) Chalmers Univ. of Tech., "Nordic Symposium on Earth Heat Pump Systems", Goteborg, Sweden, Oct. 15-16, 1979.

CONTRACT INFORMATION

START DATE April 24, 1980 END DATE Oct. 31, 1981 CONTRACT VALUE $130,700.00

MILESTONES

Item:		Due date:
1.	Complete collector/rejector prototype testing	Complete July 1980
2.	Preliminary system thermal modeling Final TRNSYS modeling	Complete Oct. 1980 Aug. 1981
3.	Design & construct ground coupling test facility	Complete Jan. 1981
4.	Steady state and transient ground coupling experiments, heat extraction and injection	Aug. 1981
5.	Final commercialization & marketing analysis	Oct. 1981

EXTENSION OF PHOENIX/CITY OF COLORADO SPRINGS SOLAR ASSISTED HEAT PUMP PROJECT

KAMAN SCIENCES CORPORATION

DOUGLAS M. JARDINE, P.E.

DE-AC03-79-CS30207

OBJECTIVE

The objectives of this project are to stimulate the development of preferred solar assisted heat pump systems; and, to improve the data base for these solar assisted heat pump systems.

DESCRIPTION OF WORK

The word Phoenix in the project refers to the name of the system developed on this project. This system provides space and water heating and space cooling service for a broad range of building types. Figure 1 shows the basic system concept where the system employs an electric water source heat pump. utility; and, the system must be competitive in cost and reliability with other available systems.

Phoenix systems have been installed in 3 types of buildings in 3 different climatic locations and operated for 21 months to produce performance data, reliability and availability profiles, cost data, prove the annual thermal energy storage carry over of the patented volume dominated ground coupled storage device used, and to produce hereto for unpublished data on the dynamic thermal gradient and moisture migration characteristics that occur in the ground around the cost-effective type of storage device employed in the Phoenix System. The Phoenix System employs

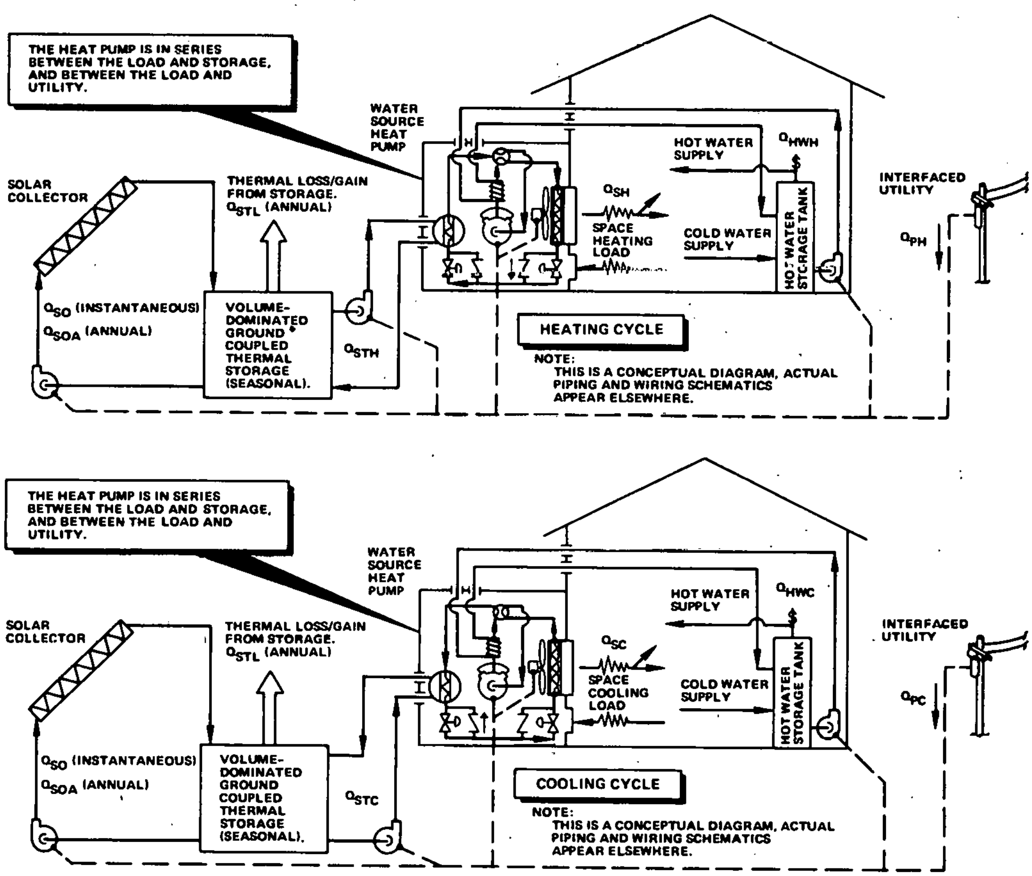


FIGURE 1 BASIC PHOENIX SYSTEM CONCEPT WITH ELECTRIC HEAT PUMP

The basic criteria that have guided the successful development and testing of the Phoenix System are that the system must be considered as a subsystem to the utility with which it interfaces; the system must be compatible with the interfaced off-the-shelf components which have a successful commercial history in similar applications.

Three of the systems have been stress tested under continuous load to produce reliability and availability data, while the fourth system has been operated normally in a residential application to focus on commercialization aspects of the system in two specific utility service areas - Colorado Springs and Denver, Colorado. Tests were conducted employing an electric heat pump, and the design of a natural gas powered heat pump Phoenix System has been completed.

TECHNICAL ACCOMPLISHMENTS

- The Phoenix System won the coveted IR-100 award for 1980 for being one of 100 most significant products developed during the year.

- It has been demonstrated that utility compatibility is a separate issue for each different utility - they are all very different. The Phoenix System is proven as a new capacity and fossil fuel substitute when interfaced with either a natural gas or an electric utility, and such is capable of avoiding significant utility marginal costs.

- The cost of energy from the Phoenix System's storage is significantly cheaper than the cost of energy from natural gas or electricity in Colorado Springs and Denver, and the first cost of the Phoenix System with an electric heat pump after Colorado Tax Credits is lower than first cost of a natural gas furnace and water heater for the same load.

- The Phoenix System's availability under normal use exceeds 99% and this sytem has reliability equal to a natural gas space and water heating system.

- The Phoenix System's thermal storage has annual carry-over and is an infinite capacity heat source and heat sink for the heat pump - thus eliminating the need for a backup system. It has been proven that thermally driven moisture migration occurs in the ground around the storage tank which optimizes system performance during the peak heating season. It has been proven that a non-cohesive soil envelope of proper gradation and at least one foot thick around this system's ground coupling storage device is of strategic importance. It appears that under normal operating conditions the majority of the thermal interchange with the ground occurs within three feet of the storage device, and that under extended peak load the thermal gradient moves farther out in the soil.

- Figure 2 summarizes the comparison of owning and operating costs for an average residential

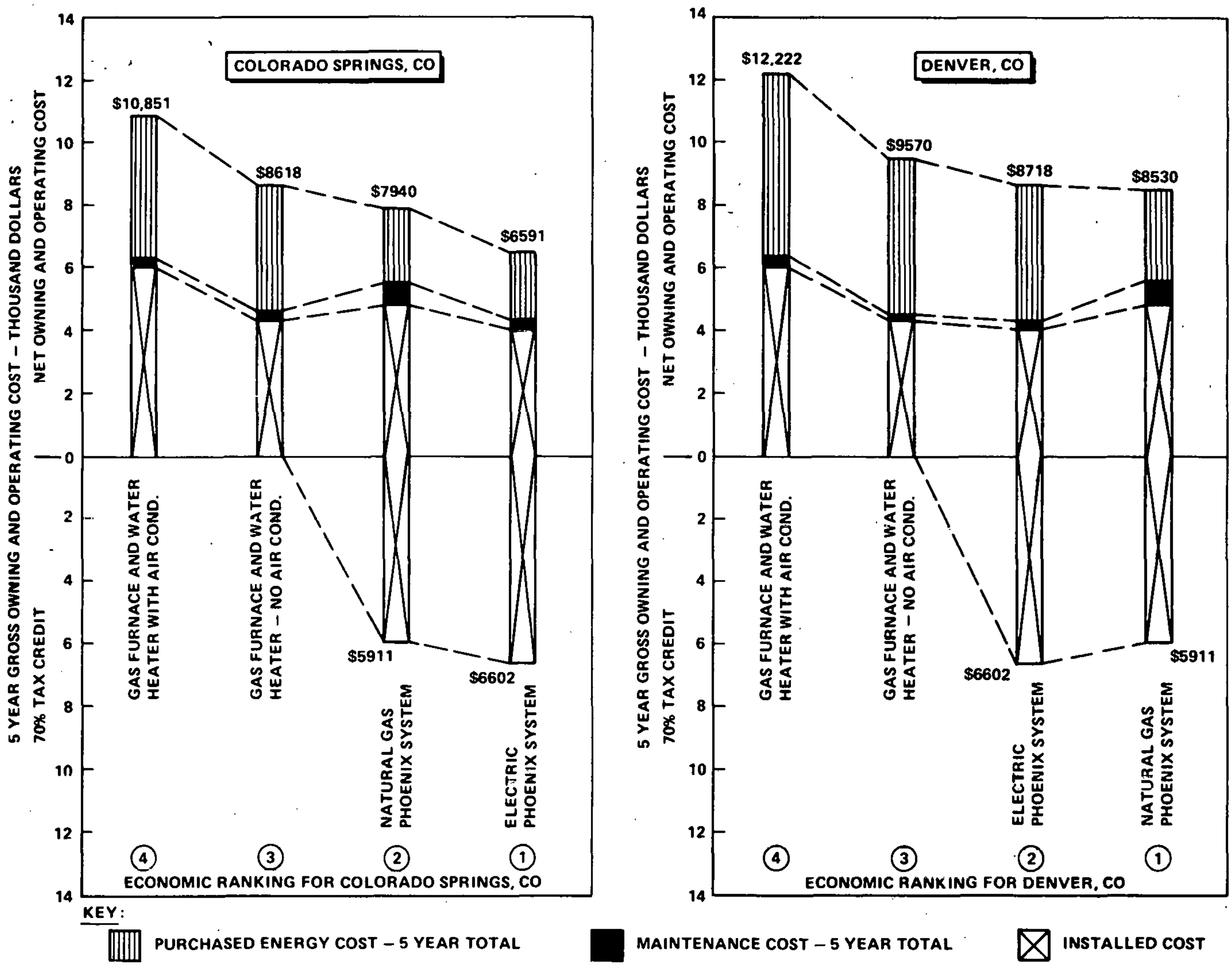


FIGURE 2 FIVE YEAR OWNING AND OPERATING COST COMPARISONS AND ECONOMIC RANK ORDERING OF CANDIDATE SYSTEMS

heating customer in Colorado Springs and Denver using either a natural gas furnace and water heater system or the Phoenix System, and shows the electric Phoenix System as most cost-effective in Denver.

- Figure 3 shows storage performance at the Colorado Springs project over the term of the project demonstrating these attributes for this storage: 1) Storage supplied heat required for first heating season from cold start in fall within a temperature range that allowed the heat pump to supply full space and water heating load; 2) Storage absorbed condenser and collector heat during cooling season within an acceptable temperature range for the heat pump; and, 3) the summer stored heat carried over into the second heating season and allowed the storage to support the heat pump at a significantly higher storage temperature during the peak heating season load than occurred during the first heating season. Thus annual stored heat carry-over has been proven.

FUTURE ACTIVITIES

The Phoenix System employing an electric heat pump is ready to be commercialized for new building and retrofit (where the existing heating system is being replaced as part of an upgrading project) applications. The Phoenix System employing the natural gas heat pump is ready for prototype testing.

Plans are made to commercialize the Phoenix System. Venture capital and the other aids necessary to overcome the institutionalized market that must be penetrated are sought. These plans provide a market path through traditional HVAC market channels for potential users who would like to purchase the system, and a second market path is defined employing system leases for potential users who wish to neither own the system nor be responsible for its maintenance.

Plans are made and funds are sought to complete the prototype testing of the Phoenix System employing the natural gas heat pump.

PUBLICATIONS/REPORTS/REFERENCES

Jardine, D. M., Jones, D. W., "Phoenix House: Solar Assisted Heat Pump Evaluation," Final Report, EPRI ER-712, March 1978.

Jardine, D. M., Jones, D. W., "Extension of Phoenix/City of Colorado Springs Solar Assisted Heat Pump Project," Final Report, June 1981, DOE Contract DE-AC03-79-CS30207.

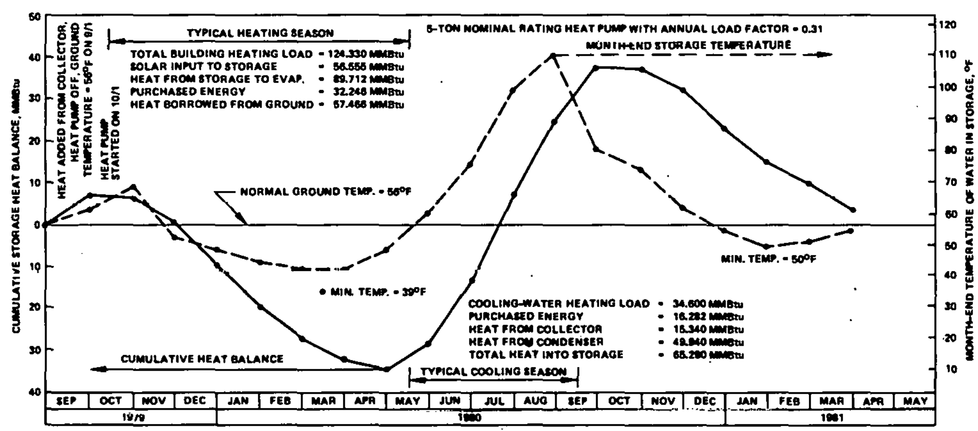


FIGURE 3 CUMULATIVE NET STORAGE BALANCE AND MONTH END STORAGE TEMPERATURE - COLORADO SPRINGS SYSTEM

CONTRACT INFORMATION

START DATE 6/25/79 END DATE 6/25/81 CONTRACT VALUE 465,939

MILESTONES

Item:	Due date:
1. Final Report	June 1981
2.	
3.	
4.	
5.	

Ground Coupling and Heat Pump Compatible Solar Collectors

Alternate Energy Systems Division, Science Applications, Inc.

Dr. Jerry M. Alcone

DE-AC03-80CS30219

Abstract

Thermal storage for various solar heat pump systems concepts via ground coupling shows promise in contributing to the economic viability of these concepts. Similarly there is a need for collectors that are expressly suited to solar heat pump applications. The effort reported here consisted of a survey to identify and document existing ground coupling heat transfer analyses and simulation codes and to abstract and organize the literature in this field. Ground heave, freezing and moisture migration models and analyses were also investigated. In conjunction with this effort the performance and economic characteristics of solar heat pump compatible collectors were identified and the existing commercially available collectors surveyed to identify promising collectors. Innovative collectors and ground coupling concepts were also identified and discussed.

Objective

The primary objectives of this effort were to:

- Identify and characterize solar heat pump compatible collectors.
- Locate and describe existing analyses, models and simulation programs for in-ground heat and moisture transfer as well as ground heave and freezing.

Approach

A graduated search of the ground coupling literature was made to identify potential information sources. First the division's rather extensive file on ground coupling analyses and models was searched to identify the data that was on hand. This search also served to define and refine a key word list for use in the more formal computerized literature search. It also served to help define the information to be gathered and to refine the abstracting and reporting formats to be used. This was done by abstracting the literature selected from the division's files and submitting the abstracts to BNL for review. The experience gained during this exercise was used to define a set of selection criteria designed to focus the survey on the specific information desired by BNL.

The selection criteria included:

For experimental literature
- suitability for validation efforts
- data taking time interval
- duration of experiment
- type of data taken
  - temperature profiles
  - heat flux
  - moisture
- climate region

For analysis literature
- degree of experimental validation
- model type
- applicability to heat pump ground coupling
- complexity of required inputs

For computer models
- generic type of model
- validation status
- inputs
- level of documentation
- completeness and level of representation for a given generic model type
- availability

In all over 200 papers and reports were identified and obtained for final selection evaluation. From this initial set we selected 30 reports and 5 computer programs for indepth assessment. The results of which are currently being documented in the final report for this project.

The heat pump compatible collector evaluation proceeded in a similar fashion. The first effort was to define just what was meant by a heat pump compatible collector by establishing a set of compatbility criteria. These criteria as drawn from a variety of studies of solar heat pump systems are shown below:

Collector Compatibility Criteria
- collector slope < -8 watt/^{o}cm^2
- incremental installed cost < \$50/m^2
- capable of collecting energy from ambient air (desirable)

Existing compilations of manufacturer's literature such as the Solar Source Book as well as the open literature (ads, brochures) were surveyed to obtain literature on promising collectors. This information was then used to determine the performance cost characteristics for the various collectors. This information has been summarized for presentation in the final project report.

Results and Conclusions

Ground Coupling

Adequate models and analyses exist for indepth analyses of ground coupling devices. They are difficult to use and require expensive computer facilities. The simpler models are too simple and still hard to use. Ground heave and freezing have been analyzed and studied extensively but design analyses and models haven't been developed for use by design professionals.

Heat Pump Compatible Collectors

Few if any truly compatible collectors are on the market. Several innovative collector designs are close to being marketed that are expressly aimed at the solar heat pump market.

CONTRACT INFORMATION

START DATE 6/16/80 END DATE 6/15/81 CONTRACT VALUE $27,433

MILESTONES

Item:	Due date:
1. Project Status Reports	7/80, 8/80, 9/80, 10/80, 11/80, 12/80, 1/81, 2/81, 3/81, 4/81, 5/81, 6/81
2. Task 1 Report	3/81
3. Final Report	6/81
4.	
5.	

Heat Pump Demonstration Analysis

Alternate Energy Systems Division, Science Applications, Inc.

J. Alcone, L. Walker

Prime EG-77-C-01-4042

Abstract

The use of a heat pump in conjunction with solar energy collection and storage subsystems appears to offer unique advantages in SHAC system performance. Past system studies and some implementations of this concept have not consistently verified the expected advantages. The primary weakness of many of the prior efforts is that they failed to recognize the unique characteristics of solar heat pump systems. In some cases the efforts followed conventional solar design practices and attempted to either "add-on" a currently available conventional heat pump (or some linear extrapolation of conventional heat pump performance characteristics) or to extrapolate the results of a conventional SHAC system study (or design) to a heat pump configuration. In other cases inappropriate initial assumptions led to biased or inconsistent results. In many of the designs and studies, design considerations arising from the dynamic behavior of the system were ignored. A heat pump introduces significantly different operational characteristics into a SHAC system and the analysis must include these effects. Since many prior studies did not consider the heat pump dynamics as a part of the total system, their conclusions and results have been rather confusing and often contradictory.

The effort reported on here serves to clarify and resolve the conclusions of selected prior studies. The validity of past analyses was assessed by carefully studying the effects of the individual study assumptions on the reported results and conclusions. Comparisons were also made in a careful, consistent manner to results that have been observed in the field.

Objective

The primary objective of this effort was to clarify and resolve the conclusions of selected systems studies through comparison with operational data from appropriate experimental/demonstration sites.

A further objective was to identify and evaluate those system components and/or configurations that warrant further analysis and testing in order to develop recommendations regarding programmatic needs in the solar heat pump area.

Concept/Methodology

The evaluation of the study results was accomplished by carefully studying the effects of the assumptions and design decisions made in the lected studies on the conclusions reached in ose studies. These conclusions were then compared to results observed in the field in a consistent and methodical manner.

The goal of identifying components or configurations warranting further analysis and testing was achieved throughout the project on a cumulative basis. The results of this effort are based on discussions with site personnel, system reliability analyses, experience gained and observations made in developing system models and exercising simulations of the various selected configurations.

The methodology used to accomplish the study objectives was to divide the project into several subtasks which addressed specific elements of the overall scope of effort. These subtasks are described below.

- Selection Criteria

  Selection criteria were carefully defined to allow only appropriate Solar Heat Pump (SHP) configurations and useful sites to be included in this study in order to allow a consistent, legitimate comparison of operational SHP's and analytical models.

- Selection of Operating Systems

  Six operating systems which met the selection criteria mentioned above were chosen for this effort. In addition to meeting the selection criteria these systems were chosen as being representative of the generic configurations used in the systems studies in order to allow consistent comparisons.

- Performance Measures

  In order for this study to provide valid results and recommendations, performance measures were developed to eliminate conclusions based on a single viewpoint. These measures were chosen to allow consistent comparison both among the solar heat pump configurations defined in the Selection Criteria Subtask and between those configuration and other alternative energy systems. The performance measures were developed to reflect economics, energy usage, and societal impact.

- Selection and Evaluation of Systems Studies and Selected Operation Systems

  These two subtasks were performed concurrently since the objectives and analysis methods were similar. Four major systems studies selected by SERI for use in this effort were obtained and abstracted. Documentation and performance data for selected operating systems was already in hand in most cases. The approach to this evaluation was to establish certain major assumptions which served as a basis for examining agreements or discrepancies between the sites and the studies. TRNSYS models of the different generic configurations were developed based on several of the actual operating systems. These models were exercised extensively to investigate the effects of the identified assumptions on system performance.

Summary of Project Conclusions and Recommendations

Systems Studies Analysis Conclusions

The major conclusions resulting from the detailed analysis of the major assumptions in the systems studies and design decisions in the operational sites are presented below.

- Valid comparisons between different generic solar heat pump configurations can be made in systems studies only when the heat pump characteristics are appropriate for each configuration. Some study results are based on the same heat pump characteristics for all generic configurations. This yields unrealistic results since for proper operation the heat pump characteristics should not be identical for all the configurations.

- Heat pump sizing is an important assumption which affects conclusions in the systems studies. In some cases studies used conventional sizing methods for the parallel configurations. This assumption causes the heat pump to be undersized in a solar assist configuration resulting in use of auxiliary energy below the balance point for the heat pump. The parallel configuration calls for heat pump operation well below the design point for current generation heat pumps. Heat pumps optimized to a lower balance point for this configuration would probably show increased system performance.

  Series configured systems were oversized in two of the studies. This oversizing results in an increased system cost and therefore affects the results of these studies.

- The assumption of "current generation" reciprocating compressor heat pumps for use in solar configurations has an important effect on results of any simulations of solar heat pumps. This is especially true for series systems which operate at higher source temperatures and over wider ranges of source temperatures. Operational performance from at least one site corroborates this effect.

  One study used an "improved" heat pump (60-80% of an ideal vapor cycle) and found that increased series system performances were possible with this heat pump. The conclusion was that series systems are penalized using current generation heat pumps which cannot accomodate the increased mass flows due to higher source temperatures in the series configuration. This conclusion was corroborated by results of experiements performed on the University of Tennessee liquid series system.

- Control strategies such as that used in one of the studies appear to penalize series systems. This strategy limits solar collection above 33.9°C apparently to correct for the use of better than needed collectors and current generation reciprocating heat pump characteristics.

- Collector and storage sizing assumptions also have important effects on study results, particularly in series systems. Storage and collectors must be sized to eliminate heat pump starvation in the series configuration. Contrary to conclusions stated in the studies, improved series system performance is possible with improvement in heat pump COP if collectors and storage are resized to accomodate the improved heat pump.

- Collector characteristics play an important (though generally not addressed) role in system performance as simulated in the various studies. Collector characteristics need to be "tailored" to the particular generic application before realistic comparisons can be attempted. Series configured systems have potential for lower cost collectors due to lower required storage temperatures. Unfortunately, none of the studies addressed this point adequately.

- The fraction of total load met by non-purchased energy is very sensitive to changes in the load/collector area ratio at all values of storage size/collector area.

- TRNSYS simulations of the University of Tennessee liquid series system using an "improved" heat pump (60% of Carnot) indicate the possibility of an optimum storage size/collector area for a given load/collector area ratio in the range of .15-2m^3/m^2 for a water based series system.

- A small effect on system performance is indicated from domestic hot water (DHW) draw on storage. For a series configuration this may slightly increase the possibility of heat pump starvation. For the parallel configuration reduced storage temperatures increase the possibility of solar not being able to meet the load. Studies have not adequately addressed this effect particularly when a heat pump desuperheater is used to produce the DHW.

Systems Studies Recommendations

- Any future studies of solar heat pump systems should be based on careful design of an optimum system including component characteristics other than site, for each generic type.

- A more complete investigation of the design space relating storage size/collector area ratio to load/collector area ratio is recommended for both series and parallel systems. This investigation should use generically optimized components as well as heat pumps which are optimized for the different configurations.

- Care should be taken to include a broader range of component characteristics. The range should include variations in basic operating principles as demonstrated by the use of reciprocating and rotary compressors.

- A similar recommendation holds for the collector characteristics, i.e., unglazed collectors while touted for series systems have actually received little attention; freon expansion collectors capable of subambient operation were not considered in the studies while industry is actively pursuing designs based on them.

- Thermal storage has also been unnecessarily restricted in the prior studies with no attempt to identify (except in one case) and characterize desirable thermal storage attributes.

Operating System Recommendations

As a result of the detailed review of the selected operating systems, the site visits, and discussions with site personnel, the following recommendations are made.

In regard to experiments/demonstrations in general there exists a need for:

- standardized descriptions of the physical system
- more consistent reliability data acquisition and documentation
- documentation of design, construction and operating experiences as well as any modifications
- standardized cost reporting (capital and O&M)
- consistent data reporting of the kind that can be used to verify design assumptions and validate design or analysis codes

In specific regard to solar heat pump systems:

- Many of the systems are using modified heat pumps operating in off-design circumstances yet few have directly measured the performance of these heat pumps as they are being operated.
- Some systems use site-built collectors whose performance characteristics are not specifically known. The effects of collector characteristics have been shown to be important and therefore should be known.

Performance/Cost Limitations for Solar Assisted Heat Pumps

Conclusions which resulted from the analyses of the systems studies and operational systems addressed in this effort were presented. Limitations based on performance and/or cost which were discovered during this analysis and recommendations for overcoming them are presented below.

- A major limiting factor for series solar heat pump systems and any analyses of them appears to be the use of current generation reciprocating compressor heat pumps. Performance analyses of these systems (both in this effort and at least one of the systems studies) using "next generation" heat pumps has shown greatly improved system performance. There are heat pumps currently on the market (for example, the Fedders rotary compressor machine) which should be investigated for solar applications.
- For parallel solar heat pump systems the heat pump is usually constrained to operate under "worst" case conditions due to current generation heat pumps being optimized in a way that causes heat pump undersizing in many cases. Heat pump operation in the parallel configuration is usually well below the design operating point for current generation heat pumps. Next generation heat pumps would also help to alleviate this problem.
- Collector costs are a major portion of total system cost in solar heat pump systems. For the parallel system these costs are probably going to be invariant in the future. However, for the series system this factor is not so limiting. The performance of the series concept actually degrades relative to that for a parallel system as collector performance (and hence cost) increases. Fortunately, the reverse is also true.
- Complexity and number of components appears to limit marketability of solar heat pumps. Simplifications of these systems is possible using current technology. A simplified air series system which uses low-cost collectors and a unique ground-coupled storage system has a life-cycle present value cost competitive with the conventionally based systems addressed in the systems studies.

CONTRACT INFORMATION

START DATE April 7, 1980 END DATE Feb. 28, 1981 CONTRACT VALUE $65,994

MILESTONES

Item:	Due date:
1. Subtask Reports	6/9/80, 12/1/80,12/15/80,1/12/81,1/26/81
2. Final Report	2/16/81
3.	
4.	
5.	

LOW-COST HEATING AND COOLING USING A DIRECT-EXPANSION SOLAR COLLECTOR AND HEAT PUMP

Sigma Research, Inc.

Victor I. Neeley

DE-AC03-79SF10542

OBJECTIVES

The two primary goals of this project are: to develop a low-cos. lightweight, thermally efficient direct-expansion solar collector with a microprocessor-controlled heat pump; and to establish and verify system responses to nonsolar energy sources (convection and condensation). Successful completion should extend the use of solar energy systems to a larger segment of the population by decreasing purchase and installation costs and increasing operating efficiency in locations where this energy source has, heretofore, been considered inappropriate or of marginal usefulness.

DESCRIPTION OF WORK

The work being performed under this contract is based in part on prior efforts in the area of solar collectors, heat pumps, and heat and mass transfer. For example, a working model is in place in Seattle, Washington (see Figure 1), and an existing 80-ft^2 solar panel has been modified for tests scheduled in this project. Current efforts are extensions and refinements of a continuing program in this field.

In the solar collector/heat pump design under investigation, solar energy is absorbed by exposed panels and directly vaporizes a refrigerant fluid, which is pumped to a high temperature and pressure. Then, it is condensed to release the heat that was absorbed in the vaporization process. The solar panels operate at or below ambient temperature, which significantly reduces heat loss to the environment and eliminates the need for glass covers and expensive insulation around the collectors.

This system was specifically designed for geographical areas where adverse meteorological conditions such as frequent heavy cloud cover or abundant rainfall limit the effectiveness of standard flat plate solar collectors and restrict the attainment of maximum benefits. The improved performance (see Figure 2) is due to the fact that the panels continue to absorb energy by convection, radiation, and condensation and provide significant thermal input even during periods when insolation is impossible. Therefore, this design will be suitable for use in regions not normally considered appropriate for solar energy collection.

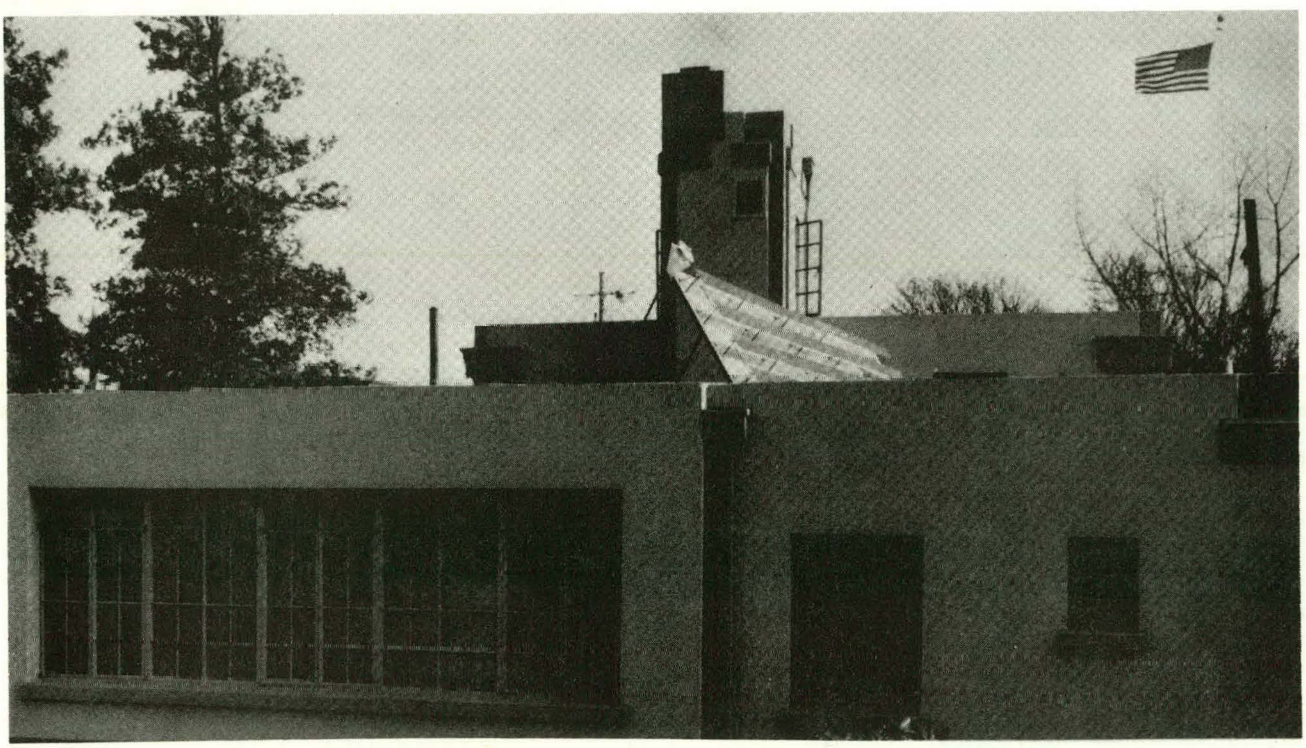


Figure 1. Seattle, Washington, Fire Station No. 13 with collector system installed. (Pilot project sponsored by Seattle City Light.)

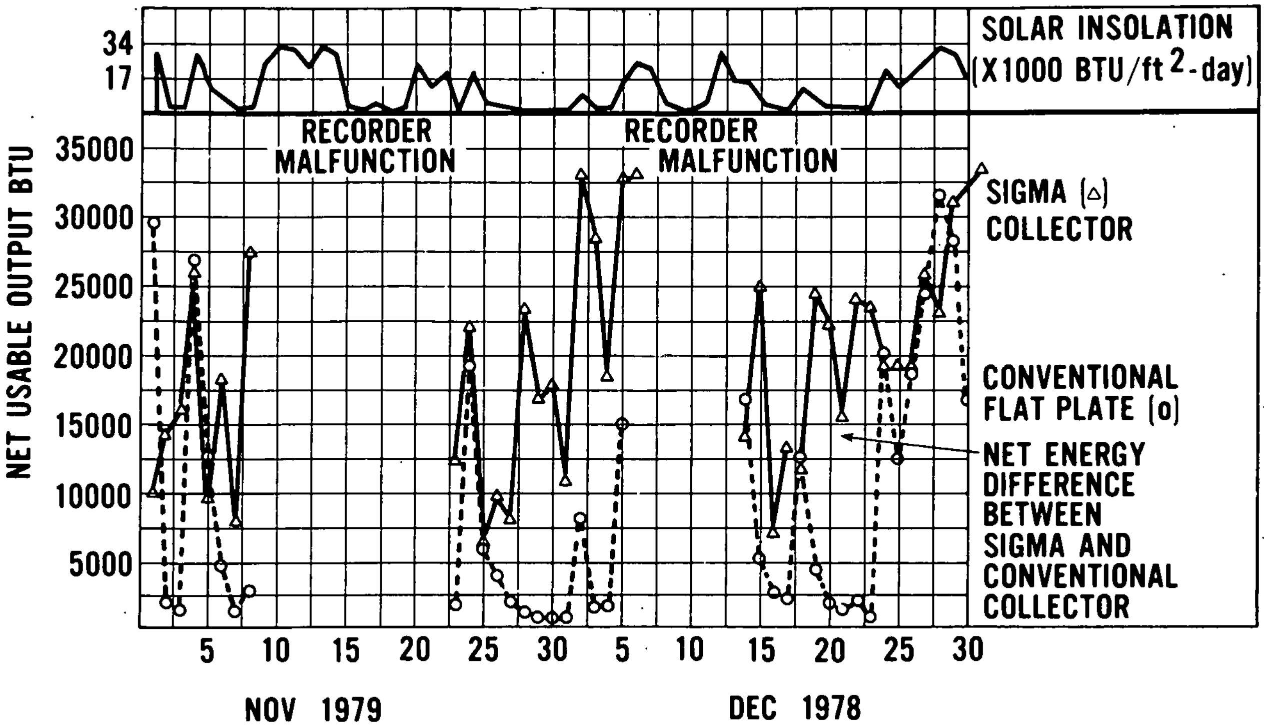


Figure 2. Performance comparison between Sigma Multi-Therm Solar Panel and conventional flat plate collector installations in Seattle, Washington. (Program sponsored by City of Seattle.)

TECHNICAL ACCOMPLISHMENTS

- Commercially available or Sigma-owned components were used to modify the solar panel. These items will allow microprocessor control of system.
- The data acquisition and control system was designed for use during verification and optimization of thermal models and laboratory tests.
- Thermal hydraulic design modifications were performed on an existing solar-assisted heat pump.
- The isolated signal interface was designed and constructed in-house, and the existing solar panel and heat pump were reconditioned before installation of the modification components.
- After the unit assembly was completed, the system was pumped down and charged with refrigerant. Preliminary tests were performed under manual and computer control. The system appeared to operate satisfactorily.

During the spring and summer of 1980, unavoidable circumstances led to a request for an extension of the contract expiration date, which is now June 30, 1981.

FURTHER ACTIVITIES

Fully computerized system operation will be tested during the spring of 1981. The major area to be investigated is the effectiveness of the microprocessor controls for the heat pump.

Using a microprocessor to control the heat pump should improve the average coefficient of performance and extend the life of the compressor. The microprocessor collects temperature data throughout the system and controls the compressor speed to obtain optimum performance. It also controls system start-up and reduces the potential for compressor damage that might be caused by entrained liquid.

Despite the fact that these activities have been deferred and test results are incomplete, plans are being made for post-contract marketing and commercialization of the Multi-Therm Solar Panel. Demonstrations to date have proved that the concept is sound and the system design is efficient.

Figure 3 is a schematic of a typical installation. Although the prototype is a viable product itself, its commercial appeal would be increased greatly if the solar panels can be redesigned so that they become an integral part of the structure (i.e., as roofing material); if installation and connection procedures are refined to gain the utmost ease and simplicity; and if a thermal storage module is included as part of the system.

World events and the public's steadily growing interest in alternate energy sources--plus the existence of regions where available solar collector systems are not feasible or can offer only minimal efficiency--make further development and manufacture economically attractive and commercially feasible.

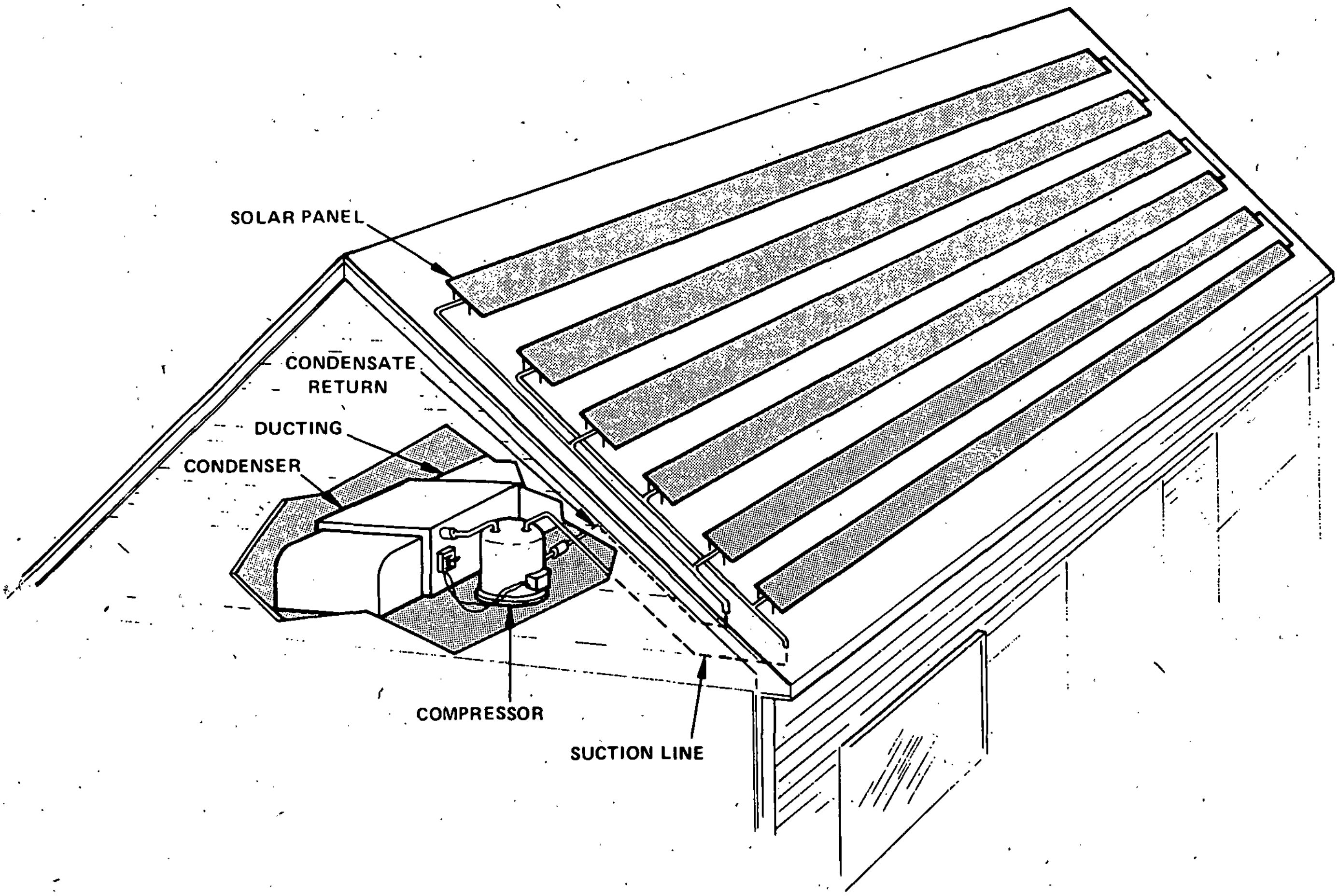


Figure 3. Schematic of the major components of an installed solar panel/heat pump system.

CONTRACT INFORMATION
START DATE August 16, 1979 END DATE June 30, 1981 CONTRACT VALUE $96,184.00

MILESTONES

Item:		Due date:
1.	Final Report	June 30, 1981
2.		
3.		
4.		
5.		

INSTRUMENTATION AND MONITORING OF THE TWIN CROWN REALTY BUILDINGS IN DENVER, COLORADO

SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INC.

DAVID K. HAYS

DE-AC03-79CS-30115

OBJECTIVE

The Crown Monitoring project has two distinct tasks which are of importance to the solar community. The first is a performance comparison of the two solar augmented heat pump systems; one of which is an air collection system with the other being a liquid collection system. The second task is to simulate real-time data filtering, reduction and analysis on the data gathered from the two systems.

PROJECT BACKGROUND

Solar augmented heat pumps have been the subject of considerable discussion where the economic viability and energy effectiveness is concerned. In an effort to provide some answers to the many questions, Solar Environmental Engineering Company (SEEC) has been contracted to monitor and evaluate the performance of the twin Crown Realty buildings.

The standard manner in which data is reduced and analyzed is time consuming, requires the transfer of the data on a storage device from the acquisition system to a mainframe computer and considerable computational expense. It is possible to reduce time and expense by processing the data onsite in real-time by an acquisition system which has processing and computational capability.

Real-time processing necessitates the use of sophisticated algorithms which can be used to filter and process the acquired data. These algorithms are developed with Luenberger observer and Kalman filtering techniques. These techniques have been employed by the Principal Investigator to predict future ambient temperatures, filter data and observe heat loss coefficients and heat capacitances of building models (Refs. 1 and 2).

SUMMARY

Two 3500 square foot commercial office buildings are environmentally conditioned by a system of seven solar augmented heat pumps and are identical in mechanical design with the exception of the solar collection loop. In one of the buildings, the collection loop is an air system while the other collection loop is a hydronic system. Thus, a direct comparison of an air and a hydronic collection system can be made.

By applying Luenberger observer theory techniques to the data, sensor noise can be filtered and actual key parameters may be identified. Some examples of these parameters are the building heat loss coefficient, heat exchanger effectiveness, heat pump coefficient of performance and the solar heating fraction. In the present application, real data will be filtered and observed on a mainframe computer in order to demonstrate the worthiness of these techniques.

TECHNICAL ACCOMPLISHMENTS

• The two systems have been instrumented so as to provide all necessary data for complete system and subsystem performance analyses. The performance of the two systems will be determined by performing standard energy balances on the gathered data. Comparisons of the two systems will be made on the basis of collector efficiency, energy stored, energy utilized and other performance factors associated with the two systems.

• First and second order approximations to the dynamic systems have been assembled. These differential equations are used in the formulation of the observers which identify the parameters in question. An example of one such differential equation is

$$\frac{d\,T_e}{dt} = \frac{q_{in}}{C_e} - \frac{UA}{C_e}(T_e - T_a)$$

By monitoring the enclosure temperature (T_e) and the difference of the enclosure and ambient (T_a) temperature, it is possible to converge on approximate values of the heat loss coefficient (UA), the heat capacitance of the enclosure (C_e) and energy input rates to the system (q_{in}).

It is also possible to establish values for heat loss coefficients and energy balances on thermal storage tanks. All of the appropriate equations and necessary software has been assembled for conducting this analysis.

FUTURE ACTIVITIES

Contract Activities. It is expected that the parameters of interest will be determined by the use of observer techniques and that these results will compare favorable with the performance results obtained in the conventional manner.

Post Contract Activities. The results of this effort can be realized and utilized by all sectors of the analysis field. Future efforts will apply these methods on a real-time basis with a dedicated microprocessor based computer. The advantages of applying these techniques on a real-time basis are as follows:

- Reduction of turnaround time of results from months to minutes

- Major reduction of mass storage requirements.
- Immediate access to the quantities of interest rather than raw data.
- Reduction of the cost of data analysis.

CONTRACT INFORMATION

- Start Date - June 11, 1979
- End Date - August 31, 1981, Extended from December 11, 1980
- Face Value - $78,964
- Major Milestones
  - Specify and order instrumentation - July, 1979 (M)
  - Instrumentation Installation - January, 1980 (M)
  - System parameter identification - July, 1981 (P)
  - System performance identification - July, 1981 (P)
  - Final Report - August 31, 1981 (P)

REFERENCES

1. Hays, D. and Winn, C. B., "The Development of an Ambient Temperature Observer/Predictor (ATOP) for Use With Solar Heating Systems," Proceedings of the International Solar Energy Society, May, 1979.

2. Hays, D., Parkinson, B. W. and Winn, C. B., "Real-Time Identification of Parameters in Building Models," Proceedings of the International Solar Energy Society, 1979.

3. Hays, D. and Jacobs, P. C., Engineering Assessment of the Crown Realty Buildings, Solar Environmental Engineering Co. (SEEC), January, 1980.

4. Analytic Sciences Corp., Applied Optimal Estimation, Edited by Arthur Gelb, Cambridge, Massachusetts, M.I.T., Press, 1974.

Section 5: SOLAR HOT WATER SYSTEMS

5

SOLAR HOT WATER TEST PROGRAM

NATIONAL BUREAU OF STANDARDS

A. H. FANNEY

DE/AI01-76PR06010

OBJECTIVES

To assist the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) in the development and validation of a standard test procedure for solar domestic hot water systems; and to conduct controlled experiments on typical solar domestic hot water (SDHW) heaters to determine the extent to which TRNSYS, F-Chart, and Solcost can accurately predict their performance.

DESCRIPTION OF WORK

The Steering Committee of the American National Standards Institute on Solar Energy Standards designated ASHRAE to develop a standard test method for SDHW systems. NBS staff members have participated in the development of this standard test method, ASHRAE Standard 95, for the testing and rating of residential SDHW systems.

Test equipment has been designed and fabricated at NBS in accordance with the standard. Three methods were investigated which allowed the net thermal output of an irradiated array to be duplicated under nonirradiated conditions. The first method used an electric heat source only. The second method uses a nonirradiated array in series with an electric heat source. Electric strip heaters attached to the back of nonirradiated absorber plates are employed in the third method. All system components are located indoors, in a controlled environment, allowing comparisons of system performance independent of outdoor meteorological conditions and geographical location of the laboratory. Tests have been conducted to determine if the control functions of a system tested according to ASHRAE Standard 95 are similar to those of a system tested under irradiated conditions.

In addition to assisting ASHRAE, NBS has collected experimental data for a second 12-month period to determine the performance of six SDHW systems and one conventional hot water system. The systems tested during the second twelve months are:

- Direct, Single-Tank Drain Down System
- Direct, Double-Tank Drain Down System
- Indirect, Single-Tank System Using Ethylene Glycol With a Wrap Around Heat Exchanger
- Indirect, Double-Tank System Using Ethylene Glycol With a Coil-In-Tank Heat Exchanger
- Indirect, Double-Tank System Using Evacuated Tube Air Collectors and an Air to Water Heat Exchanger
- Single Tank Direct Thermosyphon System
- Conventional Electric Hot Water System

The experimental results will be compared to the predictions of computer programs used to predict the thermal performance of SDHW systems.

TECHNICAL ACCOMPLISHMENTS

- Governing equations required to determine the input power supplied to the electric heat source and electric strip heaters have been developed. The analysis includes collectors connected in series and parallel.
- Two identical SDHW systems have been fabricated which allow the performance of a SDHW system using outdoor irradiated collectors to be compared to the performance of a SDHW system in which the irradiated array has been replaced with an electric heat source, an electric heat source downstream of a nonirradiated array, or a nonirradiated array with electric strip heaters attached to the back of the absorber plates.
- The SDHW system using irradiated collectors operated for four selected days. Using the recorded meteorological data for each test day as input data, the SDHW system using an electric heat source duplicated the thermal output of the irradiated array within four percent even on an intermittently cloudy day, Fig. 1.
- SDHW system using irradiated collectors was allowed to operate for two selected days. An electric heat source downstream of a nonirradiated array was used to duplicate the thermal output of the irradiated array. Excellent agreement between the thermal output of irradiated array and the nonirradiated array with downstream heat source, Fig. 2. Control functions indoors almost identical to those observed during operation of the irradiated system.
- Electric strip heaters attached to the back of nonirradiated absorber plates used to duplicate the thermal output of irradiated collectors. Excellent agreement achieved, Fig. 3.
- Twelve months of experimental data collected for six SDHW systems and one conventional hot water system.

FUTURE ACTIVITIES

Future work will include expansion of the scope of ASHRAE Standard 95, investigation of a standard rating day criteria, and experimental investigation

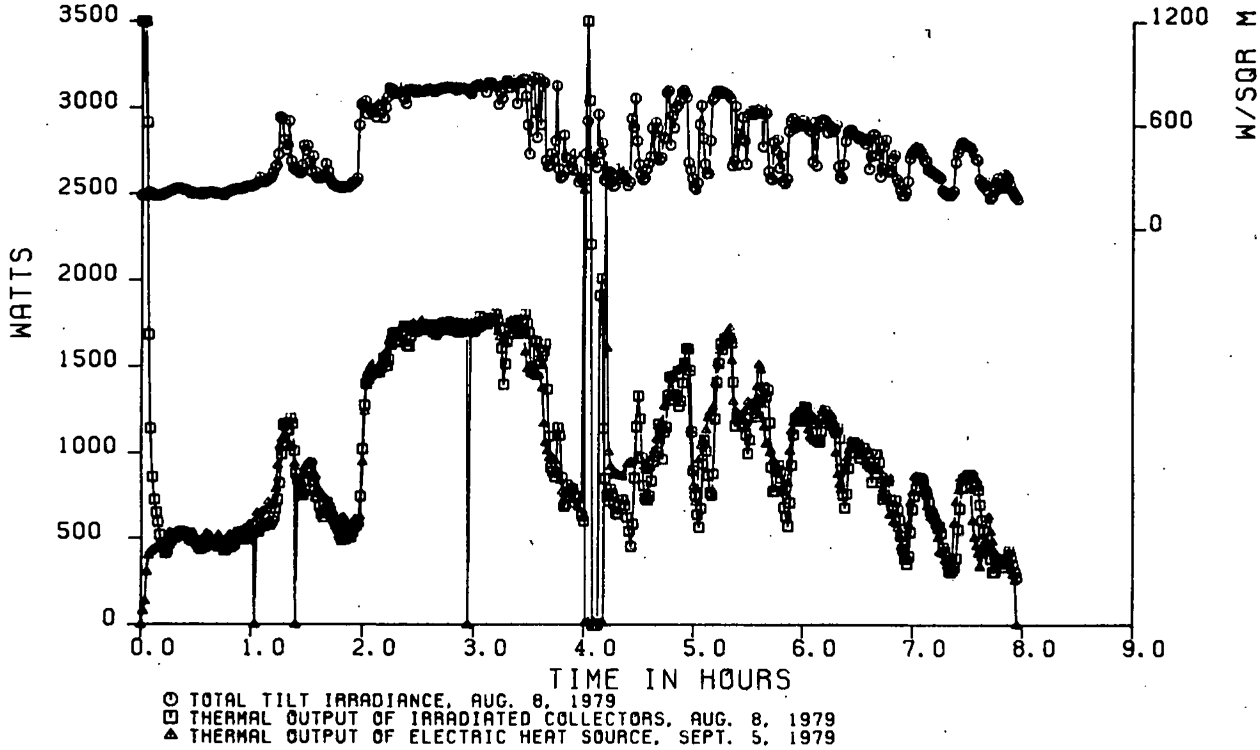


Fig. 1 Thermal Output Comparison of Irradiated Collector Array for Aug. 8, 1979 and Electric Heat Source for Sept. 5, 1979

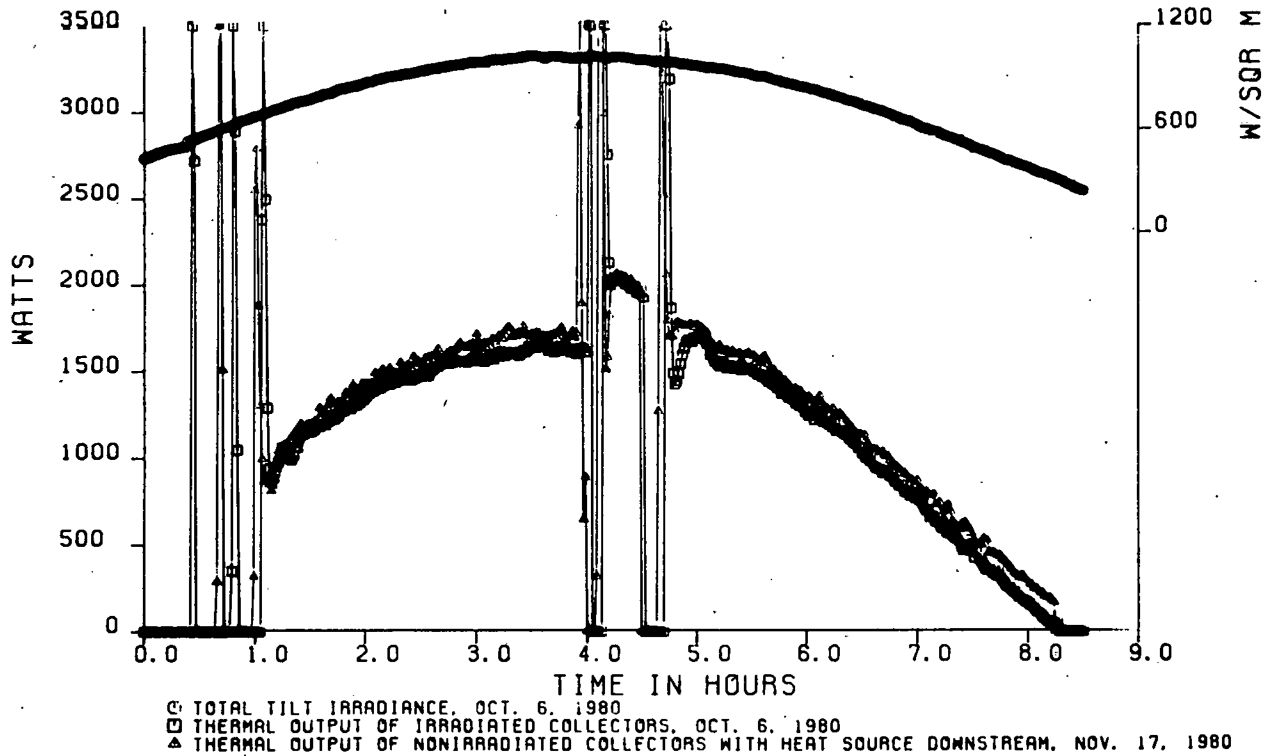


Fig. 2 Thermal Output Comparison of Irradiated Collector Array for Oct. 6, 1980 and Nonirradiated Collector Array with Downstream Heat Source for Nov. 17, 1980

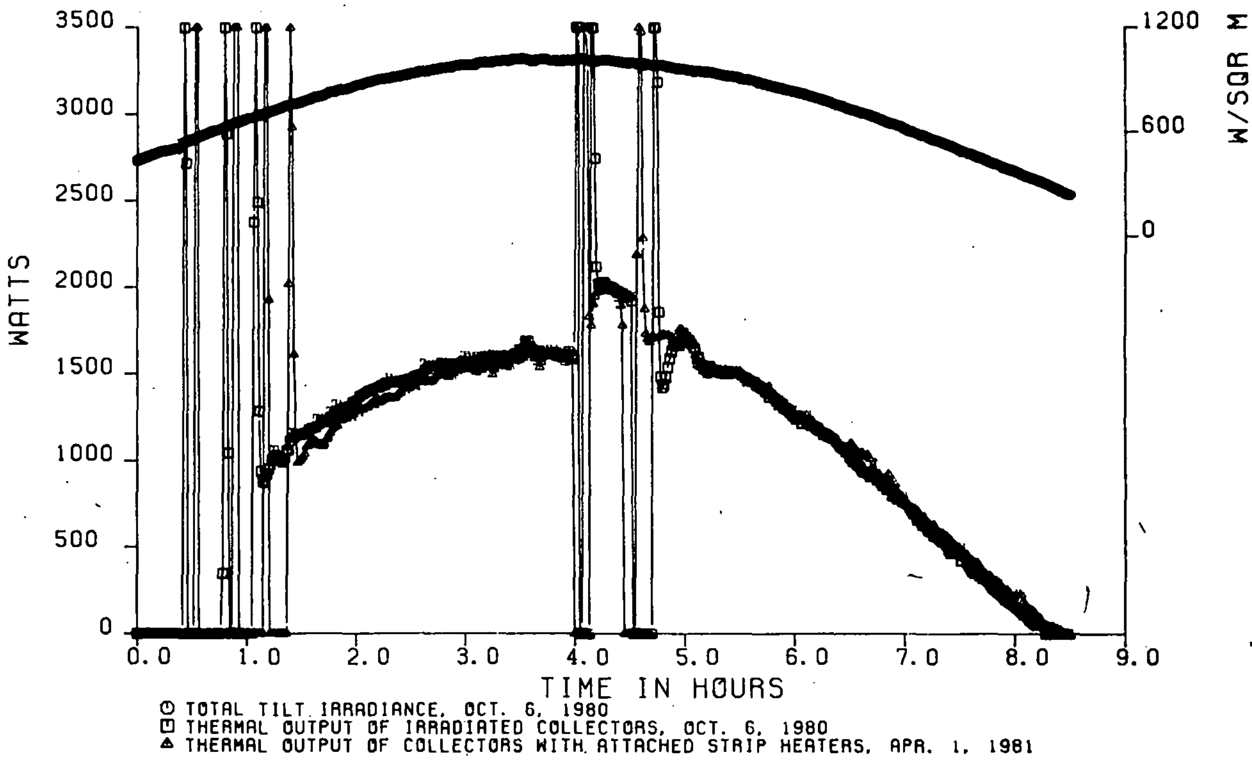


Fig. 3 Thermal Output Comparison of Irradiated Collector Array for Oct. 6, 1980 and Nonirradiated Collector Array With Attached Strip Heaters for April 1, 1981

of advanced SDHW systems.

PUBLICATIONS

Fanney, A.H.; Liu, S.T., "Comparison of Experimental and Computer-Predicted Performance for Six Solar Domestic Hot Water Systems", ASHRAE TRANSACTIONS, Vol. 86, Part 1, PP. 823-835; New York, N.Y.; ASHRAE(02/80)

Fanney, A.H.; Liu, S.T., "Experimental System Performance and Comparison with Computer Predictions for Six Solar Domestic Hot Water Systems", PROCEEDINGS OF THE 1979 INTERNATIONAL CONGRESS OF THE INTERNATIONAL SOLAR ENERGY SOCIETY; Killeen, Texas; ISES(05/79)

Fanney, A.H.; Liu, S.T., "Performance of Six Solar Domestic Hot Water Systems in the Mid-Atlantic Region", PROCEEDINGS OF THE SECOND ANNUAL SOLAR HEATING AND COOLING OPERATIONAL RESULTS CONFERENCE; Washington, D.C.;DOE(11/79)

Fanney, A.H.; Liu, S.T., "Test Results on Hot Water Systems Show Effects of System Design", SOLAR ENGINEERING, PP. 25-29; Dallas, Texas; SEIA(05/80)

Hill, J.E.; Fanney, A.H., "A Proposed Procedure of Testing for Rating Solar Domestic Hot Water Systems", ASHRAE TRANSACTIONS, Vol. 86, Part 1, PP. 805-822; New York, N.Y.; ASHRAE(02/80)

CONTRACT INFORMATION

START DATE October 1977 END DATE T.B.D. CONTRACT VALUE FY 81 225k Estimated

MILESTONES

Item:	Due date:
1. A paper describing the experimental technique of simulating a solar collector array by using the actual collectors indoors in series with an auxiliary heat source will be submitted to the ASME Journal of Solar Energy Engineering	February 1981 m
2. An NBSIR will be published containing the results of the NBS work pertaining to the development and validation of ASHRAE Standard 95	June 1981 p
3. A paper describing the second year of the validation experiments for the six SDHW systems and the conventional hot water system will be submitted to ASHRAE for publication in ASHRAE Transactions	September 1981 p
4.	
5.	

HVAC MARKET DATA ANALYSIS

PLANCO, INC.

C. ROBERT COATES

CONTRACT NO. DE-AC03-80CS30208

OBJECTIVE

The specific objectives of this project were to design and build a computerized data base from previously collected HVAC market data; to develop computer programs for producing strategic reports from the data base; and to assess the market potential for solar HVAC products.

DESCRIPTION OF WORK

Background

HVAC market data for 1970 through 1979 were collected and analyzed during an earlier contract period. That work resulted in a market survey report,[1] and a large volume of data giving annual shipments and, in many cases, shipment values as a function of equipment capacity for virtually all statistically significant types of HVAC products. Shipments of many HVAC products according to geographic distribution and end use are included in the collected data. The data are in the form of individual annual files from a number of different sources, and are in a wide variety of formats.

HVAC Data Base

One part of this project was to computerize the above HVAC data files and generate a comprehensive data base that can be readily updated. The data base is to be used in further analysis of the HVAC market and in assessing the market potential of solar HVAC products.

Because of the large amount of data and the nature of the differences, editing to make the source files uniform in content and format was not feasible. Therefore, the first step was to design a flexible data encoding system capable of accommodating all of the variations. The encoding system was applied to each file; key files were entered on computer media; and the data base was assembled and validated.

Computer Programs

Computer programs were developed for rearranging, aggregating, and analyzing selected files in the data base to produce several fundamental types of reports. One of the principal reports gives the breakdown of the annual shipments, capacity shipped, and shipment value for a specified HVAC product (or combination of products) according to capacity. A related report gives a historical analysis in which total shipments, total capacity shipped, and total shipment value by year are assembled and listed for specified products.

Other fundamental reports include market growth trends (average annual compounded growth rates between selected years); product cost analysis (equipment cost per unit capacity); and installed stock inventory (cummulative units shipped less attrition); all by individual product or combinations of products.

The development of computer programs for generating these reports involved the design of common routines for searching the data base for arbitrarily selected product types, time periods, etc. Individualized routines were required for data interpolation, regrouping, aggregation, conversion, analysis and printing.

The HVAC data base and the computer programs are described in the final report for this contract period.[2]

Solar Air Conditioning Market Assessment

The assessment of the market potential for solar HVAC products focused on delineation of the conditions under which solar air conditioning (both residential and commercial) could become a viable competitor in the HVAC marketplace. An economic model for calculating return on investment (ROI) for the additional initial cost of solar systems compared to conventional systems was developed for this purpose.

All significant factors contributing to initial costs and operating costs were identified and assessed in determining the ROI for solar relative to conventional HVAC systems. This involved defining and analyzing numerous scenarios including various combinations of capital costs, fuel cost escalation rates, inflation rates, purchase dates, government economic incentives, etc. The sensitivity of ROI to each parameter was first investigated, and plausible combinations which showed potential for yielding a favorable ROI (assumed to be 20%) were then analyzed in more detail.

The results were expressed in terms of design-to-cost goals which, if met during the 1985-1990 time-frame, should lead to significant levels of market penetration (as many as 500,000 systems per year) by solar air conditioning by the end of this century. The market history of the heat pump was analyzed and used as a precedent for forecasting solar air conditioning market penetration.

The solar air conditioning market assessment is described in detail in a topical report.[3]

TECHNICAL ACCOMPLISHMENTS

- A flexible data encoding system capable of accommodating a wide variety of HVAC market data files was developed and applied to construct a computerized data base. The data base contains over 350 individual files (i.e., shipment data on one product for one year) covering the period 1970-1979. These files give the annual shipments of 37 kinds of HVAC products such as boilers, furnaces, heat pumps and different types of air conditioners, all as a function of capacity.

- Computer programs were developed for preparing selected fundamental reports from the data base. Key reports include shipments of individual or combined products as a function of capacity and as a function of time; market growth rates, product cost analysis; and installed stock inventory.

- An economic model was developed for parametric analysis of return on investment (ROI) for solar air conditioning and heating. The model was used to calculate ROI for both residential and commercial solar systems for a wide variety of scenarios involving initial cost, fuel cost escalation, inflation, purchase date, government economic incentives, etc. It was found that ROI is quite sensitive to most of these factors; that current solar HVAC system prices are too high to make their purchase economically attractive; and that the expiration of federal energy tax credits may negate any cost improvements made by the end of 1985. Fig. 1 shows the sensitivity of ROI to fuel cost escalation and inflation rates for 1985 purchase of a hypothetical 3-ton residential system costing $10,100.

- Solar air conditioning design-to-cost goals were established based on the assumption that a 20-percent ROI on the additional initial cost relative to conventional HVAC systems would be economically attractive. Fig. 2 shows the allowable incremental cost for a nominal 3-ton residential system as a function of purchase date and reference conventional system. Fig. 3 shows corresponding information for a nominal 25-ton commercial system. Incremental cost based upon current actual costs are generally a factor of three higher than the goals shown in Figs. 2 and 3. It is noted that the effect of the federal energy tax credit (not included in Fig. 2) is to increase the allowable incremental investment for residential solar systems by as much as $4,000 through the end of 1985.

FUTURE ACTIVITIES

Planco, Inc. recommends that future activities stemming from this project include updating the data base with 1980 HVAC shipment data now available. The updated data should be analyzed to identify the impact of energy conservation and reduced housing construction on the current makeup and trends of the HVAC market, and on the future market for solar air conditioning.

It is further recommended that the ROI model be updated to account for the impact of improved conventional HVAC equipment efficiency and reduced building loads on the economics of solar air conditioning. Updated design-to-cost goals for solar HVAC should be developed for a wider range of energy price escalation scenarios including precipitous price increases.

REFERENCES

1. "Survey of the HVAC Market," Planco, Inc., August 1980.

2. "Data Base and Software for HVAC Market Analysis," Planco, Inc., March 1981. (preliminary draft)

3. "Assessment of Active Solar Air Conditioning; 1980-2000," Planco, Inc., January 1981. (preliminary draft)

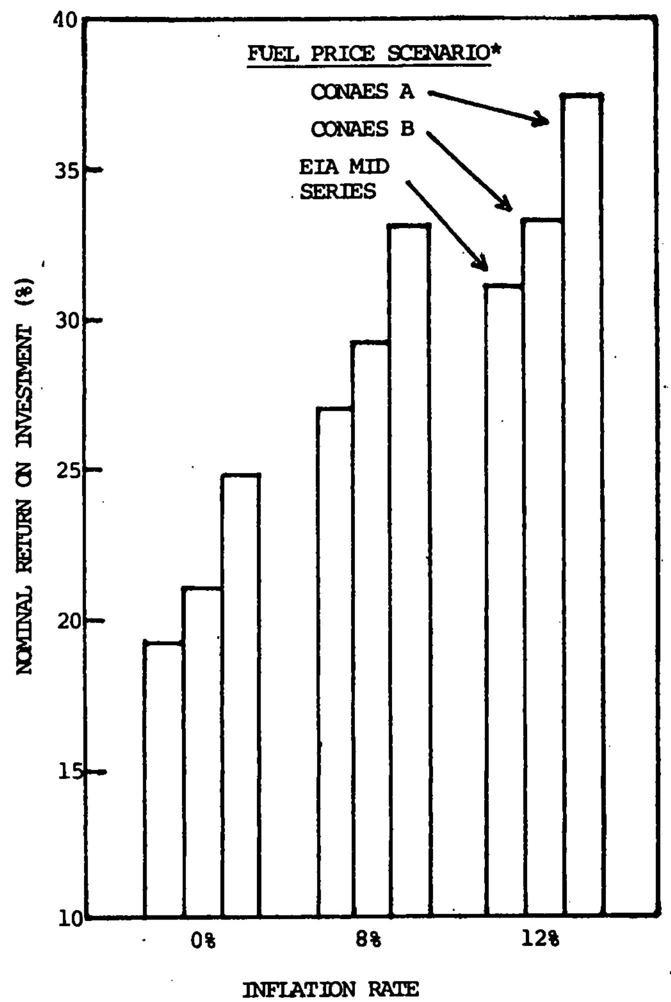


Figure 1. ROI for DOE Average Case Residential Solar System (13,500,000 BTU Cooling and 22,500,000 BTU Heating Annually) Relative to Heat Pump Given 1985 Purchase Date and Existing Federal Tax Credits

*Mid-1980 national averages with escalation: CONAES A - approximately 3.3% annual increase for electricity and 5.7% for gas. CONAES B - 2.0% and 4.5%. EIA MID SERIES - 0.5% and 1.5%.

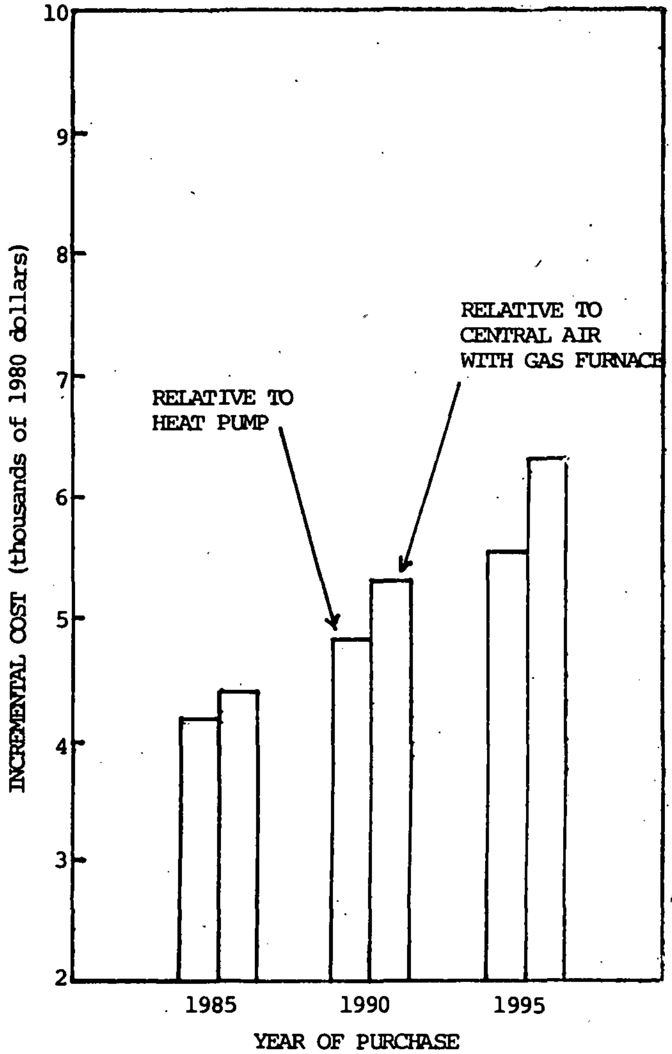


Figure 2. Maximum Incremental Investment for 20% Nominal ROI on Residential Solar Cooling and Heating System (13,500,000 BTU Cooling and 22,500,000 BTU Heating Annually) with 10% Inflation, CONAES A Fuel Price Escalation, and No Tax Credits

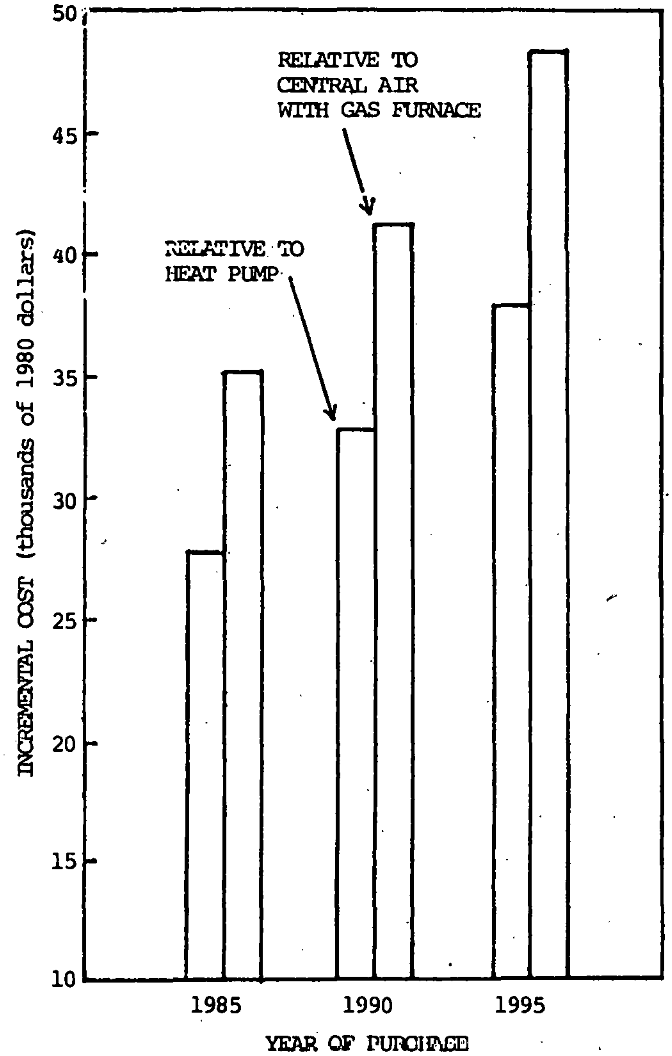


Figure 3. Maximum Incremental Investment for 20% Nominal ROI on Commercial Solar Cooling and Heating System (169,000,000 BTU Cooling and 94,000,000 BTU Heating Annually) with 10% Inflation, CONAES A Fuel Price Escalation, and No Tax Credits

CONTRACT INFORMATION

START DATE August 15, 1980 END DATE March 20, 1981 CONTRACT VALUE $106,157

MILESTONES

Item:	Due date:
1. Topical Report	January 1981
2. Final Report	March 1981
3.	
4.	
5.	

ASSESSMENT OF SOLAR WATER HEATING INDUSTRY

SCIENCE APPLICATIONS, INCORPORATED

ROBERT LECHEVALIER

DE-AC03-80CS30217

OBJECTIVE

To determine the technical feasibility and commercial potential of solar water heating products being supplied to the marketplace.

DESCRIPTION OF WORK

Data were compiled and used to establish the technology readiness and the industry's capabilities to implement the solar water heating technology into the anticipated market place.

The performance, reliability and economics were determined for all identified commercially available solar water heaters. A comparative analysis with conventional water heaters was made to assess the economic competitiveness of solar water heating.

TECHNICAL ACCOMPLISHMENTS

- An adequate supply of packaged solar hot water systems are currently available. These systems look and act like the conventional competition. The best products are available in most metropolitan areas. The product suppliers recognize the importance of matching the design to the marketplace and therefore are currently supplying six different generic configurations.

- Solar hot water systems are maturing very rapidly, and are performing well, with remarkably few problems. The leading problems that do exist are related to installation, improper materials selection, and design inadequacies. The products are protected with adequate warranties.

- Most of the designs should perform quite adequately when matched to the climatic environment. The home-owner can expect solar energy to provide 60 to 80% of the hot water with these systems. Some of the systems being sold will not perform to the levels claimed as they have been erroneously represented, usually due to an over-optimistic collector performance prediction.

- Solar hot water economics have improved substantially as the utility costs have continued to escalate and federal and state governments have introduced incentive programs. Solar hot water systems compete very favorably against most electric utility rates and are now beginning to compete with gas water heaters.

- The solar hot water industry contains a sufficient number of large and small business enterprises, producing well designed and documented products. Five of the top twelve manufacturers were previously involved in the water and HVAC industries and had the necessary distribution outlets for a successful commercial venture.

- Solar hot water systems are well matched to the best market environments. They compete most favorably as a replacement for the electrical water heater in single-family residences in the high radiation environments of the southern and western states.

FUTURE ACTIVITIES

Actions which the government could support to accelerate the commercialization of this hot water technology and provide a better product to the consumer are as follows:

- Create a materials information center which could be made available to manufacturers. The information center could also conduct special tests for the smaller manufacturers.

- Promote quality systems through government sponsored systems test programs, such as RCS, Federal Buildings Program, Military Purchases Programs, and other federal purchases.

- Support improved and simplified data collection on installed systems to identify systems' performance and reliability. This information could be useful in rating systems.

- Provide industry with support for installer training programs to be operated and taught by manufacturers.

- Continue existing tax credit programs at their current levels to insure the rapid introduction of solar water heating into the residential sector.

PUBLICATIONS/REPORTS/REFERENCES

Comparison of Conventional and Solar Water Heating Products and Industries SAI Report, July 11, 1980.

Assessment of Commercial Readiness of Solar Water Heating, paper presented at ASME SSEA meeting, Reno, Nevada, May 1, 1981.

CONTRACT INFORMATION

START DATE 1/80 END DATE 7/80 CONTRACT VALUE $69,000.

MILESTONES

Item:		Due date:
1.	Final Report	7/80
2.		
3.		
4.		
5.		

Section 6: SPECIAL PROJECTS

6

EXPERIMENTAL AND ANALYTICAL SYSTEM STUDIES OF A COMBINED PV/T RESIDENTIAL SOLAR SYSTEM

Arizona State University

Byard D. Wood

DE-AC-03-79CS-30203

OBJECTIVE

The goal of this research is to help evaluate the commercial viability of combined photovoltaic/thermal (PV/T) solar systems using concentrator collectors. Specific goals are: to define and categorize potential PV/T concentrator collector systems, to do computer simulation analyses of PV/T systems for industrial process heat, absorption space cooling, space heating and domestic hot water applications, to compare PV/T concentrator systems with side-by-side solar thermal (only) and PV (only) systems, to measure both the electrical and thermal performance of PV/T prototype concentrator collectors, and to evaluate appropriate methods of testing PV/T concentrator collectors.

DESCRIPTION OF WORK

This project combines both analytical and experimental studies aimed at assessing the role of concentrating PV/T collectors. The broad and fundamental nature of the work is a result of a major rescoping in mind-1980 of the original contract consumated in mid 1979. Prior to that time, the project concerned only an assessment of PV/T for use in residential absorption systems. The publication list below includes references to documents completed under the original scope of work; only work under the new scope of work will be discussed here.

Under the new scope of work, this project will attempt to determine when PV/T collectors have an advantage over side-by-side PV arrays and thermal collectors. Analytical work is being done using the TRNSYS compatible PV/T computer codes developed at Arizona State University. The collector being used as a baseline in the modeling is the E-System's prototype PV/T concentrator developed for the Dallas-Fort Worth (DFW) Airport PRDA program.

In comparing combined versus side-by-side collectors, costs and energy production must be considered. A relatively simple but useful concept for combining costs and energy production is through the levelized cost methodology. Figure 1 shows the results for annual TRNSYS simulations using an inlet temperature of 40 C. The solid lines are for Phoenix, AZ, TMY data and the dashed curves are for Madison, WI, TMY data. Each line is for a different PV/T collector capital cost.

To use this information consider the following example for Phoenix. Suppose that a thermal (only) collector produced 1900 kWh_t of energy at an inlet temperature of 40 C and could be installed at a cost of $200/sq. m of aperture. This is E-System's estimate and will be referred to as a Baseline Thermal case ($0.105/$kWh_t$/ yr.

Suppose also that the PV/T collector could be installed for $300/sq. m (E-System's estimate). Entering Fig. 1 on the vertical axis at $0.105/$kWh_t$/ yr, proceeding horizontally until intersecting the $300 Combined Collector Cost curve and then proceeding downward, shows that when PV only array costs are above $0.60/$kWh_e$/yr, stand alone systems are unattractive. That is, it is more economical to install the PV/T system rather than side-by-side units under these conditions.

Figure 2 was constructed to relate costs for thermal only collectors as a function of combined (PV/T) collector costs for PV (only) array costs of $0.70/$W_p$ and $2.70/$W_p$. Further simulations are being conducted to look at the sensitivity of the results to (a) the thermal conductance between the cells and the coolant fluid. (b) the collector loss coefficient and mode of tracking, and (c) the energy values.

A technique is being developed for collapsing the data shown in Figure 1 for Phoenix and Madison onto a single family of curves valid for any city location. This has been done for flat-plate thermal collectors as shown in Figure 3 in which monthly collection efficiencies or monthly utilizabilities are correlated with collector input variables that are commonly used in thermal test procedures i.e., collector inlet temperature, mean monthly ambient temperature, and the Liu and Jordan clearness factor. Figure 3 provides an easily interpreted and quick to use performance map that covers a wide variety of operational conditions. This method, in general, gives good results compared to long term hourly simulation.

The experimental part of this work involves measurements on a prototype PV/T concentrating collector to establish a first hand working knowledge of such collectors. This test program will also confirm the analytical modeling discussed previously. Participants in this phase of the program are also working with national groups establishing standards for PV/T collector testing.

TECHNICAL ACCOMPLISHMENTS

- Development of generalized cost comparisons for comparing PV/T to side-by-side solar converters. This methodology is demonstrated in the Description of Work above. The methodology does not rely on the often made assumption of "the thermal output is assumed to have a value 1/3 that of the electrical output."
- A new formulation of the utilizability concept of Whillier, Liu and Jordan, and Klein has been developed. This new approach is useful in predicting the monthly thermal gains of a

thermal (only) collector operating with a fixed inlet fluid temperature. This formulation relies on knowledge of only a very minimum of site dependent data. The method is useful in the cost methodology mentioned above when comparing PV/T with side-by-side units.

- Several potential uses of PV/T collectors are being studied in detail. These include dewatering of crude oil, boiler feed water heating, and hospital uses.

- Team members are working on national committees formulating standards for testing PV/T collectors. Responsibilities have ranged from overall standards development, generally, to development of methods of data presentations, specifically. Figures 4 and 5 demonstrate the methods of data presentation as they are currently envisioned.

FUTURE ACTIVITIES

Contract activity will end on or about July 31, 1981. A final report will be issued shortly thereafter, describing the details and findings of the program under the expanded scope of work.

PUBLICATIONS/REPORTS/REFERENCES

"Experimental and Analytical System Studies of a Combined Thermal-Photovoltaic Residential Solar System" ASU Report ERC-R-80029 (Draft, 1980).

"Residential Solar Absorption Chiller Thermal Dynamics" ASU Report ERC-R-81013 March 1981.

"Design and Validation of a Thermal Simulator for Solar System Performance Testing" ASU Report ERC-R-80031, May 1981.

"A New Look at Long Term Collector Performance and Utilizability" ASU Report ERC-R-81015, April 1981.

PARTICIPANTS

D. L. Evans, U. Gurdal, K. Janzen, R. Lenhart, T. T. Rule and B. D. Wood.

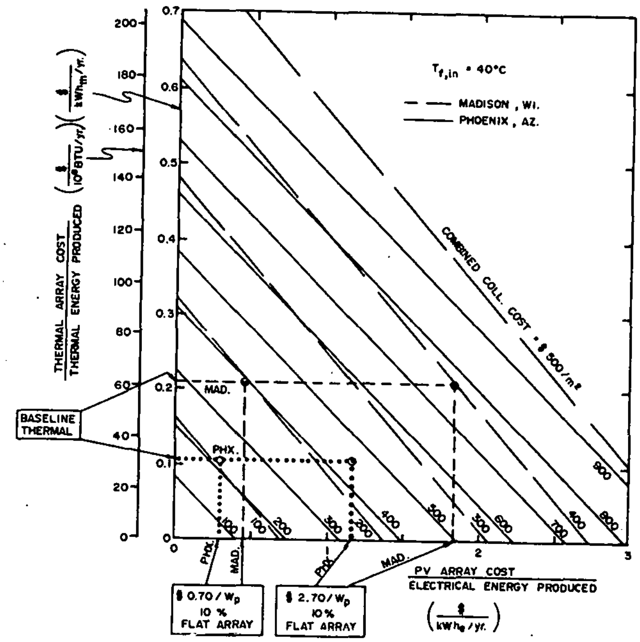


Figure 1. Cost comparison curves for E-Systems prototypical concentrating PV/T collector for an inlet temperature of 40°C. Baseline thermal collector is E-Systems concentrating thermal (only collector) performance based on hourly simulations.

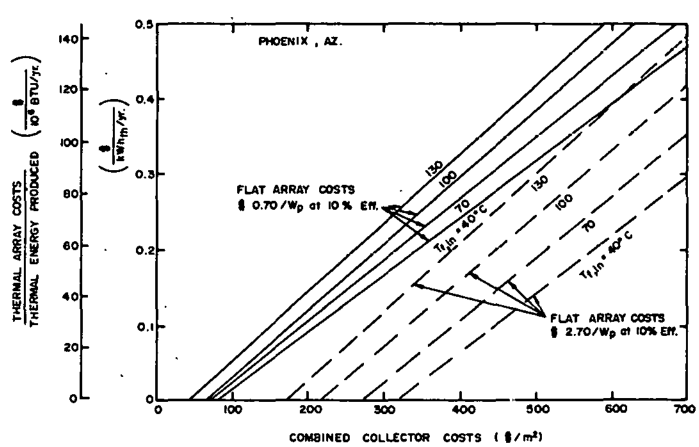


Figure 2. Cost comparison of thermal (only) collectors as a function of E-Systems concentrating PV/T collector at PV (only) flat array costs of $\$0.70/W_p$ and $\$2.70/W_p$.

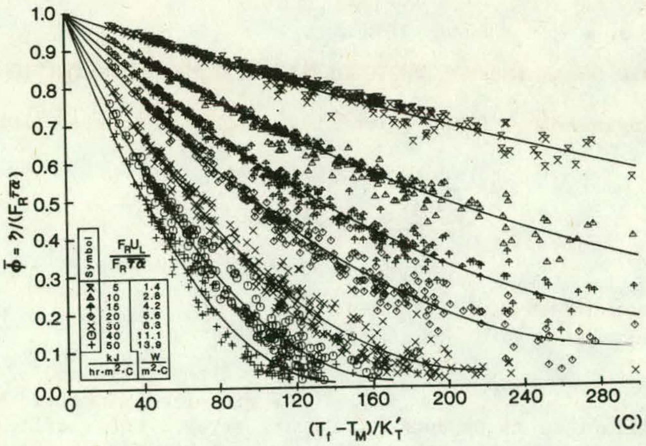
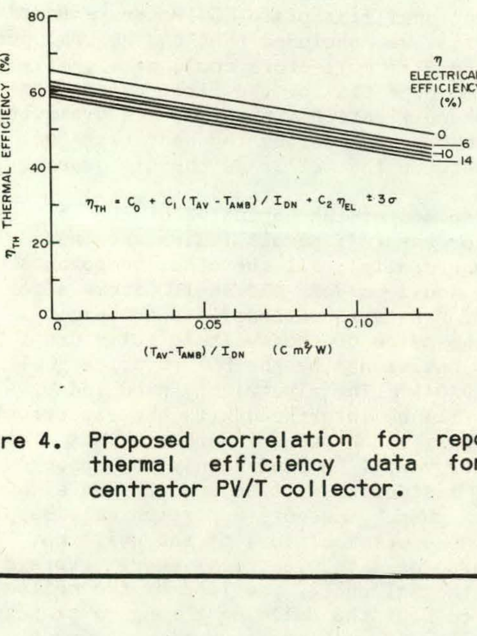


Figure 3. Monthly efficiencies or monthly utilizabilities for flat-plate thermal collectors. Monthly values for 8 cities and 3 inlet temperatures were calculated using hourly computer simulation and SOLMET weather data.



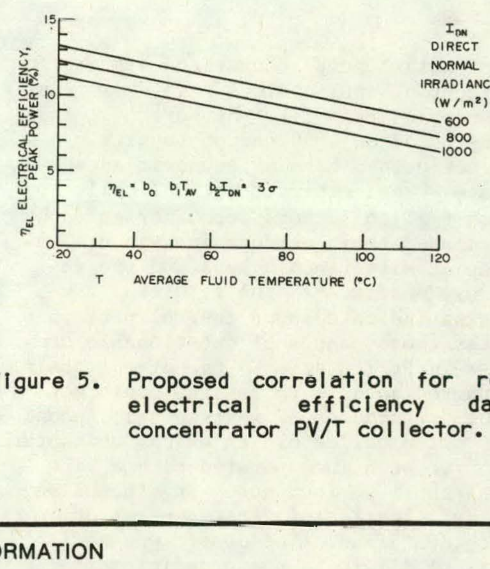


Figure 4. Proposed correlation for reporting the thermal efficiency data for a concentrator PV/T collector.

Figure 5. Proposed correlation for reporting the electrical efficiency data for a concentrator PV/T collector.

CONTRACT INFORMATION

START DATE July 1, 1980 END DATE August 15, 1981 CONTRACT VALUE $194,024

MILESTONES

Item:		Due date:
1.	Define and categorize PV/T concentrator	August 1981
2.	Modified TRNSYS systems simulations	August 1981
3.	Cost comparisons of PV/T collectors	August 1981
4.	Modify ASU collector test facility to test PV/T concentrator collectors	August 1981
5.	Determine appropriate test methods for PV/T concentrator collectors	August 1981

HYBRID SOLAR THERMAL PHOTOVOLTAIC SYSTEMS DEMONSTRATION

Division of Engineering, Brown University, Providence, Rhode Island 02912

Joseph J. Loferski

DE-AC03-79-CS30205

OBJECTIVE

The objective of the contract is to produce a conceptual design of a combined photovoltaic/thermal (PV/T) solar energy system utilizing a heat pump for space conditioning intended for a single family residence; to design, construct and test PV/T panels for this application; to generate a computer model to simulate the performance of the system; to evaluate the economic potential of the PV/T system; to design a building into which the PV/T system will be incorporated; to construct the building and the PV/T system; to monitor its performance and to compare the performance with predictions based on a model of the system.

DESCRIPTION OF WORK

Analysis of solar energy conversion systems for individual residential applications have shown that in certain geographic areas like the Northeast and Midwest, systems based on combined photovoltaic/thermal (PV/T) collectors have an economic advantage over separate PV and separate thermal collectors. First generation PV/T collectors were fabricated by ARCO and Spectrolabs; their performance was evaluated by the group at MIT--Lincoln Labs and the results reported by Hendrie.(2) The resulting η vs. ΔT characteristics indicated poor thermal performance, which makes those panels of questionable usefullness for use in PV/T systems. One of the goals of the work reported here is to design, construct and evaluate the performance of what we call second generation air cooled collectors in which substantial design changes have been incorporated with a view toward improving their performance. To accomplish this goal, the deficiencies of first generation collectors were identified. The design was modified to suppress or eliminate these deficiencies. The η vs. ΔT characteristics of the ARCO and Spectrolab collectors have an intercept on the η vs. ΔT axis which is in the 0.40 to 0.46 range whereas good thermal-only collectors have intercepts in the 0.55 to 0.70 range (see Fig. 1).

We chose to focus our attention on collectors, like the Spectrolab model, which use air as the heat transfer fluid and in which the light receiving surface of the cells is bonded to a pane of glass. The glass serves as a rigid superstrate which protects the cells against fracture from flexure. In such a PV/T design, the glass plate with the cells bonded to it becomes the absorber plate of the thermal part of the collector. The objective of good design is to reduce losses from this plate and to incorporate changes which lead to a large heat transfer coefficient from the underside of the "absorber plate", i.e. from the PV cells, to the air. It is important that the difference between the temperature of the cells and of the air flowing past the cells be minimized since if the cells are hotter than the air stream, their efficiency as PV cells decreases without benefit to the thermal performance of the collector. We concluded that the main reasons for the poor thermal performance of the first generation PV/T air collectors was excessive thermal resistance between the cell/absorber surface and the air stream. This would cause the cells to run hot and reduce their PV performance. In addition, we condluded that the low value of the intercept on the η vs. ΔT characteristic was attributable to the lower absorptivity of the glass/cell "absorber plate" of the PV/T collector as compared to the absorptivity of the "black" metal absorber plates used in conventional flat plate collectors. Based on this analysis, we concluded that the thermal performance of the PV/T collectors could be significantly improved over that of the first generation collectors by modifications in surface absorptivity of the cells and by increasing the heat transfer coefficient between the cells and the air stream.

It was decided at the beginning of the project that except for the PV/T panels (which were not available commercially), all the other components in the system would be "off the shelf" items since the whole PV/T system is intended for commercialization when the price of photovoltaic cells drops to the levels envisioned by the DOE PV price goals for the mid 1980's. The electricity produced by the PV cells will be interfaced with the electrical utility through a synchronous inverter. This electrical energy will be used mainly for space conditioning; most of it will be used to run a conventional heat pump. However, a portion will supply the distributed electrical load of the building. There will be no on-site electrical energy storage system. The thermal energy provided by the collector will be used to heat the building through a standard air heating solar thermal configuration. A rock storage bin will be incorporated in the system. Figure 2 is a schematic representation of our system. The building we have designed is of unconventional construction. It will be prefabricated from framed sandwich panels consisting of two plywood sheets enclosing a foam insulator interior. The exterior surfaces of the panels can be finished with fiberglass or aluminum sheets, gypsum board, hardwood panels, etc. The foam type, density and thickness are selected to achieve a desirable balance of structural, thermal and acoustical properties. The building will be consigned to Brown University for the duration of the project by its manufacturer, Goldmark Industries of Newburg, N.Y. The floor area will be 1200 ft^2; the roof is of A frame construction, an optimum angle having been chosen after modeling of the performance of the building in Rhode Island.

During the first phase of the project much of the effort was devoted to developing a computer model which would satisfactorily simulate the performance of PV/T panels and of the whole system. By combining computer programs from the University of Wisconsin (TRNSYS - A Transient Simulation Program), Arizona State University (PV/T collector and inverter simulation routines), and Brown University (system controller and heat pump simulation routines), it has been possible to build a computer model that can simulate our complex, multi-mode PV/T system (shown schematically in Fig. 1) and that can accept frequent changes in the system's configuration or control scheme.

A computer model of a baseline all-electric heat pump residence was also written and used to provide a basis for comparison over the full test year. This baseline simulation, together with simulations of various configuration of the PV/T-heat pump system formed the basis for choosing the size of various components and for optimizing the control strategy.

An important question about any energy system is its economic viability. In the case of the PV/T system under consideration, it is first necessary to determine the amount of electrical and thermal energy produced by the system and to determine its economic value. The simulation program described above provided this information. The next step is to determine the cost of the system components,installation costs and maintainance costs. Having collected this information, we then computed the return on an investment in PV/T and thermal only systems added to the building. Various reasonable assumptions about the inflation rate, the discount rate,interest rate, tax credits, tax savings, etc. were made and cash flow projections for the assumed twenty year life of the system were made.

Finally, components for the system have been ordered. A construction schedule has been set up and work on implementing the system has begun.

The project has attracted financial support ($50,000 for 1981) from the New England Electric System (NEES), the parent company of the local electric utility. The value of the building being consigned to the project by Goldmark Industries is about $40,000. Other industrial organizations are expected to participate in the project by donating or consigning other equipment needed in the system.

TECHNICAL ACCOMPLISHEMENTS

A "second generation" PV/T panel was designed and constructed. Tests at the University of Conn Connecticut have shown that the performance of this panel is significantly better than that of the Spectrolab and ARCO panels which comprised the first generation PV/T panels. The performance improvement resulted from two factors. The first was an increase in the absorptance of the cells by recourse to textureed cells covered by an anti-reflection coating and to blackening of the metal grid contacts on the front of the cell. The second was an increase in the heat transfer coefficient by narrowing the air flow channel under the cells or by attaching fins to the backs of the cells. The test panel consisted of two sections. In one of them,heat transfer was increased by attaching fins to the cells as shown in Fig. 3; in the other half of the collector, heat transfer was increased by decreasing the channel width to 0.30" as shown in Fig. 4. Figure 5 is a plot of the overall (thermal plus electrical) efficiency η_o vs. x (i.e. $\Delta T/I$) for this two section collector. As is evident from this figure, the performance of both the finned and narrow channel (labeled "plain" in the figure) is substantially superior to the performance of the first generation PV/T collectors (Fig. 1).

A flexible "streamlined" computer simulation model for the complete PV/T system was developed. It allows for exploration of fourteen modes of operation of the system. A weather tape for Rhode Island was fed into the program. It was found that the PV/T system would provide about 65% of the total energy needs of the building. About one half of the energy is thermal; the other half is electrical. Of the electrical energy, about one half is produced at a time when it can be used in the building, the other half is returned to the utility. With reasonable assumptions about utility payback rates, the utility bill of the inhabitants of the building wiould be about 45% of what it would have been in the absence of the PV/T system.

The economic value of the PV/T system was calculated by comparing the savings on energy associated with the presence of the PV/T system on the building to the cost of the system. For this analysis, it was assumed that the system has a life of twenty years. Reasonable assumptions about possible inflation rates, escalation rates in the real price of energy, interest rates, discount rate, tax credits and tax deductions were incorporated into the model. It was found that a homeowner purchasing the PV/T system would have a return on his investment ranging between 10% and 20% over the twenty year period, depending on which combination of assumptions about the inflation rates, etc. involved is used. The PV/T system has a rate of return which is almost twice as large as the rate of return on a thermal-only system serving this building. A crucial assumption in the economic analysis is that the DOE price goal for PV cells in 1986 will be reached.

An innovative prefabricated building using construction materials and practices which may be prevalent in the mid 80's has been designed.

We have identified components needed for the system like the synchronous inverter, heat pump, etc. and have placed orders for most of them.

We have attracted significant financial support from the local electric utility and from the building fabricator.

FUTURE ACTIVITIES

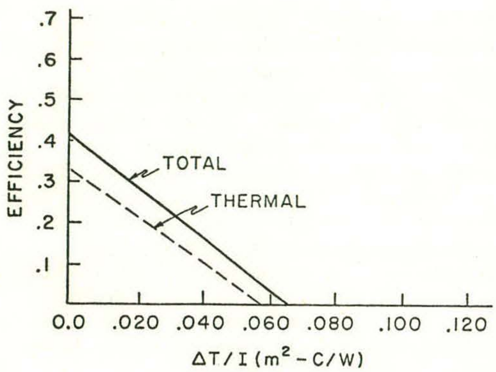
We are proceeding with construction of the system which should be completed by September, 1981. We shall then monitor the performance of the system for at least two years. We have attracted as participants in this project an innovative design firm REDE, Incorporated; a potential fabricator of a complete building with a PV/T system incorporated (Goldmark Industries); the local utility which is interested in participating in monitoring the performance of the system in anticipation that such buildings may appear in its territory during the next decade, and a potential consortium for the fabrication of the PV/T panels. The project has already served as a source of one Master of Science thesis and can be expected to attract other students interested in solar energy systems.

PUBLICATIONS/REPORTS/REFERENCES

1. We submitted a Draft Copy of the Final Report on Phase I of the project to DOE in February, 1981.

2. A paper describing the PV/T collector design, fabrication and testing is being presented at the Fifteenth IEEE Photovoltaic Specialists Conference in Orlando, Florida on May 15, 1981.

FIRST GENERATION PV/T COLLECTORS



SPECTROLAB AIR PV/T COLLECTOR

Figure 1

PV/T SYSTEM SCHEMATIC

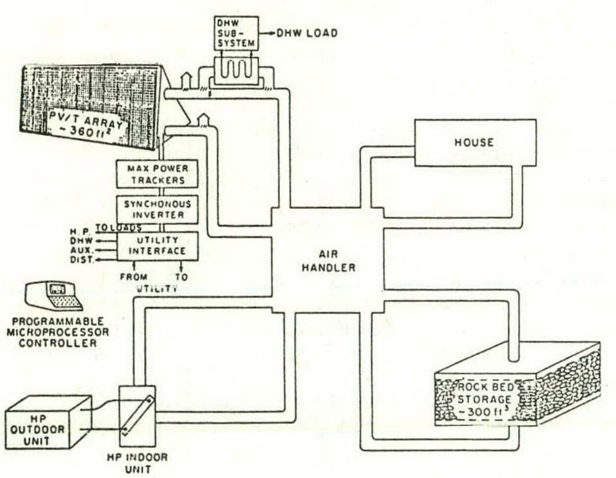


Figure 2

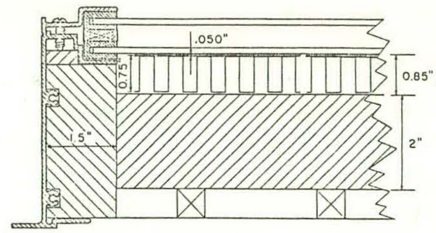


Figure 3

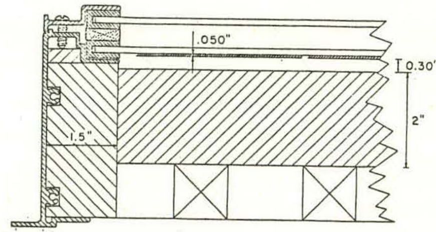


Figure 4

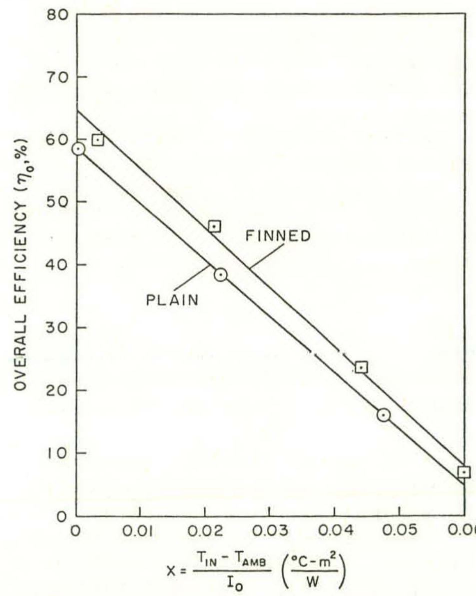


Figure 5

CONTRACT INFORMATION		
START DATE 7/1/79	END DATE 9/30/81	CONTRACT VALUE $449,991.00

MILESTONES

Item:		Due date:
1.	Final Report	October 31, 1981
2.	Two PV/T test panels	October 31, 1981
3.		
4.		
5.		

STUDIES OF HEAT TRANSFER AND WATER MIGRATION IN SOILS

COLORADO STATE UNIVERSITY

WYNN R. WALKER

DE-AS02-79CS30139

OBJECTIVE

The primary objective of this project was to investigate the thermal properties of partially saturated soil which may be located around or in buried heat reservoirs or pipes. Four specific objectives were outlined: to model soil thermal conductivity in relation to mineralogical composition, water content, and bulk density; to study drying rates around warm surfaces; to investigate the water vapor permeability of possible buried reservoir materials; and to evaluate heat exchange characteristics of buried pipes.

DESCRIPTION OF WORK

The thermal regime of partially saturated soils is an important design and operational parameter for solar energy heat storage and heat pump assisted systems. A moist sand has a thermal conductivity of more than an order of magnitude greater than a dry clay soil. To maximize the efficiency of buried heat reservoirs, the conductivity of surrounding soil should be minimized by maintaining it in a dry aggregated form. This project involved first a series of laboratory studies aimed at providing an accurate predictive model of soil thermal conductivity. A small reservoir consisting of a buried soil mass enclosed in a sealed plastic bag was constructed to evaluate the thermal storage efficiency of such systems. The movement of soil moisture away from the reservoir as well as from coils of plastic heat exchange piping within the reservoir was studied in laboratory soil columns. The reservoir concept, illustrated in Fig. 1, was heated and cooled to develop basic operational data. The results were then extrapolated to a 880 cubic meter reservoir which could be coupled via a heat pump to a solar collector system to provide hot water and space heating to a residential sized building. A final phase of the work involved a complex finite element simulation of heat and moisture movements away from heated surfaces.

TECHNICAL ACCOMPLISHMENTS

- A computational procedure was developed and verified for predicting the thermal conductivity of a partially saturated soil having variable water contents, mineralogical composition and bulk densities. A summary of the results, shown in Fig. 2, include four soils: (1) a bentonite clay (90% clay and silt, 10% sand); a sandy clay loam (46% clay and silt, 54% sand); a clay loam (66% clay and silt, 34% sand); and a loamy sand (12% clay and silt, 88% sand). The accuracy of the model covering these soils, a wide range of densities, a moisture content and temperature was within ±11%.

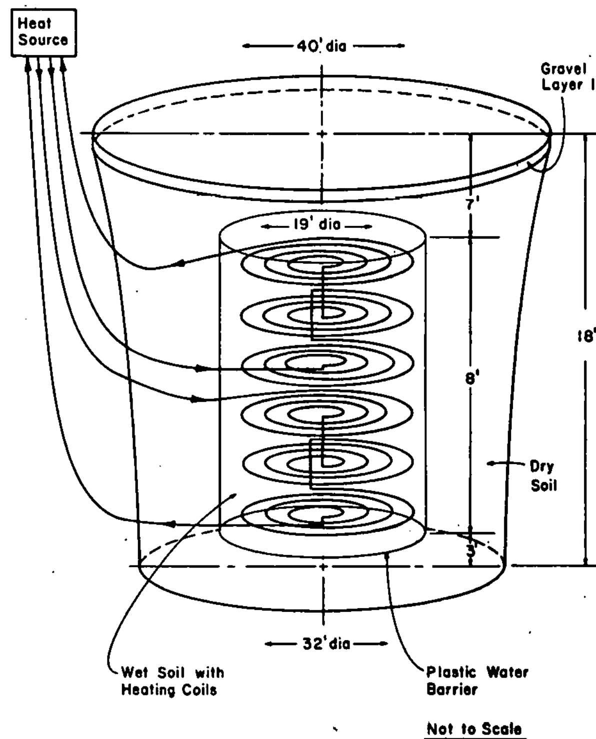


Fig. 1. Illustration of the field heat storage reservoir using insitu soil materials.

- The extrapolation of the prototype heat storage reservoir using insitu soil materials to a full scale installation coupled to a solar hot water and space heating system improved the solar function of the system from 0.58 to 0.84. The small reservoir actually studied experienced heat losses of 1.6% of the stored heat per day at maximum temperature.

- Water vapor permeabilities of various materials that could be used to enclose buried soil heat storage reservoirs were measured. Table 1 presents a summary of these results.

- A detailed finite element model of heat and water movement away from heated surfaces in a soil was formulated and tested. Two cases were modeled: (1) one-dimensional flux near plane surfaces; and (2) cylindrical flux around pipes. An illustration of the predictive capability is given for one plane flow case in Fig. 3.

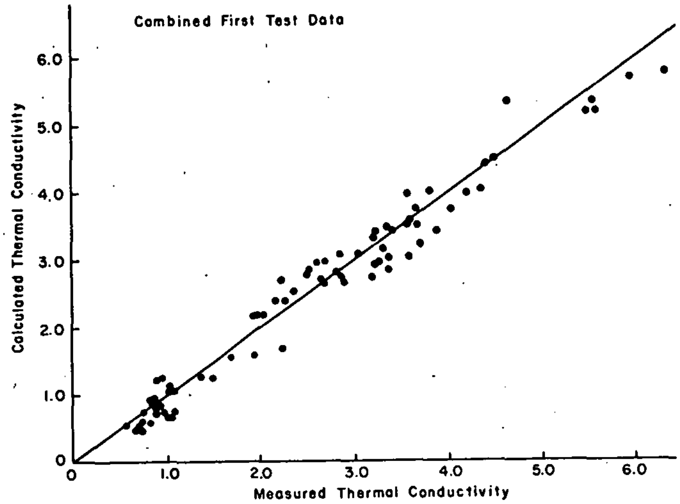


Fig. 2. Composite comparison of measured and predicted thermal conductivities.

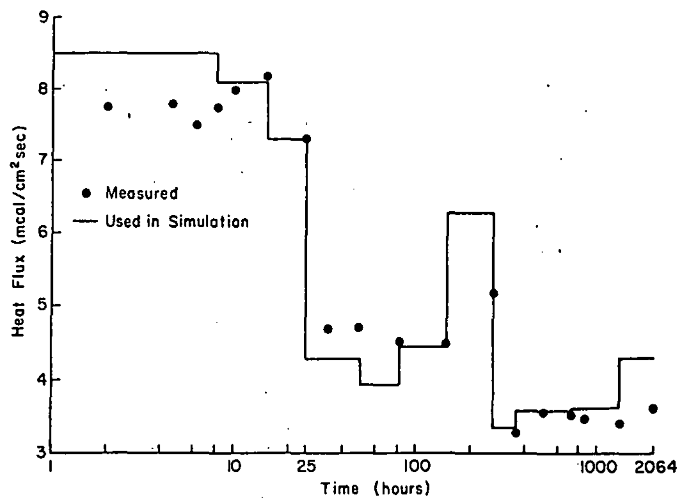


Fig. 3. Predicted and measured heat flux through a cross-section in the Solar Village soil column.

TABLE 1. WATER TRANSPORTATION CHARACTERISTICS OF POSSIBLE THERMAL RESERVOIR BARRIER MATERIALS.

Material	Temp. °C	Water Transmission (gm day^{-1}m^{-2})
Polyethylene Plastic		
10 mil low density	80	200
	50	55
	20	10
20 mil low density	80	110
6 mil medium density	80	70
4 mil high density	80	60
2 mil high density	80	250
20 mil Hypalon	80	70
45 mil Butyl Rubber	80	20
50 mm Polyurethane Foam	20	10

FUTURE ACTIVITIES

The research has been completed and the final report has been submitted to the Department of Energy. No further studies are anticipated. Results of this project will be written into papers and submitted to one or more professional journals.

PUBLICATIONS/REPORTS/REFERENCES

Walker, W. R., J. D. Sabey and D. R. Hampton. 1981. Studies of Heat Transfer and Water Migration in Soils. Final Project Report, Available from the DOE Technical Information Center.

CONTRACT INFORMATION

START DATE May 1, 1979 END DATE Sept. 30, 1980 CONTRACT VALUE $60,000

MILESTONES

Item: Due date:

1. see technical accomplishments

2.

3.

4.

5.

NATIONAL SOLAR DATA NETWORK

VITRO LABORATORIES DIVISION, AUTOMATION INDUSTRIES, INC.

DONALD M. ROHA

DE-AC01-79CS30027

OBJECTIVE

The objective of the National Solar Data Network (NSDN) is to assist in the development of solar technologies by providing data and information on: (1) the effectiveness of specific systems around the country, (2) the effectiveness of particular solar technologies, (3) areas of potential improvement in system and component effectiveness, and (4) the effectiveness of new technologies under development for solar applications in actual operating environments.

DESCRIPTION OF WORK

The NSDN effort encompasses the selection of sites to be incorporated into the network and the development of analysis procedures to evaluate solar system performance. Solar sites are located throughout the United States and include commercial, residential and industrial applications. Active domestic hot water, space heating, space cooling, and passive systems are evaluated. In addition to DOE funded sites, the DOE/NASA Operational Test Site Program and privately funded sites are included. Design of the instrumentation system to collect data from the sites, as well as calibration, operation, and maintenance of the instrumentation is accomplished. Data reduction, analysis and reporting of the solar performance is a major activity. Reports describe the performance of systems, compare various applications, and discuss the effectiveness of particular technologies. Technical papers are presented at professional/solar conferences to disseminate the solar development status.

TECHNICAL ACCOMPLISHMENTS

The 1980-1981 time period involved a significant transition of the NSDN program. Two major facets of the program were emphasized: (1) upgrading of the NSDN data collection, analysis, reporting and dissemination of information, and (2) restructuring of the program to support the new DOE goals of evaluating the developmental status of solar systems and identifying those attributes of installed systems and components which are limiting the development of solar technology applications.

Upgrading NSDN

The Vitro staff developed new analysis techniques as a result of its own studies and from inputs from the user community including site owners, designers, universities, DOE, Argonne National Laboratory (ANL), Department of Housing and Urban Development (HUD), National Bureau of Standards (NBS), and NSDN Advisory Board. A Solar Energy Analysis Guide was developed to assure standard analysis procedures. Concentrated efforts were applied to the maintenance of site instrumentation, resulting in nearly tripling the number of sites in reporting status. Vitro assumed from other agencies direct responsibility for maintenance and repair actions for site instrumentation, thereby shortening the time to restore a site to reporting status.

A repretoire of report types was implemented to meet the needs of the solar communities. The Monthly Performance Report was enlarged to include interpreted information and graphics to present the energy flows. The Solar Bulletin, a concise performance summary, was initiated to reach a greatly expanded list of potential solar users. Seasonal or annual reports were provided for a significant number of sites. Major documents were issued which compared the performance of solar systems within each of the major applications: space heating, domestic hot water, space cooling, and passive systems. An "Overview Report", summarizing the solar design and installation experiences, has been issued in draft form for review. Over thirty Technical Papers have been submitted, including many to conferences sponsored by ASME, ISES, ASHRAE, National Association of Home Builders (NAHB), and passive solar groups. In addition, Environmental Data Reports and National Solar Data Program Performance Results (3 volumes) have been issued.

In order to expand awareness of the solar results, the NSDN Exhibit was displayed at eight conferences with a total attendance of approximately 55,000 people. Samples of NSDN reports were mailed to 700 state energy organizations, universities and colleges, publications, and regional energy groups.

Restructuring of the NSDN Program

The current sites in the NSDN were reviewed to determine their ability to contribute continuing, useful information on the effectiveness of solar systems. Approximately 50% of the sites were terminated as having already provided the needed information or being unlikely to provide additional information due to poor design, component installation or application features. Simultaneously, new site selection criteria were developed to support DOE solar goals. Recommendations for privately funded sites were solicited from state energy offices, RSEC's, utilities, manufacturers, solar experts and governmental agencies. Over 600 recommendations were reviewed and approximately 40 sites were recommended to DOE for incorporation into the NSDN. These sites were selected to provide information on systems utilizing new technologies and operational techniques as installed and operated in the user environment. A new system was developed to shorten the former one year period required to instrument a new site to less than four months.

A Draft Program Plan has been developed by DOE to provide guidance and review of the NSDN effort. Due to funding reductions, the number of sites in the network has been decreased.

The NSDN also assumed responsibilities in supporting other programs. The Operational Test Site (OTS) Program managed by Marshall Space Flight Center was supported by the NSDN. The "Class A" passive program also utilizes the NSDN. Cooperative agreements with the National Association of Home Builders, Niagara-Mohawk Electric Power, Long Island Light Company, and a southern California utility have provided for interchange of information needs.

Through these reports and technical papers, Vitro has been able to identify the critical features of successful solar system design, installation, and operation as well as provide insight into areas needing further development.

FUTURE ACTIVITIES

Emphasis is placed upon evaluating the performance of solar technologies as incorporated in actual settings. Increased interpretation of results and cross comparisons of system and applications will be provided. The development status of specific technologies will be reported. An aggressive program of communicating the results will be provided through reports, technical papers, mailings, and exhibits. The NSDN program will continue to add sites representing new technologies and will drop sites which will not produce further useful information. The NSDN will be used to collect information in the reliability and maintainability area, in the corrosion effects area, and in the development and validation of lower cost/short term monitoring techniques.

PUBLICATIONS

<u>Comparative Reports</u>:

- Performance of Active Solar Space Heating Systems, SOLAR/0025-80/42, 1979-1980 Heating Season.
- Performance of Active Solar Domestic Hot Water Systems, SOLAR/0024-80/41, 1979-1980 Season.
- Performance of Active Solar Space Cooling Systems, SOLAR/0023-81/40, 1980 Cooling Season.
- Performance of Passive Solar Space Heating Systems, SOLAR/0022-81/39, 1979-1980 Heating Season.

Solar Design and Installation Experience: An Overview of Results from the National Solar Data Network, SOLAR/0009-81/37.

The above reports, along with a listing of all NSDN reports (Availability of Solar Energy Reports from the National Solar Data Program, SOLAR/0020-81/43) may be obtained by writing: U.S. Department of Energy, Technical Information Center, P.O. Box 62, Oak Ridge, Tennessee 37830.

CONTRACT INFORMATION

START DATE October 1, 1979 END DATE Sept. 30, 1982 CONTRACT VALUE $18,340,810

MILESTONES

Item:		Due date:
1.	Develop solar analysis procedures, operate NSDN, issue required reports.	Current
2.	Incorporate twenty-two (22) new solar sites into the NSDN	09/30/81
3.	Issue fifty-five (55) Seasonal (annual) Performance Reports.	09/30/82
4.	Prepare and present twenty (20) papers at conferences.	09/30/82
5.	Issue four (4) Comparative Performance Reports.	09/30/82

Section 7: ADMINISTRATION/MANAGEMENT SUPPORT

7

SOLAR COOLING SYSTEMS EVALUATION

HITTMAN ASSOCIATES, INC.

HENRY M. CURRAN

DE-AC03-79CS-30202

OBJECTIVE

The project objective is to provide assistance to Lawrence Berkeley Laboratory in the monitoring and evaluation of DOE solar cooling contracts, and to perform related research activities.

DESCRIPTION OF WORK

Contract activities include site visits, review of contractor reports, assistance to contractors in development of equipment test programs, evaluation of unsolicited proposals, preparation of topical reports in support of solar cooling developments, and assistance to LBL in development of the Solar Cooling Program.

TECHNICAL ACCOMPLISHMENTS

- A paper on thermal storage for solar Rankine and absorption cooling was presented at the DOE Solar Energy Storage Options Workshop [1]. This paper provides an overview of the use of sensible and latent hot side and cold side thermal energy storage units in solar cooling systems. Summary data on 17 solar cooling projects are included.

- A paper on the DOE solar cooling program activities was published [2]. This is an overview of the solar cooling technologies being developed under DOE sponsorship.

- A paper on thermal energy storage criteria was presented at the Seventh Energy Technology Conference [3].

- The use of organic working fluids in Rankine engines was surveyed and the results documented in a report [4]. This report provides a compilation of data on the use of organic working fluids in operational Rankine engines in the U.S.A. and other countries. Primary emphasis is placed on the maximum temperatures, and on the identification of thermal instability and chemical reaction problems related to these temperatures. Data are presented for 2,150 operational Rankine engines from 20 different manufacturers and using 16 different working fluids. A procedure for dynamic stability testing of organic working fluids was prepared in connection with this work.

- Performance test plans were developed for Rankine and desiccant cooling equipment.

- Technical input was provided to the DOE solar cooling commercialization readiness assessment.

- A presentation on future prospects for solar systems was made in a panel discussion of "Solar Energy for the Second Century" at the ASME Century 2 Solar Energy Conference, San Francisco, August 1980.

- A study on the use of thermal energy storage in solar cooling systems was completed [5]. This report is a follow-on effort to an earlier study [6] prepared under another contract. This report concentrates on design requirements of thermal storage subsystems for active solar cooling systems. It includes an overview of solar cooling technologies, collector subsystems, thermal energy storage subsystems and configurations, and thermodynamic and heat transfer considerations.

- Technical assistance was provided to LBL and DOE on the development of a multi-year Solar Cooling Program.

- A study on the hybrid solar/fossil Rankine cooling concept was prepared [7]. A paper based on this study is to be presented at the 16th IECEC [8]. This paper provides a technical and economic review of the hybrid solar/fossil solar cooling concept in which a dual energy input Rankine engine is used to drive a vapor compression chiller. In the Rankine engine a solar energy input is used to evaporate the water working fluid and fossil fuel is used to superheat the steam. The concept is found to provide a higher coefficient of performance than an organic Rankine chiller, and to require about one-half as much solar collector area. The economic analysis indicates that the hybrid concept would lose its advantage over the organic Rankine chiller when and if the necessary conditions for widespread market penetration of solar cooling systems actually occur - i.e., higher fossil fuel costs and lower solar collector costs.

- A preliminary plan for experimental testing of control strategies for solar cooling systems was developed [9]. Factors related to the environmental control of buildings are discussed, including the structural shell, the HVAC system, the control system, and human factors. The testing of control strategies is considered with respect to modeling and computer simulation and experimental testing of installed equipment.

- A topical report was prepared on high-temperature solar cooling systems [10]. A paper based on this work is to be presented at the ASHRAE meeting in Houston, January 1982. This study examines the feasibility of extending upward from the present level of about 150 C the input temperature of thermally-activated solar cooling systems. Because of inherent temperature limitations for solar absorption and desiccant systems, the primary consideration is with respect to solar Rankine cooling. There appear to be no significant technical obstacles to the design of Rankine chillers with input temperatures up to the 500 to 600 C range, and a substantial technological base exists. Using existing technology a 500 C Rankine chiller could be expected to have a design point COP about 1.3 to 1.4 times as large as that of 150 C chillers currently being developed. Specialized design might raise this ratio to about 1.6. There are no existing or proposed building code provisions which would limit the temperature, other than safety limitations inherent in the materials. Most jurisdictions could be expected to require licensed stationary engineers. A general estimate indicates some potential for high-temperature systems to be somewhat less costly than low-temperature systems.

- As of May 1981 the principal investigator had participated in 19 site visits to DOE contractor solar cooling projects, and had reviewed 28 contractor topical and final project reports and 11 unsolicited proposals.

- A computer listing by key-words of solar energy and related documents has been established. As of May 1981, approximately 1000 documents had been listed.

FUTURE ACTIVITIES

The previous types of activities will be continued. A study of on-site solar thermal electric power generation is currently in progress (May 1981).

PUBLICATIONS/REPORTS/REFERENCES

1. H.M. Curran and S. Heibein, "Thermal Storage for Solar Rankine and Absorption Cooling Systems," Proceedings of Solar Energy Storage Options Workshop, San Antonio, Texas, March 1979.

2. W. Scholten and H.M. Curran, "Solar Cooling Update," Solar Age, Vol. 4, No. 8, June 1979.

3. J. DeVries, "Thermal Energy Storage Criteria," Proceedings of Seventh Energy Technology Conference, Washington, D.C., March 1980.

4. H.M. Curran, "The Use of Organic Working Fluids in Rankine Engines," report submitted to LBL, September 1979, and presented at the 15th Intersociety Energy Conversion Engineering Conference, Seattle, Washington, August 1980. To be published in Journal of Energy, May-June 1981.

5. H.M. Curran and J. DeVries, "Options for Thermal Energy Storage in Solar Cooling Systems," topical report submitted to LBL and ANL, September 1980, revised May 1981.

6. Lee, C., L. Taylor, J. DeVries, and S. Heibein, "Solar Applications of Thermal Energy Storage," report prepared for U.S. Department of Energy, January 1979.

7. H.M. Curran, "Evaluation of Hybrid Solar/Fossil Rankine Cooling Concept," topical report submitted to LBL, November 1980, revised March 1981.

8. H.M. Curran, "Solar/Fossil Rankine Cooling," Proceedings of 16th Intersociety Energy Conversion Engineering Conference, Atlanta, Georgia, August 1981.

9. H.M. Curran, "Experimental Testing of Control Strategies for Solar Cooling Systems," draft topical report submitted to LBL, February 1981.

10. H.M. Curran, "High Temperature Solar Cooling Systems," draft topical report submitted to LBL, March 1981.

CONTRACT INFORMATION

START DATE 1 April 1979 END DATE 31 Jan 1982 CONTRACT VALUE $426,512

MILESTONES

Item: Due date:

1.

2.

3.

4.

5.

TECHNICAL SUPPORT FOR THE ACTIVE SOLAR RANKINE AND ABSORPTION COOLING PROGRAM*

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
Michael Wahlig, Mashuri Warren, Ron Glas

Contract No. W-7405-ENG-48

OBJECTIVE

To provide technical support for the Rankine and absorption elements of the active solar cooling program.

DESCRIPTION OF WORK

The technical support activities provide assistance in the active solar cooling program area to the DOE San Francisco Operations Office (SAN) Conservation and Solar Division and to the DOE Headquarters (HQ) Active Heating and Cooling Division, Office of Solar Applications for Buildings. These activities include program planning, technical monitoring and evaluation of ongoing projects, including site visits and review of progress reports, coordination of review of unsolicited proposals, assistance in the preparation and evaluation of responses to program solicitations, and coordination of related activities by other organizations.

TECHNICAL ACCOMPLISHMENTS

The following are representative of the program planning activities that took place over the past fiscal year:

- Preparation of first and second drafts of multiyear Program Plans for Rankine and Absorption Solar Cooling Systems.
- Writing of a "white paper" on solar cooling technologies, as input to the DOE's five-year planning exercise.
- Preparation of documents for DOE/HQ on solar cooling's potential to achieve eventual market penetration and on the DOE solar cooling program's role in accomplishing this.
- Participation in major planning meetings for the Active Solar Heating and Cooling Program at DOE/HQ and DOE/SAN.

Some of the major technical monitoring and evaluation activities over the past fiscal year include:

- Conduction of, and participation in, 21 site visits and project reviews covering 14 different DOE contractors; review of 7 final reports and phase reports; assistance to DOE/SAN in specifying the Statements of Work for follow-on efforts by several of these contractors.
- Initiation of a contract with SERI for LBL to provide technical monitoring of five U.S.-Saudi (SOLERAS) solar cooling projects.
- Preparation and sending to DOE/SAN of monthly summary reports on all the DOE solar cooling projects; preparation and sending to DOE/HQ of several reports on solar cooling R&D program accomplishments and status.

During the past fiscal year, LBL conducted the review of nine unsolicited proposals. For each proposal, the comments of all the reviewers were summarized and sent to DOE along with a recommendation for action.

LBL assisted DOE/SAN in preparing and evaluating responses to an RFP on the Determination of Properties of Fluids for Solar Cooling Applications.

LBL staff have engaged in a number of coordination activities related to the active solar cooling program, including:

- Coordination with NASA/MSFC (Manned Space Flight Center in Huntsville, Ala.) on the status and future priorities of the solar cooling projects that they are managing for DOE.
- Coordination with Oak Ridge National Laboratory concerning the cooling projects (for which they are technical monitors) that make use of waste heat sources.
- Coordination with the Gas Research Institute on cooling and heat pump programs and projects of mutual interest, especially solar-powered cooling applications using gas auxiliary energy.
- Assistance to the American Samoa Energy Office with their plans for using large-scale solar cooling systems as a solution to one of their major energy problems, the scarcity and high-cost of diesel fuel.
- Coordination of the utilization of the LBL Building 71 Federal Buildings Solar Demonstration Project as a field test installation for a new 25-ton packaged absorption chiller recently developed by Arkla as part of the DOE solar cooling R&D program.

* This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

FUTURE ACTIVITIES

It is expected that similar types of technical support activities to those described above will continue in the future. Completion of the new active solar cooling multiyear plan should occur, followed by its implementation, largely through the preparation and issuance of new solicitations. The cost and performance goals for the program should be refined, and used to establish priorities for supplying the R&D activities. Unsolicited proposal reviews will continue to be carried out as received. Site visits will be conducted for all appropriate active cooling contractors, and progress and topical reports will be reviewed. Finally, the critical coordination activities with other organizations involved with similar programs will continue to be pursued diligently.

CONTRACT INFORMATION

START DATE 10/79 END DATE Cont. CONTRACT VALUE $755K

MILESTONES

Item:		Due date:
1.	Summary reports on all the active solar cooling projects.	Monthly
2.		
3.		
4.		
5.		

PROGRAM SUPPORT FOR ACTIVE BUILDINGS DIVISION SYSTEM DEVELOPMENT BRANCH, OFFICE OF SOLAR APPLICATIONS FOR BUILDINGS*

LOS ALAMOS NATIONAL LABORATORY

CHARLES A. BANKSTON

W-7504-ENG-36

ABSTRACT

Program support work performed by Los Alamos National Laboratory for the Department of Energy, Office of Solar Applications for Buildings, Division of Active Heating and Cooling is described. Background information and accomplishments are included.

OBJECTIVE

This program provides technical management support and contract monitoring for the Systems Development Branch, Division of Active Heating and Cooling, Office of Solar Applications for Buildings, Department of Energy, in the areas of collectors for solar-assisted heat pumps, collectors for Rankine and absorption cooling, and materials used in these collectors. As of October 1980, there were 28 such projects requiring contract monitoring and technical management.

The primary responsibility involves the continuous and close monitoring and evaluation of the technical activities of DOE contractors. This includes review of all their reports and publications, site visits, technical progress evaluation and redirection, contract modifications, analyses of contractor time schedules and goals, and the coordination of these projects with the overall solar heating and cooling program.

Other responsibilities include assisting with the preparation of solicitations of new proposals (RFPs and PRDAs); the review and evaluation of new proposals, both solicited and unsolicited; review of statements of work for new contracts; short- and long-term overall program planning; and the promotion of exchange of information between contractors, government agencies, other national laboratories, and industry and university groups involved in solar energy work.

These responsibilities apply to the areas of collectors and materials for solar-assisted heat pumps, for Rankine cooling, and for absorption cooling.

BACKGROUND

This program support is a continuing effort that began in 1975 when Los Alamos conducted an assessment of solar heating and cooling technology and, on the basis of that assessment, prepared the first draft of the National Program Plan for Research and Development in Solar Heating and Cooling for Buildings, Agriculture and Industrial Applications, DOE/CS-0008. The Laboratory's role in implementing the R&D Plan and supporting the resulting program has been a major one involving primary responsibility for the collector and materials R&D and supporting responsibility for systems analysis and AIPH programs. As a result of reorganization and restructuring of the Office of Solar Applications, the collector R&D program is now imbedded in the various programs of the Systems Development Branch.

TECHNICAL ACCOMPLISHMENTS

Programs supported by the technical staff at the Laboratory have now reached a mature level. The collector program, which was largely implemented in FY-77 through a series of four solicitations, has involved as many as 96 projects for which Los Alamos had technical monitoring responsibility. The program currently involves 39 active projects. Not all of these projects can be monitored on the funding of this proposal, which is primarily oriented toward providing technical support for collectors for Rankine, absorption, and heat pump systems. Many development projects have already been completed, but many important results from study and research projects are just beginning to surface. The nature of the support work now concentrates on review and evaluation of accomplishments and utilization of results.

SUPPORT ACTIVITIES SINCE OCTOBER 1, 1980

- Major Contractor Reports Reviewed. We reviewed four semiannual reports, six draft final reports, and six final reports.
- Site Visits. Our technical monitors made nine site visits to review the projects, assess accomplishments, and help guide future work.
- Project Reviews. We conducted evaluations and reviews of six projects.
- Coordination Activities. We participated in the work of two committees, the Solar Optical Materials Program Activity Committee and the American Society for Testing and Materials Committee on Materials Performance, whose purpose is the improvement of materials for solar applications.
- New Projects. We wrote Statements of Work and Justifications for Noncompetitive Procurement for two unsolicited proposals that we had recommended for funding. These new projects started work in February 1981.

*Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

CONTRACT INFORMATION

START DATE April, 1976 END DATE Continuing CONTRACT VALUE FY-81 $220k

MILESTONES

Item:		Due date:
1.	Comprehensive summary report on the technical status of the program subelements mentioned in Paragraph 1.	September, 1981.
2.		
3.		
4.		
5.		

SOLAR COOLING STUDIES

University of Maryland

D.K. Anand, R.W. Allen

Contract DE-AC03-79CS30204

OBJECTIVE

This contract provides technical support to DOE and conducts in-house research in solar cooling. The objectives of the research are:

- To conduct transient studies of the Li-Br absorption cycle;
- To develop a simplified cooling design chart; and
- To study photovoltaic/thermal cooling/heating systems.

DESCRIPTION OF WORK

Transient Simulation

A lithium-bromide/water absorption machine consists of a generator, a condenser, an evaporator, an absorber, a pump, and a solution heat exchanger interposed between the absorber and the generator. Heat exchanger components of such a machine are usually manufactured in the shell-and-tube configuration. Large absorption machines are equipped with spray headers in the absorber and evaporator components, whereas residential-sized units are usually equipped with drip headers in the absorber and evaporator components. One intermediate-sized commercial machine utilizes a drip header in the generator so as to provide liquid-film boiling instead of pool boiling of the solution. The present transient modeling effort is based on a residential machine with a pool boiling generator and drip headers in the absorber and evaporator components.

The simulation of the transient behavior of the absorption cycle provides information on the transient response both during the start-up phase and during the shut-off period. The simulation model incorporates such influencing factors as the thermodynamic properties of the working fluid, the absorbent, the heat-transfer configuration of different components of the chiller and related physical data. The time constants of different components are controlled by a set of key parameters that have been identified in this study. The results show a variable but at times significant amount of time delay before the chiller capacity gets close to its steady-state value. The model is intended to provide an insight into the mechanism of build-up to steady state performance. By recognizing the significant factors contributing to transient degradation, steps can be taken to reduce such degradation. The evaluation of the residual capacity in the shut-off period will yield more realistic estimates of chiller COP for a chiller satisfying dynamic space cooling load.

Simplified Cooling Design

Predictions of the performance of solar cooling systems on a long term basis have been generally obtained through the use of detailed simulation programs. However, use of these programs becomes expensive for design purposes; in addition, not all designers have access to computers that can handle detailed simulations. An alternative approach is a simplified cooling design correlation similar to the f-chart method for heating designs which was based on a direct correlation of the results from detailed simulation runs.

Analysis of a solar cooling system on a long-term basis has shown that the solar cooling fraction can be correlated in terms of two dimensionless parameters which incorporate the long-term average of values of the insolation, ambient temperature, cooling load, the long-term collector parameters and the chiller COP. In the present work, regional solar cooling fraction charts have been constructed using the two derived dimensionless parameters. The simplified cooling design chart method is validated by direct comparison of systems performance predictions with detailed system simulation results.

Photovoltaic/Thermal Analysis

The purpose of the photovoltaic/thermal work is to simulate and compare under varying operating conditions the thermal and electrical performance of a combined PV/T solar collector-series heat pump system when applied to the heating and cooling of a building. Design parameters of importance are the collector area, flow rate, performance parameters, orientation; electrical and thermal storage size; control temperatures for direct and heat pump heating; and location dependent weather and building energy loads. A detailed computer simulation program is developed incorporating performance models for the solar collector, storage components, heat pump, electrical power conditioning equipment, and service system simulations for Washington, DC, Madison, WI and Phoenix, AZ. The critical design parameters are isolated and broad guidelines developed for system design and optimization. Results are based on a comparison of long-term performance indices including electrical and thermal solar fractions, collector efficiencies and component COP's.

The second part of this work develops a general design procedure for the PV/T collector-series heat pump system that may be used to estimate the monthly solar fractions for a given load.

TECHNICAL ACCOMPLISHMENTS

The technical accomplishments are presented for each of the above studies. For transient simulation of Li-Br absorption cycles, they are:

- The individual components have been mathematically formulated and simulated on the computer. These simulations indicate that the significant time constants are in the natural convection phase of the boiler, condenser hot well and in the wetting of evaporator tubes.
- Simulation of the total cycle gives results that are comparable to experimental data from BNL and Arizona State University (See Figs. 1 and 2).

For the simplified cooling design for residential systems the major accomplishments are:

- The simplified design charts can be developed for solar cooling provided they are done on a regional basis for minimizing error. It is found that four distinct regions are necessary for the simplified design charts (See Fig. 3).
- The errors between the simplified charts and detailed simulation are less than 5% (See Fig. 4).

For the photovoltaic/thermal system the technical accomplishments can be summarized as follows:

- The electrical and thermal storage capacities as well as the collector flowrate are found to have only a small effect on the long-term performance of the PV/T collector-heat pump system over a wide range of values of practical interest.
- From point of view of maximizing photovoltaic output, expensive collector thermal designs with low heat loss coefficients and employing multiple glazings are not justified.
- The long term system performance is found to drop off rapidly at small collector areas because 'starvation' of the heat pump evaporator results in poor utilization of the series heat pump capability. Large collector areas, however, lead to elevated storage temperature and degraded collector efficiencies, because the system tends to be thermally oversized a lot of the time. The optimum system size can be determined by examining system costs, fuel savings and other economic factors.

FUTURE ACTIVITIES

In addition to the technical support to DOE, it is anticipated that the cooling design charts and photovoltaic/thermal analysis will be completed during the next year.

PUBLICATIONS

1. Venkateswaran, S.R. and Anand, D.K., "A Design Procedure for Combined Photovoltaic/Thermal Solar Collector - Heat Pump Systems," ISES Conference, Phoenix, Arizona, May 1980.
2. Anand, D.K., Allen, R.W. and Kumar, B., "Transient Simulation of Absorption Machines," ASME/DOE System Simulation Conference, Reno, Nevada, April 1981.
3. Anand, D.K., Kumar, B. and Allen, R.W., "Simplified Cooling Design Charts," ISES Conference, Philadelphia, Pennsylvania, May 1981.
4. Anand, D.K., Kumar, B. and Allen, R.W., "Regional Simplified Solar Cooling Design Charts," Intersociety Energy Conversion Engineering Conference, Atlanta, Georgia, August 1981.

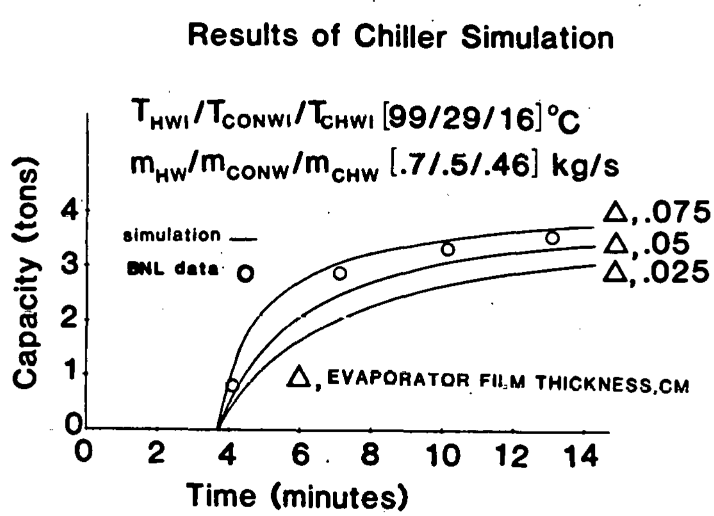


Figure 1. Transient simulation results for an absorption chiller

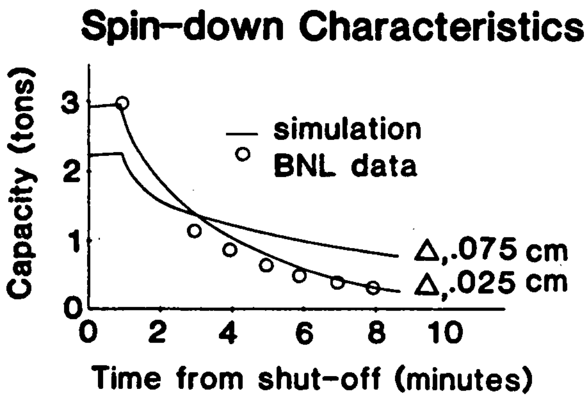


Figure 2. Spin-down characteristics for a 3-ton chiller

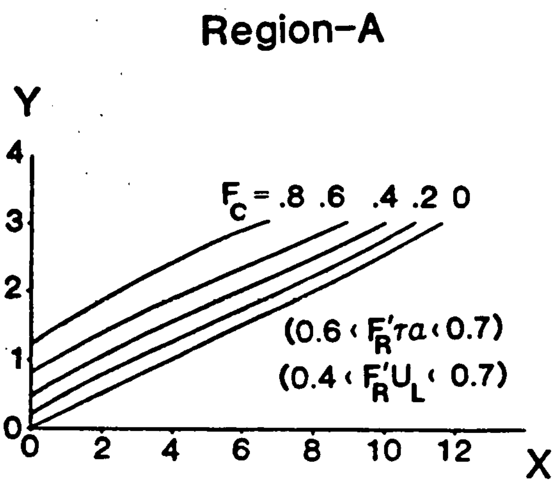


Figure 3. Simplified regional cooling design charts for Region-A

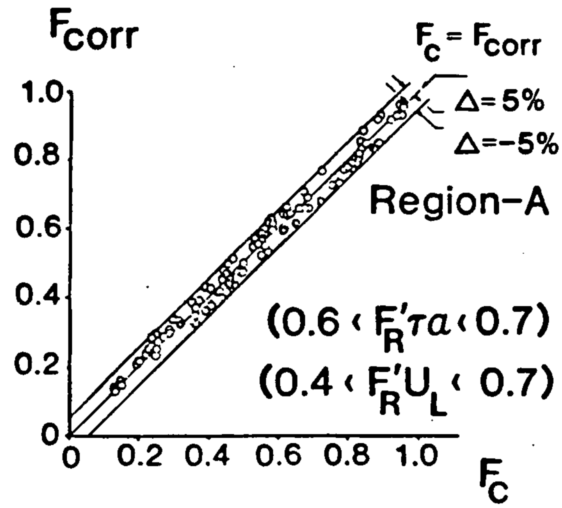


Figure 4. Results from the chart in figure 3 compared against simulation results

CONTRACT INFORMATION

START DATE 7/1/80 END DATE 9/30/83 CONTRACT VALUE $100,000

MILESTONES

Item: Due date:

1. Contract is for the Period July 1, 1980 to September 30, 1983 - $100,000.
2. Major deliverables are DOE presentations on an as-needed basis and technical papers when work is completed.
3.
4.
5.

SYSTEM DEVELOPMENT

NASA/MSFC

N/A

N/A

DEVELOPMENT in SUPPORT of DEMONSTRATION

In 1974, the NASA was asked to undertake the "Development in Support of Demonstration" portion of the National Program. The Marshall Space Flight Center (MSFC) was assigned the development of marketable heating, cooling and water heating systems for use in the Demonstration Program. The term "marketable" meant to ensure design approaches with supporting drawings that would allow the hardware to be manufactured according to "mass production" knowledge and techniques.

The schedule for this development task called for delivery of heating systems that met prototype requirements by mid 1977. The combined heating and cooling system delivery milestone was mid 1979. These dates were consistent with the terms of the legislative acts which initiated the Program. The schedule took into account the state-of-the-industry at the time and the best trade between the accomplishments envisioned versus the cost of accelerating the development of a solar industry.

The technical approach to the Development Program was based on the technology status and the overall focus was for system development. All of the necessary intermediate steps of system criteria, standards, analysis, testing, and evaluation were employed to bring the variety of technology available into integrated systems. A procurement strategy was developed to bring into the Program a good representation of the national industry both to assess and to stimulate solar capabilities.

The Program was introduced with briefings to industry followed by requests for proposals. A total of 88 proposals were received. A summary of the types and numbers of contracts awarded and systems to be delivered and tested at Operational Test Sites is shown in Figure 1.

PROGRAM PROCUREMENT STRATEGY

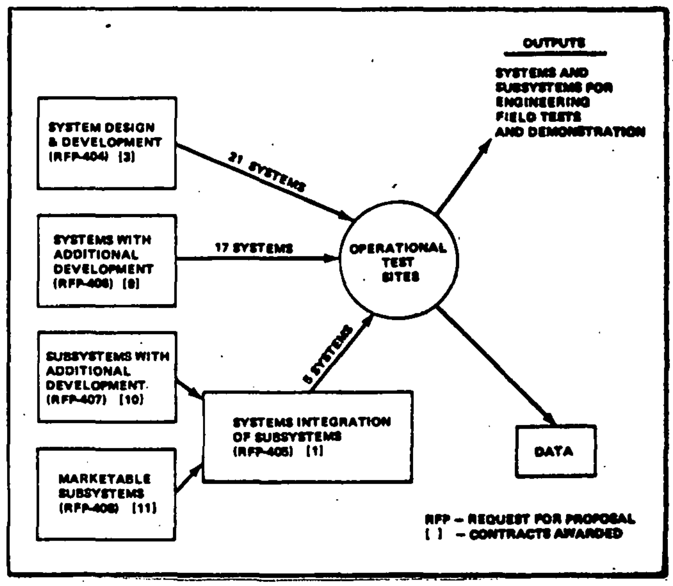


Figure 1

The Program is being accomplished essentially as planned with some modification in the high cost, large system deliveries. The decision to reduce numbers of systems to be delivered, installed, tested, and evaluated resulted from technical and budgetary considerations. Certain large, heating-only systems would not produce new information commensurate with system costs and were traded for several technical improvements indicated after the development was under way.

OPERATIONAL TEST SITES

System Operational Test Sites were chosen from among local, state or federal government buildings and were representative of the several regions of the nation. They were fully instrumented to provide for performance analysis and system "health" monitoring. Test periods were through one operational season, nominally one year. Summary information for the systems delivered for installation are shown in Figure 2. The wide range of sizes, types, and locations is indicated. The collector area is indicative of the capacity of the solar system. Two systems, one at Clear Lake, Texas and one at Las Vegas, Nevada, are being refurbished using 75 Ton Carrier absorption chillers. The test periods for these sites will conclude in 1983.

The Honeywell/Stillwater site is an example of a system and site for which the data indicates that performance is as predicted. This confirms the ability to project load conditions and solar performance. The General Electric/Normal site also is indicative of this capability for space and water heating systems.

The air systems, particularly those developed by the smaller companies, generally perform much below that expected because of leakage, poorer heat transfer, and other system inefficiencies. Water heating contribution is often considerably off design because of errors in predicted use rates (Elcam/Tempe). The lessons to be learned are often a unique combination of influences at each test site.

PROGRAM REPORTING

An integral part of the Program was the provision of information on development work accomplished to all interested elements of industry, business and other agencies through submission of reports to the DOE Technical Information Center. These reports include information on contractor progress, systems design, systems development, technical studies, installation design, performance analysis, and related data of use to National Program participants.

At the end of April, 1981, 302 reports had been prepared. Many final performance reports are yet to be completed since the site tests are still in progress. A list of these reports is summarized in Figure 3 below.

REPORTS TO TECHNICAL INFORMATION CENTER

PRELIMINARY DESIGN PACKAGES	23
QUARTERLY REPORTS	76
FINAL DESIGN PACKAGES	21
INSTALLATION PACKAGES	23
DESIGN DATA BROCHURE	10
TEST REPORTS	67
FINAL REPORTS	55
TECHNICAL REPORTS	27

Figure 3

PROGRAM EFFECTIVITY

Most milestones for the Program have been met and objectives achieved. Several key developments have been accomplished and valuable lessons learned from Program experiences. Of the original 35 Program contractors, 32 have mature hardware engineered for production. Nine collector manufacturers have supplied hardware, brought to maturity under this development, to the National Demonstration Program. All of the system developers, with one exception, have marketable systems ready to commit to volume production with conventional market stimulation and logistic support.

Some of the outstanding developments accomplished during the Program were:

- Three approaches to Rankine cycle solar cooling subsystems
  - An integrated single-fluid motorized turbocompressor
  - An integrated motorized expander/compressor
  - A geared turbine/motor-compressor with clutch
- Specialized heat exchangers, condensers, evaporators, regenerators, demisters, expansion valves, and pumps for solar/Rankine refrigerant loops
- Programmable microprocessor system controllers
- Evacuated tube collector manufacturing
- Collector analysis and test techniques

SITE SUMMARY CHART

0733-81

RFP/CONTRACTOR	SITE LOCATION	TYPE BLDG	COLLECTOR AREA SQ. FT.	OPERATIONAL DATE	DESIGN PERCENT SOLAR CONTRIBUTION
					H/C/HW
404					
AIRESEARCH	● CLEAR LAKE, TX	COMM	13,020	–	100/43/95
	● LAS VEGAS, NV	COMM	9,500	–	89/47/92
GENERAL ELECTRIC	● FT. MEADE, MD	SF	384	4/79	29/ /44
	● NORMAL, IL	SF	320	3/78	21/ /58
	● DALLAS, TX	SF	336	6/79	64/56/64
	● MILWAUKEE, WI	COMM	1,392	6/79	25/ /60
	● SPOKANE, WA	COMM	4,800	6/78	18/ /67
	● MUSCLE SHOALS, AL	COMM	1,536	–	
	● MURPHY, NC	COMM	1,536	–	
HONEYWELL	● NEW CASTLE, PA	SF	504	8/78	46/ /66
	● STILLWATER, MN	SF	594	11/77	45/ /47
	● LAWRENCE, KS	MF	4,536	9/78	50/40/87
	● OCMULGEE, GA	COMM	5,040	8/79	72/62/98
	● CARROLLTON, TX	COMM	7,776	8/79	80/49/92
	● LAWRENCEBURG, TN	COMM	630	8/79	60/70/60
	● DUFFIELD, VA	SF	648	9/79	61/47/80
	● ALLAIRE, NJ	SF		–	56/99/56
	● NEWNAN, GA	SF	648	–	
	● PHOENIX, AZ	COMM	8,208	4/81	89/16/
	● MSFC, AL	COMM	3,306	9/81	19/43
405	● ALBUQUERQUE, NM	COMM	4,938	7/81	13 KVA
IBM	●● HUNTSVILLE, AL	COMM	720	10/77	58/ /57
	●● CARLSBAD, NM	SF	400	6/78	70/ /70
	● TOGUS, ME	SF	100	10/77	/ /56
	● GLENDO, WY	SF	300	10/78	46/ /80
	●● CLINTON, MS	COMM	240	9/78	35/ /63
406					
COLT	● YOSEMITE, CA	COMM	980	8/78	52/ /
	● PUEBLO, CO	COMM	583	4/78	30/ /
CONTEMPORARY SYS	●● NEWNAN, GA	SF	400	4/79	
	●● MANCHESTER, NH	SF	1,630	7/78	92/ /58
COPPER DEVELOPMENT	● TUSCON, AZ	SF	1,923	6/77	
ELCAM	● TEMPE, AZ	SF	64	8/77	/ /85
	● SAN DIEGO, CA	SF	64	5/78	/ /85
FERN ENGINEERING	●● LANSING, MI	SF	240	10/77	46/ /46
	●● TUNKHANNOCK, PA	SF	180	11/77	37/ /37
SOLAR ENG. AND MFG.	● LOXAHATCHEE, FL	SF	80	8/77	/ /90
	● MACON, GA	SF	80	8/77	/ /80
SOLAR ENG. AND EQUIP.	●● EL RENO, OK	SF	1,070	2/78	60/ /
	●● LINCOLN, NB	SF	490	12/77	60/ /
SOLARON INC.	●● DUFFIELD, VA	SF	420	7/79	51/ /48
	●● AKRON, OH	SF	546	8/78	36/ /[illegible]
WORMSER SCIENTIFIC	● COLUMBIA, SC	MF	266	2/78	
SUNMASTER	● ST. THOMAS, VI	COMM		11/79	

LEGEND:

- SF – SINGLE FAMILY DWELLING
- COMM – COMMERCIAL BUILDING
- MF – MULTI-FAMILY DWELLING
- ● – LIQUID MEDIUM
- ●● – AIR MEDIUM
- H/C/HW – HEATING/COOLING/HOT WATER

Figure 2

- System analysis techniques
- Installation cost reduction.

Many valuable lessons have been learned at the detail level during the Development Program. Numerous practical details were immediately obvious, others were more insidious. Many were discovered when manifested as problems. Collectors experienced corrosion, leakage, thermal buckling, condensation, outgassing, header thermal expansion, freezing, galvanic action, and deterioration of performance. Storage systems experienced problems with flow tunneling, heat leakage and corrosion. Material compatibility studies and tests throughout the Program helped to prevent or alleviate problems arising from the large number of system materials in combination and the environment. Many of the lessons of larger scope relate to the systems installation criteria. Solarization of many buildings is impractical and each installation must be properly assessed to achieve optimum and effective performance.

CONCLUSIONS and RECOMMENDATIONS

Several conclusions and related recommendations can be drawn from the experiences of the Program:

- Solar heating and cooling of buildings has been significantly advanced by Federal efforts to accelerate the development of the industry. Many areas of the business and industry structure have been stimulated. The Program has involved a multiplicity of agencies and hardware developers/manufacturers
- The standards development and testing agencies have advanced these areas into a state comparable to conventional heating and cooling equipment
- The societal interfaces at the Operational Test Sites have given experience with local legal considerations, building codes, and user responses
- The quality and quantity of data required to evaluate the performance and economic viability of systems have been determined and systems analysis procedures have been refined for effective feedback
- A separation can now be made of those items that will hold or gain momentum, those that need more development, and those that do not appear promising
- The next logical step for systems that qualify is an engineering field testing of several production units. Among the qualification requirements, after successful completion of development prototype testing, are evidence of cost effectiveness in mass production, significant energy displacement compared to conventional systems, acceptable reliability, simplified installation requirements, acceptable maintenance features and projected low operating and maintenance cost factors
- Those areas for which further development work is indicated are more clearly evident and project costs and schedules can be more defined. A new wave of technology advancement has been made in the interim and can be incorporated to overcome problems that were not resolved in this development cycle.

CONTRACT INFORMATION

START DATE ______________ END DATE ______________ CONTRACT VALUE ______________

MILESTONES

Item:	Due date:
1.	
2.	
3.	
4.	
5.	

SOLAR COOLING WORKSHOP

STEPHENS ENGINEERING CO.

Wallace O. Stephens

DE-AC03-80SF11447 (SB 3-4-0-8(a)80-C-2169)

OBJECTIVE

To obtain industrial and other outside interest group input into the DOE Solar Cooling Research and Development Program; to provide a free interchange of ideas; and to provide DOE with background information necessary to help establish a program consistent with goals of the administration.

DESCRIPTION OF WORK

The cooling workshop involved representatives from the solar cooling industry, utilities, financial institutions, architect and engineering firms, and other organizations able to influence the implementation of solar cooling systems in the United States.

The format of the workshop centered around the use of small groups, in which each group discussed in detail each topical area.

Prior to the small group discussions an overview of the subject matter of the session was given. Four topical areas were discussed:

- Technical factors;
- Regulatory and implementation factors;
- Financial factors; and,
- Marketing factors.

After the overview speakers provided the background, the workshop divided into four (4) small groups. Each group then discussed, according to that group's priorities, the various issues related to that topic. Group discussions were guided by facilitators provided by Stephens Engineering Company and Planning and Management Associates. At the end of the detailed discussion period each group elected a spokesperson to present that group's findings to the entire workshop.

At the conclusion of each topic's small group presentations, areas of agreement and disagreement among the groups were noted and a short general discussion of the total findings occurred. At the conclusion of the workshop, the total program was discussed and a prioritization of issues, agreements and disagreements was made.

TECHNICAL ACCOMPLISHMENTS

The group was in general agreement that the appropriate role for DOE was to support work in the areas of high risk research and development. Additional appropriate government roles were to support recognized industrial societies to accelerate the development of standards for solar energy systems and to serve as an information clearing house for the solar industry.

More specific recommendations were made concerning each of the four topical areas. The topics, with areas of agreement and disagreement, are briefly discussed below:

I. TECHNICAL FACTORS

A. Significant Areas of Agreement

1. For discussion and planning purposes there should be a consistency between the terminology used by industry and the government. Cooling machines for residential application in the 1.5 to 6.0 ton range and small commercial applications in the 7.5-50 ton range should be referred to as "unitary" systems. Commercial machines of 60 tons and up should be referred to as "built-up" machines.

2. In general, the coefficient of performance (COP) is a good measure of performance. However, the COP should be based on seasonal system performance and there should be a method of determining seasonal COP which allows for a comparison between competing systems, e.g. heat pumps, vapor compression, absorption, Rankine and desiccant systems. Another, and sometimes preferred, measure of performance is the seasonal efficiency ratio (SER).

3. Research is needed to: develop air cooling (vs. water cooling) for smaller systems; minimize parasitic losses; improve control strategies; conduct fluid research; and develop desiccant systems, high temperature cooling machines, low cost collectors which can operate effectively at high temperatures, and data to provide design and training manuals.

B. Significant Areas of Disagreement

1. There will be no major breakthrough in cooling machine technology. Major cost reductions must come from other components of solar cooling system.

TECHNICAL ACCOMPLISHMENTS (continued)

II. REGULATORY AND IMPLEMENTATION FACTORS

A. Significant Areas of Agreement

1. There is a multiplicity of codes and standards which are currently a barrier to the sale and installation of solar systems of any kind. Recommendations were made to examine existing codes before instituting new codes and to simplify and eliminate unnecessary codes.

2. The government role should be to provide financial support (e.g. travel) for industry participation to existing organizations to support their development of codes and standards and to support NBS research in the development of the data necessary to write standards. Also, the government should serve as a major information source, particularly to develop and maintain a single compendium of information on codes, standards, certifications, regulations and other issues affecting active solar cooling systems.

3. The industry role is the consensus development of necessary codes and standards.

4. Local governments should pattern their codes after the national model.

5. In general, the workshop group was opposed to mandating utility financing of solar applications. However, utilities should not be prevented from financing such installations if it is in their best interests.

6. Toxic refrigerants and high temperature devices should not be a major concern since existing codes adequately address these risks.

7. High temperature solar systems are not appropriate for residential application.

B. Significant Areas of Disagreement

None

III. FINANCIAL FACTORS

A. Significant Areas of General Agreement

1. The economics of solar cooling systems are not well analyzed as yet.

2. There must be a considerable regional bias in the economic analysis because each system is site specific and application specific.

3. Economic analysis should be business-oriented (e.g. "cash flow" vs. "payback").

4. Federal financial incentives must be perceived by suppliers as stable and relatively longer term than they are presently. Tax credits were the consensus favorite of all financial incentive measures.

5. Some incentives for builders, manufacturers, and non-profit organizations need to be developed, such as low interest loans.

B. Significant Areas of Disagreement

None.

IV. MARKETING FACTORS

A. Significant Areas of Agreement

1. Active solar cooling systems should profit from research done in waste heat recovery systems.

2. There are specific areas and applications wherein solar systems can be competitive today. The difficulty is in determining the special market niches for early penetration.

3. The market consistently changes; therefore, the market analysis requirement is a continuing one.

4. Cost and performance goals are needed for the total system. The component cost goals can then be determined.

5. The buyer cash flow analysis is a better method than payback and return on investment.

6. Industry must follow established market patterns to reach target groups and needs to concentrate sufficient resources on market targets in order to get the volume of sales desired.

7. There is no government role in the marketing area.

B. Significant Areas of Disagreement

None.

FUTURE ACTIVITIES

No post-contract activities are contemplated.

PUBLICATIONS/REPORTS/REFERENCES

Workshop report

CONTRACT INFORMATION

START DATE October 1, 1980 END DATE June 30, 1981 CONTRACT VALUE $73,968

MILESTONES

Item: Major Deliverables	Due date:
1. Workshop	May 1981
2. Workshop Report	June 1981
3.	
4.	
5.	

IEA SOLAR HEATING AND COOLING R&D PROGRAM

TPI, INCORPORATED

SHEILA B. BLUM

DE-AC03-80CS30512

BACKGROUND

In 1977, the U.S. joined with fourteen other countries* and the Commission of the European Communities to establish a cooperative solar heating and cooling R&D program under the International Energy Agency (IEA). This was one of a number of cooperative R&D programs formed by IEA countries in promising energy technologies such as biomass, geothermal, wind power, coal technology, etc.

The following areas were agreed upon for joint efforts in solar heating and cooling:

- System Performance
- Component R&D Information Exchange
- Collector Testing
- Insolation and Related Meteorological Information
- Evacuated Tubular Collector Systems
- Central Solar Heating Systems with Seasonal Storage

There are currently six tasks (projects) underway in the above areas, and one completed task. All are task-sharing as opposed to cost-sharing efforts. The work is outlined in an Implementing Agreement signed by the Participants.

The overall program is managed by an Executive Committee, composed of one member from each Contracting Party, which meets semi-annually to review progress and accomplishments, approve new work plans and resolve problems. The U.S. representative to the Executive Committee is Fred Morse, Director of the Office of Solar Applications for Buildings. The implementation and day-to-day operation of each task is the responsibility of a lead organization, or Operating Agent, which acts on behalf of the other Task Participants and reports regularly to the Executive Committee. The Executive Committee is responsible to the IEA Committee on R&D and submits annual progress reports on each task.

TPI, Inc. has responsibility for tasks such as preparing status reports on the international work, organizing meetings, drafting project descriptions, supporting the Executive Committee and coordinating the work of the various U.S. participants.

DESCRIPTION OF TASKS

Task I. Investigation of the Performance of Solar Heating and Cooling Systems

The Participants in Task I have collaborated to improve the prediction, measurements and reporting of solar heating and cooling system performance and in assessing the issue of system optimization.

Two reports on measurement and reporting guidelines have been published: The first, "Data Requirements and Thermal Performance Evaluation Procedures for Solar Heating and Cooling Systems," was based on the NBS 76-1137 document. The second, "Reporting Format for Thermal Performance of Solar Heating and Cooling Systems in Buildings," assures completeness of reporting and uniformity of presentation that facilitate comparability and interpretation of data.

In the modeling and simulation studies, each participating organization applied its computer code to model the performance of a liquid and an air heating system. Good agreement in performance prediction was obtained among the eight different simulation programs employed. This work was followed up by two validation studies (DHW and heating/cooling) comparing predicted performance to measured data. Final reports have been completed on the modeling and validation activities. A special validation experts meeting was held in July 1981 to assess the state-of-the-art, to identify obstacles to accurate system performance prediction, and to formulate recommendations on improving performance prediction capability.

A late addition to Task I was a project designed to enhance the understanding of the integration of conservation and solar techniques (both active and passive) in solar-assisted low energy dwellings (SALEDs). The Participants have agreed to transfer the SALED work to a new IEA Passive and Hybrid Low Energy Buildings Task now being organized.

Operating Agent: Technical University of Denmark
U.S. Participants: J. Hedstrom (LANL)--U.S. Lead, T. Freeman (Altas), W. Kennish (TPI), R. Rittelmann (BHKR)
Duration: January 1, 1977 to December 31, 1981

Task II. Coordination of Research and Development on Solar Heating and Cooling Components

The objective of Task II has been the sharing of information among the participating countries on national plans for component R&D and on government-sponsored component R&D projects. This has been carried out through discussions at annual meetings and the publication of a summary of R&D plans and a compilation of R&D project summaries. Periodic reviews of national programs have enabled members to track the status, change in scope, funding, strategies, etc. and to note opportunities for closer cooperation. R&D Project Summaries allow researchers to become aware of R&D work of

*Austria, Belgium, Canada, Denmark, Germany, Greece, Italy, Japan, The Netherlands, New Zealand Spain, Sweden, Switzerland, United Kingdom.

interest that is underway in other IEA countries.

Task II has recently expanded its scope to include system R&D. Furthermore, a subtask has been added dealing with operating experiences with solar heating and cooling systems and components. A survey will be compiled covering size of the solar energy industry, technical problems in installation and maintenance, training and education for installers, possibilities for cost reduction, etc.

Operating Agent: Agency of Industrial Science and Technology, Japan
U.S. Participants: F. Morse (DOE)--U.S. lead, W. Shertz (ANL)
Duration: January 1, 1977 to June 30, 1984

Task III. Performance Testing of Solar Collectors

Task III has dealt with the critical area of collector testing and performance test procedures in particular. Focussing first on thermal performance, the experts applied the ASHRAE 93-77 (U.S.) and BSE (FRG) test procedures to two different commercially-available liquid heating flat plate collectors. The final report on this round robin test work, in which sixteen laboratories from twelve countries participated, concluded that both procedures are applicable and effective for determining thermal performance.

A second stage of round robin work is now in progress, involving evacuated tubular collectors. The objective is to determine what modifications to the ASHRAE and BSE test methods are required for this type of collector. Two subgroups are also looking at related subjects: 1) reference heat source for calorimetric calibration and 2) all-day collector performance.

Discrepancies in pyranometer measurements, which came to the attention of the IEA researchers during the round robin activity, pointed out the need for better understanding of pyranometer measurements and calibration. Accordingly, a joint Task III/Task V subproject was established which undertook two pyranometer comparison testing experiments in Davos, Switzerland during 1980 and 1981. The purpose of these tests and related expert meetings was to establish the state-of-the-art in pyranometer measurements and determine ways to improve the accuracy of pyranometers by better understanding of the instruments' performance characteristics.

Another area being studied is collector reliability and durability testing. A report will be published this year on, "Design and Operational Deficiencies of Flat Plate Collector Systems under Operating Conditions." Additionally, twelve absorber plates, utilizing various materials and coatings, will be tested by the Participants employing accelerated aging methods.

The final area of Task III collaboration concerns solar simulators. A report surveying solar simulator test facilities was distributed in 1980. Further testing is planned to investigate the potential of solar simulators for indoor collector thermal performance evaluation.

Operating Agent: Kernforschungsanlage-Jülich, Federal Republic of Germany
U.S. Participants: Kent Reed (NBS)--U.S. lead, W. Dokos (DSET)
Duration: January 1, 1977 to December 31, 1982

Task IV. Development of an Insolation Handbook and Instrument Package

Task IV focussed on obtaining improved basic information for the design of solar heating and cooling systems through a better understanding of insolation and related meteorological data and through improved techniques for the measurement of such data.

A handbook entitled, "Meteorological Measurements and Data Handling for Solar Energy Applications" was prepared and published, with chapters contributed by many eminent experts who participated in this task. The document is intended to familiarize the solar scientist with insolation data requirements and measurement techniques and also to enhance the meteorologist's understanding of the needs of the solar community.

The second major activity involved the compilation of design and performance specifications for a low-cost, portable instrumentation package capable of measuring insolation and related weather data at a variety of potential and actual sites for solar system installations. Several participating countries built prototype machines in accordance with specifications and then conducted a joint testing of the instruments to determine the validity of the guidelines. The results were reported in another Task report.

Task IV was completed in December 1979.

Operating Agent: U.S. Department of Energy
U.S. Participants: Michael Riches (DOE)--U.S. lead, G. Carter (Univ. of Alabama), E. Flowers (NOAA)

Task V. Use of Existing Meteorological Information for Solar Energy Applications

Task V seeks to improve the availability of existing meteorological data and to support the effective collection and presentation of such data for the solar community.

To accomplish these objectives, the IEA members have undertaken the joint preparation of four documents. Two have recently been completed--A compilation of sources for relevant meteorological data and a report containing recommendations for meteorological networks. The remaining reports are nearing completion. One is a handbook on solar radiation estimation methods, including modeling and validation, and the other provides a uniform format for data presentation.

A new program of work has been identified and will be implemented shortly: 1) small-scale variability of solar radiation, 2) survey of user requirements of solar radiation data in real time and forecasting and 3) cross validation of radiation estimation methods. Furthermore, the pyranometer work, previously a joint Task III/IV ad hoc activity, will become a formal part of the meteorological project.

Operating Agent: Swedish Meteorological and Hydrological Institute
U.S. Participants: Michael Riches (DOE)--U.S. lead, E. Flowers (NOAA), T. Stoeffel (SERI)
Duration: January 1, 1977 to December 31, 1981

Task VI. Performance of Solar Heating, Cooling and Hot Water Systems Using Evacuated Collectors

The objective of this task is to study a range of evacuated tubular collector systems, report on their performance, and jointly evaluate the results. The eight participating installations cover a variety of applications--including heating, heating and cooling, and industrial process heat--and a variety of climates. Thus, the information generated under Task VI will greatly enlarge the data base on evacuated collector system performance.

A unique and important feature of this project has been required commonality in project instrumentation, data collection, and reporting. For example, each project must provide the equivalent of a full-time data engineer. Another standard requirement calls for the use of the IEA system performance reporting format for preparation of the annual performance report on each system. Participants have found that adoption of a mandatory common reporting structure has greatly enhanced exchange of results.

Final reports on the U.S., German and Japanese installations will be completed at the end of 1981. When the system reports on the remaining installations are finished, a summary report will be prepared.

Operating Agent: U.S. Department of Energy
U.S. Participants: W. Duff (CSU)--U.S. and Task Lead, C. Bankston (ANL), G. Löf (CSU)
Duration: October 1, 1979 to December 31, 1985

Task VII. Central Solar Heating Plants with Seasonal Storage

The purpose of this project is to determine the technical feasibility and cost-effectiveness of seasonal storage for large-scale solar district heating systems. Since the design and construction of such systems is a very costly undertaking, considerable savings can be realized by the collaborative assessment of the merits of various large-scale system configurations and their suitability for particular climatic regions.

The members of this Task are carrying out a closely coordinated series of activities culminating in the preparation of detailed site-specific system designs. In the systems analysis work, computer models are being developed which are suitable for performance simulation and parametric optimization of large seasonal storage solar heating systems. Under the guidance of lead countries, the Participants are investigating the collector, storage and heat distribution subsystems. They are looking at state-of-the-art of the technologies, cost data, and performance information to help determine the most technically feasible and cost-effective components and concepts. The findings of these subtask groups will be provided as input to the system optimization activity.

Utilizing the recommended computer codes and the system and subsystem optimized parameters, the Participants will develop preliminary site specific designs followed by detailed system designs. Naturally, many countries will proceed with the actual construction of a large-scale solar heating system.

Operating Agent: Swedish Council for Building Research
U.S. Participants: A. Michaels (ANL)--U.S. lead, C. Bankston (LANL), F. Baylin (SERI), A. Davis (ANL)
Duration: February 1, 1980 - January 31, 1984

POSSIBLE NEW PROJECTS

The IEA Participants have expressed their desire to undertake new cooperative projects in promising areas as some of the tasks are completed. A new task is currently being planned in Passive and Active Solar Low Energy Buildings. As presently envisioned, this task--which should be underway in the fall of 1981--will consist of modeling, performance measurement, and design methods activities plus a design and construction phase.

Also under discussion presently are possible projects in solar retrofit, solar-assisted heat pumps, DHW system performance, and air heating systems. It may be that some of the future cooperative efforts may be established on a less formal, shorter-term basis than the existing tasks. Incorporating new work as a subtask of an existing project is another approach that might be utilized.

INTEGRATION WITH U.S. ACTIVITIES

DOE has attempted to maintain a strong link between the IEA program and related U.S. solar heating and cooling work. The United States played an active role in the formation of the IEA program and U.S. representatives supported the selection of projects which were aligned with the needs of the U.S. R&D program. Key experts from the U.S. research community have been involved in the IEA projects and have reported on the progress and results of the cooperation to fellow members of the research community.

Attempts have also been made to inform and involve the U.S. solar industry and to assess whether the international work takes account of industry needs and interests. For example, special meetings were held with key industry representatives to discuss the issue of international collector testing work and solar standards. An industry expert has also participated regularly in the Task III working group. Similarly, evacuated tubular collector manufacturers have been invited to Task VI meetings.

Through its involvement in the IEA, the DOE has, at a relatively low cost, participated in cooperative projects which complement and support its R&D program. The collaboration has also provided access to foreign technical expertise and enabled U.S. researchers to monitor potentially significant technical developments in other countries.

CONTRACT INFORMATION

START DATE Sept. 30, 1980 END DATE Sept. 30, 1982 CONTRACT VALUE $248,484

MILESTONES

Item:	Due date:
1. International Program Review Meeting	Oct. 1981 (P)
2. IEA Executive Committee Meetings	Oct. 1980 (M), Apr. 1981 (M), Oct. 1981 (P), May 1982 (P)
3. IEA Workshop on National Programs at ISES/Brighton, U.K.	Aug. 1981 (M)
4. Edit Annual IEA Task Reports	Dec. 1980 (M), Dec. 1981 (P)
5. Reports on IEA Validation Work	May 1980 (M), Oct. 1980 (M), Dec. 1981 (P)

Section 8: SOLAR COLLECTOR TECHNOLOGY GROUP

8

FURTHER DEVELOPMENT TO COMMERCIALIZE A LOW-COST SOLAR PANEL

Acurex Corporation -- Alternate Energy Division

Timothy K. Muller

Contract No. DE-AC04-79AL12032

OBJECTIVE

The objective of this program is to develop a liquid-heating, nonconcentrating, thin-film collector to be cost-effective and suitable for rapid commercialization. The primary applications for the collector will be space and water heating at temperatures in the 120°F to 160°F range. Specific goals of the current contract are to implement a materials testing and evaluation effort of suitable thin-film plastic materials, to continue development of adhesive lamination and thermal bonding techniques of these thin-film materials, to fabricate and test a full-scale prototype panel, and to continue development of high-speed manufacturing processes for fabrication of the above-mentioned panel.

DESCRIPTION OF WORK

Acurex Corporation has been working with the low-cost solar panel concept for over 5 years and is currently working on the extension of a contract from the Solar Heating and Cooling Research and Development Branch of DOE to develop and commercialize a low-cost thin-film plastic solar panel. The purpose of the initial contract was to fabricate and test a full-scale prototype LCSP absorber structure. Design activity included refinement of the flow configuration through the panel and selection of a suitable thin-film material. Fabrication methods were manual screen printing and template adhesive lamination of Hytrel film and dielectric heat sealing of urethane-coated nylon fabric. Testing was performed on the full-scale prototype panel to characterize inflation, flow pattern, and thermal performance. A manufacturing assessment was included in the project to evaluate the manufacturing methods and costs necessary to commercially market the LCSP.

The current extension of the LCSP program is intended to continue development of the LCSP concept toward commercialization as a viable consumer product. A more extensive materials testing and evaluation effort has been implemented with the support of Springborn Laboratories Inc., of Enborn, Connecticut. Two thin-film plastics presently appear to be the most promising materials for use on the LCSP. These materials are polyurethane for low-temperature applications and polybutene for high-temperature applications. Hytrel and nylon are being considered as backup materials. Springborn Labs will also investigate the possible use of thermoset materials for the LCSP.

Technical activity in absorber structure development has included investigation of

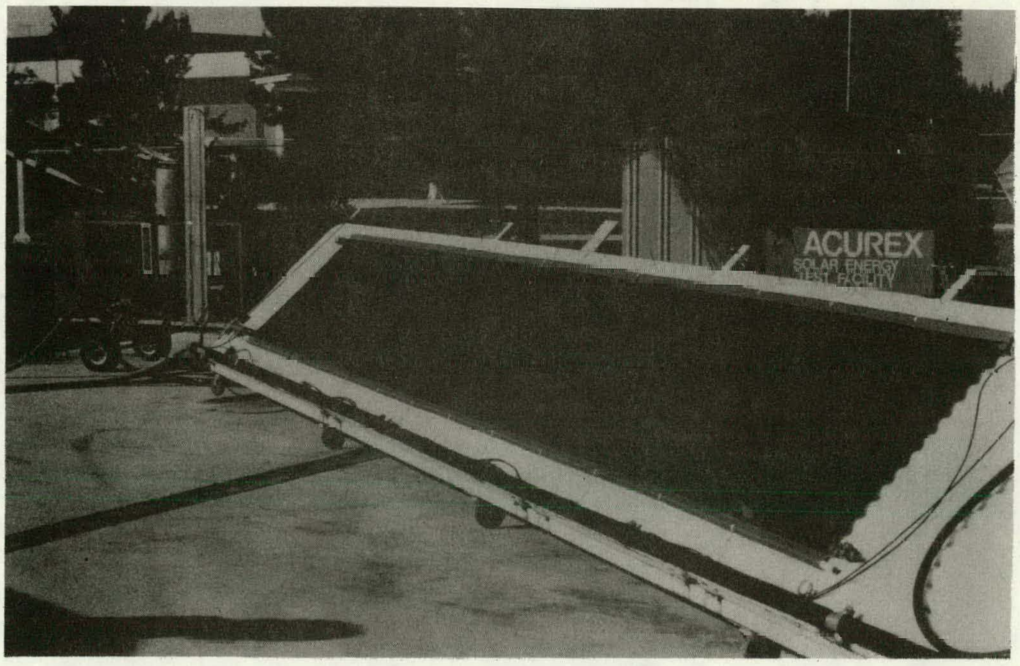


Figure 1. Low-Cost Solar Panel Prototype

film stock production, absorber structure fabrication, and prototype testing to verify structural performance. Completion of the current contract requires testing of a high-temperature prototype panel.

TECHNICAL ACCOMPLISHMENTS

- Initial funding for this project resulted in the fabrication and testing of a low-cost solar panel prototype. Testing was performed to study flow distribution, panel inflation, and structural integrity. The successful fabrication of this prototype panel provided the basis for further funding to commercialize the LCSP concept.

- A materials screening effort was performed on over 60 different thin-film thermoplastics to find the most desirable materials for use on the LCSP. Results of this screening suggest the use of polyurethane for low- temperature applications and polybutene for high-temperature applications. Backup materials are Hytrel and nylon. Selection criteria included cost, availability, peel strength, UV resistance, water vapor transmission rate, and ease of fabrication.

- An investigation of fabrication techniques has resulted in the best method of fabrication for the LCSP. The high-temperature prototype panel will be heat sealed on a commercial 50 kW heat sealing machine. Tests run with chemical additives intended to enhance the heat sealing properties of the plastic film stock have indicated that high carbon black or nitrite rubber content may decrease dielectric sealing times.

- Studies by Acurex have indicated that the best method of film stock fabricaton is adhesive lamination of the plastic film to the reinforcing fabric. In this process the plastic film is initially blown or flat cast and then laminated to the reinforcing fabric in a second operation.

FUTURE ACTIVITIES

Full-scale, glazed panels are currently being fabricated and will be tested for high-temperature operation of up to 160^{o}F. Market survey studies indicate that the LCSP concept can compete in the identified service applications of pool and domestic hot water heating and for industrial process heat. Acurex is committed to participation in the commercialization of this concept and will be exploring the various alternatives with others from the solar heating and heat transfer product industries at the conclusion of this contract.

CONTRACT INFORMATION

START DATE Sept. 28, 1979 END DATE Sept. 1, 1981 CONTRACT VALUE $344,778

MILESTONES

Item:	Due date:
1. Results of material screening tests	August 1981
2. Results of investigation into fabrication techniques for the LCSP	August 1981
3.	
4.	
5.	

"THE DEVELOPMENT OF COST EFFECTIVE DEVICES FOR SOLAR FLAT PLATE COLLECTORS"

ALTAS CORPORATION

FRANCIS DE WINTER

DE-AC04-80AL13101

OBJECTIVE

The objective of the project is to develop and test an analytic model of the risk of hail damage to flat plate solar collectors. The ultimate use of such a model is to assign hail risk factors for various locations in the country and incorporate these in determination of the incremental life-cycle cost due to hail damage for different collector designs.

DESCRIPTION OF WORK

The incidence of hailstone damage to flat plate collectors imposes an additional cost in the maintenance of a collector system. To determine the risk of hail damage, we have established a statistical computer model based on four probability relationships: the frequency of haildays in a given location, the distribution of hail size, the distribution of areal density (total stones falling per square meter), and the probability of damage to a collector given that a stone of a certain size falls.

Preliminary analysis thus far indicates that the first three of these distributions are independent, but may, however, be highly variable geographically. In other words, one would need to have specific hail data for a location in order to use the hail risk model. Large sets of hail data gathered over several years must be available to provide a reasonable basis for the accurate application of our model. Only two major sets of hail data currently exist--one from the Illinois State Water Survey and one from the Colorado National Hail Research Experiment. These data represent a portion of the Midwest in and around Illinois, and a section of Colorado located against the Rocky Mountains.

Hail risk factors can be generated by the use of our computer model. These factors combined with a life-cycle cost analysis of a collector system provide a value of the incremental life-cycle cost due to hail damage. However, the most important aspect in deriving these costs is adequate representation of the four probability functions already described. Of these four, a sufficient data base exists only for hailday frequency.

A sensitivity analysis of the computer model is also being undertaken. Results from this work should indicate which input parameters are the most critical for a proper analysis of hail risk.

TECHNICAL ACCOMPLISHMENTS

Our computer model has been revised to accommodate a broad range of sets of input parameters. Risk is geographically specific. Input parameters include: the mean and variance of the frequency of haildays per year; the hail size and areal distribution parameters; the mean and standard deviation of the normal curve representing impact energy required to break a collector glazing; wind velocity; geographic location; and collector orientation, exposed area, and years of operation.

- Given the results from the hail risk model an economic methodology has been devised to calculate the incremental life-cycle cost due to hail damage. Tables of these costs which correspond to a given set of parameters will be provided. Inflation and discount rates are included.

FUTURE ACTIVITIES

Because of the paucity of impact damage resistance data for various types of collectors, a follow-on study may be useful for application of our model to many different types of collector glazing. This would be a systematic set of impact tests on a representative set of collector glazings. A method of manufacturing artificial hail would need to be developed.

Insurance companies may be interested in our hail risk results, applying our model for the purpose of creating actuarial tables.

PUBLICATIONS/REPORTS/REFERENCES

- "A Statistical Model for Assessing the Risk of Hail Damage to Any Ground Installation," by Michael Cox and Peter Armstrong, Altas Corporation, U.S. DOE Technical Report, Contract No. EM-78-C-04-4291, September 1980.
- "Need for and Evaluation of Hail Protection Devices for Solar Flat Plate Collectors," Final Report, by Michael Cox, Peter Armstrong, and Francis de Winter, Altas Corporation, U.S. DOE Contract No. EM-78-C-04-4291, March 1980.

CONTRACT INFORMATION
START DATE August 12, 1980 END DATE Sept. 11, 1981 CONTRACT VALUE $99,000

MILESTONES

Item:		Due date:
1. Final Report	September 11, 1981	
2.		
3.		
4.		
5.		

DEVELOPMENT OF A LOW-COST, BLACK-LIQUID SOLAR COLLECTOR, PHASE II

BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES

D. KARL LANDSTROM - PRINCIPAL INVESTIGATOR, S.G. TALBERT AND V.D. McGINNISS - TASK LEADERS

CONTRACT DE-AC04-79CS30171

OBJECTIVE

The primary objective of the Phase II program was to evaluate several candidate plastic materials and solar-collector designs suitable for black liquid use prior to specific development for commercial entry. Secondary objectives were: to obtain sufficient data to design a full-scale black-liquid collector for commercial application; to work closely with a company willing to commercialize black-liquid plastic collectors; to recommend suitable plastics, designs, and applications which will allow long life and good performance; to investigate overall system performance for variations in design, materials and specific uses; to monitor and incorporate improved black liquids; and to test suitable plastics and collector designs under realistic and accelerated conditions.

DESCRIPTION OF WORK

This project was an attempt to define the black-liquid concept when applied to solar-collector designs and determine the specific advantages and disadvantages of the concept when compared to conventional collectors. The prime advantage has been identified as the projected low cost resulting from the essentially one-piece, extruded-type plastic construction, which eliminates much of the labor inherent in manufacturing conventional metal and glass collectors.

The background of this work has been extensively covered in the publications cited at the end of this paper, and this project has proved that the black-liquid collector can operate as theoretically projected and can be built to have an efficiency curve closely matching that for a conventional, single-glazed collector. Stagnation problems can be minimized by the use of a drain-back system, since the empty collector does not absorb appreciable solar energy and will remain cool. This feature can also contribute to extended service life, since stagnation conditions should never be experienced under normal operation.

This Phase II program was conducted to provide additional information about the long-term durability of plastic, black-liquid collectors through exposure/operation of collectors under varying experimental conditions and environments. Considerable information has been obtained on the weatherability of candidate plastics and a determination of some of the major long-term performance requirements that will be necessary for collectors constructed from polymeric materials.

TECHNICAL ACCOMPLISHMENTS

- It has been determined that the black-liquid collector has several potential advantages over conventional flat-plate collectors for specific applications. Some of the demonstrated interdependent advantages are:

  - Lower cost
  - Lighter weight
  - Higher strength
  - Minimal stagnation problems
  - Low shipping cost
  - Less corrosion
  - Comparable efficiency
  - Application versatility
  - Minimal freezing problems
  - No metals required.

  As a result of this project, some areas of potential risk have also been identified:

  - Overall life of polymeric materials
  - Temperature limitations
  - Water/polymeric reactions
  - Stress limitations of collector assembly
  - Polymeric materials costs
  - UV stability/protection.

- One important accomplishment of this program has been the collection of available data about long-term materials problems that are associated with plastic materials in solar applications (see publications list). Certain polymeric materials have been shown to exhibit long life under solar exposure; however, conditions existing or required for use in solar collectors are generally not directly applicable to most test data and the materials must be investigated under actual collector operating conditions to be realistic. This is a vast area of research, and this program has considered only certain candidate polymeric materials most suitable for direct application to solar collectors at this time.

- Outdoor Solar-Collector Test Facilities. Fig. 1 is a photograph of an outdoor solar-collector test facility located in Columbus, Ohio. An identical unit was also built for use in Phoenix, Arizona, to provide two different areas of solar exposure. Columbus provides a relatively cloudy environment and freeze-thaw conditions, while Phoenix has a maximum of solar insolation and high ambient temperatures.

  Fig. 2 is a schematic flow diagram of the outdoor solar-collector test facility and is constructed to allow four basic modes of operation for evaluating various combination of black liquids and solar collectors:

  - Typical daily temperature cycle, representative of a domestic solar water heater
  - Constant low temperature operation, representative of a swimming pool heater or heat-pump

application
- Constant high temperature operation, representative of process-heating or home-heating applications
- Stagnation temperature operation, for achieving maximum temperature and possible destructive testing.

Fig. 3 is a close-up view of one of the black-liquid collectors constructed for the outdoor test facility at Columbus, Ohio. It consists of an acrylic extruded panel and tubular acrylic headers containing flow distribution orifices which are cemented across both ends of the panel. This type of construction was tested both with and without an additional acrylic cover to determine operating characteristics over long periods for both a glazed and an unglazed black-liquid collector. Daily efficiency data for this type of collector under varying amounts of solar insolation are presented in Figs. 4 and 5.

- Another important result from this program was the determination that conventional antifreeze additives such as glycol solutions will attack the candidate polymers and accelerate stress cracking. Also, the use of brines such as calcium chloride tended to interfere with the suspension of the carbon black particles in the black liquid. Although the collector can be operated in a drain-back mode to minimize freezing problems, it was also determined that the alternative wetting and drying of the polymers from this mode of operation will promote stress cracking.

- In order for the black-liquid system to develop in the consumer market, it must appeal to the typical consumer. Cost effectiveness is a critical issue. Using an FCHART computer analysis (developed by the Solar Energy Laboratory at the University of Wisconsin) for a typical black-liquid system, the projected potential savings and payback periods for both residential and commercial domestic hot water (DHW) systems at two locations are given in Table 1. This analysis assumes that the total installed system cost is $2,000 for the residential system (based on an installed cost for the collector of $12.50 per square foot), and $31,325 for the optimized commercial system for a 100-room motel, and an electricity cost of 6¢/kWhr escalating at 12 percent per year. The net savings represent the cost difference between an electric only DHW system and the electric backup cost with a solar system. Maintenance and insurance costs were added to the solar system. Tax credits currently existing at the two locations were also incorporated into the analysis. The payback period was calculated from the yearly net cash flows, and represents the time required to balance fuel cost savings with the net system cost.

- Conclusions. The black liquid concept has been developed to the point where commercial application is now possible and the economics of the system make it a viable candidate for consideration in future solar systems. Additional research in areas of polymeric protection, enhancement of collector lifetime, and suitable antifreeze solutions are still necessary, but these areas presently seem technical achievable when applied as specific goals for improvement of existing polymeric materials and black liquids.

TABLE 1

PROJECTED POTENTIAL SAVINGS AND PAYBACK PERIODS FOR RESIDENTIAL AND COMMERCIAL BLACK-LIQUID SOLAR SYSTEM

	Residential (5.89 m^2)		Commer. (103 m^2)
	Phoenix	San Diego	Phoenix
Sale price	$2,000	$2,000	$31,325
Federal tax credit	800	800	7,831
State tax credit	700	300	0
Net cost	500	900	23,494
Net savings in electricity cost over 10 yrs	$3,940	$3,113	$43,379
Number of years required for payback	2.10	4.21	6.73

FUTURE ACTIVITIES

It is presently planned to investigate areas of possible commercialization for the black-liquid concept, not only for conventional solar collector uses, but for other uses such as greenhouse design, where the unique properties of the black-liquid system may be used to advantage. Currently, one manufacturer has plans for eventual marketing of a black-liquid collector and there is considerable interest being expressed from other manufacturers both in this country and in foreign countries.

PUBLICATIONS/REPORTS

D.K. Landstrom, S.G. Talbert, G.H. Stickford, Jr., R.D. Fischer, and R.E. Hess, "Development of a Low-Temperature, Low-Cost Black-Liquid Solar Collector", Final Report, Contract No. EG-77-C-04-4097, Report No. ALO-4097-1, U.S. Department of Energy, Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, October, 1978.* (* Available through NTIS)

D.K. Landstrom, G.H. Stickford, Jr., S.G. Talbert, and R.E. Hess, "Development of a Low-Temperature, Low-Cost Solar Collector Using a Black-Liquid Concept", Proceedings of the 1978 Annual Meeting, American Section of the International Solar Energy Society, Inc., Denver, CO., Volume 2.1, 228-233, August 28-31, 1978.

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D.K. Landstrom, S.G. Talbert, and V.D. McGinniss, "Development of a Low-Temperature, Low-Cost, Black-Liquid Solar Collector, Phase II", Battelle report presented at Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Lake Tahoe, NV, March 1980.

D.K. Landstrom, S.G. Talbert, and V.D. McGinniss, "Development of a Low-Temperature, Low-Cost, Black-Liquid Solar Collector, Phase II", Semi-Annual Report, September 1, 1979-February 29, 1980, U.S. Department of Energy Report No. ALO-30171-1, March 20, 1980.*

V.D. McGinniss, F.A. Sliemers, D.K. Landstrom, and S.G. Talbert, "Compendium of Information on Identification and Testing of Materials for Plastic Solar Thermal Collectors", U.S. Department of Energy Report No. DOE/CS/30171-1, July 31, 1980.*

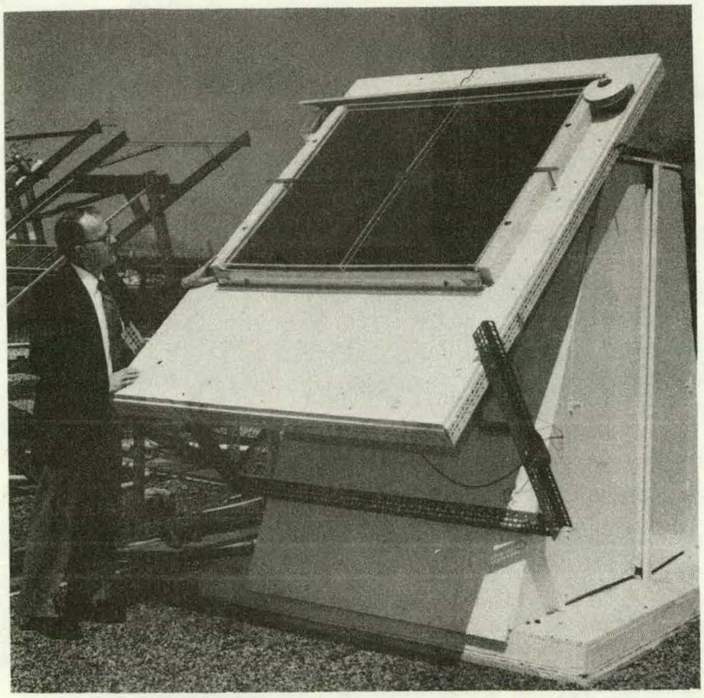

FIGURE 1. OUTDOOR SOLAR COLLECTOR TEST FACILITY

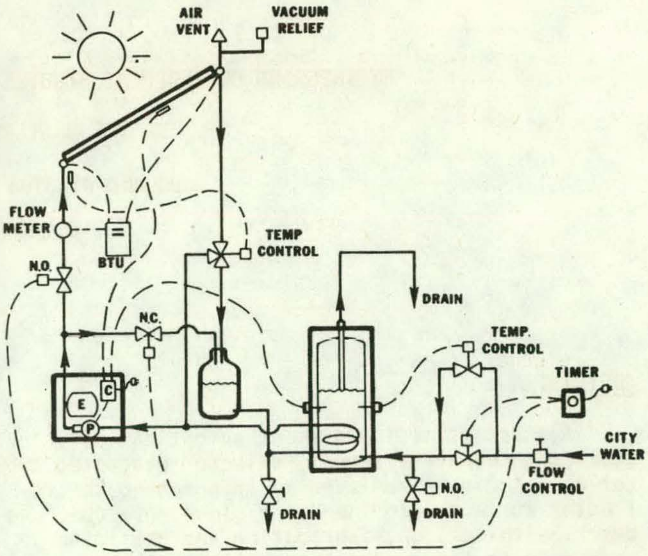

FIGURE 2. SCHEMATIC OF OUTDOOR SOLAR COLLECTOR TEST FACILITY

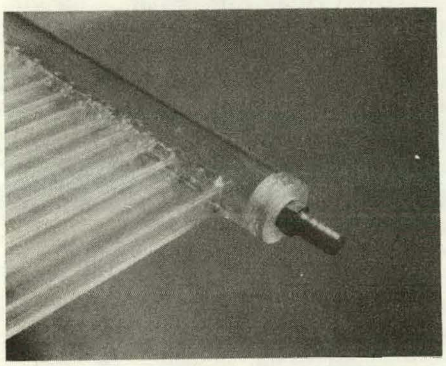

FIGURE 3. CLOSE-UP OF EXTRUDED COLLECTOR AND MANIFOLD

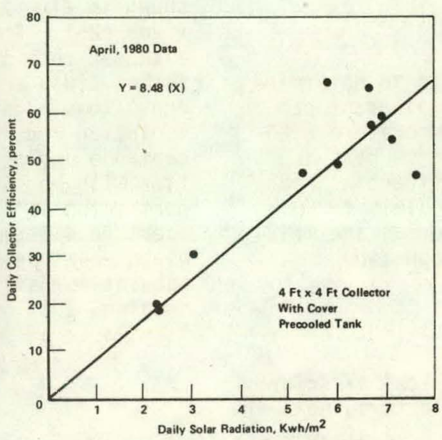

FIGURE 4. BLACK-LIQUID COLLECTOR PERFORMANCE WITH COVER

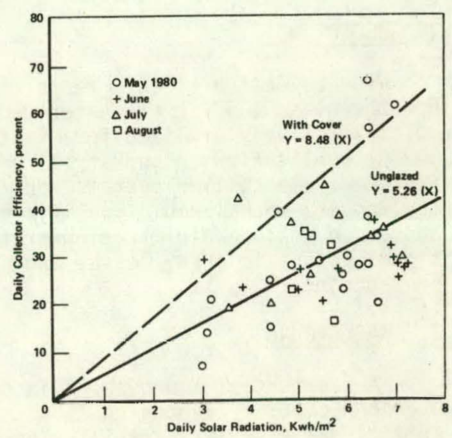

FIGURE 5. BLACK LIQUID COLLECTOR PERFORMANCE UNGLAZED

CONTRACT INFORMATION

START DATE 1 September 1979 END DATE 31 July 1981 CONTRACT VALUE $149,202

MILESTONES

Item:		Due date:	
1.	Paper presented at DOE Active Solar Heating and Cooling Contractors Review Meeting	March 1980	m
2.	Semi-Annual Report September 1, 1979 - February 29, 1980	March 1980	m
3.	Literature Survey on Materials for Plastic Collectors	July 1980	m
4.	Semi-Annual Report March 1, 1980 - August 31, 1980	September 1980	m
5.	Final Report, Phase II, Draft	July 1981	m

ENGINEERING DEVELOPMENT STUDIES FOR INTEGRATED EVACUATED CPC ARRAYS

THE UNIVERSITY OF CHICAGO

ROLAND WINSTON & JOSEPH O'GALLAGHER

DE-AC04-81AL16223

ABSTRACT

A substantial improvement in optical efficiency over contemporary external reflector evacuated tube collectors can be achieved by integrating the reflector surface into the outer glass envelope. We describe the design, fabrication and preliminary test results for a prototype collector based on this concept. Efficiencies above 40% up to nearly 300°C may be achieved. This study is concerned with the evaluation of practical problems associated with the use of arrays of such collectors in a variety of applications. Projections of long term energy delivery show that these stationary collectors are competitive with line focus tracking concentrators.

1. OBJECTIVE

The objective of this research is to determine how the glass tubular evacuated CPC collector can be most effectively utilized for mid-temperature (100-300°C) applications. Industrial process heat and Rankine cycle chiller systems for residential space cooling are emphasized. Specific problems to be addressed include minimization of thermal and frictional parasitic array losses and stagnation protection.

2. BACKGROUND

A substantial improvement in optical efficiency over contemporary evacuated tube collectors, both in initial value and its stability over a relatively long lifetime can be achieved by integrating a concentrating reflecting surface of the nonimaging CPC type[1] into the vacuum enclosure itself by shaping the outer glass envelope to the desired profile[2] as illustrated in Fig. 1. The performance gain is a consequence of two obvious advantages of the integrated design.

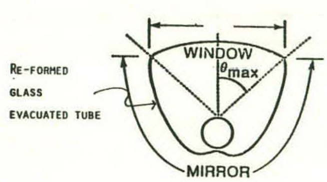

Fig. 1 Cross section of integrated design suggested in Ref. 2.

A. Since the reflector surfaces are in vacuum, high quality front surface mirrors (silver or aluminum with reflectances ρ = 0.91-0.96) can be used instead of anodized aluminum sheet metal or thin film reflectors (ρ = 0.80-0.85) typical of the external reflector designs.

B. The integrated design eliminates the need for an external cover glass and the effects of exposure of the reflector surfaces to the elements.

Clearly the lifetime of such reflecting surfaces in vacuum can be expected to be essentially indefinite as long as the integrity of the enclosure is maintained.

3. DESIGN DETAILS

The basic design of the concentrating tube is shown in Fig. 2 in both cross section (2a) and side views (2b). The concentrator profile curve is an extended cusp type CPC[3] matched to a circular absorber cross section of diameter 9.5 mm (0.375 in.) and allows a gap of 1.9 mm (0.075 in.) for thermal isolation and mechanical clearance. The design acceptance angle is ±35° to permit stationary operation with no tilt adjustments. The geometric concentration is 1.6X corresponding to a collecting aperture 4.9 cm (2.0 in.) in width. The outer glass envelope was formed from a standard 57 mm O.D. tube of borosilicate (Pyrex$^{(R)}$) glass which has an original I.D. of 52 mm. The reflector surface is a thin layer of vacuum deposited silver.

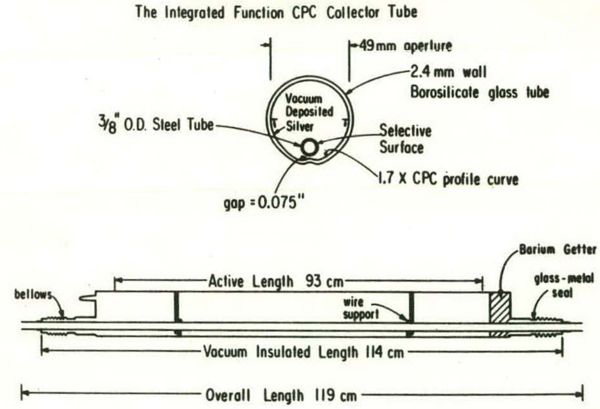

Fig. 2 Schematic illustration of prototype design: a) cross section profile, b) side view (not to scale).

The absorber tubes are 9.5 mm (3/8 in.) O.D. type 304 stainless steel with a wall thickness of 0.9 mm (0.035 in.). A selective surface is provided by vacuum deposition of a multilayer stack. Special features of the mechanical design include:

A. doubled-ended unidirectional flow-through configuration,

B. copper glass-to-metal "housekeeper" seals,

C. metal bellows to allow for differential expansion between the absorber and glass tube,

D. barium getter to preserve long lifetimes)r vacuum (<10^{-6} torr.).

Because of the length taken up by bellows, seals and the getter, the active length is limited to 93 cm (36.6 in.) and the relative effect of the end losses is more important in the prototype design than would be the case for a length optimized for production (probably ∿6 ft.).

4. PERFORMANCE

The optical and thermal performance parameters for the integrated CPC tube are listed in Table 1. The predicted heat loss Q_L has been parameterized according to the form

$$Q_L = U_m A_1 (T-T_a) + \sigma\varepsilon^* A_2 (T^4-T_a{}^4) \quad (1)$$

where A_1 and A_2 are the net active aperture and absorber areas, respectively, σ is Stefan-Boltzman constant, and T and T_a are the collector average temperature and ambient temperature,respectively. The effect of conduction losses from the manifold and ends is included by introducing the linear manifold heat loss coefficient U_m and the effective emittance per unit active collector area ε^* (increased above the actual value to include radiative losses from inactive portions of the absorber tube length). If the optical efficiency relative to total insolation I_o is η_o, the instantaneous efficiency can be represented by

$$\eta(T,T_a) = \eta_o - \frac{U_m(T-T_a)}{I_o} - \frac{\sigma\varepsilon^*}{CI_o} (T^4-T_a{}^4) \quad (2)$$

where $C = A_1/A_2$.

TABLE 1 PARAMETERS OF CPC COLLECTOR TUBE

	DESIGN GOAL	PROTOTYPE COMPONENT
CONCENTRATOR		
CONCENTRATION RATIO	1.7X	1.6X
ACCEPTANCE ANGLE θ	± 35°	± 30°
OPTICAL PERFORMANCE		
GLASS TUBE TRANSMITTANCE (τ)	0.91	0.92▼
REFLECTANCE (ρ)	0.96	0.95 ± .02
EFFECTIVE REFLECTANCE $\rho^{(0.8)}$	0.97	0.96 ± .02
"GAP" LOSS (L) (AVERAGED OVER ± θ)	0.06	.05 - .1 (EST.)
ABSORPTANCE (α)	0.85	0.85 - 0.88
OPTICAL EFFICIENCY		
η_θ (WITHIN ACCEPTANCE ANGLE)	0.71	
η_0 (RELATIVE TO TOTAL*)	0.68*	
THERMAL PERFORMANCE		
EMITTANCE (ε)	0.07	0.08
EFFECTIVE EMITTANCE (ε*) (INCLUDING INACTIVE ABSORBER)	0.078	0.10
LINEAR HEAT LOSS COEFFICIENT (MANIFOLD AND END LOSSES) (W/m^2-°C)	0.13	0.20

*ASSUMING I_{DIF} IS 0.1 TIMES I_{BEAM}.

▼MEASURED BY K. REED AT ARGONNE NATIONAL LABORATORY.

Values listed in Table 1 characterize the prototype panel for the prototype tubes shown in Fig. 2b while the values listed under "design goal" are for tubes with an active length of 6 feet and the same inactive length per end as the prototypes. Predicted instantaneous performance based on Eq. 2 for the design goal is shown in Fig. 3 as well as -- estimate for the prototype panel based on mea- red subcomponent performance. Shown for compari- ..n is a shaded region representing the performance of contemporary evacuated tube collectors[4].

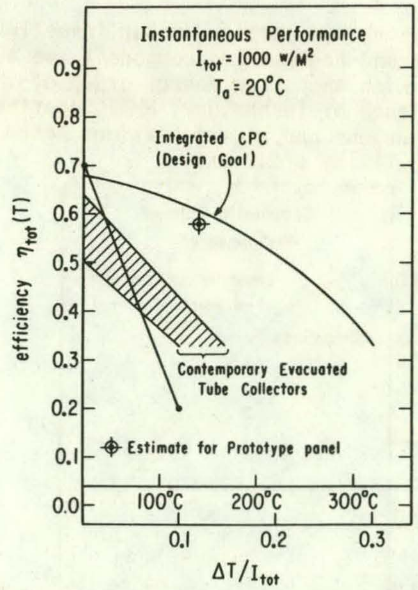

Fig. 3 Predicted efficiency curves for integrated CPC collector tube compared with contemporary evacuated collectors and a very good double glazed flat plate.

5. POTENTIAL APPLICATIONS

The instantaneous performance curves shown in Fig. 3 show efficiencies relative to total insolation greater than 40% across the full range from ambient temperautre to nearly 300°C. This can be achieved with a totally stationary collector system comprised of an array of integrated function tubes. This temperature and performance range makes it truly an all purpose solar collector with applications for space heating and cooling, industrial process heat, irrigation pumping and low temperature electrical power generation. The features will be particularly advantageous in climates characterized by a large diffuse component since this concentrator collects more than half the available diffuse. Using the recently developed model developed by Rabl[5] for predicting comparative energy collection, the annual performance projection for this collector and for a good East-West aligned tracking trough have been determined and are plotted for the relevant temperature range in Fig. 4. Results for two locations, Boston and Albuquerque are shown. As can be seen the output from the integrated concentrating tube exceeds that for the trough up to temperatures of 260°C-300°C. This is because the extra diffuse radiation available to the CPC in both climates compensates for its slightly greater thermal losses. The relative improvement is most dramatic in the northeastern climate.

6. APPLICATIONS STUDIES

We are investigating specific issues associated with the deployment of arrays of integrated function CPC tubes and their interface with other mid-temperature systems. The activities are divided into the following areas:

A. array development,

B. manifold optimization and interconnect strategy,

C. applications development, and

D. performance analysis and projections.

to assist us with this portion of our investigation which has a strong engineering component, we are collaborating with the solar energy group of the Illinois Institute of Technology, MMAE Department. Results, conclusions and recommendations based on these studies will be presented.

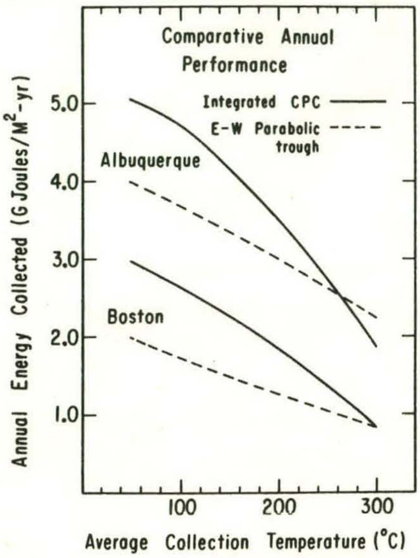

Fig. 4 Calculated annual energy delivery for an integrated CPC and an East-West aligned tracking parabolic trough using the method of Ref. 5.

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1. W. T. Welford and R. Winston, Optics of Nonimaging Concentrators, Academic Press, New York (1978).

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4. B. J. Graham, "A Survey and Evaluation of Current Design of Evacuated Collectors", Final Technical Report for U.S. Department of Energy Contract No. DE-AC02-79CS05350 (September 1979).

5. A. Rabl, "Yearly Average Performance of the Principal Collection Types", SERI Technical Report TR-631-716 (January 1981).

CONTRACT INFORMATION

START DATE Jan. 19, 1981 END DATE Jan. 18,1982 CONTRACT VALUE $74,242

MILESTONES

Item:	Due date:
1. Semi-Annual Technical Progress Report	7-18-81 p
2. Semi-Annual Technical Progress Report	1-18-82 p
3. Final Technical Report	1-18-82 p
4.	
5.	

STUDY OF ALUMINUM CORROSION IN ALUMINUM SOLAR HEAT COLLECTORS USING AQUEOUS GLYCOL FOR HEAT TRANSFER

GINER, INC.

LARRY L. SWETTE, DAVID K. WONG, FRANKLIN H. COCKS

DE-AC04-79CS31072

OBJECTIVE

The goal of this program was to establish the conditions for successful operation of aluminum solar heat collector panels with aqueous glycol heat transfer fluids for periods of up to 20 years. Within this goal the experimental objectives were to determine the effect of extended elevated temperature exposure (130° - $150^{\circ}C$) on the pH and corrosiveness of aqueous glycol solutions; to determine the critical pitting potential of aluminum in the presence of chloride ion in aqueous glycol solution; to determine the effectiveness of inhibitor formulas in preventing aluminum corrosion; and to determine the effectiveness of zinc powder in protecting aluminum under corrosive conditions beyond the normal range of inhibitor effectiveness.

DESCRIPTION OF WORK

Pure aluminum (1100 series) and the Mn alloys (3000 series), were investigated for corrosion susceptibility in aqueous ethylene and propylene glycols under a variety of temperature, flow, contamination and inhibitor conditions. Conventional weight-loss methods were used to determine corrosion rates. In addition, polarization resistance measurements were used to determine <u>overall</u> corrosion rates using the Stern-Geary equation:[1-4]

$$i_{corr} = \beta_a\beta_c/2.3(\Delta E/\Delta i)(\beta_a+\beta_c) \qquad (1)$$

in which:

i_{corr} = corrosion current density (A/cm^2)

β_a, β_c = slopes of logarithmic local anodic and cathodic polarization curves (V/decade)

$\beta_a\beta_c/(\beta_a+\beta_c)$ = 0.16 for ethylene glycol and 0.07 for propylene glycol

$\Delta E/\Delta i$ = measured potential/measured current density at low polarization ($ohms/cm^2$)

The corrosion rates were then determined by converting i_{corr} to mils/year (e.g., $i_{corr} \times 4.1 \times 10^5$).

The <u>pitting</u> corrosion damage was assessed by measuring pit density and maximum pit depth. The pit growth constant, <u>k</u>, was determined by the cube root law:[5]

$$D = kt^{1/3} \qquad (2)$$

where <u>D</u> is the measured pit depth in microns and <u>t</u> is the exposure time, in days. Pitting analysis was done by quantitative metallographic examination. These results were extrapolated from laboratory samples to working system surfaces by the following equation:[6]

$$p = kt^{1/3}A^a \qquad (3)$$

where <u>p</u> is the maximum probable pit depth to be found on the surface of such a working system, <u>k</u> and <u>t</u> are as defined in Eq. (2), <u>A</u> is the working system/laboratory sample surface area ratio, and <u>a</u> is an empirical parameter derived by dividing an exposed sample surface into <u>N</u> equal sections and measuring minimum and maximum pit depths; then

$$a = \log(D_{max}/D_{min})/\log N \qquad (4)$$

The typical value of <u>a</u> was determined to be ∿0.14.

Commonly encountered contaminants that can accelerate corrosion are Cl^-, Fe^{3+} and Cu^{2+}; corrosion effects of these contaminants were examined at a typical concentration of 200 ppm.

Pure and contaminated glycol solutions with and without inhibitor were thermally degraded by heating in pressure vessels to 100°, 140° and $190^{\circ}C$ for up to 6000 hours. Aluminum corrosion rates were then measured in these solutions.

The critical pitting potential of 1100 series aluminum was determined for uninhibited aqueous ethylene and propylene glycols over the temperature range 25° to $100^{\circ}C$ and a chloride ion concentration range of $10^{-4}M$ to 1.0M, using a potentiostatic step technique.[7]

Corrosion inhibitor formulations, both commercially available coolants as well as laboratory preparations based on commercial formulas, were evaluated for effectiveness in protecting aluminum by using weight-loss, linear polarization measurements and pitting analysis techniques.

Finally, the use of zinc powder as a floating sacrificial anode was evaluated both in terms of effectiveness in preventing pitting under extremely aggressive conditions and in terms of the approximate zinc consumption rates. Electrochemical corrosion parameters were measured followed by high temperature testing in laboratory scale circulators.

TECHNICAL ACCOMPLISHMENTS

- Aluminum is marginally corrosion resistant in <u>uninhibited</u> glycol solutions of <u>high purity</u> under moderate temperature conditions (below $100^{\circ}C$, no stagnation).

- Common contaminants Cl^-, Fe^{3+}, Cu^{2+}, accelerate corrosion substantially in <u>uninhibited</u> glycol solutions; chloride and copper ions, in particular, induce severe pitting.

- Ethylene glycol solutions are, in general, somewhat more corrosive than propylene glycol solutions, and corrosiveness increases with increasing water dilution.

- Both ethylene and propylene glycol solutions, inhibited and uninhibited, become increasingly acidic in direct proportion to temperature (above 100°C) and exposure time.

- After 2000 to 3000 hours at 140°C, glycol solutions without inhibitors show pH values of less than 5; such solutions are highly corrosive to aluminum, (one mil Al foil samples pitted through in one week).

- Standard automotive coolant inhibitor was found to provide better corrosion protection for aluminum than currently available inhibitor solutions specifically marketed for solar thermal application.

- Inhibited ethylene and propylene glycols aged at 100°C did not degrade below pH 8 after 6000 hours, with or without Cl^-, Cu^{2+} and Fe^{3+} contaminants present. Aluminum exposed to such solutions was still satisfactorily protected by the inhibitor.

- The inhibitor formulation was increasingly less effective at temperatures above 100°C.

- At 140°C, inhibited glycols were degraded below pH 8 within 3000 hours; aluminum corrosion rose to a rate of 1 mpy in such solutions. The presence of Cl^-, Cu^{2+}, and Fe^{3+} accelerated pH drop at 140°C, as well as aluminum corrosion in subsequent testing, particularly pitting attack.

- The critical pitting potential, E_p, of aluminum in 50% aqueous glycol solutions was found to obey the following relationship:

$$E_p = E_p^o + S \log Cl^- \qquad (5)$$

  in which E_p^o and S are temperature dependent constants.

- The critical pitting potential of aluminum was found to become more negative with increasing temperature and with increasing chloride ion concentration. For example, at 10^{-4}M Cl^-, E_p vs. SHE shifts from -280mV at 25°C to -380mV at 100°C in 50% aqueous ethylene glycol; and at 100°C, E_p shifts from -380mV at 10^{-4}M Cl^- to -590mV at 10^{-1}M Cl^-.

- Zinc metal in contact with aluminum was found to prevent pitting corrosion under conditions beyond the normal range of inhibitor effectiveness (e.g. at 130° - 140°C in the presence of Cl^-).

- Zinc powder effectively scavenges heavy metal ions like Fe^{3+} and Cu^{2+} from solution.

- Zinc exhibits a more negative potential than aluminum in uninhibited glycol solutions; thus zinc powder in contact with aluminum can lower the potential below the critical pitting potential of aluminum.

- The zinc/aluminum potential relationship is pH dependent; in inhibited glycols (pH 10-11), aluminum is slightly more negative than zinc, but without effect on corrosion (i.e., the inhibitor is still functional).

- In laboratory circulator tests at 130° - 150°C, 10 micron zinc powder was found to prevent or substantially reduce pitting attack of chloride containing glycol solutions, with and without inhibitor, for 900-1600 hours of continuous operation (maximum test durations). For example:

  a) In 85% propylene glycol with 200 ppm Cl^- and 2 wt% Zn powder, but without inhibitor, no pitting was observed after ~1500 hours of exposure at 150°C (N_2 atmos.).

  b) In 85% ethylene glycol with inhibitor, 200 ppm Cl^- and 2 wt% Zn powder, no pitting was observed after 1600 hours at 125° - 150°C (air atmos.).

  c) In 50% propylene glycol (pressurized system) with inhibitor, 200 ppm of Cl^-, Fe^{3+} and Cu^{2+}, and 3 wt% Zn powder, the maximum pit depth observed was 8μ after 900 hours of operation at 140° - 150°C. Using Eq. (3) above, the maximum probable pit depth in 20 years would be 8-10 mils. For the same system without Zn after 900 hours at 150°C (stagnant), the maximum pit depth was 22μ, equivalent to 20-25 mils in 20 years. Zinc powder replenishment would probably be necessary on an annual or bi-annual basis.

FUTURE ACTIVITIES

Current contract was completed March 31, 1981. Commercial interest in the results of this work is being explored.

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4. M.S. Walker, Materials Performance, July, 37 (1974).

5. H.P. Godard, W.D. Jepson, M.R. Bothwell and R.L. Kane, Corrosion of Light Metals, p. 60, John Wiley and Sons, Inc. (1967).

6. H.H. Uhlig, Corrosion Handbook, p. 1052, Wiley, New York (1948).

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REPORTS

A1. J. Giner, F.H. Cocks and D. Wong, Annual Progress Report (COO-2934-4) June 1, 1977; for the period 6/1/76 - 5/31/77.

A2. D. Wong, F.H. Cocks, J. Giner and P.S. Majahad, Annual Progress Report (COO-2934-7) August, 1978; for the period 6/1/77 - 7/31/78.

A3. D. Wong and F.H. Cocks, Annual Technical

Progress Report on Contract DE-AC04-79CS31072, August, 1980; for the period 7/30/79 - 7/31/80.

A4. L. Swette and F.H. Cocks, Final Report and Corrosion Control Manual on Contract DE-AC04-79CS31072; for the period 7/30/79 - 3/31/81 (in progress).

PUBLICATIONS

B1. D. Wong, L. Swette and F.H. Cocks, J. Electrochem Soc., 126, 11 (1979).

B2. D. Wong and F.H. Cocks, Corrosion-NACE, Vol. 36, No. 9, 513 (Sept., 1980).

B3. D. Wong and F.H. Cocks, Corrosion-NACE, Vol. 36, No. 11, 587 (Nov., 1980).

CONTRACT INFORMATION

START DATE 7/30/79 END DATE 3/31/81 CONTRACT VALUE $99,923

MILESTONES

Item:	Due date:
1. Annual Report	July, 1980 (m)
2. Final Report	May, 1981 (p)
3. Corrosion Control Manual	May, 1981 (p)
4.	
5.	

COLLECTOR RESEARCH AND DEVELOPMENT*

LOS ALAMOS NATIONAL LABORATORY

DONALD A. NEEPER

W-7504-ENG-36

ABSTRACT

Current solar collector research of the Los Alamos National Laboratory is described. The document is divided into three sections dealing with the three aspects of the program: reliability and maintainability, optical materials, and evacuated tube collector testing.

I. RELIABILITY AND MAINTAINABILITY (John Avery)

OBJECTIVE

The objective of this work is to provide meaningful and useful solar reliability and maintainability information on corrosion of metallic components of solar collectors and the performance of various heattransfer fluids.

DESCRIPTION OF WORK

This task involves generation of both laboratory and field data regarding corrosion and fluids of interest to active solar applications. The real-time field data collected by Los Alamos will be used to validate the results of existing and continuing DOE-funded research and development projects. A subsequent report will supply needed information on fluid and hardware lifetimes.

The laboratory data generated by Olin Corporation under DOE Contract DE-AC04-81AL16222, consist of screening tests on more than 150 metal/fluid combinations: Cu, Al, steel, galvanic couples and solder joints, with various waters, glycols, and aqueous heat-transfer fluids.

The field data come from field sites specially instrumented to obtain data relevant to corrosion. Corrosion coupons and fluids will be withdrawn every 6 months and evaluated. Figures 1-3 show the collector array and corrosion coupons to be studied at the Los Alamos National Laboratory's newly constructed Support Facility.

FUTURE ACTIVITIES

Fluid and hardware lifetime data will be supplied to the private sector as the information becomes available.

MAJOR MILESTONE

State-of-the-art report on corrosion.

II. OPTICAL MATERIALS (Stanley Moore)

OBJECTIVE

The objectives of the optical materials investigation include operation of a high-altitude, materials exposure facility; investigation of chemical conversion coatings for passive or low-temperature selective surface applications; and determination of collector materials durability and reliability.

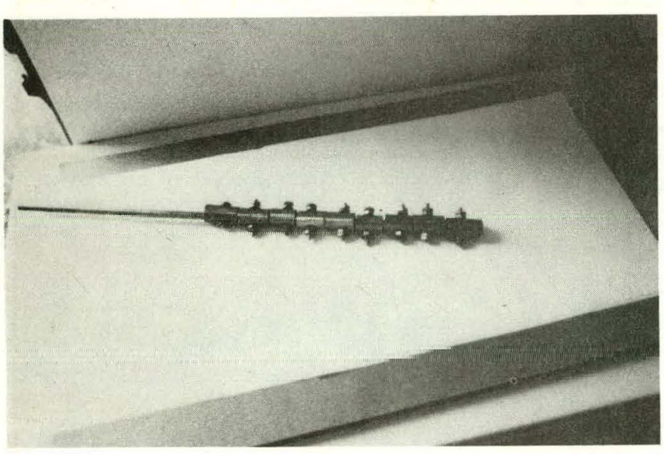

Fig. 1. Removable corrosion coupons

Fig. 2. Location of corrosion coupon rack

*Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

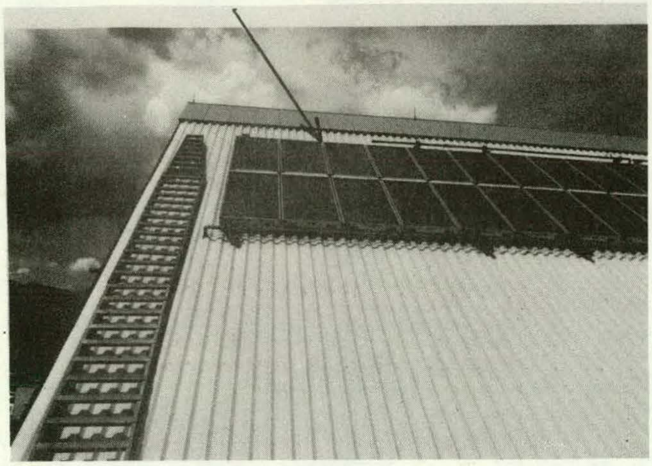

Fig. 3. Location of manifold in solar installation plumbing

DESCRIPTION OF WORK

A high-altitude exposure facility complements the environmental regional testing in desert control and industrial environments. Both developmental and commercially available glazings, reflectors, and absorber materials are being tested at this facility. Types and rates of degradation will be determined.

Chemical conversion coatings offer the promise of providing inexpensive selective absorbers for low-temperature and passive applications. A general study has been undertaken to determine prospective coatings followed by detailed optimization and environmental testing.

TECHNICAL ACCOMPLISHMENTS

- The high altitude exposure facility has been completed, instrumented, and is operational. The first round of Solar Energy Research Institute/Desert Sunshine Exposure Tests (SERI/DSET) commercially available materials is on test. Developmental materials are being installed.
- Chemical conversion solutions and substrate materials consisting of aluminum, zinc, cadmium, copper, stainless, galvalume and aluminized nylon have been procured. Screening samples of aluminum and copper have been prepared, and optical evaluation is under way.
- A 5-year stagnation test on black chrome selective absorber collectors has been completed. Optical evaluation has shown no degradation in either solar absorptance or emittance.
- A status report covering the progress of the DOE programs on painted coatings has been completed and is being published.
- Anti-reflectance-treated glass, etched by Honeywell/Nor-Ell, Inc., is undergoing outdoor exposure testing. Neither the AFG Solatex nor the CE Heliotherm has shown any loss in transmittance after exposures of 10 months and 5 months, respectively.

FUTURE ACTIVITIES

Topical reports covering the detailed results of the black chrome and absorber paint durability evaluations will be published and made available for commercial evaluation and use.

PUBLICATIONS/REPORTS/REFERENCES

S. K. Reisfeld and D. A. Neeper, "Solar Energy Research at Los Alamos: April 1, 1980 - September 30, 1980, Los Alamos National Laboratory Report LA-8782-PR.

III. EVACUATED TUBE COLLECTOR TESTING (John Krall)

OBJECTIVE

The objective of this work is to test and evaluate the use of heat pipes configured in evacuated tube solar collectors.

DESCRIPTION OF WORK

Two evacuated tube collector modules were tested. One module employs heat pipe absorbers designed and built by Thermacore, Inc., under DOE Contract DE-AC04-77CS34099. The 5/16-in. steel heat pipes with the trimethylborate working fluid replaces the hairpin absorber of the standard General Electric evacuated tube collector. The heat pipes are brazed to the standard two-piece copper fin. The second module is a standard, 8-tube, parabolic cusp reflector, General Electric TC-100 collector.

The initial test objective was to duplicate and analyze apparent sporadic behavior of the heat pipe collector observed by General Electric. The sporadic behavior could not be duplicated, and we concluded that it resulted from the testing arrangement at the General Electric facility. The evacuated tube modules were tested side by side in parallel test loops using 100% glycol as the loop working fluid. Since the efficiency data were generated utilizing 100% glycol, the presented results should be used only for comparison and not for absolute efficiency data. Figures 4-6 show performance test data.

Both collector modules were also stagnated, and a brief study of oxidation of the copper absorber fin was conducted for comparison with observations of corrosion in collectors in the field. One collector was tested with the copper absorber fins removed to determine the worst case, i.e., the copper absorber fins had corroded completely away. Observed oxidation after two days of stagnation revealed that loose scale (Cu_2O or CuO) 1-mil thick had developed on a previously cleaned area on the copper fins and the general appearance of the majority of tubes was that of loose curled-up scale of a larger magnitude than that observed prior to the two-day stagnation. It is expected that because of the lower stagnation temperatures of the heat pipe collector, oxidation rates on the copper fins will be decreased.

Thermacore's latest copper heat pipes with water as the working fluid are currently being tested and evaluated, and the results will be compared to Thermacore's steel-trimethylborate heat pipes.

Additionally, Phillips' evacuated tube heat pipe collector is being tested and evaluated.

TECHNICAL ACCOMPLISHMENTS

- The GE-TC-100 evacuated tube collector configured with heat pipes (Fig. 4) was shown to have an efficiency comparable to that of the standard GE-TC-100 (Fig. 5) in the normal operating range.

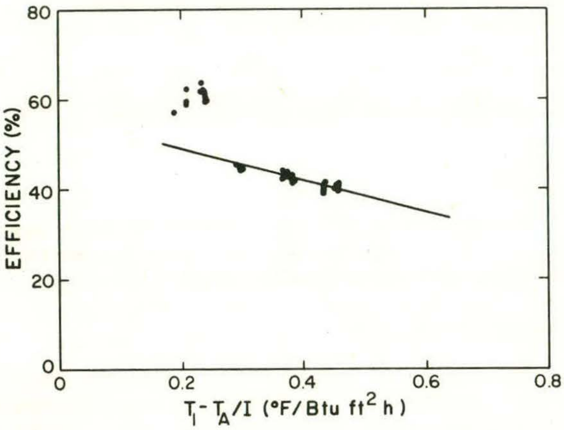

Fig. 4. GE-TC-100 evacuated tube collector configured with Thermacore heat pipes.

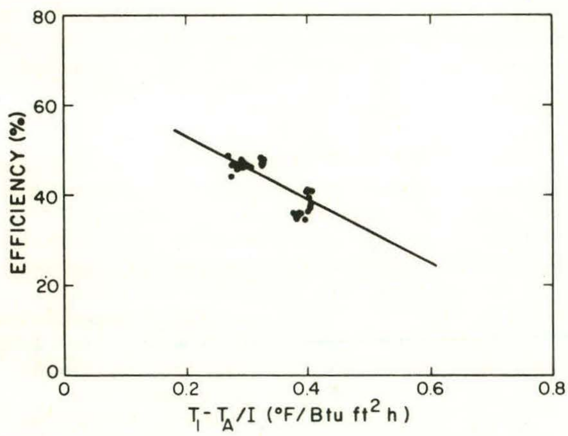

Fig. 5. Standard GE-TC-100 evacuated tube collector

- Stagnation temperatures of the GE-TC-100 evacuated tube collector configured with heat pipes are lower than stagnation temperatures of the standard GE-TC-100. Our tests under 300 Btu/ft^2 insolation at an ambient temperature near 80°F showed that the fin in the standard GE-TC-100 reached a temperature of 742°F. The heat pipe absorber fins remained considerably cooler. The range of temperatures on the heat pipe fins was 430-700°F.

- The removal of the heat conducting fins reduced the efficiency of the heat pipe, evacuated tube collector by 14% (Fig. 6).

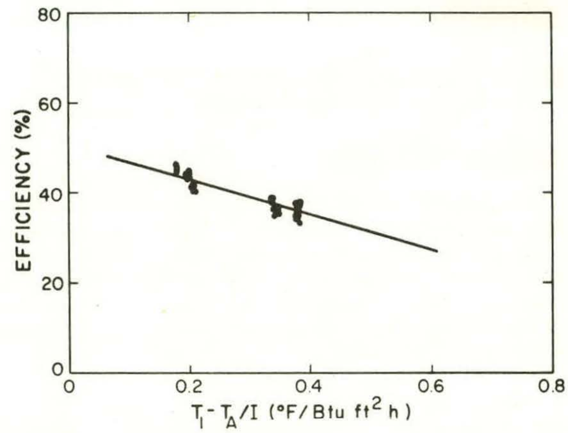

Fig. 6. GE-TC-100 evacuated tube collector with fins removed

FUTURE ACTIVITIES

Thermacore's new copper heat pipe with water as the working fluid will be evaluated and compared to the steel heat pipe with trimethylborate as the working fluid. The Phillips evacuated tube collector configured with copper heat pipes and isobutane as the working fluid will be tested and evaluated.

CONTRACT INFORMATION

START DATE October 1, 1980 END DATE Continuing CONTRACT VALUE $220k

MILESTONES

Item:	Due date:
1. Deliverables include progress reports and topical reports on materials investigations and exposure testing results.	As needed
2.	
3.	
4.	
5.	

EVALUATION OF SOLAR POND PERFORMANCE

MONSANTO RESEARCH CORPORATION

LAYTON J. WITTENBERG

DE-AC04-76-DP00053

OBJECTIVE

This project is directed toward data collection and evaluation of the thermal performance and operational characteristics of the largest, operational, salt-gradient solar pond in the United States; to gain firsthand experience regarding the maintenance, adjustments and repairs required of a large, operational solar pond facility; and to provide technical consultation regarding the operation and the optimization of the pond performance.

DESCRIPTION OF WORK

This project required the installation of appropriate instrumentation, and the collection and evaluation of data on the performance of the large solar pond located in Miamisburg, Ohio. This task required, also, firsthand observation and technical consultation with the operator of the pond regarding the construction, operation and maintenance required of this large facility.

During 1978 the City of Miamisburg constructed a large, salt-gradient solar pond as part of its community park development project. The thermal energy stored in the pond is being used to heat an outdoor swimming pool in the summer and an adjacent recreational building during part of the winter (see Fig. 1). This solar pond, which occupies an area of 2020 m^2 (22,000 ft^2), was designed from experience obtained at smaller research ponds located at Ohio State University and the University of New Mexico, and similar ponds operated in Israel.

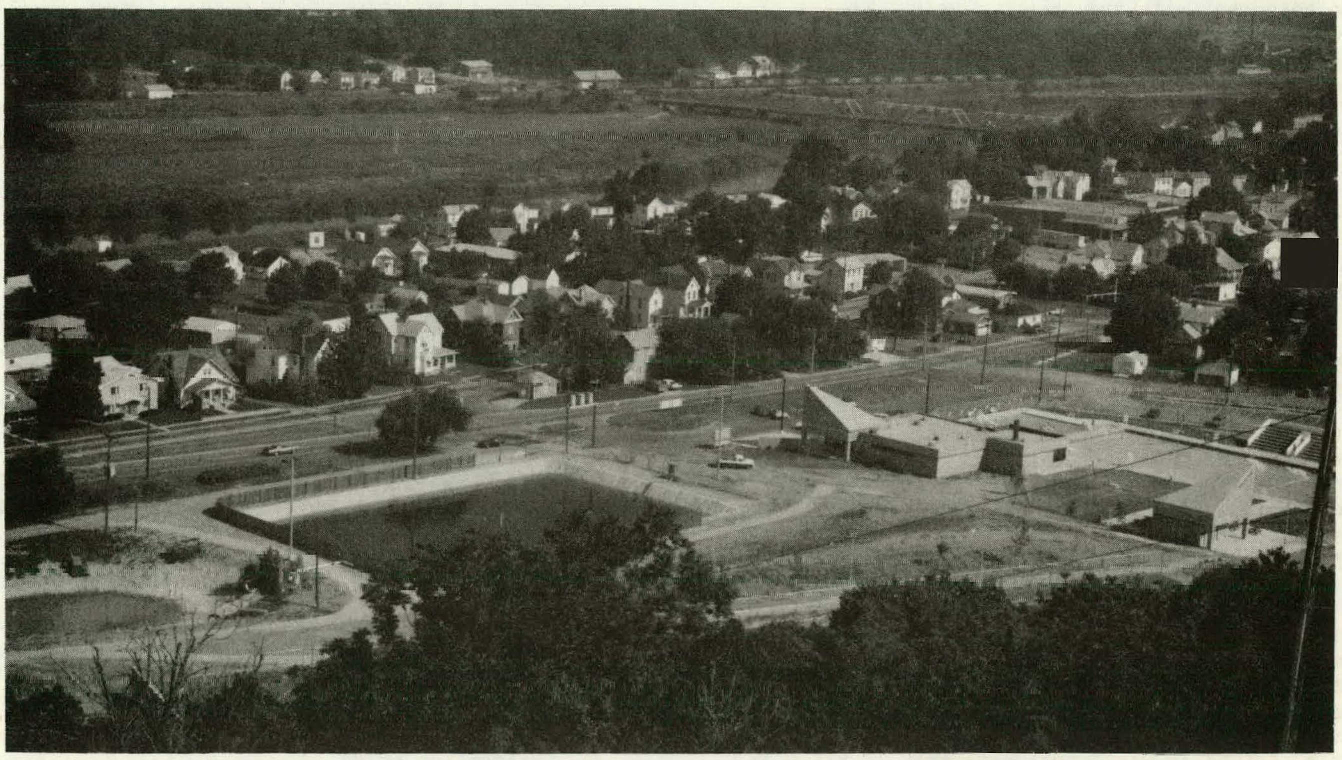

Figure 1. The Miamisburg solar pond (center) is used to heat the outdoor swimming pool (right) during the summer and the adjacent recreational building for part of the winter.

The solar pond combines low-cost solar energy collection with the annual storage of low-temperature heat. The installation cost to the city for this pond was $70,000. The cost of this type of combined solar collector and heat storage system is, therefore, only $35/m^2$ ($3.20/$ft^2$). Because the pond is an annual storage system, it may require two to three years to reach a steady-state condition at which time it is projected to deliver annually 300,000 kWH (1 billion BTU) of heat. If the cost of the pond is depreciated over 15 years, the cost of this heat will be only 3.2¢/kWH ($9.45/million BTU).

TECHNICAL ACCOMPLISHMENTS

- During July, August, and September 1979, useful heat (40,000 kWH, 136 million BTU) was withdrawn for the first time from the solar pond to maintain the outdoor swimming pool at approximately 80°F.

- Instrumentation was installed and tested to measure the total solar insolation, the solar radiation penetration into the water, air temperature, and temperatures at numerous depths and locations in the water and in the earth beneath the pond. All of these sensors are automatically read and recorded on a pre-determined schedule by the use of a small computer. During 1980, an automated conductivity probe was added to scan the salt concentration at all levels in the pond. Also, the automated data collection system was updated and made fully operational.

- A simple, heat-flow model based upon the University research ponds was constructed and tested by comparison of the observed with the predicted temperatures for the storage layer during each month of 1979. The predicted values were in good agreement with the observed values except for March when a large amount of heat was probably lost to groundwater. Based upon this model, the pond is predicted to deliver 300,000 kWH/yr (1 billion BTU/yr) of heat when it has reached a steady-state condition.

- Water quality was determined frequently by measurements of salinity and acidity on samples extracted from various depths of the pond. Copper sulfate, in the 1-2 ppm concentration range, served successfully as an algaecide; however, the acidity of the water had to be readjusted several times during the year with hydrochloric acid to maintain a pH of 6 so that the copper sulfate remained in solution.

- Corrosion of the solder joints of the copper tube heat exchanger caused by the hot, concentrated saline solutions became severe. All of the original solder joints, composed of 95% tin-5% antimony, were subsequently refabricated with a brazing alloy of high silver content.

- Corrosion of the base of the copper-tube heat exchanger immersed in the storage layer became severe when a differential electrochemical cell was inadvertently formed. This heat exchanger was removed from the pond.

- A tube-in-shell heat exchanger is being installed external to the pond. The hot brine will be pumped from the pond through the heat exchanger and returned to the pond.

- Several seam failures have occurred in the plastic liner and some of the brine has leaked from the pond. These faulty seams have been successfully repaired underwater without the need to completely drain the pond.

- The pond was reconstructed during 1980 with the addition of more salt and the reformation of the gradient zone. The pond will be available for heating the swimming pool water by the summer of 1981.

FUTURE ACTIVITIES

No current plans exist for marketing/commercialization of this system. The cost and performance information derived from this project has been given wide circulation. This information will provide engineering data for design and construction of future ponds planned in the U. S. For low-temperature process heat and certain types of community development projects, such ponds have the potential for displacing significant amounts of fossil fuels. Based upon such interest and need, a more formal marketing/industrial information strategy may be proposed, if a National Solar Pond Development Plan is implemented.

PUBLICATIONS

1. R. S. Bryant, R. P. Bowser, and L. J. Wittenberg, "Construction and Initial Operation of the Miamisburg Salt-Gradient Solar Pond," Proc. International Solar Energy Congress, Atlanta, GA, May 28 - June 1, 1979, pp. 1005-1009, Pergamon Press, New York, 1979.

2. L. J. Wittenberg and M. J. Harris, "Evaluation of a Large Non-Convective Solar Pond," Proc. Solar Energy Storage Options, San Antonio, March 19-20, 1979, pp. 193-202, CONF 790328-P1 (1979).

3. L. J. Wittenberg and M. J. Harris, "Performance of a Large Salt-Gradient Solar Pond," Proc. 14th Intersociety Energy Conversion Engineering Conference, Boston, August 5-10, 1979, pp. 49-52, American Chemical Society Publ., 1979.

4. M. J. Harris and L. J. Witenberg, "Heat Extraction from a Large, Salt-Gradient Solar Pond," Proc. Solar Heating and Cooling Operational Results Conf., Colorado Springs, Nov. 27-30, 1979, pp. 161-163, SERI/TP-245-30 (1979).

5. "Solar Ponds," Solar Age Magazine, p. 37, January 1980.

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7. L. J. Wittenberg and M. J. Harris, "Management of a Large, Operational Solar Pond," Proc. 15th Intersociety Energy Conversion Engineering Conference, Seattle, Wash., August 18-22, 1980, pp. 1435-1437, AIAA Publ., New York.

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9. M. J. Harris, D. E. Etter, and L. J. Wittenberg, "Observations Regarding Materials and Site Preparation for Salt-Gradient Solar Ponds," American Section/International Solar Energy Soc. Annual Mtg, May 27-30, 1981, Philadelphia, PA.

10. L. J. Wittenberg, "Salt-Gradient Solar Ponds: Design, Construction and Power Production," The 1980 International Symposium on Solar Energy Utilization, The University of Western Ontario, Canada, August 10-24, 1980 (in press).

11. L. J. Wittenberg and M. J. Harris, "The Miamisburg Salt-Gradient Solar Pond," Non-Convective Solar Pond Workshop, July 30-31, 1980, Desert Res. Inst., U. of Nevada (Pub)., pp. 13.1-13.15.

12. L. J. Wittenberg, "Reconstruction of a Large Solar Pond," ASME Solar Energy Division/Operational Results Conference, April 28-30, 1981, Reno, NV.

CONTRACT INFORMATION

START DATE May 1, 1978 END DATE Sept. 30, 1980 CONTRACT VALUE FY1978-FY1980 = $138,000 FY1981 (not funded)

MILESTONES

Item: Due date:

1. (No deliverables required)
2.
3.
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5.

LOW-COST MIRROR CONCENTRATORS, BASED ON DOUBLE-WALLED, METALLIZED, TUBULAR FILMS

MONSANTO RESEARCH CORPORATION

GEORGE L. BALL III, JAMES L. SCHWENDEMAN, AND JAMES W. LEFFINGWELL

DE-AC04-78AL04227

OBJECTIVE

The purpose of this work was to develop an innovative nontracking cylindrical mirror concentrator of about 3X concentration ratio that utilizes inflation for shape generation and film type plastic materials and processes to minimize cost. Low cost was to be emphasized over performance.

DESCRIPTION OF WORK

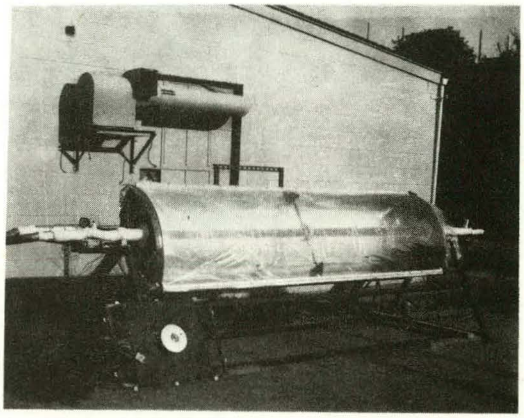
The practicality of extending previous concentrator designs to make available a cost-effective, durable, inflatable cylindrical (tubular) concentrator was examined. Previous tubular collectors have been made using polyester-type materials - aluminized for reflectors and clear for covers. These expensive materials require stabilization against ultraviolet (UV) light to prevent degradation from solar exposure, and the long-term optical properties of the reflectorized film are not certain.

Low-cost, durable, reflective aluminum foil-plastic film laminates were evaluated as an alternative to relatively expensive aluminized polyester-type reflectors. These materials were used to build a truncated cylindrical designed unit which eliminates about 40% of both the cover and reflective surfaces of conventional cylindrical collectors. This innovative design resulted in a type of construction which greatly facilitated the assembly of the mirror/window to the collector, reduced wind resistance, and makes more efficient use of land area. A prototype unit shown in the figure was fabricated in 1979 and was tested outdoors with the expected thermal output.

TECHNICAL ACCOMPLISHMENTS

- A commercially available aluminum foil/polyester laminate (Lamotape) was selected as the mirror material for its cost-effectiveness, good reflectance and mechanical properties. The foil/polyester mirror is bonded to 4-mil black PVC film to improve its outdoor durability.

- Window material was fabricated from clear XP1029 stabilized, 4-mil PVC film laminated to ∿5-mil polyester (Mylar) film. This type of laminate gave adequate strength, a good degree of flexibility, and good light transmission. Exposed to intense UV radiation in a test chamber, the film containing XP1029, after becoming pale yellow within 24 hours of exposure (0.4 year), did not change markedly in color within 557 hours (9.6 equivalent years exposure). More important, the film did



not stiffen during this exposure and was still capable of being deployed by inflation using air pressure.

- A concentrator design made up of two cylindrical segments joined along their longitudinal edge was developed. This design reduces the cover and mirror area by about 40% without undue sacrifice in reflective capability and can result in a savings of about 22% in land use.

- The absorber tube is the principal structural member of the concentrator, supporting the entire concentrator and providing the base for the end plates and transverse support which fixes the dimension and shape of the concentrator.

- The sides of the concentrator are closed by use of side rails and sealing strips. Side rails are supported by end plates and a transverse support. The concentrator is symetrical.

- The design permits easy assembly of the mirror and window material to a collector without disturbing the structure of the collector or disconnecting the heat transfer fluid plumbing.

- An inner insulation sleeve made of commercially available fluorinated ethylene/propylene copolymer is mounted on the absorber tube. The absorber tube is coated with state-of-the-art selective coating.

- Outdoor testing of the efficiency of the concentrator around a black chrome absorber was conducted in August 1980. Thermal efficiencies at inlet temperatures of 35 to 60°C ranged from 30 to 15%, respectively.

- 15 month outdoor exposure of the concentrator had no apparent effect on its performance.

FUTURE ACTIVITIES

No additional work is planned.

PUBLICATIONS/REFERENCES

Gerich, J. W., "An Inflated Cylindrical Solar Concentrator for Producing Industrial Process Heat", Lawrence Livermore Laboratory, December 19, 1977 (informal, limited distribution report - U.S. Energy Research and Development Administration, Contract No. W-7405-Eng-48, UCID-17612 Rev. 1.).

Hataria, Viraf and Horsfield, B. C., University of California, Davis, ASAE, 1976, "Analysis of a Low-Cost Inflated Plastic Cylindrical Solar Collector for Heating Air".

Tabor, H. and Zeimer, H., Solar Energy Vol. 6, No. 2, 1962, "Low-Cost Focussing Collector for Solar Power Units".

Draft of Final report on project submitted to DOE on 21 January 1981.

CONTRACT INFORMATION

START DATE Feb. 20, 1978 END DATE Aug. 20, 1980 CONTRACT VALUE $220,330

MILESTONES

Item:		Due date:
1.	Prototype collector demonstration unit: Constructed	11/79 M
2.	Prototype collector demonstration unit: Tested	8/80 M
3.	Prototype collector demonstration unit: Ready to Ship	3/81 P
4.	Semi-Annual Reports	10/78, 4/79, 11/79 M
5.	Final Report (Draft)	1/81 M

FRESNEL CONCENTRATING COLLECTOR

Rensselaer Polytechnic Institute

William Rogers
David Borton

DE-FG04-80AL13121

INTRODUCTION

During the oil embargo of 1973-74, the Northeastern part of our country was shown to be particularly vulnerable to shortages of fossil fuels which, for the most part, were coming from overseas sources. Other energy technologies had to be found. To displace fuels in many applications, though, alternative energy sources had to be able to deliver high quality energy reliably. Therefore, even though the direct sunlight available in the Northeast may only total one half that available in the sunniest region of our country, there appeared to be a real potential for cost effective solar hardware even seven years ago. The energy user who could diversify into alternative energy sources could reduce the impact of sudden fuel price increases and also reduce the risks of having to shutdown operations because of a lack of sufficient heat, process steam or conventional cooling.

The two major hurdles we had to overcome before we could begin an extensive effort to produce active alternative energy equipment were:

1. To provide solar energy even during the harsh cold weather for which the northeast is infamous, and

2. To provide this alternative energy at a price competitive with traditional fuels.

With energy consumption increasing worldwide we believed that, in a reasonable amount of time, prices of traditional fuels would increase sufficiently to make focused solar energy a viable alternative.

Concentrating the sun allows heat losses to be minimized once the energy has been captured. Therefore, even sunlight during the winter months could be utilized. With the sun's energy being reflected from 864 square feet of mirrored surface onto a few square feet of heat transfer material, subzero temperatures become less of a factor in useful energy production.

Although focusing the sun overcame our first perceived hurdle without difficulty, it tended to amplify the effects of the second hurdle. Any complexity added to solar energy equipment increases the already large front-end costs associated with equipment which gathers significant quantities of low density energy. Our research efforts over the last seven years, for the most part, were directed towards the need to develop mechanical and procedural methods for reducing hardware costs. See figure 1.

HARDWARE DESIGN

Major goals which directed our efforts in engineering cost effective designs for concentrating solar energy were:

1. The minimization of the overall weight of the solar energy collection equipment,while utilizing inexpensive materials;

2. The simplification of components and optimization of the number of different parts along with the manufacturing procedures needed to produce them;

3. The embodiment of designs which can be readily shipped, rapidly assembled and optically aligned, easily tested and quickly repaired by available labor; and

4. The incorporation of features and components which augment reliable, safe and durable operation.

Minimizing the weight of the collector prescribed the implementation of two concepts:

1. The distribution of forces from wind and gravity loading on the equipment, and

2. The use of a Fresnel concept.

Distributing the forces of wind and gravity over many parts allows lightweight components to be adequate for bearing the six tons of force anticipated from a 90 mph wind. The Fresnel concept is complementary to the concept of distributed loading. Eight thin one foot square mirror tiles treated for outdoor use have been supported by lightweight aluminum stressed-skin support panels which are pivoted on their centers of gravity to produce the motion necessary for elevation tracking. Using the Fresnel mirror concept and distributed loading permits wind to pass through the collector structure when the mirrored columns are positioned to "feather" in the wind like open Venetian blinds. The small surface area of each column allows common materials and construction techniques to meet the demands on these parts for stability and durability. Consequently, material weight is minimized and the corresponding cost associated with material quantity avoided.

The simplification of components and their material manufacturing processes was aided by several iterations of design, and construction of several generations of prototype equipment. Our current designs use large numbers of identical parts. Because the demands for strength in any one of these parts is small, exotic materials are avoided. During the installation of equipment at a site, special erection equipment is usually unnecessary due to the manageable size of individual parts. We found these choices in design promoting our goals for reducing the overall installed cost of equipment.

The embodiment of practical aspects of design which provide the packer, shipper, site erection crew and operator with items which make their jobs easy, promotes acceptance of the technology and enhancesits cost/benefit ratio.

We have found that by incorporating operational schemes, such as keeping the reflector surface upside down except during operation, limits reflector exposure to dust, ice, snow and vandals and enhances safety. Upon loss of power or occurence of other stow parameters, the unit returns the mirrors to this inverted position "over the top" so that the intense focused radiation at no time comes below the receiver. The design of other components and software subroutines incorporates this kind of failsafe orientation. We have found that "add on" safety packages are seldom as reliable, and have an undesirable "add on" cost.

Although developing the objectives for our goals demanded more common sense than any other resource, the technical capabilities of Rensselaer Polytechnic Institute, the organization within which we performed our research, were essential to every stage of finalizing and testing component designs. With the right combination of simplicity and complexity, we believe we have achieved a design for collecting solar energy which is compatible with the special needs of our region of this country.

SYSTEM TESTING

Based on the preliminary work and receiver heat transfer analysis, two receiver designs were selected for manufacture and testing. The first was a conically wound copper monotube boiler with 30 degree cone half angle, and the second, a steam unit heater employing steel tubes with aluminum fins. (See Figs. 2 & 3).

Solar energy input was determined by an Eppley normal incidence pyrheliometer with a 5 1/2 degree aperture which had been recently calibrated by the Atmospheric Sciences Research Center in Albany, N.Y. This was coupled to a strip chart recorder which provided a record of instantaneous insolation readings. Integrated values corresponding to the discrete time periods for collector output measurements are utilized to calculate collector efficiencies throughout the day.

Output was determined by measurement of the quantity of water converted to steam and the pressure of the saturated steam transferred to the RPI steam system. System efficiency figures include losses from 120 feet of insulated steam line. Water flow was calculated by two methods: 1) by a Badger Recordall Flowmeter and 2) by measurement of lost weight from the boiler feed tank. The test fluid loop is illustrated in Figure 4 . Note that steam condensate is returned to the boiler feed tank from the steam trap. In the test of the fin tube boiler, the variation of efficiencies to some extent are a function of water source. That is, part of the time water is fed directly to the boiler from the city water supply at 60F. When sufficient condensate accumulated in the feed tank, the water source was switched to the feed tank at >150F.

The results of performance testing of these boilers are presented in Figures 5 and 6 . The fin tube boiler exhibited an average daily efficiency of 57%. The conical monotube boiler had an average daily efficiency of 68% and a peak efficiency of 79%. The graph of the test results indicates the dependence of efficiency on solar conditions. The collector has an effective aperture much less than the pyrheliometer. Thus the pyrheliometer accepts a greater amount of circumsolar radiation.

Significant improvements in performance can be expected when the department store mirror tiles are replaced by thin low iron glass mirrors with 10% better reflectivity. Also, the forming of the curves of the reflector columns to more precise tolerances are now possible which will result in an additional improvement in performance. The fin tube boiler had very wide fins between and in front of the fluid tubes, which contributed to enhanced convective losses. The use of copper fins would improve the performance of this type of receiver.

CONCLUSION

This advanced point focusing solar technology has demonstrated potential for near term commercialization as an effective renewable energy technology. The unique design features combine to produce a highly-efficient, low cost, safe, adaptable, durable system which is simple to manufacture, install and maintain.

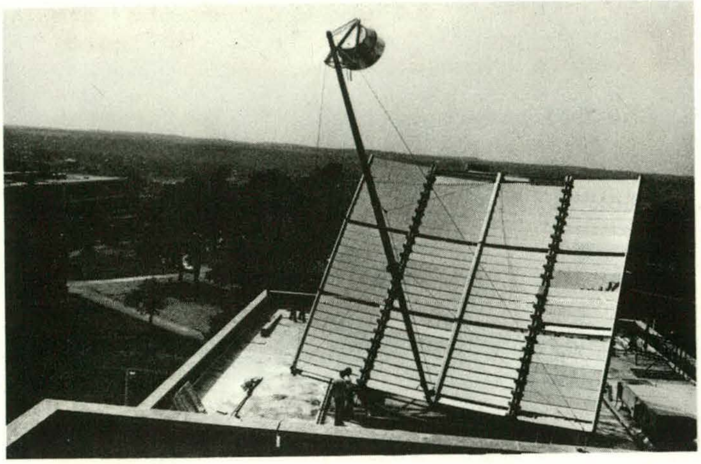


Fig. 1 80 sq.m. Collector

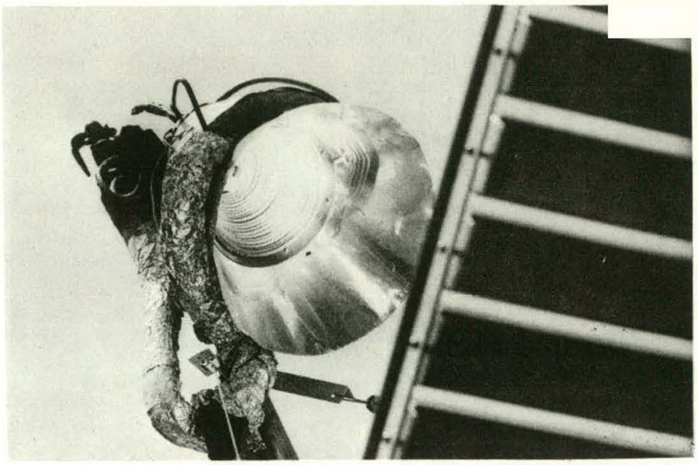


Fig. 2 Copper Monotube Receiver

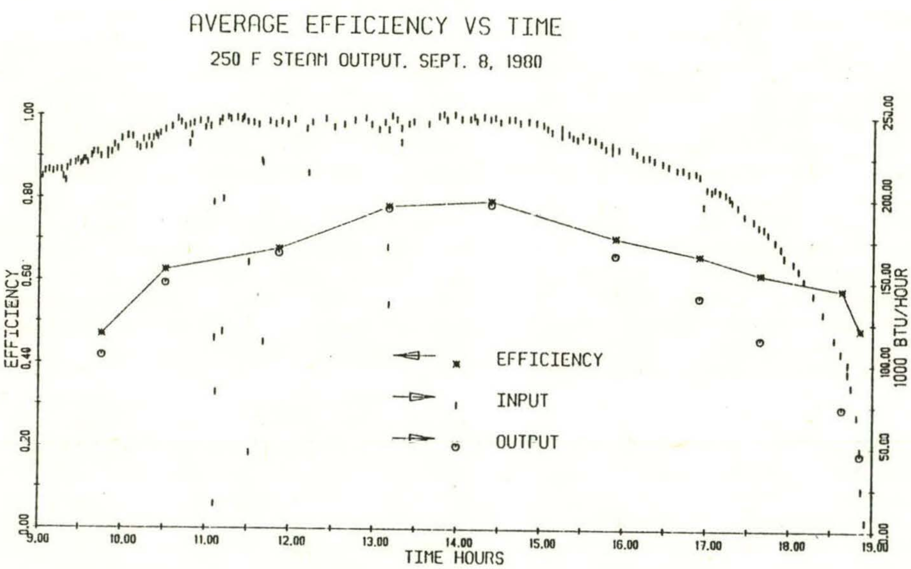


Fig. 5 Monotube Performance

CONTRACT INFORMATION

START DATE 6/1/80 END DATE 9/30/80 CONTRACT VALUE $21,680.

MILESTONES

Item:	Due date:
1. Final Technical Report	Oct. 30, 1980
2.	
3.	
4.	
5.	

DESIGN OF IMPROVED COATING AND CONSTRUCTION OF AN EVACUATED SOLAR RECEIVER

SUNMASTER CORPORATION, 35 W. WILLIAM STREET, CORNING, NEW YORK 14830

JOSEPH R. FRISSORA

DEN8-000008

OBJECTIVE

The objective of this project was to design and fabricate a low-cost improved evacuated glass tube solar collector which uses a special coated nickel-based foil as the solar energy absorber.

The secondary objective was to develop manufacturing procedures and processes for the improved evacuated glass tube collector.

DESCRIPTION OF WORK

The Sunmaster Corporation, Corning, New York, entered into a contract with NASA Marshall Space Flight Center in March 1980 for the "Design of Improved Coating and Construction of an Evacuated Solar Receiver."

The Sunmaster Corporation has developed and markets the Sunmaster^{tm} solar collector which consists of eight evacuated glass tube solar collectors attached to insulated supply and drain lines, and mounted to special double cusp reflectors designed by the Argonne National Laboratories. The evacuated glass tube collectors are 4-feet long and are comprised of two concentric glass tubes sealed together at each end with a vacuum between the tubes. The outside circumference of the inner tube has a vacuum deposited coating which serves as the solar energy absorber. A smaller diameter tube is inserted most of the length of the inner tube and the assembled tube is mounted to the supply and drain manifold. During operations, water is pumped up the inner tube where it is heated by the heat absorber by the absorber surface. When the heated water reaches the level of the top of the small insert tube, it overflows over and down through the inserted tube to the drain line in the manifold and then to storage tanks or the load.

The Sunmaster^{tm} Solar Collectors have been installed in many sites for various sites for various applications, and have successfully demonstrated a high degree of reliability, efficiency, and effectiveness. The experiences accumulated in fabricating, marketing, installing, and operating these collectors led to the conclusion that significant improvements in performance and efficiencies as well as lowered costs could be achieved by improving the solar absorber and its fabrication, and by increasing the effective solar absorption area.

The vacuum deposition of the absorber coating on the inner glass tube of the collector is a very expensive and complex procedure. The effort to develop an inexpensive low-cost absorber led the Sunmaster Corporation to select a thin nickel-based foil surfaced on one side with a highly absorptive coating and on the reverse with a highly emmissive coating. In initial configurations, the foil was wrapped around the inner tube, emmissive coating adjacent to tube, and constrained to the tube by spring clamps. After evacuating the volume between tubes and testing for solar energy collection efficiencies, it was determined that the lack of a continuous contact between foil and glass tube degraded the transfer of thermal energy from foil to tube significantly below acceptable limits. consequently, subsequent efforts were based on bonding the foil to the glass tube to insure continuous conductive thermal energy transfer between absorber foil and tube. Development of bonds, assembly techniques, and optimum combinations of baking and evacuating the tubes to assure proper vacuum is continuing.

The Sunmaster^{tm} solar collector has an effective solar absorption area of 14 square feet using the 4-feet long collector tubes. The Sunmaster Corporation developed a 6-feet long tube which when substituted for the 4-feet long tubes and mounted to the existing insulated supply and drain manifold will increase the effective absorption area by approximately 57 percent or 22 square feet. By using the existing Sunmaster^{tm} solar collector manifold and support structure, substantial increases in energy absorbed and efficiencies are achieved with no increase in thermal losses due to the nonproductive insulated manifold or support structure. The anticipated increase in costs for the 6-feet long collector versus the 4-feet long collector are minor, and the longer collector will be able to deliver significantly more Btu for each dollar spent than the shorter collector. Additionally, the longer collector will be capable of delivering more Btu than the shorter collectors when installed on equal sized collector field areas as on a limited area rooftop.

The Sunmaster Corporation intends to continue development of the nickel-based foil absorber, and to apply the absorber to the 6-feet long collector tubes with the objective of marketing a highly effective and low cost solar energy collection system.

CONTRACT INFORMATION

START DATE 3/18/80 END DATE ______ CONTRACT VALUE $199,885

MILESTONES

Item:	Due date:
1. Design Review	July 1980
2. Complete	June 1981
3.	
4.	
5.	

Section 9: SOLAR CONTROLS TECHNOLOGY GROUP

A STUDY OF CONTROL PROBLEMS IN ACTIVE SOLAR SYSTEMS

DREXEL UNIVERSITY

PETER HERCZFELD and ROBERT FISCHL

Contract #AS02-77CS34512

OBJECTIVE

The purpose of this study was to develop control models and simulation techniques that correctly describe the behavior of the controller, including cycling and other forms of instabilities. The model was utilized to analyze the sensitivity of controller performance to various system parameters and control strategies. The control models and simulation techniques were experimentally validated.

DESCRIPTION OF WORK

Extensive studies of the active solar demonstration program indicate that a large fraction of system failures are directly attributable to control malfunctions. These control related problems lead to poor collection efficiencies, component damage and as a result tend to erode consumer confidence in active solar applications. In order to understand and eventually eliminate undesired controller actions, it is necessary to develop analysis and design techniques which account for uncertaintities in the system operation (i.e., deviation from ideal conditions). These uncertainties may include stochastic climatic conditions, sensor tolerances, time delays and other phenomena. To understand the affect of these non-ideal conditions on the controller it is imperative to develop accurate control models which "track" controller action during potential malfunctions.

In control studies the accuracy and the validity of techniques involved cannot be over emphasized. The computer simulations must be carefully verified to eliminate computational errors and the results of the computer simulations must be validated against carefully executed experimentation.

In our work we emphasized the reliability as well as the efficiency of the controller and concentrated on the accuracy of the models, verification of the simulation and validation of results.

TECHNICAL ACCOMPLISHMENTS

Modeling

The collector of the active solar energy system was modeled consisting of component models and interface models. The modeling yielded an analytic description of the temperature.

Components Models The following components were modeled: collector, transport piping heat exchanger and storage.

The most important component of the active solar energy system in terms of control is the collector itself. To account for time delays associated with the collector capacitance and to be able to relate sensor position to controller performance a distributed parameter collector model was considered [1]. A closed form analytic solution was found for the distributed parameter collector [2], which "tracks" the collector performance with great accuracy. A closed form analytic solution was also obtained for the transport piping which was also modeled as a distributed parameter system. The analytic solution of the heat exchanger problem is in progress. For the storage existing models were utilized.

Interface Models Since the thermal time-constants and driving functions for each component differs, and under no flow condition one obtains a discontinuity in the spatial temperature profile around the loop at the boundaries between the components. In reality, however; under stagnant conditions, the temperature and its first derivative across the boundaries are smooth and the transition (or boundary) region extends spatially into the component. In order to reflect this transition mathematically, the temperature $T(\xi)$ across the boundary region $0 \leq \xi \leq 1$ is modeled by a third order polynomial:

$$T(\xi) = \sum_{j=0}^{3} a_j \xi^j \qquad 0 \leq \xi \leq 1 \qquad (1)$$

where

$a_0 = T(0)$

$a_1 = T'(0) = dT/d\xi$ evaluated at $\xi=0$

$a_2 = 3[T(1)-T(0)] - [T'(1)+2T'(0)]$

$a_3 = [T'(1)+T'(0)] - 2[T(1)-T(0)]$

Note that $\xi=0$ represent the points considered to be the start of the boundary region in the inlet component. Similarly, $\xi=1$ is a point in the outlet component which represents the end of the boundary.

Computer Simulation Model & Verification

Most simulation models of real or natural processes have limitations and constraints. These limitations and constraints affect the model's ability to accurately represent the natural process. The method (or philosophy) of the simulation now becomes the major contributor to the accuracy of the model. The basis for the simulation are the analytic solutions discussed above. Here, modeling of the solar collector is accomplished by first solving the basic differential equation analytically and then programming the resultant solution on the computer. This approach reduces or eliminates truncation and integration errors which usually arise as a result of having the computer solve the partial differential equation directly. Such errors can be particularly significant during switching from stagnant to flow conditions and thus lead to an incorrect simulation.

A variety of tests were performed to evaluate the adequacy of the simulation model. These tests consisted of parametric studies in which different forcing functions (such as radiation intensity) and initial conditions were applied under static (no fluid flow) and dynamic (fluid flow) conditions. Some of these tests were discussed in a recent paper [3] In general we concluded that the computer simulation even under severe conditions produces an error considerably below 1%.

Parametric Sensitivity Analysis

In order to establish the tradeoff between the energy collected, J_1, and pump cycling, J_2 it is necessary to establish the dependence of these performance indices on the various system and control parameters. This was established via a parametric study in which a set of parameters are varied. These are:

Control Parameters:

$\Delta T_{off} = T_{off} - T_s$ - pump turn-off set-point (°C)

$\Delta T_{on} = T_{on} - T_s$ - pump turn-on set-point (°C)

$\mathring{m}$ - fluid flow rate (kg/hr)

System Parameters:

τ_{tc} - system dynamic time constant

τ_{fc} - system static time constant

Climatic Parameters:

I_0 - peak solar insolation (kj/m^2-hr)

$\Delta T_{sa} = (T_s - T_a)$ = storage to ambient temperature difference (°C)

The sensitivity of the system performance (J_1 and J_2) was investigated by systematically varying each parameter about a base line system.

Based on the parametric sensitivity analysis the following statements can be made:

* The most important parameter in terms of both energy collection and reduction of cycling is the turn-off set point, ΔT_{off}. This should be set as low as possible (usually limited by parasitic pump losses).

* The flow rate, for the on/off controller, should be reasonably high for good collection efficiency.

* The turn on set point, ΔT_{on}, can be set high without significantly affecting energy collection while markedly reducing pump cycling.

Control Set Point Selection

The sensitivity analysis presented above, gives valuable insight into the performance of a collector controlled by an on/off controller which can be exploited to derive practical expressions for selecting the set point ΔT_{on} in terms of ΔT_{off} so as to reduce the chance of cycling without greatly affecting the energy collection. The analytic solution was used to derive a condition for the selection of ΔT_{on} and ΔT_{off} [4]. The results for a clear sky condition are:

$$\Delta T_{off} = P(\mathring{m})/\mathring{m} \qquad (2)$$

where $P(\mathring{m})$, is the pumping power to maintain flow rate $\mathring{m}$, and

$$\Delta T_{on} = \left[\frac{1}{1+\omega^2\tau_{fc}^2}\right]\left[G - \omega\tau_{fc}(\alpha_c^2 - F^2)^{1/2}\right] \qquad (3)$$

where

$$G = \Delta T_{off}\, \tau_{fc}/\tau_{tc} + (T_s - T_a). \qquad (4)$$

Sensors Location

From the above discussion it is seen that the selection of control set points ΔT_{on} and ΔT_{off} is crucial to the performance of the controller. The question arises what effect the sensor location may have on the actual measurement of these set points and hence on the operation of controller. In theory the collector outlet temperature is sensed at the top of the collector, which represents the highest temperature in the collector if boundary effects are ignored. However if the boundary between the collector and the storage (or piping) is accounted for then one will have a non-uniform temperature profile at the top of the collector. We have simulated the performance of the controller for a number of different sensor locations. The results indicate that the optimal sensor location is at the beginning (i.e., upstream) of the boundary region. If the sensor is located downstream from this point then the system turns on at a later time, thus reducing the useful energy gain. Note that this is equivalent to raising the turn on set point ΔT_{on}. If however, the sensor is located up-stream from the optimal position then the collector area wil appear smaller than it actually is. This will cause cycling and a reduction in the energy collection.

Experimental Validation

Experiments designed to validate the control studies were performed at the Middlebury College Test Facility.

Experimental Setup The Middlebury College Solar Controls Test Facility comprises of a pair of identical solar hot water systems designed for flexibility in the implementation and analysis of control strategies. The systems are provided with numerous sensors and solenoid valves, with monitoring and control performed by a minicomputer (DEC PDP 11-V03). Control and monitoring routines have been linked into the computer's BASIC language, so that control strategies and data acquisition schemes may be programmed simply and changed readily. The computer's floppy disk unit permits storage of substantial amounts of data. The actual system used in the validation is depicted in Figure 1 showing sensor locations.

Experiments The set of experiments performed can be classified into two categories. First, experiments were performed to obtain data on the collector thermal time constants, τ_c, and transit times, τ_{tc}. These are needed for the simulation modeling studies and to provide accurate measurement of the collector capacitance. Next a set of experiments was performed to study the system performance under different control strategies, such as different set points and different sensor locations.

A typical result of the thermal time constant measurement is shown in Fig. 2 which depicts the change in collector temperature measured by sensor #S21 (see Fig. 1) as a result of covering and uncovering the collector with a non-transparent plate The transit-time, τ_{tc}, represents the results of turning the pump-on and observing the time delay in temperature readings between sensors S17 and S22 as shown in Fig. 3. Similar measurements were made on the transport piping.

The results of a typical control study is shown in Fig. 4. It shows the temperature profile when the pump cycles on and off due to improper setting of the on/off controller set points for the articular mass flow rate and solar insolation.

The primary goal of this study is to validate the performance of the simulation model when the pump cycles. A detailed comparison between the simulation and experimental results is shown in Figure 4, which compares the temperature measured experimentally at sensor S21 to that computed using the measured system time constants. Note that the model predicts this temperature profile under pump cycling very accurately.

FUTURE ACTIVITIES

A proposal extending the present work has been submitted to DOE. The continuation work would utilize the present results and would emphasize the reliability problem of controllers.

PUBLICATIONS

1. R. Fischl, P.R. Herczfeld, A. Orach, S. Konyk, Jr., "Control and Sensitivity Analysis of Liquid Flat-Plate Solar Collector Systems", Proc. of the 18th IEEE Conference on Decision and Control, Ft. Lauderdale, Fla., Dec. 1979.

2. P.R. Herczfeld, R. Fischl, S. Konyk, Jr., "Solar Flat Plate Collector Control System Sensitivity Analysis", Second Annual Systems Simulation and Economic Analysis Conf., San Diego, CA, Jan. 1980.

3. P.R. Herczfeld, R. Fischl, G. Vardakas, R.L.T. Wolfson, "Experimental Validation of Dynamic Control Models", Third Annual System Simulation and Economic Analysis Conference, Reno, Nev., April 1981.

4. S.J. Sokolowski, M.J. Fisher, P.R. Herczfeld, R. Fischl, and R. Wolfson; "Computer Simulation for Evaluating Control Strategies", Thrid Annual System Simulation and Economic Analysis Conference, Reno, Nev., April 1981.

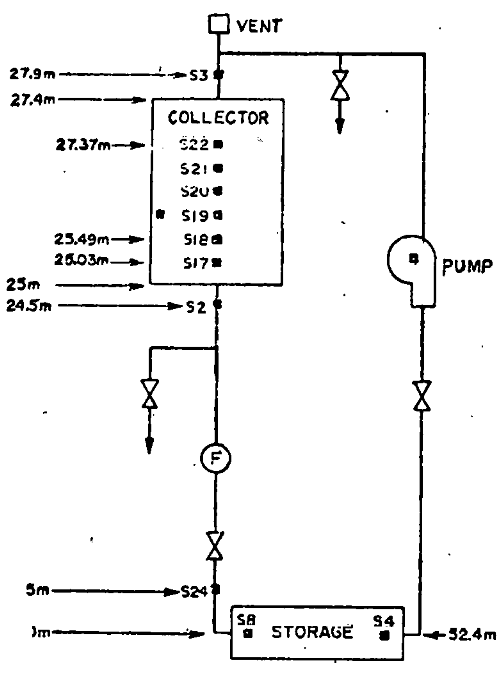


Figure 1: Experimental System Diagram (S8 is the pump controller temperature sensor in the storage)

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1. S.A. Klein et al., "Transient Considerations of Flat-Plate Solar collectors", T.A.S.M.E., J. of Eng. for Power, pp 109-113, April 1974.

2. R. Fischl, P.R. Herczfeld, R.D. Klafter, A. Orbach, "Study of Pump Cycling in the Control of Solar Heating and Cooling Systems", Workship on Control of Solar Energy Systems for Heating and Cooling, Hyannis, Mass., May 23-25, 1978.

3. P.R. Herczfeld, R. Fischl, G. Vardakas and R. Wolfson, "Experimental Validation of Dynamic Control Models", Third Annual Systems Simulation and Economic Analysis Conference, Reno, Nev., April 1981.

4. P.R. Herczfeld, R. Fischl, and S. Konyk, Jr., "Solar Flat-Plate Collector Control System Sensitivity Analysis", Second Annual Systems Simulation and Economic Analysis Conference, San Diego, CA, January 1980.

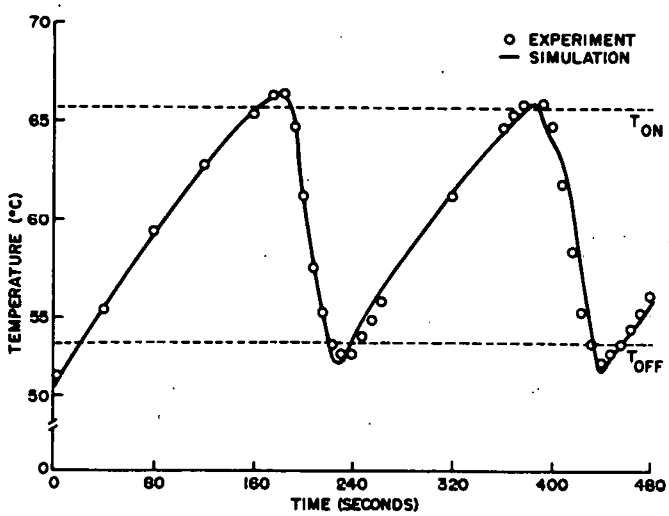

Figure 4: Collector's Output Temperature.

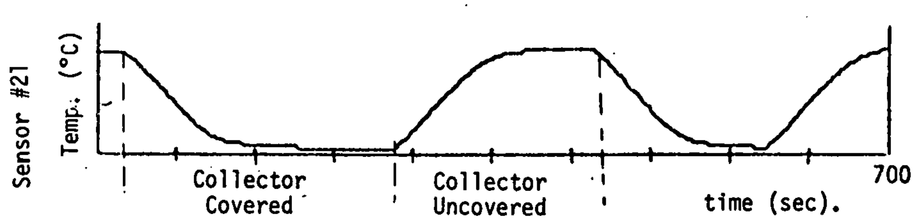

Figure 2: Experimental Data to Determine the Collector Thermal Time Constants (τ_c)

Contract Period - Begin: January 1, 1979
End: June 30, 1981

NOVEL CONTROL STRATEGIES FOR SOLAR SYSTEMS THAT REDUCE ELECTRIC UTILITY PEAK LOADS

Franklin Research Center

Dr. Harold G. Lorsch

DE AC-0377 ET 20085.

ABSTRACT

Novel control systems and strategies were developed which reduce electric utility load peaks resulting from back-up demands of solar systems. Utility costs and homeowner costs were added in order to determine the lowest total cost systems which are "optimum" from the societal point of view.

METHODOLOGY

Since electrical tariffs do not always reflect costs of service, it was deemed desirable to eliminate the effects of tariffs from the study. The homeowner/utility system was therefore considered as a unit, and "internal" payments within this system (i.e., payments between homeowner and utility) were ignored. The external costs incurred by this system are (1) the utility's cost to serve the homeowner and (2) the cost to the homeowner of installing (and maintaining) the equipment in his house. The system which minimizes the sum of these costs is the optimum system for society as a whole. As will be shown later, it was not always possible to ascertain the true costs of service for all the utilities investigated. In those cases, recently introduced time-of-day tariffs were used, after adjustments, as indicators of the actual cost of service.

A typical single-family suburban home expected to be built throughout the 1980-1990 period was defined. Hour-by-hour energy consumption calculations were performed for this house equipped with conventional and solar heating and cooling systems with and without off-peak thermal storage for three locations: Philadelphia, PA, Daytona Beach, FL, and San Diego, CA. The results were checked against consumption measurements; where necessary, the analysis was modified to have the results agree with measured values.

At each of the three locations, solar systems were analyzed that are suitable for the local climate. The conventional comparison systems were those frequently encountered in the respective utility service territories. This permitted a check of the analysis by measured data.

UTILITY COST COMPONENTS

Cost data were obtained from the Philadelphia Electric Company (PECo) for the Philadelphia house, from the Florida Power Corporation (FPC) for the Daytona Beach house, and from the San Diego Gas and Electric Company (SDGE) for the San Diego house. Although Daytona Beach is not within the FPC service territory, its climate is representative of the climate in the shore areas of that territory. Since extensive weather and solar radiation data do not exist for any other location within the FPC territory, the data for Daytona Beach were therefore used.

Demand related costs pertain to the capital cost of constructing a utility generation, transmission, and distribution system. Energy costs are essentially fuel costs. A differential cost between off-peak and on-peak energy of 0.5¢/kWh was used for PECo. Cost escalation rates were provided by PECo.

The demand related costs for FPC and SDGE were calculated based on the utilities' installed capacity costs for 1980, 1985, and 1995 using a capital recovery factor of 0.15. The cost components were escalated 8.7 percent per year for FPC and 8.0 percent per year for SDGE.

OWNING AND OPERATING COSTS

Installed costs were determined for the systems analyzed using manufacturer and contractor data. Equipment costs were escalated at an annual rate of 5 percent from 1980 to 1990. Annual costs were calculated assuming that these costs are repaid by the homeowner over 20 years at an annual interest rate of 12% on the unpaid balance. This results in a capital recovery factor of 0.134.

RESULTS AND CONCLUSIONS

The results of the performance and cost calculations for the three locations are shown in Tables 1 through 6.

- The addition to a solar system of a separate storage device that is electrically charged during off-peak hours is beneficial in many cases. Combining solar and off-peak storage in a single container is practical in highly stratified devices only, such as tall cylindrical tanks or rock beds.
- The air-to-air heat pump is the most economical of all combined space heating/cooling systems investigated.
- Adding off-peak electrical storage to a solar water heater decreases utility cost to serve but increases total cost.
- At no location investigated is solar heating cost competitive with electric resistance heating through the end of the century. The utilities cost to serve solar systems is less than the cost to serve resistance heating systems; however, the high capital cost of the solar systems makes their total cost higher than that of electric resistance systems.
- Adding off-peak storage to a solar space heating system increases energy consumption 9% to 27% at the locations studied although reducing the cost to serve those systems. Overall costs increase or decrease depending on location.

Table 1. Annual Costs for Space and Water Heating in Daytona Beach, FL

Consumption and Cost Data	Resistance Space Heating	Conventional Solar Space Heating	Resistance Water Heating	Conventional Solar Water Heating	Solar Water Heating w/ Off-Peak Storage
Annual Consumption, kWh	7797	6734	3486	1489	1534
1980 Installed Cost, $	2269	7523	360	2459	2499
Demand Related Costs, $	703.18	703.18	31.32	10.96	0
Metering Cost, $	0	0	0	0	36.42
Energy-Related Costs, $	754.36	652.26	404.13	172.11	70.04
Subtotal Cost to Serve, $	1457.54	1355.44	435.45	183.07	106.46
Homeowners Loan Repayment, $	245.01	1011.09	48.38	330.49	335.87
TOTAL ANNUAL COST (1985), $	1703	2367	484	514	442
TOTAL ANNUAL COST (1995), $	3854	4769	1082	960	789

Table 2. Annual Costs for Air Conditioning in Daytona Beach, FL

Consumption and Cost Data	Resistance Space Heating, Conventional Air Conditioning	Solar Space Heating, Solar Air Conditioning	Solar Space Heating, Solar Air Conditioning w/Off-Peak Hot Storage
Annual Consumption, kWh	7797	15231	16003
1980 Installed Cost, $	2269	28908	33296
Demand Related Costs, $	703.18	9.40	9.40
Metering Cost, $	0	0	36.42
Energy Related Costs, $	754.36	1394.19	893.58
Subtotal Cost to Serve, $	1457.54	1403.59	939.40
Homeowners Loan Repayment, $	245.01	3885.24	4474.98
TOTAL ANNUAL COST (1985), $	1703	5289	5414
TOTAL ANNUAL COST (1995), $	3854	9562	9399

Table 3. Annual Costs for Space and Water Heating in San Diego, CA

Consumption and Cost Data	Resistance Space Heating	Resistance Space Heating w/Off-Peak Storage	Resistance Space and Water Heating	Conventional Solar Space and Water Heating	Solar Space and Water Heating w/Off-Peak Storage
Annual Consumption, kWh	4316	4743	8213	3238	4413
1980 Installed Cost, $	1823	4391	2182	8015	9980
Demand Related Costs, $	199.50	12.60	291.90	273.00	12.60
Energy Related Costs, $	325.46	257.18	689.08	283.69	264.16
Subtotal Cost to Serve, $	524.96	269.78	980.98	556.69	276.76
Homeowners Loan Repayment, $	245.01	590.15	293.26	1077.22	1341.31
TOTAL ANNUAL COST (1985), $	770.	860.	1274.	1634.	1618.
TOTAL ANNUAL COST (1995), $	1532.	1544.	2595.	2956.	2782.

Table 4. Annual Costs for Air Conditioning in San Diego, CA

Consumption and Cost Data	Resistance Space Heating, Conventional Air Conditioning	Solar Space Heating, Solar Air Conditioning	Solar Space Heating, Solar Air Conditioning w/Off-Peak Hot Storage
Annual Consumption, kWh	4316	1279	1954
1980 Installed Cost, $	1823	17203	20433
Demand Related Costs, $	199.50	12.60	12.60
Energy Related Costs, $	324.46	125.80	120.99
Subtotal Cost to Serve, $	524.96	138.40	133.59
Homeowners Loan Repayment, $	245.01	2312.08	2746.20
TOTAL ANNUAL COST (1985), $	770.	2450.	2880.
TOTAL ANNUAL COST (1995), $	1532.	4065.	4762.

Table 5. Annual Costs for Space Heating in Philadelphia, PA

Cost Data	Resistance Heating	Conventional Solar Heating	Solar With Separate Off-Peak Storage (2 Tanks)	Conventional Air-to-Air Heat Pump	Solar Assisted Dual Source Heat Pump w/Direct Solar Heating
Subtotal Cost to Serve, $	1176.28	960.19	765.85	800.82	742.54
Homeowners Loan Repayment, $	258.39	2307.00	2855.00	324.25	2787.00
TOTAL ANNUAL COST (1985), $	1435.	3267.	3621.	1125.	3529.
Subtotal Cost to Serve, $	2159.89	1829.00	1390.83	1546.92	1457.68
Homeowners Loan Repayment, $	422.82	3776.10	4689.48	503.59	4560.64
TOTAL ANNUAL COST (1995), $	2583.	5605.	6080.	2051.	6018.

Table 6. Annual Costs for Air Conditioning in Philadelphia, PA

Cost Data	Resistance Heating, Conventional Air Conditioning	Conventional Solar Heating, Solar Air Conditioning	Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Cold Storage (2 Tanks)	Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Hot Storage (2 Tanks)
Subtotal Cost to Serve, $	1176.28	1303.69	641.57	640.94
Homeowners Loan Repayment, $	258.39	3745.00	4712.00	4271.00
TOTAL ANNUAL COST (1985), $	1435.	5049.	5354.	4912.
Subtotal Cost to Serve, $	2168.98	3169.54	1104.99	1123.59
Homeowners Loan Repayment, $	422.82	6129.58	7711.33	6985.44
TOTAL ANNUAL COST (1995), $	2592.	9299.	8816.	8109.

- Solar assisted heat pumps have lower energy consumption and lower cost to serve but higher total costs than solar space heating systems with electric resistance back-up. The addition of off-peak storage to solar assisted or conventional heat pumps is not cost effective.
- Solar heating combined with solar absorption air conditioning is not competitive with conventional electric heating and air conditioning. Off-peak storage increases energy consumption by 20% to 35%, but decreases the cost to serve considerably. Overall costs are decreased in unfavorable solar climates and increased in favorable climates.

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CONTRACT INFORMATION

START DATE Sept. 19, 1977 END DATE Dec. 31, 1979 (Sept. 15, 1980) CONTRACT VALUE $125,509

MILESTONES

Item:	Due date:
1. Annual Progress Report, No. I-C4827	October 1978
2. Final Report Draft, No. F-C4827	September 1980
3.	
4.	
5.	

CONTROLS FOR SOLAR HEATING AND COOLING*

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

Mashuri Warren, Steven Schiller, Michael Wahlig
Contract No. W-7405-ENG-48

OBJECTIVES

The LBL solar controls program has three principal objectives: To use the LBL test facility to evaluate experimentally the relative performance of different solar heating control strategies for a variety of input meteorological conditions and output load demands; to analyse problems in the control of active solar systems that effect system performance and reliability and carry out theoretical studies of collector and load loop performance in support of the experimental work; and to perform technical support activities as part of the Department of Energy (DOE) solar heating and cooling R&D program. Program support tasks include program planning, preparation and evaluation of solicitations, proposal reviews, and technical monitoring of DOE solar contracts.

DESCRIPTION OF WORK

The experimental test facility was constructed to evaluate the operation and performance of active hydronic solar energy system control strategies and equipment. The facility consists of a collector loop heat input simulator, a storage tank, a load loop air channel with fan coil, an auxiliary heater, and associated pumps and valves. Only the apparent temperature of the collector and the load demand thermostat condition are simulated, enabling control strategy and equipment comparisons based on identical meteorological and load conditions. The facility is described in detail elsewhere [1,2,3,4].

This year the experimental test facility was operated to simulate a specific residential solar assisted heating system for several days, using both simulated weather and typical meteorological year (TMY) weather and insolation data for Madison, Wisconsin in January. The residential building loads are calculated using incident insolation, along with the TRNSYS and are used as inputs, to drive the experimental system simulation. Early in the year a number of four hour and one day experiments were repeated to verify operation and energy balance of the collector loop and of the load loop separately. At the end of the year a number of two day experiments using TMY year data were run.

The performance of a solar system during a particular day is dependent on the insolation, ambient temperature (which determines collector losses and building load), and the system's performance during the previous day as indicated by the starting storage tank temperature. A knowledge of what will happen on the next day is also important to measure the utilization of energy collected on a particular day. The weather and insolation patterns for January in Madison and hourly storage tank temperatures predicted by TRNSYS for January were examined to determine categories such as high amount of insolation, low ambient temperatures, and poor previous day. Two pairs of days were chosen for detailed test facility simulation: a "bad-good" series and a "good-bad" series.

Performance indicators, used for evaluating solar systems, include: collection efficiency, system thermal efficiency, solar coefficient of performance, system overall efficiency, and solar fraction. In addition, the change in storage tank temperature indicates the extent to which available solar energy is taken from or added to the storage tank over a given period.

Test Facility Results

Experiments were run using simulated meteorological and load inputs to evaluate experimental repeatability and verify system energy balances. Experiments also compared two control strategies: a storage-coupled heating mode and a direct collector to load heating mode. In the storage-coupled heating mode, collectors heat the storage tank and energy is drawn from storage to heat the load when available and needed. With the direct heating mode, the collectors can supply heat to the load without going through the storage tank. The direct heating mode requires additional piping, valves, and control.

Table I shows results from test facility experiments. The quantities used in the tables are defined as follows: building load (QLOAD), auxiliary energy for load (QAUX), the natural gas usage (GAS), solar energy delivered to the load (QSOLAR-LOAD), insolation onto the collector (QI), collected energy (QC), predicted collected energy (QC_{th}), storage tank losses (SLOSS), load loop piping losses (LLOSS), collector loop piping losses (CLOSS), parasitic energy used (PARA), average storage tank temperature (T_{tank}), stored energy (QS), and change in stored energy (DQS).

Table I shows typical one day summaries for a cold January day in Madison, Wisconsin with good insolation. The 24 hour system energy balance is within 2 %, indicating good accounting of energy flows in the collector and load loops and in the storage tank. This energy accounting is done minute by minute as the experiment progresses. Energy flow quantities are calculated from measured temperatures and flow rates. Energy losses are calculated from measured fluid and room temperatures and experimentally estimated loss coefficients. The parasitic and auxiliary gas consumption are measured with standard utility meters interfaced to the experiment instrumentation.

Test days were run twice for each of two different control strategies: direct heating and storage-coupled heating. The different runs show excellent agreement in the load demand, QLOAD, the total energy inputs to the system, Qin, the total energy output from the system, Qout, and the energy balance, Q. The energy loss terms, SLOSS, LLOSS, and CLOSS also agree well from run to run. However, there is some variation from run to run in the auxiliary energy usage, QAUX, in the change in stored energy, DQS, and in the contribution to the load from solar, QSOLAR-LOAD. This variation is of the order of 25 MJ over the day and represents less

*This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

Table I. Comparison of Test Facility Runs with TRNSYS Simulation for January 18 in Madison, Wisc., a cold weather day with good insolation.

Quantity	Units	Run 7	Run 11	Run 8	Run 12	TRNSYS
Strategy	-	Direct	Direct	Storage	Storage	Series
Time	hr	0-24	0-24	0-24	0-24	408-432
$Tamb_{avg}$	oC	-10	-10	-10	-10	-10
Initial T_{tank}	oC	31.1	31.5	31.1	31.6	31.2
Final T_{tank}	oC	32.5	33.3	32.3	32.4	36.4
Change T_{tank}	oC	1.4	1.8	1.2	0.8	5.2
DQStank	MJ	24.7	32.8	21.0	14.6	94.7
SLOSS	MJ	27.6	27.4	27.4	25.6	35.4
QLOAD	MJ	517.8	517.9	517.9	517.3	514.6
LLOSS	MJ	38.6	38.5	36.0	32.1	24.2
QAUX	MJ	234.5	248.0	230.5	204.9	268.3
QI	MJ	831.0	831.0	832.1	831.5	831.4
QC_{th}	MJ	410.7	401.1	424.0	428.5	421.8
QC	MJ	390.7	388.7	386.8	412.5	421.9
CLOSS	MJ	12.4	11.8	11.8	11.2	15.6
PARA	MJ	32.7	30.9	33.4	31.9	-
Qin	MJ	600.5	603.9	596.3	602.8	595.5
Qout	MJ	596.4	595.6	593.1	586.2	589.8
Balance (ΔQ)	MJ	4.1	8.3	3.2	16.6	5.7
Balance (%)	-	0.7	1.4	0.5	2.8	0.97
QSOLAR-LOAD	MJ	321.9	308.4	323.4	344.5	270.5
Solar to load	%	62	60	62	67	53

than 5 % of the total energy flow during the day which was the accuracy goal for measuring energy flows in the test facility.

Comparison of Test Facility Results with TRNSYS

To assist in evaluating the results obtained from the test facility, TRNSYS simulations are run for the same test days. The TRNSYS simulation was started on January 1 at 1 AM, using TMY weather data, with a storage tank temperature of 20 °C, and run continuously for the entire month. Initial average storage tank temperatures and time dependent building loads, as determined by TRNSYS for a given period, were then used for the experiments.

The test facility operating strategy uses an auxiliary heater to boost the temperature of the water to the fan coil as long as the return water temperature is not greater than the storage tank bottom temperature. Existing TRNSYS modes for parallel and series auxiliary heating do not model this operation. The parallel mode unrealistically draws the storage tank down to room temperature, thus underestimating the auxiliary energy consumption. The series auxiliary heating mode of TRNSYS draws the storage tank temperature down until the storage can no longer satisfy the building heating requirements. It then switches to an auxiliary only mode. This is closer to typical control action and is used to model the test facility. For identical conditions in Madison the TRNSYS parallel auxiliary mode used only 9424 MJ of auxiliary energy while the TRNSYS series auxiliary mode required 11060 MJ of auxiliary energy to meet the January heating load.

Table I compares energy flows predicted by TRNSYS with the direct heating and the storage-coupled heating modes run on the test facility. The solar energy collected, (QCth), as predicted by the test facility simulation Hottel-Whillier-Bliss collector model, agrees well with the TRNSYS simulation for clear days with good insolation, although in the direct heating mode the collector loop tends to be on for a slightly shorter time. For both modes, the pseudocollector boiler system delivers slightly less energy (QC) than predicted. This may be due to a limitation in the boiler output control.

Differences between the TRNSYS simulation and the test facility direct and storage strategies indicated in Table I include: the change in stored energy; the load loop piping losses; the load handled by solar; and the auxiliary energy. As expected, the test facility boost mode of operation increases the system performance slightly by using the stored solar energy at slightly lower temperatures than the TRNSYS series mode.

The energy input to the system for the TRNSY and test facility runs, Qin, (energy from the collectors, from auxiliary, and from storage) agrees very well, as does the energy output, Qout (energy to the load and all losses). The overall energy balance is quite good for all of the 24 hour runs. The only discrepancy of note is the solar contribution to the load which varied an average of about 10%. Parasitic energy for the control valves, pumps, and fans is not accounted for in the TRNSYS simulation.

Comparison of Storage Coupled and Direct Heating

A series of experiments was conducted using both direct heating and storage-coupled heating modes using real weather and insolation data for two January days in Madison, Wisconsin. Table II indicates the difference in the performance between the two strategies for these two days. Solar coefficient of performace (SCOP) is the ratio of the solar energy utilized by the load to the parasitic energy required to run the solar system. Solar fraction is the ratio of the solar energy utilized by the load to the total load. As indicated in the table, no significant difference exists between the control strategies for these days. Both modes of test facility operation utilize greater energy from storage than predicted by the TRNSYS simulation, as indicated by the storage tank temperature change. To determine long term comparisons, more testing would be required.

Table II. Comparison of two-day runs of test facility for direct heating and storage coupled heating modes for identical building load and meteorological conditions (January 18-19 in Madison, Wisc.). TRNSYS results are included for comparison.

Quantity		Direct Run 7	Direct Run 11	Storage Run 8	Storage Run 12	TRNSYS
QC/QI	Collection efficiency	35.5	36.3	37.7	40.3	43.4
QSOLAR-LOAD / QI	Thermal efficiency	39.0	42.0	42.0	46.1	37.6
QSOLAR-LOAD / PARA	SCOP	7.3	8.3	7.4	8.8	-
QSOLAR-LOAD / QLOAD	Solar fraction	45.3	48.7	48.8	53.5	43.4
ΔT_{tank}	Storage change (°C)	-4.8	-6.4	-5.4	-7.2	-1.0

Theoretical Studies to Support Experimental Program

During FY 1980 work was completed on modeling of collector loop dynamics[5,6]. A model of a residential building, a fan coil heat-delivery system, and a bimetal thermostat to simulate the effects of heat input on room air dynamics, has been applied to examine the building thermal behavior in response to heat input from an acti- solar space heating system[7].

The effects of the variable storage tank temperature, of outdoor temperatures, and of fan coil sizes on the cycling rate, on the on-time and off-time of a heating cycle, on room air temperature swing, and on offset of the average air temperature from the setpoint (droop) are determined by computer simulation. Heat input is provided directly to the air as, for example, when a heating fan coil is turned on.

For given conditions of outdoor temperature, anticipation, and thermostat setpoints, the storage tank temperature has a direct effect on swing as shown in Figure 1. The droop, the offset of average room temperature from the setpoint, also depends on the amount of thermostat anticipation and on the heat delivery duty cycle. The higher the storage tank temperature, the larger is the swing in room temperature and the smaller is the droop. Results indicate that to maintain room temperatures within comfort limits by minimizing both swing and droop, a hydronic solar space heating system requires a control system that adjusts anticipation and setpoints in relation to the outdoor and the storage tank temperatures. This will require more than a simple on-off bimetal thermostat.

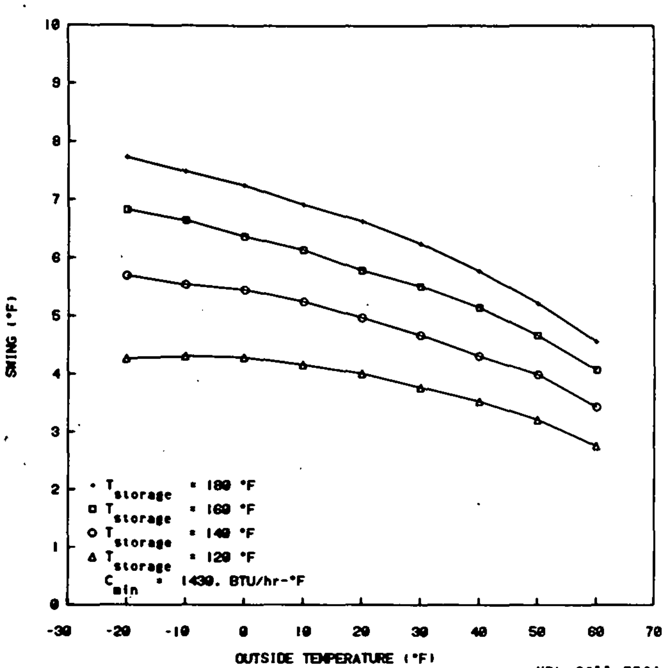

Figure 1. Solar storage tank temperatue influences room air temperature swing. As the storage tank temperature decreases, the swing decreases for a given outside temperature.

Technical Support Activities

This past year the laboratory has been actively involved in proposal review and contract monitoring for the Controls Element of the DOE solar heating and cooling R & D program. Activities have included coordination with SERI, conducting project reviews, and reviewing the reports of DOE controls contractors.

TECHNICAL ACCOMPLISHMENTS

- Several two day "typical day" experiments were run on the test facility using TMY weather data.
- Comparison of test facility results shows poor agreement with TRNSYS simulation in the parallel auxiliary mode, but good agreement in the series auxiliary mode. The test facility operates in a series boost mode.
- Solar heating system operation with two different operating strategies were run: direct collector to load heating and storage-coupled heating. No significant improvement in system performance was found for the direct heating strategy.
- Simulation analysis of the interaction of the solar heating system with the building load and thermostat was completed and presented. The analysis indicates that, using a conventional room thermostat, large temperature swings can be expected when the storage tank is charged to a high temperature.

FUTURE ACTIVITIES

The experimental test facility work has been concluded.

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CONTRACT INFORMATION

Period of Contract: Begin 7-74, End 9-80.

FY80 Funds: $220K.

Total value of contract: $785K.

MODEL VALIDATION AND SENSITIVITY ANALYSIS OF SOLAR COLLECTOR LOOPS

MIDDLEBURY COLLEGE

RICHARD L. T. WOLFSON

DOE AC 0386CS-30218

OBJECTIVE

The objective of this project is the use of the Middlebury College solar energy test facility for direct experimental testing of theoretical solar collector loop models developed at Drexel University. This joint effort is intended to bring clearer understanding of the dynamic effects of control cycling on the operation of all components of the solar collector loop.

DESCRIPTION OF WORK

The Middlebury solar test facility comprises a pair of identical solar collector systems which are heavily instrumented and interfaced to a minicomputer. The computer provides both data acquisition and control, so that control strategies may be modified through software changes. The facility has been described in detail elsewhere.[1] A simplified diagram of the configuration used in the present project is shown in Figure 1. Use of the Middlebury system in this work involved a series of short term studies (typically 5 to 30 minutes) of the operation of a single collector loop with different control set points. On/Off control was used throughout. Data from these experiments were supplied to the Drexel University group for comparison with their theoretical models. Prior to the actual experiment, a series of collector loop tests was made, including step response and collector bypass tests, to determine time constants, heat capacities, and other system parameters.

TECHNICAL ACCOMPLISHMENTS

The major technical effort on this project involved modification of the Middlebury facility to make possible collector parameter measurement and short time resolution studies required for comparison with the Drexel models. To this end the following instrumentation was added:

1. Seven additional temperature sensors on the collector plate, permitting detailed spatial resolution of the plate temperature profile under dynamic operating conditions.

2. Accurate turbine flowmeters (Flow Technology Omniflow), conditioned for computer data acquisition.

3. Pump power monitors.

4. Bypass piping and valving allowing rapid switching of circulating water from a collector bypass loop to a hot, stagnant collector, allowing determination of temperature profile as a function of time as the slug of cold water moves through the collector.

5. A simple collector cover which could be removed rapidly to permit measurement of collector response to a step function in insolation.

6. Modification of ADC inputs to permit more accurate differential temperature measurements.

In addition to these hardware improvements, considerable effort was expended developing software for monitoring, control, and plotting of results from parameter measurements and experimental runs.

This work was accomplished between May 15 and July 30, 1980, with actual experimental runs occurring in late July. Members of the Drexel group visited Middlebury during some of the experiments, resulting in valuable interaction between the experimental and theoretical groups. Results of this collaborative effort are described in two publications.[2] [3]

FUTURE ACTIVITIES

Contract activities are complete. In the future we may explore the possibility of using the Middlebury facility for experimental tests of proportional control strategies.

PUBLICATIONS/REFERENCES

[1] Wolfson, R.L.T. and Harvey, H.S. "Experimental Comparison of Control Strategies for Solar Energy Systems Incorporating Dual Storage Tanks", Journal of Solar Energy Engineering, 103, 47, 1981.

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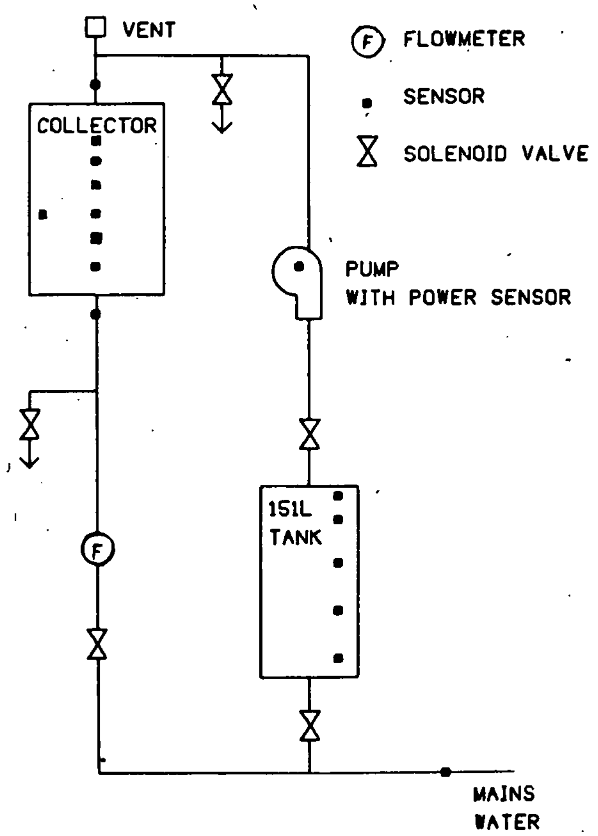

Figure 1: System Configuration for Present Experiments

CONTRACT INFORMATION

START DATE 5/15/80 END DATE 8/31/80 CONTRACT VALUE $15,710

MILESTONES

Item:	Due date:
1. Completion of System Modifications	7/15/80
2. Delivery of Data to Drexel University Group	7/30/80
3. Completion of Publications (with Drexel Group)	12/1/80
4.	
5.	

Section 10: SOLAR STORAGE TECHNOLOGY GROUP

DEVELOPMENT OF TES DEVICE USING CROSS-LINKED HDPE*

Argonne National Laboratory

Roger L. Cole

49507

OBJECTIVE

The objective of this project is to develop a prototype latent-heat storage device for solar-powered cooling applications using cross-linked high-density polyethylene (HDPE) as a storage medium.

DESCRIPTION OF WORK

Cross-linked HDPE was developed by Monsanto Research Corporation under DOE Contract No. EY-76-C-05-5159 for use as a thermal storage material. Its melting point of 130°C suggests using it as hot-side storage for absorption chillers, and it provides approximately 40-46 cal/g thermal storage. Because of molecular cross linking, the HDPE does not flow when it melts, but retains its shape with only a slight tendency for individual pellets to stick together at points of contact. According to Monsanto [1] HDPE can be produced cheaply and in large quantity from sources other than petroleum or natural gas.

Other DOE-sponsored projects have produced chillers operating on absorption, Rankine, and desiccant cycles as well as vacuum-tube, CPC, and parabolic trough collectors capable of supplying heat at the required temperatures. The result of this project will be an advanced prototype storage unit capable of coupling these high-performance collectors and chillers together.

A general system configuration has been defined and the prototype storage unit will be designed and fabricated accordingly. The prototype storage unit will be tested in cooperation with Oak Ridge National Laboratory using the test procedures developed by ANL under project number 49506. In addition, cost estimates for the storage unit will be prepared.

TECHNICAL ACCOMPLISHMENTS

- The general system configuration has been defined as 3-ton residential absorption chiller. At least one such chiller is commercially available, and others are in the prototype stage. The 3-ton size was chosen because of the availability of chillers of that size and the size limitations of existing test loops. The storage unit will operate the chiller for six hours at a COP of 0.7. A collector area sufficient to fully charge the storage during a sunny day is assumed.

- Two prototype storage units have been designed. The first will use 100% ethylene glycol as its heat-transfer fluid and will operate at atmospheric pressure plus 3.4 kPa (0.5 psig) overpressure of nitrogen to exclude oxygen and minimize corrosion. In mild climates the ethylene glycol can be used directly in the solar collectors, but in colder climates a heat exchanger is required because ethylene glycol freezes at -12°C (10°F).

  The second prototype will be designed for 0.41 MPa (60 psi) pressure per ASME Pressure Vessel Code, Section VIII. Although the pressure vessel will cost more than the unpressurized tank, it can use a variety of heat transfer fluids including water, heat exchangers can be avoided by using a mixture of ethylene glycol and water, and a nitrogen blanket will not be necessary.

  The prototype will provide the 325 MJ (308000 BTU) of storage required to operate the chiller for six hours. This requires a 2160 ℓ (570 gal) tank which is approximately 1.2 m (4 ft) diameter by 2.0 m (6.5 ft) high as shown in Figure 1. Insulation requirements were calculated on an economic basis [2] for four cities. Thicknesses of fiberglass are: Ft. Worth 42 cm (16.5 in), Washington 45 cm (17.6 in), Phoenix 49 cm (19.4 in), and Miami 60 cm (23.6 in). Although these amounts of insulation seem large they are justified because solar energy is a relatively expensive form of heat and the temperature difference between the HDPE and the ambient is large. A 42 cm insulation thickness has been selected for the prototype. The insulation will be covered with a weathertight aluminum enclosure.

- Installed cost of the HDPE thermal storage system has been estimated using the prototype as a basis [3,4]. Costs are summarized in Table 1. Total costs are $12.99/MJ ($13,687/MBtu) for the pressurized tank and $7.27/MJ ($7660/MBtu) for the unpressurized tank. These costs are at the upper and lower ends of the range of commercially-available latent-heat storage units, but the heat stored at 130°C is a much higher quality than the heat stored in the commercially-available units.

- Performance of the prototype will be measured using the test procedures being developed under project number 49506 as a basis. The initial part of the testing will be done at ANL. Testing will be completed in FY 1982 in cooperation with ORNL.

FUTURE ACTIVITIES

ANL has submitted a proposal to investigate improvements on the technology discussed in this

*Work supported by the Active Solar Heating and Cooling Division, Office of Solar Applications for Buildings, U.S. Department of Energy, Contract No. W-31-109-ENG-38.

paper. In particular, the use of latent-heat transfer fluids (such as steam) and investigation of polypropylene as a latent-heat storage material have been proposed. A latent-heat transfer fluid could substantially reduce the thermodynamic losses caused by the use of sensible heat transfer fluids. Polypropylene melts at a higher temperture than HDPE melts at and could couple effectively with the Rankine-cycle chillers that are under development.

ANL will continue its participation in ASHRAE Committee 94.1 activities. The committee is developing standards for testing latent heat storage systems.

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ACKNOWLEDGEMENT

The author gratefully acknowledges John A. Kelley and Prince Walker for technical assistance on this project and Jacquiline M. Bertoletti and Denise M. Voss for secretarial services.

TABLE 1. ESTIMATED INSTALLED COSTS

Item	Cost, $, Pressurized Tank	Cost, $, Unpressurized Tank
2160 ℓ pressure vessel, glass lined	2315.80	
2160 ℓ tank, nonpressure, unlined		168.86
Interior coating for tank		100.00
1456 kg HDPE @ $0.64/kg	928.87	928.87
650 ℓ, 50% ethylene glycol @ $0.29/ℓ	187.48	
650 ℓ, 100% ethylene glycol @ $0.58/ℓ		374.96
tank installation	254.00	254.00
42 cm fiberglass, installed	164.53	164.53
0.60 mm aluminum cover, installed, unpainted	337.67	337.67
thermostat	35.00	35.00
totals	$4223.35	$2363.89
for 60 cm fiberglass insulation add	240.74	240.74

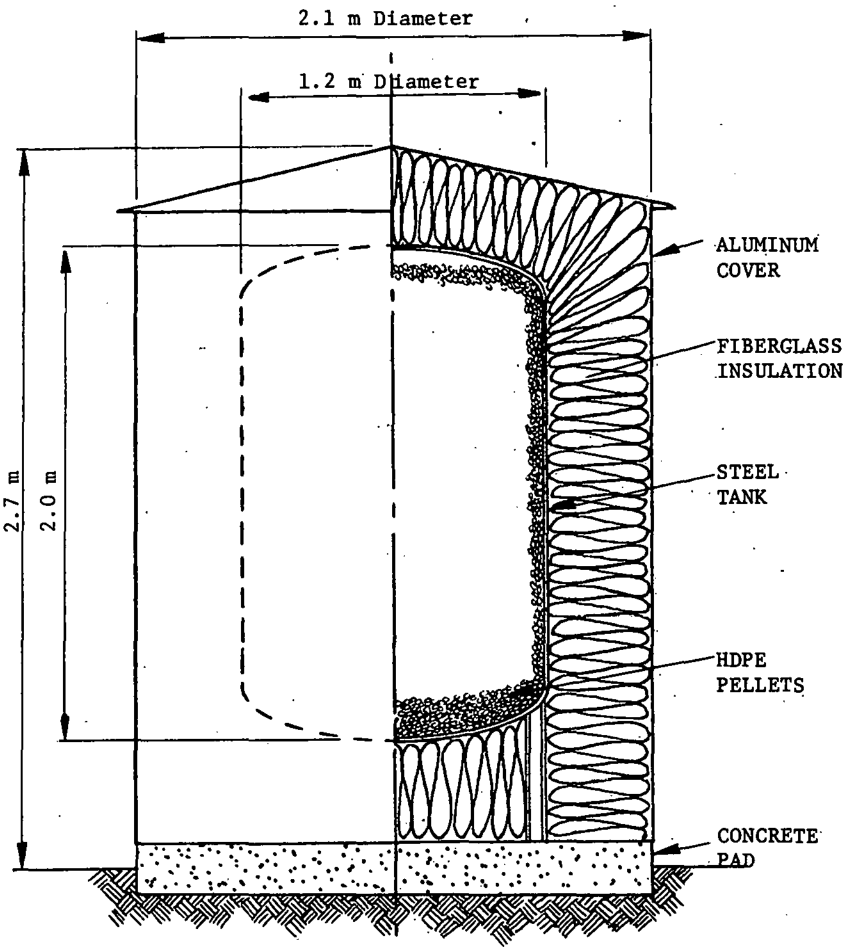


Figure 1. Half Section Through HDPE Storage Unit

CONTRACT INFORMATION		
START DATE 9/80	END DATE 9/83	CONTRACT VALUE $65 K

MILESTONES	
Item:	Due date:
1. Define System Parameters (m)	12/80
2. Design, Fabrication, and Procurement (ρ)	10/81
3. Testing (ρ)	07/82
4. Cost and Commercialization Analysis (ρ)	12/81
5. Advanced Concepts Development (ρ)	09/82

TESTING LATENT HEAT STORAGE UNIT FOR SOLAR APPLICATIONS*

Argonne National Laboratory

Yung Sheng Cha and Roger L. Cole

49506

OBJECTIVE

To develop a procedure for testing low and medium temperature latent-heat storage (LHS) units; and to coordinate the testing of the LHS units.

DESCRIPTION OF WORK

The ASHRAE Standard 94-77, Reference 1, was developed for testing sensible and latent heat thermal energy storage devices based on thermal performance. During its three years of application, experience has shown that the ASHRAE standard did not yield reliable results when applied to latent heat thermal energy storage (LHTES) units. Therefore, a close review of the ASHRAE standard was made to identify the problem areas and resolve their shortcomings. Most of the problems of the ASHRAE standard lie in defining the test parameters and their calculation methods and in heat loss test procedures. The source of these problems arises from combining the test procedures of sensible heat and latent heat thermal energy storage units into a single format.

A draft test procedure was developed at ANL. In this test procedure, major efforts were made to resolve the shortcomings of the ASHRAE standard and to emphasize the sections which contain the problem areas. This preliminary test procedure will be verified carefully, or improved, by the results of the bench-scale tests at ANL and the subsequent full-scale tests at ORNL.

A total of ten LHS manufacturers were contacted to acquire technical information about their products, and a review of these LHS units was conducted. The Heatbank unit of Calmac Manufacturing Corporation was selected and procured for the bench-scale test at ANL.

An uncertainty analysis, based on reference 2, of the experimental parameters was carried out to identify the critical parameters for the testing of the LHS units.

TECHNICAL ACCOMPLISHMENTS

- Developed a preliminary test procedure for comparing the performances of latent heat thermal energy storage (LHTES) units on equal terms regardless of the type and size of each unit.
- Reviewed commercially available LHS units; selected and procured a LHS unit (Heatbank of Calmac Manufacturer Corporation) for the bench-scale testing at ANL.
- Performed uncertainty analysis of the experimental parameters to identify the critical parameters for the testing of a LHS unit.

FUTURE ACTIVITIES

Bench-scale tests of the Calmac LHS unit will be conducted. The results of these tests and that of the full scale tests at ORNL will be used to verify and improve the preliminary test procedure developed by ANL. A final version of the test procedure will be issued at the conclusion of this project. This procedure will be suitable for testing low and medium temperature LHS units.

PUBLICATIONS

Yu Lwin, "Preliminary Test Procedure for Testing Latent Heat Thermal Energy Storage Unit for Solar Applications", available upon request from Office of Solar Applications, Building 362, Argonne National Labortory, 9700 South Cass Avenue, Argonne, Illinois 60439.

REFERENCES

1. "Methods of Testing Thermal Storage Devices Based on Thermal Performance", ASHRAE Standard 94-77, American Society of Heating, Refrigerating, and Air-Conditioning Engineerings, Inc., New York, NY (1977).

2. "Standard Measurement Guide, Engineering Analysis of Experimental Data", ASHRAE Standard 41.5-75, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, NY (1976).

*Work supported by the Active Solar Heating and Cooling Division, Office of Solar Applications for Buildings, U.S. Department of Energy, Contract No. W-31-109-ENG-38.

CONTRACT INFORMATION

START DATE 8/80 END DATE 10/82 CONTRACT VALUE $250K

MILESTONES

Item:	Due date:
1. Analyze test methods and outline test procedure (m)	1/81
2. Bench-scale experiments (ρ)	1/81
3. Write preliminary test procedure (m)	3/81
4. Evaluate test results (ρ)	3/82
5. Revise and publish test procedure (ρ)	5/82

DEVELOPMENT, FABRICATION, AND DELIVERY OF THREE (3) IDENTICAL THERMAL ENERGY STORAGE SUBSYSTEMS

ARTECH CORP.

DR. FRED ORDWAY

NAS8-32254

OBJECTIVES

To develop a practical thermal energy storage module, for installation in air circulating systems, based on the use of salt hydrate mixtures as phase change materials; to fabricate, test, and deliver three prototypes.

DESCRIPTION OF WORK

A self-contained thermal energy storage module was developed for incorporation in solar heating systems using circulating air for heat transfer. The modules are based on permanently sealed containers made of high-density polyethylene, which can be filled with any of the well known salt hydrate mixtures used for thermal energy (heat or coolness) storage. Each container is two feet square and three inches high; a stack of eight containers forms a module two feet high. Other standard modules are four and six feet high.

In the module (trade marked TESmod™), each container is independently supported by a modular frame element. The structure is so designed that it can be lifted from the top, rolled on a base equipped with casters, or disassembled into parts that can be lifted by one person.

The modules are designed for use in a chamber or duct carrying a horizontal air flow, the containers being ribbed on their top and bottom surfaces for air passage and heat transfer. By appropriately selecting the size, number, and arrangement of TESmods, the designer can tailor the storage assembly to the system requirements for capacity, heat transfer rate, and external dimensions. Any suitable enclosure may be used.

Development of the TESmod design required compromises between cost of filling and sealing, which calls for a large container, and the maximum weight that an average person can handle alone; between the heat transfer rate, which calls for a large container surface, and the limitations of the molding process and cost of the polyethylene resin; and between the strength and rigidity of the supporting frame and the cost and weight of the assembly.

The final design was developed through several lengthy iterations, using production processes best suited to prototype and small quantity production, owing to budgetary constraints. It is suitable for large-scale production, however, with little or no modification.

To perform the tests required by the program, a circulating air test loop providing flow rates up to 1000 cubic feet per minute was constructed, its design and instrumentation conforming to the requirements of ASHRAE Standard 94-77. The three 2-ft TESmods, arranged in series, were tested by the ASHRAE test procedure, in which the storage capacity is evaluated over a limited period at the beginning of the charge or discharge cycle, and the total storage capacity was also determined by integration over the entire cycle. Testing was performed with TESmods whose containers were filled with ARTECH TES-90™, a proprietary salt hydrate mixture containing about 80 percent sodium sulfate decahydrate.

The characteristics of the assembly under test were as follows:

Dimensions: 72 in. long (in direction of air flow), 24 in. wide, 28-3/4 in. high (including casters, but without lifting frame)

Weight: 1460 lb.

Weight of TES-90: 1080 lb.

The tests were performed after the assembly had completed 30 full charge-discharge cycles. The temperature change prescribed for the transition between charging and discharging was 63°F. The following results were obtained:

Test at 500-cfm air flow

Pressure drop across assembly: 0.048 in. of water

ASHRAE test duration: 4 hr.

Charge cycle

Heat absorbed: 55,100 Btu
Heat transfer rate: 13,800 Btu/hr

Discharge cycle

Heat released: 42,400 Btu
Heat transfer rate: 10,600 Btu/hr

Total heat absorbed: 80,900 Btu

Total heat released: 81,600 Btu

Test at 1000-cfm air flow

Pressure drop across assembly: 0.18 in. of water

ASHRAE test duration: 2 hr.

Charge cycle

Heat absorbed: 41,700 Btu
Heat transfer rate: 20,800 Btu/hr

Discharge cycle

Heat released: 35,300 Btu
Heat transfer rate: 17,600 Btu/hr

Total heat absorbed: 76,700 Btu

Total heat released: 69,400 Btu

TECHNICAL ACCOMPLISHMENTS

- Development of a practical thermal energy storage module based on the heat of fusion of salt hydrate mixtures, suitable for installation in air circulating systems either as a unit, with heavy equipment, or by hand.
- Characterization of the module's performance in an instrumented test loop according to ASHRAE Standard 94-77.

FUTURE ACTIVITIES

Arrangements will be made for several demonstration installations, whose performance in working domestic solar heating systems will be monitored through at least one heating season.

PUBLICATIONS/REPORTS/REFERENCES

Quarterly progress reports to sponsor.

CONTRACT INFORMATION

START DATE 9/30/76 END DATE 9/30/80 CONTRACT VALUE $151,306.

MILESTONES

Item:	Due date:
1. Deliverables: Three thermal energy storage modules	9/30/80 (m)
2.	
3.	
4.	
5.	

SERIES PARALLEL SOLAR AUGMENTED ROCK BED HEAT PUMP

CALIFORNIA STATE UNIVERSITY FULLERTON

EDWARD F. SOWELL

EN78-7-01-4697

OBJECTIVES

The objectives of this work were to establish the feasibility and cost-effectiveness of the Series-Parallel solar-augmented rock bed heat pump system.

DESCRIPTION OF WORK

This contract dealt with a system representing an alternate arrangement of the components in an air-type, heat pump augmented solar heating system. In this system, referred to as Series-Parallel, the heat pump coils are at opposite ends of the rock bed, Fig. 1, allowing heating and cooling of the air entering and leaving the bed. This allows a number of unique modes of operation, some of which allow off-peak use of the necessary utility power. Cooling modes are also available, including off-peak cooling-effect storage, night cooling, and free cooling (economizing). The system finds applications principally in single-family residences.

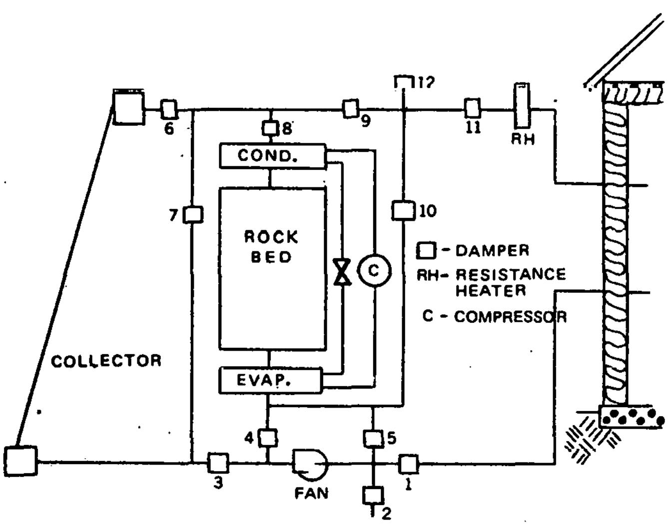


Figure 1. Series-Parallel System

The study examined the performance of this system at three locations (Sacramento, Albuquerque, and New York) by means of a simulation model. Seasonal heating and cooling performance factors of about 3 were obtained for Albuquerque for the system integrated into a 200m^2 residence. Design integration studies suggest an installed cost of approximately $28,000 above a conventional heat pump system using commercially available components. This high cost is largely due to solar hardware, although system complexity also adds. Availability of low-cost air type collectors may make the system attractive.

The study also addressed the general problem of predictive control necessary whenever off-peak storage is employed.

TECHNICAL ACCOMPLISHMENTS

- A computer model of the system was developed using TRNSYS.
- Several new TRNSYS subroutines were developed, including a convolution-principle rock bed model, and a heat pump model.
- Cases were executed for Sacramento, Albuquerque, and New York. Performance data is shown in Table 1.

Case	Location	Annual Heating GJ	COPH[1]	Annual Cooling GJ	COPC[1]
S1	Sacramento	73.33	1.687	18.68	3.326
S2	Sacramento	73.57	1.940	18.66	3.077
S3	Sacramento	74.05	1.459	17.72	4.933
A1	Albuquerque	89.23	1.845	22.98	3.182
A2	Albuquerque	89.93	3.020	22.84	3.006
A3	Albuquerque	90.23	3.331	24.06	3.321
N1	New York	107.6	1.560	7.83	2.108
N2	New York	108.5	1.561	7.82	2.263

Note: Seasonal values. Frequently called SPF.

Table 1. Summary of Predicted Performance

- Design integration was performed for a single-family residence.
- Life Cycle Cost estimates were developed as shown in Table 2.

	Heat Pump	Series-Parallel
Electrical Energy Costs	$15,206	$11,125
Investment Costs	5,895	33,896
Maintenance	620	620
Total Life Cycle Cost	$21,721	$45,641
Cost per delivered GJ ($/GJ)	6.42	13.49

Table 2. Life Cycle Costs (30 Years) Albuquerque

- Conclusions drawn from the study are that while the concept is technically feasible, it is not economically viable. Although the best Albuquerque case indicates a 28% reduction in energy relative to a high-performance heat pump, the cost is about $28,000 greater; life-cycle cost is over twice that of the stand-alone heat pump. This is due largely to the solar collectors. Load shifting capabilities are present, but the currently available utility rate structures do not offset the high equipment cost.

FUTURE ACTIVITIES

Further work on this concept should focus on cost reduction and identification of optimum site selection. There is a strong possibility that a liquid-type system would be less expensive and more compact. The contract has been completed and there is no current activity.

PUBLICATIONS

- Sowell, E. F. and P. W. Othmer, "Series-Parallel Solar Augmented Rock-Bed Heat Pump", Technical Progress Report, COO-4697-1, 31 July 1978.
- Sowell, E. F. and P. W. Othmer, "Series Parallel Solar Augmented Rock-Bed Heat Pump", Final Report, COO-4697-2, 31 December 1979.
- Sowell, E. F. et al, "Series-Parallel Solar Augmented Rock-Bed Heat Pump - Convolution Model of Rock Bed", COO-4697-3, 31 December 1979.
- Sowell, E. F. and R. L. Curry, "A Convolution Model of Rock Bed Thermal Storage Units", Solar Energy, Vol. 24, pp. 441-449, 1980

CONTRACT INFORMATION

START DATE 1 Feb 1978 END DATE 31 Dec 1980 CONTRACT VALUE $95,000

MILESTONES

Item:	Due date:
1. Model Development	30 Oct 78
2. Subsystem Performance Mapping	31 Mar 79
3. Sensitivity Analysis	31 Dec 80
4. Design and Integration	31 Dec 80
5.	

GEL STABILIZATION AND ADDITIVE EFFECTS ON SALT HYDRATE PCMS

CALMAC MANUFACTURING CORPORATION

CALVIN D. MACCRACKEN

86X-70522V

OBJECTIVE

Calmac's objectives under this contract will be to evaluate a gelling agent, developed by Calor, Ltd. of England, (1) as a means of preventing stratification in sodium thiosulfate pentahydrate and Glauber salt eutectic phase change materials; to determine techniques for the field filling and to develop repair procedures for systems incorporating the Calor gel; to study the effects of ethylene glycol and glycerin on the thermal performance of sodium thiosulfate pentahydrate and Glauber salt eutectic PCM; and to evaluate the effect of pH modification on sodium thiosulfate pentahydrate, specifically with regard to subcooling behavior.

DESCRIPTION OF WORK

Calmac Manufacturing, through previous research, has gained extensive experience with the properties and performance of sodium thiosulfate pentahydrate. In fact, Calmac was successful in designing a commercially available thermal storage system, with consistently repeatable high performance, through the use of a stirring apparatus to prevent stratification. (Fig. 1) However, the development of a stabilizing gelling agent offers many benefits. The cost of a stirring mechanism with associated wiring and controls would be eliminated. The absence of a mechanism within the storage tank reduces the possibility of system malfunction. Parasitic power requirements, although minimal, would be eliminated. Distortion of the heat exchanger due to buoyant forces would be controlled. Also, a gel could be used for those PCMs where a stirring pump is not successful, such as Glauber's salt and its eutectics. For this purpose, a eutectic of Glauber's salt, developed by Calmac, with a fusion point of 45°F (7.2°C) will also be tested with the Calor gel. (2).

Because of developments including the use of additives to modify the fusion point and other thermal properties of PCMs, (3) we will also study the effects of ethylene glycol and glycerin, specifically with regard to fusion point, latent heat capacity, stratification and type, rate and size of crystal growth. Also, acidic and basic pH ranges will be induced in sodium thiosulfate pentahydrate to determine the effects on thermal performance and subcooling.

All initial testing will be performed in 2-gallon containers with internal plastic tube heat exchangers which are, basically, miniature duplicates of Calmac's 360-gallon commercial units. (Fig. 2) As much testing as possible, regarding the effect of additives, will be done concurrently with the evaluation of the Calor gel. If the performance of the gel is less than optimal, we will hopefully be able to apply what we learn, concerning the additives, to improve the gel-PCM performance.

After the best possible thermal response of the gel system has been obtained in 2-gallon units, testing will then proceed to evaluation of 90-gallon units.

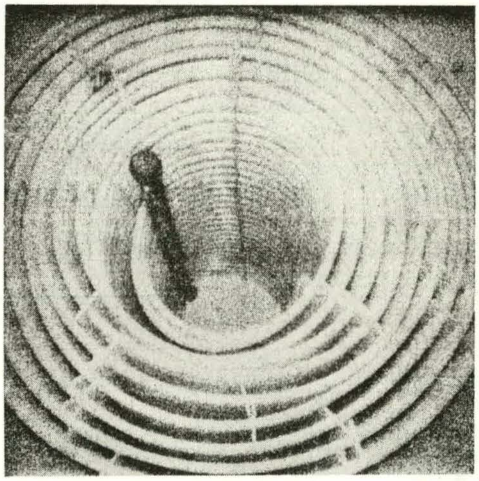


Figure 2, CALMAC flexible plastic tube heat exchanger.

The Calor gel is described as a "water-insoluable hydrogel formed from a water soluble synthetic polymer having pendant carboxylic or sulphonic acid groups cross-linked with rations of a polyvalent metal (for example, aluminum or magnesium)" (1). Because this cross-linking process is fairly rapid (15-30 minutes) and transforms the gel from a pumpable liquid to a gel of semi-solid consistency, difficulties in field filling, mixing and repair of these systems is anticipated. The appropriate techniques necessary to circumvent these obstacles will be evaluated at the time testing in 90-gallon units is begun.

TECHNICAL ACCOMPLISHMENTS

Because we are in the initial weeks of our investigation, our efforts have been directed toward modification of our present testing equipment and refinement of our experimental procedures for the specific needs of this contract.

Initial observations indicate the expansion of the gel during the cross-linking process may induce excessive stress in the storage vessel. However, a number of proposed solutions to this problem are already under consideration.

FUTURE ACTIVITIES

Calmac is, of course, a manufacturing concern. Although a comprehensive cost analysis of the TES system under investigation is not included in our statement of work, we are committed to the concept of phase change energy storage and would incorporate all viable techniques in the marketing of our already expanding line of thermal energy storage systems.

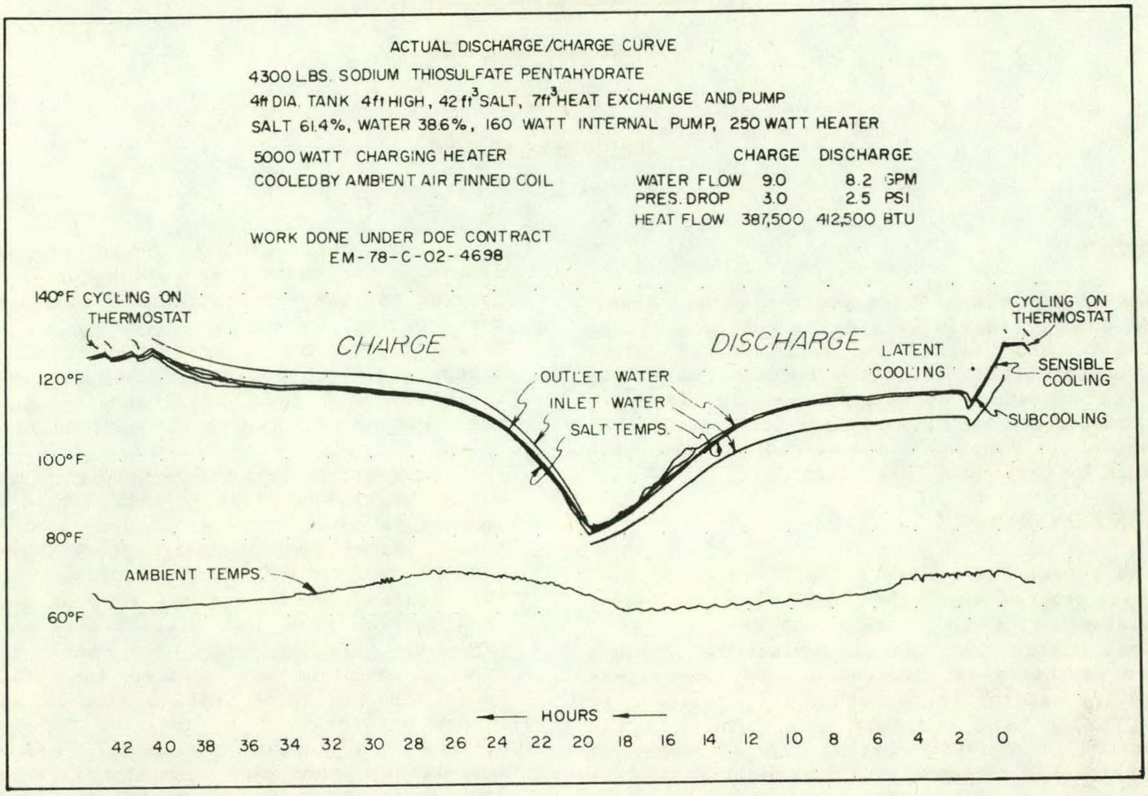


Figure 1, Typical Charge-Discharge Curve for STP with internal stirring mechanism

PUBLICATIONS/REPORTS/REFERENCES

1. Peter J. C. Kent and John K. R. Page, U. S. Patent 4,209,413, June 24, 1980 (Calor Group Ltd., England)

2. Donald E. Truelock, Federal Republic of Germany Patent Application, 2,844,810, October 12, 1978 (Kay Laboratories, Inc., San Diego, California)

3. Calmac Manufacturing Corporation, Bulk Storage in PCM, Englewood, New Jersey, 1980

CONTRACT INFORMATION

START DATE April 1, 1981 **END DATE** March 1, 1982 **CONTRACT VALUE** $90,207.00

MILESTONES

Item:		Due date:
1.	Summary of Gelling Agent Evaluation	August 1, 1981
2.	Report on Field-mixing/filling and Repair Techniques	October 1, 1981
3.	Report on Experimental Results of Additive Effects	November 1, 1981
4.	Report on the Effects of pH Modification on STP	December 30, 1981
5.	Final Project Report	January 31, 1982

Thermal Storage for Solar Cooling Using Paired Ammoniated Salt Reactions

Martin Marietta Corporation

DE—AC02—78CS34700

Edward Fox

July 1978 to July 1981

OBJECTIVE

The objectives of this program were: demonstrate concept feasibility using subscale system testing of both liquid and solid salts; determine compatibility of construction materials with the candidate ammoniates; select the optimum combination of ammoniates for residential conceptual design; and demonstrate system performance by testing a full-scale unit.

DESCRIPTION OF WORK

The reversible energy storage system studied in this program uses the heat of reaction of ammoniated salts to convert thermal energy to chemical energy that can be reclaimed. Ammonia gas is exothermally absorbed at one temperature to provide heating and endothermally released by adding solar heat, condensed, and then is reevaporated to provide cooling. A schematic of the residential system, in the cooling mode is shown in Figure 1. It operates similarly to an ammonia absorption refrigeration unit, except the unit contains sufficient absorber to be used for thermal storage. It also operates in a batch mode rather than continuously. The upper halt ot the tigure shows the charge mode and the lower half shows the discharge mode.

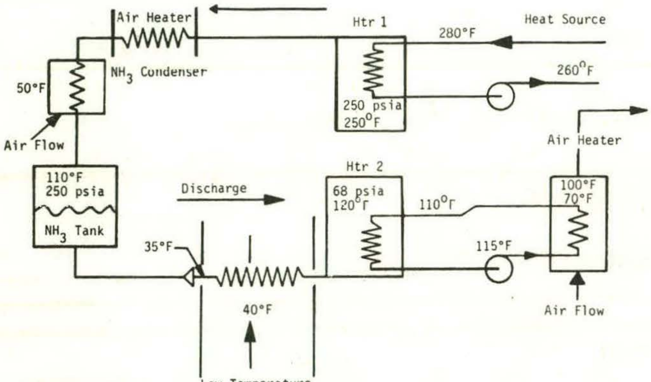


Figure 1 Flow Diagram for $NH_3/NH_3NO_3 \cdot 3NH_3$ Heating Conditions

If the system is used in the heating mode, heat is supplied to both high temperature reactors to charge the system. The ammoniate dissociates endothermally releasing ammonia gas that is condensed and stored as a liquid in the NH_3 tank.

In the cooling mode, heat is supplied to discharge one reactor at a time, while the other is used to absorb the ammonia that has been used for cooling. To cool a building, liquid ammonia flows through the expansion valve to an evaporator where it cools air. It is absorbed in the other high temperature reactor and the excess heat is rejected to the outside atmosphere.

The subscale tests were conducted in a 5,000 Btu capacity system using both liquid and solid ammoniates. The tests showed heat transfer coefficients were 1 Btu/h-ft^2-^{o}F for solids and 50 Btu/h-ft^2-^{o}F for liquids. Density of the liquids was three times that of solids, and the reaction rates for liquids were an order of magnitude greater than for solids. Consequently emphasis was shifted to liquid ammoniates for the residential system because these properties resulted in smaller, more efficient designs. To support residential system design activities, corrosion compatibility tests on various construction materials were conducted in parallel to the subscale testing.

An engineering test system was then designed using ammonium nitrate and ammonia, instead of a pair ot ammoniated salts, because this combination was predicted to be most cost effective. The full-scale system had a total storage capacity of 600,000 Btu. Design difficulties were encountered in operation of the high pressure/high temperature rotating seal for the high temperature reactor. The rotating seal was required to seal around the stirrer shaft which is needed in the liquid reactors. Also, a problem was encountered with corrosion of the welds in the heat exchanger. Inadvertantly, weld rods were used that contained a small amount of copper, which is very reactive in the ammoniate of ammonium nitrate. A limited number of tests were run due to the fabrication problems but from the data a COP of 1.2 for heating and 0.7 for cooling were predicted.

TECHNICAL ACCOMPLISHMENTS

Subscale reactors with a 5,000 Btu storage capacity and 1,000 Btu/hr heat transfer rates were used to test the ammoniates. Experimental test results showed heat transfer coefficients of 1 Btu/h-ft^2-^{o}F with the solid ammoniate systems and coefficients of 50 Btu/h-ft^2-^{o}F with liquid ammoniates. A summary of the results is shown in Tables 1 and 2 for solid and liquid ammoniates respectively.

Table 1
Subscale Test Results - Solid Ammoniates

Calcium Chloride

- Internal recirculation increases deammoniation by 15 to 20% for any flowrate above 76 SCFM, but does not improve ammoniation.
- Exhibits steady drop in NH_3 flowrate with time during either phase due to large temperature gradients.
- Heat rate drops to about 1/2 the design value during a 6-h test run.
- The already large heat exchanger would have to be doubled to be sized for the worst-case conditions that occur at the end of the run.

Manganese Chloride

- No change in reaction rates were noted at any blower speed due to the nonporous nature of $MnCl_2 \cdot 6NH_3$.
- NH_3 flowrate drops to 50% after only 3 h.
- Overall heat transfer coefficient ranges from 0.3 to 1.2 Btu/h-ft^2-^{o}F (6.8 W/m^2-^{o}C) rather than the anticipated 5-10 Btu/h-ft^2-^{o}F (28-57 W/m^2-^{o}C).
- Due to low heat transfer rates, deammoniation only went to 60% completion and ammoniation to only 90% completion.

Table 2
Subscale Test Results - Liquid Ammoniates

- Requires stirring during ammoniation but no improvement in uptake was found going from 430 to 870 rpm.
- Design ammoniation rates of 1.36 lbm/h with a ΔT of about 20^{o}F were verified.
- A design limit of 50% maximum and 10% minimum was set on the solids mass (NH_4Cl_2) concentration in the slurry.
- Overall heat transfer coefficients were between 40 to 45 Btu/h-ft^2-^{o}F.
- Heat transfer rates of 700 to 800 Btu/h were measured.
- The rate of heat transfer and not the reaction kinetics limits the reaction within the specified concentration limits.

Corrosion tests were conducted on the following potential construction materials: 304L and 306L stainless steel, 5083 aluminum alloy, A-36 structural carbon steel; Teflon (TFE); Polyvinyl chloride (PVC); and a fiberglass-epoxy composite. The material specimens were exposed to the ammoniates at projected operating pressures and temperatures for 8 months and then were visually inspected to determine the effect of the ammoniate on the specimen. The results of the corrosion test program are summarized in Tables 3 and 4 for solid and liquid ammoniates respectively.

Table 3 Corrosion Testing of Solid Ammoniates

- Metal test specimens that underwent visible corrosion in general displayed significant weight changes as well as corrosion product formation.
- Nonmetal specimens that did not disintegrate (PVC) or delaminate (fiberglass), did not reveal any gross mechanical property changes in density and tensile strength.
- $CaCl_2/CaCl_2 \cdot 6NH_3$ was generally most benign and $MnCl_2/MnCl_2 \cdot 6NH_3$ the most aggressive medium tested.
- Stainless steel samples were found to be most resistive metals, 5083 Al and A36 carbon steel most susceptible.
- Teflon displayed excellent resistance in all tested environments. Two nonmetals, PVC and fiberglass are unacceptable in $MnCl_2$ and $MgCl_2$ anhydrous and ammoniated salt systems.

Table 4 Liquid Ammoniates Corrosion Testing

- 304L stainless steel is not appreciably corroded by $NH_4Cl \cdot 3NH_3$ or $NH_4NO_3 \cdot 3NH_3$ after 8 months some corrosion was found with $NH_4SCN \cdot 2NH_3$.
- A-36 carbon steel is not suitable for use with any liquid ammoniate, however surface treatments offer increased corrosion resistance.
- 5052 aluminum is suitable only for use with $NH_4NO_3 \cdot 3NH_3$, the other two liquid ammoniates caused appreciable corrosion.

Prototype residential conceptual designs were completed for solid and liquid ammoniate systems and the cost data showed solid systems were 10 times more costly than liquid systems. For this reason liquid ammoniates were considered. After testing of the various ammoniated salts individually and in pairs, it was found that the combination of an ammoniated salt, ammonium nitrate, and ammonia gas was the simplest system with the highest predicted performance capability for heating and cooling. Preliminary cost estimates for the components of the system shown in Figure 1 are listed in Table 5.

Table 5 Reactor Cost Estimates

High Temperature Reactors		
Capacity	250,000 Btu (Madison)	
Tank Volume	300 gal	
Weight-$NH_4NO_3 \cdot 3NH_3$	2,230 lb	
Cost of Salt, 1360 lb	$ 65	
Cost of Ammonia	$ 50	
Cost of Heat Exchanger	$ 160	
Cost of Tank	$ 600	
Total Cost of Two Reactors	$1,750	
Low Temperature Reactor		
Weight of Ammonia	798 lb	
Tank Volume	165 gal	
Cost of Ammonia	$ 100	
Cost of Tank	$ 330	
Cost of Heat Exchanger	$ 200	
Total Reactor	$ 630	
Total Cost (Reactors and Chemicals)		$2,380

Along with the costs of the chemicals and reactors, the following needs to be added to achieve a total system cost.

	Unit Price	Total Price	
High-Temperature			
Reactor Stirrer (2)	$250	$ 500	
Evaporating Condenser		990	
Circulating Pump (2)	120	240	
Controls		330	
Valves			
- 1in. Solenoid (12)	90	1,080	
- 1/2 Manual		35	
- Expansion Valve		50	
- 1 in. Check (5)	17	85	
Dampers and Motors (4)	70	280	
Blowers (2)	140	280	
Heating Coil		555	
Cooling Coil		425	
Total Cost (Components)			$4,850
Total System Cost (Minus Cost of Solar Collectors)			$7,230

Costs Are in 1981 Dollars

Prototype Tests Plans were reduced because of the previously mentioned design problems in weld areas. However, sufficient data was obtained to predict a reactor performance for both ammoniation and deammoniation order.

These limited data pointed to a COP of 1.2 for heating and 0.7 for cooling could be obtained in this system. These performance capabilities compared favorably to other chemical heat pump systems. The corrosion problems and the mechanical seal problems that were encountered can be readily solved by use of different construction materials and different rotating shaft seals such as magnetic couplings, each of which will raise the initial cost but perhaps decrease the long-term layout.

FUTURE ACTIVITIES

Recommended future activites for the ammoniated salt chemical heat pump systems should be focused on improved heat transfer coefficients for solid ammoniates and improved corrosion protection for an A-36 Carbon Steel System.

PUBLICATIONS/REPORTS/REFERENCES

1. Thermal Storage for Solar Cooling Using Paired Ammoniated Salts. Interim Report July 1979 and Final Report Martin Marietta Corporation, July 1981.
2. W. R. Haas, F. A. Jaeger, T. J. Giordano, Ammoniated Salt Heat Pump, 2nd International Conference on Alternative Energy Sources, Miami, Florida.
3. Jaeger, F. A. and Hall, C. A., Ammoniated Salt Heat Pump/Thermal Storage System, International Seminar on Thermochemical Energy Storage, Stockholm, Sweden, January 1980.

CONTRACT INFORMATION

Start Date 5/15/78; End Date 7/30/81
Contract Value $427,553;
Milestones:

- Interim Report June 1979
- Final Report July 1981

THE MONITORING OF THERMAL STRATIFICATION OF THE STORAGE TANK OF THE MABEL LEE HALL SOLAR HOT WATER SYSTEM

UNIVERSITY OF NEBRASKA-LINCOLN

EDWARD E. ANDERSON

DE - AC02 - 79CS30247

OBJECTIVE

The principal objective of this project was to obtain temperature data in a large liquid solar storage tank to be used for the verification of numerical thermal stratification models. Testing was to be conducted under a variety of operating conditions including charging, discharging and simultaneous charging-discharging. Two methods of charging were included in the testing; one technique involved an internal heat exchanger while the second technique circulated the storage water. Heat removal was accomplished with an internal heat exchanger. Finally, test data were to have sufficient spatial and temporal resolution for numerical model verification.

DESCRIPTION OF WORK

The Mabel Lee Hall solar facility was designed to preheat the hot water required by one of the physical education buildings located on the University of Nebraska-Lincoln Campus. This large system uses two different collector types; a liquid collector system employing "Rol-Bond" panels and an air collector of the volume type. Both systems have 1750 square feet of aperture with identical glazing and service the same storage tank.

Storage consists of a 32'x16' (interior) reinforced concrete block structure lined with 3" of expanded polystyrene insulation and a PVC pre-seamed liner. This tank was filled with 32,000 gallons of water to a depth of 8'10". Water from the liquid collector is circulated through an internal heat exchanger located near the bottom of the tank. This exchanger is fabricated from copper tubing and is uniformly distributed over the tank floor area. A similar internal heat exchanger near the top of the tank preheats the water supply to Mabel Lee Hall. An external air to liquid heat exchanger is used for the air collector. Storage water is uniformly extracted from the bottom of the tank to supply this heat exchanger. Following heating, the storage water is uniformly reinjected back into the tank near the top. This design permits a variety of operating conditions.

By using two different flowrates in the three storage heat exchange circuits, a total of fourteen different combinations of charging and discharging were possible. Tests of two days duration were conducted for each of these combinations to assess the effect of charge and discharge upon stratification.

Thirty-five thermocouples were placed in the storage tanks. These were located just above and below the internal heat exchangers and tank mid-depth in arrays of five thermocouples. The arrays were placed in the storage tank in a manner consistent with a numerical model. An additional array was placed in the ground outside the tank to monitor wall heat losses. Additional instrumentation consisting of flowrates, inlet and outlet temperature was used for each of the three storage streams to monitor the heat transfer rates.

All data were monitored with a data acquisition system. This system was programmed to sample each data point once every fifteen minutes during a test. This time increment was selected to provide ample temporal resolution for any numerical model.

TECHNICAL ACCOMPLISHMENTS

- A total of fourteen tests have been completed. Each test involved a different storage charging and discharging as illustrated in Table I.
- Appropriate temperature and flowrate data were obtained every fifteen minutes during each two day test. Over the entire program, over 54,000 individual pieces of data were obtained.
- All the data have been reported to DOE Argonne National Laboratories in a series of Interim Reports. These data have been put into a form suitable for checking aginst numerical models generated by the contracting agency or others.

FUTURE ACTIVITIES

The project has been completed and all work reported to DOE. In view of the nature of the project, no additional work is contemplated. A summary final report is under preparation.

TABLE I. Schedule of Charge-Discharge Tests Conducted

Discharge	No Charge	Charging with Liquid Collector Low Flowrate	Charging with Liquid Collector High Flowrate	Charging with Air Collector Low Flowrate	Charging with Air Collector High Flowrate
Low Flowrate	*	*	*	*	*
High Flowrate	*	*	*	*	*
No Discharge		*	*	*	*

REPORTS

E.E. Anderson, "Description of System, Instrumentation and Testing Procedures," Interim Report #1, August 15, 1980 (Available from ANL)

E.E. Anderson, "Results of the Air Collector Charging Tests," Interim Report #2, September 1, 1980 (Available from ANL)

E.E. Anderson, "Results of Storage Discharge Tests," Interim Report #3, October 1, 1980 (Available from ANL)

E.E. Anderson, "Results of Liquid Collector Charging Tests," Interim Report #4, November 15, 1980 (Available from ANL)

E.E. Anderson, "Results of Liquid Collector and Discharging Tests," Interim Report #5, December 20, 1980 (Available from ANL)

E.E. Anderson, "Results of Air Collector and Discharging Tests," Interim Report #6, January 8, 1981 (Available from ANL)

CONTRACT INFORMATION

START DATE Sept. 15, 1979 END DATE Sept. 30, 1980 CONTRACT VALUE $23,573

MILESTONES

Item: Due date:

1. Complete set of test data, due as they become available.
2. Summary Final Report, September 30, 1980.
3.
4.
5.

MEMBRANE-LINED FOUNDATION SYSTEMS FOR LIQUID THERMAL STORAGE

UNIVERSITY OF NEBRASKA

Robert J. Youngberg

DE-AC03-80CS30227

OBJECTIVE

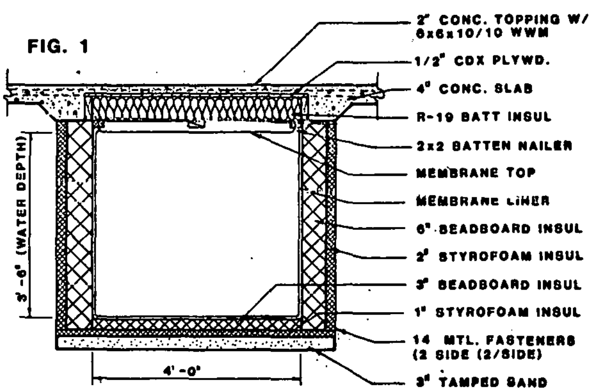
The objectives of this project are to complete development of baseline membrane-lined storage systems, including selection of preferred membrane materials and domestic water preheater configurations, and to begin technology transfer efforts.

DESCRIPTION OF WORK

Membrane-lined liquid thermal storage systems promise lower costs and easier installation than conventional steel or fiberglass tanks. A project to investigate and further develop membrane storage systems was begun in May, 1978, at the University of Nebraska-Lincoln, with funding from the Research and Development Branch, Office of Solar Applica-tion, USDOE (1). The membrane-lined storage alternative being investigated and further developed in this project has the potential advantages of reducing corrosion problems, simplifying access problems common to prefabricated tanks, facilitating installation of domestic water preheaters and other heat exchangers, and reducing cost.

One of the primary objectives of this project is to determine the preferred liner material for membrane-lined storage systems. Materials under examination are 30 mil EPDM, 20 mil PVC, and 4 mil crosslaminated polyethylene. Two six-cell test containers have been constructed, lined with the candidate membrane materials, and filled to a depth of 10" with water. Duplicate cells are maintained at 160 deg. F and 200 deg. F. Membrane design life is assessed by subjecting candidate materials to elongation, seam, and patch tests. Domestic water preheaters are also being tested to determine a preferred combination of configuration, location, and support method.

FIG. 1

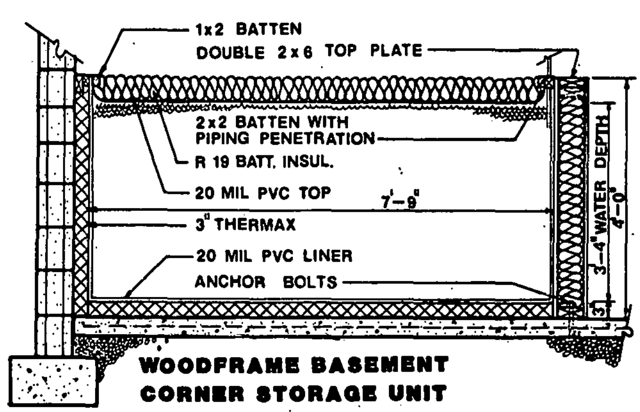


UNDERSLAB "FOAMWALL" TANK

To evaluate the cost and feasibility of under slab storage units, a "foamwall" tank was constructed in cooperation with Trident Energy Systems, Inc. of Davis, CA. The 860 gallon tank, which uses foam for structural wall support, is detailed in Figure 1.

Design and construction of the wood frame basement corner storage unit was performed. This 1400 gallon system consists of two 2x6 frame walls and utilizes common walls of the existing basement to create a cost effective configuration (See Figure 2). Three different piping configurations are to be tested at various flow rates to determine the effect of sensible heat distribution in the unit. An engineering field test will be conducted to monitor the first year performance of the system.

FIG. 2



WOODFRAME BASEMENT CORNER STORAGE UNIT

The final emphasis of the project will go to determination of the most appropriate method for introduction of the membrane-lined storage system concept to the solar industry. Input will be solicited from a broad spectrum of participants in the solar field to identify the preferred method. Construction manuals are to be prepared and workshops conducted to disseminate the developed information.

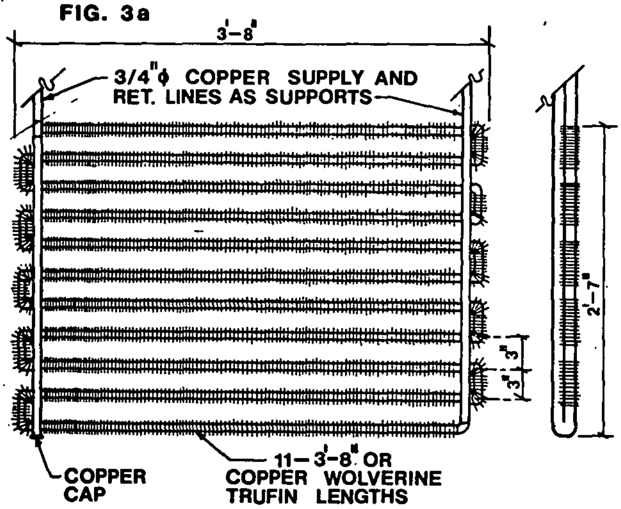
TECHNICAL ACCOMPLISHMENTS

- Membrane test cells have been constructed and short-term hot water exposure tests have been completed, the 120 day tests are half completed, and the 540 day tests are in their sixth month.

- Elongation testing has been completed on membrane samples exposed for 7 and 30 days. The data is inconclusive.

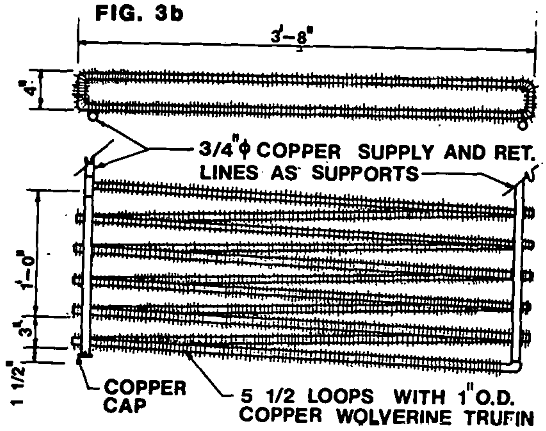
- Construction and a summary of costs have been completed for an underslab foamwall tank. It was determined that the "foamwall" tank would not support the structural loads imposed by the floor and a bearing wall spanning the tank. A cost analysis indicates that poured concrete walls would have been a preferred alternative. No further testing will be performed on the "foamwall" tank under this contract.

FIG. 3a



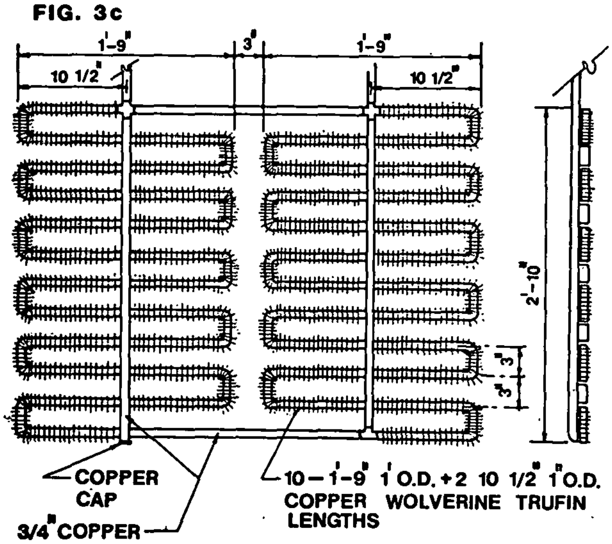
SINGLE SERPENTINE PREHEATER DESIGN #1

FIG. 3b



SINGLE TROMBONE PREHEATER DESIGN #2

FIG. 3c



PARALLEL SERPENTINE PREHEATER DESIGN #3

●Three domestic water preheating heat exchanger configurations have been fabricated and tested. Designed to be easily supported along the sidewall of membrane tanks, they were made from 46' lengths of 5/8" finned tubing manufactured by Wolverine. Di of VOP, Inc. (Fig. 3) These were tested in the "foamwall" tank at 3 GPM flow rates, with and without a circulating pump running, to determine the effect of mixing. Efficiency was calculated from the total heat transferred to a fixed volume of water and was based on drawing water directly from the tank. It was found that measured preheater performance is best characterized by calculating "U" values as opposed to reporting performance in terms of a heat exchanger effectiveness factor (∈). This is because the value of ∈ is highly dependent on the degree of stratification in the storage tank. See Table I.

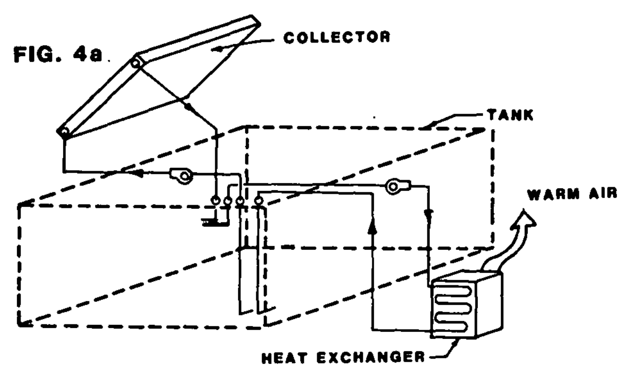
TABLE I

Material	160°F		200°F	
	7 Day	30 Day	7 Day	30 Day
EPDM	+4.4%	-8.5%	-10.3%	-23.0%
PVC	+6.1	-4.7	- 9.4	-10.3
PE	-4.8	- 0 -	-18.4	N/A

● Design development of the woodframe basement corner storage unit was completed. A field test unit was constructed. Installation process documentation and cost evaluation was completed.

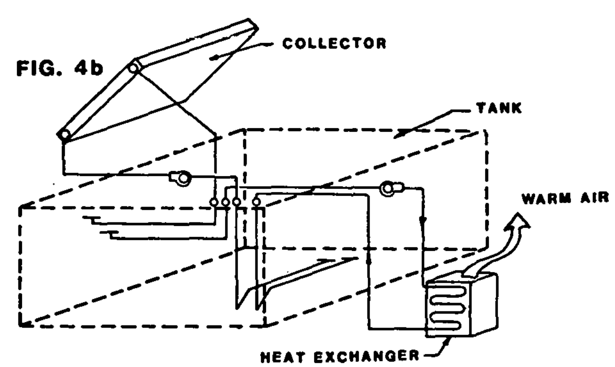
● Piping in flow and out flow testing for two piping arrangements was completed. Scheme I piping (Fig. 4a) and Scheme II piping (Fig. 4b) were tested at three different flow rates. The Scheme I

FIG. 4a



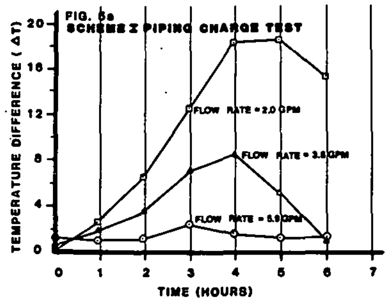
SCHEME I PIPING ARRANGEMENT

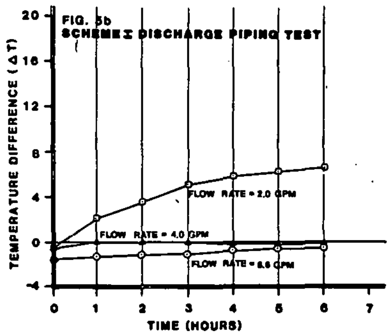
FIG. 4b

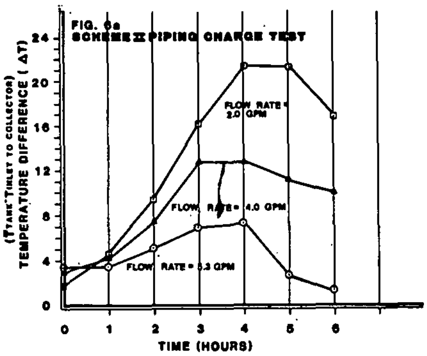


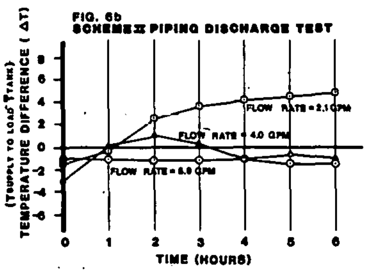
SCHEME II PIPING ARRANGEMENT

piping charge graph plots the differential between the average tank temperature ($\bar{T}_{tank}$) and (T_{in}), the collector inlet temperature, as a function of time (Fig. 5a). The Scheme I piping discharge graph shows the differential between the tank supply tem-



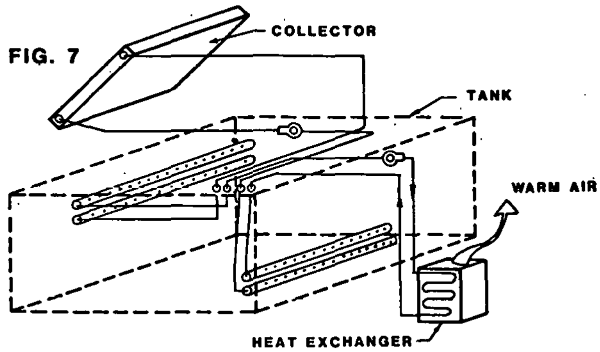






perature to the load (T_{supply}) and the average tank temperature ($\bar{T}_{tank}$) as a function of time (Fig. 5b). Comparative test charging of Scheme II piping is shown in Fig. 6a and Scheme II discharge is shown in Fig. 6b. The sensible heat storage performance is improved by the greater temperature stratification developed by the Scheme II piping. Scheme III piping tests (see Fig. 7) are underway.

FIG. 7



SCHEME III PIPING ARRANGEMENTS

FUTURE ACTIVITIES

The wood frame basement corner unit shall be tested for reliability and overall operation when coupled with an active collector system for a year including an assessment of storage heat loss rate.

Alternative technology transfer paths will be evaluated to determine the most appropriate method to commercialize the membrane-lined storage system concept. Installation manuals will be prepared for use in the technology transfer effort. Workshops will be conducted to train attendees in the design and construction techniques involved.

REFERENCES

1) BOURNE, RICHARD C., "Membrane-Lined Foundation Systems for Liquid Thermal Storage" Proceedings of Third Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Washington, D.C., September 1978.

CONTRACT INFORMATION

START DATE 8-1-80 END DATE 7-31-82 CONTRACT VALUE $235,950

MILESTONES

Item:	Due date:
1. Annual Report 8-1-81 (p)	8-1-81
2. 500 Copies of Installation Manuals (p)	2-1-82
3. Topical Report on Workshop attendance and participation (p)	7-1-82
4. Final Technical Report containing drawings, test results, specifications, technology transfer results, etc. (p)	7-31-82
5.	

Section 11: SOLAR ANALYSIS GROUP

11

DEVELOPMENT OF TWO SOLAR HANDBOOKS

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

WILLIAM S. FLEMING & ASSOCIATES, INC. AND ALWIN B. NEWTON

SERI #XH-9-8265-1 UNDER DOE CONTRACT #EG-77-C-01-4042

OBJECTIVE

This project has the objective of developing a Solar Domestic and Service Hot Water Manual and to develop a Solar Collector Performance Manual.

PROJECT DESCRIPTION

Solar Domestic and Service Hot Water Manual

A review of various existing domestic hot water design and installation handbooks was performed to determine if an existing handbook is adequate for widespread use in the HVAC industry. The review included the HUD Solar Domestic Hot Water Handbook developed by AIA/RC and the HUD DHW Installation Guidelines Handbook.

As a result of this review, the determination of the necessity to further develop a solar hot water handbook was made. This handbook will attempt to provide all needed information for the design, control, sizing, economics, installation, testing, operation, and maintenance of directly and indirectly heated, circulating and non-circulating service hot water systems for domestic and commercial applications.

Solar Collector Performance Manual

ASHRAE Standard 93-77, "Methods of Testing to Determine the Thermal Performance of Solar Collectors", provides testing methods for determining the thermal performance of solar energy collector modules which heat fluids for use in thermal systems. ASHRAE committee members determined that there exists a need for a manual which would cover the uses of the information generated from tests under ASHRAE Standard 93-77. As a result, we hope that this handbook will provide guidelines for the use of ASHRAE Standard 93-77 for the design and installation members of the solar collector industry.

TECHNICAL ACCOMPLISHMENTS

Solar Domestic and Service Hot Water Manual

In an effort to provide a means which will assist market development of cost effective renewable energy sources the manual was written to accomplish the following:

- Provide a concise "how to" approach to making systems work and to be used as a comprehensive "design/installation" tool.
- Address all professionals who are involved in design, installation, and operation of solar domestic and service hot water heating systems, i.e.:
  - -architects
  - -builders
  - -contractors
  - -design engineers
  - -plant operating engineers
- Provide a manual to the design profession that equally addresses energy effectiveness and economic value during installation, operation, and maintainence.
- Provide a manual to the builder and the contracting and service profession that equally addresses factors which effect technical quality, energy effectiveness, and economic value during design.
- Because the document integrates all professionals' technical awareness, a system of checks and balances will occur which is rare within the construction industry. With improper design, the builder or contractor may address the A/E and with improper installation the A/E may address the builder/contractor by utilizing the same reference manual.
- Provide a manual that documents one method to determine energy and cost effectiveness of solar domestic and service hot water that is published by ASHRAE (a professional organization that is well known for professional and industrial solar energy regulations and standards).
- Integrate all elements of design into one manual in a manner which will reduce design time, cost of professional service(s), and result in greater cost effectiveness.
- Provide a manual which allows effective marketing of goods and services which is written and distributed by an organization and individuals without preference to specific markets of solar products, systems, or services. Such a manual will relieve any consumer of questions concerning quality and validity of solar domestic and service hot water systems estimated to be cost effective.

Solar Collector Performance Manual

The Solar Collector Performance Manual provides clear directions and examples of the use of the results of ASHRAE Standard 93-77 tests in predicting the performance of solar collectors on any type of building heating and/or cooling job in any location.

The Manual shows methodology for calculating the performance of collector arrays for any location at any time of year, and accounts for the normal losses in piping and storage or the effects of row shading in arrays. The net useful solar input is indicated with greater accuracy than has usually been the case previously.

Methodology is provided for reducing the 8760 hour/year calculations used in many programs with large computers to a 12 day per year method of calculation based on defined typical days, one for each month. The resulting calculations with hand calculators of the programmable type are shown to agree with the calculations made by large computers.

The program structure and listings are given for both the programmable hand calculators and for small interactive computers such as the TRS-80.

Examples of calculations are given by three methods - hand calculation, programmable hand calculators, and interactive computers. The choice of examples is consistent throughout the Manual for ease in comparison.

FUTURE ACTIVITIES

Solar Domestic and Service Hot Water Manual

This manual is intended to stimulate solar utilization by providing system designers and installers with the information required to design solar domestic and service hot water heating systems which are technologically correct and cost effective. These solar systems are the most frequently installed, readily available, and easily understood of today's solar applications. This manual will demonstrate that stand-alone solar domestic and service hot water heating systems, systems that do not provide space heating, are practical today for most parts of this country. Domestic water is primarily for human use, i.e. food preparation, personal hygiene, and washing (clothing, dishes, etc.). ASHRAE plans to publish and sell this manual.

Solar Collector Performance Manual

ASHRAE plans to publish the Manual for use of all classes of solar designers and installers. We believe this is the first broad-based manual to show how the output of ASHRAE Standard 93-77 can be used to provide better and more effective designs for all classes of solar heating and/or cooling applications.

Several other handbooks or manuals are planned for early development, and the Solar Collector Performance Manual will be a useful source on which these new manuals can draw, thus simplifying their individual content.

ASHRAE is considering training sessions at strategic areas in the U.S., or internationally, which will use the Manual as a source document and will result in ever wider acceptance and understanding of solar systems.

CONTRACT INFORMATION

START DATE February 15, 1980 END DATE July 1, 1981 CONTRACT VALUE $82,801

MILESTONES

Item:	Due date:
1. Camera-ready copy of the Solar Domestic and Service Hot Water Manual.	July 1, 1981
2. Camera-ready copy of the Solar Collector Performance Manual.	July 1, 1981
3.	
4.	
5.	

SHAC SYSTEM COST/PERFORMANCE ANALYSIS, MODEL DEVELOPMENT AND VALIDATION, AND TESTING EXPERIENCE VALIDATION

SOLAR ENERGY APPLICATIONS LABORATORY, COLORADO STATE UNIVERSITY

WILLIAM DUFF, SUSUMU KARAKI

EG-77-C-01-4042 (XI-9113-1)

OBJECTIVE

Objectives are to perform validation studies of F-Chart and TRNSYS using CSU Solar House data from present and earlier tested systems, to use the results to guide improvement in systems operation and data collection and to develop documentation of the data base of measured systems performance; to implement initial development of a fast-running modular (TRNSYS-type) simulation for use in studies such as cost/performance analyses and to carry out software/software validation studies of this model with TRNSYS; to use the validated models to make performance predictions for CSU systems in different climatic regions of the country to determine relative cost/performance, to compare the tested systems with conventional systems, to develop cost/performance goals and to determine the most effective way to use the models to identify possible cost reductions and performance increases and for determining the technological requirements to meet those goals; and to provide comprehensive analysis and reporting of the experiences of operating the CSU Solar Houses including significant findings, lessons learned, and problems encountered during all phases of design, installation, instrumentation, data collection and data analysis.

DESCRIPTION OF WORK - GENERAL

Many different configurations for residential SHAC systems are under development and have been installed. Comparative studies should be performed to determine those configurations which can attain the most favorable cost/performance in various regions of the country. It is also desirable to compare SHAC systems with conventional systems to obtain cost/performance goals and to determine the technological improvements needed to approach or meet those goals.

Testing and performance-monitoring of SHAC systems designed for residential use is taking place at a number of installations. Systems performance data obtained from these testing sites should be used in validation studies of SHAC simulations and design codes to indicate needed improvements of the systems and/or the models. In addition, the experience gained during system testing should be communicated to the solar industry so that it can benefit from significant findings, lessons learned, and problems encountered.

CSU has been testing and monitoring the performance of residential SHAC systems for the past seven years. The CSU data base provides long-term high quality performance data from a variety of state-of-the-art system configurations which can be utilized in cost/performance and validation studies. A documentation of the experiences of operating the CSU Solar Houses will provide invaluable information to the solar community.

Work performed during the subcontract period consists of four tasks. These tasks include (1) SHAC systems model validation activities using CSU Solar House data (2) development of a fast-running SHAC detailed simulation, (3) analyses of the cost/performance which the CSU Solar House systems would obtain in different climatic regions of the country and (4) documentation of the testing experience of the CSU Solar House systems.

DESCRIPTION OF WORK - MODEL VALIDATION

Model validation activities are being performed individually for Solar House I and Solar House II. Precise information on the capacitances, flow rates, and so forth, of each system of interest was obtained. A heating data set was obtained and a cooling data set is being built up. Refined validation methodologies were developed. The methodologies differed somewhat for the two houses.

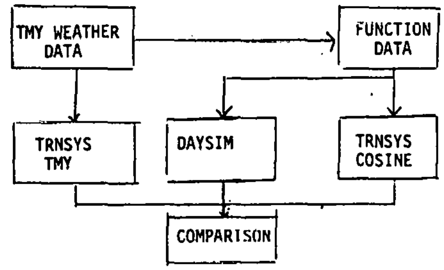
Component TRNSYS models for heating were set up and component TRNSYS models for cooling are being put together. Most TRNSYS heating model components have been validated with the heating data set. The remaining TRNSYS heating models and the cooling models are currently being validated.

TECHNICAL ACCOMPLISHMENTS - MODEL VALIDATION

- o Component TRNSYS models of all SHII heating components have been validated and a SHII load model has been validated.
- o Component TRNSYS models of all SHI heating components have been validated. The SHII validated load model was used in conjunction with these models to accomplish other tasks in this research.

DESCRIPTION OF WORK - FAST RUNNING SIMULATION

An initial heating season version of the fast running simulation model was developed and debugged. The initial version was then tested with a preliminary set of analytic function coefficients and this version refined. A heating data base from three geographic regions was then curve fit to determine coefficients for the analytic function data base required for the model. Software to software validation runs were made with both the new model and TRNSYS as shown below.



TECHNICAL ACCOMPLISHMENTS - FAST RUNNING SIMULATION

- A simulation program for solar heating, cooling and hot water systems using event incremented time-steps has been developed. Event incrementing is made possible through the use of analytic functions for data input. This approach yields a substantially compressed data representation and allows direct analytic solutions for the system of non-linear differential equations over long time-steps. These time-steps do not occur at fixed intervals, but instead are determined by events such as collector pump turn-on time, domestic hot water withdrawal, or a switch from solar to auxiliary usage.

- As can be seen below resulting accuracies of this program are comparable to those obtained from short time-step TRNSYS type programs while computer times are greatly reduced and much of the detail in the performance results is retained. Running time reductions of 20 to 50 times over TRNSYS runs with comparable accuracies have been achieved.

Heating Season Performance Madison, Days 1-90, 274-365

	Incident Solar	Solar Collected	Total Heating Load	Solar to Heating Load	Storage Loss	Solar to DHW	Solar Dumped
TRNSYS, TMY	91.95	47.33	90.36	40.21	2.079	5.577	.2640
TRNSYS, Cosine	95.17	48.86	90.32	41.43	2.123	5.683	.2065
DAYSIM	95.17	49.70	90.19	42.41	2.192	6.277	.2122
1 - TRNSYS,TMY / DAYSIM	.034	.048	-.002	.052	.052	.111	-.244
1 - TRNSYS, Cosine / DAYSIM	0.	.017	.001	.023	.031	.097	.027

All quantities in Gagajoules

DESCRIPTION OF WORK - COST/PERFORMANCE ANALYSIS

Meetings were held with SERI to set up guidelines on how a cost performance analysis was to be conducted and to determine the directions for follow on studies. A study outline was developed which included cities used, load models used, economic assumptions to be made and so forth and this outline was finalized with SERI. This outline was then used as a basis for performing cost/performance analyses for CSU systems.

TECHNICAL ACCOMPLISHMENTS - COST PERFORMANCE ANALYSIS

- Cost/performance sensitivity analyses were run using validated heating season component models from SHI and SHII. The maximum capital cost that the solar energy system could have in order to compete with conventional energy was computed for three different cost/performance measures. Sample results for the sensitivity of one of the parameters, down payment fraction, is given below.

DESCRIPTION OF WORK - TESTING EXPERIENCE DOCUMENTATION

Previous technical SEAL reports were reviewed, all log records for systems tests were reviewed, significant results were itemized and specific problems encountered were listed. Significant lessons learned were then identified. A synopsis of operating experiences and lessons learned was prepared and used to construct a report on testing experiences. The draft report was reviewed by SERI and approved

TECHNICAL ACCOMPLISHMENTS - TESTING EXPERIENCE DOCUMENTATION

- A report documenting SHI, II and III operating experiences has been prepared. The report should be very helpful for designers and manufacturers of solar equipment, installers of solar equipment, those who maintain solar equipment as well as some individual home owners.

FUTURE ACTIVITIES

As a research facility, the Solar Energy Application Laboratory does not have any plans for the marketing or commercialization of products of this research. However, manufacturers and marketers of solar equipment and other researchers can utilize the outputs of this research.

The fast running simulation continues to be used as a planning and analytic tool at the lab and is available to other researchers. A solar assisted heat pump component has been added to the model. Other components will be added as these components are used in SHI, II or III.

The cost/performance computer analysis and graphics routines are available to perform other analyses. Validated TRNSYS models of SHI and II components are available to other researchers.

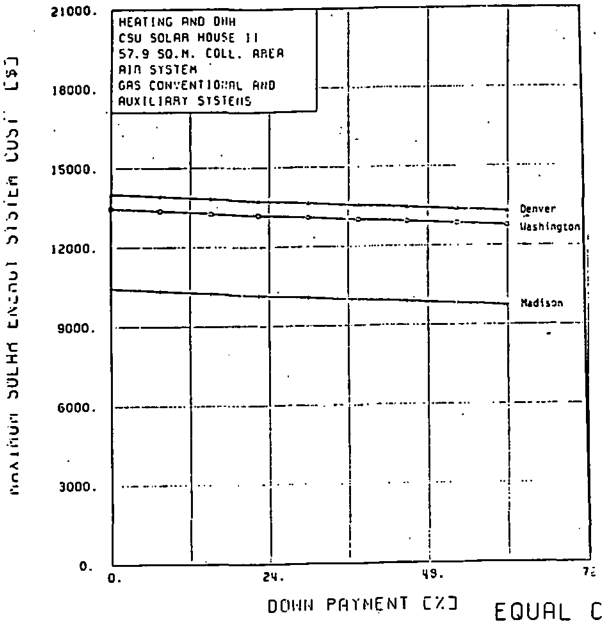
An operating experiences document is available to manufacturers, installers and other interested persons

PUBLICATIONS

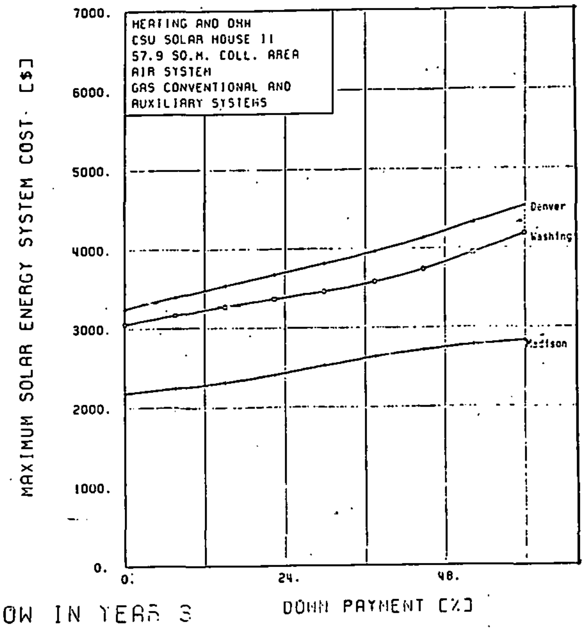
Duff, W.S., G.J. Favard and K.R. Den Braven, "Development of a Day-by-Day Simulation of Solar Systems," Proceedings of the ASME Solar Energy Division's Third Annual Systems Simulation and Economic Analysis/Solar Heating and Cooling Operational Results Conference, Reno, Nevada, April, 1981.

Karaki, S. "Design and Installation Consideratio for SHAC Systems Based on Systems Developed and Evaluated at the Solar Energy Applications Laboratory," January 1981.

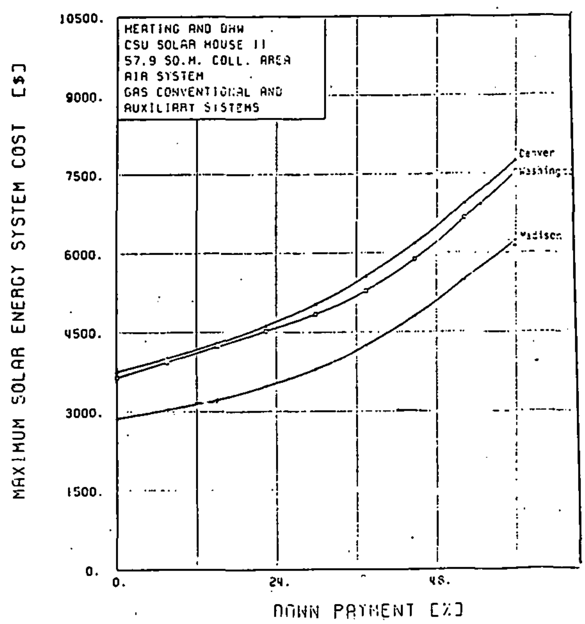
EQUAL LIFE CYCLE COST



8 YEARS PAYBACK PERIOD



EQUAL CASH FLOW IN YEAR 3



CONTRACT INFORMATION

START DATE 1 November 1979 END DATE 31 December 1980 CONTRACT VALUE $50,063

MILESTONES

Item: Deliverables include: Due date:

1. Final reports for the day-by-day simulation
2. Cost/performance analysis
3. Validation activity
4. Operating experiences summation
5.

SOLAR HEATING AND COOLING OF BUILDINGS - SYSTEMS RESEARCH, DEVELOPMENT AND TESTING

SOLAR ENERGY APPLICATIONS LABORATORY, COLORADO STATE UNIVERSITY

SUSUMU KARAKI, GEORGE LÖF, WILLIAM DUFF

DE-AC03-81CS30569

OBJECTIVES

To develop and evaluate solar heating systems of liquid and air types employing flat plate and evacuated tubular solar collectors; to develop and evaluate solar cooling systems using absorption chillers, both liquid and air cooled; to design, install and evaluate heat pump systems in a solar assisted mode using air-to-air and water-to-air configurations; to support the Department of Energy as Operating Agents in Task VI of the IEA Solar Heating and Cooling Program; to analyze operational data obtained from long-term, continuous monitoring of systems.

DESCRIPTION OF WORK

Four solar heating and cooling systems are operational in three solar houses at Colorado State University. Two liquid systems are in Solar House I, an air system is in Solar House II, and another liquid system in Solar House III. One of the liquid systems in Solar House I utilizes evacuated tubular collectors, and the other is supplied with heat from a commercial flat plate collector. The system in House II employs a flat plate collector of the air type and House III has been heated and cooled by energy from another commercial liquid collector. An evacuated tube collector of a different type is planned for use in House III during 1981. These systems are being used to test, develop and analyze the performance of various solar heating and cooling configurations, using absorption chillers, solar assisted heat pumps, stratified storage and optimal control strategies as appropriate.

SOLAR HOUSE I

DESCRIPTION OF WORK

The projects in Solar House I involve the Philips Mark I heat-pipe evacuated tube collectors, optimally controlled off-peak auxiliary system, the third generation Arkla chiller, stratified liquid storage, and a Northrup solar assisted heat pump. From continuous data collection, computer models are being developed so observed performance can be extrapolated to other conditions.

The Arkla chiller unit combines in one package the chiller with the cooling tower to substantially reduce electric power required to operate fans and pumps, making a more compact unit and one perhaps more acceptable to consumers. Testing of the cooling system will begin in June, 1981, using the Philips collectors and a pressurized water storage tank outside the conditioned space. Until then, the collectors are being used in a closed-loop anti-freeze mode with the prefabricated Bally storage tank, incorporating stratification devices, and an off-peak auxiliary heating system employing a programmable observer-predictor controller. Data are being used to validate TRNSYS and day-by-day simulation models for performance prediction in other geographical regions. A domestic hot water system is included in both the heating and cooling system. A Northrup water-to-air solar assisted heat pump will be installed for the 1981-82 heating season, and a simulation model will be developed and validated using the performance data collected. The heat pump will provide auxiliary space heating when the storage temperature is too low.

TECHNICAL ACCOMPLISHMENTS

- The data aquisition system in Solar House I has reliably provided high quality data with good continuity. A real time diagnostic program has been implemented on the mini computer in the data system thus providing the capability to quickly detect instrument failures and other system problems. Redundant instrumentation for measurement of all important quantities has also contributed to increased reliability. The quality and continuity of data taken in Solar House I has increased substantially over previous years. The continuous acquisition of high quality data over periods of one month and longer is necessary for the validation of computer models.

- Computer models of recent systems in Solar House I are being developed and compared to observed performance. When the models have been refined to the point that computer prediction compares well with measured performance ("validated"), the models are used to produce seasonal performance data from shorter data sets, to compare performance with other systems and in other climates, and to aid in the design of future systems. The program, TRNSYS, has been validated in this way for several systems. A new program, DAYSIM, has been developed and validated as a part of this task and promises to greatly reduce computer costs of simulation while maintaining accuracy comparable to TRNSYS.

- A micro processor based optimal controller has been installed and tested as part of the off-peak auxiliary system. The ambient temperature observer-predictor (ATOP) algorithm has been implemented in order to predict energy needs for future periods. The ATOP algorithm has been found to be inferior to the previous very simple control for off-peak charging. More sophisticated control strategies are being investigated to determine under what circumstances the micro processor based system might be justified.

- The Philips Mark I heat pipe evacuated tubular collector was installed in July 1980 and has operated reliably with both water and ethylene-glycol/water solution as circulating fluids. Since the circulating fluid flows only through the headers (heat is transferred from the absorber plate to the header by the heat pipe) the pressure drop for this collector is low and energy required to run a collector pump is only about one percent of total energy collected. The performance of this collector is comparable to the Corning evacuated tubular collector previously tested here.

- The storage tank to be used in the system for the summer of 1981 is a steel pressure vessel with six inches of sprayed on urethane foam insulation and is located outside the conditioned space. The installation of this tank treats several problems that have been observed in the two prior cooling seasons during which the Bally modular sectional storage container was used. The maximum allowable temperature of the Bally tank has been 92°C, near the boiling point of water in Fort Collins (94.5°C). With the increased pressure which should occur in the new tank at high temperatures, the boiling point should increase, permitting a higher maximum storage temperature. Since the minimum operating temperature of the Arkla chiller is estimated to be 80°C, any increase in the maximum storage temperature can significantly increase the storage capacity of the system. Another limiting factor in the Bally tank has been concern about possible damage to the waterproof liner at high temperatures.

An additional disadvantage of the Bally tank at high temperatures is that all penetrations are through the top. Suction is required to draw water from the tank through the top cover, and when that water is near the boiling point the reduced pressure in the pipe resulting from this suction can be enough to allow the water to flash into steam within the pipe. Penetrations are through the side of the new tank, so the supply to the pump is always under some pressure.

- The Arkla "third generation" absorption chiller was installed during August of 1980. During September 1980 this machine was closely monitored and some performance deficiencies were observed. Based on the data collected in 1980, engineers at Arkla have recommended modifications to correct these problems in the 1981 cooling season.

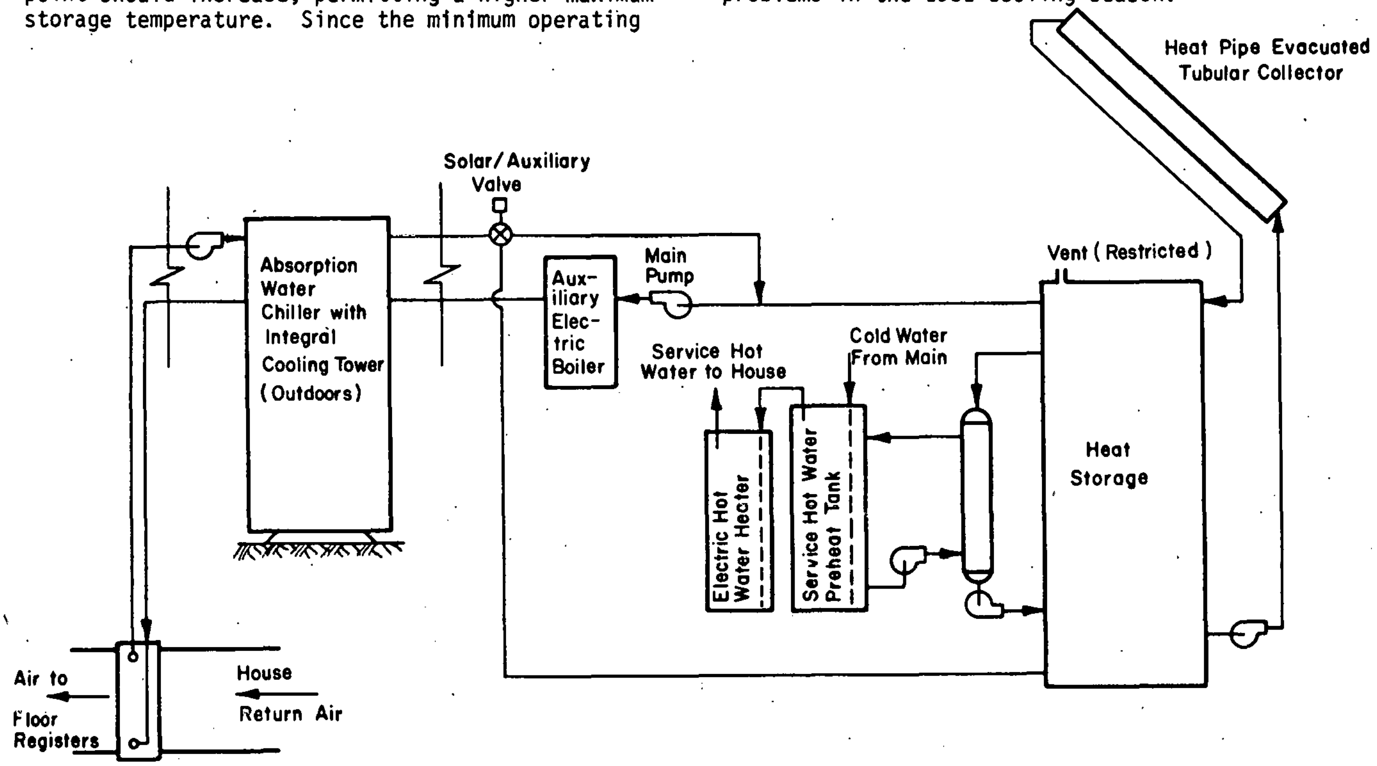


Figure 1. Solar House I Heating and Cooling System With Evacuated Tube Collectors

See Figure 4, third page, for a chart of COP of the Northrup heat pump.

SOLAR HOUSE II

DESCRIPTION OF WORK

The air system in Solar House II has been adapted for the solar assisted air-to-air heat pump operation, utilizing rock storage to deliver warm air to the evaporator coil when the storage temperature is too low for direct space heating. The evaporator coil is especially designed for this use with a larger accurator (expansion valve) than would normally be used. A variable speed blower has been installed for optimum heat exchange at the evaporator coil while avoiding the possibility of over-pressuring the system at the warmer temperature. Data will be analyzed especially with regard to temperature profiles within the rock storage and the recovery of storage temperature.

TECHNICAL ACCOMPLISHMENTS

- The cold charged storage was insufficient to carry the house cooling load through the "peak" power period during hot days, days in the mid 90's or above, despite the increase in storage volume over the previous years data for cold charging.

The limiting factor became the heat pump capacity over the defined off peak period.

• The ratio of peak power rate to off peak power rate did decrease slightly with the larger rock volume as did the overall COP of the heat pump during the cold charge. With the previous rock storage the break even ratio for power rates was 1.71 and it has now gone down slightly to 1.65 with the newer and larger storage box.

• The use of a selectable speed blower and "smart" controller in the solar storage strategy results in an improvement in performance over the single speed blower and control strategy. A complete seasonal simulation based on the data obtained shows a 55% solar fraction with the 4 speed blower used, against 47% for the single speed blower.

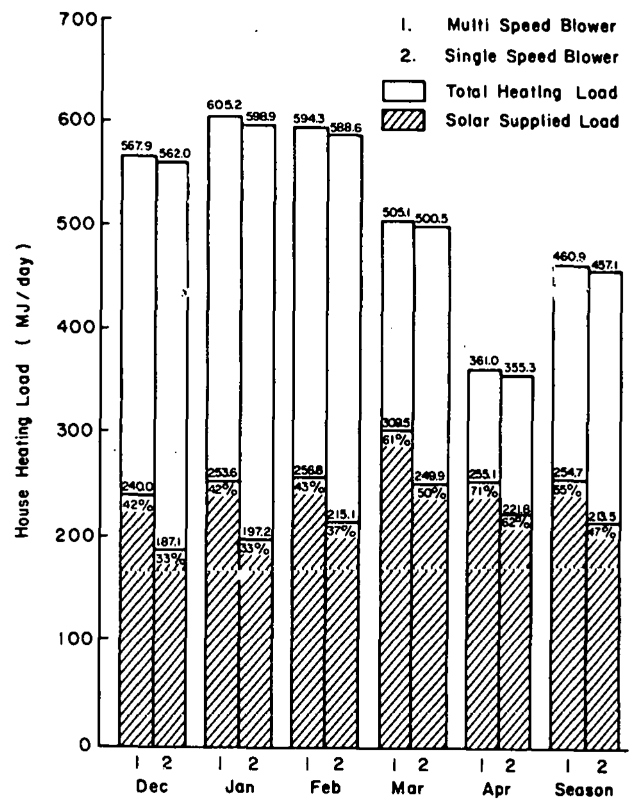


Figure 2. Comparison of Multi-Speed and Single-Speed Blowers, by Simulation - Solar House III

• With the solar assisted air to air heat pump system in operation, COP for the heat pump was improved ranging from a high of 2.6 to a low of 2.0. The COP is very sensitive to correct refrigerant charge and "accurator" (expansion value) sizing at the evaporator coil and considerable time has been spent attempting to set up the system.

• The solar assisted air to air heat pump results in unusual stratification temperature zones in rock storage. Alternating between storing heat and then, in effect cold charging, has produced thermoclines in storage that may cause control strategy problems. The net result on overall performance is not known nor is it known yet how well storage will rebound from a depressed temperature resulting from heat pump use.

See Figure 3 for a plot of the COP of the solar assisted air-to-air heat pump against a change in evaporator orifice size.

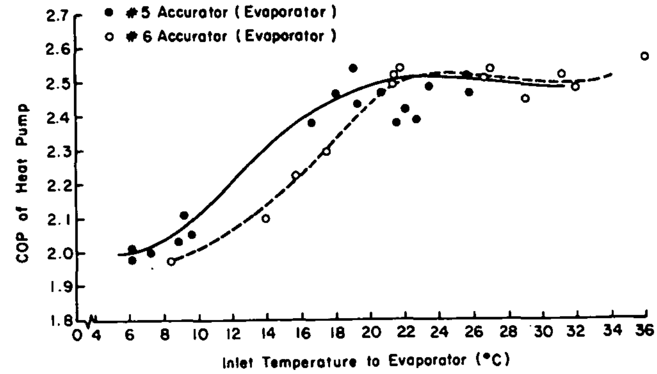


Figure 3. COP of Solar Assisted Air-to-Air Heat Pump With Change in Accurator Size

SOLAR HOUSE III

DESCRIPTION OF WORK

Evacuated tube collectors will be installed on Solar House III this summer in preparation for the installation of the Carrier air-cooled absorption chiller. Evacuated tube collectors are necessary to provide the 110°C firing temperature of the chiller. The chiller is not expected to be delivered before August, 1981. Detailed computer simulation studies are being conducted to determine the optimum design of the system. This will be the first installation of the new Carrier chiller in an operating solar system, and studies will be made of installation design characteristics.

TECHNICAL ACCOMPLISHMENTS

• Activity on this project will not begin until June, 1981.

INTERNATIONAL ENERGY AGENCY

DESCRIPTION OF WORK

The cooperative efforts of participants in the IEA Task VI project should result in more effective international communication and understanding of the performance of evacuated tube collectors in solar heating, cooling and hot water systems. Participants in the Netherlands, Japan, the U.S., West Germany, Switzerland, Sweden, Canada and the United Kingdom study, document and compare the performance characteristics of such collectors in different systems and climates. The leadership of the Solar Energy Applications Laboratory is directed toward a required commonality in data collection and reporting, data from a comprehensive variety of installation types, collectors and other components, acceptance of some similarities in installation types and collectors and interaction with other IEA tasks. As a result, each participant will have as easy access to and gain as much information from each of the Task VI installations as if all installations were part of his national program. Performance comparisons will be made and reported which would be difficult or impractical with separate non-coordinated projects.

Each participant in this task is responsible for the operation and analysis of at least one evacuated collector solar heating and/or cooli system. Tables I and II show the Task VI participants and their installations and the evacuated collectors used in each installation.

Table 1.
IEA Task VI Participants and Their Installations.

PARTICIPANTS	
Netherlands	Solar House of the Eindhoven University of Technology Single Family Residence - Heating and DHW
Japan	Sanyo Osaka Solar House Single Family Residence - Heating, Cooling and DHW
U.S.	Colorado State University Solar House I Single Family Residence - Heating, Cooling and DHW
West Germany	Solarhaus Freiburg Twelve Unit Apartment - Heating and DHW
Switzerland	Geneva SOLARCAD District Heating System Project District Heating
Sweden	The Knivsta District Heating Project District Heating
Canada	Mountain Spring Bottle Washing Facilities Solar Project Industrial Process Heat - Bottle Washing
United Kingdom	Solar Test Installation at Bracknell, England Collection System with Simulator for DHW Load

Table 2.
IEA Task VI Member Countries and Evacuated Collectors Used or Planned

	Japan	USA	West Germany	Netherlands	Canada	Switzerland	Sweden	United Kingdom
Corning		X	X			2		
Philips MKIV		X	X					
Philips MKI		X	2	X			X	X
Sanyo	X					X		
General Electric	X						X	
Owens-Illinois		X			1	2	X	
Swiss Evacuated Flat Plate						2		

1. Solartech Version 2. Under Consideration

TECHNICAL ACCOMPLISHMENTS

- Three Task VI meetings have been held on:
  October 3-5, 1979 in Fort Collins, Colorado, USA
  April 22-24, 1980 in Stuttgart and Freiburg, West Germany
  December 2-5, 1980 in Kobe and Osaka, Japan

- A small working group meeting on Task VI internal reporting structure was held on September 28-October 2, 1980 in Pingree Park, Colorado, USA. The next Task VI meeting is scheduled for August 17-19, 1981 in London, England.

FUTURE ACTIVITIES
OF THE SOLAR ENERGY APPLICATIONS LABORATORY

As a research facility, the Solar Energy Applications Laboratory does not have any plans for the marketing or commercialization of the equipment or systems involved in this project. Equipment manufacturers may make marketing or development plans based on the data collection and analysis from these systems.

The established functioning solar heating and cooling systems of the three solar houses provide an opportunity for ongoing research into all configurations of system design. Opportunities are especially abundant for the study of controller design and validation of computer simulations. Future activities are planned to include research in these areas, as well as equipment operation and system design not yet determined.

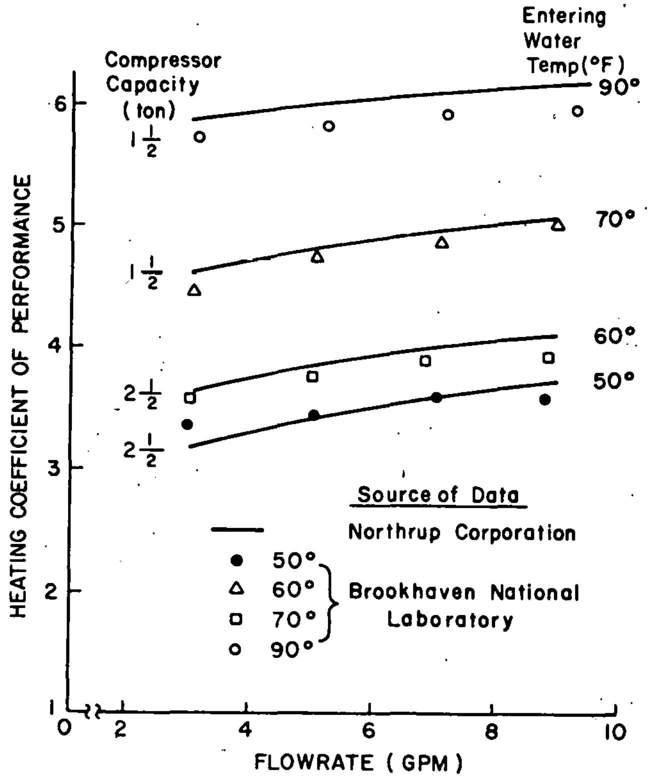


Figure 4. Northrup Heat Pump Coefficient of Performance

PUBLICATIONS

1. Löf, G.O.G., Duff, W.S. and Hancock, C.E. (1981), "Development and Improvement of Liquid Systems for Solar Space Heating and Cooling - CSU Solar House I", Presented at the 1981 Operational Results Conference, SSEA.

2. Weaver, N.L. and Duff, W.S. (1981), "Implementation of an Ambient Temperature Observer-Predictor (ATOP)", Presented at the 1981 Operational Results Conference, SSEA.

3. Duff, W.S., Favard, G.J. and DenBraven, K.R. (1981) "Development of a Day-by-Day Simulation of Solar Systems", Presented at the 1981 Operational Results Conference, SSEA.

4. Millard, R.A. and Duff, W.S. (1980) "Procedures for On-Line Detection of Sensor and Operating Faults in Solar Energy Systems", Presented at the AS/ISES Meeting.

5. Karaki, S. and G.O.G. Löf (1980), "Solar Heating and Cooling of Residential Buildings - Design of Systems", Revised and re-edited manual prepared for the U.S. Department of Commerce,

Economic Development Administration, September.

6. Karaki, S. and G.O.G. Löf (1980), "Solar Heating and Cooling of Residential Buildings - Sizing, Installation, and Operation of Systems", Revised and re-edited manual prepared for the U.S. Department of Commerce, Economic Development Administration, September.

7. Karaki, S. and P. Brothers (1980), "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings", Final Report prepared for the U.S. Department of Energy, Report No. COO-2867-8, June.

8. Karaki, S. and G.O.G. Löf (1980), "Solar Air-Heating Systems Installation, Operation and Service", Training Manual prepared for the Solar Training Institute, Sheet Metal and Air Conditioning Contractor's National Association, September.

9. Baer, C.A., Pryor, D.V., Winn, C.B., and Lantz, L. (1980) "Enhancement of Performance of Active Solar Systems by Optimal Control and System Identification Techniques," San Diego, SSEA.

10. Duff, W.S. (1981), "Annual Progress Report", IEA Task VI, January.

CONTRACT INFORMATION

START DATE 1 February 1981 END DATE 31 Jan. 1982 CONTRACT VALUE $580,000

MILESTONES

Item:	Due date:
1. Monthly Reports	15th
2. Final Report for each Task	28 Feb. 1982
3. System Development Proposal Plan for 1981-83	31 Jan. 1982
4.	
5.	

SYSTEMS SIMULATION AND ECONOMIC ANALYSIS FOR ACTIVE SOLAR COOLING*

LAWRENCE BERKELEY LABORATORY

UNIVERSITY OF CALIFORNIA

Mashuri Warren, Michael Wahlig

Contract No. W-7405-ENG-48

OBJECTIVES

The LBL system simulation and economic analysis program has four principal objectives:

- To perform economic analysis to establish cost/performance goals for active solar cooling/heating systems.
- To review and to perform analysis using TRNSYS and other simulation codes for evaluation of active solar space cooling and heating systems.
- To provide a library for chiller, storage, and other component models developed for TRNSYS for solar cooling applications.
- To provide limited technical support as part of the Department of Energy solar cooling and heating R & D program. Program support tasks include program planning, preparation and evaluation of solicitations, proposal review, and technical monitoring of system simulation and economic analysis contracts.

DESCRIPTION OF WORK

The attainment of reasonable market penetration of active solar cooling systems, beginning with introduction of commercial units in the late 1980's and continuing through the 1990's, can be related to meeting certain cost goals for these systems. A principal objective of the work at LBL has been to develop a methodology to establish realistic cost goals for active solar cooling/heating systems, and to establish preliminary cost goals for representative solar air conditioning systems.

In general, air conditioning demands are expected to grow significantly over the next 20 years, driven by population shifts to the "sun belt" regions of the country. It is estimated that over 90% of the new construction in this region will have central air conditioning. Energy conservation and passive cooling measures are expected to reduce significantly the sensible cooling and heating loads. However, the substantial latent (i.e., humidity) cooling loads in all buildings and internal heat gains in commercial buildings will remain and will require the use of mechanical cooling systems.

Economic Performance Goals. Certain cost and economic performance goals must be achieved by the solar industry before market demand will rise to a level that will produce the desired market penetration. Marketing studies[1] indicate that for heating and air conditioning products the relationship between market penetration and payback period is as shown in Figure 1. The payback period, the number of years for the undiscounted fuel cost savings to equal the incremental cost to produce those savings, is related to a real return on investment. Postulating market penetration goals per year necessary to achieve 20% annual penetration by the year 2000, the corresponding payback and return on investment goals as a function of year of purchase have been calculated and are shown in Figure 2.

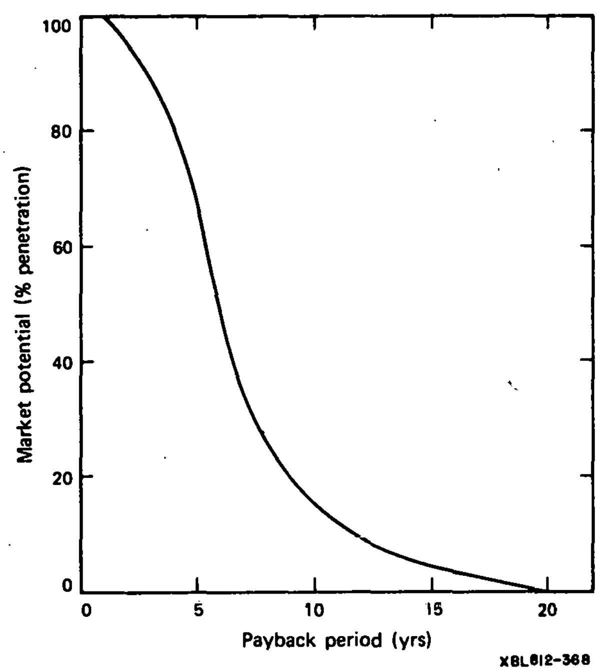


Figure 1. Market potential as a function of payback period.

Thermal Performance Analysis. Annual system simulations of the thermal performance of active solar Rankine and absorption cooling/heating systems have

*This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

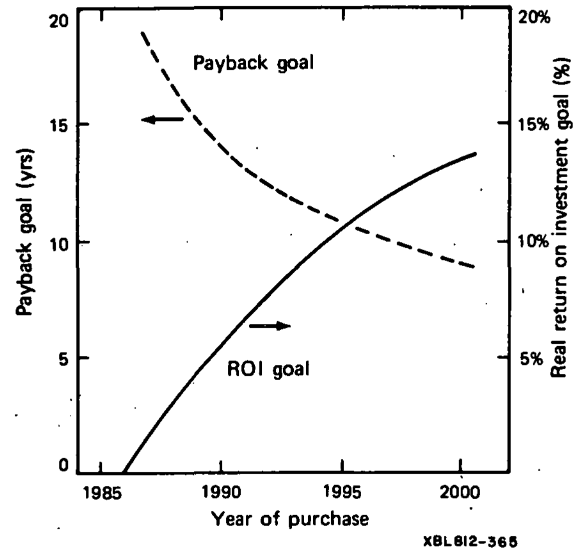


Figure 2. Payback goal and real return on investment (ROI) goal as a function of year of purchase to reach a 20% market penetration in the year 2000.

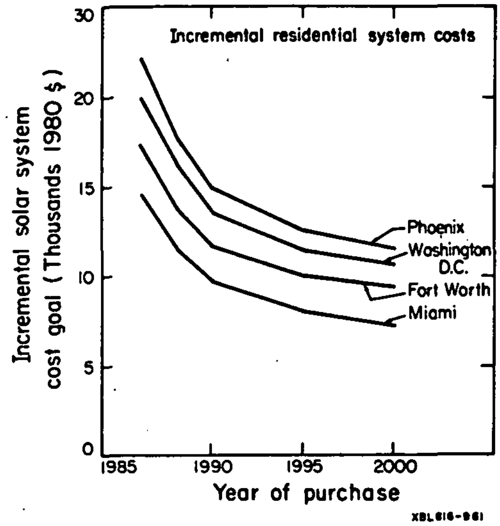


Figure 3. Incremental solar system cost goals (1980$) as a function of year of purchase for a 3 ton residential cooling/heating system without tax credits assuming a 20% market penetration by the year 2000.

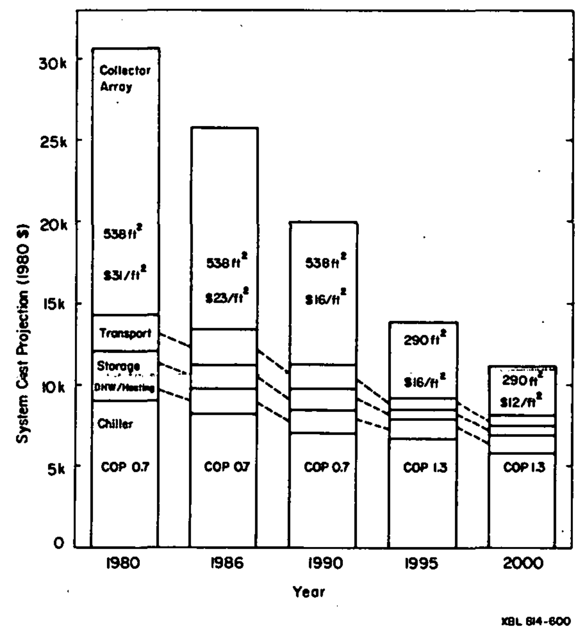


Figure 4. Preliminary solar system cost projections for a 3 ton residential absorption cooling, heating, and hot water system, showing breakdown into subsystem costs.

been conducted by SAI using TRNSYS.[2,3] These calculations have been carried out for residential solar cooling/heating systems in four cities (Fort Worth, Phoenix, Miami, and Washington, D.C.) and for commercial solar cooling-only systems in three cities (Fort Worth, Phoenix, and Miami) which are representative of the cooling market. Three types of systems were evaluated: residential 3 ton absorption (ARKLA), commercial 25 ton absorption (ARKLA), and commercial 25 ton Rankine (AiResearch).

Incremental Solar System Cost Goals. It is assumed that a solar cooling or cooling/heating system is cost-effective when the incremental solar system cost is equal to (or less than) the present value of the energy savings. The present value over the life of the system (20 years) of the fuel saved by an active solar system has been calculated and is a function of the fuel escalation rates and the expected real return on investment. Details of the analysis are presented elsewhere. [4,5].

Combining these calculations of the incremental solar system cost as a function of real return on investment with the real return on investment goals as a function of year (as contained in Figure 2), incremental system cost goals as a function of year have been generated for residential solar cooling/heating systems and are displayed Figure 3. Similar analysis has been performed for commercial solar cooling systems.

Subsystem Costs. The total solar cooling system cost goals for different locations can, in turn, be subdivided into subsystem cost and performance goals. It is anticipated that the major reductions in subsystem costs will be achieved by technical improvements in subsystem performance (e.g., increased chiller efficiency resulting in reduced collector subsystem array size), by volume production economies, and by improved packaging that will reduce system engineering and installation costs. Preliminary subsystem cost estimates for a residential system are shown in Figure 4. These values are based on estimates of current subsystem costs plus expectations for subsystem cost and performance improvements. Similar analyses have been done for commercial absorption and Rankine systems.

Collector Array Costs. The collector array is one of the major cost items of any active solar cooling system. The key to cost effective cooling systems is reducing the collector array costs. For residential systems with less that about 50 m^2 (500 ft^2) of collector, the collectors are mounted directly on the roof, and no support structure is usually needed. For commercial systems a support structure is needed.

For the high temperature, high COP future scenario, either evacuated tubes with reflectors or cylindrical trough collectors will likely be used. Collector manufacturing costs of $14/$ft^2$ have been projected[6] for evacuated tube concentrating collectors. A key to low cost collectors is the use of light weight and inexpensive materials. The Low

Cost Collector Program has recently projected[7] the manufacturing cost of a linear trough collector with a light-weight reflector and iron pipe absorber at $6-8/ft^2.

It may be possible to achieve system and subsystem cost goals using current chiller technology, with a COP of 0.7 and operating temperatures below 200^{o}F, if very low cost, (about $6/ft^2) good performance collectors can be developed. "Good performance" in this context means an efficiency of about 40% to 50% at a typical absorption chiller driving temperature of about 185^{o}F. Work underway at Brookhaven National Laboratory[8] is directed toward the development of solar collectors that may meet these cost and performance requirements. A recent evaluation of the potential for cost reduction indicates that with automation and a production volume of greater than 200,000 panels per year in a single facility, the cost of evacuated tube collectors can be reduced to $6.50/ft^2.[9]

Summary

A consistent methodology has been developed by which general solar cooling market capture goals have been translated into specific cost and performance goals for solar cooling systems and subsystems. Preliminary results indicate that realistic cost/performance goals can be established for active solar cooling systems and that, with aggressive development, these goals can be reached by the year 2000. As the technology develops, tax incentives will be required to bridge the gap between the actual costs and the cost goals, so that the scenario of an ever increasing share of market penetration can be maintained over the 1986 to 2000 time period.

It must be emphasized that the actual numbers used so far -- although the best numbers available at this time -- are nonetheless still preliminary. Efforts are currently underway to acquire better estimates of the market penetration vs. payback relationship, better estimates of cost and performance projections, and more realistic systems analysis models of the thermal performance of the cooling systems.

Finally, this methodology for establishing cost goals and developing cost and performance improvement pathways to reach those goals is not limited to active solar cooling applications. It could equally well be used for other technologies such as passive cooling and heating.

TECHNICAL ACCOMPLISHMENTS

- Developed preliminary cost/ performance goals for active solar cooling/heating systems.
- Produced a background report describing methodology for developing cost/performance goals.
- Worked with other contractors performing systems analysis work to characterize realistic buildings and active solar cooling systems for simulation.

FUTURE ACTIVITIES

Continue to work with other systems analysis contractors in developing realistic models of active solar cooling systems.

Continue to develop inhouse capabilities for systems simulation and economic analysis for active solar cooling.

Develop a library of chiller, storage, and other component models developed for TRNSYS for solar cooling applications.

Refine the calculation of cost goals and cost projections for active solar cooling systems, using better estimates of market penetration curves and better estimates of subsystem cost and performance improvements.

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[3] P. J. Hughes, et. al., "Evaluation of Thermal Storage Concepts for Solar Cooling Applications", Science Applications, Inc., Final Report, January 1981.

[4] Mashuri L. Warren and Michael Wahlig, "Methodology to Determine Cost and Performance Goals for Active Solar Cooling Systems," To be presented at the ASME Winter Meeting, 15-20 November 1981, Washington, DC. LBL-12343, July 1981.

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CONTRACT INFORMATION

Period of Contract: Begin 10-80 . End continuing .
Funding FY81: $100k.
Total of contract: $100k.

ANALYSIS OF SOLAR ABSORPTION AND RANKINE COOLING SYSTEMS

SCIENCE APPLICATIONS, INCORPORATED

JEFFREY MOREHOUSE

SERI-XB-0-9145-1

OBJECTIVE

To analyze the performance and economics of state-of-the-art absorption and Rankine systems on a comparative basis with conventional systems.

DESCRIPTION OF WORK

SAI has previously done a preliminary analysis comparing absorption and Rankine systems. This study is an extension that will analyze residential and commercial sizes of both technologies, on a performance and cost basis, against competing conventional systems in order to both assess their status and help formulate program goals. As part of this task, updated cooling systems simulation models will be developed and baseline thermodynamic studies will be performed.

TECHNICAL ACCOMPLISHMENTS

- TRNSYS - compatible models were developed for a wet cooling tower, CALMAC latent storage tank, ARKLA 25 ton absorption chiller, Honeywell 195°F design point 25 ton Rankine chiller, and Honeywell 300°F design point 25 ton Rankine chiller.
- Development of a methodology capable of evaluating developmental residential and commercial solar powered chillers for the purpose of determining the cost/performance status with respect to stated goals of the systems incorporating them.
- Evaluation of systems designed around three 25 ton developmental chillers: the ARKLA absorption, the Honeywell 195°F design point Rankine, and the Honeywell 300°F design point Rankine.

FUTURE ACTIVITIES

- Evaluations of systems designed around other solar powered chillers under development by the active solar cooling program will continue.

PUBLICATIONS/REPORTS/REFERENCES

- Methodology and Configurations for the Analysis of Solar Absorption and Rankine Cooling Systems, Science Applications, Inc., Task 5 Report (April 1981).
- Component Model Documentation, Science Applications, Inc., Task 3 Report (April 1981).

CONTRACT INFORMATION

START DATE 10/80 END DATE 7/81 CONTRACT VALUE $242,000

MILESTONES

Item:		Due date:
1.	Task 3 Report	April 1981
2.	Task 5 Report	April 1981
3.	Industry Briefing Report	July 1981
4.	Final Report	July 1981
5.		

ANALYSIS OF STORAGE SUBSYSTEMS FOR SOLAR COOLING SYSTEMS

SCIENCE APPLICATIONS, INCORPORATED

JEFFREY MOREHOUSE

SERI-XI-0-9083-1

OBJECTIVE

To analyze storage for solar cooling applications and perform various trade-off studies.

DESCRIPTION OF WORK

The tradeoffs of performance and cost between hot-side and cold-side storage and between sensible and phase-change storage and between single and multiple stage storage were examined. This was done by establishing baseline systems (absorption and Rankine) for residential and commercial applications, modeling these systems, and performing comparative analyses of the various storage configurations within these systems. These analysis were made for the following four locations: Miami, Phoenix, Fort Worth and Washington, D.C.

TECHNICAL ACCOMPLISHMENTS

The following conclusions were drawn from this study:

- The solar systems investigated have considerable energy savings potential, as high as 72% on a primary energy basis, depending on location, storage option and system type.
- Solar cooling systems are most cost effective in Phoenix, followed by Miami, Fort Worth and Washington, D.C.
- The choice of storage option for an absorption cooling system is important since system thermal performance can vary by up to 15% and the life-cycle cost can differ by 20% between the various storage types.
- It is difficult to draw strong conclusions concerning Rankine machines and storage options simply because the variations shown for the modeled machine are slight.
- Vapor compression cooling machines are tough competition presently for solar cooling, and future conventional chillers will be even more competitive. Development of Rankine chillers will aid the development of improved vapor compression machines, thus negating much of the Rankine improvement.
- Of all of the storage options investigated, cold-side latent storage appears most promising.
- Multiple tank sensible storage can be eliminated from further programmatic consideration.
- Because of the dominant role of parasitic power requirements, solar Rankine systems should be designed to generate electricity when possible to drive their own parasitics, provide sell-back to utilities, and/or meet other onsite electrical needs. A technology of this type could operate using industrial waste heat as well as solar energy, and thus have more diverse market opportunities.

FUTURE ACTIVITIES

The following recommendatons are offered for future modeling activities:

1. Develop an improved model for phase change storage
2. Simulate system performance for various types of collectors and control schemes
3. Develop models for other chillers and simulate performance of systems containing these chillers.
4. Perform further systems modeling using building temperature level control simulation, and develop the models necessary to do so. This will provide information concerning the system/storage interaction with the building load.

PUBLICATION/REPORTS/REFERENCES

1. "Evaluation of Thermal Storage Concepts for Solar Cooling Applications,", Draft Final Report, Science Applications, Inc., McLean, VA, January 1981.
2. "Thermal and Economic Assessment of Solar Cooling Systems for Small Commercial Buildings", paper presented at ASME SSEA meeting, Reno, Nevada, May 1, 1981.

CONTRACT INFORMATION

Period of Contract: Start, 04/80; end, 03/81
Funding, FY 81: $202,000
Milestones: Final Report, June 1981.

BEPS TECHNICAL SUPPORT

SCIENCE APPLICATIONS, INCORPORATED

PATRICK HUGHES

SERI-XP-9-8292-1

OBJECTIVE

To provide ongoing support to DOE and the Solar Energy Research Institute in the solar analysis effort's contribution to the final rule for the Building Energy Performance Standards (BEPS) program.

DESCRIPTION OF WORK

This work consisted of technical and management support, integration of BEPS activities, and development of design tools for BEPS. Specific activities included:

- o Development of an Alternate Evaluation Technique (AET) approval process;
- o Comparison analysis of Typical Reference Year (TRY), Typical Meteorological Year (TMY), and Typcial Weather Year for Energy Calculations (WYEC) data to determine their effects on the BEPS rule and the impact of using solar energy to meet BEPS;
- o Continued testing of DOE-2.1 Component Based Simulator (CBS); and,
- o Development of a Manual of Recommended Practice (MORP) to lend guidance as to combining passive and active solar designs with appropriate conservation measures to meet the standards.

TECHNICAL ACCOMPLISHMENTS

- o Developed TRY Weather Data Interface for DEROB
- o Developed Modified DEROB Computer Code for BEPS
- o Modified the DOE-2.1 Weather Packer to Read TMY Weather Data
- o Supported testing of Component Based Simulator for DOE-2.1.
- o Developed a Draft Alternate Evaluation Technique Approval Process
- o Developed Two Calculation Methodologies for a Manual of Recommended Practice

FUTURE ACTIVITIES

No further activities are anticipated at this time.

PUBLICATIONS/REPORTS/REFERENCES

1. Standard Evaluation Technique technical support document to the BEPS Notice of Proposed Rulemaking, November 1979.
2. BEPS Addendum to the TRNSYS Manual, November 1979.
3. BEPS Addendum to the DEROB Manuals, November 1979.
4. Draft Alternate Evaluation Technique Approval Process, August 1980.
5. Draft Manual of Recommended Practice, August 1980.
6. Status Report on the Recommended Comparison of TRY, TMY and WYEC Weather Data Sets, August 1980.
7. A Review of the Building Regulatory Process and its Supporting Documents, August 1980.
8. "The Use of Energy Analysis for Performance Path Compliance to Building Energy Performance Standards", paper presented at Third World Energy Engineering Conference Atlanta, Georgia, October, 1980 .

CONTRACT INFORMATION

START DATE 06/79 END DATE 09/80 CONTRACT VALUE $492,000.

MILESTONES

Item:	Due date:
1. Standard Evalution Technique Technical Support Document	November 1979
2. BEPS Addendum to TRNSYS Manual	November 1979
3. BEPS Addendum to DEROB Manuals	November 1979
4. Report on Testing of the Component Based Simulator	March 1980
5.	

GENERAL SUPPORT TO SERI IN SYSTEMS ANALYSIS

SCIENCE APPLICATIONS, INCORPORATED

JEFFREY MOREHOUSE

SERI-XI-8283-1

OBJECTIVE

To provide technical support to the Solar Energy Research Institute (SERI) for the Systems Analysis and Testing Program.

DESCRIPTION OF WORK

Primary work was related to the preparation of material for the SERI Standard Assumptions and Methods manual. This contract also included general technical support to SERI to attend planning meetings, System Simulation and Economic Analysis (SS/EA) working group meetings, and technical conferences.

TECHNICAL ACCOMPLISHMENTS

- o Completion and revision of reports on comparative analysis tasks;
- o Development of standard commercial building cooling load tapes; and,
- o Provision of information to SERI in support of a Standard Assumptions Manual.

FUTURE ACTIVITIES

Follow-on activities have occurred under separate contracts that are reported on separately in this publication.

PUBLICATIONS/REPORTS/REFERENCES

1. Evaluation of the "Typical Meteorological Years" for Solar Heating and Cooling Systems Studies. SAI Final Report, August, 1979.
2. A TRNSYS Compatible, Standardized Load Model for Residential System Studies, SAI Final Report, October, 1979.
3. Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses, SERI/TR-351-402, January, 1980.

CONTRACT INFORMATION

START DATE 04/79 END DATE 04/80 CONTRACT VALUE $140,000.

MILESTONES

Item:		Due date:
1.	Typical Meteorological Year Report Revision	September 1979
2.	Revised Heat Pump Report	October 1979
3.	Revised Cooling Report	October 1979
4.	Cooling Load Tape	October 1979
5.	Report on Standard Load Model	January 1980

SYSTEMS ANALYSIS OF SOLAR ASSISTED HEAT PUMP GROUND-COUPLED STORAGE AND DUAL SOURCE STRATEGIES

SCIENCE APPLICATIONS, INCORPORATED

JEFFREY MOREHOUSE

SERI-XP-8288-1

OBJECTIVE

To evaluate the performance and economic advantages to solar assisted heat pumps (SAHP) of ground-coupled storage and dual-source strategies.

DESCRIPTION OF WORK

The study performed an analysis of ground--coupled stand-alone and series configured solar-assisted liquid-to-air heat pump systems for residences. The year-round thermal performance of these systems for space heating, space cooling, and water heating was determined by simulation and was compared against the performance of non-ground-coupled solar heat pump systems as well as conventional heating and cooling systems in three geographic locations: Washington, D.C., Fort Worth, Texas, and Madison, Wisconsin. Sensitivity analyses were performed on egineering and economic parameters that influence the cost-effectiveness of the systems.

TECHNICAL ACCOMPLISHMENTS

The following conclusions were drawn from the results of the study.

- o Without tax credits a combined solar/ground-coupled heat pump system for space heating and cooling is not cost competitive with conventional systems. The sensitivity analyses did not identify any parameter variations that would render the combined solar/ ground-coupled heat pump system cost competitive with conventional systems.
- o For ground coupled systems, better performance is obtained with buried tanks than with buried pipes.

FUTURE ACTIVITIES

The following recommendations were made for future ground-coupled heat pump development activities:

1. Buried tanks should be given higher program priority than buried pipes. An attempt should be made to relate optimum buried tank storage size to tank geometry and climate.
2. The soil properties of each location should be experimentally measured.
3. Other storage configurations, particularly thermal wells, should be studied to determine if they would improve the thermal and economic performance of ground-coupled solar heat pump systems over buried tanks.

PUBLICATIONS/REPORTS/REFERENCES

1. Parametric Sensitivity Study for Solar Assisted Heat Pumps, SAI Draft Final Report, March, 1980.
2. Comparison of Ground-Coupled Solar Heat Pump Systems to Conventional Systems for Residential Heating, Cooling and Water Heating, SAI Final Report, February, 1981.

CONTRACT INFORMATION

START DATE 10/79 END DATE 03/80 CONTRACT VALUE $109,000.

MILESTONES

Item:	Due date:
1. Dual Source Report	November 1979
2. Ground-Coupled Survey	November 1979
3. Sensitivity Analysis Report	March 1980
4. Ground-Coupled Report	March 1980
5.	

DISTRICT HEATING FOR SOLAR PONDS

SOLAR ENERGY RESEARCH INSTITUTE

CECILE M. LEBOEUF

EG-77-C-01-4042

OBJECTIVE

The objectives of this project were:

- to validate the SERI in-house solar pond simulation code with actual measured solar pond data
- to use this code in analyzing the technical feasibility of district heating and cooling with solar ponds
- to assess the economic feasibility of solar ponds for district heating of new housing
- to design a solar pond/district heating system which might be a "blueprint" for communities considering applications for new neighborhoods

DESCRIPTION OF WORK

The first part of this project involved acquisition of operating data from the Miamisburg solar pond, for use in a performance prediction verification exercise with the SERI in-house solar pond model. Once the code was verified, it was used to produce a series of sizing and sensitivity analyses for application to district heating and cooling. Two locations were examined, and parametric studies of neighborhood size, pond supply temperature, and pond geometry were examined. Space heating, space cooling, and domestic hot water (DHW) supply scenarios were explored. Components for both the solar pond and distribution subsystems were sized and costed. Finally, with completed technical designs, the overall system costs and delivered energy costs were projected for the solar pond/district heating system.

TECHNICAL ACCOMPLISHMENTS

- District heating, cooling, and DHW supply with energy from a solar pond were shown to be technically feasible. Optimum pond geometries were defined for Fort Worth, Texas, and Washington, DC, including analysis of trade-offs in pond temperature, community size, and pond geometry.
- Costs for the solar pond and distribution system, amortized over 20 years and assuming an 18% fixed charge rate, result in delivered energy costs of $16 to $28/Mbtu, depending on the location and the price paid for the salt (which can vary considerably). These projected costs compare favorably with projections of delivered energy costs for flat plate collectors used in DHW and space heating applications.
- A solar pond/district heating system which supplies 100% of the load of a residential community without auxiliary was shown to be an economically viable alternative.

PUBLICATIONS

Henderson, J., Leboeuf, C.M. "SOLPOND- A Simulation Program for Salinity Gradient Solar Ponds". (1980) Proceedings of the 2nd Annual SS/EA Conference. San Diego, California.

Leboeuf, C.M., et al. "Solar Ponds for District Heating and Electricity Generation". (1980) Proceedings of the 15th IECEC, Seattle, Washington.

Leboeuf, C.M. Application of Solar Ponds to District Heating and Cooling. (1981) SERI/TR-731-1031. Golden Colorado.

CONTRACT INFORMATION

START DATE 10/79 END DATE 12/80 CONTRACT VALUE 97K

MILESTONES

Item:		Due date:
1.	Validation of SOLPOND complete	2/80
2.	Feasibility of several cooling concepts complete	7/80
3.	Analysis of neighborhood-scale solar ponds complete	8/80
4.		
5.		

SIMULATION AND DESIGN OF SOLAR PROCESSES

UNIVERSITY OF WISCONSIN-MADISON

JOHN A. DUFFIE, WILLIAM A. BECKMAN, SANFORD A. KLEIN AND JOHN W. MITCHELL

XK-0-9101-1

OBJECTIVE

The objectives of this work are to increase the utility of the TRNSYS simulation program, to extend the library of TRNSYS components and system analysis capabilities, and to improve the utility of FCHART programs by developing capability to design new kinds of systems not covered by FCHART 3.

DESCRIPTION OF WORK

Simulations are powerful tools in research and development, in design of large systems, and in development of simplified methods for design of standard systems. Thus, further TRNSYS development begins with the identification of a system or application that has not been (adequately) studied. The appropriate component models are programmed and exercised in system studies. These system studies are the vehicle by which TRNSYS component subroutines are checked and entered into the library. These studies also indicate the need to improve existing component models and how the executive routines can be improved to increase utility and decrease simulation costs.

Numerical experiments (simulations) have been used as the basis for development of simplified design methods such as f-chart. The computer program FCHART 3 uses the f-chart method which covers standard liquid-and-air-based space heating systems and DHW systems. Using simulation results, new methods (based on utilizability concepts) have been developed for predicting the long-term performance of systems using a variety of collectors, storage devices, energy transfer subsystems, energy delivery subsystems and auxiliary devices. These methods have been programmed into a more versatile design program, FCHART 4.0.

Both TRNSYS and FCHART developments depend on adequate methods of processing available solar radiation data. Thus we have used new and detailed data to study such topics as the distribution of beam and diffuse radiation, the calculation of monthly average radiation on inclined surfaces and the calculation of monthly utilizability functions.

TECHNICAL ACCOMPLISHMENTS

This contract includes a diversity of activities under the two major topics outlined above. Technical accomplishments are described in the references indicated. Highlights can be summarized as follows:

- Estimation of Hourly, Daily and Monthly Diffuse Fractions (1,2,3).

  Relationships for estimating the beam and diffuse components of hourly, daily and monthly-average global radiation have been developed from a set of recent hourly pyrheliometer and pyranometer data recorded at four U.S. locations. The large variance of the hourly data from the hourly diffuse correlations is shown to be the result of clouds and the effect of not considering this variance on TRNSYS simulation results is shown to be negligible for the systems considered. The seasonally dependent daily diffuse correlation is used along with the generalized k_T distributions of Liu and Jordan to derive a seasonally dependent monthly-average correlation.

- TRNSYS 11.1 (6)

TRNSYS Version 11.1, released in April, 1981, includes two new components, enhanced versions of several older components, an improved algorithm for the solution of differential equations and a new library of contributor-supported components.

The new components consist of an economic processor and a microprocessor based controller The economic processor can be used to calculate life cycle costs and savings associated with system ownership and operation based on a one-year simulation. The microprocessor controller component incorporates five double-ended comparators with hysteresis, a 12 mode look-up table and 18 control signal outputs as well as several other features which make it useful for simulating systems which use complex control strategies.

Several other components have been modified to extend their range of application. These include the TYPE 1 collector which has been modified to allow the simulation of any number of identical collectors connected in series. In addition, a new mode, MODE 6, has been added. This mode allows the modeling of collectors based on test results which include 2-axis incident angle modifier data. This is suitable for the modeling of evacuated tube and other types of collectors which are optically non-symmetric. The radiation processor, TYPE 16, has been modified to allow specification of an arbitrary orientation of the rotational axis for single axis trackers.

Many of the components which use differential equations have been modified to allow analytic solutions of those equations. These include the TYPE 4 tank, the TYPE 10 pebble bed, the TYPE 12 MODE 2 degree-hour house, the TYPE 19

MODE 2 room model and the TYPE 22 combined air collector-storage subsystem. The use of analytic rather than numerical solutions significantly increases the speed of TRNSYS.

Version 11.1 includes a new experimental library of user-contributed and supported components that have been contributed by users outside the Laboratory. The first components to be included in this library are a set of four routines that can be used to simulate thermal-photovoltaic and photovoltaic only systems (from ASU).

- Calculation of Monthly-Average Radiation on Inclined Surfaces (7)

An analytical method was developed for estimating $\overline{R}$, the ratio of the long-term monthly-average daily radiation on an inclined surface to that on a horizontal surface. This method differs from the Liu and Jordan (1) method in the manner in which the beam radiation component is determined. The method is applicable for surfaces of any orientation. $\overline{R}$ values calculated in this manner and by the Liu and Jordan method have been compared with integrated hourly calculations for 23 years in Madison, WI, Albuquerque, NM, and Miami, FL; the comparisons show that the new method agrees more closely with the integrated hourly calculations, especially for surfaces facing east or west of south.

- Calculation of Average Collector Operating Time and Parasitic Energy Requirements (8)

The monthly-average daily utilizability radiation, $\overline{U}$, is the average daily total insolation above a specified critical level, I_c, during the hours of collector operation. $\overline{U}$ can be expressed as

$$\overline{U} = \frac{1}{N}\int^{\text{month}} \gamma\ (I_T - I_c)\ dt$$

where N is the number of days in the month, I_T is the radiation (per unit area) incident on the plane of the collector aperture, and γ is a collector control function defined such that it is 1 if the collector fluid circulation pump is operating, and 0 otherwise. $\overline{U}$ is the product of $\overline{H}_T$, the monthly-average daily radiation on the collector surface, and $\overline{\phi}$, the fraction of this radiation which is above the critical level. The average daily number of hours of solar collector operation, $\overline{t}$, is the time integral of the collector on/off control function for a month divided by the number of days in the month. An estimate for $\overline{t}$ can be obtained by evaluating the derivative of $\overline{U}$ with respect to I_c at the monthly-average critical level, $\overline{I}_c$. From Equation (1),

$$\overline{t} = \frac{1}{N}\int^{\text{month}} \gamma\ dt = -\left(\frac{d\overline{U}}{dI_c}\right)_{\overline{I}_c}$$

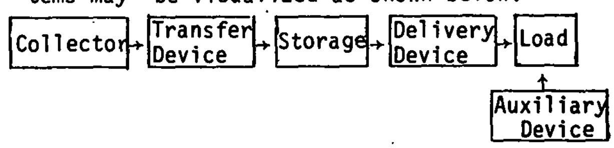
Values of $\overline{t}$ calculate from this equation have been compared to $\overline{t}$ values obtained by numerically integrating the control function over monthly periods with quarter-hour time steps. The standard deviation of 8400 values of $\overline{t}$ so calculated from values calculated by numerical integration of radiation data for a wide range of critical levels, collector slopes, latitudes, and monthly clearness indices, is 0.47 hours.

- $\overline{\phi}$ Design Method for Solar Hot Water Systems (9, 10)

The $\overline{\phi}$,f-chart method, originally developed for closed-loop solar energy systems, has been shown to be applicable to open-loop systems as well. This method can be used to estimate the thermal performance of solar energy systems for domestic water or industrial processing heating, with either flat-plate or concentrating solar collectors. In a related effort, analytical equations have been devised for the Liu and Jordan generalized hourly utilizability curves. These utilizability curves are useful for estimating the solar energy contribution to IPH processes having little or no thermal storage.

- FCHART 4.0 (11)

FCHART 4.0 was completed and its distribution started in 1980. It is an interactive program for analysis and design of active solar and heat pump heating systems. Active solar systems may be visualized as shown below.



Collected solar energy is transferred to storage. A delivery device supplies this energy to the load, with auxiliary energy meeting any additional energy requirement. FCHART 4.0 allows several options for system types, the components comprising each system, and the analysis to be performed.

System Types

Space Heating	Domestic Water Heating
Combined Space & Water Heating	Closed-Loop Process Heating

Component and Analysis Options

Collectors
  Flat-plate
  Compound Parabolic Concentrators (fixed aperture) } Liquid Based Systems Only
  Imaging Collectors (1- or 2-axis tracing) }
Collector-Storage Transfer
  Heat Exchanger — Air Duct Leaks
  Pipe or Duct Heat Losses
Storage Device
  Liquid Tank
  Rock Bed } Air based space heating only
  Phase-Change Material }
Storage-Load Delivery Device
  Heat Exchanger } Liquid based systems only
  Heat Pump }
Load Calculation Methods
  Space Heating (User-supplied monthly loads, UA-degree day)
Water Heating
  Based upon usage, set temperature, and mains temperature (includes auxiliary tank losses)
  Process Heating
  User-Supplied Monthly Loads
Auxiliary Device
  Conventional Fuel (Gas, Elec. or Oil)
  Ambient-source Heat Pump (Space Heating only)
Economics
  Life-Cycle Purchase and Operating Costs
  Comparisons Between Alternatives
  Optimization of Any One System Parameter

A stand-alone ambient source heat pump for space heating systems can be considered by specifying a load and an auxiliary only. For all systems, system performance is estimated at monthly time intervals, using equipment characteristics and weather data. Data are included with the program for 240 locations in North America.

FUTURE ACTIVITIES

A proposal for the continuation of this work and for continuing TRNSYS and FCHART user services, at reduced levels, is pending. This work provides tools that are in widespread use by system developers, designers, architects, and process engineers in the development and sales of their product.

REFERENCES (Reports and papers from this research.)

1. Erbs, D.G., M.S. Thesis, Mech. Engr., Univ. of Wisconsin (1980).

2. Erbs, D.G., Duffie, J.A. and Klein, S.A., paper for Philadelphia meeting, AS/ISES (1981): "Relationships for Estimation of the Diffuse Fraction of Hourly, Daily and Monthly-Average Global Radiation."

3. Erbs, D.G., Duffie, J.A. and Klein, S.A., paper presented at Phoenix AS/ISES meeting (1980), submitted to Solar Energy, "The Basis and Effects of Inaccuracies in Diffuse Radiation Correlations."

4. McLinden, M.O., M.S. Thesis, Chem. Engr., Univ. of Wisconsin (1980).

5. McLinden, M.O. and Klein, S.A., paper presented at Phoenix AS/ISES meeting (1980), "Comparison of Chemical Heat Pump and Conventional Solar Heating Systems."

6. TRNSYS 11.1 Users Manual, Engineering Experiment Station Report 38-11, Univ. of Wisconsin-Madison.

7. Klein, S.A. and Theilacker, J.C., Solar Energy, 103, 29 (1981).

8. Mitchell, J.C., Theilacker, J.C. and Klein, S.A., accepted, Solar Energy (1981), "Calculation of Monthly Average Collector Operating Time and Parastic Energy Requirements."

9. Pearson, K.A., Klein, S.A. and Duffie, J.A., paper for Philadelphia AS/ISES meeting (1981), "Generalized $\bar{\Phi}$ Design Method for Solar Hot Water Heating Systems."

10. Pearson, K.A., M.S. Thesis, Mech. Engr., Univ. of Wisconsin (1981).

11. FCHART 4.0 Users Manual, Engineering Experiment Station Report 50, (1980), Univ. of Wisconsin.

12. Piessens, L., M.S. Thesis, Mech. Engr., Univ. of Wisconsin (1980).

13. Piessens, L., Beckman, W.A. and Mitchell, J.W., presented at ASME Conference, Reno, Nevada (1981), "A TRNSYS Microprocessor Controller."

14. Odegard, D.S., M.S. Thesis, Mech. Engr., Univ. of Wisconsin (1980).

CONTRACT INFORMATION

START DATE 1/1/80 END DATE 12/31/80 EXTENDED TO 6/30/81 CONTRACT VALUE $299,000

MILESTONES

Item:		Due date:
1.	FCHART 4.0	Available 9/80
2.	TRNSYS 11.0	Available 4/81
3.		
4.		
5.		

OPERATION AND MAINTENANCE OF THE MSFC SOLAR TEST FACILITIES

WYLE LABORATORIES INCORPORATED

WILLIAM EARL SCHULTZ

DEN8-000006

ABSTRACT

Wyle Laboratories has been actively involved in Marshall Space Flight Center (MSFC) solar programs for several years. Currect activities include the operation and maintenance of the MSFC Solar Test Facilities, including 6000 square feet of collector test bed, a solar demonstration and training center, a large scale terrestrial solar simulator and information management. The following activities are intended to be representative of current projects, but are not all inclusive.

TRACKING CONCENTRATOR

For most flat plate solar collectors, normal operating temperatures are under 200°F for solar heating/cooling, domestic hot water and swimming pool heating. For industrial process heat, the typical flat plate will not meet the requirement due to their high heat loss at high operating temperatures. Therefore, concentrating collectors with low heat loss are usually a cost-effective choice.

At MSFC, a 25 ton Rankine cooling unit, designed to use solar energy as the heat source, is soon to be installed. An array of parabolic trough solar concentrating collectors will be utilized to meet the required load. A test program was conducted to determine the collector array performance and number of collector modules required for the operation.

A four-module collector array was installed at the MSFC Solar Test Facility. The array was mounted horizontally in a north-south orientation, for best cooling application, tracking the sun from east to west. The modules have a metalized acrylic film FEK 244 on the parabolic contoured aluminum mirror surface to reflect the solar radiation onto a black chrome plated steel receiver which is covered by a stagnant air annulus pyrex glass tubing to reduce convective heat losses.

The collector array was tested following the ASHRAE Standard 93-77, Method of Testing to Determine the Thermal Performance of Solar Collectors, test procedures using Therminol 44 as the heat transfer fluid. Figure 1 is a schematic of the high temperature fluid supply loop, designed and fabricated at the Solar Test Facility to maintain a constant collector inlet temperature and to remove the heat gained through a specially designed tube-in-tube heat exchanger. Figure 2 presents the results of the time constant test. For the four-module array, the time constant was approximately 1 minute. Figure 3 presents the results of the instantaneous thermal efficiency test. The inlet temperature was controlled for steady-state conditions ranging from 140°F to 270°F in order to obtain the thermal efficiency curve; however, the Rankine unit will be operated at approximately 300°F. The first order fit for the test points is:

$$\eta = .592 - .115\ \frac{T_{ave} - T_a}{I_{dir}} \qquad (1)$$

where T_{ave} = Average fluid temperature

T_a = Ambient temperature

I_{dir} = Direct solar radiation

Although not required by ASHRAE 93-77, a test to determine the effect of off-axis tracking was conducted. The test was conducted by manually moving the collector array 15 minutes ahead of the sun, then turning off the tracking system such that the collector array was stationary. This approach allows the sun to move from out of focus to focus and then out of focus again. The inlet and outlet temperatures were monitored to determine the thermal efficiency. Figure 4 shows the results of these tests occurring at different times of the day. The results indicate that if the collector tracking system was off by 1 degree (4 minutes of solar movement), the efficiency will drop as much as 20% of its peak efficiency.

Figure 5 presents the parabolic trough collector performance under an all-day test on a clear, winter day. Both the direct solar radiation and the thermal efficiency based on direct radiation at an inlet temperature held to a constant at 270°F are plotted. Dips were found for both radiation and thermal efficiency curves due to the fact that the collector array being mounted horizontally in a north-south orientation creates the maximum incident angle to the collector at solar noon, as the sun moves east to west.

In conclusion, the parabolic trough collector should effectively supply the required energy for the Rankine unit.

BTU METER TESTING

An alternate method of monitoring solar hot water system performance is using BTU meters. The method eliminates the required temperature and flow conversion equipment, which are generally expensive and require manpower to reduce the data. A BTU meter is a combination of flow and temperature measurement with an electronic circuit to accumulate the total energy gain or consumption for a system.

Before the BTU meters are installed in a system, they should be tested to verify the manufacturer's claimed accuracy. A calibration loop was set up at MSFC Solar Test Facility such that flow rates and temperature ranges can be kept steady for the test period. The percentage error generally decreases with increasing flow rate and temperature differential. Some of the BTU meters are programmable so that heat transfer fluids, other than water, can be used or different types of flow sensors can be installed if the output of the sensor is known.

After laboratory bench tests, two of the BTU meters were chosen to be installed in a solar hot water system for field testing. The result of this field test indicated that the accuracy of the BTU meters agree very well with the bench tests.

Results of the test program prompted the following conclusions. In order to choose the most appropriate BTU meter, one should consider the guide listed below:

- Determine the range of flow rate and temperature.
- Type of heat transfer fluid used in the system.
- Differential temperature range of high and low temperature lines.
- Pressure drop introduced by the flow sensor.
- BTU meter output requirements (gallon count), BTU count, temperature display, etc).
- BTU meter power supply requirement.
- The ability to interchange temperature or flow sensors with the BTU meter electronic control/display.
- Price.

RADIATION STUDY

The efficiency of a solar collecting system is proportional to its incoming solar energy. Therefore, the prediction of the availability and quantity of radiation on the collector surface is extremely important to an engineer, designer, or researcher for their system design, evaluations, or performance simulations.

There are many weather stations in the United States; however; at most of them, only total solar radiation on a horizontal surface is recorded. This is the case for NOAA (National Oceanic and Atmospheric Administration), which publishes a monthly summary of solar radiation data for several sites. To convert these hourly data from a horizontal surface to the collector tilt plane is a State-of-the-Art Science. Numerous authors have presented their methods, among them, Lui & Jordan's method is the most widely used. To apply Liu & Jordan's technique, one must know the total and diffused solar radiation on the horizontal plane. Unfortunately, the diffused solar radiation on the horizontal plane is rarely available. In addition, determination of the diffused radiation using a shadow band requires periodic adjustment of the altitude angle and additional equipment (pyranometer, recorder).

One of the purposes of a project at the MSFC Solar Test Facility is to investigate a method to convert solar radiation from the horizontal to the tilt plane knowing only the total solar radiation. This algorithm will then be utilized in the evaluation of system designs. Solar radiation has been recorded at two-minute intervals for 10-12 hours, depending on the season. On a fixed surface, horizontal total and tilt total (45 degrees) and on a tracking plane, direct, total and diffused radiation are measured. These hourly data are tabulated monthly. The data will be utilized for comparison with weather data by ASHRAE, NOAA, ASHMET, and SOLRAD for purposes of algorithm evaluation.

Figure 6 shows a typical clear day where TOT (total), NIP (direct normal), and DIF (diffuse) were measured in the tracking plane and HOR and 45T were the total radiation on the horizontal surface and 45 degree tilt surfaces, respectively.

Liu & Jordan's equation to convert from the horizontal surface to a tilt surface is given below:

$$G_T = (G_H - D_H)\frac{\cos\theta}{\sin\alpha} + D_H\cos^2\frac{s}{2} + \rho G_H\sin^2\frac{s}{2} \quad (1)$$

where G_T = Global radiation on tilt surface.

G_H = Global radiation on horizontal surface.

D_H = Diffused radiation on horizontal surface.

θ = Solar incident angle.

α = Solar altitude angle.

s = Surface tilt angle.

ρ = Ground reflectance.

It is obvious that G_H and D_H must be known since they are on the right hand side of the equation to determine the unknown, G_T, the radiation on the tilt surface. An algorithm has been developed and is currently being validated, which determines the diffused fraction for each hour, based on total horizontal only. Then, equation (1) can be used to convert the horizontal radiation to any tilt surface. Using the data obtained at MSFC, the March and April, 1981, data were evaluated; the results are shown in Figure 7. For the range of solar radiation from 5 to 340 BTU/hr-ft^2, i.e., all types of days (clear, partly cloudy, and cloudy days), the deviation from measured value is within ±10 BTU/hr-ft^2. Despite its good results, more data will be evaluated for refinement of the technique to reduce some of the scattering and to determine the applicability to all geographical locations.

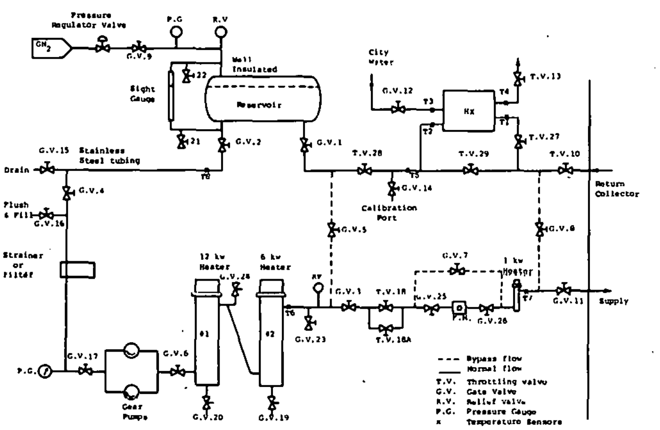


Figure 1 NASA High Temperature Fluid Supply Loop

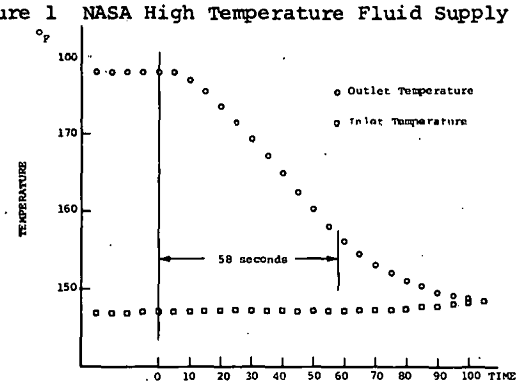


Figure 2 Solar Collector Time Constant Test

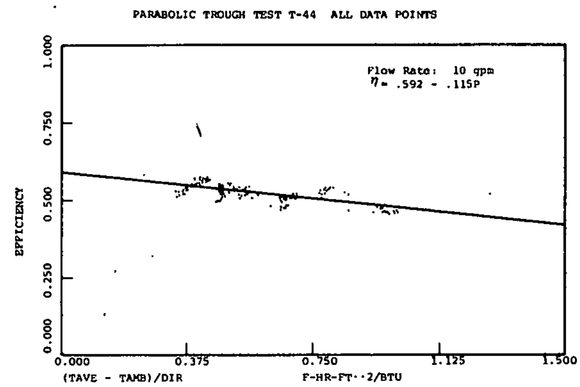


Figure 3 Collector Thermal Efficiency Based On Direct Solar Radiation

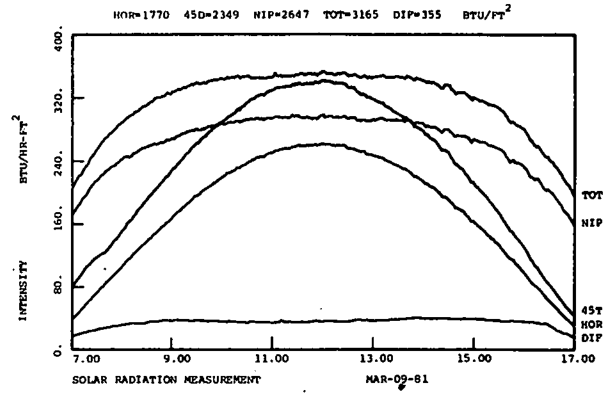


Figure 6 Typical Clear Day Radiation Measurements

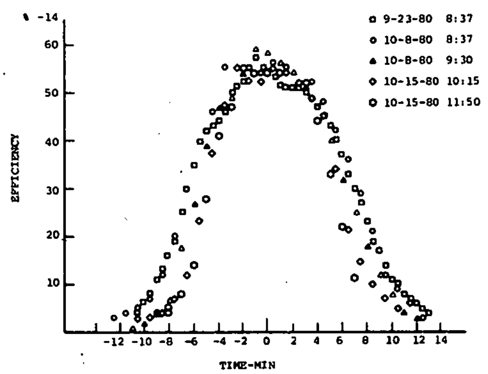


Figure 4 Solar Collector Tracking Accuracy Test

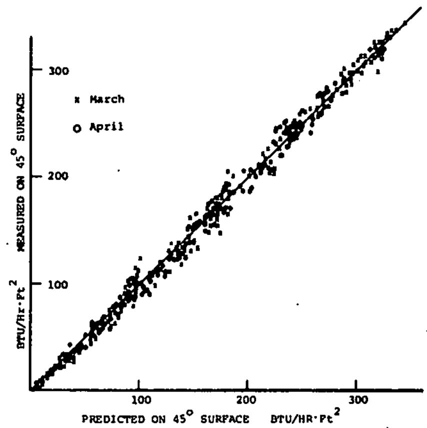


Figure 7 Comparison of Prediction from Hourly Horizontal Data to 45° Surface With Measured Data for the Month of March and April, 1981

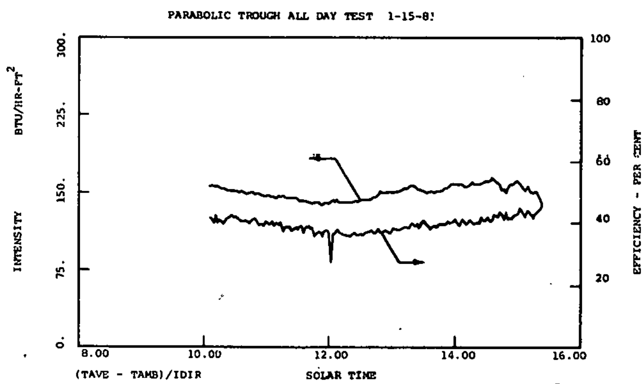


Figure 5 All Day Performance With $T_{IN} = 270^{\circ}F$

CONTRACT INFORMATION

START DATE 11-1-80 END DATE 9-30-82 CONTRACT VALUE 427,404

MILESTONES

Item: Due date:

1.

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Section 12: SOLAR MATERIALS GROUP

12

Development of Selective Surfaces

The Berry Group

John L. Cotsworth

DE-AS04-78CS34293

OBJECTIVE

The objectives of the work are to develop improved techniques of producing selective surfaces on stainless steel, aluminum and copper; to test several of these surfaces under conditions of ultraviolet radiation, heat and humidity and to investigate feasibility of large scale production of the selective surfaces.

DESCRIPTION OF WORK

The importance of a selective coating in medium and high temperature solar collectors has been recognized during the last four years. The coating must be durable, offering 20 years life under a wide range of atmospheric conditions and stagnation temperatures of about 450°F. The absorber materials must, likewise, withstand internal corrosion from liquids. Both the absorber material and its coating must be cost effective and durable in service.

The commonly used absorber materials are stainless steel, aluminum and copper. Stainless steel offers the advantages of easier fabrication, excellent corrosion resistance, stability at higher temperatures and somewhat lower cost in thin gauge strip. The disadvantage is its lower thermal conductance which makes it impractical for the tube-in sheet type design and its lower electrical conductance which makes it difficult to electroplate. At present, two selective coatings on stainless steel are commercially available, the one being the coating produced by dipping 444 stainless steel in hot sodium dichromate solution[1] and the other being a color produced by a proprietary process.[2]

Aluminum strip at twice the thickness of copper achieves equal conductivity for fintube type absorbers and is less costly per square foot than copper. However, selective coatings like black chromium or black nickel cannot be directly electrodeposited on aluminum. An intermediate treatment like double zincating followed by copper strike is required. This multi-stage operation increases the cost of the coating. Nickel impregnation into anodized aluminum seems to be a cost effective selective surface on aluminum[3]. But its durability under humidity is questionable. An overcoating is required, which however increases the ivity.[4]

Multilayer coatings on aluminum could be produced by vapor deposition[5] or by sputtering[6] but at present these are limited to be applied on thin foils only.

Copper with its higher thermal conductivity and electrical conductance is best suited for solar applications. Electrodeposition on copper is easier, so also its fabrication. Copper tubes can be soldered, welded or brazed to copper fins. Copper oxide selective coating[7] is not durable. Black nickel coatings failed under humidity testing[8]. Black chrome on 0.1 to 0.2 mil nickel plated on copper has been tested and found to be more durable under humidity and temperatures up to 450°F. Thicker intermediate coatings of nickel have indicated improved durability, but the substrate used was carbon steel. There is a necessity to test its durability on copper.

In order to find durable, cost effective coatings on the above three materials, it is decided to develop an accelerated testing procedure to carefully examine several commercially available selective and non-selective coatings under conditions normally experienced by a solar collector in service. Some of the chosen coatings have only been produced in the laboratory with the idea being to determine their feasibility for large scale production.

The testing procedure consisted of simultaneous exposures of the selective and non-selective coatings to solar irradiance and thermal cycling between $450 \pm 35^{o}F$ and $200 \pm 25^{o}F$. The test box is shown in Fig. 1.

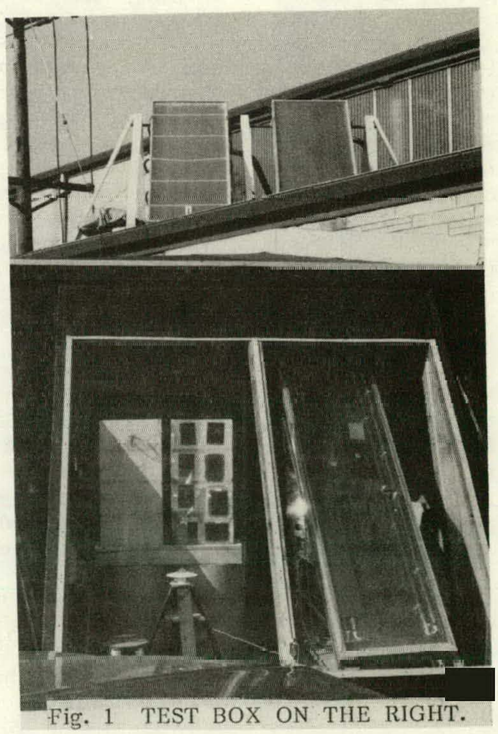

Fig. 1 TEST BOX ON THE RIGHT.

After 78 cycles and 21,851 Langleys of exposure, the coatings which did not show any deterioration were further exposed to solar irradiance of 8:1 concentration up to 156,270 Langleys. The maximum temperature was 450°F. At the same time thermal cycling test was continued to 161 cycles and 42,307 Langleys. The results of the tests are given in Tables 1 & 2.

Some of the coupons were also tested under natural weathering conditions in a box for a period of two years and the optical properties were measured at six month intervals[9].

TECHNICAL ACCOMPLISHMENTS:

1. Most of the selective coatings did not change in emissivity when tested under thermal cycling conditions. The maximum decrease in absorptance was 15% in the case of Black Zinc on Steel. The other selective coatings showed a maximum of 7% decrease in absorptance. Black chrome plated did not show significant deterioration. Black Nickel on the other hand deteriorated when exposed under natural weathering conditions including humidity.

2. Most of the non-selective coatings did not show any decrease in the absorptance value. However, physical damage such as peeling, discoloration, pitting, rusting and scratching occurred in the tests performed.

3. The accelerated test developed in this program gave us a quick insight into the durability of the coatings. The total duration of the test was not more than two months. Simultaneous exposure to thermal cycling and solar irradiance was performed for the first time tin this program.

4. Black Chrome, when plated under commercial plating conditions, exhibits a powdery substance, called "soot", which is essentially chromic oxide (Cr_2O_3) and under these conditions hues of black, blue and red are commonly obtained when the plating temperature is varied. These different colors are due to different particle sizes of the chrome metal and chromic and chromic oxide. Plating should be conducted at lower temperatures to obtain black color. The optical properties of Black Chrome of different hues did not change significantly when exposed to natural weathering for a period of 24 months. Similar results were obtained when tested under thermal cycling and solar irradiance. However, some users tend to reject black chrome with different hues purely for cosmetic reasons. Results of this study indicates that black chrome need not be black to possess good optical properties and durability. It is therefore recommended that, for the benefit of average users of "black chrome," who do not have optical property measuring instruments, the finish henceforth be referred to as "Solar Selective Chrome." This suggested simple change in nomenclature also discriminates between chrome with low emissivity and thick surface of electroplated Black Chrome of high emissivity which are widely used for decorative applications.

5. Continuous electrodeposition of black chrome on nickel plated copper is successfully being accomplished. The cost of processing is proving in commercial practice to be less than that of batch plating.

6. Nickel-impregnated-anodized aluminum appears to be an ideal selective coating for aluminum. The absorptivity of .92 and emissivity of .12 can be achieved in commercial production. Its humidity resistance can be increased by applying a thin Silicone resin overcoating with emittance increasing from .12 to .19. The application is limited however to stagnation temperatures of about 350°F.

7. Correlation of the optical properties between D & S alpha and emissometers INTEC alpha and ambient emissometers and a reflectometer has been determined. The results are given in Table 3.

FUTURE ACTIVITIES

Selecting a suitable overcoat for black chrome and other selective surfaces.

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8. R.J.H. Lin and P.B. Zimmer, "Optimization of Coatings for flat plate collectors, ERDA Contract No. EY-76-C-02-2930. *000. (C00-2930-12), (1976), 86.
9. Technical Progress Report I, DE-AS0478C534923, August, 1979.
10. Technical Progress Report II, Berry Solar Products. DE-AS-4-78CS34923, Nov., 1979
11. Technical Progress Report III, Berry Solar Products, DE-AS04-78CS34923, June, 1980.

63	-do-	Cu	Dark grey	94.5	.84	92.6	.96	-	-	92.0	.92
58	Polyester	Al	Dark grey	92.5	.95	90.5	.95	-	-	88.0	.92
61	Alkyd Carbon	Cu	Dark grey	94.5	.89	95.0	.90	97.0	.91	94.5	.94
64	Waterbase Inorganic	Al	Pitting	93.5	.84	95.0	.86	-	-	95.0	.96
65	-do-	Cu	Cracks	93.5	.84	95.0	.87	96.0	.92	94.5	.94
66	-do-	S**	Rust spots	93.5	.84	95.0	.83	-	-	94.5	.92
40	Epoxy Enamel	Al	Pitting	92.5	.78	87.5	.68	-	-	94.5	.93
47	Baked Enamel	Al	Pitting	95.0	.86	91.5	.90	-	-	91.0	.92
46	Vinyl based Enamel	Al	Dark grey	92.5	.92	93.8	.87	96.0	.85	93.0	.89
51	Silicone Carbon Black	Al	Dark grey	96.0	.94	93.8	.93	95.0	.88	94.0	.88
60	Fluoropolymer	S**	No change	90.5	.79	92.6	.89	87.0	.94	92.0	.88
36	Iron Oxide	S**	Rust Spots	90.0	.49	83.4	.60	86.0	.82	92.0	.88
37	Al. Oxide	Al	No change	93.0	.79	87.9	.84	89.0	.92	92.0	.90
34	Anodized	Al	-do-	93.0	.68	87.9	.88	-	-	91.0	.90
52	Inorganic	S**	-do-	88.5	.90	86.6	.84	-	-	85.0	.89
54	Inorganic	S**	-do-	92.5	.90	93.8	.90	-	-	94.0	.89

* Exposed to EMMA after 21,851 ly and 78 Cycles
** Steel

TABLE 3

Comparison of absorptance and emittance measurement

	International Technology Corpo.	Devices & Services Co.	Gier-Dunkle Inst.	Integrating Sphere Reflectometer
ABSORPTANCE	Model 2150 x	Alphatometer x-0.01	MS-251 Solar Reflectometer x-.03	x-.018
EMITTANCE	Model #2158 y	Emissometer y ± .02	DB-100 Infrared Reflectometer y-.018	- -

CONTRACT INFORMATION

START DATE 9/25/78 END DATE 4/30/81 CONTRACT VALUE 4148,049

MILESTONES

Item: Due date:

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TABLE 1
Accelerated Testing of Coupons
Selective Coatings

Code	Coating	Under-layer	Sub-strate	Initial Readings α	Initial Readings ε	21,761 ly 73 Cycles α	21,761 ly 73 Cycles ε	156,170 ly* Under-Emma α	156,170 ly* Under-Emma ε	41,361 ly 161 Cycles α	41,361 ly 161 Cycles ε
1	Bl. Cr.		Cu	94.0	.08	84.5	.04	———Failed———			
3	Bl. Cr. Black hue	Ni	Cu	96.5	.10	95.5	.08	-	-	95.0	.08
5	Bl. Cr. Blue hue	Ni	Cu	95.5	.06	96.5	.09	-	-	96.5	.09
69	Bl. Cr.	Ni	Cu	94.5	.11	96.0	.09	96.0	.08	97.0	.09
76	Bl. Cr.	Ni	Cu	97.0	.15	96.0	.06	95.0	.10	96.0	.06
77	Bl. Cr.	Ni	Cu	96.0	.14	95.5	.12	96.0	.07	96.0	.09
78	Bl. Cr.	Ni	Cu	96.0	.18	95.0	.19	95.0	.13	96.0	.20
85	Bl. Cr.	Ni	Cu	98.0	.05	95.0	.08	95.0	.10	95.0	.09
86	Bl. Cr.	Ni	Cu	98.0	.18	96.0	.15	96.0	.10	96.0	.10
7	Bl. Cr.	Zn	Al	94.5	.12	92.5	.18			93.5	.25
24	Bl. Cr.	Zn	Al	98.0	.15	92.0	.09			93.5	.11
19	Bl. Cr.	Zn/Ni/Cu	Al	94.5	.08	94.0	.08	95.0	.11	93.0	.13
33	Bl. Cr.	Ni	Al	95.0	.09	92.6	.05			93.0	.10
75	Bl. Cr.	Ni/Cr	Al	97.0	.14	95.0	.11	96.0	.17	95.0	.07
25	Bl. Cr.	Cr	Al	94.0	.20	93.5	.20			93.0	.23
35	Bl. Cr.		Ni	95.5	.09	95.0	.08	95.0	.07	95.0	.20
30	Bl. Ni		Cu	92.0	.04	87.0	.02	———Failed———			
22	Bl. Ni		Ni	97.0	.06	97.0	.06	96.0	.06	97.0	.06
18	Ni	A**	Al	93.5	.04	90.5	.08			92.0	.20
28	CuO		Cu	89.0	.28	76.5	.16	———Failed———			
29	CuO		Cu	94.0	.13	88.5	.09	———Failed———			
17	Conv.		SS	91.0	.24	88.0	.18			88.0	.18
26	Conv.		SS	86.0	.15	82.5	.14			83.0	.18
20	CoO	Zn	CS	90.5	.12	84.5	.12			80.0	.64
21	Zno	Zn	CS	91.5	.12	84.5	.10			86.0	.11
74	A**		SS	93.5	.09	88.0	.10			85.0	.13
27	M***		Al	96.0	.07	94.5	.05	95.0	.09	96.0	.07
79	AMA		Cu	98.0	.13	95.0	.13	89.0	.31	96.0	.26
82	AMA		Al	97.0	.09	90.0	.04	92.0	.12	90.0	.10
84	AMA		SS	98.5	.05	95.5	.15	84.0	.61	95.0	.21
91	Bl. Cr.	Ni	Cu	97.0	.06			03.0	.11	06.0	.10
89	Ni	A**	Al	94.0	.13	95.0	.14	92.0	.16		
90	Ni	A**	Al	97.0	.11	96.0	.12	95.0	.10		
18A	Ni	A**	Al	95.0	.12	95.0	.15	94.0	.26		
87	CuO	Cu	Cu	93.0	.10	90.0	.16	86.0	.14		
88	CuO	Cu	CS	93.0	.10	90.0	.15	88.0	.15		

* Exposure at DSET after 21,762 ly and 73 Cycles
Bl. Cr. ——— Black Chrome
Bl. Ni. ——— Black Nickel
A** ——— Anodized
M*** ——— Multilayer
SS ——— Stainless Steel
CS ——— Carbon Steel

TABLE 2
Accelerated Testing of Coupons
Non-Selective Coatings including a Selective Paint

Code	Coating	Sub-strate	Visual Appearance After Exposure	Initial Readings α	Initial Readings ε	21,851 ly 78 Cycles α	21,851 ly 78 Cycles ε	156,270 ly* of Emma α	156,270 ly* of Emma ε	42,307 ly 161 Cycles α	42,307 ly 161 Cycles ε
45	Si/F-6331	Al	Dark Grey; scratches	93.5	.04	90.5	.08	93.0	.15	91.0	.15
31	Fluoropolymer binder with special pigment	Al	-do-	93.0	.38	93.5	.39	-	-	92.0	.43
32	-do-	Cu	-do-	92.5	.39	94.5	.39	-	-	93.0	.43
41	Nextel	Cu	Peel-off	94.0	.93	95.0	.90	97.0	.91	97.0	.90
50	Nextel-SCS208	Al	Edge peeling	97.0	.94	96.5	.91	96.0	.95	96.0	.90
48	Silicone modified paint	Al	Micro cracks	94.0	.59	95.0	.62	-	-	94.5	.62
49	-do-	Cu	-do-	94.0	.49	93.8	.68	87.0	.70	94.5	.61
56	Baked Paint	Al	Dark grey	92.5	.90	93.7	.92	-	-	92.0	.87
57	Epoxy	Al	Dark grey	92.5	.84	93.7	.90	-	-	89.0	.91

SELECTIVE PAINT SCALE-UP DEVELOPMENT

HONEYWELL, AVIONICS DIVISION

PAUL B. ZIMMER

DE-AC04-78CS14287

OBJECTIVE

The program objectives are to demonstrate large scale producibility of a low cost, durable, thickness sensitive selective paint (TSSP) coating for flat plate solar collector panels and to optimize the optical properties of the thickness insensitive selective paint (TISP) coating.

DESCRIPTION OF WORK

The TSSP coatings require precise control of film thickness on low emittance substrates to achieve solar selectivity. These coatings produced for DOE (Ref. 1) offer high selectivity ($\alpha_s = 0.92/\varepsilon = 0.10$), low material cost (1¢/ft^2), good durability (20 year simulated exposure in a weatherometer) and high thermal stability (450^o).

Current development emphasizes large scale application techniques such as dip coating, electrostatic spraying, roll coating and printing to demonstrate production feasibility while maintaining all the properties of the coating from laboratory size batches and application techniques. Also investigated are various manufacturing techniques for the coating and development of a solar tape.

The TISP coatings developed under a previous DOE program (Ref. 2) showed an $\alpha_s = 0.90$ and ε of 0.31. This was achieved by incorporating aluminum pigment in the paint system. TISP coatings can be applied to any surface, including non-metallic substrates. The current program emphasizes the optimization and repeatability of the optical properties with a goal of achieving $\alpha_s = 0.90$ and $\varepsilon = 0.15$. While TISP coatings are insensitive to thickness, they are sensitive to application techniques, thus characterization and engineering of the basic optical properties of the coating is under investigation. A computer program that takes coating surface finish and coating scattering into account will be used to help optimize the properties.

TECHNICAL ACCOMPLISHMENTS

Thickness Sensitive Selective Paint (TSSP)

- Use of a low index coating (Dupont FEP Teflon) over the TSSP coating to reduce surface reflectance significantly increasing solar absorptance by 3-4% while holding the increase in emittance to 3-4%.
- Harshaw pigment was found to be equivalent to the Ferro pigment but causes gelling of certain binders. It has high solar absorptance, IR transparency, low refractive index, thermal stability and is easily processed into a paint coating.
- Preliminary coating scale-up tests on the foil substrate have shown that the optical properties of the selective paint can be maintained under production conditions.
- SCR controlled IR ovens have been tested that will allow high speed, high temperature cure rates thus eliminating slow production web speeds and long oven cure times.
- A study of the effect of pigment volume concentration (PVC) and particle size on shelf life has provided coating solution stability information.
- Large scale paint manufacturing techniques have produced TSSP coatings that exhibit optical properties comparable to those achieved with small laboratory batches.

Thickness Insensitive Selective Paint (TISP)

- A binder material has been identified for the thickness insensitive paint that will cure under ambient conditions yet has the thermal stability necessary for flat plate solar collectors and passive solar applications. This binder is compatable with the pigment systems, exhibits good solution stability and has proven weather durability.

- Low emitting leafing and non-leafing metal pigments were identified that are compatible with the TISP coating systems.
- Various metallic pigments were studied with respect to particle size range, and materials identified that exhibited the best optical properties.

FUTURE ACTIVITIES

Thickness Sensitive Selective Paint (TSSP)

Post contract plans for commercialization are under consideration. Licensing of the patentable features of the coating to solar collector manufacturers is being considered.

Scale-up production of 10,000 sq. ft. of coated aluminum foil along with 10 - 3ft x 6 ft aluminum test panels will be made.

The environmental durability and material performance will be tested under both accelerated and outdoor conditions.

Develop an adhesive system for the TSSP coated aluminum foil that is able to withstand the stagnation temperature (450°F) of a flat plate collector with no outgassing or blistering.

Thickness Insensitive Selective Paint (TISP)

The optical properties will be optimized with the goal of achieving $\alpha_s = 0.9$ and $\varepsilon = 0.15$.

Work will be done to decrease the dependance of the coating performance on the method of application. This is a major problem with TISP coatings and will be emphasized.

Preliminary testing will be done for passive solar system requirements. Items to be studied are ease of application by spray, brush and roller over various substrates.

Experimental work will continue on the environmental effects and durability of the coating as they relate to material performance.

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CONTRACT INFORMATION

START DATE 9-15-80 END DATE 3-31-82 CONTRACT VALUE $176.9K

MILESTONES

Item:		Due date:	
1.	Semi-annual	March 9, 1981	M
2.	Semi-annual	September 8, 1981	P
3.	Final	March 8, 1982	P
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5.			

EVALUATION OF SELECTIVE SOLAR ABSORBER SURFACES

LOCKHEED PALO ALTO RESEARCH LABORATORY

STANLEY A. GREENBERG† AND RICHARD A. OSIECKI

DE-AC04-78CS 15361

In recent years the interest in solar energy and its associated technology has increased greatly. One of the expressions of interest is the relatively large number of surface finishes which are being used or developed for use as selective solar absorbers in solar collectors. These surface finishes vary from paints to electrochemically deposited coatings to evaporated and sputtered films. Concurrent with the use or development of these surface finishes is the need to develop test methods to accelerate the in-use degradation of the finishes which is apparent primarily as the decrease in the solar absorptance of the finish. If an effective accelerated test method could be found, the development of new long-term finishes would be accelerated and the selection of an optimum long-term finish of those currently available would be eased. The study reported herein is an effort to determine such a means of accelerated testing.

The study is divided into two phases. Phase I was the sampling and limited environmental exposure of a large number of current and developmental selective absorber surface finishes. Phase II, currently in progress, is the extended environmental exposure of surface finishes chosen from those of Phase I and the subsequent analysis of the degraded (environmentally exposed) and non-degraded finishes in an effort to determine the degradation mechanisms operative in the coatings.

The surface finishes studied in Phase I are listed in Table I. Samples of each were obtained from the listed suppliers in mid-to-late 1979 and exposed to the following environments:

1. Humidity: 95% relative humidity at 30°C for 30 days.
2. Thermal Cycling: -40°C to + 120°C, 60 cycles.
3. Ultraviolet Irradiation: 12,000 equivalent sun hours (at 5 sun UV illumination operates at 120°C.

4A. Humidity: same as 1.

4B. Thermal Cycling: same as 2.

5. Temperature Soak: 250°C for 200 hours.

One set of samples was exposed to environments 1, 2 and 3 sequentially and then split with half the set being exposed to environments 4A and the other half being exposed to environment 4B. A second set of samples was exposed to environment 5 only. The solar absorptance and near-normal emittance of the samples were determined and after each environmental exposure.

The spectral reflectance of the surface finishes in Phase I was determined with a Cary 14 and, later, Cary 17, spectrophotometer in the wavelength range 0.3 μm to 1.8 μm. The total spectral reflectance for Air Mass (AM) 2 in this wavelength range was determined using a 20 point integration grid. This wavelength range was used because of equipment limitations at the start of the study. In Phase II the solar absorptance will be determined by a 20 point integration grid for AM 1.5 and the full solar energy spectrum. The new means of integration results in an apparent solar absorptance between 0.01 and 0.03 lower than that determined by the old method. The near normal emittance is determined with a Gier-Dunkle DB-100 reflectometer.

TABLE I. SURFACE FINISHES TESTED IN PHASE I

1.	Surface Finish:	BLACK CHROME
	Substrates:	Copper, Aluminum, Stainless Steel, Mild Steel
	Vendors:	Olympic Plating Industries, Inc. Canton, Ohio. Highland Plating Company, Los Angeles, Ca. The Harshaw Chemical Company, Cleveland, Ohio (Mild Steel only)
2.	Surface Finish:	BLACK CHROME on nickel plated copper.
	Vendor:	Berry Solar Products (Solarstrip), Edison, N.J.
3.	Surface Finish:	NICKEL-CHROMIUM OXIDE on nickel foil.
	Vendors:	Ergenics (Maxorb), Waldwick, N.J.
4.	Surface Finish:	CHROMATE CONVERSION
	Vendor:	State Industries, Inc., Ashland City, Tennessee.
5.	Surface Finish:	EVAPORATED COATINGS/ SPUTTERED COATINGS
	Vendors:	Optical Coating Lab., Inc. Santa Rosa, Ca. (Evap.Coatings) Telic Corp., Santa Monica, Ca. (Sputtered Coatings).
6.	Surface Finish:	PAINTS, thickness sensitive and non-sensitive, silicone and urethane based.
	Vendors:	Honeywell, Systems and Research Center, Minneapolis, Minn.
7.	Surface Finish:	COPPER OXIDE on copper on mild steel.
	Vendors:	American Heliothermal, Denver, Co.

†Current Address: Aerojet ElectroSystems, Azusa, Ca.

Space limitations preclude the possibility of presenting all the data obtained in Phase I so only the optical properties of three of the surface finishes after various environmental exposures will be given. One finish exhibits optical property degradation typical of most of the samples and the other two exhibit the observed deviations from this typical behavior. The optical property degradation of all the surface finishes as a function of environmental exposure is available in reference 1.

Table II lists the change in optical properties of the Highland Plating Black Chrome finish on copper as a function of exposure to the various environments. This surface finish behavior was typical of most of the surface finishes studied. The solar absorptance decreased by approximately 0.03 while the emittance remained unchanged or decreased slightly. It should be noted that the change induced by the temperature soak induced changes comparable to those induced by the sequential environmental exposures, while the humidity exposure had the greatest effect of the sequential tests.

cycling and ultraviolet irradiation appear to have little influence on the degradation of the finishes. For this reason, the extended environmental exposure used in Phase II was chosen to be high humidity and relatively high temperature.

Phase II of this study is the exposure of selected surface finishes (see Table IV) to 95% relative humidity at 90°C for 1,000 and 5,000 hours. The six finishes which show the greatest change in optical properties because of this exposure will be analyzed by scanning electron microscope, auger spectroscopy, secondary ion mass spectroscopy and other appropriate means.

The goals of these analyses are to determine the changes which have occurred in the finishes because of the environmental exposure and the subsequent attempt to define the degradation mechanisms operative in the finishes. The samples of Phase II are currently in environmental exposure. It is anticipated that all the analytical work will be completed by the end of 1981 with a final report shortly thereafter.

TABLE II. THE OPTICAL PROPERTIES OF HIGHLAND BLACK CHROME ON COPPER AFTER EXPOSURE TO VARIOUS ENVIRONMENTS

	Optical Properties													
			After Exposure to Environments*											
Sample	Initial		1*		1,2		1,2,3		1,2,3,4A		1,2,3,4B		5	
	α	ε	α	ε	α	ε	α	ε	α	ε	α	ε	α	ε
1	.962	.130	.963	.132	.952	.127	.932	.116	.926	.119	-	-		
2	.949	.120	.950	.118	.941	.107	.924	.094	-	-	.923	.094	-	-
3	.964	.134	-	-	-	-	-	-	-	-	-	-	.932	.111

*Environments are as indicated in the 3rd paragraph of this paper.

TABLE III. THE OPTICAL PROPERTIES OF THE CHROMATE CONVERSION AND COPPER OXIDE SURFACE FINISHES AFTER EXPOSURE TO VARIOUS ENVIRONMENTS

	Optical Properties													
			After Exposure to the Following Environments											
Sample	Initial		1*		1,2		1,2,3		1,2,3,4A		1,2,3,4B		5	
	α	3	α	ε	α	ε	α	ε	α	3	α	ε	α	ε
Chromate Conversion														
1	.830	.131	.816	.145	.800	.153	.760	.175	.771	.174	-	-	-	-
2	.837	.136	.812	.145	.800	.159	.756	.171	-	-	.754	.168	-	-
3	.834	.133	-	-	-	-	-	-	-	-	-	-	.782	.159
Copper Oxide														
1	.835	.131	.774	.179	.763	.186	.684	.153	.662	.184	-	-	-	-
2	.828	.129	.732	.177	.723	.183	.673	.156	-	-	.679	.158	-	-
3	.832	.134	-	-	-	-	-	-	-	-	-	-	.745	.163

*Environments are as indicated in third paragraph of this paper.

Table III shows the optical properties of the State Industries Chromate Conversion surface finish and the American Heliothermal copper oxide/copper on mild steel coating. These two finishes showed the greatest changes in the optical properties of those tested. The solar absorptance of the chromate coating decreased from approximately 0.05 to 0.09, while that of the copper oxide coating decreased by between 0.10 and 0.18. The emittance of both increased by about 0.04. Once again, the temperature soak induced changes comparable to those induced by the multiple environment exposure and the humidity exposure had the greatest effect of the multiple environment exposures.

The most severe degradation in selective solar absorber finishes was incurred by high humidity and high temperature environments. Thermal

TABLE IV. FINISHES BEING TESTED IN PHASE II

1. Black Chrome on aluminum by Olympic Plating.
2. Black Chrome on copper by Olympic Plating.
3. Black Chrome on copper by Highland Plating.
4. Black Chrome on nickel plated copper by Berry Solar Products.
5. Copper Oxide/Copper on mild steel by American Heliothermal.
6. Nickel-Chromium Oxide on nickel foil by Ergenics (Maxorb)
7. Chromate Conversion Coating by State Industries
8. Thickness Sensitive, Silicone based paint by Honeywell.

REFERENCES

1. Greenberg, S. A., "Evaluation of Selective Solar Absorber Surfaces", Final Technical Report, April 1980, LMSC D-766220.

CONTRACT INFORMATION
START DATE 25 Sep. 1978 END DATE 30 Sep. 1981* CONTRACT VALUE $256,400

MILESTONES	
Item:	Due date:
1. Phase I Draft Final Report - April 1980 - M	
2. Phase II Semi-Annual Report - April 1981 - M	
3. Phase II Draft Final Report - 30 Sep 1981*	
4. *being negotiated to 29 Jan. 1982.	
5.	

THE CORROSION RESISTANCE OF METALLIC SOLAR ABSORBER MATERIALS IN RANGE OF HEAT TRANSFER FLUIDS

OLIN-METALS RESEARCH LABORATORY

EDWARD F. SMITH III

DE-AC04-81AL16222

OBJECTIVES

The objectives of this program are to generate long-term corrosion data applicable specifically to solar collectors; to test commercially available heat transfer liquids with a variety of alloys currently used in solar absorbers; to establish the susceptibility of these metals to various forms of corrosive attack in each of the liquids; and to establish a correlation between laboratory corrosion data and the corrosive attack found in actual solar collectors.

DESCRIPTION OF WORK

The experimental program is divided into two areas. The initial part of the program will utilize an Olin developed test procedure to evaluate the corrosion compatibility of four alloys with a wide variety of commercially available heat transfer liquids. The metals to be used in this program are 1100 aluminum, 1010 low carbon steel, 122 copper and 444 stainless steel. In addition, the program will examine the extent of galvanic corrosion between the following couples: 1010 steel and 444 stainless steel, 1010 steel and 122 copper, and 122 copper and 444 stainless steel.

A six month exposure period will be utilized in this initial laboratory screening test. Sample withdrawals will occur at one, two, three and six months. In addition to recording the weight loss, all samples will be thoroughly examined for evidence of localized attack. The experimental equipment allows simultaneous testing of up to twenty different liquids. During the initial test, all four alloys will be contained in the same test cell. The following manufacturers are supplying either test liquids or additives for this program: Nutek, Nalco, Dow Chemical, Union Carbide, Olin, Sunworks, Bray Oil, Monsanto, Dow Corning, Sherman Williams and Climax Molybdenum. Additional heat transfer liquids will be evaluated as space becomes available.

In addition to the six month screening test, the program will also use a limited number of actual solar collectors to examine potential corrosion problems. The absorbers in these collectors will be fabricated from the four alloys used in the laboratory test. The test fluids will be selected from those which provided adequate corrosion protection in the laboratory test. The roof mounted collectors will be tested for at least one year. Data generated from periodic examination of the metals and fluids used in the collector tests will be compared to similar data from the laboratory test.

TECHNICAL ACCOMPLISHMENTS

This program was initiated in the first quarter of 1981 with the actual experimental program beginning in the second quarter. As of the submission date for this paper, no technical data is available.

FUTURE ACTIVITIES

The data generated from this program will document the corrosion susceptibility of absorber materials with a wide range of commercially available heat transfer liquids. This information can be used by various segments of the solar industry (designers, installers, manufacturers, architects, etc.) to avoid specific conditions which favor corrosion related failures. Efforts in this area should improve the reliability and maintainability of metallic components used in solar energy systems.

CONTRACT INFORMATION

START DATE 16 Feb. 1981 END DATE 16 Feb. 1983 CONTRACT VALUE $150,000

MILESTONES

Item:	Due date:
1. Semiannual Report	8/81
2. Annual Report	2/82
3. Semiannual Report	8/82
4. Annual Report	2/83
5.	

RELIABILITY AND MAINTAINABILITY PROGRAM

SOLAR ENERGY RESEARCH INSTITUTE

ANTHONY EDEN

EG-77-C-01-4042

OBJECTIVE

The objective of this program at the Solar Energy Research Institute (SERI) is to accelerate the adoption of active solar energy systems in building applications by improving the reliability and maintainability (R&M) of installed systems. The project is designed to accomplish this by providing the latest information from research and development to groups with R&M concerns; by assisting the industry in improving R&M; by assisting in design, manufacture, installation, and maintenance of reliable and durable systems; and by assisting in the development of codes and standards.

DESCRIPTION OF WORK

SERI has the lead managerial role in executing the Program Plan for Reliability and Maintainability in Active Solar Heating and Cooling Systems (DOE/CS/36010-01; Oct. 1980). As such, SERI developed a plan for attaining the objectives of the DOE program, concentrating on solar domestic hot water (SDHW) and space heating systems.

dhr, Inc., as a subcontractor, assessed the current state of R&M. This assessment illustrates the effects of existing programs in the Federal Government, universities, and industry. The subcontractor performed an R&M literature search and evaluated existing solar R&D activities for R&M application. Finally, they evaluated existing training, manufacturers, and design manuals for R&M content and quality. The National Solar Data Network (NSDN) program was reviewed to ascertain whether its present data and analysis are useful for R&M research. SERI proposed modifications of the data gathering system at selected sites.

SERI recognizes a need to be able to assess the reliability of systems in the field and to troubleshoot failed systems. The Field Assessment Coordinating Team (FACT) concept was developed. The FACT can go to a demonstration site and determine the performance of the system in a one- or two-day period. If a failure has been reported, the FACT may take samples of materials for research into the causes. The concept will apply first to SDHW and subsequently expand to space heating.

Much of the emphasis in the R&M Program is on materials research and development and R&M analysis. This portion of the program involves the coordinated efforts of SERI, Argonne National Laboratories (ANL), and Los Alamos National Laboratory. A laboratory method was developed for analyzing R&M data and problems encountered in the field. Using this method, causes of problems are discovered and solutions are developed to prevent material failures. The development of formats for data and field data requirements allows a unified approach to R&M information. The R&M libraries of ANL and the National Bureau of Standards (NBS) were examined for inclusion in a central library at SERI. The NSDN databanks were also evaluated for R&M data. SERI researchers then prepared the output of the materials effort for transfer to the industry. ANL also participated through the development of the SDHW guidelines handbook, fluid corrosion test loops, atmospheric corrosion experiments, and site examinations and failure analysis.

Workshops held at SERI and the four regional solar energy centers (RSECs) brought together R&M experts from industry, the national laboratories, national agencies, and universities to discuss the problems encountered in the field and to help SERI plan the program to solve them. Materials experts spent two days discussing problems and their solutions. The four regional R&M workshops gathered together manufacturers, installers, and designers for direct contact with the beneficiaries of the program. They discussed industry's requirements and offered suggestions for SERI's program and ANL's SDHW guidelines handbook. A product of these meetings was the Industry Directory, a listing of the R&M experts in the different regions to enable less experienced members of industry to find guidance.

Continued assessment and improvement of the technical training courses and manuals will enhance information transfer to industry. The R&M Quarterly Bulletin, instituted in response to suggestions by workshop attendees, provides direct contact with industry. It allows dissemination of current field data, analysis results, information, meeting schedules, laboratory findings, expert opinions, and R&M program status to the industry.

The SERI Quality Assurance and Standards Branch is developing codes and standards and the R&M program supports that activity through close coordination and assistance in developing draft standards or supplying data to the staff. The National Bureau of Standards works closely with SERI, supplying data and information from their R&M library and sharing their expertise. Members of the R&M group help local officials develop models for state legislatures to consider in the solar energy applications field.

SERI was requested to assist DOE/SAN in monitoring the demonstration sites of the Western Region in a technical management role. DOE Headquarters also requested SERI technical monitoring of the sites formerly monitored by NASA. This activity allows the R&M program to gain experience in field evaluation and to apply its expertise to actual system problems. The lessons learned are then relayed to industry through the Quarterly Bulletin. Fourteen western sites and two national ones were under SERI technical management by April 1981.

TECHNICAL ACCOMPLISHMENTS

- R&M kickoff meeting. Experts from industry, national laboratories, national agencies, and universities gathered at SERI to offer their views on the program; its approach, goals, and objectives; and the best ways to impact the industry.

- Materials workshop. The experts in the materials research and development field gathered at SERI for a two-day intensive workshop to discuss the status of materials in solar energy systems and components and to guide the development of the reliability R&D effort.
- Four RSEC regional R&M Workshops. Manufacturers, designers, and installers gathered in each region to discuss their needs and requirements and to review the ANL SDHW guidelines handbook.
- Development of a corrosion sensor for collector systems. Rockwell Science Corporation studied corrosion sensors to determine the most effective way to monitor the corrosivity of a solar collector system fluid. A monitor resembling a fuse was then developed and tested.
- Assessment of current R&M conditions. Upon completion of a subcontract with dhr, Inc., SERI consolidated the results and published an assessment of R&M for SDHW and space heating systems.
- R&M Quarterly Bulletin. The first issue of this newsletter presented the findings of the R&M program to industry in a concise and timely manner.
- Development and test of the Field Assessment Coordinating Team (FACT) concept in the field environment. This team was sent to SDHW sites to compare recorded data with data gathered by their nonintrusive, portable equipment and to evaluate the field procedures.
- Evaluation of inexpensive thermographic equipment for use by the FACT. The least expensive thermography techniques in use today were applied to typical solar collector array systems to ascertain their effectiveness in system analysis and fault detection during reliability evaluations and as a future maintenance tool.
- Performance of fluid corrosion and atmospheric corrosion research. A fluid test loop was operated to explore the corrosion characteristics of selected fluid and metal combinations under the operating conditions of a solar energy system. Samples of collector absorbers were exposed at demonstration sites to determine their deterioration characteristics in different field environments.
- Determination of the characteristics of typical solar collector parameters during system failure. This activity determined the least amount of monitoring required to warn the owner/operator of failure of a solar collector array.
- Modification of the NSDN to gather R&M data directly. The site data acquisition system was modified at selected NSDN SDHW sites to allow the gathering of reliability statistics and data for analysis of the performance and durability of current technology systems and applications.
- Development of the R&M library. A central library, consolidating those of NBS, ANL, and NSDN, was set up in the SERI computer to allow the technical community access to the data gathered by the program in past and present efforts. This data and information may then be used to make informed decisions on system configurations, component selection, material design, and maintenance schedules.
- Development of R&M analysis methodology. The SERI Materials Branch developed a method for evaluating reliability from gathered samples of materials and system components brought into a laboratory from the field. The researchers outlined the actions of an assessment team in the field examining a failed system to discover the cause of the failure. Postmortem laboratory analysis techniques were also developed.

FUTURE ACTIVITIES

SERI has developed a multiyear plan for DOE in the R&M area, expanding the FY 1981 effort in SDHW into solar heating and cooling (SHAC). The FACT will be expanded into SHAC and the commercial possibilities will be demonstrated by the use of inexpensive equipment, new techniques, new procedures, and technical personnel. Reliability R&D will continue to examine current technology, especially in SHAC. The fluid and atmospheric corrosion tests will result in improved understanding of the deterioration mechanisms of materials under the typical operating conditions of solar energy systems. The R&M Quarterly Bulletin will continue to relay the findings of the R&M program and others to industry so that past mistakes can be avoided through technology transfer. Continued scrutiny of controls and related problems will aid the development of more reliable systems and fault detection possibilities. The codes and standards activities will continue to be supported so that consensus committees and coding officials will have the most current information available to them.

PUBLICATIONS

- Assessment of R&M Status (SERI)
- R&M Quarterly Bulletin (SERI)
- Reliability Research and Development Methodology (SERI)
- SERI R&M Program Final Report, FY 1981 (SERI)
- Inexpensive Thermographic Techniques for Determining Reliable Solar Collector Array Performance (SERI)
- R&M Industry Directory (SERI)
- DOE/SAN Demonstration Sites Quarterly Reports (SERI)
- Reliability and Materials Design Guidelines for Solar Domestic Hot Water Systems (ANL/SDP-9)

CONTRACT INFORMATION		
START DATE 1 Oct. 1980	END DATE 30 Sept. 1981	CONTRACT VALUE $1,293,000

MILESTONES	
Item:	Due date:
1. RSEC R&M Workshops, March 1981	
2. Assessment of R&M Status, April 1981	
3. Reliability R&M Methodology, June 1981	
4. R&M Quarterly Bulletin (No. 1), September 1981	
5. SERI R&M Program Final Report, FY 1981; September 1981	

SOLAR COLLECTOR STUDIES FOR
SOLAR HEATING AND COOLING APPLICATIONS

SPRINGBORN LABORATORIES, INC.

BERNARD BAUM, Ph.D.

CONTRACT DE-AC04-78CS35359

OBJECTIVE

The project objectives are: to evaluate weather-resistant, low-cost glazing and housing materials that will have a lifetime of up to twenty years under varying stress and high (300°F) temperature; to screen surface etching processes and anti-reflective coatings to reduce reflection losses and increase transmission of plastic glazing: to develop coatings and films for UV protection of plastics.

DESCRIPTION OF WORK

A nonglass glazing (or housing) and surface coating must withstand many years of outdoor weathering in a terrestrial environment. As new structural materials, plastics offer attractive opportunities for outdoor use. Like most organic materials, however, they are reactive to atmospheric oxygen, moisture, and light. Thus, in extended outdoor use they gradually deteriorate by discoloration, loss of gloss, crazing, chalking, erosion, cracking, embrittlement, and loss of strength and extensibility.

The problems of weathering are complicated because of the multiplicity of conditions which may be imposed. Conditions of exposure, the nature of the plastic and its formulation, and the performance requirements are all interrelated and must be considered in choosing a material for an application.

Since an ultraviolet absorber in the interior of the polymer may still permit attack on the polymer, it is desirable to apply a surface coating containing a high concentration of ultraviolet absorber in a coating binder such as acrylic, which is relatively stable to weathering, to minimize attack on the polymer matrix and enhance long term stability.

An alternate approach to meet the proposed objectives of 20 year service life is the development of stable films containing UV absorbers capable of protecting the polymer substrate under adverse environmental conditions.

The plastic glazing must have minimum reflectivity to allow the maximum percentage of solar energy to pass through to the collector. One way of achieving this is through use of an AR coating applied to the glazing surface.

TECHNICAL ACCOMPLISHMENTS

Accelerated aging techniques were employed in a preselection process to optimize the probability of selecting candidate materials for in depth evaluation. Representative samples of the following generic classes of materials- fluorocarbon, acrylic, polyarylate, UV stabilized polycarbonate and UV stabilized crosslinked ethylene vinyl acetate copolymer - have shown little, if any deterioration after eight months on the EMMAQUA in Arizona. Thermoplastic polyesters, including UV impregnated materials, are degraded. (Table I)

. The following potential housing materials have evidenced no significant change in properties after one year's exposure on the Weather-Ometer: (FRP) Fiberglass-reinforced UV stabilized polyester and carbon black filled, peroxide crosslinked high density polyethylene. (Table II)

. Several candidate fluorocarbon and thermoset polyester glazing materials have withstood long term aging at 150°C (simulating stagnation temperature) without significant change.

. Acrylic coating systems containing UV absorbers have been developed to protect collector glazings. Three glazings - polycarbonate, acrylic homopolymer and glass scrim reinforced, peroxide crosslinked ethylene vinyl acetate copolymer - have been coated with these systems and are being subjected to accelerated weathering as well as EMMAQUA exposure. (Table III)

. Methods of bonding UV screening polymer films to several polymer glazings have been developed. Under exterior exposure polyvinyl fluoride film containing a UV absorber is promising as a means of protecting a less stable polymeric glazing substrate. Specific fluorocarbon films laminated as a top layer over peroxide crosslinked ethylene vinyl acetate copolymer shows little if any degradation after four months in the Weather-Ometer. (Table IV)

Magnesium fluoride antireflective coating increased the light transmission characteristics of several plastic sheets.

FUTURE ACTIVITIES/PUBLICATIONS

This program has provided a selection of materials for solar collector glazings which under laboratory as well as actual service conditions have demonstrated successful performance. It has also provided a methodology for accelerated laboratory screening as well as correlating field and laboratory results. The results of this program should assist manufacturers of solar collectors in selecting the optimum polymeric materials for their specific applications and in developing lower cost glazing composites that would have long outdoor life. Technical presentations and publications will be prepared to provide a transfer of technology to the private sector.

TABLE I

WEATHER RESISTANT(1)
POLYMERIC GLAZINGS

Material	Chemical Nature
Tedlar 400-XRB160SE	Fluorocarbon
PFA	Fluorocarbon
Halar 500	Fluorocarbon
Filon 558	Thermoset Polyester
Sunlite Premium II	Thermoset Polyester
Tuffak CM-2	Polycarbonate
Plexiglass V-811	Acrylic
Flexigard 7410	Polyester/Acrylic Laminate
EVA	Crosslinked Ethylene Vinyl Acetate Copolymer

(1) Eight months under EMMAQUA

TABLE II

WEATHER RESISTANT(1)
POLYMERIC HOUSING MATERIALS

- Fiberglass Reinforced, U.V. Stabilized Polyester Sheet
- Carbon Black Filled, Crosslinked High Density Polyethylene

(1) One year in the Weather-Ometer

TABLE III

ACRYLIC COATINGS - UV STABILIZATION SYSTEMS

Substrates	Acrylic Coatings
Polycarbonate	Latex - Thermoset
Acrylic	Solvent - Thermoset
Crosslinked EVA	Solvent - Thermoplastic

UV Absorbers	Antioxidants
Benzophenone	Distearylthiodipropionate
Benzotriazole	Hindered Phenolic
Oxalic-Anilide	Isocyanurate
	Phosphite

TABLE IV

PROMISING LAMINATES AFTER
FOUR MONTHS IN THE WEATHER-OMETER

Substrate	Cover Film	Adhesive
EVA(1)	Tedlar 100-XRB160SE(3)	Lupersol 101(2)
EVA	Halar 500(4)	Lupersol 101

(1) Peroxide crosslinked ethylene Vinyl acetate copolymer
(2) Peroxide
(3) Polyvinyl fluoride
(4) Ethylene/chlorotrifluoroethylene

CONTRACT INFORMATION

START DATE October 1978 END DATE August 1981 CONTRACT VALUE $177,535

MILESTONES

Item:	Due date:
1. Complete sheet weathering exposure	
2. Evaluate critical properties	
3. Complete EMMAQUA exposure	
4. Develop UV protective coatings	
5. Complete weathering of coated glazings	

DEVELOPMENT OF SELECTIVE SURFACES

TELIC CORPORATION

Dr. JOHN A. THORNTON

DE-AC04-80AL13116

OBJECTIVE

The goal of this program is to develop the materials and technology for producing inexpensive and durable solar selective coatings in a continuous or semicontinuous mode on plates or metal strips, by means of planar magnetron sputtering. An important adjunct to this goal is the preparation of continuously coated strip to be provided to interested manufacturers for the fabrication of collectors and tested in the field by firms working in the solar industry.

DESCRIPTION OF WORK

In a previous program metal/oxide layered coatings of the Al_2O_3-Mo-Al_2O_3 (AMA) type, with hemispherical absorptances (α) of $\sim$0.95 and room temperature emittances (ϵ) of $\sim$0.07, were deposited onto Mo-coated stainless steel flat plates and tubes by sputtering. (1) Cylindrical-post and cylindrical-hollow magnetron sputtering sources were used. An Al_2O_3 diffusion barrier was used between the stainless steel and the Mo low emittance base layer. Coatings were deposited with the Al_2O_3 layers formed by direct rf sputtering from alumina targets and by reactive sputtering from Al targets. The AMA coatings with direct rf sputtered Al_2O_3 layers appeared to be stable (no change in α after $\sim$10 hrs of testing) to 550°C in air and to 700°C in vacuum. By contrast, similar coatings with Al_2O_3 layers formed by reactive sputtering were stable to about 300°C in air and to about 400°C in vacuum. The feasibility of continuously coating metal strip was demonstrated.

Planar magnetron sputtering sources of the type shown in Fig. 1 are particularly attractive for coating flat plates and strip in a continuous or semicontinuous manner. Sputtering occurs from the cathode surface region underneath the loop of magnetically confined plasma. The magnetron sources can be scaled to long lengths (several m). The emission of sputtered flux is uniform along the length. Strip or plates are generally, passed in front of the sources in a direction perpendicular to the long axis of the plasma loop. Several sources can be placed in series to deposit multilayer coatings or to build up coating thickness. Large in-line planar magnetron coating facilities are used, for example, to coat (2m x 3.5m) sheets of architectural glass at production volumes up to about 10^6 m^2/yr. (2)

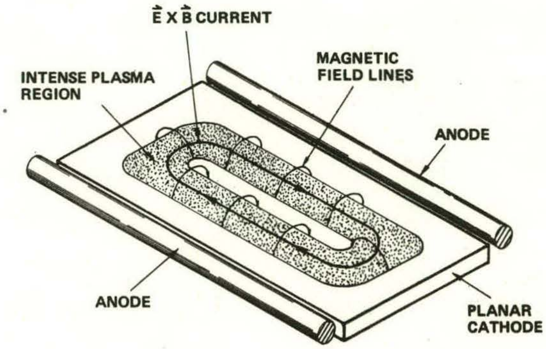

FIG. 1 Schematic illustration of planar magnetron sputtering source.

The present program addresses the application of planar magnetron sputtering for the continuous or semicontinuous deposition of AMA type coatings onto plates or metal strip. It recognizes the potential importance of reactive sputtering (which is less costly to scale to large coating facilities) as a method for depositing low cost coatings of high optical quality for medium temperature collectors, as well as coatings with rf sputtered Al_2O_3 for higher temperature applications. Thus work on the project is being carried out in four basic areas.

One task is to investigate materials other than Mo for the metal layer, in order to achieve improved thermal stability in air. Materials for use with both reactive and rf-sputtered Al_2O_3 are being examined. The objective is to find materials that yield increased lifetimes under hot oxidizing conditions up to 500-600°C and at lower temperatures (100°C) in water. Previous work has examined the stability of various dielectric-metal-dielectric coatings for high temperature applications in vacuum, but not in air. (3) In a preliminary evaluation on the present program Cr, Ni, and Pt have been selected for examination along with additional work using Mo. The apparatus shown in Fig. 2, which incorporates a multi-substrate holder with three planar magnetron sputtering sources, is being used for the basic material studies. Figure 3 shows the hemispherical spectral reflectance of an Al_2O_3-Cr-Al_2O_3 coating on a Cr-base layer with reactively sputtered Al_2O_3 layers. Coatings of this tube were stable in five-day humidity tests at 95°C and 95% relative humidity, but degraded at 300-350°C in air. Al_2O_3-Cr-Al_2O_3 coatings, with direct rf-sputtered Al_2O_3 layers, appear to be stable to higher temperatures (at least

450°C) as was the case for the Mo coatings. Figure 4 shows the spectral reflectance for an Al_2O_3-Pt-Al_2O_3 coating with rf sputtered Al_2O_3 layers. Coatings of this type have yielded $\alpha = 0.93$ and $\epsilon(20) = 0.08$ and were stable in the humidity test and in air up to 600°C. (4) Pt/Al_2O_3 coatings show promise for achieving high thermal stability, with reactive sputtered Al_2O_3. (5)

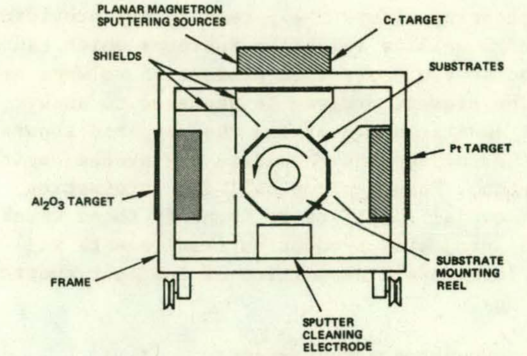

FIG. 2 Experimental apparatus used to test new materials.

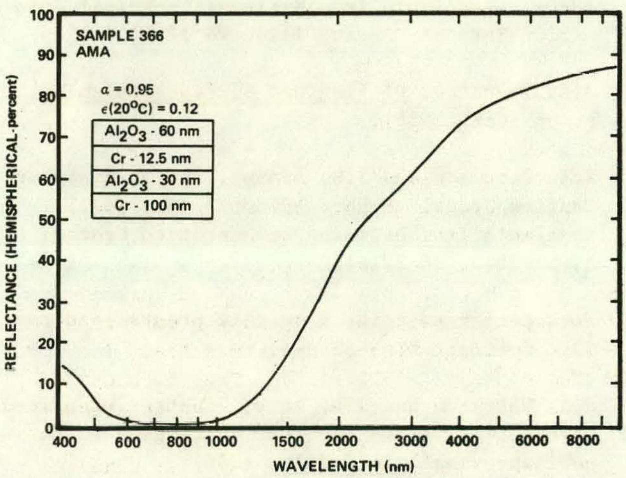

FIG. 3 Spectral reflectance of AMA coating with a Cr M-layer.

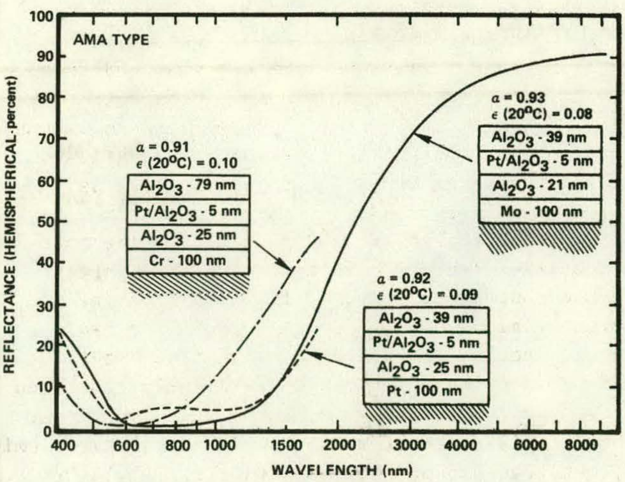

FIG. 4 Spectral reflectance of AMA coating with Pt/Al_2O_3 M-layer.

A second objective is to investigate methods for improving the performance of planar magnetron sputtering sources when driven by rf methods for the purpose of sputtering Al_2O_3. The objective of this task is to demonstrate deposition rates (500 Å/min or more) that would facilitate continuous processing. Deposition rates of about 150 Å/min have been achieved. However, problems of target cracking have been encountered at high power levels. Work is continuing.

A similar objective is to investigate methods for increasing the rate of aluminum oxide reactive sputtering. The objective of this task is to demonstrate rates of 2000 Å/min (3.33 nm/s) or more. The problem encountered in reactive sputtering is that increasing the rate of O_2 injection to a value sufficient to cause a stoichiometric Al_2O_3 coating to form on the substrates, also causes an oxide layer to form on the cathode. The development of such a poisoned cathode causes a sharp decrease in deposition rate. Experiments are being conducted using the apparatus configuration shown in Fig. 5, which attempts to separate the sputtering process from the substrate reactions and therefore to avoid cathode poisoning under conditions where stoichiometric coatings are deposited. Deposition rates of about 1000 Å/min have been achieved, but the coatings are non-stoichiometric.

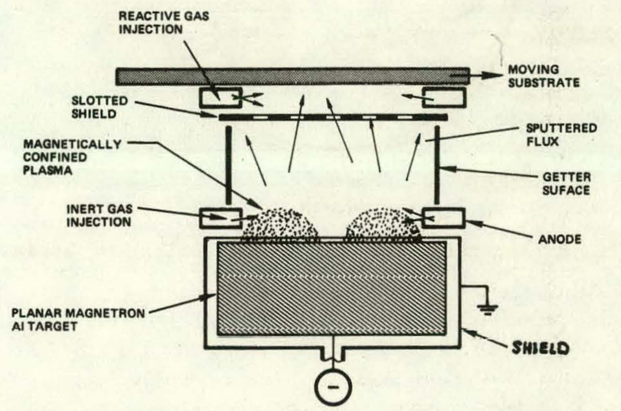

FIG. 5 Experimental configuration used for reactive sputtering studies.

A final task will investigate the continuous deposition of AMA type coating onto moving strip by means of the simultaneous operation of three planar magnetron sputtering sources. The apparatus that has been designed for this task is shown in Fig. 6. The apparatus is designed to coat 6 inch wide strip up to about 200 feet in length. An important aspect of this task is to provide coated copper or aluminum strip to interested manufacturers for fabrication into collectors and testing.

TECHNICAL ACCOMPLISHMENTS

- An experimental apparatus (Fig. 2), which combines a heatable substrate holder with three planar magnetron sputtering sources and provisions for substrate sputter cleaning, has been designed and fabricated for use in testing new material combinations (4).

- An experimental apparatus (Fig. 6), which will permit the continuous deposition of AMA type coatings onto moving strip by means of the simultaneous operation of three planar magnetron sputtering sources, has been designed and is under construction.

- AMA type coatings with high absorptances ($\alpha \sim 0.95$) and low emittances ($\epsilon \sim 0.1$) have been demonstrated for both Cr (Fig. 3) and Pt (Fig. 4) M-layers. The effectiveness of Mo M-layers was demonstrated in previous work. Coatings with thin (~5 nm) Pt/Al_2O_3 M-layers show promise as a configuration that might provide high thermal stability with low-cost reactive sputtered Al_2O_3 layers.

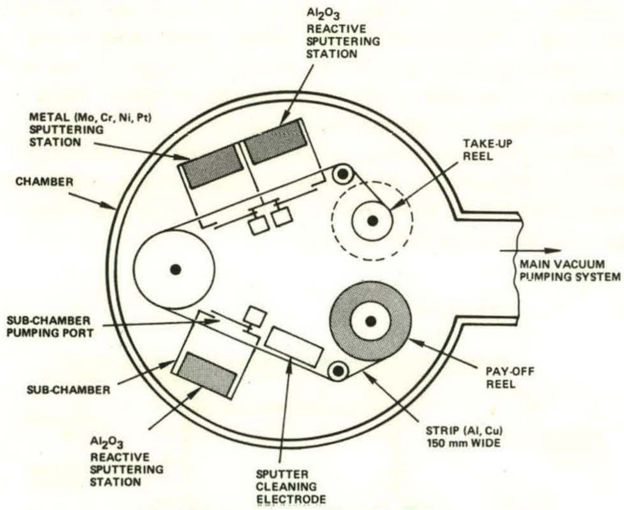

FIG. 6 Apparatus for continuous coating of strip.

FUTURE ACTIVITIES

Contract activities. Progress during the first few months of the project was delayed by the availability of equipment. Work is now proceeding. A no-cost contract time extension will be requested to recover time lost in the early delays.

Post-Contract activities

Sputtering offers the potential for providing stable high quality selective surfaces which can be deposited at low costs when production volumes are high. The present program is designed to answer critical questions concerning the required apparatus configurations and therefore the needed capital investments. Future plans call for interacting with commercial suppliers to identify those cases where the projected production requirements will justify large scale deposition of low cost sputtered coatings.

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4) Work performed jointly on this program and on SERI Contract XE-9-8260-1.

5) J.A. Thornton and J.L. Lamb, "Sputter Deposited Pt/Al_2O_3 Selective Absorber Coatings," to be published Thin Solid Films (1981).

CONTRACT INFORMATION

START DATE Sept. 5, 1980 END DATE Sept. 11, 1981 CONTRACT VALUE $127,672

MILESTONES

Item:	Due date:
1. Technical Progress Report	April 1981 (p)
2. Final Technical Report	Sept. 1981
3.	
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STUDIES FOR PREDICTABLY MODIFYING THE OPTICAL CONSTANTS OF DOPED INDIUM OXIDE FILMS

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DE-AC04-78CS35307

OBJECTIVE

Correlate the wavelength dependence of the optical constants of polycrystalline films of doped indium oxide with structure, composition, and thermal history, and arrive at a useful model of the electromagnetic behavior of doped indium oxide so that one could predictably modify its optical constants and those of related metal oxides.

BACKGROUND

Generally, photothermal absorbers and photovoltaic cells are fabricated from substances (e.g., Si) with a relatively high solar spectrum refractive index (e.g., $n_{Si} \sim 3$ to 4). Consequently, there is a need for an antireflection (AR) coating to minimize the considerable reflection loss (e.g., $R_{Si} \sim 35\%$). Furthermore, to prevent loss of heat by radiation in the thermal infrared it is necessary to have high purity, defect free, (and therefore costly), material to avoid free charge carrier absorption - or emission, per Kirchhoff's radiation law. At Tufts [1,2], it was shown that a tin-doped indium oxide coating is a good candidate for providing both AR properties as well as high thermal infrared reflection (TIRR) [Ref. 1]. Additionally, it was shown that the properties of such a coating were relatively independent of coating thickness, of angle of incidence of radiation, and of temperature (for T < 500°C). Finally, such a coating could also serve as a transparent electrode for photovoltaic solar cells. Several questions remained: (1) to what practical extent could one modify, by composition changes (doping), the solar spectrum optical constants of such coatings and still maintain the high TIRR, allowing one to fabricate a graded index coating with nearly ideal AR/TIRR; (2) could one achieve composition changes by an economical spray pyrolysis process; (3) would stoichiometry changes (by oxidation or reduction) drastically alter the optical constants; and (4) could one arrive at a model(s) sufficiently useful to enable one to predict the effects on the optical constants of composition changes? It was the objective of this project to answer these questions.

SUMMARY

The studies have demonstrated that composition changes, and particularly cation doping, could be achieved. This has been accomplished for 9 dopants by a simple and economic spray pyrolysis process. The refractive index at 633 nm wavelength (n_{633}) can be modified by such doping - n_{633} changes of ≤ 5% occur for dopant concentrations ≤ 20 mole percent (the size and sign of the change being a function of the dopant). Oxidation and reduction anneals likewise result in modifications in n_{633}.

Two very useful optical measurement techniques have been developed to precisely and sensitively measure the relatively small changes in refractive index, as well as to otherwise optically evaluate the films; and two useful phenomenological models have been developed to understand the effects of composition changes.

TECHNICAL ACCOMPLISHMENTS

- Cation dopants (Al, B, Bi, Cd, Fe, Sb, Sn, Zn, Zr) can be incorporated into indium oxide coatings by a simple and economic spray pyrolysis technique. Concentrations ≲ 25 mole percent have been readily achieved by this technique.

- n_{633} has been modified by cation doping by spray pyrolysis, with the largest changes occurring for bismuth doping (20% Bi → Δn_{633} = +0.11), and for boron doping (16% B → Δn_{633} = -0.11).

TABLE 1

MODEL A PREDICTIONS AND COMPARISONS

DOPANT ION	STARTING DOPANT CONCENTRATION	DOPANT OXIDE	PUBLISHED n DOPANT OXIDE	MODEL A PREDICTED n_{D10}	MEASURED n_{D10}
NO DOPANT	- - -	In_2O_3	2.10	2.10	2.03-2.10
B^{3+}	0.16	B_2O_3	1.46	1.97	1.99
"	0.74	"	"	1.6	1.8
Fe^{3+}	0.20	Fe_2O_3	2.88	2.22	2.12-2.15
Bi^{3+}	0.20	Bi_2O_3	2.57	2.18	2.21
Sb^{3+}	0.20	Sb_2O_3	2.087	2.097	2.08-2.125
Al^{3+}	0.20	Al_2O_3	1.65	2.00	2.063-2.075
Sn^{4+}	0.10	SnO_2	2.03	2.09	2.02
"	0.15	"	"	2.08	1.7
Zr^{4+}	0.03	ZrO_2	2.17	2.10	2.05
Cd^{2+}	0.20	CdO	2.49	2.19	2.07
B^{3+}, Sn^{2+}	0.10,0.10	- - -	- -	2.02	2.0
" "	0.50,0.10	- - -	- -	1.68	1.88
Zn^{2+}	0.20	ZnO	1.97	2.05	1.98

- n_{633} has been found to be insensitive to oxidation or reduction anneals, for temperatures ≤ 450°C and for anneal times ≤ 100 mins. For times ≥ 2 hours, however, changes in n_{633} of approximately 10% or larger are observed, for anneal temperatures 400-450°C. Such changes are reversible: a decrease caused by a reduction anneal can be reversed by an oxidation anneal, restoring the original n_{633}.

- A very precise and sensitive refractive index measurement technique, the prism-coupled optical waveguide technique [4] has been developed.

- A very precise and sensitive reflection vs. angle measurement technique, the Brewster-Abeles technique [5] has been developed for spatially mapping the refractive index.

● Two different local polarizability models have been developed and both yield good fits to the n_{633} data. Model A estimates the polarizability of a composite oxide by weighting the polarizabilities of each oxide molecule according to the percentage of each, using the Clausius-Mosotti relationship [6]; Model B estimates the polarizability of a composite oxide by weighting the polarizability of each constituent ion both according to the relative percentages of each ion as well as by the relative local electric fields at each site, Model B has been useful for estimating the polarizabilities of the 9 cation dopants studied, and for estimating the relative local fields in the dopant cation oxides.

Table 2. Model B Estimates of Cation Polarizabilities (α_D) and local field Weighting Factors (w_D) in Dopant Oxides Obtained from Refractive Index (n_{DIO}) Measurements of Doped Indium Oxide (DIO) Films. Oxygen Polarizability, α_o = 1.5 (Å)$^{3(a)}$.

Cation Dopant	Dopant Concentration	Measured n_{DIO} (± .005) (633 nm)	DIO Lattice Const (Å) (± .005 Å)	Dopant Oxide	Published Average $\bar{n}$ dopant oxide	Oxygen Weighting Factor w_o in Dopant Oxide	w_D	Est. α_D(Å)^3 (This work)	Reported Cation Polarizab. α_D(Å)^3
UNDOPED In_2O_3	- - -	2.09	10.10	In_2O_3	- - -	3	0.56	6.5$^{(c)}$	6.5
Cd^{2+}	0.20	2.07	10.13	CdO	2.49	1	0.69	5.7	0.8–4.59
Zn^{2+}	0.20	1.98	- - -	ZnO	1.97	1	0.84	1.59	1.7–3.28
Al^{3+}	0.20	2.01	10.09	Al_2O_3	1.65	1.33$^{(b)}$	0.56	3.02	0.05–3.83
Sb^{3+}	0.20	2.08	10.18	Sb_2O_3	2.09	3	1.18	6.14	6.74
Bi^{3+}	0.20	2.21	10.18	Bi_2O_3	2.44	3	0.79	11.4	4.8
B^{3+}	0.20	1.99	9.99	B_2O_3	1.46	1.95$^{(b)}$	0.56	2.11	0.003–1.59
Fe^{3+}	0.20	2.12	10.01	Fe_2O_3	2.88	3	0.53	8.07	- - -
Sn^{4+}	0.15	2.08	10.12	SnO_2	2.03	2	0.26	6,02	
Zr^{4+}	0.04 ±.01	2.07	10.11	ZrO_2	2.18	2	0.79	2.48	0.37

(a) The reported values for α_o = 0.5 to 3.2 (Å)^3.

(b) To avoid negative values of w_D, yet retain α_o = 1.5 (Å)^3, we assumed that w_D was the same as for In_2O_3 (0.56), and computed w_o for Al_2O_3 and B_2O_3. This could have been avoided if we had relative local field data, in which case we could have checked the validity of using α_o = 1.5 (Å)^3 in these two oxides.

(c) The basis for all the estimates was that α_{In} = 6.5 (Å)^3, the value reported by Pandey et al.[7]

POLARIZABILITY MODEL A

$$\left(\frac{n^2-1}{n^2+2}\right) = X\left(\frac{n_1^2-1}{n_1^2+2}\right) + (1-X)\left(\frac{n_2^2-1}{n_2^2+2}\right) \quad (1)$$

n = refractive index of composite system.

n_1 = refractive index of component 1.

n_2 = refractive index of component 2.

X = fractional mole concentration of component 1.

$1 - X$ = fractional mole concentration of component 2.

POLARIZABILITY MODEL B

UNDOPED CASE: (2)

$$\left(\frac{n^2-1}{n^2+2}\right) = \left(\frac{4\pi N}{3}\right) A_{Molecule} = \left(\frac{4\pi N}{3}\right)(W_C A_C + W_A A_A)$$

CATION DOPED CASE:

$$\left(\frac{n^2-1}{n^2+2}\right) = \frac{4\pi N}{3} \cdot [W_C(XA_D + (1-X)A_C) + W_A A_A]$$

n = Refractive Index.

$1/N$ = Volume per "Molecule". (Å)^3

$A_{Molecule}$ = Polarizability of Molecule. (e.g., of In_2O_3) (Å)^3

W_C = Combined stoichiometry and local electric field weighting factor at cation site.

A_C = Polarizability of cation. (Å)^3

W_A = Combined stoichiometry and local electric field weighting factor at anion site.

A_A = Polarizability of anion. (Å)^3

A_D = Polarizability of cation dopant. (Å)^3

X = Fractional mole concentration of cation dopant (= [dopant]/{[dopant]+[cation]})

● A characteristic matrix program has been developed to predict reflection or transmission as a function of angle and wavelength, and is particularly useful for antireflection and heat mirror coatings.

POST CONTRACT ACTIVITIES

1. Attempts will be made to use the prism coupled optical waveguide technique to measure th extinction coefficients of thin films and to extend the measurement capability to films of arbitrarily small thickness.

2. Attempts will be made to establish and evaluate two different techniques for determining

arbitrary optical constants profiles.

3. Attempts will be made to spray deposit thick, highly textured DIO films and determine the applicability of such films as selective absorbers.

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CONTRACT INFORMATION

START DATE 5 JUNE 1978 END DATE 31 DEC 1980 CONTRACT VALUE $88, 086

MILESTONES

Item: Due date:

1. Publication - R. B. Goldner et al., Appl. Optics, 20, 15 June 1981.
2. Final Report - pending.
3.
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5.

IMPROVED SOLAR COLLECTOR SEALANTS

WESTINGHOUSE ELECTRIC CORPORATION

MORRIS A. MENDELSOHN, LAWRENCE W. FROST

DE-AC04-78CS15362

OBJECTIVE

To study properties of several possible solar collector sealants, and choose the best candidates; to study the effects of breathing in flat-plate thermal solar collectors; to improve long term performance of best candidates by chemical modifications and by reformulation.

DESCRIPTION OF WORK

This investigation has two phases. In Phase 1, data were collected from manufacturers and from the technical literature on the endurance of Class PS (preformed seals and gaskets) and Class SC (sealing compounds) elastomers under service conditions. Environmental stresses evaluated experimentally were: elevated temperature, moisture, ultraviolet light, ozone and oxygen, and fungus. Compression set, tensile properties, hardness and weight loss (condensable volatiles) were chosen as the major criteria of thermal stability. The effects of design, fabrication, materials, sealing techniques, and absorber plate coatings on the durability of solar collectors were also investigated. Phase 2, which started in Oct., 1980, includes a synthetic program to improve the properties of the best materials chosen in Phase 1, by modifying their chemical structures. The search for and testing of new elastomeric candidates as they are offered by suppliers, is continuing, with emphasis on cost effectiveness.

TECHNICAL ACCOMPLISHMENTS

- An extensive literature survey followed by laboratory screening tests was used to select Class PS (preformed rubber seals) and Class SC (sealing compounds or caulks) elastomers for laboratory testing of their performance under the harsh environment of a thermal solar collector cell.

- Although none of the PS elastomers tested was found to be entirely satisfactory, a fluorocarbon (Viton) displayed the best durability and thermal stability overall. The silicones were second best. The fluorocarbons exhibit excessive low temperature compression set, which could be a serious problem in areas having cold winters. The silicones show poor resistance to compression set on thermal aging. The fluorocarbon is much better in this respect, but still has undesirably high values.

- The polyacrylate and acrylic copolymers and one of the ethylene-propylene terpolymers (EPDM - Nordel) were the best of the intermediate temperature elastomers. Except for resistance to compression set, these materials were inferior to the silicones in thermal stability. The other EPDM compounds and butyl rubber were considerably inferior to these three compositions. Figure 1 shows compression set aging data.

- The only Class SC compositions which retained moderate physical integrity on thermal aging were the silicones. Studies showed that the Class SC elastomers generate considerably more volatiles (and condensables) during thermal aging than do the Class PS elastomers.

- Five collectors, which had been in service at three different locations, were examined with regard to their design and quality of fabrication. A typical solar collector design is shown in Fig. 2. Problems observed consisted of corrosion, glaze deposits, and degradation of sealants and absorber plate coatings. Only one of the collectors appeared to be in very good condition.

- Synthetic modifications of silicones and fluoroelastomers, involving bulky substituents, occasional rigid linkages, interpenetrating networks of other polymers, and use of unconventional crosslinking methods, are being explored in order to decrease siloxane bond interchange and fluorocarbon chain crystallization, thought to be the cause of excessive compression set and emission of condensable volatiles. Siloxane diamines and diphenols have been synthesized for use as fluoroelastomer crosslinkers and chain separators.

- The elastomers listed in Table 1 (all different or improved versions of those evaluated in Phase 1 of this project) were acquired at the beginning of Phase 2. They were tested for tensile strength, modulus, elongation, hot and cold compression sets, volatiles, and hardness change, according to the proper ASTM methods. Only three of the materials failed any test, and that was low temperature compression set. These results show that the industry has independently upgraded the pertinent properties of the materials designed for solar collector use.

FUTURE ACTIVITIES

Develop sealants which exhibit improved long term stability. This is exemplified by low compression set, low volatile loss and high retention of original physical properties on prolonged exposure to the environmental conditions encountered by the collector.

PUBLICATIONS/REPORTS/REFERENCES

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2. M. A. Mendelsohn, et al., "Degradation of Solar Collector Sealants", 118th Meeting of the ACS Rubber Division, Detroit, Oct. 1980.

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4. M. A. Mendelsohn, et al., "Degradation of Solar Collector Sealants", SPE's 39th ANTEC, Boston, May 1981.

5. R. M. Luck and M. A. Mendelsohn, "Formation of Degradation Products From Solar Collector Sealants and Their Effects Upon Collector Efficiency", SPE's 39th ANTEC, Boston, May 1981.

6. M. A. Mendelsohn, et al., "Collector Sealants and Breathing", Final Report Contract DE-AC04-78CS15362, U.S. Dept. of Energy, Feb. 20, 1980.

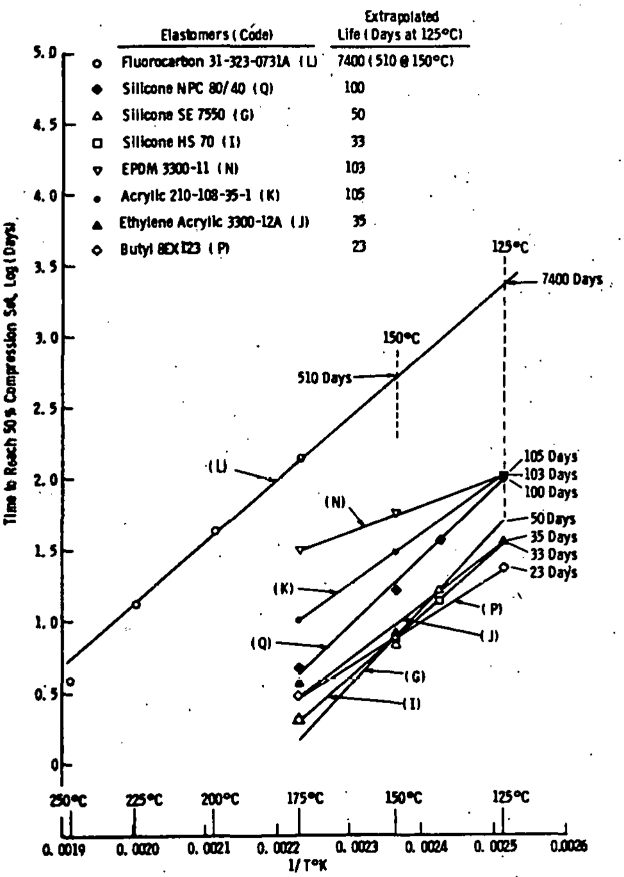

Fig. 1 — Arrhenius plot of compression set aging data

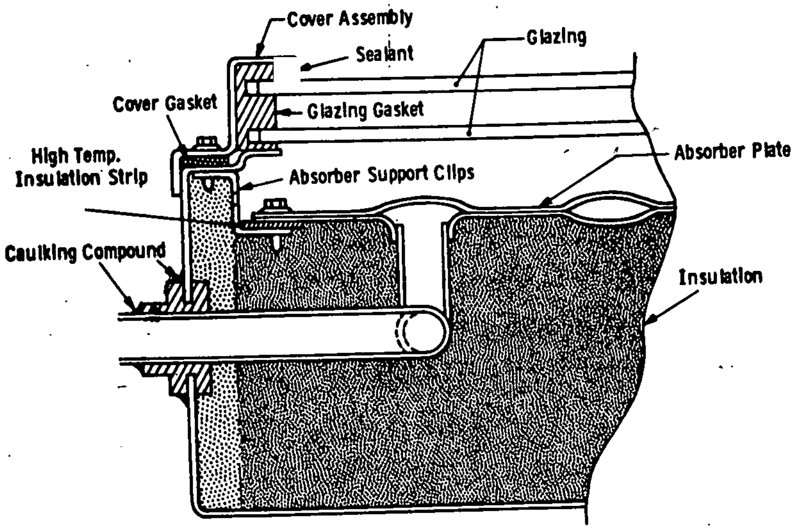

Fig. 2 – Assembly of a typical solar collector.

TABLE 1

SOLAR COLLECTOR MATERIALS

ITEM	POLYMER CLASS	SEAL TYPE	MATERIAL GRADE	SUPPLIER
1	EPDM	PS	VISTALON 404	EXXON CO.
2	"	"	NORDEL 1070	DUPONT CO.
3	"	"	EPSYN 4506	COPOLYMER CO.
4	"	"	EPCAR 545	B.F. GOODRICH
5	"	"	EPCAR 585	"
6	"	"	ROYALENE 580HT	UNIROYAL
7	ACRYLIC	"	CYANACRYL R	AMERICAN CYANAMID
8	"	"	HYCAR 4054	B.F. GOODRICH
9	ETHYLENE ACRYLIC	"	VAMAC B-124	DUPONT
10	FLUOROELASTOMERS	"	VITON AHV	"
11	"	"	FLUOREL 2179	3M CO
12	SILICONE	"	TUFEL SE-845	GE
13	"	"	SE-7603U	"
14	"	"	SE-3715U	"
15	"	SC	1576LV	"
16	"	"	160-3-381	"
17	"	PS	SILASTIC 747U	DOW CORNING
18	"	"	SILASTIC 745U	"
19	"	SC	3145	"
20	"	"	3140	"
21	"	"	795	"
22	"	"	738	"
23	"	"	SWS951	SWS CO.
24	"	PS	SWS7162U	"
25	CHLOROBUTYL	"	1066	EXXON

CONTRACT INFORMATION

START DATE Sept. 25, 1978 END DATE May 31, 1982 CONTRACT VALUE $368,631

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2. p - Semi-annual Report, Second Phase (Sept. 1980-May 1982).	May 1981
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