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**FINAL REPORT FOR PROGRAMMATIC SUPPORT
AND PUBLIC INFORMATION DISSEMINATION**

**FINAL REPORT
FOR PERIOD OCTOBER 1, 1977-DECEMBER 31, 1978**

S. KARAKI

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Final Report
for Period October 1, 1977-December 31, 1978

S. Karaki

Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

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ABSTRACT

Research projects in solar heating and cooling, photovoltaics, and industrial heating, and training programs in solar heating and cooling have been conducted in the CSU/SEAL program. Major accomplishments are:

- Development of a solar heating and cooling system with evacuated tube collectors
- Determination that solar air heating and liquid heating systems of comparable collector quality have comparable seasonal performance and parasitic power requirements
- Development of photovoltaic cells of ITO/Silicon that have 10 percent efficiency.
- Installation of a commercial scale solar laundry drying facility.

Detailed results are described in final reports, publications and dissertations that are listed in Sections 4, 5, and 6 of this report.

FINAL REPORT FOR PROGRAMMATIC SUPPORT AND PUBLIC INFORMATION DISSEMINATION

1. INTRODUCTION

The purpose of this work is to coordinate and manage solar energy research at the CSU Solar Energy Applications Laboratory. The principal tasks were to:

- Coordinate the research concerned with solar energy applications among the faculty of many academic departments of the university.
- Disseminate the information derived from research in an appropriate form for the public.
- Conduct conference on performance experiences of solar heating systems so that the public may benefit from the experience of others.
- Prepare monthly reports to summarize important activities and results developed within the CSU program.

2. COORDINATION OF RESEARCH AT CSU/SEAL

An overall programmatic proposal was submitted to DOE for support of a broad-based research and development program in solar energy applications at CSU/SEAL. The programmatic plan, however, was not fully supported by DOE and specific projects were selected for support instead. The individual projects receiving DOE support were ongoing projects for:

- (a) solar heating and cooling systems development
- (b) photovoltaic cell development.

New projects supported were:

- (a) study of optimal controllers for solar heating and cooling systems

- (b) investigation of stratification enhancement in water thermal storage tanks
- (c) identification of cost-effective fabrication and installation methods for solar systems
- (d) supplement of solar heat for a laundry drying facility
- (e) investigation of integrating off-peak electric auxiliary heating units with solar heating systems
- (f) development of low-cost methods for sky temperature measurement
- (g) development of stochastic models of solar weather data for hardware systems design

3. PROGRAM ASSESSMENT

3.1 Solar Heating and Cooling of Buildings

3.1.1 Systems

The solar heating and cooling program at SEAL focuses on systems and component R&D. The overall goals are to evaluate system performance, improve efficiencies of components and systems and investigate opportunities for reductions in costs of manufacture and installation.

The four experimental buildings in the Solar Village at Colorado State University are devoted to research and development of solar energy systems for heating and cooling of space and heating service hot water. Three are identical buildings with similar heating loads that incorporate four different systems. (There are two systems for Solar House I.) One building is an active/passive air-heating system in a greenhouse/residence combination that stores the excess heat from the direct gain of solar energy into the greenhouse and an active system for night-time heating.

All of the systems are designed to provide a substantial portion of the space and water heating needs from solar energy, and the three liquid systems are designed to provide a significant contribution from solar energy for space cooling using absorption water chillers. The cooling system in Solar House II, which utilized nocturnal evaporative cooling of the pebble bed was replaced with an air-to-air heat pump for operation during mid-summer of 1978.

The flat-plate system which has been in operation in Solar House I since 1974 has been an effective solar heating system providing between 70 and 80 percent of the space heating needs. The data produced from the experimental system are among the few definitive system performance records in existence to date in published literature, and have contributed significantly to the validation of simulation models. The validated models are being used by many other researchers to assess the applicability of the solar systems, in technical and economic terms, in various regions of the United States.

The flat-plate air-heating system in Solar House II, in operation since early 1976, has been fully evaluated and compared with the liquid systems in Solar House I. An important conclusion resulting from the experimental evaluation is that an air-heating solar system can deliver as much heat as a comparably sized flat-plate liquid-heating solar system. Both have low parasitic power requirements of 5 to 7 percent of the solar energy collected. The comparison is the first definitive result and is viewed as an important conclusion because more system choices are made available to the public by development of air systems as well as liquid systems.

Although the performance of site-built air- and liquid-heating solar systems have been greatly improved and shown to be practical, it is important that state-of-the-art systems with flat-plate collectors that are being manufactured today be examined critically with the goal of providing performance information to the public. Work to acquire performance comparisons with state-of-the-art collectors for liquid and air systems are currently being conducted. The collectors for both systems are flat-plate, single-glazed with selective surfaces.

Two "advanced" evacuated-tube collector designs have been evaluated in the CSU Solar Houses and a third type is now under test. The collectors designed by Corning had been tested for one year in Solar House I, and were replaced with collectors from the Philips Company (Germany) in a cooperative IEA program. The other collector, developed by Owens-Illinois, was evaluated for 16 months on Solar House III.

There were difficulties of several types associated with the Owens-Illinois collectors on Solar House III. Because continuous acquisition of data was not possible due to operating problems with the collector subsystem, sufficient data was procured to indicate that system performance (while operating) is superior to that of the flat-plate system (site-built) on Solar House I. Generally the thermal output per unit area from the evacuated tube collector systems is greater than from flat-plate collectors but the evacuated tube collector tested in Solar House III clearly requires some mechanical improvement before wide-scale use can be encouraged. (Owens-Illinois Co. has modified the collectors and a new design is now being marketed). Experimentation with evacuated tube collector designs should be continued because the excellent performance achieved by the system indicates a potential to lower the cost of solar heating and cooling

from present high costs. Higher temperatures can be obtained with evacuated tube collectors, at satisfactory efficiency which make them particularly suitable for absorption cooling system operation.

3.1.2 Components

Early in the development program of the liquid-heating system, a combined heat-exchanger/storage subsystem was conceptually conceived; a unit that could significantly improve the system efficiency by reducing the temperature difference between storage fluid and an antifreeze fluid circulated through the collector. The concept utilizes direct contact of droplets of collector fluid within the liquid (water) storage container, resulting in only a fraction of a degree temperature difference between the fluid recirculated to the collector and the storage fluid. The experimental development of the liquid-liquid heat exchanger subsystem has progressed independently of the working systems in the solar houses, with critical fluid properties and flow dynamics being addressed as hardware design progressed. The liquid-liquid heat exchanger/storage system is currently being tested in Solar House I with flat-plate collectors. Results of early tests of the direct contact unit and the old site-built collectors had many problems, primarily with low flow rates. Collectors with large tubes must be used with the immiscible fluid of the direct contact system.

A simple (inexpensive) passive device inside a water storage tank was developed to improve the flat-plate liquid-heating system performance through stratification of temperature in a water storage tank. A simple "tee" with perforated holes in riser pipes connected to the inlet pipe from the collector (or heat exchanger) and a similar device attached

to the return pipe from the load were found to reduce thermal mixing in the tank, creating 20 to 25°C temperature differences between the top and bottom of the tank. With this magnitude of temperature stratification in storage, an improvement of about five percent in system performance can be expected. Full-scale testing of the storage stratification device in the flat-plate system of Solar House I was interrupted by tests for the direct contact system and tests are now being conducted with the evacuated tube collector system in Solar House I.

Another effort toward improving the performance of solar systems is the development of controls to optimize collection and delivery of solar heat in conformance with prevailing climatic conditions and the building requirements. While optimal controllers are applicable to any system, they have their greatest benefits to improve efficiencies in flat-plate collector systems.

To minimize the auxiliary electric energy cost used in homes for space heating, a project was initiated to investigate off-peak electric energy, stored in the form of heat, for use during peak hours when solar energy is not available. The system in Solar House I was provided with a unit to test the off-peak element established by utility companies, the units could contribute to reduced heating costs.

3.1.3 Installation Cost Reductions

The installed cost of a solar heating system presently ranges from \$30 to \$40 per square foot of collector for a moderate-size residential building. Of the total cost, approximately one-third is for system installation and significant reductions in cost may be possible if contractors are aware of potential problems and methods to overcome them. A major difficulty occurs in installing collectors because many manufacturers

do not consider the problems of mounting the collectors, interconnecting the units, and flashing around and between collectors. Installing and insulating water tanks are also major items of cost for the system.

3.2 Photovoltaics

The photovoltaics program at Colorado State University is a coordinated research effort directed towards the development of conducting oxide/semiconductor solar cells. The goal in this research is to develop solar cells with 10 percent conversion efficiency. To meet the goal, capabilities have been developed to:

- Fabricate ITO/Silicon Cells
- Model the performance of solar cells
- Perform electrical and optical measurements and analyses
- Determine properties of materials and interfacial characteristics
- Determine cell degradation and make lifetime predictions
- Perform economics and cost evaluations

All major fabrication and measuring techniques, computer programs and analytical methods are currently operational. The major established facilities and techniques include:

- A versatile system which permits variation and control of the fabrication parameters
- Instrumentation which allows measurement of:
 - Composition of the deposited materials and the interface (Auger)
 - Map of photoresponse (scanning light spot)
 - Qualitative map of the minority carrier lifetime (EBIC)

- Topological features and defects (SEM)
- Thickness of the deposit films (Ellipsometer)
- A computer model to analyze and predict cell performance
- Instrumentation to measure the electrical properties as well as spectral and temperature responses
- Techniques and equipment to perform accelerated life testing and methods of determining the reliability of a cell
- Computer programs and the base of information required to realistically investigate the production costs of the cells

To date, the research has emphasized indium tin oxide (ITO) sputter deposited on single and polycrystalline silicon. Twelve to thirteen percent efficiency has been achieved on single crystalline silicon and 7 percent on polycrystalline silicon.

In addition to demonstrating the high efficiency of the cells and determining the important fabrication parameters, we have found that grain boundaries do not seriously reduce the efficiency of the ITO/silicon cells, but a high density of defect clusters is detrimental to cell efficiency. The single crystal ITO cells have not degraded under temperature stress. At 200°C, the cells have withstood over 800 hours of stress and at 250°C over 100 hours. Thus, the cells can be predicted to operate at 50°C (in the dark, illumination tests are underway) for in excess of 50 years. Polycrystalline cells also appear stable but sufficient testing times have not yet been completed.

3.3 Agricultural and Industrial Applications

The research projects in agricultural applications have been funded through the USDA/SEA program in cooperation with DOE. Because of

government guidelines SEAL will continue to participate in agricultural applications through that program. A solar air-heating system to assist a hospital laundry drying facility was constructed, and although operational experience and data are limited, the system is working well. Data collection is needed in the coming year to assess the performance of the system.

3.4 Education and Training

The training of HVAC practitioners in the principles of design and installation of solar heating and cooling systems is another important activity of SEAL. Recognizing that capabilities for solar system design and installation are needed among thousands of practitioners in this country, the major emphasis during the span was placed in the training of vocational education teachers from 32 states so that they can teach the principles of solar heating and cooling system design and installation to practitioners in their regions. For solar energy use to make an impact in the building industry, large numbers of well-trained HVAC practitioners are needed throughout the nation.

4. TECHNICAL REPORTS

Technical reports have been prepared for each project separately and are listed below:

Karaki, S., P.R. Armstrong and T.N. Bechtel (1977) Evaluation of a Residential Solar Air Heating and Nocturnal Cooling System. Solar House II CCMS Report, December, C00-2868-3.

Karaki, S. (1978) A Performance Comparison Between Air and Liquid Residential Solar Heating Systems. Prepared for DOE and NTF, January, C00-2868-4.

- Sharp, M.K. and R.I. Loehrke (1978) Stratified Thermal Storage in Residential Solar Energy Applications. June, C00-4523-1
- Duff, W.S., T.M. Conway, G.O.G. Löf, D.B. Meredith and R.G. Pratt (1978) Evaluation of High Performance Evacuated Tubular Collectors in a Residential Heating and Cooling System: Colorado State University Solar House I. CCMS report prepared for the U.S. Department of Energy, July, C00-2577-14).
- Smith, C.C. (1978) Solar Supplement to Laundry Drying. Annual progress report for the period 31 October 1977 to 31 October 1978, C00-4517-1.
- Thayer, S.B., P. Jacobs and N. Weaver (1978) Cost-Effective Ways to Improve the Fabrication and Installation of Solar Heating and Cooling Systems for Residences. Final report for the period 1 June 1977-30 September 1978, October, C00-4520-1.
- Leboeuf, C. and G.O.G. Löf (1978) Analysis of a LiCl Open-Cycle Absorption Air Conditioner Which Utilizes a Packed Bed for Regeneration of the Absorbent Solution Driven by Solar Heated Air. October, C00-4546-1.
- Johnson, J.E. and H.G. Olson (1978) Measurement of Rn-222 Build-Up in Solar Heated Buildings and Calculation of Radiation Doses. October, C00-4546-2.
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- Leflar, J.A., P.J. Burns and C.B. Winn (1978) Preliminary Analysis of a Total Solar Heating System. October, C00-4546-4.
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- Job, R.C. and P.J. Kelleher (1978) An Improved Fe_2O_3 Photoelectrochemical Cell. October, C00-4546-6.
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- Murphy, V.G. (1978) Methane Production by Anaerobic Digestion of Biomass. October, C00-4546-8.
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- Schierholz, P.M. and H.W. Downs (1978) Industrial Process Heat for Sugar Processing. October, C00-4546-10.
- Kress, G.J. (1978) Problems Encountered by Lending Institutions and Appraisers with Respect to Solar-Equipped Buildings. October, C00-4546-11.

- Hiller, R.L. (1978) Legal Aspects of Financing Solar-Heated Residential Buildings. October, C00-4546-12.
- Miller, B.F. (1978) Treatment of Meat Processing Wastewater; Ferry, D.K. (1978) Carrier Effects on Solar Cell Performance. October, C00-4546-13.
- Jones, T.B. and P.J. Wilbur (1979) Off-Peak Electric Auxiliary Heat for Solar Air-Heating Systems. Final report for the period 1 June 1977 to 31 December 1978, January, C00-4516-1.
- Ward, D.S., J.C. Ward and H.S. Oberoi (1979) Residential Solar Heating and Cooling Using Evacuated Tube Solar Collectors - CSU Solar House III. Final report for the period 1 February 1976-30 September 1978, March, C00-2858-24. Includes Executive, Management and Technical Summaries.
- Karaki, S. (1979) Performance Evaluation of a Solar Air-Heating and Nocturnal Cooling System in CSU Solar II. Final report for the period 1 June 1977 to 30 September 1978, April, C00-2868-5.
- Duff, W.S., G.O.G. Löf, T.M. Conway and R.G. Pratt (1979) Comparative Performance of Two Types of Evacuated Tubular Solar Collectors in a Residential Heating and Cooling System. Final report for the period 1 October 1977-30 September 1978, August, C00-2577-19.
- Karaki, S. and P. Brothers (1979) Experimental Investigation of an Inexpensive Sky Temperature Measuring Device. Final report for the period 1 June 1977-30 June 1979, August, C00-4522-1.
- Wilmsen, C. Degradation of ITO/Silicon Solar Cells. In preparation.
- Winn, C.B. Optimal Controls. In preparation.
- DuBow, J.B. Solar Cells of Oxide Semiconductors on Polycrystalline and Amorphous Silicon. In preparation.
- Shen, H.W. Stochastic Models of Solar Weather Data for Hardware Systems Design. In preparation.

5. PAPERS IN JOURNALS AND CONFERENCES

The following papers on solar energy subjects were submitted for publication by staff and students in the SEAL program.

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- Duff, W.S. and N.S. Kenney (1977) Evaluation of Evacuated Tubular Collectors in a Residential Solar Heating and Cooling System. Proceedings of the International Conference on Energy Use Management, Tucson, Arizona, October.
- Winn, C.B. and Nguyen Duong (1977) Control Optimization for Peak Load Reduction in Heating and Cooling of Residential Solar Houses. Lawrence Symposium on Systems and Decision Science, Berkeley, California, October.
- Winn, C.B. (1977) Discussion of Simplified Design Programs. Report prepared for the Systems Simulation and Economic Analysis Advisory Committee for U.S. Department of Energy.
- DuBow, J. (1977) Oxide Semiconductors for Solar Energy Applications. Invited paper, 1st DOE Materials Research for Energy Conversion Conference, Ames, Iowa, November.
- Hull, D.E. and C.B. Winn (1977) Optimal Temperature Control Using a Microprocessor. IEEE Decision and Control Conference, New Orleans, Louisiana, December.
- Wilbur, P.J. and S. Karaki (1977) Solar Cooling. The Franklin Institute Press, Philadelphia, Pennsylvania.
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- DuBow, J. (1978) Feasibility of ITO/Silicon Solar Cell Applications. Proceedings of the ISES Congress, New Delhi, India, January.
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- Duff, W.S. and J.A. Leflar (1978) Simulation and Design of Evacuated Tubular Solar Residential Air Conditioning Systems and Comparison with Actual Performance. Proceedings of the ISES Congress, New Delhi, India, January.
- Karaki, S., G.O.G. Löf and P.R. Armstrong (1978) Space Heating with Solar All-Air Systems -- CSU Solar House II. ISES Congress, New Delhi, India, January.
- Lameiro, G.F. and W.S. Duff (1978) A Markov Model of Solar Energy Systems. Proceedings of the ISES Congress, New Delhi, India, January.

- Ward, D.S., W.S. Duff, J.C. Ward and G.O.G. Löf (1978) Integration of Evacuated Tubular Solar Collectors with Lithium Bromide Absorption Cooling Systems. Proceedings of the ISES Congress, New Delhi, India, January. Accepted for publication in Solar Energy Journal in September 1978.
- Ward, D.S. and J.C. Ward (1978) Design Considerations for Residential Solar Heating and Cooling Systems Utilizing Evacuated Tube Solar Collectors. Accepted for publication in Solar Energy Journal, September 1978.
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- Karaki, S. and P.R. Armstrong (1978) Air Conditioning by Nocturnal Evaporative Cooling of a Pebble Bed. Proceedings of 3rd Workshop on Use of Solar Energy for Cooling of Buildings, San Francisco, California, February 15-17.
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- DuBow, J., J. Schewchun, A. Myszkowsky and R. Singh (1978) The Operation of the Semiconductor-Insulator-Semiconductor (SIS) Solar Cell, Part 1, Theory. Journal of Applied Physics, February.
- DuBow, J. (1978) Fabrication and Properties of SIS Solar Cells by Ion Beam Sputtering. Invited Seminar, Northern Illinois University, Dekalb, Illinois, March.
- Conway, T.M. (1978) Heat Flow Instrumentation in Colorado State University's Solar Houses. Proceedings, Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April.
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- Sharp, M.K. and R.I. Loehrke (1978) Stratified Versus Well-Mixed Sensible Heat Storage in a Solar Space Heating Application. ASME Paper 78-HT-49, AIAA/ASME Thermophysics and Heat Transfer Conference, May.
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- Hays, D., B.W. Parkinson and C.B. Winn (1979) Real Time Identification of Parameters in Building Models. Proceedings of the Annual Meeting AS/ISES, May 28-June 1, Atlanta, Georgia.
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6. THESES

Student theses that have been completed or in final stages are listed below:

Fall 1977

- C. Dennis Barley (ME)
Relative Areas Analysis of Solar Heating System Performance
- Michael H. Walker (ME)
Feasibility of Adapting Optimization Techniques to Solar

Spring 1978

Eddie R. Hoover (ME)

Design and Computer Simulation of Solar-Heat Pump System

Dwight E. Hull (ME)

Optimal Control for Solar Heated Buildings

James A. Leflar (ME)

Solar Evacuated Tube Collector - Absorption Chiller Systems Simulation

David B. Meredith (ME)

The Dessicant/Rock Bed Method of Solar Cooling with Air Collectors

Michael J. Potishnak (ME)

Real Time Simulation of a Solar Energy System

Michael Keither Sharp (ME)

Thermal Stratification in Liquid Sensible Heat Source

Spring 1979

Syed Faruq Ahmed (ME)

Nocturnal and Daytime Performance of a Single Stage Solar Still

Peter R. Armstrong (ME)

How Weather Persistence Affects Solar Heating System Performance

Gary C. Cheek (EE)

Fabrication of ITO on Polycrystalline Silicon Solar Cells

Cecile M. Leboeuf (ME)

Solar Driven LiCl Open Cycle Absorption Cooling with Packed Bed Absorbent Reconcentration

Chris M. Parsons, Jr. (ME)

Impact of Indium Price and Availability on the Economic Viability of Indium/Tin Oxide Solar Cells

Jack E. Wallick (Agric & Chemical Engr)

Anaerobic Digestion of Cellulosic Residues (partial support through GRA on V.G. Murphy innovative research)

Summer 1979

David K. Hays (ME)

Optimal Control and Identification in Space Heating Systems

Fall 1979

Patrick S. Bremner (ME)

Cooling System Parameter Analysis

Robert R. Hemphill (ME)

Climatic Performance Variations in Passive and Active Solar Systems

Robert G. Pratt (ME)

Turbulent Free Convection Duct Flow for Trombe Walls