CONF 800340

MASTER

PROCEEDINGS
OF THE ANNUAL DOE

ACTIVE
SOLAR HEATING AND COOLING CONTRACTORS' REVIEW MEETING

MARCH 26-28, 1980

U.S. Department of Energy
Assistant Secretary for Conservation & Solar Energy
Office of Solar Applications for Buildings

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $21.00
Microfiche $3.50

CONF 800340
Distribution Category UC-59c

MASTER

PROCEEDINGS
OF THE ANNUAL DOE

ACTI /E

SOLAR HEATING AND COOLING CONTRACTORS' REVIEW MEETING

MARCH 26-28, 1980

U.S. Department of Energy
Assistant Secretary for Conservation & Solar Energy
Office of Solar Applications for Buildings

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 Solar 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 Building Systems Branch of the Office of Solar Applications for Buildings. DOE uses the following resources in the management and implementation of this program:

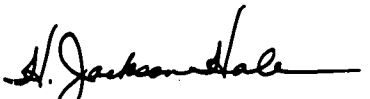
- o DOE Operations Offices
- o DOE National Laboratories
- o National Aeronautics and Space Administration (NASA)
- o Solar Energy Research Institute
- o Contractors

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 Building Systems Branch program management structure which includes the following eight 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 Space Heating Systems	Solar Materials Technology
Solar Hot Water Systems	
Special Projects	
Administrative/Management Support	

Due to the practical limitation of the time period for this meeting, only selected papers were 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.



H. Jackson Hale, Chief
Active Building Systems Branch
Systems Development Division
Office of Solar Applications for Buildings
Conservation and Solar Energy

ACKNOWLEDGEMENTS

The Department of Energy (DOE), Office of Solar Applications for Buildings, gratefully acknowledges the support of key individuals, organizations and contractors in the preparation and conduct of the Active Solar Heating and Cooling Contractors' Review Meeting and the preparation of the associated Proceedings.

DOE extends particular appreciation to Mr. Fred Glaski of the DOE San Francisco Operations Office, who served as Meeting Chairman, and to Ms. Linda Smith of Planning & Management Associates, who coordinated the Meeting and the preparation and publication of the Proceedings.

Thanks are also extended to the session chairmen for their papers and their assistance in organizing, presenting and documenting the session materials.

A special thanks is given to the participating contractors for their informative presentations at the meeting and for contributions for this Proceedings.

TABLE OF CONTENTS

	PAGE
FOREWORD	i
ACKNOWLEDGEMENTS	ii
AGENDA	xiii
ATTENDEES	xix

SECTION I: RANKINE SOLAR COOLING SYSTEMS

Overview of Absorption/Rankine Solar Cooling Program Michael Wahlig, Al Heitz, Barbara Boyce LAWRENCE BERKELEY LABORATORY	1-1
Development of an Advanced Rankine/Rankine Solar Heating and Cooling System George McDonald AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA	1-5
Development of a High Temperature Solar Powered Water Chiller Richard A. English CARRIER CORPORATION	1-7
Steam Rankine Engine for Solar Cooling Terry Kolenc, John Keba, Jonathan Martin ENERGY TECHNOLOGY, INCORPORATED	1-11
Rankine Cycle Solar Driven Heat Pump Development James C. Graf GENERAL ELECTRIC COMPANY	1-13
Solar Heating and Cooling Development Steven E. Scarborough HONEYWELL, INCORPORATED	1-19
Chiller Driven by a Solar Steam-Powered Rankine Engine (SSPRE) Noam Lior and Hsuan Yeh UNIVERSITY OF PENNSYLVANIA	1-22
Development of a Solar-Powered 18 Ton Rankine Cycle Heat Pump Frank Biancardi, Gorken Melikian, J. Sitler UNITED TECHNOLOGY CORPORATION	1-26

SECTION II: ABSORPTION SOLAR COOLING SYSTEMS

Overview of Absorption/Rankine Solar Cooling Program 2-1
Michael Wahlig, Al Heitz, Barbara Boyce
LAWRENCE BERKELEY LABORATORY

Unitary Solar Heating/Cooling System Package Development 2-5
Richard H. Merrick
ARKLA INDUSTRIES, INCORPORATED

Development of a Single Family Absorption Chiller for Use in a Solar Heating and Cooling System 2-9
Wendell J. Biermann
CARRIER CORPORATION

Prototype Modular 15 Ton Solar Absorption Air Conditioning System 2-13
Wendell J. Biermann
CARRIER CORPORATION

Development of Solar Driven Absorption Air Conditioners and Heat Pumps 2-15
Kim Dao, Michael Wahlig, E. Wali, J. Rasson, E. Molishever
LAWRENCE BERKELEY LABORATORY

Multiple Effect Absorption Cycle Analysis 2-17
Gary C. Vliet
UNIVERSITY OF TEXAS AT AUSTIN

SECTION III: DESICCANT SOLAR COOLING SYSTEMS

Overview of the National Solar Desiccant Cooling Program 3-1
Douglas W. Hooker and Frances H. Arnold
SOLAR ENERGY RESEARCH INSTITUTE

Development of a Solar Desiccant Dehumidifier 3-5
John Rousseau
AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

Open Cycle Lithium Chloride Solar Cooling 3-7
George O.G. Löf
COLORADO STATE UNIVERSITY

Development of a Solar Desiccant Dehumidifier 3-9
Zalman Lavan and Dimitri Gidaspow
ILLINOIS INSTITUTE OF TECHNOLOGY

Solar-Mec Development 3-11
Robert A. Macriss and Jaroslav Wurm
INSTITUTE OF GAS TECHNOLOGY

Systems Evaluation Study of Solar Desiccant Cooling Systems 3-14
John A. Duffie and John W. Mitchell
UNIVERSITY OF WISCONSIN-MADISON

Integrated Solar Zeolite Collector 3-17
Dimiter Tchernev
THE ZEOPOWER COMPANY

SECTION IV: SOLAR HEAT PUMP SYSTEMS

Overview of the Solar Assisted Heat Pump Program and Summary of Work at Brookhaven National Laboratory 4-1
John W. Andrews
BROOKHAVEN NATIONAL LABORATORY

Overview of Solar Assisted Heat Pump Studies - Heat Pump Hardware and Experiments, Simulations, Earth Coupling Contracts and Supporting Contracts 4-5
Edward A. Kush
BROOKHAVEN NATIONAL LABORATORY

Multiple Slide Screw Compressor 4-9
David N. Shaw
DUNHAM-BUSH, INCORPORATED

Ground-Coupled Solar Assisted Heat Pump Field Performance 4-13
Sam V. Shelton
E-TECH, INCORPORATED

Phoenix/City of Colorado Springs Assisted Heat Pump Project-Phase III 4-15
Douglas M. Jardine
KAMAN SCIENCES CORPORATION

Development of Marketable Solar Assisted Heat Pump 4-17
Roger Hundt
LENNOX INDUSTRIES, INCORPORATED

Development of a Solar Assisted Heat Pump for the Heating and Cooling of Buildings 4-20
Amir L. Ecker
NORTHRUP, INCORPORATED

Design and Field Testing of Solar Assisted Earth Coils 4-24
James E. Bose
OKLAHOMA STATE UNIVERSITY

Low-Cost Heating and Cooling Using a Direct-Expansion Solar Collector and Heat Pump 4-28
Elrick W. Saaski
SIGMA RESEARCH, INCORPORATED

SAHP-2 Analytical Selection of Marketable SAHP Systems 4-30
William Kahan
THE SINGER COMPANY

Instrumentation and Monitoring of the Twin Crown Realty Buildings in Denver, Colorado 4-34
David K. Hays
SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INCORPORATED

SECTION V: SOLAR SPACE HEATING SYSTEMS

Overview of Solar Collector and Materials R&D for Active Buildings: Materials Engineering and Collector Development for Space and Water Heating 5-1
Charles A. Bankston
LOS ALAMOS SCIENTIFIC LABORATORY

Solar Space Heating Systems Using Annual Heat Storage 5-10
F. C. Hooper
UNIVERSITY OF TORONTO

Development of a Site-Fabricated Building-Integrated Air Solar Heating System 5-12
Peter L. Temple
TOTAL ENVIRONMENTAL ACTION, INCORPORATED

SECTION VI: SOLAR HOT WATER SYSTEMS

Overview of Solar Collector and Materials R&D for Active Buildings: Materials, Engineering, and Collector Development for Space and Water Heating 6-1
Charles A. Bankston
LOS ALAMOS SCIENTIFIC LABORATORY

Development of a Gas Backup Water Heater Properly Integrated With Solar Heated Domestic Hot Water Storage Tanks 6-10
Dennis J. Morrison
ALTAS CORPORATION

Solar Hot Water System Test Program 6-13
A. Hunter Fanney, Stanley T. Liu, James E. Hill
NATIONAL BUREAU OF STANDARDS

Installation and Checkout Handbooks for Solar Domestic Hot Water Systems 6-16
C. Byron Winn
SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INCORPORATED

Controls and Installation and Checkout Handbooks for Solar Domestic Hot Water Systems 6-17
C. Byron Winn, Keith Sharp, Jim Leflar, Thomas Kent
SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INCORPORATED

SECTION VII: SPECIAL PROJECTS

Overview of Photovoltaic/Thermal Hybrid Projects 7-1
Edward A. Kush
BROOKHAVEN NATIONAL LABORATORY

Experimental and Analytical Systems Studies on a Combined Thermal-Photovoltaic Residential Solar System 7-3
Byard D. Wood, Donovan L. Evans, Berry W. McNeil
ARIZONA STATE UNIVERSITY

Combined Solar Thermal-Photovoltaic Systems Demonstration-Phase I 7-6
Joseph J. Loferski
BROWN UNIVERSITY

Studies of Heat Transfer and Water Migration in Soils 7-9
Wynn R. Walker
COLORADO STATE UNIVERSITY

Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings 7-13
Susumu Karaki
COLORADO STATE UNIVERSITY

Self Controlling, Self Pumping Heat Circulation System Study 7-16
George P. Wachtell
FRANKLIN RESEARCH CENTER

Solar Hybrid Energy Project 7-18
Miles C. Russell
MASSACHUSETTS INSTITUTE OF TECHNOLOGY/LINCOLN LABORATORY

Evaluation of Solar Pond Performance 7-20
Layton J. Wittenberg
MONSANTO RESEARCH CORPORATION

Solar Pond Studies: Phase III 7-22
Howard C. Bryant
THE UNIVERSITY OF NEW MEXICO

Salt-Gradient Solar Pond Development 7-24
Carl E. Nielsen
OHIO STATE UNIVERSITY

A Market Assessment of Active Solar Heating and Cooling Products-Category B/A Survey of Decision-Makers in the HVAC Marketplace 7-27
Paul E. Johnston and Gary L. Lilien
OR/MS DIALOGUE, INCORPORATED

SOLERAS Cooling Projects 7-29
Richard E. Davis
SOLAR ENERGY RESEARCH INSTITUTE

SECTION VIII: ADMINISTRATION/MANAGEMENT SUPPORT

Overview of the Active Heating/Cooling Systems Support 8-1
Charles J. Bishop
SOLAR ENERGY RESEARCH INSTITUTE

Solar Cooling/Systems Evaluation 8-9
Henry M. Curran
HITTMAN ASSOCIATES, INCORPORATED

DOE/NASA Systems Development 8-10
William F. Richardson
NASA/MARSHALL SPACE FLIGHT CENTER

SECTION IX: SOLAR COLLECTOR TECHNOLOGY GROUP

Overview of Solar Collector and Materials R&D for Active Building Systems: Development of Low Temperature Collectors for Heat Pump Applications 9-1
Charles A. Bankston
LOS ALAMOS SCIENTIFIC LABORATORY

Overview of Solar Collector and Materials R&D for Active Building Systems: Development of High Temperature Collectors for Solar Cooling Applications 9-2
Charles A. Bankston
LOS ALAMOS SCIENTIFIC LABORATORY

Overview of the Test Results on Vacuum Tube Collectors 9-4
Bernhard L. Wiesenmaier
NASA/MARSHALL SPACE FLIGHT CENTER

Further Development of a Low-Cost Solar Panel 9-7
Eric V. Nelson and Timothy K. Muller
ACUREX CORPORATION

Evaluation of Hail Protection Needs and Devices for Solar Flat Plate Collectors 9-9
Francis de Winter
ALTAS CORPORATION

Evaluation of Solar Collectors for Heat Pump Applications 9-11
C. Gary Skartvedt
AMERICAN HELIOTHERMAL CORPORATION

Development of Compound Parabolic Concentrators for Solar Heating and Cooling Applications 9-14
Kent A. Reed
ARGONNE NATIONAL LABORATORY

Development of a Low-Temperature, Low-Cost, Black Liquid Solar Collector, Phase II 9-16
D. Karl Landstrom, S. G. Talbert, V. D. McGinniss
BATTELLE COLUMBUS LABORATORIES

Transpired Solar Air Heaters 9-20
Harold Bushberg and D. K. Edwards
UNIVERSITY OF CALIFORNIA AT LOS ANGELES

Study of Aluminum Corrosion in Aluminum Solar Heat Collectors Using Aqueous Glycol for Heat Transfer 9-22
David Wong
GINER, INCORPORATED

Solar Collector Studies for Solar Heating and Cooling Applications 9-24
P. Nelson Brittle and Raju Yenamandra
INTERTECHNOLOGY/SOLAR CORPORATION

Active Solar Collector and Materials Research 9-28
Donald A. Neeper
LOS ALAMOS SCIENTIFIC LABORATORY

Low-Cost Mirror Concentrators,Based on Double-Walled, Metallized, Tubular Films 9-30
George L. Ball III, James L. Schwendeman, James W. Leffingwell
MONSANTO RESEARCH CORPORATION

Development of Standard Methods for Testing Solar Collectors 9-32
John P. Jenkins, Elmer R. Streed, James E. Hill
NATIONAL BUREAU OF STANDARDS

Evaluation of Heat Transfer Enhancement in Air-Heating Collectors 9-35
Donald L. Mattox
NORTHROP SERVICES, INCORPORATED

Advanced Heat Transfer Studies in Flat Plate Solar Collectors 9-37
Stuart W. Churchill, Noam Lior, Hsuan Yeh
UNIVERSITY OF PENNSYLVANIA

Collector Array Studies 9-40
Noam Lior and Hsuan Yeh
UNIVERSITY OF PENNSYLVANIA

Forced and Natural Convection Studies on Solar Collectors for Heating and Cooling Applications 9-43
Joseph T. Pearson
PURDUE UNIVERSITY

A Point Focusing Fresnel Solar Concentrator for Solar Heating and Cooling 9-48
William Rogers and David Borton
RENSSELAER POLYTECHNIC INSTITUTE

Image Collapsing Concentrators 9-51
Carlyle J. Sletten
SOLAR ENERGY TECHNOLOGY, INCORPORATED

Development of a High Performance Air Heater Through Use of an Evacuated Tube Cover Design 9-53
Dennis Jones
SOLARON CORPORATION

Solar Collector Studies for Solar Heating and Cooling Applications 9-56
Bernard Baum
SPRINGBORN LABORATORIES, INCORPORATED

Wind Effects on Collectors 9-58
Hudy C. Hewitt, Jr.
TENNESSEE TECHNOLOGICAL UNIVERSITY

Structural Integrity of Solar Collectors 9-60
Howard L. Chevalier and Robert A. Wilke
TEXAS A&M UNIVERSITY

A Survey and Evaluation of Current Design of Evacuated Collectors 9-62
B. J. Graham
TRIDENT ENGINEERING ASSOCIATES, INCORPORATED

Heat Transfer in Partial Vacuum 9-66
James R. Thomas
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Collector Sealants and Breathing 9-68
M. A. Mendelsohn
WESTINGHOUSE ELECTRIC CORPORATION

SECTION X: SOLAR CONTROLS TECHNOLOGY GROUP

Overview of the Solar Controls Program 10-1
Lyle Groome
SOLAR ENERGY RESEARCH INSTITUTE
Mashuri L. Warren
LAWRENCE BERKELEY LABORATORY

Optimal Control of SHAC Systems 10-5
C. Byron Winn
COLORADO STATE UNIVERSITY

A Study of Control Instabilities in Solar Heating and Cooling Systems 10-9
Peter Herczfeld and Robert Fischl
DREXEL UNIVERSITY

Novel Control Strategies for Solar Systems That Reduce Electric Utility Peak Loads 10-13
Harold G. Lorsch
FRANKLIN RESEARCH CENTER

Controls for Solar Heating and Cooling 10-17
Mashuri L. Warren, Steven R. Schiller, Michael Wahlig
LAWRENCE BERKELEY LABORATORY

Adaptive Control for Energy Conservation 10-19
Donald R. Farris
LOS ALAMOS SCIENTIFIC LABORATORY

Variable Capacity Compressor Controller 10-21
Edward S. Peltzman
RHO SIGMA, INCORPORATED

SECTION XI: SOLAR STORAGE TECHNOLOGY GROUP

Overview of the Thermal Energy Storage Projects 11-1
Allan I. Michaels
ARGONNE NATIONAL LABORATORY

Modeling and Development of Thermocline and Halothermocline Storage Systems 11-7
W. T. Sha, E. I. H. Lin, K. V. Liu, J. G. Bartzis, Y. S. Cha
ARGONNE NATIONAL LABORATORY

Stratified Storage Measurement and Analysis 11-11
Roger L. Cole
ARGONNE NATIONAL LABORATORY

Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models 11-13
John K. Kuhn
BOEING COMPUTER SERVICES COMPANY

Salt Hydrate Thermal Energy Storage System for Space Heating and Air Conditioning 11-15
Calvin D. MacCracken
CALMAC MANUFACTURING CORPORATION

TRNSYS Simulation of Chemical Heat Pumps for Solar Heating, Cooling and Storage: Part II: Simulations for Washington, D.C. and Fort Worth, Texas, Including Window Effects 11-18
Peter O'D. Offenhartz
EIC CORPORATION

Solar Cooling Thermal Energy Storage Study 11-23
Henry M. Curran
HITTMAN ASSOCIATES, INCORPORATED

Development of an Improved Water Tank for Thermal Storage 11-24
William Hudson and William Jones
INDEPENDENT LIVING, INCORPORATED

Thermal Storage for Solar Cooling Using Paired Ammoniated Salt Reactions 11-26
Fred Jaeger
MARTIN MARIETTA CORPORATION

Thermal Energy Storage Code Analysis 11-28
Joseph Greenberg
NATIONAL BUREAU OF STANDARDS

The Monitoring of Thermal Stratification of the Storage Tank of The Mabel Lee Hall Solar Hot Water System 11-29
Edward E. Anderson
UNIVERSITY OF NEBRASKA

Membrane-Lined Foundations for Liquid Thermal Storage 11-30
Richard C. Bourne
UNIVERSITY OF NEBRASKA

Cost Effective Improvement of Rock Beds Used in Solar Air Heating Systems 11-34
Dennis Jones
SOLARON CORPORATION

Lightweight Concrete Materials and Structural Systems for Water Tanks for Thermal Storage 11-35
William Buckman, Jr.
WESTINGHOUSE ELECTRIC CORPORATION

SECTION XII: SOLAR ANALYSIS GROUP

Solar Heating and Cooling of Buildings - Systems Research, Development and Testing 12-1
S. Karaki, D. S. Ward, W. S. Duff, G. O. G. Löf, C. B. Winn
COLORADO STATE UNIVERSITY

Solar Cooling Studies and Systems Analysis 12-6
David K. Anand and Redfield Allen
UNIVERSITY OF MARYLAND

Solar Heating and Cooling System Analysis 12-9
Jeffrey H. Morehouse
SCIENCE APPLICATIONS, INCORPORATED

Simulation and Design of Solar Thermal Processes 12-11
J. A. Duffie, W. A. Beckman, S. A. Klein, J. W. Mitchell
UNIVERSITY OF WISCONSIN-MADISON

Development of Selective Surfaces 13-1
John L. Cotsworth
THE BERRY GROUP

Development of Superior Liquid Coolants CCF-1 13-2
James A. Marinik
DOW CORNING CORPORATION

Development of Improved Insulation Materials 13-4
James A. Rabe
DOW CORNING CORPORATION

Low-Cost Solar Anti-Reflection Coatings 13-6
Ray J. H. Lin
HONEYWELL, INCORPORATED

Selective Paint and Black Chrome Coating Development 13-7
R. J. H. Lin and P. B. Zimmer
HONEYWELL, INCORPORATED

Selective IR Reflective Coatings 13-9
A. R. Lefkow and J. C. Lee
HONEYWELL, INCORPORATED

Superior Heat Transfer Fluids for Solar Heating and Cooling Applications 13-10
Leo Parts
MONSANTO RESEARCH CORPORATION

Non-Glass Glazing 13-12
Colin G. Pitt
RESEARCH TRIANGLE INSTITUTE

Development of Polyimide Materials for Use in Solar Energy Systems 13-14
John Gagliani
SOLAR TURBINES INTERNATIONAL

Development of Selective Surfaces 13-15
John A. Thornton
TELIC CORPORATION

Studies for Predictably Modifying the Optical Constants of Doped Indium Films 13-17
Ronald B. Goldner
TUFTS UNIVERSITY

Survey and Evaluation of Available Thermal Insulation Materials for Use on Solar Heating and Cooling Systems 13-19
Bill H. Cheng and Ralph D. Gift
VERSAR, INCORPORATED

INDEX 14-1

ANNUAL DOE ACTIVE SOLAR HEATING AND COOLING
CONTRACTORS' REVIEW MEETING

HYATT LAKE TAHOE
INCLINE VILLAGE, NEVADA
MARCH 26-28, 1980

AGENDA

Tuesday, March 25, 1980

6:00 - 9:00 p.m. — Registration - Grand Ball Room Lobby

7:00 - 9:00 p.m. — Reception/Cash Bar

Wednesday, March 26, 1980

7:30 - 8:30 a.m. — Danish and Coffee

8:00 - 12:00 p.m. — Registration - Grand Ball Room Lobby

8:30 a.m. — OPENING REMARKS - Grand Ball Room

Overview of DOE's Federal Solar Programs
- Frederick H. Morse, Director, Office of Solar Applications for Buildings, DOE

Overview of Systems Development Program
- J. Michael Davis, Acting Director, Systems Development Division, Office of Solar Applications for Buildings, DOE

Goals and Objectives of the Active Solar Program
- H. Jackson Hale, Acting Branch Chief, Active Building Systems Branch, Office of Solar Applications for Buildings, DOE

Field Implementation Aspects of the Active Solar Program
- Fred Glaski, Senior Program Coordinator, San Francisco Operations Office, DOE

9:30 a.m. — SPACE HEATING AND HOT WATER PROGRAM

Introduction and Overview of Collector Work in this Program Area
- Charles A. Bankston, Los Alamos Scientific Laboratory

10:00 a.m. — Coffee Break

10:20 a.m. — Development of a Site-Fabricated Building-Integrated Air Solar Heating System
- Paul W. Sullivan, Total Environmental Action, Inc.

Design of a High Performance Air Heater by the Use of an Evacuated Tube Cover System
- Dennis Jones, Solaron Corporation

Salt-Gradient Solar Pond Development
- Carl Nielsen, Ohio State Research Foundation

Solar Collector Studies for Solar Heating and Cooling Applications
- Nelson Brittle, Inter-Technology/Solar Corporation

Collector Array and Convective Heat Transfer Studies
- Noam Lior, University of Pennsylvania

Hail Protection Needs and Devices for Solar Collectors
- Francis de Winter, Altas Corporation
- Michael Cox, Altas Corporation

12:20 p.m. LUNCHEON

Guest Speaker
- Fran Koster, Tennessee Valley Authority

2:30 p.m. Test Results on Vacuum Tube Collectors
- Bernhard Wiesenmaier, National Aeronautics and Space Administration

Overview of Storage Work in Support of the Space Heating and Hot Water Program Area
- Allan Michaels, Argonne National Laboratory

Membrane-Lined Foundations for Liquid Thermal Storage
- Richard Bourne, University of Nebraska and Solar Concept Development Corp.

Modeling and Development of Rock Bed, Solar Pond and Thermocline and Halothermocline Storage Systems
- William Sha, Argonne National Laboratory

Lightweight Concrete Materials and Structural Systems for Water Tanks for Thermal Energy Storage
- William Buckman, Westinghouse Electric Corporation

4:10 p.m. Coffee Break

4:30 p.m. CONTROLS PROGRAM

Overview of Controls Program
- Lyle Groome, Solar Energy Research Institute
- Mashuri Warren, Lawrence Berkeley Laboratory

A Study of Control Instabilities in Solar Heating and Cooling Systems
- Peter Herczfeld, Drexel University

Novel Control Strategies for Solar Assisted Systems
- Harold Lorsch, Franklin Research Center

Controls and Installations Checkout Handbooks for Solar Domestic Hot Water Systems
- C. Byron Winn, Solar Environmental Engineering Company

6:00 p.m. CONCLUSION OF WEDNESDAY'S SESSIONS

6:00 - 7:00 p.m. Reception/Cash Bar

Thursday, March 27, 1980

8:00 a.m. Danish and Coffee

8:30 a.m. Overview of Work Ongoing at Colorado State University
- Dan Ward, Colorado State University

8:50 a.m. ABSORPTION/RANKINE COOLING PROGRAM

Introduction of Absorption/Rankine Cooling Projects
- Michael Wahlig, Lawrence Berkeley Laboratory

Development of a Single Family Absorption Chiller for Use in a Solar Heating and Cooling System--Prototype Modular 15 Ton Solar Air Conditioning System
- Wendell Biermann, Carrier Corporation

Unitary Solar Heating/Cooling System Package Development
- Richard Merrick, Arkla Industries, Inc.

Development of a High Temperature Solar Powered Water Chiller
- Richard English, Carrier Corporation

Chiller Driven by a Solar Steam Powered Rankine Engine
- Noam Lior, University of Pennsylvania

10:20 a.m. — Coffee Break

10:40 a.m.

Development of a Solar Powered 18 Ton Rankine Cycle Heat Pump
- Frank Biancardi, United Technology Research Center

Overview of Remaining Work and Concluding Remarks
- Michael Wahlig, Lawrence Berkeley Laboratory

Overview of Storage Work in Support of the Cooling Program
- Allan Michaels, Argonne National Laboratory

Salt Hydrate Thermal Energy Storage System for Space Heating and Air Conditioning
- Calvin MacCracken, CALMAC Manufacturing Corporation

Thermal Storage Studies for Solar Heating and Cooling Applications Using H_2SO_4/H_2O and NH_3/Salt Chemical Heat Pumps
- Peter Offenhartz, EIC Corporation

12:20 p.m. — LUNCHEON

2:30 p.m.

Overview of Collector Work in Support of the Cooling Program
- Charles A. Bankston, Los Alamos Scientific Laboratory

A Survey and Evaluation of Current Design of Evacuated Collectors
- Bill Graham, Trident Engineering Associates, Inc.

A Point Focusing Fresnel Solar Concentrator for Solar Heating and Cooling
- William Rogers, Rensselear Polytechnic Institute

Simulation and Design of Solar Thermal Processes
- John Mitchell, University of Wisconsin-Madison

Overview of the SOLERAS Work Related to the Cooling Program
- Rick Davis, Solar Energy Research Institute

4:10 p.m. — Coffee Break

4:30 p.m.

Overview of NASA's Work in Support of the Cooling Program
- William Richardson, National Aeronautic and Space Administration

Design and Development of Single Family, Multi-Family, Light Commercial and Commercial Size Solar Heating, Cooling, and Hot Water Systems
- Steve Scarborough, Honeywell, Inc.

Design and Development of Single Family and Commercial Size Solar Heating, Cooling and Hot Water Systems
- James Graf, General Electric Company

Design and Development of Single Family, Multi-Family, Light Commercial and Commercial Size Solar Heating and Cooling Systems
- George McDonald, AiResearch Manufacturing Company of California

5:40 p.m. — CONCLUSION OF THURSDAY'S SESSIONS

Friday, March 28, 1980

8:00 a.m. — Danish and Coffee

8:30 a.m. — Comments on the Active Solar Heating and Cooling Program: Where It's Been and Where It's Going
- J. Michael Davis, Acting Director, Systems Development Division, Office of Solar Applications for Buildings, DOE

9:00 a.m. — SOLAR ASSISTED HEAT PUMP PROGRAM

Overview of the Solar Assisted Heat Pump Program and Discussion of BNL's Research Work
- John Andrews, Brookhaven National Laboratory

Heat Pump Development and Photovoltaic Thermal Hybrid Work
- Edward Kush, Brookhaven National Laboratory

Development of a Solar Assisted Heat Pump for the Heating and Cooling of Buildings
- Amir Ecker, Northrup, Inc.

10:00 a.m. — Coffee Break

10:20 a.m. — Multiple Slide Screw Compressor
- David Shaw, Dunham-Bush, Inc.

Design and Field Testing of Solar Assisted Earth Coils
- James Bose, Oklahoma State University

Phoenix/City of Colorado Springs Solar Assisted Heat Pump Project, Phase III
- Doug Jardine, Kaman Sciences Corporation

Overview of Collector Work in Support of the Heat Pump Program
- Charles A. Bankston, Los Alamos Scientific Laboratory

Evaluation of Solar Collectors for Heat Pump Applications
- C. Gary Skartvedt, American Heliothermal Corporation

Development of a Low-Temperature, Low-Cost, Black Liquid Solar Collector, Phase II
- D. Karl Landstrom, Battelle Memorial Institute/Columbus Laboratories

12:25 p.m. — LUNCHEON

2:00 p.m. — Introduction to Storage Work in Support of the Heat Pump Program
- Joseph Peerson, Argonne National Laboratory

Studies of Heat Transfer and Water Migration in Soils
- Wynn Walker, Colorado State University

2:30 p.m. — DESICCANT COOLING PROGRAM

Overview of the Desiccant Cooling Program
- Kirk Collier, Solar Energy Research Institute

Discussion of SERI's In-House Desiccant Research
- Frances Arnold, Solar Energy Research Institute

Component and Systems Evaluation Study of Solar Desiccant Cooling
- John Mitchell, University of Wisconsin-Madison

Integrated Solar Zeolite Collector
- Dimiter Tchernev, The Zeopower Company

3:30 p.m. — PROGRAM SUPPORT

Overview, with Emphasis on Systems Analysis
- Charles Bishop, Solar Energy Research Institute

Studies and Analyses for Solar Heating and Cooling Applications
- Jeff Morehouse, Science Applications, Inc.

Simulation and Design of Solar Thermal Processes
- John Mitchell, University of Wisconsin-Madison

4:30 p.m. CLOSING REMARKS

Field Implementation Aspects and Implications
- Fred Glaski, DOE

Summary Remarks
- H. Jackson Hale, DOE

5:00 p.m. CONCLUSION OF MEETING

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ANNUAL DOE ACTIVE SOLAR HEATING AND COOLING
CONTRACTORS' REVIEW MEETING

HYATT LAKE TAHOE
INCLINE VILLAGE, NEVADA
MARCH 26-28, 1980

ATTENDEES LIST

Carl Ahlberg
U.S. Department of Energy
Chicago Operations Office
9800 South Cass Avenue
Argonne, IL 60439
(312) 972-2513

Jerry M. Alcone
Science Applications, Inc.
200 Lomas N.W.
Suite 600
Albuquerque, NM 87102
(505) 247-4291

Redfield Allen
University of Maryland
Department of Mechanical Engineering
College Park, MD 20742
(301) 384-6598

David K. Anand
University of Maryland
Department of Mechanical Engineering
College Park, MD 20742
(301) 454-4994

John Andrews
Brookhaven National Laboratory
Solar Technology Group
Building 701
Upton, NY 11973
(516) 345-7726

Frances Arnold
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1174

Charles Banksten
Los Alamos Scientific Laboratory
M/S 571
P.O. Box 1663
Los Alamos, NM 87545
(505) 667-2618

Frank Baylin
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1969

Frank Biancardi
United Technology Corporation
4000 Main Street
E. Hartford, CT 06108
(203) 727-7234

Wendell J. Biermann
Carrier Corporation
Energy Systems Division
P.O. Box 4895, Summit Landing
Syracuse, NY 13221
(315) 432-3805

Charles J. Bishop
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1018

David Borton
Rensselaer Polytechnic Institute
Department of Mechanical Engineering
JEC 5037
Troy, NY 12181
(518) 270-6301

James E. Bose
Oklahoma State University
101 Industrial Building
Stillwater, OK 74078
(405) 624-5638

Richard C. Bourne
Solar Concept Development Company
Box 601
719 2nd Street, Suite 3
Davis, CA 95616
(916) 753-1100

P. Nelson Brittle
Inter Technology/Solar Corporation
100 Main Street
Warrenton, VA 22186
(703) 347-7900

A. Brunger
University of Toronto
Department of Mechanical Engineering
Toronto, Canada M5S 1A4
(416) 978-2903

R. William Buckman, Jr.
Westinghouse Electric Corporation
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, PA 15236
(412) 892-5600

Sheldon Butt
Olin Corporation
Shamrock Street
E. Alton, IL 62024
(618) 258-2770

Wayne Burwell
United Technologies Research Center
27 Robbinswood Drive
Withersfield, CT 06109
(203) 727-7546

Richard E. Cawley
Lennox Industries, Inc.
P.O. Box 877
Carrollton, TX 75006
(214) 245-2525

Bill H. Cheng
Versar, Inc.
6621 Electronics Drive
Springfield, VA 22151
(703) 750-3000

Robert Coates
Planco, Inc.
5944 Luther Lane, Suite 302
Dallas, TX 75225
(214) 361-4761

Roger L. Cole
Argonne National Laboratory
Building 362
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-6245

Kirk Collier
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1761

Charles H. Cox
MIT/Lincoln Laboratory
MS/D-332
P.O. Box 73
Lexington, MA 02173
(617) 862-5580

Michael Cox
Altas Corporation
500 Chestnut Street
Santa Cruz, CA 95060
(408) 425-1211

John D. Crane, Jr.
Science Applications, Inc.
4318 Majestic Lane
Fairfax, VA 22030
(703) 378-5626

Bob Cummings
Energy Technology, Inc.
2778 Avon Lake Road
Litchfield, OH 44253
(216) 722-5621

Henry M. Curran
Hittman Associates, Inc.
9190 Red Branch Road
Columbia, MD 21045
(301) 730-7000

Patrick D'Addario
Stronberg & D'Addario, Ltd.
211 South Alfred Street
Alexandria, VA 22314
(703) 549-6161

Kim Dao
Lawrence Berkeley Laboratory
1 Cyclotron Road B90-2024
Berkeley, CA 94720
(415) 486-6364

Keith Davidson
Gas Research Institute
10 West 35th Street
Chicago, IL 60616
(312) 567-6653

J. Michael Davis
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8150

Rick Davis
Homes & Narver
P.O. Box 1
Mercury, NV 89023
(702) 986-9368

Francis de Winter
Altas Corporation
500 Chestnut Street
Santa Cruz, CA 95060
(408) 425-1211

Eugene Doering
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8160

Amir L. Ecker
Northrup, Inc.
302 Nichols Drive
Hutchins, TX 75141
(214) 225-4291

Richard A. English
Carrier Corporation
Energy Systems Division
P.O. Box 4895, Summit Landing
Syracuse, NY 13221
(315) 432-3804

Donovan Evans
Arizona State University
Mechanical Engineering Department
Tempe, AZ 85281
(602) 965-7298

Donald R. Farris
Los Alamos Scientific Laboratory
E4, MD 429
P.O. Box 1663
Los Alamos, NM 87545
(505) 667-6295

Robert Fischl
Drexel University
328 Chestnut Street
Philadelphia, PA 19104
(215) 895-2254

Carol S. Gates
U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-7946

Dimitri Gidaspow
Illinois Institute of Technology
3424 South State Street
IIT Center
Chicago, IL 60616
(312) 567-3045

Fred Glaski
U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-7946

James Graf
General Electric Company
P.O. Box 8661
Philadelphia, PA 19101
(215) 962-5565

B. J. Graham
Trident Engineering Associates, Inc.
48 Maryland Avenue
Annapolis, MD 21401
(301) 267-8128

Joseph Greenberg
National Bureau of Standards
Building 226, Room B210
Washington, DC 20234
(301) 921-2758

Lyle Groome
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1362

Robert Guddat
Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208
(503) 234-3361 Ext. 4359

Gottfried Haacke
American Cyanamid Company
1937 W. Main Street
Stamford, CT 06904
(203) 348-7331

H. Jackson Hale
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8153

Leonard A. Hall
Carrier Corporation
Energy Systems Division
P.O. Box 4895, Summit Landing
Syracuse, NY 13221
(315) 432-3801

James C. Hartl
Sigma Research, Inc.
2950 George Washington Way
Richland, WA 99352
(509) 375-0663

Bob Hassett
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8160

Al Heitz
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road B90H-9
Berkeley, CA 94720
(415) 486-4239

Peter Herczfeld
Drexel University
Department of Electrical Engineering
32nd & Chestnut Streets
Philadelphia, PA 19108
(215) 895-2256

Hudy C. Hewitt
Tennessee Technological University
Mechanical Engineering Department
Box 5161 - TTU
Cookeville, TN 38501
(615) 528-3254

Theodore L. Heying
Olin Corporation
275 Winchester Avenue
New Haven, CT 06511
(203) 789-5491

Tomas Hill
Science Applications, Inc.
8400 West Park Drive
McLean, VA 22102
(703) 821-4300

Frank C. Hooper
University of Toronto
Department of Mechanical Engineering
Toronto, Canada M5S 1A4
(416) 978-2903

Roger Hundt
Lennox Industries, Inc.
P.O. Box 877
Carrollton, TX 75006
(214) 245-2525

Frod A. Jaeger
Martin-Marietta Corporation
Aerospace Division
P.O. Box 179
Denver, CO 80201
(303) 973-4804

Douglas M. Jardine
Kaman Science Corporation
1500 Garden of the Gods Road
Colorado Springs, CO 80907
(303) 599-1555

M. J. Johnson
Tennessee Valley Authority
240 Chestnut Street Tower
Chattanooga, TN 37401
(615) 755-3877

Dennis Jones
Solaron Corporation
440 Galleria Tower
720 S. Colorado Boulevard
Denver, CO 80222
(303) 759-0101

William M. Jones
Independent Living, Inc.
5965 Peachtree Corners East, Suite A-4
Norcross, GA 30071
(404) 449-5900

Paul Kando
5112 MacArthur Boulevard, N.W.
Washington, DC 20016
(202) 244-6898

Susumi Karaki
Colorado State University
Solar House II
Ft. Collins, CO 80523
(303) 491-8617

Bill Kaspar
U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-7946

Charles A. Kezar
U.S. Department of Energy
Conservation & Solar Energy
1804 Horseback Trail
Vienna, VA 22180
(703) 938-6308

Tom King
Mueller Associates, Inc.
1900 Sulphur Spring
Baltimore, MD 21227
(301) 621-1632

Fran Koster
Tennessee Valley Authority
426 United Bank Building
Chattanooga, TN 37401
(615) 755-6741

John Kuhn
Boeing Computer Service
P.O. Box 24346
Seattle, WA 98124
(206) 575-5004

Edward A. Kush
Brookhaven National Laboratory
Solar Technology Group
Building 701
Upton, NY 11973
(516) 345-3567

D. Karl Landstrom
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
(614) 424-4803

Zalman Lavan
Illinois Institute of Technology
3110 South State Street, Room 252C
Chicago, IL 60616
(312) 567-3189

Charles W. Leach
Dow Corning Corporation
2200 W. Salzburg Road
Midland, MI 48640
(517) 496-4754

Robert LeChevalier
Science Applications, Inc.
1546 Cole Boulevard
Denver, CO 80401
(303) 232-7900

Paul LeDoux
Brookhaven National Laboratory
Solar Technology Group
Building 701
Upton, NY 11973
(516) 345-2407

Joseph E. Levangie
Northeast Solar Energy Center
470 Atlantic Avenue
Boston, MA 02111
(617) 292-9250

Ken Liebelt
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415
(208) 526-1285

E. I. H. Lin
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-6032

Noam Lior
University of Pennsylvania
Department of Mechanical Engineering
Philadelphia, PA 19104
(215) 243-4803

George O. G. Löf
Solar Energy Applications Laboratory
Colorado State University
Ft. Collins, CO 80523
(303) 491-8632

Harold Lorsch
Franklin Research Center
Benjamin Franklin Parkway
Philadelphia, PA 19103
(215) 448-1591

Calvin D. MacCracken
CALMAC Manufacturing Corporation
150 South Van Brunt Street
Englewood, NJ 07631
(201) 569-0420

Robert A. Macriss
Institute of Gas Technology
3424 South State Street
Chicago, IL 60616
(312) 567-3888

Jon Martin
Energy Technology, Inc.
4914 East 154th Street
Garfield Heights, OH 44128
(216) 587-0555

Robert L. Martin
Solar Energy Research Institute
1556 Cole Boulevard
Golden, CO 80401
(303) 231-1851

J. D. McClenahan
University of Toronto
Department of Mechanical Engineering
Toronto, Canada M5S 1A4
(416) 978-2903

George McDonald
AiResearch Manufacturing Company
2525 190th Street
Torrance, CA
(213) 323-9500

Barry McNeill
Arizona State University
Mechanical Engineering Department
Tempe, AZ 85281
(602) 965-7298

Jack Meeker
Northeast Solar Energy Center
470 Atlantic Avenue
Boston, MA 02111
(617) 292-9250

Gorken Melikian
United Technologies Research Center
Silver Lane
E. Hartford, CT 06108
(203) 727-7554

Richard H. Merrick
Arkla Industries, Inc.
819 East Franklin Street
P.O. Box 534
Evansville, IN 47704
(812) 424-3331

Glen L. Merrill
Honeywell, Inc.
1700 West Highway 36-T340
Roseville, MN 55113
(612) 378-4477

Kenneth A. Meyer
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, NM 87525
(505) 667-2241

Allan I. Michaels
Argonne National Laboratory
Building 362
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-6233

A. F. Mills
University of California-Los Angeles
Los Angeles, CA 90024
(213) 825-3583

John W. Mitchell
University of Wisconsin
Engineering Experimental Station
1500 Johnson Drive
Madison, WI 53706
(608) 263-5626

Jeffrey H. Morehouse
Science Applications, Inc.
1764 Old Meadow Lane
McLean, VA 22102
(703) 827-4915

Frederick H. Morse
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8084

Timothy K. Muller
Acurex Corporation
485 Clyde Avenue
Mountain View, CA 94042
(415) 984-3200 Ext. 3442

Joseph G. Murray
Arkla Industries, Inc.
819 East Franklin Street
P.O. Box 534
Evansville, IN 47704
(812) 424-3331

Carl E. Nielsen
Ohio State University
Department of Physics
174 W. 18th Avenue
Columbus, OH 43210
(614) 889-1491

H. S. Oberoi
Colorado State University
Solar Energy Applications Laboratory
Ft. Collins, CO 80523
(303) 491-8618

Tom Ochs
Desert Research Institute
Energy Systems
1500 Buchanan Avenue
Bolder City, NV 89005
(702) 293-4217

Russell A. O'Connell
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-065
Washington, DC 20585
(202) 252-8143

Peter O'D Offenhartz
EIC Corporation
55 Chapel Street
Newton, MA 02158
(617) 965-2710

Carolyn Palmer
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8153

Leo Parts
Monsanto Research Corporation
Dayton Laboratory
1515 Nicholas Road
Dayton, OH 45407
(513) 268-3411

Donald R. Patterson
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-7708

Joseph T. Pearson
Purdue University
School of Mechanical Engineering
West Lafayette, IN 47907
(317) 494-4545

Joseph Peerson
Argonne National Laboratory
Building 362
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-6233

Dave Peters
Lennox Industries, Inc.
P.O. Box 400450
Dallas, TX 75240
(214) 783-5401

Mike Pryor
Olin Corporation
91 Shelton Avenue
New Haven, CT 06511
(203) 789-5700

G. W. "Dusty" Rhoades
FAFCO, Inc.
235 Constitution Drive
Menlo Park, CA 94025
(415) 321-3650

Richard O. Rhodes
FAFCO, Inc.
235 Constitution Drive
Menlo Park, CA 94025
(415) 321-3650

William R. Richardson
NASA/Marshall Space Flight Center
Building 4201 - FA32
Huntsville, AL 35812
(205) 453-1746

William Rogers
Rensselaer Polytechnic Institute
JEC-2049TYE
Troy, NY 12180
(518) 270-6301 Ext. 27

Donald M. Roha
Automation Industries, Inc.
Vitro Laboratories Division
14000 George Avenue
Silver Spring, MD 20910
(301) 871-2800

Corbyn Rooks
U.S. Department of Energy-Consultant
2607 Cass Street
LaCrosse, WI 54601
(608) 782-0646

Miles C. Russell
MIT/Lincoln Laboratory
D-332
P.O. Box 73
Lexington, MA 02173
(617) 862-5500

Fenwick H. Salter
Lawrence Berkeley Laboratory
1 Cyclotron Road
Building 9 Room 4128
Berkeley, CA 94720
(415) 843-2740

Jesus J. SanAgustin
U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-7946

Steve Sargent
U.S. Department of Energy
Chicago Operations Office
Denver Division
1617 Cole Boulevard-Building 4
Golden, CO 80401
(303) 231-1366

Steve E. Scarborough
Honeywell, Inc.
1700 West Highway 36
Roseville, MN 55113
(612) 378-4234

Sam Schweitzer
U.S. Department of Energy
1000 Independence Avenue, S.W.
Room 5G-033
Washington, DC 20585
(202) 252-8153

Michael R. Sedmak
Booz, Allen & Hamilton, Inc.
311 First Street, N.W.
Suite 600
Washington, DC 20001
(202) 624-0610

W. T. Sha
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-5910

David N. Shaw
Dunham-Bush, Inc.
175 South Street
West Hartford, CT 06110
(203) 249-8671

Les E. Shaw
Solaron Corporation
440 Galleria Tower
720 South Colorado Boulevard
Denver, CO 80222
(303) 759-0101

Samuel V. Shelton
E-Tech
3570 American Drive
Atlanta, GA 30341
(404) 458-6643

John Shewchun
Brown University-Division of Engineering
Hope Street
Providence, RI 02912
(401) 863-2674

C. Gary Skartvedt
American Heliothermal Corporation
2625 South Santa Fe Drive
Denver, CO 80223
(303) 778-0650

Linda J. Smith
Planning & Management Associates, Inc.
1010 Vermont Avenue, N.W.
Suite 1100
Washington, DC 20005
(202) 347-1010

Verlyn Smith
Planning & Management Associates, Inc.
1010 Vermont Avenue, N.W.
Suite 1100
Washington, DC 20005
(202) 347-1010

Louis Spanoudis
Owens-Illinois, Inc.
1020 N. Westwood Avenue
Toledo, OH 43666
(419) 247-8326

Lauren Starke
Weston
Casanova, VA 22017
(703) 788-4547

Paul W. Sullivan
Total Environmental Action, Inc.
Church Hill
Harrisville, NH 03450
(603) 827-3374

Dimitar I. Tchernev
Zeopower Company
75 Middlesex Avenue
Natick, MA 01760
(617) 655-4125

James R. Thomas
Virginia Polytechnic Institute &
State University
Mechanical Engineering Department
Blacksburg, VA 24061
(703) 961-7270

John A. Thornton
Telic Corporation
1631 Colorado Avenue
Santa Monica, CA 90404
(213) 828-7449

Anne Townsend
Planning & Management Associates, Inc.
1010 Vermont Avenue, N.W.
Suite 1100
Washington, DC 20005
(202) 347-1010

Gary C. Vliet
University of Texas
Department of Mechanical Engineering
Austin, TX 78712
(512) 471-7571

George Von Fuchs
Boeing Computer Services
565 Andover Park West
Tukwila, WA 98188
(206) 575-5992

Michael Wahlig
Lawrence Berkeley Laboratory
1 Cyclotron Road
Building 90 - Room 2024
Berkeley, CA 94720
(415) 486-5787

Wynn Walker
Colorado State University
Solar Energy Applications Laboratory
Ft. Collins, CO 80523
(303) 491-8288

Dan S. Ward
Colorado State University
Solar House I
Ft. Collins, CO 80523
(303) 491-8211

Mashuri L. Warren
Lawrence Berkeley Laboratory
1 Cyclotron Road
Building 90 - Room 2024
Berkeley, CA 94720
(415) 486-6364

Bernhard L. Wiesenmaier
George C. Marshall Space Flight Center
Associate Director for Engineering Office
Marshall Space Flight Center, AL 35812
(205) 453-5550

Jim Williamson
Solar Energy Research Institute/Soleras
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1850

C. Byron Winn
Solar Environmental Engineering Company
P.O. Box 1914
Ft. Collins, CO 80522
(303) 491-6783

Byard D. Wood
Arizona State University
Mechanical Engineering Department
Tempe, AZ 85281
(602) 965-7298

Robert J. Youngberg
Nebraska Solar Office
W 191 Nebraska Hall - UNL
Lincoln, NE 68588
(402) 472-3414

Federica Zangrando
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1865

Jerry E. Zimmerman
U.S. Department of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87115
(505) 844-8257

I RANKINE SOLAR COOLING SYSTEMS

OVERVIEW-ABSORPTION/RANKINE SOLAR COOLING PROGRAM*

MICHAEL WAHLIG, AL HEITZ, BARBARA BOYCE

LAWRENCE BERKELEY LABORATORY

1 CYCLOTRON ROAD

BERKELEY, CALIFORNIA 94720

OBJECTIVE

The overall objective of the active solar cooling program is to assist the solar industry in developing and bringing to the marketplace solar-powered active cooling systems. The benefit of reaching this objective will be to reduce the national dependence on non-renewable forms of energy.

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 contents of each project are given below in the Technical Accomplishments section.

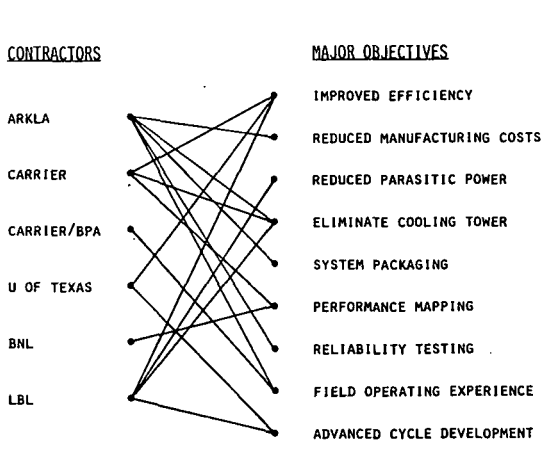


Figure 1

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 cooling systems. In the absorption program, there are six current and five essentially completed projects. In the Rankine program, there are five current projects directly supported by DOE, and three projects funded through and managed by NASA/MSFC (Manned Space Flight Center, Huntsville, Alabama). The basic features of these projects are given in the next section.

The systems under development in five of these current projects have been selected for field testing in the new SOLERAS program, a joint US-Saudi Arabian enterprise.

Some technical highlights of the program are presented in Figure 3.

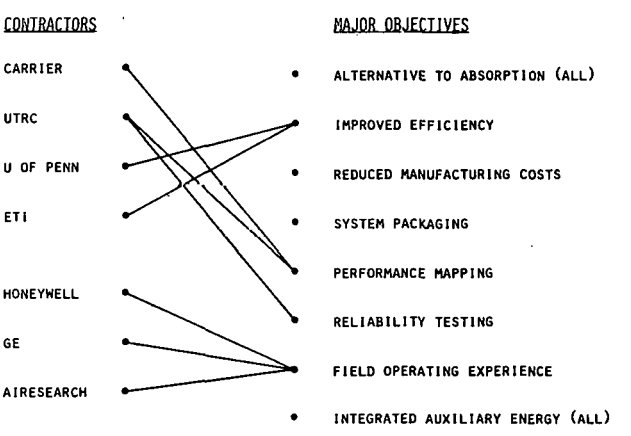


Figure 2

CONTRACTOR	ACCOMPLISHMENT
• HONEYWELL (RANKINE)	SUCCESSFUL FIELD OPERATION-LAWRENCE, KANSAS
• UTRC (RANKINE)	SUCCESSFUL LAB TEST OF PROTOTYPE UNIT
• BNL (ABSORPTION)	"SPINDOWN" TECHNIQUE FOR PERFORMANCE IMPROVEMENT DURING CYCLING
• CARRIER (ABSORPTION)	SUCCESSFUL LAB TEST OF FIRST "BREADBOARD" UNIT USING NEW FLUIDS; SUCCESSFUL FIELD OPERATION OF BPA-TYPE CHILLER
• ARKLA (ABSORPTION)	SUCCESSFUL DEVELOPMENT OF EVAPORATIVELY COOLED UNIT

Figure 3. Technical Highlights

TECHNICAL ACCOMPLISHMENTS

The individual absorption and Rankine projects are identified in this section, along with the main

Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting
March 1980

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

Features: Unitary package; fuel aux., manufacturing study; application and installation manuals; procure and use tooling for limited production; lab reliability testing of evaporatively cooled chiller.

Accomplishments:

- Two unitary 3-ton systems installed in residences (one new, one retrofit) operated and provided data during summer 1979. Retrofit site will continue to be monitored during summer 1980.
- Modified 25-ton package has been assembled in Arkla lab.
- Scale build-up on heat exchanger surfaces does not appear to be a problem for evaporatively cooled chiller. Lab testing continues.

Contractor: Arkla

Contract No.: AC03 76SF 10507

Project: Development of third-generation 3-ton $LiBr/H_2O$ absorption chiller

Features: Built-in evaporatively-cooled absorber/condenser; hermetic solution pump.

Accomplishments:

- Successful development of evaporatively cooled chiller.
- Final report approved for publication.

Contractor: Carrier

Contract No.: AC03 77CS 31587

Project: Development of 3 to 5-ton absorption chiller

Features: Air-cooled; 120° - $130^{\circ}C$ input temp.; use of fluid additives; manufacturing study; market evaluation.

Accomplishments:

- Found LiBr-glycol-water mixture to be promising fluid.
- Completed testing of breadboard unit.
- Redesign of prototype completed, and fabrication underway.
- Released reports on phases I and II for publication.

Contractor: Carrier

Contract No.: AC79 79BP 10467 (Bonneville Power Administration contract)

Project: Fabrication of two 15-ton packaged absorption cooling systems, with installation at BPA Big Eddy site and Tyler, Texas

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

Accomplishments:

- Tyler, Texas installation completed 1 Oct 79 (acceptance meeting conducted 5 Oct 79).
- Big Eddy installation completed Jan 80 (acceptance meeting scheduled spring 80).
- One year O&M and monitoring data by Carrier to run thru spring 81.
- 200-ton system to be installed in Virgin Islands (BPA-type, NASA contract).

Contractor: University of Texas at Austin

Contract No.: 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:

- First version of simulation model completed.
- Modifying model to incorporate recommendations made by site visit review team.
- Consulting with Trane on issues of corrosion (no problem) and costs.

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 $218^{\circ}F$ using NH_3/H_2O; advanced cycles with COP increasing with temperature; heat pump operation also.

Accomplishments:

- New single-effect chiller installation completed; testing and debugging underway.
- New solution pump fabricated, tested, and modified several times.
- Design of advanced cycle 2R chiller nearing completion; fabrication of components started.
- Fluid properties required for advanced cycle 1R chiller have been identified; RFP SOW drafted to solicit measurements of properties of candidate fluids.

Contractor: Brookhaven National Laboratory

Contract No.: C-02-0016

Project: Develop and use simulator to test solar cooling subsystems

Accomplishments:

- Tests of Arkla absorption chiller completed at end of FY 1979.
- Important discovery: "spindown" technique for maintaining high COP during on-off cycling of absorption chillers.

- Final reports reviewed and approved for publication.

Contractor: EIC Corporation

Contract No.: AC03 77CS 34537

Project: Design of solar air conditioner using solid-phase absorbent (chemical heat pump)

Features: Air-cooled; built-in thermal storage.

Accomplishments:

- Identified $CaCl_2$ as most promising salt.
- Preliminary design of chemical heat pump using $CaCl_2$.
- Conducted experimental cycling tests on $CaCl_2$.
- Final report reviewed and approved for publication.

Contractor: Southern Research Institute

Contract No.: AC03 77CS 31586

Project: Analysis of advanced conceptual absorption chiller designs

Features: Search for new pairs and additives; modified absorption cycles; 160° - 230°F range.

Accomplishments:

- Identified several potentially useful absorption pairs.
- Final report reviewed and partially accepted for publication following modifications.

Contractor: Institute of Gas Technology

Contract No.: AC03 77CS 31439

Project: Development of new fluids for solar absorption cooling

Features: For air-cooled condensers; estimate COP

Accomplishments:

- Several new candidate fluid pairs identified.
- Final report reviewed and approved for publication.

Contractor: University of Maryland

Contract No.: DEAC03 79CS 30204

Project: Technical program support and special studies

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

Accomplishments:

- Report on state-of-the-art review of refrigerant/absorbent pairs has been prepared.
- Support activities proceeding as required.
- Development of a transient simulation model of an absorption chiller is underway.
- A simplified design method for cooling systems has been developed.
- Work progressing on comparative assessment project.
- Work proceeding at low level on a simplified design procedure for pv/t systems.

Rankine Projects

Contractor: Carrier

Contract No.: 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.

Accomplishments:

- Detailed analysis and design phases completed. Reports on this work reviewed and approved for publication.
- Prototype chiller completely assembled at Carrier, except for turbo-compressor.
- Turbo-compressor about 75% completed at MTI. Tests of assembly at MTI scheduled for April 1980.

Contractor: United Technologies Research Center (UTRC)

Contract No.: AC03 77CS 34510

Project: Development of 18-ton Rankine heat pump

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

Accomplishments:

- Performance testing has been successfully completed at design conditions.
- Final report for original contract work is under review.
- Extended performance and reliability testing underway.

Contractor: Univ. 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 designs; stored water flashes to steam.

Accomplishments:

- System design phase mostly completed
- Philadelphia Gear completing fabrication of turbo-compressor-motor assembly.
- Work proceeding on component specification and procurement, and system integration.

Contractor: Energy Technology, Inc. (ETI)

Contract No.: AC 03 80CS 30214

Project: Development of a superheated steam Rankine turbine

Features: Solar-boiled water at 300°F; fuel-superheated to 1000°F; 5-stage, 75,000 rpm radial outflow turbine; nominal 30 ton.

Accomplishments:

- Successful preliminary tests using 3 turbine stages.

- Steam turbine test facility construction completed.

Contractor: Hittman Associates, Inc.

Contract No.: DEAC03-79 CS 30202

Project: Technical program support and special studies

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

Accomplishments:

- Rankine fluid state-of-the-art report completed.
- Support activities proceeding as required.
- Work progressing on comparative assessment project.
- Specialized tasks, such as analysis of unusual solar cooling systems, specification of performance test procedures, etc., performed as needed.

In addition to the above projects, three contractors (Honeywell, General Electric, and AiResearch) are being supported by NASA contracts to develop Rankine-cycle solar cooling systems in a variety of sizes, and to install these systems in operational test sites. These projects (often referred to as the NASA 404 projects) are the subject of an overview paper and of individual project presentations elsewhere in the proceedings of this meeting.

FUTURE ACTIVITIES

From a technical point of view, the active solar cooling program is quite successful. All of the contractors are doing first-class work, and steady advances are being made in the performance and reliability of the chillers and the cooling systems. It is expected that this type of progress will continue in the future.

However, a critical element is missing from the active cooling program: the existence of quantitative program goals. Without such quantitative goals, we are unable to measure progress towards short-term goals, nor are we able to predict with any certainty the possibility of eventual success in the marketplace.

In order to rectify this situation, the following corrective measures will be given high priority in the near future:

- use market analysis to determine details of future cooling demands;
- use comparison of solar vs. future conventional cooling technologies to determine quantitative solar cooling systems cost and performance goals;
- use comparative analysis of the solar cooling approaches to determine projects with most potential to achieve solar cooling program goals;
- use sensitivity analysis to determine most effective program actions to reach solar cooling program goals.

Establishing quantitative program goals using the steps given above will produce significant benefits:

- ability to justify each project on basis of its quantitative contribution to overall program success;
- rationale for dropping those projects that cannot be adequately justified;
- existence of a quantitative mechanism for developing annual operating plans to maximize the programmatic benefit of the funds available;
- existence of a positive strategy for achieving significant market penetration by solar cooling at the earliest possible time.

Conversely, the consequence of not establishing such program goals will be our inability to defend even the present scope of the active solar cooling program.

Meanwhile, a program is just getting underway that will provide a significant measure of field testing of new and modified solar cooling systems. This is the SOLERAS program, an element of the joint U.S.-Saudi Arabian solar energy program that comprises engineering field tests of solar cooling systems in Saudi-type climates. Five projects are involved, four in the Phoenix area (Rankine projects by Honeywell and United Technology Research Center, and two absorption projects by Carrier) and one in the Mojave Desert area (a Rankine project by General Electric). Following design and construction phases, all systems are expected to undergo field operations during the summers of 1981 and 1982. Project management is the responsibility of SERI, with technical support being provided by LBL (cooling) and ANL (reliability and materials). This program is described in more detail in a separate presentation at this meeting.

Finally, a fourth Cooling Workshop is being planned at this time, tentatively scheduled for the fall of 1980, or soon thereafter.

FOOTNOTE:

*This work has been supported by the Active Building Systems Branch, Systems Development Division, Office of Solar Applications, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

DEVELOPMENT OF AN ADVANCED RANKINE/RANKINE SOLAR HEATING AND COOLING SYSTEM

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

CONTRACT NO. NAS8-32091

C. McDONALD

PERIOD OF CONTRACT: JULY 1976 to DECEMBER 1980

OBJECTIVE

The objective of this program is to design, develop, and field-test a family of integrated solar heating and cooling systems.

CONCEPT

The heat pump package operates in two basic modes, heating and cooling. In the heating mode, it operates as a heat pump to raise the temperature level of the solar-heated water to a higher level more suitable for heating a building (e.g., from 50° or 60°F to 120°F). The heat pump permits solar energy to be collected at lower temperatures, which in turn permits more efficient collector operation. This means that less costly collectors of lower performance may be used, thus improving the cost-effectiveness of the total solar system.

HEATING OPERATION

In heating mode shown in Figure 1, solar-supplied energy in the form of hot water is supplied to the evaporator, where R-11 is evaporated. The R-11 vapor is compressed by the compressor portion of the turbocompressor. In this mode, power is supplied by an integral electric motor. The vapor then passes through the condenser. Water from the building terminal units is circulated through the condenser. The R-11 vapor is condensed in this heat exchanger and the latent heat is transferred to the water, which is supplied to the terminal units to heat the building. The condensed R-11 liquid then passes through the thermal expansion valve. This valve meters R-11 flow to the evaporator to maintain slightly superheated vapor at the inlet to the variable-speed compressor. When the solar supply temperature rises, less energy must be supplied by the compressor. The motor drive is slowed down to match the required load and electrical energy requirements are thereby minimized.

COOLING OPERATION

The cooling mode is depicted in Figure 2. In this mode, solar thermal energy is used in a Rankine cycle to produce shaft horsepower. This power drives the compressor of a reverse Rankine cycle to produce refrigeration. In the cooling mode, R-11 vapor from the boiler flows to the turbine end of the turbocompressor. This vapor is then directed from the evaporator to the compressor end of the turbocompressor.

In the power cycle, R-11 vapor is expanded through the turbine and condensed in a water-cooled condenser common to both the power and refrigeration cycles. The liquid R-11 then flows to the boiler feed pump, where its pressure is increased.

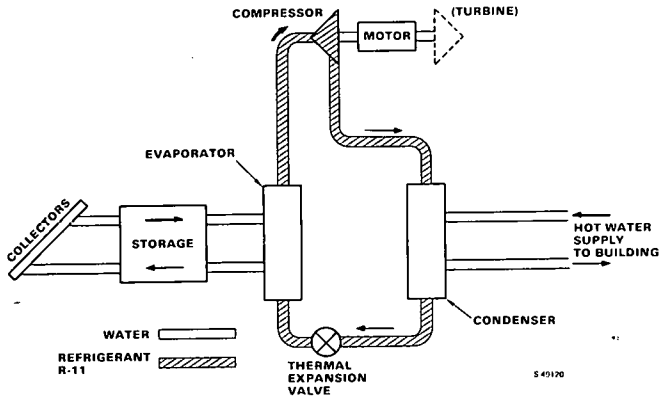


Figure 1. Solar System Flow Paths--Heating Mode

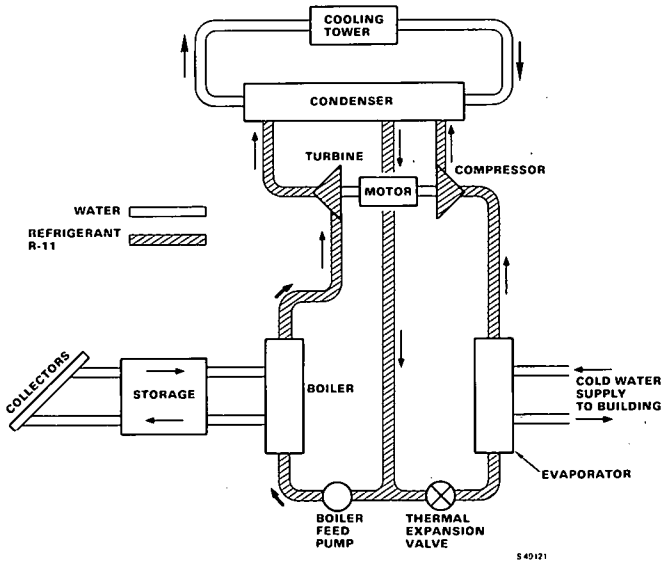


Figure 2. Solar System Flow Paths--Cooling Mode

In the refrigeration cycle, R-11 flows from the common condenser, through the thermal expansion valve; this valve meters R-11 flow to the evaporator to maintain superheated vapor conditions at the compressor inlet. The vapor flows through the compressor and back to the condenser. Refrigeration is supplied to the building by the water recirculation loop to the terminal units. The heat of condensation is rejected to the atmosphere by a water/cooling tower loop.

Under most operating conditions, the turbine supplies sufficient power to drive the compressor; however, when solar energy is insufficient, the integral electric motor is operated to augment turbine power.

TURBOCOMPRESSOR

The hearts of these systems are the motor-driven turbocompressors. These highly efficient, high-speed centrifugal machines have been developed exclusively for solar heating and cooling systems. Accordingly, their performance has been optimized for system conditions. The rotating assembly of a typical turbocompressor is shown in Figure 3. A radial inflow turbine and a radial outflow compressor are mounted at opposite ends of the shaft. Mounted on the center of the shaft is the magnet assembly of the permanent magnet motor. The rotating assembly is supported on process-fluid, resilient-foil, journal bearings. Such bearings ensure long operating life and permit system operation without lubricating oil in the R-11.

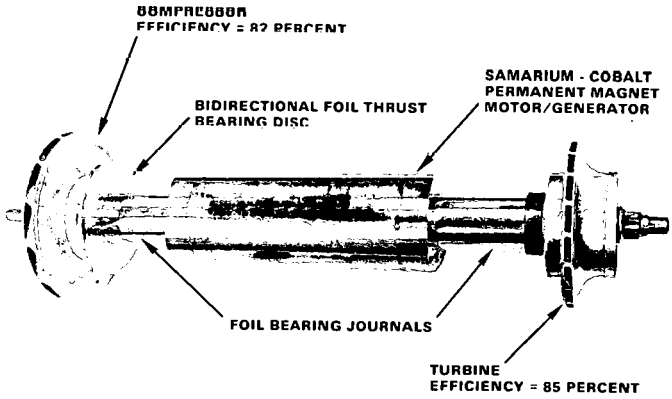


Figure 3. Typical Turbocompressor Rotating Assembly

TECHNICAL ACCOMPLISHMENTS

- Development of motor control circuitry. Circuitry has been developed to control turbine and compressor speed throughout the operating range. This circuitry converts 60-Hz electric power to 0 through 2000 Hz. In the starting mode, the control uses a rotor position sensor to control stator field position and frequency. During this time, the control maintains the current drain at or below the maximum running current. In the run mode, any speed within the operating range may be selected manually, or remotely from a programmed signal from the system microprocessor control. Automatic fault-sensing and shutdown circuitry are included in the motor control.

- 75-Ton heat pump package development. During its development, the 75-ton heat pump package was operated at the full range of solar, outside ambient, and potential building conditions. The cooling capacity test results are shown in Figure 4. In addition, the refrigerant controls for the heat pump package were successfully developed and demonstrated. Multiple thermal expansion valves are used to control both boiler and evaporator flows. Approximately 500 hr of testing has been conducted on the heat pump package.

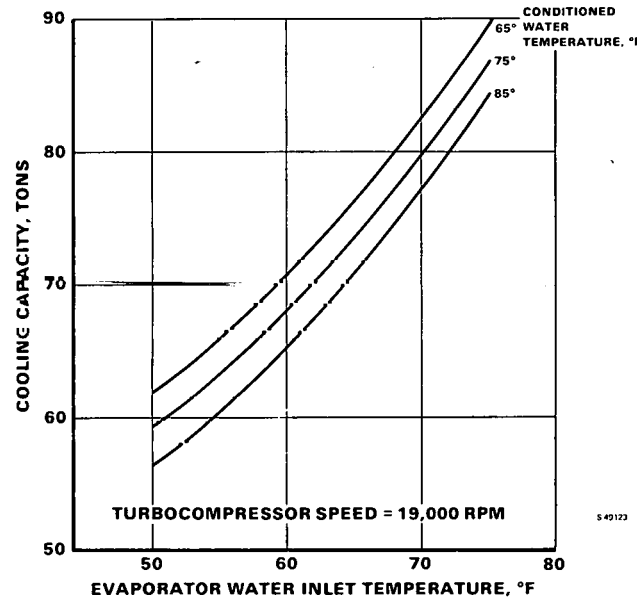


Figure 4. Test Results of 75-Ton Cooling Capacity System

- Installation of 75-ton system at University of Houston. Installation of the system at Houston is nearing completion. The collector field is installed and operational. The system controls have been installed, checked out, and operated in the heating mode. The heat pump package has been installed. All monitoring instrumentation has been installed and is fully operational.

FUTURE ACTIVITIES

Detailed acceptance tests are scheduled to be conducted on the deliverable 75-ton turbocompressors, and on the total heat pump package. Field test operations of the 75-ton systems are scheduled to start this summer in Houston, and this fall in Las Vegas.

Upon satisfactory completion of the 75-ton system acceptance tests, it is anticipated that development testing will be initiated on the 25-ton system.

DEVELOPMENT OF A HIGH TEMPERATURE SOLAR POWERED WATER CHILLER

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

DE-AC-3-77CS31590

RICHARD A. ENGLISH

OCTOBER 1, 1977 TO SEPTEMBER 25, 1980

OBJECTIVE

This program has been undertaken in response to the Department of Energy RFP on Solar Activated Projects for Heating and Cooling Applications, June 6, 1977, to develop a high temperature solar powered chiller in the 15-25 ton size range utilizing 250-300°F solar hot water. The project is to study, design, and test a prototype air cooled Rankine powered vapor compression cycle which utilizes auxiliary electric energy. The Energy Systems Division of Carrier Corporation is the prime contractor, with Mechanical Technology, Inc., as subcontractor to study, design and build the turbo/compressor/motor unit.

CONCEPT

The design concept being developed is a dual loop, Rankine power cycle driving a Rankine vapor compression cycle (Figure 1). A single working fluid, R-113, is used and both loops are connected to a common air cooled condenser. The prime mover is a high speed turbine directly driving a centrifugal compressor. Under design conditions, the chiller will produce 25 tons at 44° leaving chilled water, 95°F entering condenser air and 290°F solar hot water. The cycle employs a regenerator and a suction gas heat exchanger which act synergistically to increase cycle efficiency. The heat exchange components, working fluid, and turbo/compressor configurations were optimized to produce a high overall COP, predicted to be above 0.70 with low parasitic power. The auxiliary energy source is a variable speed induction motor which can drive the vapor compressor when solar energy is not available.

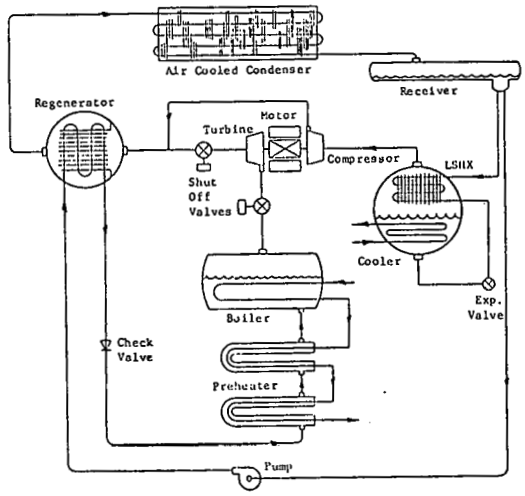


FIGURE 1. AIR COOLED DUAL LOOP RANKINE DRIVEN VAPOR COMPRESSION CYCLE.

The hermetic turbo/compressor (Figure 2) consists of a single stage centrifugal compressor with inlet guide vanes and a vaned diffuser, driven by a radial inflow turbine. The 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.

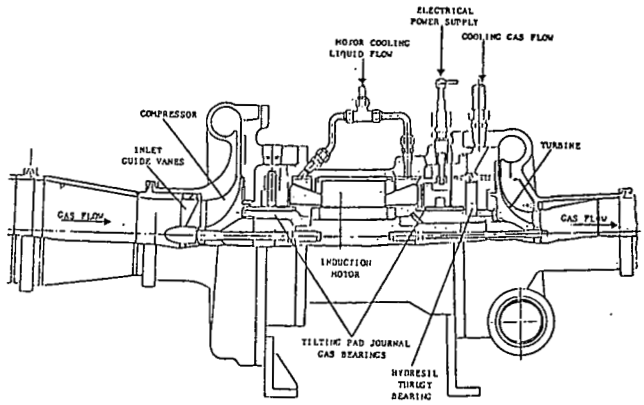


FIGURE 2. CARRIER/MTI SOLAR POWERED WATER CHILLER TURBO MACHINE SUBSYSTEM.

The chiller will be an air cooled outdoor packaged unit (Figure 3) similar to conventional rooftop air conditioning equipment. The cycle components will be mounted in a low profile configuration on the base frame, under the air cooled condenser and upward discharge fan section.

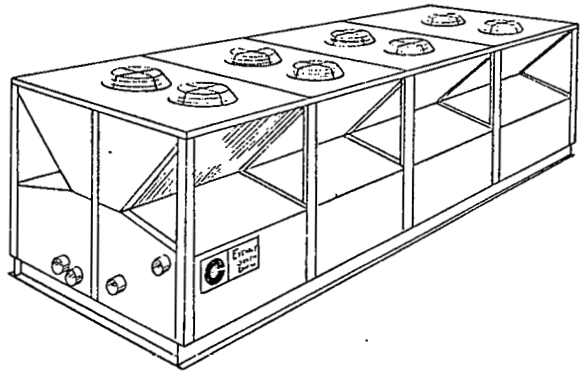


FIGURE 3. AIR COOLED SOLAR POWERED PACKAGED CHILLER CONCEPT.

SUMMARY

Phase I, the conceptual design study, was completed 6/1/78 and a report was issued (Ref. 1). This work included a state of the art survey, preliminary cycle studies, a turbo/compressor design and chiller design, and predicted performance of the chiller and a solar system including the chiller. Phase II, the detailed design, was completed on 4/1/79. This work included a detailed review of the Phase I concept, detailed component design calculations, computer optimization of components on a minimum solar system cost performance basis, preparation of detailed drawings of the entire chiller and turbo compressor, and laboratory exposure tests of R-113 in the design environment.

Under Phase III, the chiller, turbo machine and test loops are being fabricated. The refrigerant pump has been built and tested, and additional R-113 exposure tests are underway.

TECHNICAL ACCOMPLISHMENTS

● Various dual loop Rankine cycle configurations and working fluids were studied to establish optimized criteria for both the turbomachine subsystem and the overall chiller. Organic fluids studied in detail were R-11, R-113, R-114, and R-12. Representative cycle performance levels were determined for each fluid as well as state points for continuing analysis. MTI sized turbo components for each fluid and estimated performance. In this initial screening process, R-113 and R-114 emerged as the most promising choices. R-11 was eliminated due to evidence of thermal instability at the boiler design temperature level. R-12 was eliminated because of high working pressures and excessive parasitic power, as well as expected difficulty in achieving desired turbo/compressor performance due to small sizes.

Screening tests on cycle configurations have shown that the combination of a regenerator and a liquid suction heat exchanger in this high temperature cycle increases the overall COP more than the sum of the individual performance improvements. For R-113, the improvement in COP was 21.5% using this combination of heat exchangers. Normally, for conventional compression cycles, a heat exchanger between the warm condensate and the cold suction gas results in a relatively small improvement in the vapor compression cycle COP which is not sufficient to justify the cost. The increased latent heat capacity of the refrigerant is partially offset by the increased compressor work due to the higher superheat entering the compressor. However, in conjunction with the regenerator, this heat is transferred to the Rankine cycle, reducing the input of new energy to the Rankine cycle by this additional amount.

Turbo compressor designs for both R-113 and R-114 were generated with components optimized at the selected design point. Off-design maps were generated to support overall chiller performance analysis. The R-114 compressor design was somewhat more favorable due to lower Mach numbers and because turbine/compressor matching fell within a more optimistic efficiency range. The compressor was characterized by high Mach numbers and low impeller tip speeds for both refrigerants. Therefore, the compressor stage tended towards a high reaction impeller with inlet guide vanes. The initial R-113 turbine stage sizing resulted in a low specific speed configuration. Therefore, turbine rotational speed was increased to improve turbine efficiency. However, nigher Mach numbers which result at the compressor inducer mean that the optimum system performance is a trade-off of compressor and turbine performance. At rated conditions, the predicted performance of the turbine and compressor closely meet the 0.80 adiabatic efficiency design goal.

Although the R-114 turbo compressor design was more favorable, the R-113 cycle performance was clearly superior and pump work losses were much less, and R-113 was the final choice.

● A computer program was written to study the chiller performance over a range of off-design conditions, and was used to optimize the components on a minimum cost performance basis as well as to predict performance over the range of conditions. In this model, heat exchanger coefficients and pressure drops are calculated to provide realistic system variations as a function of mass flow, loading, etc. Turbine and compressor performance characteristics are modeled, and the program converges on the operating balance point of the turbine and compressor.

Cost equations were developed for major heat exchange components and subsystems. Optimization proceeded by trading off larger heat exchangers and higher COP against smaller solar collector requirements. A final OCOP increase of 19% was achieved with a cost increase of only 4.3%. The optimization was limited by practical considerations of heat exchanger and chiller size.

● Studies of system performance characteristics over the range of off-design conditions expected in service were instructive in establishing a control strategy for the turbo machine and the pump. It was found that the compressor speed curves necessary to stay within the surge and choke boundaries over the full range were related to the condenser and boiler conditions and could be controlled by regulating the boiler supply water temperature as a linear function of the outdoor ambient. Figure 4 is a performance map which is extended to the surge and choke lines. The location of the operating line can be selected to provide the performance characteristics desired. For example, Line "A" shown results in a chiller performance characteristic which has a flat capacity over the range of outdoor ambients as shown in Figure 5.

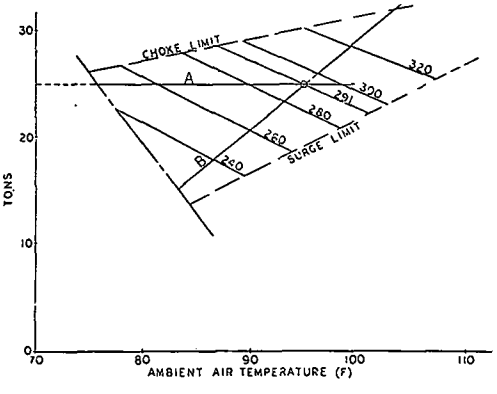


FIGURE 4. PREDICTED CAPACITY MAP OF HIGH TEMPERATURE CHILLER FOR VARIOUS SOLAR HOT WATER TEMPERATURES.

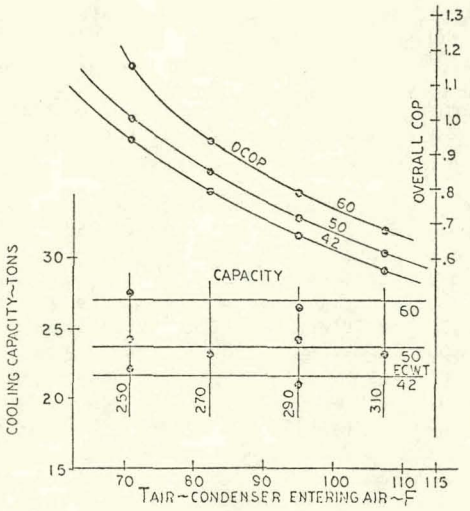


FIGURE 5. CHILLER PERFORMANCE AS A FUNCTION OF ENTERING CONDENSER AIR TEMPERATURE.

Condensate flow rates to the boiler have also been studied over the range of operating conditions and found to be a nearly linear function of the pressure difference. Because the pump is designed with a constant speed motor, a strategy was developed to modulate the pumping rate by modulating the bypass as an inverse function of the pressure difference. This has been accomplished through development of a pressure actuated modulating bypass valve.

● The turbomachine design has been finalized and fabrication is nearly complete at MTI. The design phase included the mechanical and cooling system design, electric motor and inverter design, aerodynamic design, gas bearing design, rotor dynamic analysis and manufacturing cost estimates.

The mechanical design analysis consisted of several interacting conditions; the selection of the shaft design as a rigid member suitable for gas bearings application, detailed stress analysis of critical rotating and pressure containing components, and a parasitic loss and related cooling flow analysis. The turbo machine will be cooled with 450 lb/hr of process gas plus 34 lbs/hr of liquid when the motor is operating. Cooling flow will be induced through the machine from the condenser, by a venturi located in the compressor discharge line. The energy penalty associated with cooling flow is estimated to be about 1%.

The electric motor is a nominal 200 volt, 3 phase, 400 Hz, 2 pole induction motor. The rotor is mounted on the shaft between the turbine and compressor. The stator is pressed into the main housing. Cooling of the stator will be accomplished by spraying saturated R-113 liquid on the windings at each end. The motor is rated at 40 hp at 24,000 rpm. Efficiency at full load exceeds 94% at a 94% power factor.

Studies of available power supplies and state of the art components have showed that development of a solid state variable frequency variable voltage 40 hp 3 Ø inverter is technically and economically feasible. The performance and cost of these devices has been significantly enhanced due to recent advances in high power transistor technology. The solid state inverter design has been completed and its efficiency will be approximately 95% at full load while presenting a near unity power factor to the utility source.

Aerodynamic design of the turbine and compressor have been completed and the components have been built. Figure 6 shows the compressor and turbine wheels, with the completed shaft/motor assembly. The design of the centrifugal compressor included an analysis of inlet guide vanes, impeller, vaneless diffuser space and vaned diffuser, discharge scroll, and inlet and exit piping. Inlet guide vanes introduce swirl into the impeller inducer to reduce Mach number and associated loss levels. The vanes can be adjusted during test for optimizing performance. The 6.96 inch diameter impeller has 40° backward curved blades. The 17 vane channel diffuser is oriented at 76° to diffuse the gas flow effectively. This diffuser is removable to allow other diffuser configurations to be tested. Compressor adiabatic efficiency at design is estimated at 80%. The radial inflow turbine is 6.1" dia. A removable nozzle ring will allow testing other nozzle configurations. The turbine adiabatic efficiency is estimated at 82% at design conditions.

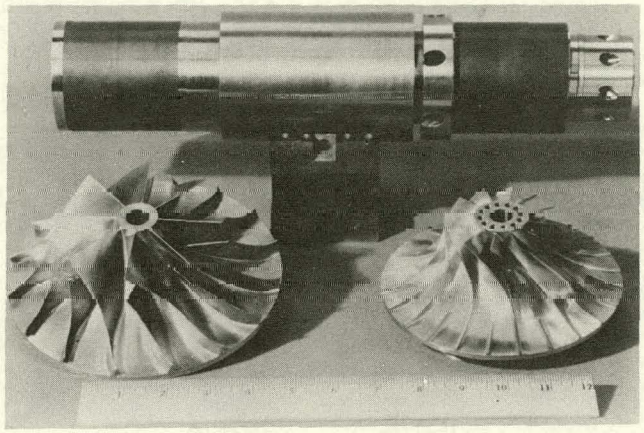


FIGURE 6. FINISHED COMPRESSOR (L) AND TURBINE WHEELS BEFORE ASSEMBLY ON MOTOR SHAFT.

The rotor is supported by gas film bearings using the R-113 process gas. The journal bearings are tilting pad type, with 3 pads on each journal. The double acting Hydresil™ split bump foil thrust bearings utilize 12 foil pads.

● Simulations of solar heating and cooling systems were used to evaluate system parameters such as relative component sizing, storage type and chiller control strategies. A final system configuration was selected based on cost/performance trade-offs. Cost effectiveness of this configuration was evaluated for a light commercial building in Phoenix, Arizona and New York City in comparison with a conventional unit, based on annual performance using average day per month data. More extensive simulations will be made when DOE load and weather tapes are available.

To simulate the system, TRNSYS Version 9.1 was modified to incorporate off-design chiller performance and a special control unit. Because the chiller in this study is of a fixed size (25 tons) and because the building load varies with the location, the size of the building was scaled to provide a cooling load which matched the chiller capacity.

Results indicated that the thermal performance of the system with either hot or cold storage was about the same. The thermal performance of the system was not significantly different with various Rankine control strategies. Load sharing between motor and turbine was found to be less efficient than operation on an "either/or" basis. The seasonal COP of the chiller was higher than the design COP due to the lower average operating ambient. In New York, for instance, the COP was 10-15% higher on solar and 20-25% higher on the electric motor.

Depending upon collector areas, energy savings ranged from 50% in New York with 100 m^2 collector to 60% for 300 m^2. Payback with 100 m^2 was less than 25 years.

- The factory assembled, unitary outdoor air cooled design concept will facilitate shipment, installation and service. The 25 ton size chiller will be applicable to both multi-family residences and commercial buildings. The physical size of this unit will be similar to a 50 ton conventional electric chiller because the size is dominated by the air cooled condensers which must reject the heat of both the vapor compression cycle and the Rankine cycle.

The air cooled condenser consists of four plate-fin coil slabs of approximately 100" x 49". Each 4-row slab is identically circuited with 78 circuits of 1/2" tubing to provide the extremely low pressure drop required with this refrigerant. 39,000 cfm air flow will be provided by eight standard fan and motor assemblies. Fans can be staged to allow operation of the chiller at low ambients.

The boiler is a flooded shell and tube designed for 40% ethylene glycol solution within the 19 fpi low fin steel tubes. The "U" bundle, which allows for thermal expansion, has 29 circuits.

The preheater is a counterflow tube-in-tube, 3 circuit assembly with a wire wound turbulator in the annular refrigerant space. This heat exchanger is designed to provide the large amount of sensible heating required prior to the boiler with a highly effective surface.

The cooler is a shell and tube assembly which contains the flooded evaporator tubes in the lower half and the plate-fin liquid suction heat exchanger in the upper half. The very low evaporator pressure dictates the use of a low pressure drop flooded cooler. The 40 fpi Turbo-Chil™ copper tubing provides 20 four pass water circuits. The vapor leaving the cooler must pass through the finned passages of the liquid suction heat exchanger with very low pressure drop, where it is heated. This also acts as an eliminator for any liquid before entering the compressor suction.

The regenerator is a similar plate-fin coil housed in a pressure shell. Hot gases from both the compressor discharge and turbine exhaust, which pass through the finned passages, are cooled with very low pressure drop.

The pressure containing vessels and piping are designed to meet the requirements of the B9.1 Safety Code and the ASME unfired pressure vessel code. Because of the system configuration, all of the vessels could be exposed to maximum working pressure and must be designed accordingly. The design pressure is 230 psig.

- A liquid pump was designed and tested which exceeded the stringent goals of 4 foot NPSH and 60% efficiency. This pump consists of a positive displacement gerotor pump boosted by a low NPSH, low head centrifugal impeller. This hybrid combination uses the R-113 fluid as a lubricant and bearing coolant.

- Refrigerant stability tests on R-113 exposed with various metals in sealed tubes to 250°F and 300°F were completed to 1700 hours. Chemical analysis and weight gain tests indicated no measurable breakdown of R-113 in these uncontaminated tests. Subsequently, additional specimens were exposed to higher temperatures, up to 350°F, and to some of the various "contaminants" expected, such as water. These tests, which are currently nearing completion, do show signs of activity at the extreme temperatures.

FUTURE ACTIVITIES

- The turbo machine will be tested on an air loop at MTI prior to installation in the chiller.

- The chiller prototype has been equipped with a water cooled condenser to facilitate initial testing. It will be used initially as a test bed for qualification of the turbo machine, other mechanical components, heat exchange components, and operating controls. Performance maps will be made as a Rankine cycle in order to assess the concept.

- The prototype will then be equipped with the air cooled condenser section and tested in its final configuration.

REFERENCE

"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, IV; Richard A. English SAN-1590-1/314 (1978).

STEAM RANKINE ENGINE FOR SOLAR COOLING

ENERGY TECHNOLOGY INCORPORATED

CONTRACT NO. AC03-80CS30214

INVESTIGATORS: TERRY KOLENC
JOHN KEBA
JONATHAN MARTIN

START: MARCH, 1980; END: JULY, 1980

OBJECTIVE

The objective of the current program phase is to demonstrate a high efficiency, hybrid Rankine engine for solar cooling. The engine is designed to utilize both low and high grade energy sources in combination. This capability significantly reduces the size of the solar collector required by the system, and thus greatly decreases system capital cost.

CONCEPT

The key element of ETI's hybrid steam Rankine engine is a multi-stage radial outflow (ROF) turbine. The basic construction of the turbine involves two parallel discs; one rotating, the other stationary. The working fluid (steam, in this case) enters at the center, flows radially outward through concentric alternating stator and rotor blade rows mounted on the discs.

By utilizing a multi-stage design, subsonic flow can be maintained in each of the individual turbine stages. This yields high turbine performance at off-design conditions which is an important design characteristic for the solar cooling application where the vast majority of the operating hours are spent at part load.

The multi-stage ROF turbine design provides a high degree of flexibility. A large number of pressure ratios can be accomodated by simply changing the number of stages. For example, by adding or removing stages at the inlet, the turbine can be matched to a wide range of collector types. Also, exit stages can be added or removed to mate with either air or water cooled condensing. This flexibility will permit a wide application of the basic design.

The test ROF turbine is a second generation design with improved mechanical strength and aerodynamics. Computerized design and manufacturing techniques produce turbine blade profiles of extreme accuracy at relatively low cost. The high tip speed capability of the design permits a greater work output per stage. Thus, for a specified power level, fewer stages are required, thereby reducing turbine cost.

The radial outflow turbine has several other low cost characteristics:

1) Two-dimensional blading allowing several low-cost methods to be utilized for blade profile manufacture.

2) Single disc rotor which greatly simplifies balancing and control of tight manufacturing tolerances.

3) Ease of assembly and disassembly for maintenance.

ETI has a large investment in the development of manufacturing techniques applicable to the ROF turbine. Through persistent effort, it is now possible, using simple tooling, to construct blade rows with a high degree of accuracy and geometric orientation.

The rotating package, currently undergoing testing at ETI, is spinning on water-lubricated journal bearings. These bearings consume significantly less power than comparable oil-lubricated bearings. In addition, they greatly reduce sealing requirements between the turbine and the load. Lube supply for these bearings is bled from the boiler feed pump. The above factors all contribute to high efficiency and reduced cost and maintenance requirements.

In conjunction with the ROF turbine, ETI is utilizing a hybrid Rankine cycle to substantially decrease system capital cost. This cycle combines a high grade energy with the low grade energy obtained from a solar collector field to reduce the heat energy delivery requirement of the collector field during design day operation. ETI received a Patent (U.S. No. 3,950,949) on this "dual heat source" Rankine cycle concept and has been pursuing its development since conception in 1972. Compared with conventional concepts, which depend entirely upon low temperature solar collectors to provide power for space cooling, the hybrid Rankine cycle can reduce the size of the collector required by a factor of 2 to 3.

In selecting the boiling temperature to be used in the Rankine engine, it was assumed that all energy required to vaporize the working fluid would be provided by the solar collector. For the current DOE program, a collector field output temperature of 300^{0}F was selected; this will be simulated at ETI's test facility. This choice was based on optimizing the product of solar collector efficiency (which decreases with temp.) and Rankine engine efficiency (which increases with temp.). Several low concentration ratio collectors are currently available which can deliver 50 percent conversion efficiency at 300^{0}F. Cost of these collectors is low enough to make them economically competitive on a dollars per square foot basis with low temperature flat plate collectors.

The boiling heat rate, which in the case described above corresponds to the collector heat rate, is a very strong function of the superheat temperature selected. A few representative values are shown in the table below. The heat rates are based on energy supplied to the hybrid Rankine engine to produce one ton (12,000 BTU/HR) of cooling.

Rankine Cycle Performance Summary
(Boiling Temp. 300°F For All Cycles Shown)

Superheat Temp.	Boiling Heat Rate	Total Heat Rate
300°F	15050 BTU/HR-TON	15050 BTU/HR-TON
700°F	10800 BTU/HR-TON	12800 BTU/HR-TON
1000°F	7950 BTU/HR-TON	10700 BTU/HR-TON

The test engine uses the 300°F/1000°F combination shown above. The collector requirement for this system is projected to be only 65 FT^2 per ton of cooling. It is important to note that all the above heat rates were computed based on air-cooled condensing temperatures of 115°F for both the power and the refrigerant loops.

The superheat energy could be provided by various means such as: combusting fossil fuel, electric resistance heat, or a parabolic dish collector. Use of one of these high grade energy sources need not be limited to providing superheat energy alone. The above could also be used to displace some of the boiling heat requirements.

In addition to reducing the solar collector field requirement, the hybrid Rankine cycle also reduces the size of the storage and the back-up system. For early applications, it may be desireable to use fuel during non-solar periods, providing only buffer-type storage to account for cloud passage.

The mix of low and high grade energy sources will depend upon an analysis of the overall system economics. The basic point to be made, however, is that small amounts of high grade energy can be utilized to displace a significant portion of the solar collector field.

ETI has selected steam as the working fluid for the hybrid Rankine engine because of these characteristics:

1) Fluid is non-toxic and chemically stable at temperatures to 1500°F.

2) Very high heat transfer coefficients for all heat exchangers resulting in compact and low cost heat exchange components.

3) Low pumping power requirement.

4) A broad, firm technological base with established support industries.

5) Fluid is inexpensive and readily available.

SUMMARY

The potential of ETI's radial outflow turbine for high efficiency over a broad operating range and low production cost, in conjunction with the hybrid Rankine cycle can make solar cooling economically competitive by the mid 1980's. The solar collector requirement of only 65 FT^2 per ton of cooling should make it possible to produce the system for a total cost less than DOE's projected cost ceiling of $4000 per ton.

Technical Accomplishments

- The design and hardware fabrication of the steam turbine rotating package has been completed.

- ETI's Steam Turbine Test Facility has been modified to simulate the hybrid Rankine cycle selected; and, has been operated at the design steam conditions for temperature, pressure, and mass flow rate.

- The rotating unit has been spin tested to 80 percent of design speed. Water lubricated bearing instabilities have been corrected, permitting stable rotor operation.

FUTURE ACTIVITIES

Contract Activities. Some additional modifications will be made to the rotating package. Upon their completion, performance testing of the ROF steam turbine will take place. The turbine will be operated over a complete spectrum of load and operating conditions. From this data, a performance map for the turbine will be derived.

Post Contract Activities. The next program phase should be the design and integration of a refrigerant compressor matched to the performance characteristics of the ROF steam turbine. In parallel with this would be the design and test of an automatic control system for the steam engine. After completion of these tasks, a field test of the complete system in cooperation with solar collector/storage subsystem suppliers would be sought.

ETI would also like to make contact with parties interested in the future commercialization of this concept.

RANKINE CYCLE SOLAR DRIVEN HEAT PUMP DEVELOPMENT (1976 TO 1979)

GENERAL ELECTRIC COMPANY
Philadelphia, PA
NAS 8-32092
JAMES C. GRAF

Introduction

Solar cooling continues to be one of the attractive uses of solar energy and an excellent opportunity to reduce America's reliance on scarce fossil energy supplies. Solar cooling offers a unique opportunity to match demand and supply. When solar cooling is required, the sun usually is available or has recently been available. Most other applications of solar energy are not so fortunate. This feature is of particular interest in the sunbelt where utilities are almost all summer peaking, i.e., the maximum demand on the utility occurs in the summer and any requirements for increased capacity will occur at that time. It is our opinion that solar cooling offers the opportunity to provide incremental capacity to these utilities at modest investment if the systems are well developed, proven and require relatively minimal maintenance. Since these goals are also important to the user, there should be little doubt about the requirements.

This paper will provide a status look at the General Electric Solar Cooling Program and is an update to the review presented in San Francisco in 1978.

System Description

The General Electric system is shown pictorially in Figure 1. The energy is collected by the GE TC-100 evacuated tubular collectors at temperatures up to 320°F. The primary solar collector loop utilizes a 35 percent mixture of ethylene glycol and water circulated by a pump through a heat exchanger which transfers the energy to a thermal energy storage (TES) loop. This loop provides the energy directly to a hydronic coil in the heating mode or to the vapor generator of the Rankine electric heat pump in the cooling mode. Energy from the TES tank may also be used for domestic water heating. The TC-100 collector is shown in Figure 2.

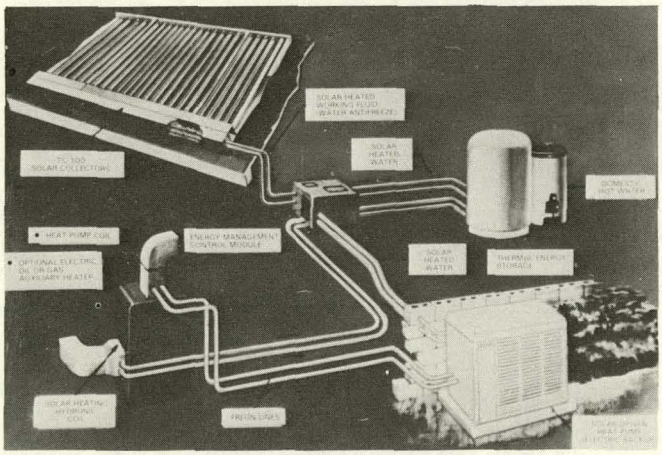


Figure 1. Solar Heating and Cooling System

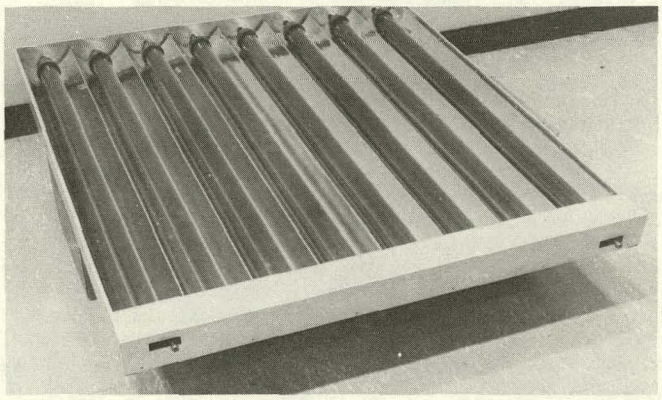


Figure 2. TC-100 Vacuum Tube Solar Collector

The collector has been in production since late 1977. It incorporates a highly reflective brightened aluminum reflector coated with a proprietary GE process developed by the Lighting Systems Department for protection of lamp reflective surfaces in environmentally polluting atmospheres such as the New Jersey Turnpike. The reflector focuses the sunlight on the evacuated glass tubes which have a spectrally selective coating on the outside of the inner glass tube. The energy is then transferred by conduction through an air gap to a copper fin which conducts the solar energy around the fin to the serpentine tubes in which the heat transfer fluid is circulated.

The solar energy collection is initiated upon command from a solar integrator which incorporates a photo sensor which integrates the solar insolation and turns on the primary loop pumps for a solar insolation in excess of 70 Btu/hr ft^2.

The circulating pumps, heat exchanger, expansion tank and the system controls were configured for residential applications in an energy management module. This configuration, Figure 3, minimized the number of interconnections, both plumbing and electrical, required in the field.

The heart of the solar cooling system is the Rankine electric heat pump shown schematically in Figure 4. Note that the system is configured with two separate hermetically sealed loops, the Rankine driver loop and the heat pump loop. The working fluid for the solar drive loop is a fully fluorinated hydrocarbon, FC88, which is circulated via a feed pump through the vapor generator and into the expander. Upon exit from the expander, the vapor is condensed in an air side condenser. The conventional heat pump loop is

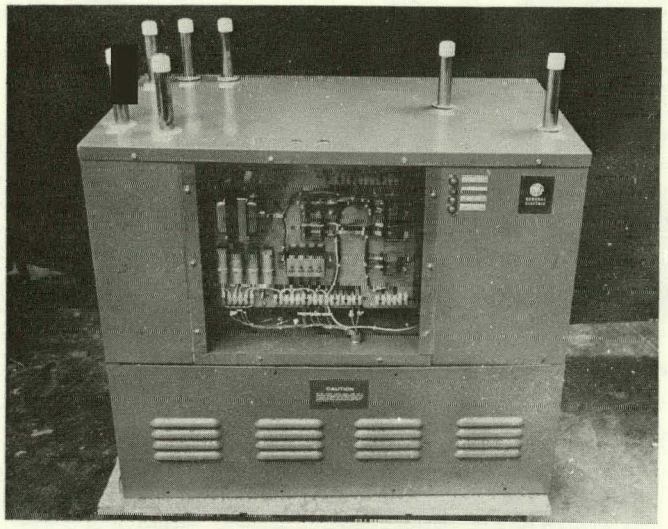


Figure 3. Energy Management Module

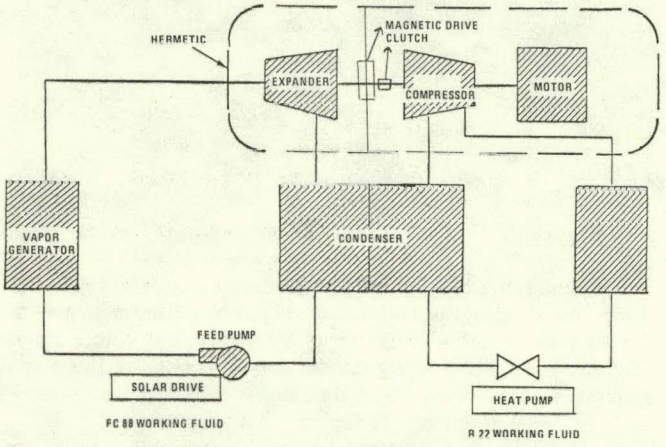


Figure 4. Solar Driven Heat Pump Schematic

converted to the expander drive through a synchronous magnetic drive and an overrunning clutch. The compressors used in these systems are modified GE Weathertron compressors using R22 as the working fluid. The solar drive is used only for cooling but the unique design provides a total integral backup electric heat pump system for heating and cooling. The outdoor unit of the three ton system is shown in Figure 5.

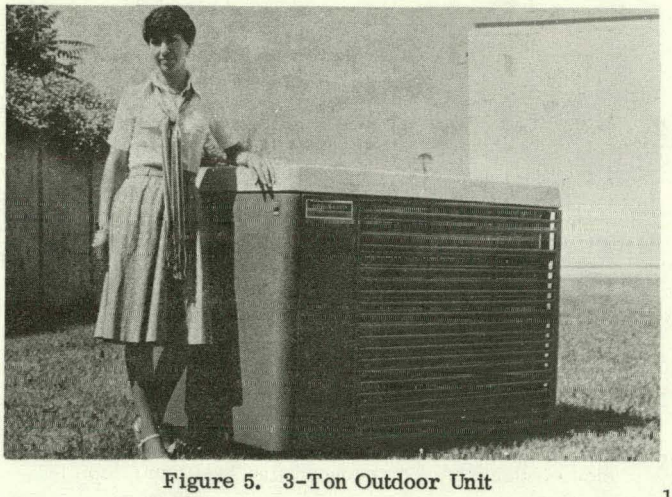


Figure 5. 3-Ton Outdoor Unit

An air side plate fin condenser has been designed to hold the FC88 and R22 to 110°F on an ASHRAE standard day. This condenser (Figure 6) sizes the outdoor unit and provides adequate space for the feed pump and vapor generator within. The air flow is through the condenser with exit from the top via a single low speed fan and orifice system. A single plate-fin tube assembly is utilized for both the heat pump and solar drive condensers; and incorporates "fin sharing" which provides for an even lower temperature of the coolant when the solar drive is not operating, thereby increasing the system EER when operating in the electric mode.

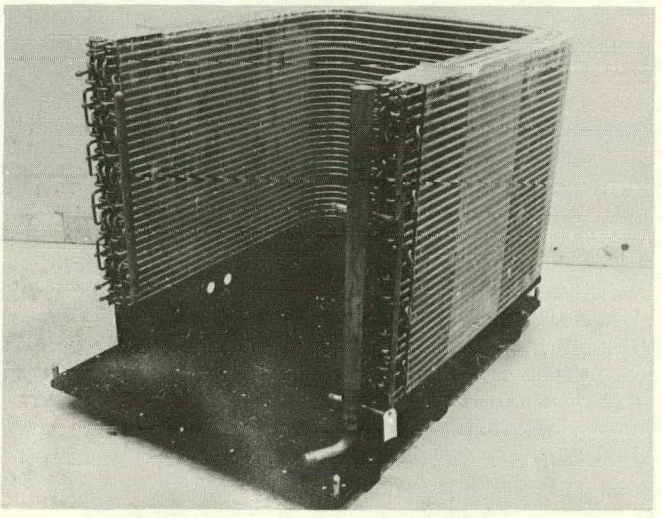


Figure 6. Outdoor Unit Condenser Coil

The feed pump (Figure 7) for the solar drive is an hermetic electric motor driven pump developed by GE to meet the high head, low NPSH requirements inherent in this application. The pump has two stages, a centrifugal and a gerotor section. This design which has accumulated over 20,000 hours on the pump section employes an injection cast rotor and an integrally lubricated thrust bearing system to provide long life. The hermetic housing for the pump also serves as the sump for the solar drive working fluid.



Figure 7. Feed Pump

The vapor generator is a helicoil pancake parallel tube, single pass preheater, vaporizer and superheater developed by Graham Manufacturing. The efficiency of the vapor generator was 98% which exceeded the requirements placed on it. The heating fluid (water) was placed on the shell side of the single pass counterflow unit. No doubt, the compactness of the unit contributed to the ease of installation and the excellent performance.

A single pass tube and shell regenerator was incorporated to maximize waste heat recovery. In this unit, the liquid was placed on the shell side for lower liquid inventory and lower heat loss.

The heart of the solar driven heat pump is the rotary vane expander. The two-stage multi-vane expander is shown schematically in an end view in Figure 8

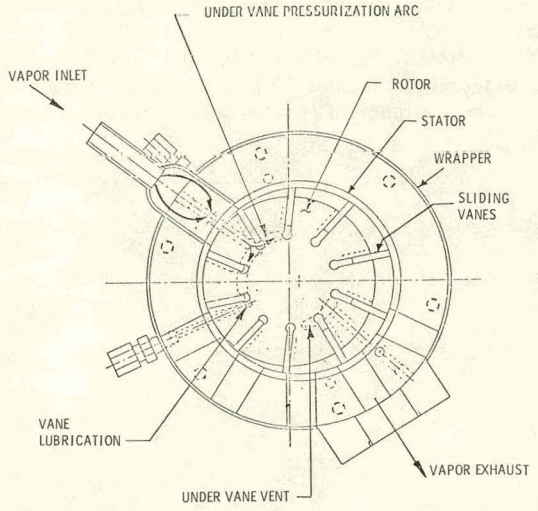


Figure 8. Multi-Vane Expander

The vapor is inlet to the expansion space and under the vane to pressurize the vane against the stator liner. As the vapor expands, the rotor moves until the vapor exhausts to the regenerator. The rotary motion is transmitted to the compressor via a synchronous magnetic drive as shown in Figure 9, with the expander mounted on the compressor. Figure 10 shows the 3-ton expander ready for test with the outer housing removed.

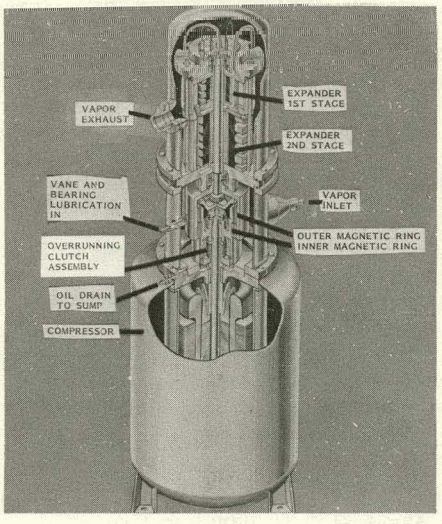


Figure 9. Rankine Expander/Compressor Assembly

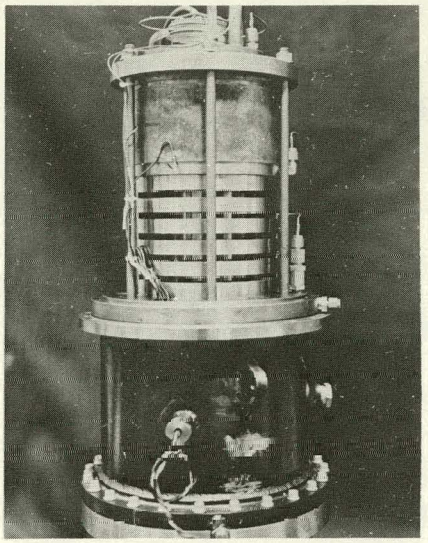


Figure 10. 3-Ton Expander

The component parts of the two-stage multivane expander are shown in Figure 11. The vanes which have been selected after years of screening tests are a metal impregnated graphite material which tests show should last 100,000 hours. This far exceeds the 20-year design life of the system. The performance of a unit after an accumulation of that amount of operating time has been approximated by grinding the vanes to the anticipated length and operating the expander. Performance degradation was essentially nonexistent. The remainder of the expander is fabricated from low cost high volume alloys (e.g., ductile cast iron) and should be quite inexpensive in production. Both the ten-ton and the three-ton systems employ essentially the same designs although they are different in size.

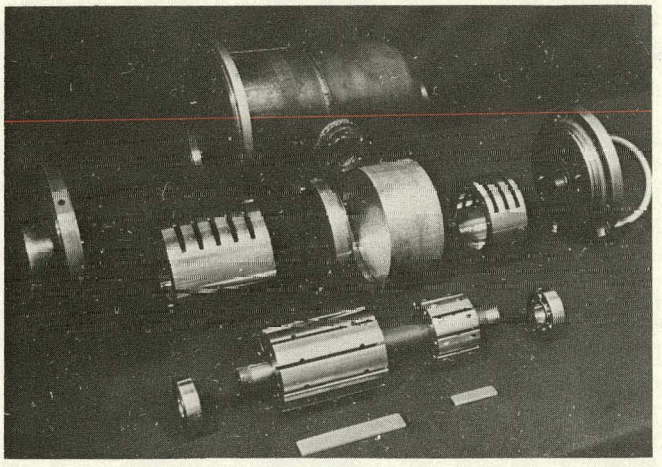


Figure 11. 3-Ton Expander Components

The configuration of the outdoor unit for the REH-100 series ten-ton units is slightly different than the three-ton. This unit, shown in Figure 12, has the feed pump, vapor generator and expander/compressor packages mounted in a sound insulated machinery compartment at one end of the outdoor unit. This is a conventional approach for commercial systems where ease of maintenance and assembly are of greater importance than aesthetics and minimum size. The condenser area again sets the size of the unit which, for comparison purposes, is roughly the same size as the conventional GE 20-ton Weathertron.

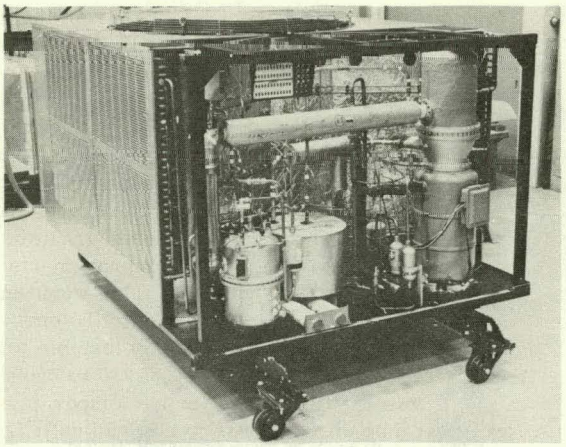


Figure 12. Outdoor Unit for REH-100

System Performance

To date, one three-ton system has been installed at Southern Methodist University and two ten-ton systems have been delivered to TVA for their installation. Each of the systems is similar but slightly different. Because of funding limitations in the solar cooling programs, the lessons learned as the development continued were not incorporated into the previously built units.

The first unit completed was the three-ton unit. The primary deficiency in that first unit is that of the Rankine engine expander. Both the expander efficiency and shaft horsepower were considerably below predicted values as shown in Table 1. The compressor efficiency and magnetic drive efficiency were greater than originally predicted. However, the compressor was limited by lubrication constraints to a minimum operating speed of 1200 rpm, which imposes a penalty on off-design performance and therefore solar cooling time. This limitation was eliminated in the ten-ton compressors.

Table 1. 3-Ton Unit Performance at Design Point (Rankine Driven)

	INITIAL PREDICTION	TEST RESULTS* 4/3/79
• NET COOLING CAPACITY	36,000 BTUH	31,500 BTUH
• COMP. EFF.	76%	80.6%
• HP COP (MECH.)	5.0	5.38
• EXPANDER EFF.	82.6%	61%
• MAG. DRIVE EFF.	96%	99%
• OCOP	.70	.59
• SOLAR EER	23	20.5

MEASURED VALUES
* 95°F O.D. AMB. 68°F WET BULB
80°F DRY BULB 1350 SCFM

It should be noted that the electric motor driven performance of the three-ton unit yielded a capacity of 36,900 Btu/hr with an EER of 11.5.

The 10-ton units were designated REH100 and REH101, the REH101 unit was the latest configuration of expander design. The design goals and design point performance of those units as measured in the laboratory are shown in Table 2.

Note that the REH101 test results agree very favorably with the design calculations predicted for the system. The

Table 2. 10-Ton Unit Rankine Driven Performance

	DESIGN GOAL	REH100 TEST RESULTS	REH101 TEST RESULTS
• NET COOLING CAPACITY, BTUH	120,000	116,573	120,000
• EER	20	19.5	20.5
• $OCOP_{TH}$	.74	.69	73
• SENSIBLE HEAT FACTOR	--	.74	.77
• EVAPORATOR TEMPERATURE, °F	49	49	49
• CONDENSING TEMPERATURE, °F	110	112	109
• TOTAL WATTS	6,000	5,974	6,123

EER (perhaps the most important criteria for payback) for the unit exceeded the predicted value even though the total power consumed was slightly higher (2%) than predicted. Another encouraging aspect of the performance was that the capacity was reached at an inlet fluid temperature of approximately 285°F. This is very encouraging since it provides for extended solar driven cooling operation should the inlet temperature go above that value. The thermal COP is shown as a function of inlet temperature in Figure 13.

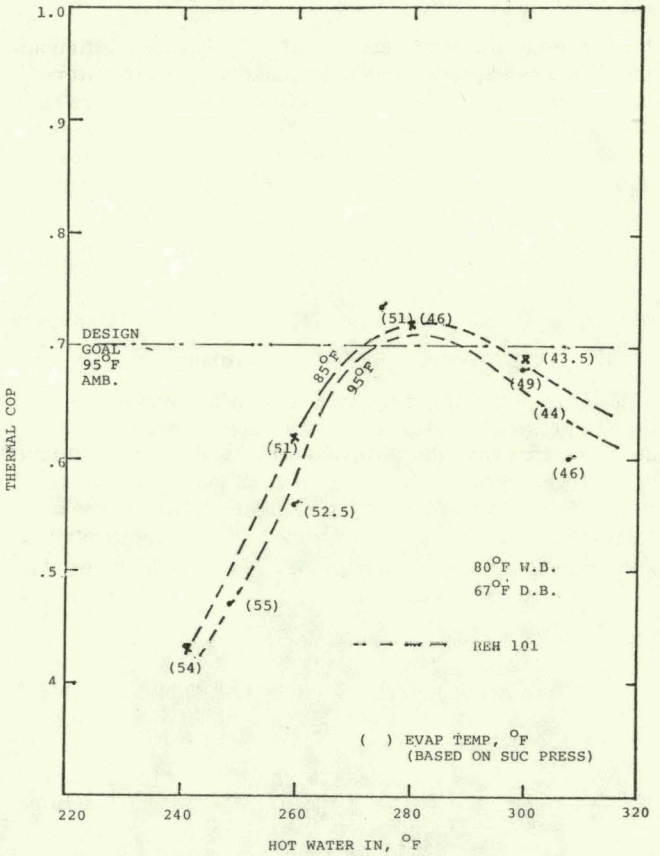


Figure 13. REH-101 Rankine Driven $OCOP_{th}$

The low speed cutoff for both the REH100 and REH101 units is 900 rpm as compared to 1200 rpm for the REH30 (3-ton) unit. This allows the units to have good off-design performance exceeding that of the electric units down to approximately 245°F as shown in Figure 14.

If the ambient temperature is less than 95°F, the EER exceeds $EER_{electric}$ down to an inlet temperature even lower (e.g., 240°F @ 85°F ambient). This off-design per-

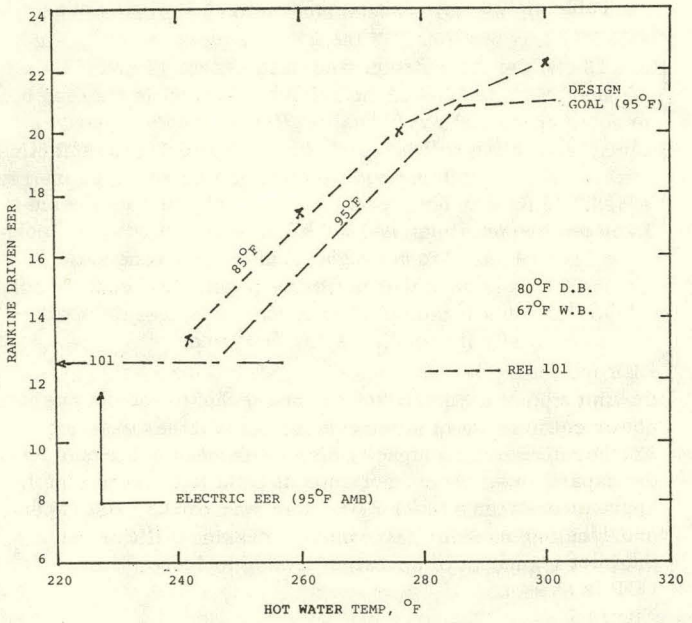


Figure 14. REH-101 Rankine Driven EER

formance results from three things: 1) expander efficiency increases as expander speed decreases, 2) evaporator temperature increases and 3) condenser temperature decreases. All three tend to increase OCOP for a time but eventually Rankine cycle efficiency and heat pump capacity decrease at a higher rate and an overall decay in performance results.

The laboratory tests further showed that upon startup, the Rankine engine/compressor are at or above design speed in less than 30 seconds with the Rankine driven heat pump stabilized at peak cooling in approximately two minutes.

Lessons Learned and Product Improvements

Several lessons have been learned in the development of the systems and in the installation of both the heating and cooling systems. Some of these are:

1. Temperatures required for cooling systems can be achieved in the summer.
2. The Energy Management Module is an attractive concept for residential applications and tends to simplify installation.
3. Bidder's briefings resulted in lower construction bids from interested contractors.
4. Installing contractors require a training program to successfully complete an installation.
5. Care must be exercised to prevent thermal siphoning, especially when operating at temperatures requires for solar cooling.
6. System design should be targeted for temperatures less than 300°F to maximize solar cooling time.
7. More effort should be spent learning from the hardware which has been built. It is still very immature hardware and significant improvement can be expected.

Recent evaluations of the solar cooling systems have led GE to believe that slight modifications to the overall design can yield improved overall system peak performance and improved off-design performance which means greater time spent on solar cooling. Anticipated improvements in the thermal COP are shown in Figure 15. This would indicate that, for air side condensers similar to the ones discussed here, $OCOP_{th} > 0.9$ are definitely feasible for expander inlet temperatures in the range of 280 to 290°F. Consideration of collector efficiency versus temperature and heat transport loop effectiveness would lead us to believe that a 285°F design point would appear to be near optimum.

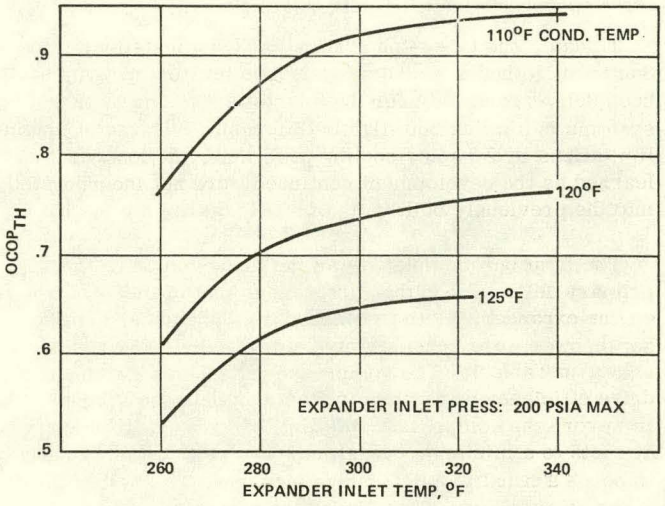


Figure 15. Overall Thermal Coefficient of Performance

The Future

The future for solar cooling is tied to the savings which can be expected and to the anticipated costs of other alternative energy costs. These economics are dependent on

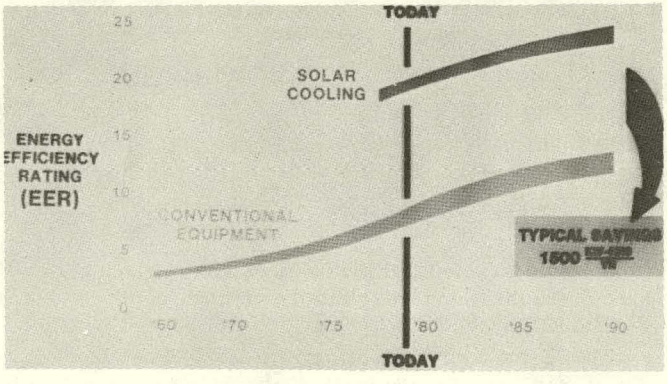


Figure 16. EER Performance

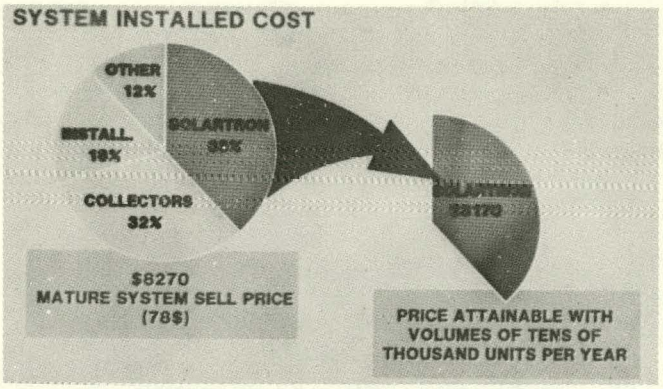


Figure 17. Economics

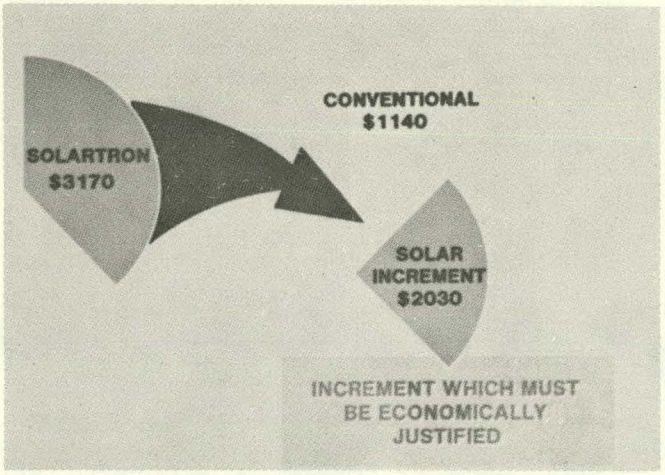


Figure 18. Cooling Economics

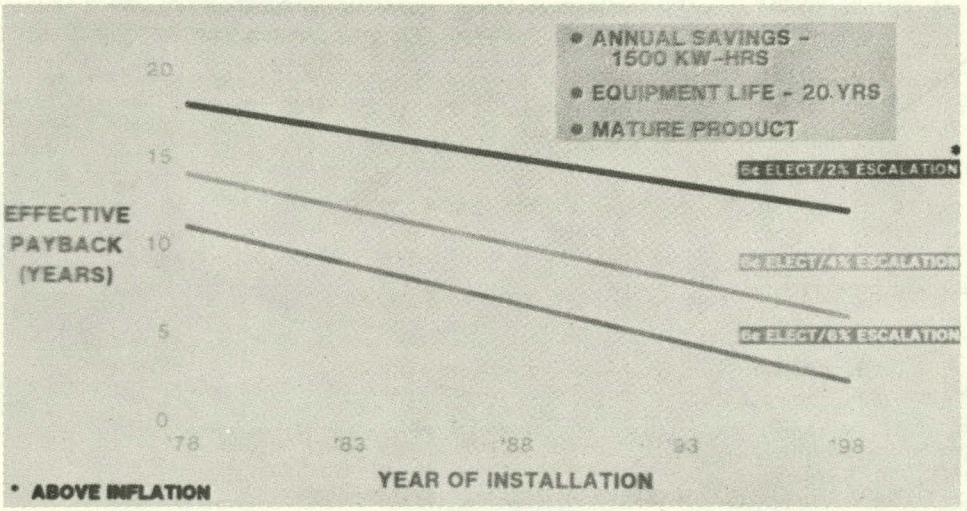


Figure 19. Effective Payback

the EER differential between conventional equipment and solar cooling systems. If the EER's are as shown in Figure 16 and the costs are as shown in Figure 17 and if it is assumed that the cost of the collector system is charged off to solar space and water heating, the incremental cost for solar cooling will be as shown in Figure 18; the effective payback may be determined based on the cost and the energy saved. In the sun belt, e.g., Fort Worth, this was calculated to be approximately 1500 kW hrs/yr. If now one looks at what is required to get significant market penetration, Figure 19, it is seen that moderate penetration could occur in the late '80's if the effort is continued to test the hardware and verify its readiness for that time.

As noted in the introduction, one technique of increasing the attractiveness of solar cooling is to further examine the effectiveness of capacity displacement of solar cooling on the utilities. At an incremental installed cost of significantly less than $\$700/kW_e$[1], this may be the least expensive peaking capacity that summer peaking utilities can find when the cost of operation is also included.

(1) Assumes approximately 1 kW required per ton of cooling.

SOLAR HEATING AND COOLING DEVELOPMENT

HONEYWELL INC.

CONTRACT NO. NAS8-32093

STEVEN E. SCARBOROUGH

PERIOD OF CONTRACT: Begin JULY 1976 End SEPTEMBER 1981

OBJECTIVES

The objectives of this program are to:

- Develop, deliver and support prototype solar heating and combined heating and cooling studies, hardware and systems for:
  - Single-family residences (3 ton),
  - Multifamily residences (25 ton),
  - Commercial (25 to 50 ton).
- Design, fabricate and deliver a prototype high-temperature (300°F) 24-ton Rankine-assisted chiller.
- Perform a cost study to identify combined heating and cooling systems and installation cost reductions.
- Design, fabricate and deliver a 16-KVA Rankine-assisted power generation module.

BACKGROUND

In July of 1976, Honeywell Energy Resources Center (Minneapolis, Minnesota) entered into a contract agreement with NASA's Marshall Space Flight Center to design and develop solar-powered building space heating and cooling systems. This ongoing engineering field test effort is known as the "404" program. The objectives of the program are the development and field testing of solar heating and cooling systems that (1) maximize efficiency, (2) have low cost potential, and (3) are modular in composition to enhance application.

Honeywell is the prime contractor for the program team. Barber-Nichols Engineering of Denver, Colorado, and Lennox Industries of Marshalltown, Iowa, are subcontractors. Honeywell is responsible for the solar system design, overall program management and subcontractor coordination. Barber-Nichols and Lennox are working as a team to develop solar-powered Rankine engine/air conditioner subsystems. Lennox Industries is supplying HVAC products suitable for application in the system, including their production flat plate solar collector.

SUMMARY

The contract calls for delivery of the following systems/products shown in Table 1. Two single-family residential (SFR) heating systems, two residential heating and cooling systems, one 25-ton multifamily residential (MFR) heating and cooling system, one 25-ton commercial heating and cooling system, and one 50-ton commercial heating and cooling system are operational. Design reviews have been completed for the remaining two residential heating and cooling systems and they are under construction. The remaining commercial 25-ton and 50-ton heating and cooling systems are in the site identification phase.

Table 1. Contract Deliverables

QUANTITY	SIZE	TYPE	APPLICATION
2	3 TONS	HEATING	RESIDENTIAL
4	3 TONS	HEATING AND COOLING	RESIDENTIAL
1	25 TONS	HEATING AND COOLING	MULTIFAMILY
2	25 TONS	HEATING AND COOLING	COMMERCIAL
2	50 TONS	HEATING AND COOLING	COMMERCIAL
1	25 TONS	HIGH-TEMPERATURE RANKINE CHILLER	COMMERCIAL
1	16 KVA	POWER GENERATION MODULE	COMMERCIAL

Development tasks under the program include: (1) fully qualifying the Lennox collector to the Interim Performance Criteria; (2) development of a residential energy transport module that includes all pumps, heat exchanger, controls and hydronic specialties; (3) development of a high-performance, low-cost heat exchanger; and (4) development of low-cost collector support structures and headers. In the Rankine cooling subsystem technical areas, the major development efforts are directed toward a nominal 3-ton Rankine-engine-assisted direct expansion air conditioner with evaporative cooling and a 25-ton Rankine-engine-assisted water chiller. The units have undergone development testing, have passed final checkout tests, and have been shipped either to application sites or to storage.

TECHNICAL ACCOMPLISHMENTS

William O'Brien--SFR Heating Site. The operational test period ended May 31, 1979, and the performance reports have been submitted. The total energy requirements during the 1978/1979 heating season were close to the predicted values, but an unseasonably high degree of cloudiness decreased the amount of available energy, reducing the solar contribution below a predicted 35 percent of the total load. Analysis of daily data (March 12) indicates that the system is functioning satisfactorily with a maximum collection rate of 83,160 Btu per hour and a peak efficiency of 49 percent. The total collected energy amounted to 395,545 Btu, with a daily overall ef-

ficiency of 43 percent. During the 24-hour period, no auxiliary fuel was required, with the solar system supplying all of the 314,000 Btu space heating load. The home owner is pleased with the system and impressed with the reliable operation and comfort provided.

New Castle--SFR Heating Site. New Castle was not occupied and was deactivated in March 1979. In October 1979, an occupant was identified, and Honeywell and IBM have worked together to reactivate the system for an abbreviated test period beginning January 1, 1980 and terminating June 30, 1980. Performance reports for the first 3 months will be submitted in April.

Thomas Village, Virginia--SFR Heating and Cooling Site. System installation is complete and has been operating as expected, with the system cooling and generating electricity during the day and heating occasionally at night. During the initial Rankine-cycle air conditioning operational period from September through mid-November, the unit logged 450 hours of air conditioning and Rankine operation. The site owner is pleased with the system and the quality of the installation work done by the contractor. The owners have seen the system operate in all modes and are comfortable with the functional reliability and the maintenance plan. Site performance equations are being prepared, and performance reports will follow.

Lawrenceburg, Tennessee--SFR Heating and Cooling Site. The system installation was completed in August 1979 and the site has been operational since that time. This system does not contain a Site Data Acquisition System (SDAS).

Shenandoah, Georgia--SFR Heating and Cooling Site. The site coordination meetings and the final lot selection have been completed. The preliminary drawing package was presented and approved. Due to weather conditions, house construction and system installation has been delayed by at least 1 month and will begin in April. All hardware fabrication, procurement, and preparation for shipment continue on schedule.

Allaire State Park, New Jersey--SFR Heating and Cooling Site. At a design review in February, the installation package was presented and the design was approved. All long-lead parts are on order and will be delivered by May 1980. Site installation and checkout will be complete by mid-June.

Kansas University--25-Ton MFR Heating and Cooling Site. The Kansas University system, the first complex heating and cooling site, functioned well during the heating and cooling seasons. Honeywell and IBM are analyzing the detailed information from the SDAS to prepare a meaningful report. Honeywell must report on performance as it applies to component commercialization and is therefore interested in subsystem data. Definition of the data analysis procedures will be precedent-setting for the balance of the Honeywell "404" sites.

Performance of the system was verified using data obtained from the SDAS. The selected day, August 6, 1979, provided good solar radiation intensity and a high cooling load, giving an indicative basis for the cooling subsystem's performance evaluation. The solar system operated continuously in the direct cooling mode, supplying all the collected energy, or 3 million Btu, to the Rankine engine. The increase in the operational temperatures, associated with the cooling mode, resulted in an overall daily efficiency of 42 percent for the collector array and a peak efficiency of 47 percent at 189°F for the collector fluid outlet. The measure of solar contribution can be determined by the reduction of the auxiliary electric power input to the compressor motor. For a total output of 1.15 million Btu of cooling, the auxiliary power input was limited to 15.6 kWh, indicating a 74 percent solar contribution. If the compressor input is further reduced by the 6.3 kWh of electrical power generated by the Rankine engine, the solar contribution increases to 84.5 percent.

The overall system performance for the 24-hour period indicates a considerable reduction in electrical power consumption over a conventional cooling system. With a total cooling output of 3.5 million Btu, the net power input, including the parasitics associated with the solar components and the cooling tower, amounted to 247 kWh, resulting in an EER of 14.08 and a system COP of 4.13. This is at least a 50 percent improvement over conventional systems.

Ocmulgee, Georgia--Commercial Heating and Cooling Site. The site is operating in the normal heating season status with the cooling modes locked out. The four air handling units remain inactive pending installation of the ductwork system for each unit, scheduled to be complete by May 31, 1980.

Carrollton, Texas--50-Ton Commercial Heating and Cooling Site. The Installation Acceptance Review (IAR) was held at the site on January 24, 1980; the demonstration showed the system to be operational in all modes. Typically, the system operates with both Rankine engines in support of the air conditioning load. At 4:30 P.M., the building cooling is turned off, and the system continues to operate in the generate mode until solar energy is unavailable. During fall operation, with reduced cooling loads, the system has generated electricity and cooled simultaneously. Site equations are in preparation, and Honeywell will initiate performance reporting after the equations are complete.

High-Temperature Rankine-Assisted Chiller Program. The high-temperature, 25-ton Rankine-assisted water chiller represents a logical extension of the work that Honeywell, Barber-Nichols Engineering, and Lennox have completed on low-temperature, 25-ton units and on the high-temperature, 100-ton chiller units used in the General Offices system at Honeywell Plaza in Minneapolis. This program involves primarily a Barber-Nichols design, fabrication, test and delivery of one high-temperature, 25-ton Rankine-assisted chiller. The unit is in development tests at this time and is scheduled for shipment to NASA by April 1, 1980.

25-Ton Rankine Subsystem Improvements. The objectives of this effort are to produce a unit with increased reliability and improved performance in both cooling and electrical generation modes. Specifically this involves development of a compressor to provide an overall performance improvement in the cooling mode, a low-cost gearbox and turbine design, heat exchangers, improved controls, a new clutch design, and individual component redesign for improved reliability. The compressor analysis and design is complete. Fabrication of compressor components has been initiated. The gearbox concept has been finalized,

and detailed design of the gearset, bearings, and housing is complete. Boost and feed pump redesign analysis is in progress and is directed at redesign of the pump to reduce power consumption and parts cost. A purge system is designed and is in development testing.

FUTURE ACTIVITIES

Contract Activities. Contract activities remaining include:

- Installing the two residential heating and cooling systems by July 1, 1980.
- Locating a 25-ton heating and cooling site in the southwest and designing and installing the system.
- Designing and installing a 50-ton heating and cooling site in the southwest.
- Completing the design, fabrication and test of the 25-ton Rankine subsystem improvements.
- Completing the design, fabrication, and test of the Power Generation Module (PGM). The unit will incorporate as many of the new designs developed under the 25-ton Rankine improvement as practical, such as the turbine-gearbox, purge, heat exchangers, and controls.
- Initiating and completing cost reduction studies emphasizing system configurations that will provide lower installation costs. Areas to be studied include configurations that maximize electrical generation while minimizing parasitic power consumption, coupled with improved life-cycle costs. Commercial systems featuring the 25-ton subsystem will be studied, as these appear to provide the best near-term benefit.

Post Contract Activities. Lennox continues to monitor the marketplace for opportunities to commercialize the hardware, subsystems and systems developed on the "404" program. At this time, the flat plate collectors are in mass production 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 "404" residential heating system and its design application are included in the Lennox product offering. The site application and component selection is now being accomplished by Lennox distributors.

The heating and cooling systems involve the more sophisticated Rankine drive subsystem and are not yet in sufficient demand to expand marketing and production efforts. However, Lennox marketing continues 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. If current conventional energy availability and cost trends continue, such systems likely will become selectively cost effective by the mid-1980s.

Honeywell will analyze the empirical data from each of the installations and, through the cost reduction study program, will define the most economic system for different regions of the United States. This information, combined with hardware cost reduction development, will define the second generation heating and cooling systems to be tested against marketability.

CHILLER DRIVEN BY A SOLAR STEAM-POWERED RANKINE ENGINE (SSPRE)

UNIVERSITY OF PENNSYLVANIA
DEPARTMENT OF MECHANICAL ENGINEERING AND APPLIED MECHANICS

AC03-78ET20110

DR. NOAM LIOR AND DR. HSUAN YEH

NOVEMBER 1, 1977 TO OCTOBER 31, 1980

OBJECTIVE

The objective of this project is the design, fabrication, testing and analysis of a solar-powered heat engine/vapor compression cycle chiller of 15-25 ton capacity. The chiller shall be designed for efficient operation with solar-heated fluid supply temperatures of 220° to 300°F, and be air-cooled.

BACKGROUND

The proposed heat engine would operate in a novel steam Rankine cycle. The cycle employs solar energy at 220° to 300°F (or less) to vaporize the water. If the steam is used directly to drive the engine, the efficiency of this power cycle is comparable to that of existing organic fluid power cycles. However, superheating the solar-generated steam by means of fuel to temperatures of about 550°C (1022°F) approximately doubles the cycle efficiency, remarkably with only about 20-25% of the total energy input supplied by the fuel. It is shown that the increase in efficiency makes the system based on this cycle potentially the most economical of all existing solar-powered cooling schemes. The design shows that a 30 HP novel steam turbine with 75% efficiency is feasible. As an alternative, a rotary engine of novel design and of similar efficiency, and which has been successfully built and tested in a smaller version, is also being considered. The chiller may be a standard mass-produced unit.

The major advantages of the proposed approach are: (1) the use of water instead of organic fluids, (2) a novel hot-water thermal storage system which releases steam to the cycle by flashing, (3) the use of a small amount of fuel (20-25%) to double the cycle efficiency (compared to organic fluid cycles), when needed, (4) highest system economy, (5) novel concepts of high efficiency (75%) small (30 HP) steam turbine, rotary expander, and rotary expander-compressor, (6) system is amenable to retrofit where vapor compression units are presently used.

The Mollier diagram of the cycle is shown in Fig. 1, and the flow configuration and hookup to a vapor compression chiller is shown in Fig. 2. The comparison of the steam cycle to some existing power cycles employing organic fluids is demonstrated in Fig. 3.

SUMMARY

The major accomplishments so far are the development of a comprehensive computer program to analyze the total system, the completed design of a novel and high efficiency (75%) double-rotating steam turbine and of a rotary engine/compressor combination, analysis of the flashed-steam thermal storage system, and specification of the system's components and instrumentation. The turbine is being manufactured at present, and the test bed for the SSPRE chiller is in the acquisition and construction phase. The data obtained so far indicate that the SSPRE approach seems to have the best economic characteristics of all other known solar cooling schemes.

TECHNICAL ACCOMPLISHMENTS

1. System Performance Analysis

- A detailed computer program was developed and is close to completion, to analyze the SSPRE-driven chiller system's characteristics. The completed subroutines are:
  - Rankine cycle
  - Turbine efficiency as a function of all operating parameters
  - Heat exchangers
  - Gas-fired superheater
  - Flashed-steam thermal storage
  - Piping pressure drop
  - Linkage to TRNSYS for the solar loop's performance
  - Properties of steam, water, and air

2. Radial Turbine (Fig. 4)

- Completed the design of the radial-flow counter-rotating turbine based on the selected on-design operation temperature combination of 600°C superheat, 100°C steam generator and 46°C condenser.
- Completed detailed off-design performance estimates. These indicated that the reaction-type blading selected, among other design features, allows the maintenance of high turbine efficiency (69-78%) throughout the off-design range of operation (Fig. 5).
- A report on the turbine's design and off-design performance has been completed.

• Concluded that the type of turbine selected can be built by precision casting requiring practically no machining based on Philadelphia Gear Corporation evaluation. The turbine is being manufactured at present.

3. Rotary Expander and Rotary Expander-Compressor (Fig. 6)

• Completed basic design of these units.

• Since the sliding contact life expectancy is uncertain, it was decided to chose the turbine for application in this project, but to also continue the investigation of the sliding contact question for the rotary engine.

4. Thermal Storage: Flashed-Steam System

• Completed comprehensive review of correlations used to determine the approach to equilibrium of flashed water and saline water. Also, incorporated these correlations into a computer-plotting program to compare them, analyze the influence of the major system parameters and optimize the storage unit design. A heat transfer and evaporation model was developed and solved to determine the transient flow rate, temperature and pressure of the steam flashing from the storage tank.

5. Superheater

• A gas-fired steam superheater and an electrically-heated one were analyzed in detail to allow proper specification in the request for quotation, and to better understand their performance.

• Quotations were sought and obtained for both types.

• A gas-fired superheater is on order.

6. Back-up Drive for Chiller

• A simple mechanical interface, based on a Sprag-type clutch, was designed to automatically engage an electric motor to the chiller's compressor when the turbine's power is too low yet cooling is desired. This is now being built.

7. Cost Estimates

• Philadelphia Gear Corporation provided cost estimates for both radial turbine and rotary expander preliminary designs on a mass-production basis.

• Completed preliminary estimate of mass-produced system cost breakdown. The solar collectors constitute the major portion of the system's cost, 64%. This fact confirms the cost-effective advantage of the SSPRE concept, which utilizes about half of the collector area required by the other cooling schemes. The total system cost is still quite high. Various methods of cost reduction will be explored, including the use of the same solar energy collection and storage system for heating in winter.

8. General

• Progress is being made with developing a control strategy and with the design, acquisition and construction of the experimental system.

• Overall methodology relating to marketing, commercialization, and environmental impact was developed with United Engineers & Constructors, Inc. Proceeding with refinements and more detailed evaluations.

FUTURE ACTIVITIES

Contract Activities. The major tasks to be completed are:

• System Performance Analysis for Chosen Climatic Regions and Cooling Loads

• Phase I Final Report to DOE

• Detailed Design

• Phase II Final Report to DOE

• Fabrication and Assembly of SSPRE/Chiller

• Inspection by GTR

• Testing of SSPRE/Chiller

• Fabrication of Solar-Powered Air Conditioning Test-Bed System

• Experiments with Test-Bed System

• Final Technical and Economical Analysis of System

• Recommendations for System Development and Marketing

Post-Contract Activities. Two of the subcontractors to this project, The Trane Co. and the Philadelphia Gear Co., are major manufacturers of heating and air conditioning equipment (TRANE) and rotary machinery (Philadelphia Gear). They, as well as other companies, would have access to consider full commercialization and marketing of the solar powered chiller, based on the prototype test and commercialization study results of this project. Furthermore, the novel Rankine cycle studied here would be seriously considered for solar power applications.

PUBLICATIONS/REPORTS/REFERENCES

1. N. Lior, "Solar Energy and the Steam Rankine Cycle for Driving and Assisting Heat Pumps in Heating and Cooling Modes," Energy Conversion, Vol. 16, pp. 111-123, Pergamon Press, 1977.

2. N. Lior, H. Yeh and I. Zinnes, "Solar Cooling via Vapor Compression Cycles," Proc. of the Abstracts of the 1979 International ISES and AS/ISES Congress, Atlanta, Georgia, May 28-June 1, 1979, p. 391.

3. R. P. Kroon, C. A. Meyer, N. Lior, and H. Yeh, "Design of a 30 HP Solar Steam Powered Turbine," Report to DOE, in print.

ACKNOWLEDGEMENTS

* Principal personnel and corporations engaged in the project are: Professor R. P. Kroon, Professor C. A. Meyer, Philadelphia Gear Corp., Trane, and United Engineers and Constructors, Inc.

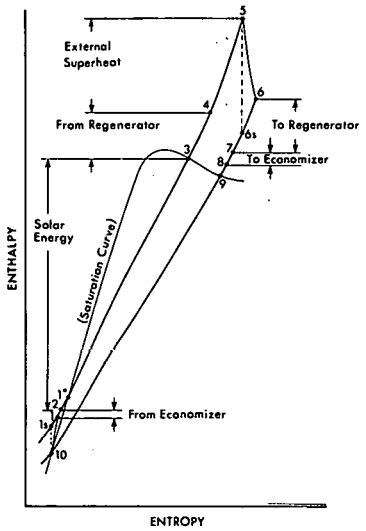


Fig. 1 Solar-Powered, Fuel-Superheated Rankine Cycle Mollier Diagram (Lior 1977)

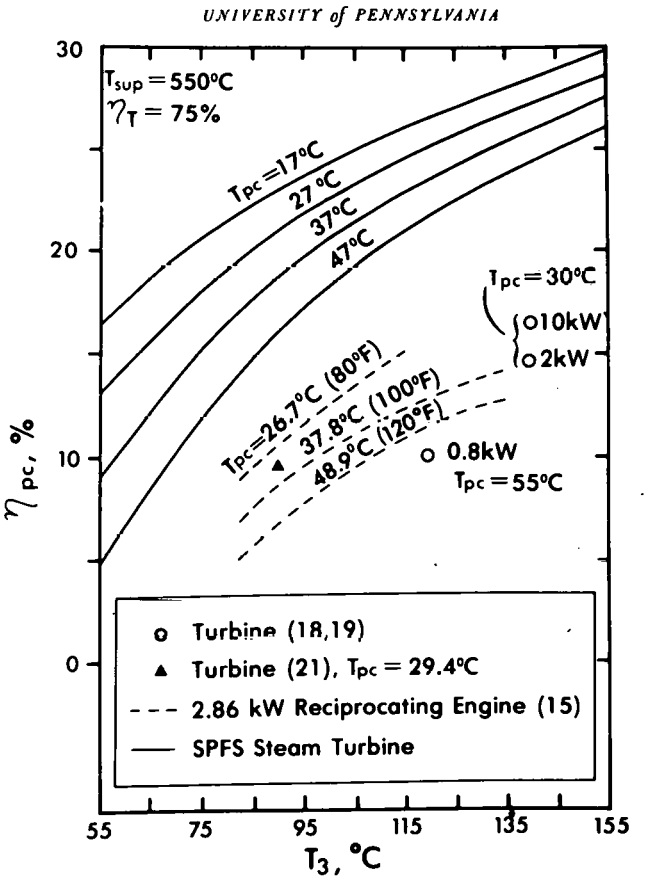


Fig. 3 Solar-Powered, Fuel-Superheated Steam Rankine Efficiency η_{pc} as a Function of Solar Collector Temperature, T_3, Compared to Existing Organic Fluid Rankine Cycle Systems (Lior 1977)

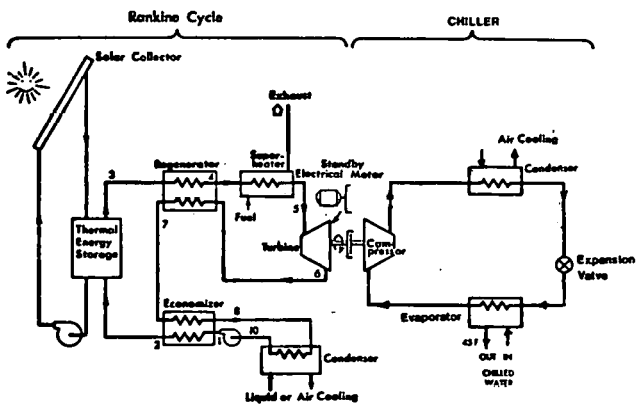


Fig. 2 Solar Steam Powered Rankine Engine (SSPRE) Driven Vapor Compression Chiller

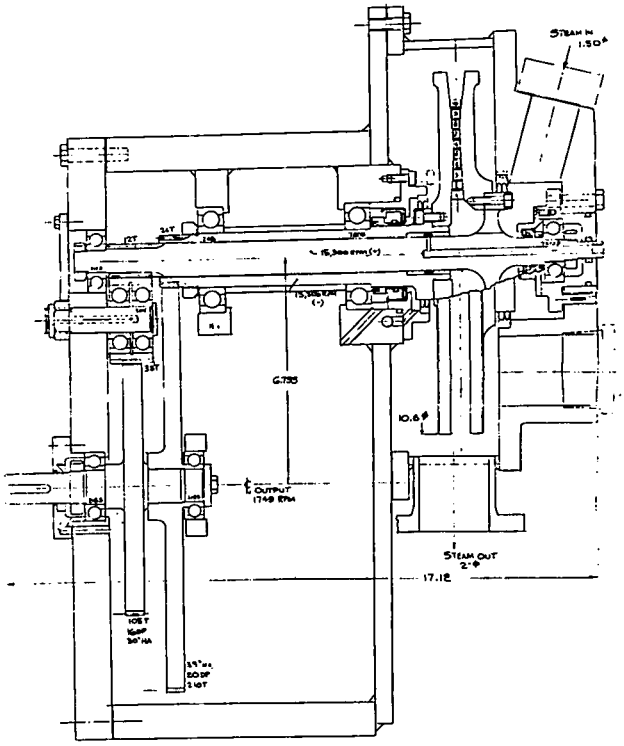


Fig. 4 The University of Pennsylvania Double-Rotating 30 HP Steam Turbine With Gear Box

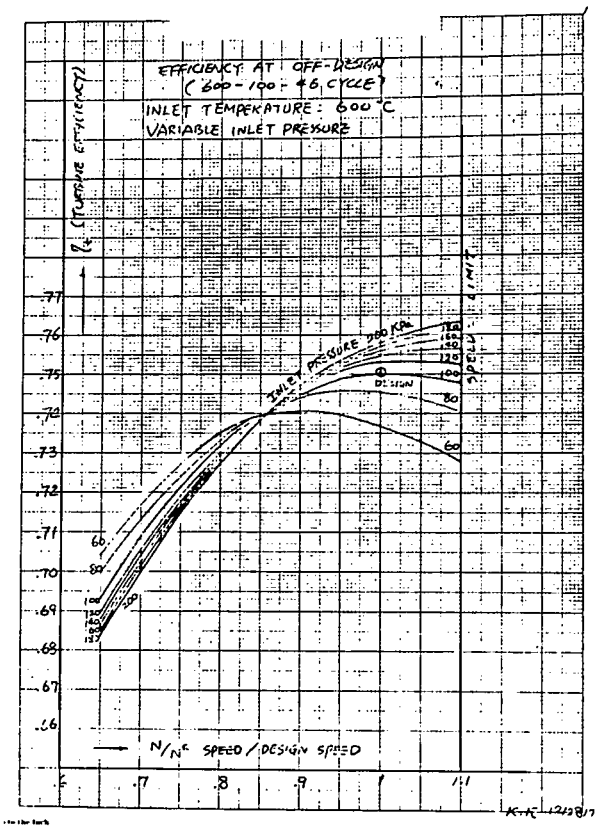


Fig. 5 Turbine Efficiency at Off-Design Conditions, as a Function of Speed, at Different Inlet Pressures

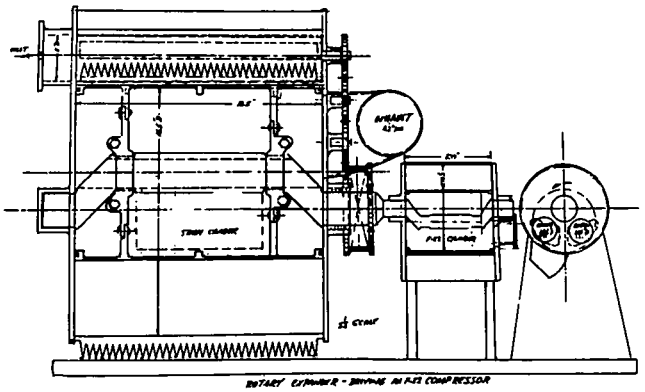


Fig. 6 Schematic of the Rotary Expander/ Compressor

DEVELOPMENT OF A SOLAR-POWERED 18-TON RANKINE CYCLE HEAT PUMP

RESEARCH CENTER AND HAMILTON STANDARD DIVISION
OF UNITED TECHNOLOGIES

DOE CONTRACT AC03-77-CS34510

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

PERIOD OF CONTRACT: SEPTEMBER 1977 TO MAY 1980

OBJECTIVE

United Technologies has designed, built and is testing a unique thermally-driven heat pump, sized for multi-family residential applications. This prototype unit was specifically designed to operate at peak temperatures typical of medium-concentration collectors and to permit efficient air cooling. The basic heat pump design data was developed under prior ERDA- and DOE-sponsored programs in which the operational feasibility and performance characteristics of a laboratory Rankine-cycle turbocompressor heat pump and air conditioning system were demonstrated.

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 approximately 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 of low-temperature solar energy in combination with power loop heat recovery. The HP is rated at 18 tons for cooling at standard ASHRAE operation conditions of 95 F db/75 F wb 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.

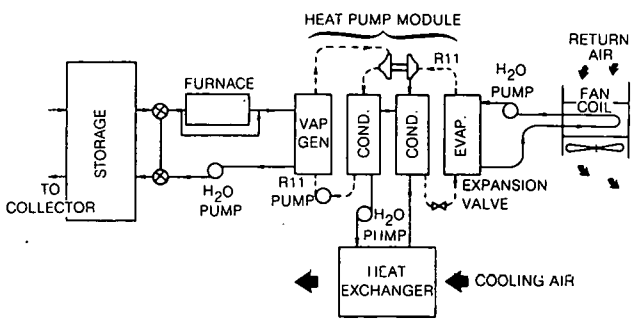


Fig. 1 Heat Pump System In Cooling Mode

SUMMARY

The prototype 18-ton solar-powered turbocompressor heat pump module has been successfully designed, built and tested in a specially-designed laboratory facility. Operation in both the cooling and heat pump mode was demonstrated at selected 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; operation and control was routine and transient response rapid. Air-cooled operation at industry standards rating conditions was demonstrated as well as such design features as wide operating range and high heat pump performance.

Seasonal performance estimates and economic analyses of the UTC heat pump were conducted for widely differing climatic conditions and energy costs. The impact of various collector types, collector array sizes, storage tank capacities, control strategies, component cost levels, overall system configurations, energy prices, escalation rates, tax credits and incentives were evaluated. The UTC heat pump has increasing economic potential as the price of energy increases and collector costs are decreased or as tax credits are increased above the current levels.

TECHNICAL ACCOMPLISHMENTS

• Heat Pump Module Fabricated. A primary program objective was to fabricate and assemble the heat pump components in a compact, easily installed and maintainable module. The module layout finally selected as it might be used for a multi-family solar heating and cooling installation is shown in Fig. 2. The module, which is approximately 3½ ft wide, 8½ ft long and 6 ft high, contains the four R11-to-water heat exchangers, the turbocompressor unit, the R11 pump, selected control elements and various valves, fittings and piping. The water-to-air heat exchanger is contained in a separate package (not shown in Fig. 2). The actual prototype module fabricated for the program retains the essential features required for field installation. An exception is the height, which is slighly greater than 6 ft, to accommodate the added ducting necessary to permit measurement of the R11 vapor flow from the turbocompressor.

The vapor generator, evaporator and R11 pump are located at the base of the module pallet. The condensers are raised to provide a simple gravity return of the R11 condensate from the condensers and to provide sufficient liquid head to prevent pump cavitation. This also allows the R11 to drain down to the proper exchangers after shutdown and permits

rapid startup of the heat pump. The turbocompressor unit is mounted directly on the evaporator outlet to minimize the piping to carry the low pressure R11 vapor from the evaporator to the compressor while reducing R11 pressure loss.

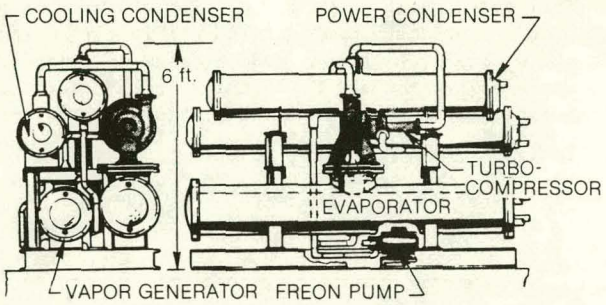


Fig. 2 Heat Pump Layout

• Laboratory Test Facility. The prototype heat pump module was tested in a specially designed and constructed laboratory facility at UTRC. To allow testing the heat pump over the range of conditions and operating modes to be encountered in an actual installation, the facility contains three subsystems which simulate: (1) the high temperature water streams from the collector or furnace; (2) the ambient air temperature variation; and (3) the heating and cooling load.

Figure 3 shows the heat pump installed in the test facility together with the simulation subsystems prior to testing. Not shown are the control panel, instrumentation and data monitor system, and mini-computer terminal.

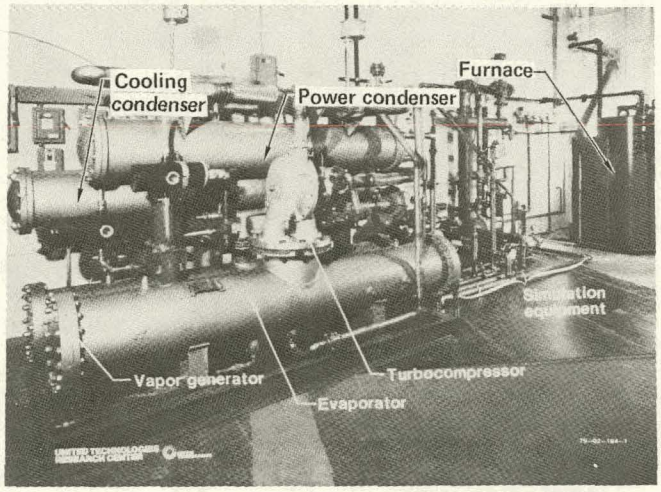


Fig. 3 Heat Pump Module in Laboratory

The data acquisition and recording system is connected to an on-site Interdata Minicomputer and also, via an MST data link, to the UTRC Computing Center and UNIVAC 1110 computer. The output from each of 64 channels is digitized and recorded onto a flexible magnetic disk utilized in the minicomputer. Data scans can be made at time intervals as low as approximately 2 milliseconds, allowing transient data to be obtained.

• Testing. After shakedown of the facility, instrumentation, and heat pump components, performance testing of the prototype heat pump module was conducted. Tests were run over a wide range of operating conditions especially in the cooling mode.

A plot of the test results during one run is shown as a function of time in Fig. 4. For this run, two condenser water temperatures were used, approximately 103 F and 85 F corresponding to ambient air temperatures of 95 and 80 F, respectively, and vapor generator water inlet temperature ranged from 313 F to 238 F with evaporator inlet water temperature near 55 F. The results illustrate the rapid response to changes in vaporizer water temperatures and the turbocompressor speed variations as it follows vapor generator temperature with only a minimal delay time.

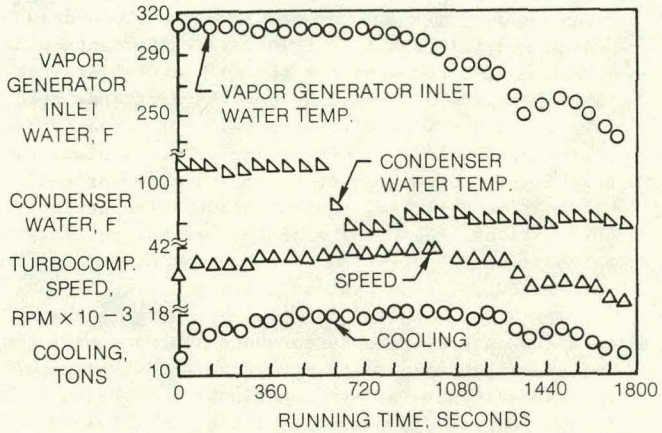


Fig. 4 Typical Data Output

During the testing, numerous test data were analyzed and compared to the predicted performance levels. Agreement between the test and predicted results were indicated at high capacity cooling conditions. The test results confirm the predicted system cooling capacity (18 tons) and COP ≈ 0.6 in the cooling mode. A COP of more than 1.67 and more than 400,000 Btu/hr were achieved in the heat pump mode.

At moderate flow, moderate lift conditions, a cooling mode COP approaching 0.8 and 10 to 13.5 tons of cooling were demonstrated. Cooling levels as low as 2 to 5 tons and heating of 200,000 Btu/hr were produced even at vapor generator inlet temperatures as low as 180 F, demonstrating the wide operating range of the heat pump. These are somewhat below predicted levels.

• Aerodynamic performance of the turbocompressor unit generally met predicted levels and turbine and compressor efficiency estimates indicate reasonable agreement with analytical predictions.

• The major heat exchanger generally performed as expected. The evaporator and condenser exceeded their heat transfer coefficients while the vapor generator water temperature drop and pinch ΔT were about as anticipated.

• The off-the-shelf R11 feed pump did not achieve the expected efficiency levels due to insufficient NSPH but the control elements provided safe, reliable operation.

• Seasonal Performance and Economic Analyses. The overall performance of the UTC heat pump system installation has been estimated by means of an analytical simulation procedure which includes performance models for each of the major components and subsystems, the thermal load characteristics of a typical multi-family residence and meteorological data for specific U.S. locations.

These models were incorporated into the basic University of Wisconsin TRNSYS building heating/cooling simulation computer program. This program was extensively modified by UTRC to allow simulation of new collector types and special components in the heat pump module, such as the Rankine-cycle turbo-compressor system and fan-coils operating with off-design sensible and latent loads. Performance models were also incorporated for the collectors, storage tank, fan-coil and auxiliaries. In addition, new computer codes were developed to: (1) model advanced east-west tracking concentrating collectors and non-tracking CPC-type collectors in any orientation, (2) utilize collector instantaneous performance data correlations, (3) model a master control routine which selects the system operating mode, and (4) read special SOLMET type weather tapes.

The installation performance analyses were conducted with hourly weather data using SOLMET tapes for typical years at six locations: New York, NY (1958); Madison, WI (1961); Fort Worth, TX (1960); Apalachicola, FL (1957); Phoenix, AZ (1962); and Santa Maria, CA (1956); which represent a wide variety of heating/cooling loads, geographic areas and solar insolation levels. A building model was established to simulate the heating and cooling loads of an energy efficient (as per ASHRAE Standard 90-75) three-story multi-family residence with six (6) apartments on each floor. Representative installation performance characteristics are presented in Table 1 for the six (6) locations. These performance simulations indicate a significant portion of the selected buildings heating and cooling energy needs can be supplied by solar energy, thereby reducing its annual fuel and electricity requirements. When used in cooling dominated areas such as Phoenix and Apalachicola, the UTC system can provide a substantial fraction of the building cooling energy needs with a minimum amount of collector. The energy distribution for the Phoenix installation is shown in Fig. 5.

A detailed evaluation of the economic potential of the UTC system has been conducted for the UTC solar HP installation in New York versus a conventional fossil-fueled furnace and electric air conditioner.

Selective rate-of-return results for the NY configuration are shown in Fig. 6 as a function of the heat pump module cost for low and high collector cost values and two fuel cost levels ($7 and 10.50/$10^6$ Btu). These fuel costs are approximately equivalent to $1.00 and $1.50/gal of oil, representative of 1980 fuel prices and near-term projections for the Northeast U.S. The Fig. 6 results indicate that the UTC system is cost effective at HP module costs of up to $60-75,000 when fossil-fuel costs are $7 per 10^6 Btu and CPC installed costs approach $10 per sq ft or less than one-half of the current installed CPC costs. If fuel costs reach about $10 per 10^6 Btu, the allowable collector costs can increase to $20 per sq ft or the allowable heat pump module costs can increase to above sixty thousand dollars and still remain competitive with a conventional heating and cooling system.

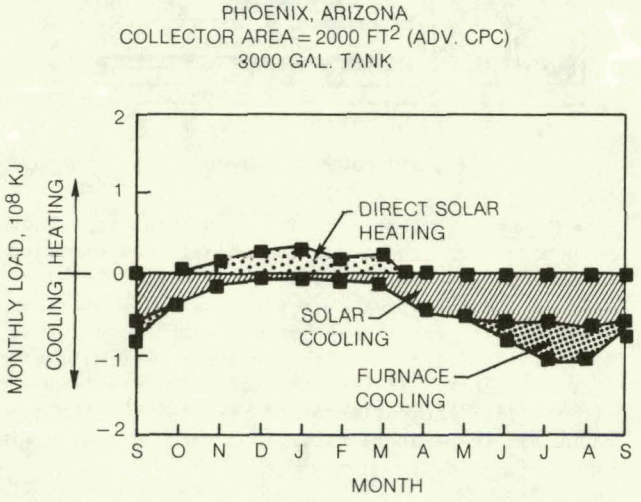


Fig. 5 Solar System Energy Distribution

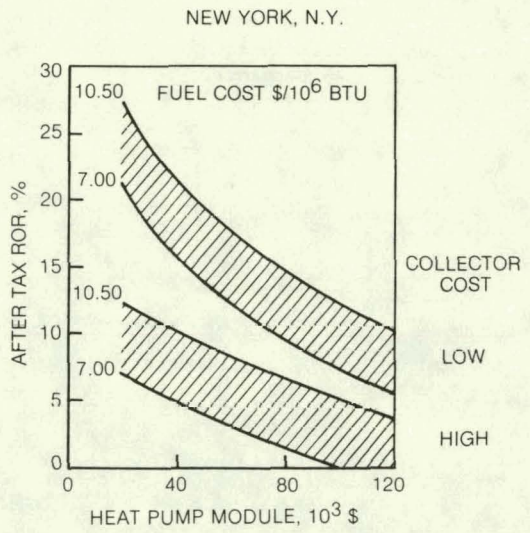


Fig. 6 UTC Heat Pump Rate-Of-Return

If the current 20 percent solar investment tax credit is increased to say 50 percent (as advocated by various governmental and industry solar experts) the allowable heat pump costs can be increased by 50 to 60 percent even at moderate values of collector and fuel cost.

FUTURE ACTIVITIES

Contract Activities. Performance, endurance and simulated building condition testing is con-

Location	Collector Type	Collector Area	Solar Energy Collected 10^6 Btu/yr	Average Thermal COP HP Heating	Solar Cooling	Furnace Cooling	Solar Contribution, % Heating	Cooling	Total
New York, NY	NTCPC/FP	2000/4000	610	1.94	0.85	0.66	48.6	92.4	56.3
New York, NY	NTCPC	4000	594	1.92	0.76	0.65	40.1	97.1	52.1
Phoenix, AZ	ACPC	2000	729	-	0.82	0.62	100	76.7	81.0
Fort Worth, TX	NTCPC	2000	471	2.02	0.77	0.61	49.1	56.3	53.3
Santa Maria, CA	NTCPC	2000	626	2.15	0.71	0.62	70.2	73.2	70.6
Madison, WI	NTCPC	4000	719	1.93	0.82	-	30.5	100.0	39.7
Apalachicola, FL	NTCPC	2000	420	2.10	0.79	0.62	76.9	50.5	57.2

TABLE 1. ALTERNATIVE UTC HP INSTALLATION CHARACTERISTICS

tinuing under the current program. Selected modifications to improve heat pump performance and operating characteristics have been identified and incorporated, where possible, during the program.

Post-Contract Activities. Field testing of the UTC heat pump will be conducted in a Phoenix, AZ light commercial office building as part of the joint US-Saudi Arabian (SOLERAS) solar cooling program. The system will be tested for two complete cooling seasons in a cooling only configuration with direct air-cooled condensers.

ACKNOWLEDGMENTS

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

PUBLICATIONS/REPORTS/REFERENCES

1. Biancardi, F. R. and G. Melikian: "Analysis and Design of an 18-ton Solar-Powered Heating and Cooling System," Paper 789524 presented at 13th IECEC, San Diego, CA, August 1978.

2. Biancardi, F. R., et al.: "Design, Development and Testing of a Solar Pow-red Multi-Family Residential Prototype Turbocompressor Heat Pump Interim Report": Draft Report R79-953050-1. prepared under DOE Contract AC03-777-CS34510, September 1979.

3. Melikian, G, T. N. Obee and B. W. Rhodes: "Results of Systems Simulations and Economic Analysis of a Solar-Powered Turbocompressor Heat Pump." Paper presented at 2nd Annual Systems Simulations and Economic Analysis Conference, San Diego, January 1980.

4. Design, Development and Testing of a Prototype Multi-Family Residential Sized Solar-Powered Turbocompressor Heat Pump System. Proceedings of 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors Meeting, March 1979.

II ABSORPTION SOLAR COOLING SYSTEMS

OVERVIEW-ABSORPTION/RANKINE SOLAR COOLING PROGRAM*

MICHAEL WAHLIG, AL HEITZ, BARBARA BOYCE

LAWRENCE BERKELEY LABORATORY

1 CYCLOTRON ROAD

BERKELEY, CALIFORNIA 94720

OBJECTIVE

The overall objective of the active solar cooling program is to assist the solar industry in developing and bringing to the marketplace solar-powered active cooling systems. The benefit of reaching this objective will be to reduce the national dependence on non-renewable forms of energy.

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 contents of each project are given below in the Technical Accomplishments section.

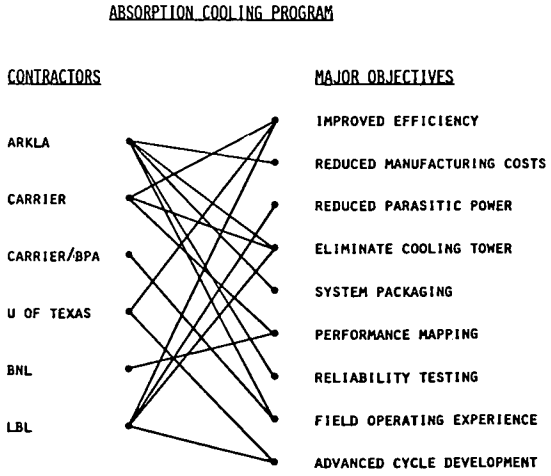


Figure 1

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 cooling systems. In the absorption program, there are six current and five essentially completed projects. In the Rankine program, there are five current projects directly supported by DOE, and three projects funded through and managed by NASA/MSFC (Manned Space Flight Center, Huntsville, Alabama). The basic

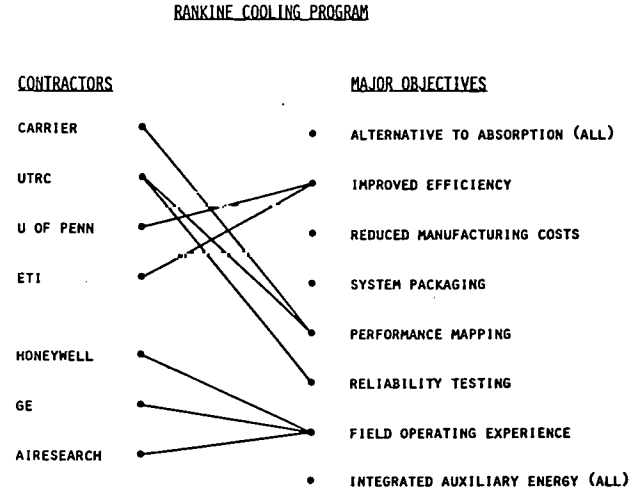


Figure 2

features of these projects are given in the next section.

The systems under development in five of these current projects have been selected for field testing in the new SOLERAS program, a joint US-Saudi Arabian enterprise.

Some technical highlights of the program are presented in Figure 3.

CONTRACTOR	ACCOMPLISHMENT
• HONEYWELL (RANKINE)	SUCCESSFUL FIELD OPERATION-LAWRENCE, KANSAS
• UTRC (RANKINE)	SUCCESSFUL LAB TEST OF PROTOTYPE UNIT
• BNL (ABSORPTION)	"SPINDOWN" TECHNIQUE FOR PERFORMANCE IMPROVEMENT DURING CYCLING
• CARRIER (ABSORPTION)	SUCCESSFUL LAB TEST OF FIRST "BREADBOARD" UNIT USING NEW FLUIDS; SUCCESSFUL FIELD OPERATION OF BPA-TYPE CHILLER
• ARKLA (ABSORPTION)	SUCCESSFUL DEVELOPMENT OF EVAPORATIVELY COOLED UNIT

Figure 3. Technical Highlights

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

Features: Unitary package; fuel aux., manufacturing study; application and installation manuals; procure and use tooling for limited production; lab reliability testing of evaporatively cooled chiller.

Accomplishments:

- Two unitary 3-ton systems installed in residences (one new, one retrofit) operated and provided data during summer 1979. Retrofit site will continue to be monitored during summer 1980.
- Modified 25-ton package has been assembled in Arkla lab.
- Scale build-up on heat exchanger surfaces does not appear to be a problem for evaporatively cooled chiller. Lab testing continues.

Contractor: Arkla

Contract No.: AC03 76SF 10507

Project: Development of third-generation 3-ton $LiBr/H_2O$ absorption chiller

Features: Built-in evaporatively-cooled absorber/condenser; hermetic solution pump.

Accomplishments:

- Successful development of evaporatively cooled chiller.
- Final report approved for publication.

Contractor: Carrier

Contract No.: AC03 77CS 31587

Project: Development of 3 to 5-ton absorption chiller

Features: Air-cooled; 120° - $130^{\circ}C$ input temp.; use of fluid additives; manufacturing study; market evaluation.

Accomplishments:

- Found LiBr-glycol-water mixture to be promising fluid.
- Completed testing of breadboard unit.
- Redesign of prototype completed, and fabrication underway.
- Released reports on phases I and II for publication.

Contractor: Carrier

Contract No.: AC79 79BP 10467 (Bonneville Power Administration contract)

Project: Fabrication of two 15-ton packaged absorption cooling systems, with installation at BPA Big Eddy site and Tyler, Texas

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

Accomplishments:

- Tyler, Texas installation completed 1 Oct 79 (acceptance meeting conducted 5 Oct 79).
- Big Eddy installation completed Jan 80 (acceptance meeting scheduled spring 80).
- One year O&M and monitoring data by Carrier to run thru spring 81.
- 200-ton system to be installed in Virgin Islands (BPA-type, NASA contract).

Contractor: University of Texas at Austin

Contract No.: 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:

- First version of simulation model completed.
- Modifying model to incorporate recommendations made by site visit review team.
- Consulting with Trane on issues of corrosion (no problem) and costs.

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 $218^{\circ}F$ using NH_3/H_2O; advanced cycles with COP increasing with temperature; heat pump operation also.

Accomplishments:

- New single-effect chiller installation completed; testing and debugging underway.
- New solution pump fabricated, tested, and modified several times.
- Design of advanced cycle 2R chiller nearing completion; fabrication of components started.
- Fluid properties required for advanced cycle 1R chiller have been identified; RFP SOW drafted to solicit measurements of properties of candidate fluids.

Contractor: Brookhaven National Laboratory

Contract No.: C-02-0016

Project: Develop and use simulator to test solar cooling subsystems

Accomplishments:

- Tests of Arkla absorption chiller completed at end of FY 1979.
- Important discovery: "spindown" technique for maintaining high COP during on-off cycling of absorption chillers.

- Final reports reviewed and approved for publication.

Contractor: EIC Corporation

Contract No.: AC03 77CS 34537

Project: Design of solar air conditioner using solid-phase absorbent (chemical heat pump)

Features: Air-cooled; built-in thermal storage.

Accomplishments:

- Identified $CaCl_2$ as most promising salt.
- Preliminary design of chemical heat pump using $CaCl_2$.
- Conducted experimental cycling tests on $CaCl_2$.
- Final report reviewed and approved for publication.

Contractor: Southern Research Institute

Contract No.: AC03 77CS 31586

Project: Analysis of advanced conceptual absorption chiller designs

Features: Search for new pairs and additives; modified absorption cycles; 160° - 230°F range.

Accomplishments:

- Identified several potentially useful absorption pairs.
- Final report reviewed and partially accepted for publication following modifications.

Contractor: Institute of Gas Technology

Contract No.: AC03 77CS 31439

Project: Development of new fluids for solar absorption cooling

Features: For air-cooled condensers; estimate COP

Accomplishments:

- Several new candidate fluid pairs identified.
- Final report reviewed and approved for publication.

Contractor: University of Maryland

Contract No.: DEAC03 79CS 30204

Project: Technical program support and special studies

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

Accomplishments:

- Report on state-of-the-art review of refrigerant/absorbent pairs has been prepared.
- Support activities proceeding as required.
- Development of a transient simulation model of an absorption chiller is underway.
- A simplified design method for cooling systems has been developed.
- Work progressing on comparative assessment project.
- Work proceeding at low level on a simplified design procedure for pv/t systems.

Rankine Projects

Contractor: Carrier

Contract No.: 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.

Accomplishments:

- Detailed analysis and design phases completed. Reports on this work reviewed and approved for publication.
- Prototype chiller completely assembled at Carrier, except for turbo-compressor.
- Turbo-compressor about 75% completed at MTI. Tests of assembly at MTI scheduled for April 1980.

Contractor: United Technologies Research Center (UTRC)

Contract No.: AC03 77CS 34510

Project: Development of 18-ton Rankine heat pump

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

Accomplishments:

- Performance testing has been successfully completed at design conditions.
- Final report for original contract work is under review.
- Extended performance and reliability testing underway.

Contractor: Univ. 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 designs; stored water flashes to steam.

Accomplishments:

- System design phase mostly completed
- Philadelphia Gear completing fabrication of turbo-compressor-motor assembly.
- Work proceeding on component specification and procurement, and system integration.

Contractor: Energy Technology, Inc. (ETI)

Contract No.: AC 03 80CS 30214

Project: Development of a superheated steam Rankine turbine

Features: Solar-boiled water at 300°F; fuel-superheated to 1000°F; 5-stage, 75,000 rpm radial outflow turbine; nominal 30 ton.

Accomplishments:

- Successful preliminary tests using 3 turbine stages.

- Steam turbine test facility construction completed.

Contractor: Hittman Associates, Inc.

Contract No.: DEAC03-79 CS 30202

Project: Technical program support and special studies

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

Accomplishments:

- Rankine fluid state-of-the-art report completed.
- Support activities proceeding as required.
- Work progressing on comparative assessment project.
- Specialized tasks, such as analysis of unusual solar cooling systems, specification of performance test procedures, etc., performed as needed.

In addition to the above projects, three contractors (Honeywell, General Electric, and AiResearch) are being supported by NASA contracts to develop Rankine-cycle solar cooling systems in a variety of sizes, and to install these systems in operational test sites. These projects (often referred to as the NASA 404 projects) are the subject of an overview paper and of individual project presentations elsewhere in the proceedings of this meeting.

FUTURE ACTIVITIES

From a technical point of view, the active solar cooling program is quite successful. All of the contractors are doing first-class work, and steady advances are being made in the performance and reliability of the chillers and the cooling systems. It is expected that this type of progress will continue in the future.

However, a critical element is missing from the active cooling program: the existence of quantitative program goals. Without such quantitative goals, we are unable to measure progress towards short-term goals, nor are we able to predict with any certainty the possibility of eventual success in the marketplace.

In order to rectify this situation, the following corrective measures will be given high priority in the near future:

- use market analysis to determine details of future cooling demands;
- use comparison of solar vs. future conventional cooling technologies to determine quantitative solar cooling systems cost and performance goals;
- use comparative analysis of the solar cooling approaches to determine projects with most potential to achieve solar cooling program goals;
- use sensitivity analysis to determine most effective program actions to reach solar cooling program goals.

Establishing quantitative program goals using the steps given above will produce significant benefits:

- ability to justify each project on basis of its quantitative contribution to overall program success;
- rationale for dropping those projects that cannot be adequately justified;
- existence of a quantitative mechanism for developing annual operating plans to maximize the programmatic benefit of the funds available;
- existence of a positive strategy for achieving significant market penetration by solar cooling at the earliest possible time.

Conversely, the consequence of not establishing such program goals will be our inability to defend even the present scope of the active solar cooling program.

Meanwhile, a program is just getting underway that will provide a significant measure of field testing of new and modified solar cooling systems. This is the SOLERAS program, an element of the joint U.S.-Saudi Arabian solar energy program that comprises engineering field tests of solar cooling systems in Saudi-type climates. Five projects are involved, four in the Phoenix area (Rankine projects by Honeywell and United Technology Research Center, and two absorption projects by Carrier) and one in the Mojave Desert area (a Rankine project by General Electric). Following design and construction phases, all systems are expected to undergo field operations during the summers of 1981 and 1982. Project management is the responsibility of SERI, with technical support being provided by LBL (cooling) and ANL (reliability and materials). This program is described in more detail in a separate presentation at this meeting.

Finally, a fourth Cooling Workshop is being planned at this time, tentatively scheduled for the fall of 1980, or soon thereafter.

FOOTNOTE:

*This work has been supported by the Active Building Systems Branch, Systems Development Division, Office of Solar Applications, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

UNITARY SOLAR HEATING/COOLING SYSTEM PACKAGE DEVELOPMENT

ARKLA INDUSTRIES INC

DE-AC03-77CS-34593

RICHARD H. MERRICK

June 1, 1977 - May 31, 1980

OBJECTIVE

One objective has been to develop 3 ton residential and 25 ton commercial unitary solar heating and cooling system hardware and software. Another has been to develop an evaporatively cooled 3 ton lithium bromide water absorption chiller and establish its reliability and manufacturability.

CONCEPT

Applying the unitary system approach to solar 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, Fig. 1, 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 air cooled. Performance insensitivity to scale accumulation derives from low heat flux wetted surfaces. Sump and pump resiliency resists freeze expansion.

SUMMARY

Residential 3 ton systems have been in operation in Evansville at the Oak Meadow solar house and the Owens Drive retrofit house. System reliability continues to be demonstrated, seasonal chiller COPs have been established and actual versus forecasted solar contributions determined.

A 25 ton skid mounted commercial package using the Arkla WF8300 chiller as its core has been built and tested. This led to a redesign toward a more compact version which has now been constructed and is ready for laboratory testing.

Four evaporatively cooled 3 ton chillers are operating. One is on field test at the retrofit house and the others are involved in reliability, scaling and development work in the Arkla laboratory. Corrugating equipment for forming the absorber/condenser surface has been buiit and tooling tryouts are now taking place.

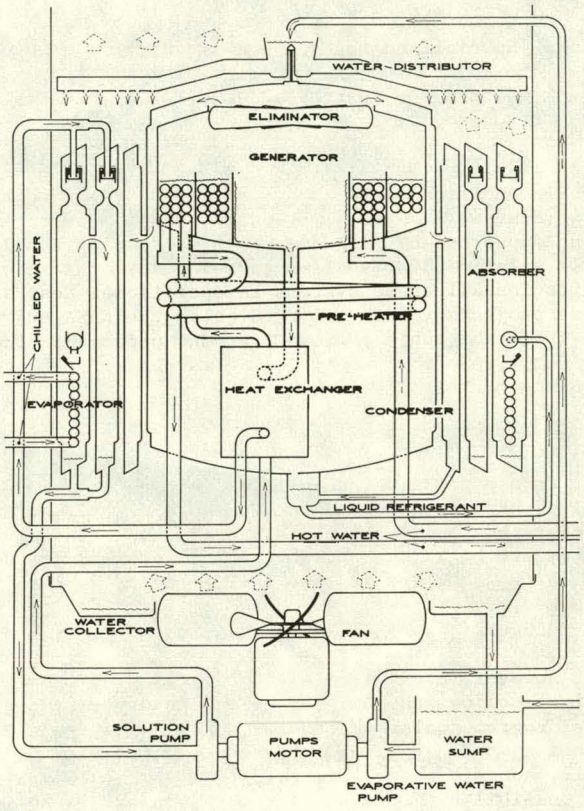


Figure 1. Schematic of Evaporatively Cooled Solar Chiller

TECHNICAL ACCOMPLISHMENTS

Residential Development

o System hardware has been proven reliable for 2 years at the Oak Meadow solar house using the tower cooled WF36. This reliability has been further confirmed through one year of operation at the Owens Drive retrofit house where the evaporatively cooled chiller is used.

o Space requirements at the retrofit house, Fig. 2, necessitated installing the skid package outdoors in a lean-to enclosure, Fig. 3. The freeze proof concepts designed into this system which allow the entire system to operate from the same inhibited water without anti-freeze have proved effective in this harsh environmental situation.

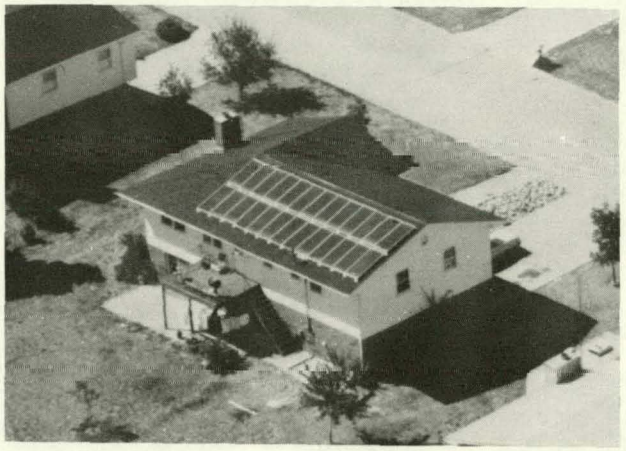


Figure 2. Aerial View of Owens Drive Retrofit Home

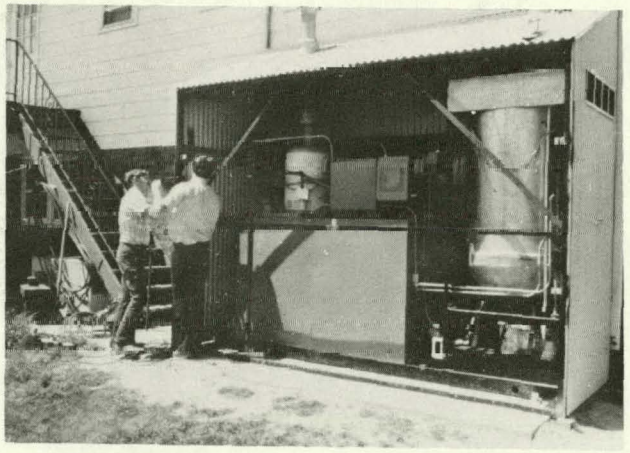


Figure 3. Hardware Enclosure at Owens Drive

o Two methods for waterproofing the insulation of the underground storage tanks have proven successful for nine months. The retrofit house is using an EPDM Jacket, Fig. 4, and the solar house a vinyl jacket.

o Seasonal chiller COPs of .648 for Oak Meadow and .643 for Owens Drive were determined from summer of 1979 testing. These were developed by combining, time weighted, measured cumulative chiller COP, Fig. 5, with recorded chiller cycle duration, Fig. 6. This shows that cycling degradation can be controlled quite nicely when the proper anticipator

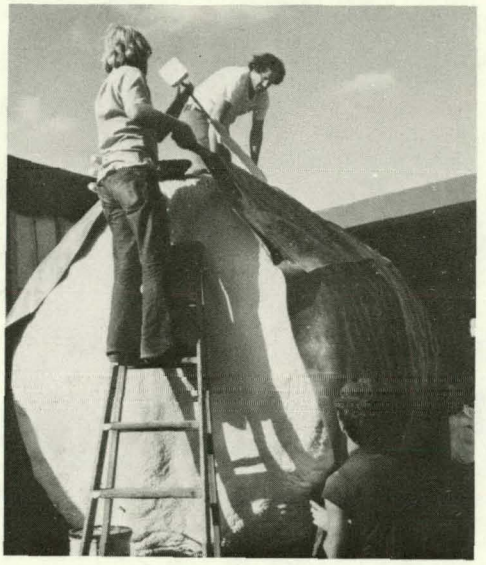


Figure 4. Hot Storage Tank with EPDM Jacket

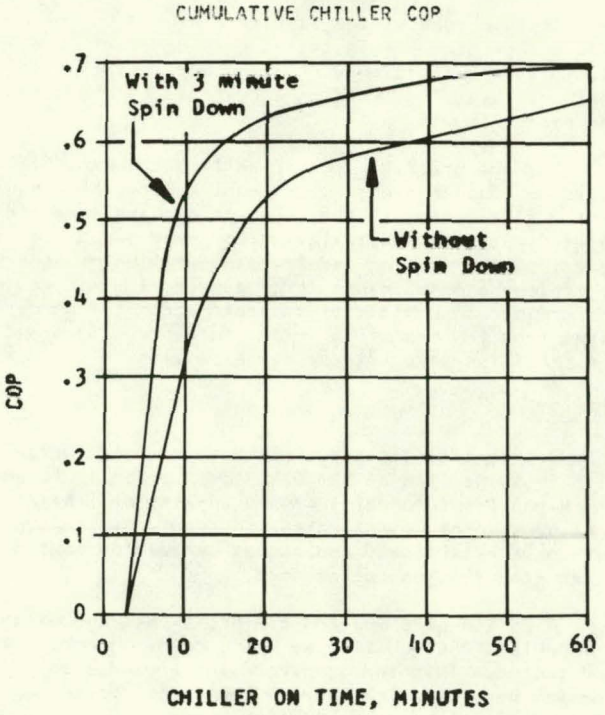


Figure 5. Measured Cumulative Chiller COP

is used in the room thermostat and "spin-down" is used to control the chiller. The average steady state COP was .70.

"Spin-down" is a 3 minute extension of air conditioning system operation after ceasing to apply heat to the generator resulting in almost full cooling during this time. The cooling comes from useful evaporation of refrigerant in transit through the condenser and evaporator that otherwise would enter the absorber as liquid with no refrigerating effect.

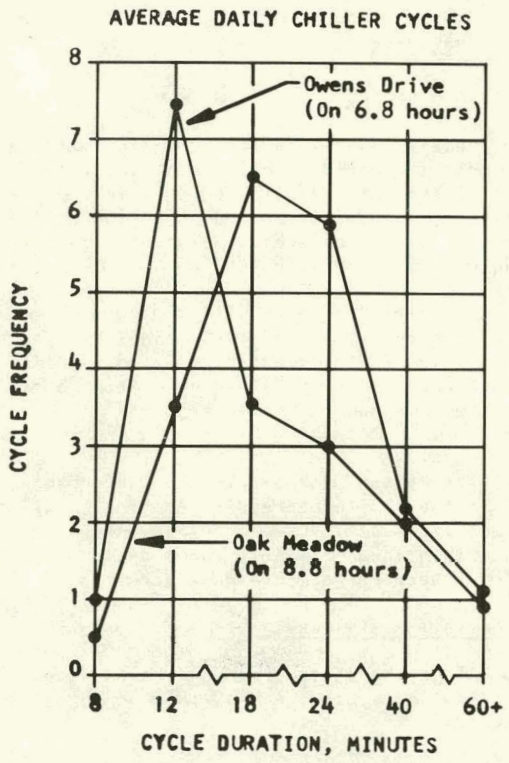


Figure 6. Recorded Average Daily Chiller Cycles

o Data from the two houses has been useful in refining our performance forecasting methodology. Oak Meadow has an 825 square foot collector array at a 38° tilt while the retrofit house has 450 square feet at 22° tilt. Correlations are presented in Fig. 7.

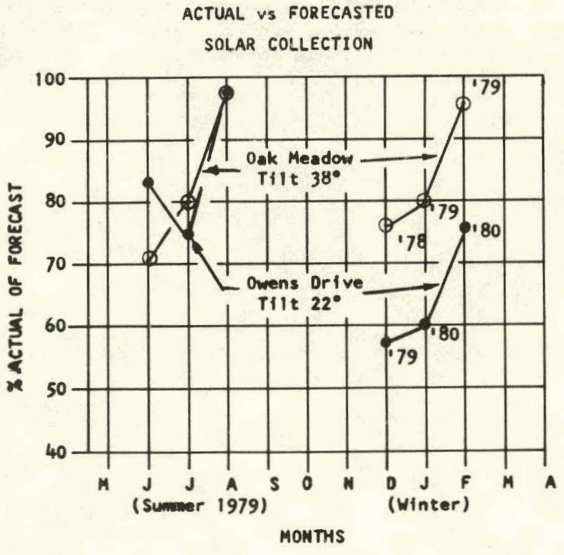


Figure 7. Actual vs Forecasted Solar Collection

Commercial System Development

o A 25 ton skid mounted commercial package using the Arkla WF8300 absorption chiller as its core and including an auxiliary boiler, systems tank, pumps and controls was built and tested. This duplicated the hardware approach used successfully in the residential unitary system packages.

o Continued system design studies and the difficulties with waterproofing underground storage indicated that the successful features of the residential system could be retained in a more compact package designed for direct connection to ground level storage thereby eliminating the "systems tank".

o A compact 25 ton skid package has now been built and is ready for laboratory testing, Fig. 8. It will be a two-pipe system using the same inhibited water throughout, storage at atmospheric pressure and drain down collectors. Skid package includes a 25 ton chiller and all system pumps and controls. Auxiliary boiler will be separate from the package offering more flexibility in selecting and applying auxiliary energy.

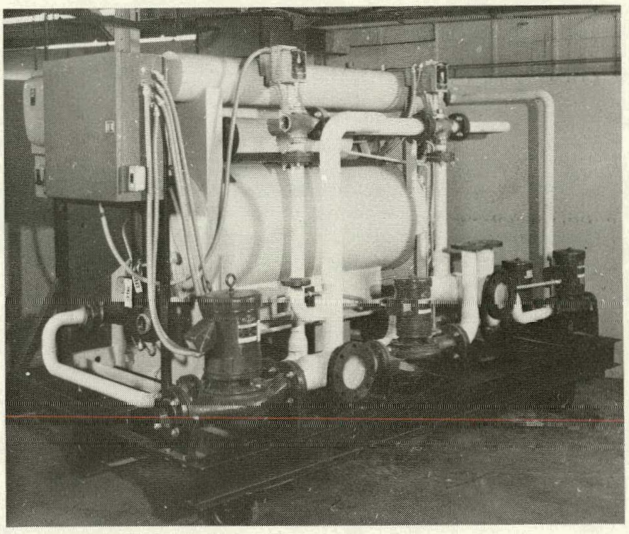


Figure 8. Compact Commercial 25 Ton Skid Package with Arkla WF8300 Absorption Chiller

Evaporatively Cooled 3 Ton Chiller

o Manufacturing study was completed which has established cost objectives and determined the solution to the unique problem of corrugating the absorber/condenser surfaces.

o The corrugating equipment has been completed by the vendor and tooling tryouts are underway.

o One chiller has been on field test at the retrofit home during the full summer of 1979. Two chillers have been on life test in the laboratory to determine reliability and the rate of scale formation and its effect on unit performance, Fig. 9.

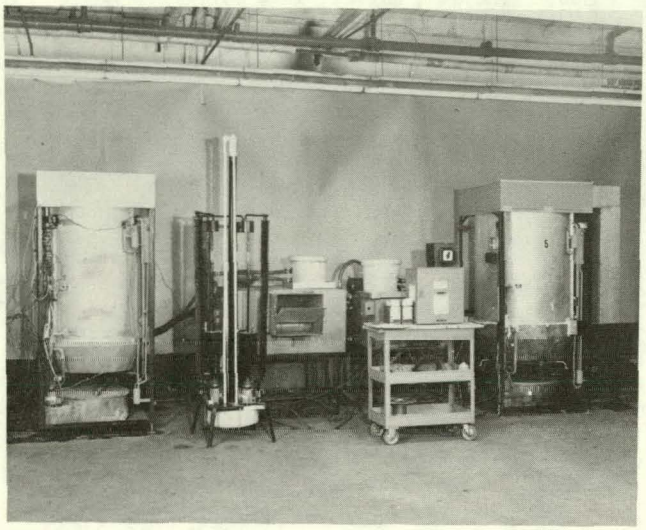


Figure 9. Evaporatively Cooled Chillers on Scaling and Life Test

o Another unit incorporating manufacturing simplifications is on lab test to evaluate these changes.

o The vendor developed solution pumps are on life test and continue to be preferred over the Arkla design for their low power consumption.

o We are prepared for a pre-commercialization engineering field test that could put 6 - 10 units into the field for operation during the 1981 cooling season.

FUTURE ACTIVITIES

Contract Activities

o Receive and install corrugating machine from vendor and build 2 chillers of the latest design utilizing parts fabricated on this equipment. Unit life testing will continue checking reliability and scaling effects. Solution pump life testing will also continue.

o The retrofit house will continue in operation through the summer of 1980. This will extend field testing of the evaporatively cooled unit installed there and be useful in generating additional data to improve our performance forecasting methodology.

o The 25 ton package will be performance tested in the lab to be readied for installation in an actual system. Clearance has been requested to place this in a privately owned system in return for 2 year performance data access.

Post-contract Activities

o After the 25 ton package proves itself in an operating system, Arkla would hope to commercialize it.

o We believe the evaporatively cooled 3 ton chiller has matured sufficiently in reliability and manufacturability to warrant a DOE supported field test of 6 - 10 units during the summer of 1981. Arkla continues to believe this product approach compares favorably with others as candidates for future commercialization. We would like to continue working aggressively with this concept but do not see a market demand at this time that would justify immediate manufacturing preparations.

o Arkla has already commercialized the unitary residential system work as the Arkla PWF36-100 skid mounted package which uses the tower cooled WF36 chiller.

DEVELOPMENT OF A SINGLE FAMILY ABSORPTION CHILLER FOR USE IN A SOLAR HEATING AND COOLING SYSTEM

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

EG-77-C-03-1587

DR. WENDELL J. BIERMANN

BEGIN SEPTEMBER 30, 1977 - END JUNE 30, 1980 (DECEMBER 31, 1980 REQUESTED)

SUMMARY

A chemical composition has been identified which meets the criteria for developing a truly air cooled absorption chiller within a short time frame. Laboratory testing has established all the chemical properties needed to utilize this system. A 10 kW (3 tons) "breadboard" machine has been built and operated to refine the design numbers and identify any potential engineering problems.

A prototype machine has been constructed to provide 10 kW (3 tons) of cooling with 110°C (230°F) solar heated water at an ambient temperature of 35°C (95°F) with a thermal coefficient of performance of 0.76.

BACKGROUND

With the support of the Department of Energy and its contract supervisory agencies, Energy Systems Division of Carrier Corporation has been developing two types of solar heat driven space cooling machinery. These also have application with other low temperature heat sources such as heat recovery and geothermal application.

The first of these types was a water cooled absorption chiller engineered to provide cooling with lowest practical hot water temperatures and give good seasonal coefficients of performance. A contract with Bonneville Power Administration gave us an opportunity to design, build and test a 53 kW (15 ton) prototype. A subsequent contract, with joint DOE/BPA participation, allowed us to refine the design and build two factory assembled solar packages which reflect the HVAC move to unitary equipment where possible.

It has become an axiom at Carrier, based on its decades of marketing experience, that small water-cooled space conditioning equipment cannot support a mass production manufacturing operation. Whether it be cooling tower, evaporative cooling or ground water, water cooling has not been economically successful in smaller than commercial sized equipment.

Accepting this premise, we welcomed the opportunity to work with NASA in designing a scaled up version of our solar absorption machine which will deliver about 700 kW (200 tons) of cooling at the Frenchman's Reef Holiday Inn engineering test site in St. Thomas, A.V.I. This scale up will increase the short term marketability of the water cooled design. Improvement of the basic design, packaging simplification and cost reduction of the water cooled machine will continue under SERI sponsorship as part of the SOLERAS agreement program.

AIR COOLED ABSORPTION CYCLE SELECTION

The primary concern of this presentation is a description of our development of an air cooled absorption machine which, by being free of problems involving the evaporation of water into the atmosphere, would be more suitable to the smaller package market. This development was undertaken in October 1977, beginning with a survey of candidate chemical systems capable of sustaining an air cooled cycle. At the last Contractor's meeting I discussed the considerations which led 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.

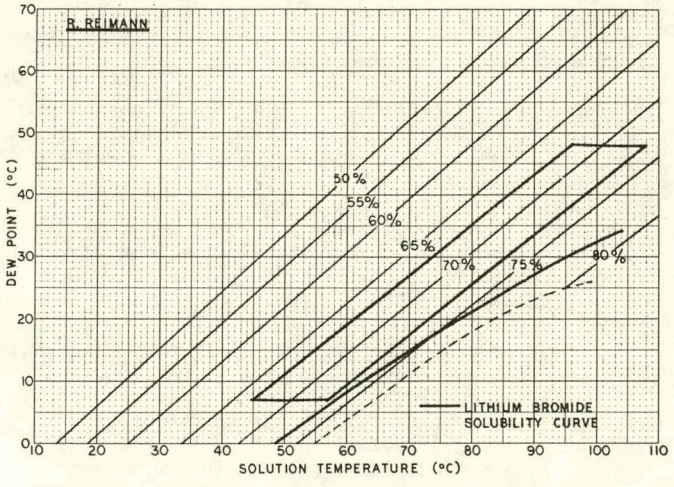


FIGURE 1

EQUILIBRIUM CHART FOR AQUEOUS SOLUTIONS OF CARROL

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

The development of a mechanical system to employ the Carrol combination is proceeding in three steps under this contract. In the first step, which has been completed, the major components (generator, absorber, condenser, evaporator, solution heat exchanger, fans, solution and refrigerant pumps, purge system and a minimal control system) were designed and sized on the basis of best available information or, in one or two cases, intuition. Rather than test each component separately, they were assembled into an easily accessible package of nominally 10 kW cooling capacity which was used to improve our knowledge of heat transfer characteristics, test our concepts of solution distribution and otherwise identify other unsuspected problem areas such as solution storage, inadequate purging in certain volumes and the like.

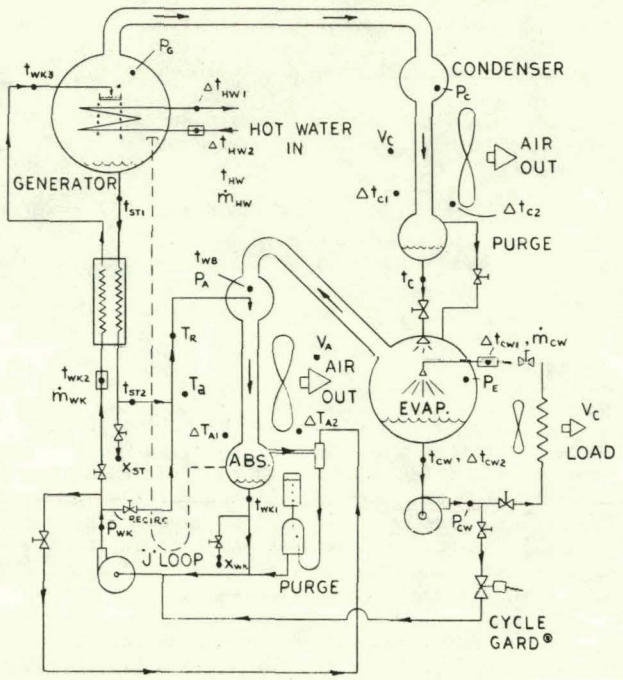
Following the confirmation of our basic design via breadboard operation, with some experiential modifications, a prototype has been designed which will be somewhat more compact and which will more closely meet our design goals.

Later this year we hope to design a second prototype with better airside coil performance (hence, reduced fan power) to be designed from basic heat transfer data for large tube coils. This information is presently being collected through experiments with a model coil.

A schematic drawing of the arrangement of the air cooled Carrol machine is shown in Figure 2. Also included are the locations of test points which are monitored and control elements.

Generator. A falling film generator has been selected, with weak solution fed to a series of weirs which are overflowed onto the exterior of the generator tubes through capillary drippers. For this application the falling film generator is preferred over the submerged tube bundle because it permits countercurrent heat transfer, eliminates submergence losses and minimizes the need for superheat to induce nucleate boiling.

Absorber and Condenser. Both are plate fin coils with one inch copper tubes, thirty inches long, and ten mil aluminum fins, 14 per inch. This coil is too tight, having a pressure drop of about 65 Pa (0.25 in H_2O) at maximum air velocity of 2 m s^{-1} (400 fpm). Both coils are appropriately headered and strong solution is overflowed from a multiplicity of weirs into the interior of the absorber tubes with the aid of a copper screen capillary feeder.



SAC 2
DOE CONTRACT NO. EG 77-C-03-1587
R. REIMANN

FIGURE 2

SCHEMATIC OF AIR COOLED ABSORPTION CHILLER INDICATING TEST POINTS AND CONTROL ELEMENTS

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. For larger units than the present 10 kW design a more conventional tube and shell chiller will be considered.

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 1% has regularly been observed.

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. A level sensor in the purge gas chamber can provide automatic purging.

Fans. Two three-speed fans with 450 W (e) maximum power demand each will be used on the first prototype unit. As ambient falls below the design temperature of 35°C, the lower speeds will be used to reduce electrical power consumption.

With improved air coil design we hope to cut this in half with the second prototype.

Pumps. A hermetic, magnetically coupled, solution pump is used to move weak solution from the absorber sump through the heat exchanger to the generator or through the jet purge. A low NPSH (0.20 m) is needed to lower the overall unit height, and the prototype unit will consume 0.170 kW (e) in the solution pump.

The refrigerant pump is similar in design and power and serves to circulate chilled water to the load.

Controls. A low refrigerant level sensor protects the refrigerant pump by turning it off when refrigerant stores on the solution side. Should overconcentration of the Carrol threaten solidification, this is detected by a high refrigerant level sensor which activates a Cycle-Guard^{R} 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.

Figures 3 and 4 show the prototype externally and as cut-away revealing some of the inner arrangements.

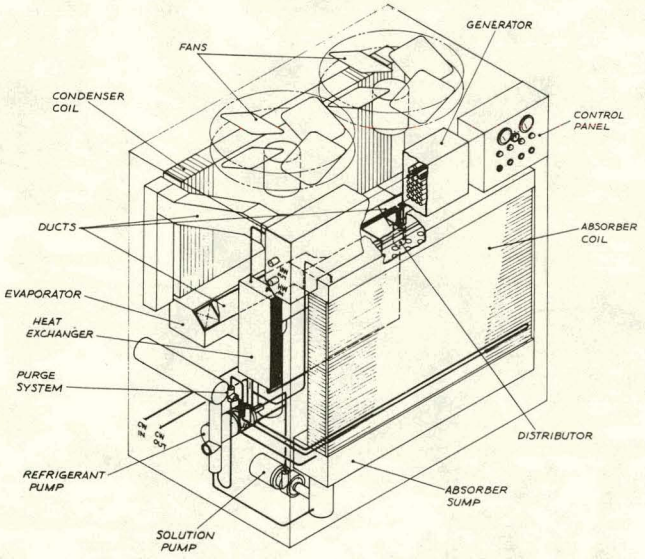


FIGURE 3

COMPONENT LOCATION IN 10 KW AIR COOLED PROTOTYPE CHILLER

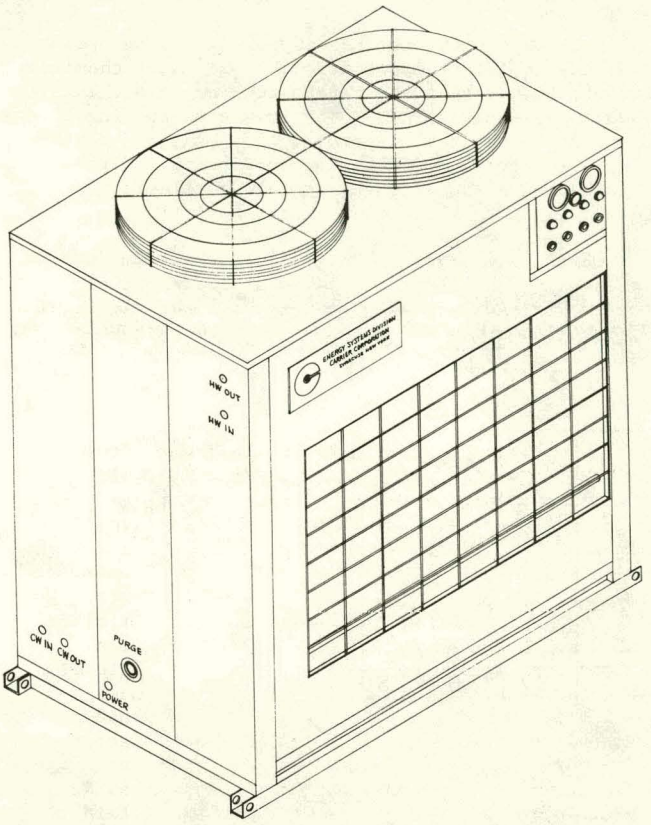


FIGURE 4

EXTERNAL APPEARANCE OF 10 KW PROTOTYPE AIR COOLED CHILLER

PERFORMANCE

The anticipated performance of the prototype, based on the data collected with the breadboard version, is summarized on the cycle diagram shown on the following page as Figure 5.

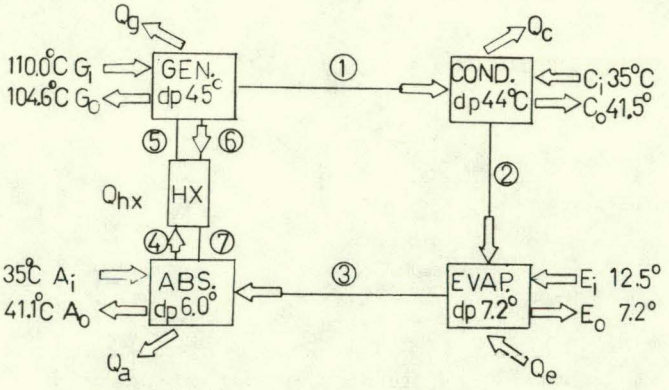
TECHNICAL ACCOMPLISHMENTS

- 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.

- Components to use in assembling an air cooled machine have been designed and tested in a breadboard configuration.

- A prototype 10 kW (3 ton) air cooled chiller has been designed along with a test facility. Both will be operating by the time this document is published.



POINT	TEMP °C	X %	DEW PT. equil.	DEW PT. actual
1	101.8	0	44.0	44.0
2	44.0	0	44.0	44.0
3	7.2	0	7.2	7.2
4	44.4	67.7	5.0	6.0
5	86.4	67.7	36.9	45.0
6	101.8	72.0	44.9	45.0
7	59.7	72.0	10.8	6.0

W_{ref} 0.0045 kg/s
W_{sol} 0.0755 kg/s
Q_{hx} 5.5 kW
Q_e 10.5 kW
Q_c 11.3 kW
Q_a 13.1 kW
Q_g 13.8 kW
COP 0.76

WJB 2/20/80

FIGURE 5

PROTOTYPE CYCLE CONDITIONS AT DESIGN. BASED UPON DATA OBTAINED FROM OPERATION OF "BREADBOARD" CHILLER

FUTURE ACTIVITIES

The prototype will be operated for about six months under varying conditions.

An improved prototype will be built mid-year 1980.

An air cooled unitary package of 35 kW (11 tons) has been contracted under the SOLERAS agreement for installation in Phoenix, Arizona in early 1981.

Carrier's International Division is contemplating displaying the air cooled prototype at the World Trade Fair at year's end.

* 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). Available NTIS.

PROTOTYPE MODULAR 15 TON SOLAR ABSORPTION AIR CONDITIONING SYSTEM

ENERGY SYSTEMS DIVISION, CARRIER CORPORATION

DE-AC79-79BP10467

DR. WENDELL J. BIERMANN

DECEMBER 22, 1978 TO APRIL 1981

SUMMARY

A design concept for a low temperature absorption chiller, proven in a previous Bonneville Power Administration contract has been completed and extended to become a unitary package for solar space heating and cooling. One version of this package, using flat plate collectors and a steam energy supplement, has been installed in Tyler, Texas. A second version, using evacuated tubular collectors in a draindown configuration, and employing an electrical driven heat pump for auxiliary heating and cooling, has been installed in the Big Eddy site of Bonneville Power Administration.

OBJECTIVES

The contract objectives call for completion of an absorption chiller design previously qualified and its incorporation into a factory assembled unitary solar heating and cooling package. Demonstration of the package, by installing and operating two diverse solar systems incorporating it, is provided.

BACKGROUND

As a portion of a previous contract with Bonneville Power Administration, a low generator temperature absorption chiller concept was qualified. A generator using a falling film instead of pool boiling contributed to this low temperature requirement by minimizing nucleation and submergence losses and approximating counter flow heat transfer.

This contract was intended to complete certain items of the machine design and to improve the marketability of the unit by unitary packaging of the chiller along with other components required for a solar space heating and cooling system. The substitution of factory assembly of the package instead of field installation of a multiplicity of components minimizes design time per job, significantly reduces the cost of the installed system and improves the chances of effective quality control of the product.

MAJOR CONTRACTUAL TASKS

The original solar absorption machine (SAM) development bypassed solution heat exchanger design and pump qualification, using functional but far from optimum options, in order to speed up the qualification of the more essential items. Our first task, therefore, was the selection of proper solution and refrigerant pumps and the design of a more effective solution heat exchanger. Capacity of the SAM as a function of hot water temperature and cooling water temperature, when delivering 7.2°C (45°F) chilled water is shown in Figure 1.

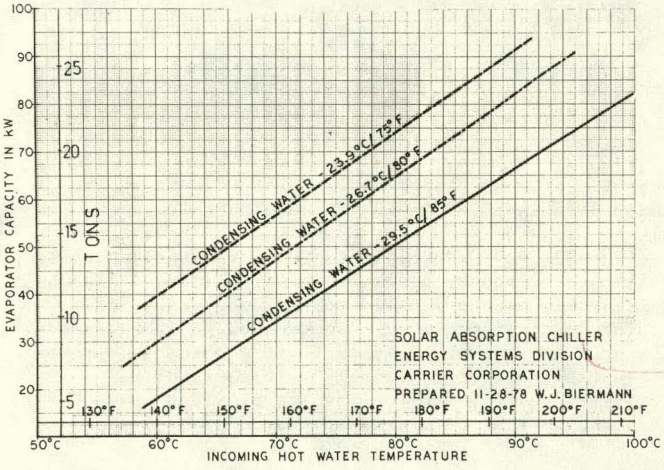


FIGURE 1. THE COOLING CAPACITY OF THE SAM CHILLERS SUPPLIED UNDER THIS CONTRACT.

It was intended that the unitary package developed would have sufficient versatility to adapt to a wide variety of the situations encountered in practice, just as one designs other HVAC unitary equipment for broadest application with the least number of models.

The two sites chosen were selected to give as diverse experiences as practical in package design. To this end, sites chosen were:

Tyler, Texas. Manufacturing plant with a large internal load. Only about 15% of the building cooling load is supplied by solar, giving a high utilization and good payback for the solar installation. No storage is used other than a small tank to give some thermal inertia. Collectors are double glazed, flat plate of the Honeywell design, without draindown. Supplementary heating and cooling from the package is supplied from a process steam boiler with a priority system to prevent diverting steam from production needs on the unusual occasion that it cannot carry both.

Figure 2 shows the Tyler version of the solar package.

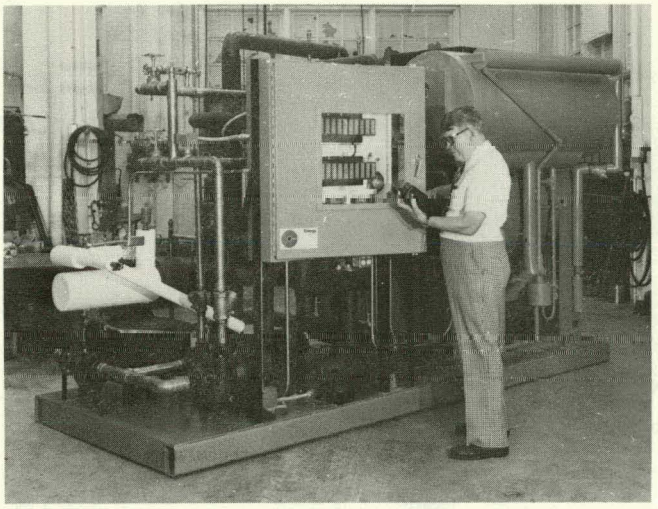


FIGURE 2. SOLAR ABSORPTION CHILLER, PUMPS, CONTROL DEVICES, MICROPROCESSOR CONTROLLER AND DATA RETRIEVAL SENSORS PACKAGED FOR SHIPMENT TO TYLER SITE.

The Dalles, Oregon. A Bonneville Power Administration control house, also with a large internal load. This system uses evacuated tubular collectors in a draindown configuration. About 6,000 gallons of cold (or hot) water storage is provided since the load and the package are approximately matched in size. Auxiliary heating and cooling are provided by a standard 15 ton electric heat pump.

Figures 3 and 4 show views of the installation at The Dalles.

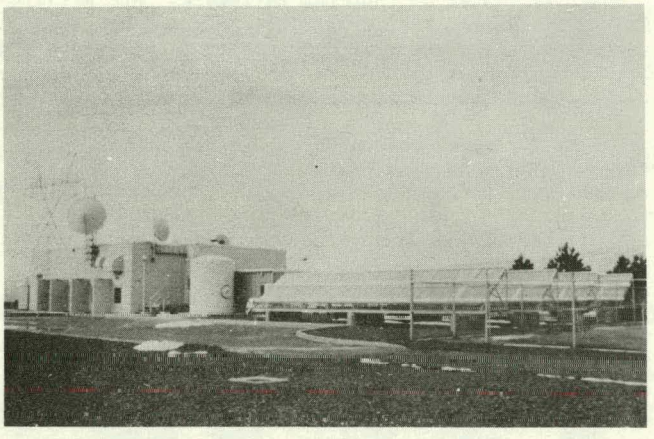


FIGURE 3. OVERALL VIEW OF BONNEVILLE POWER ADMINISTRATION BIG EDDY SITE, THE DALLES, OREGON. PHOTO: COURTESY BPA.

Both of these systems are controlled by Texas Instruments TI-5 Programmable Control System (microprocessor). Data retrieval is done with the use of "Btu Meters" whose output is read from a mechanical digital output. Each working day the cumulative energy from each stream (insolation, hot water, energy to load, etc.) is read and mailed to the project engineer at the end of the week for evaluation.

Diagnosis of malfunctions is done (locally or by telephone) by interrogation of the controller as to status of control relays supplemented by visual readout on site of strategically located thermocouples connected to a multijunction selector switch and a good quality digital meter.

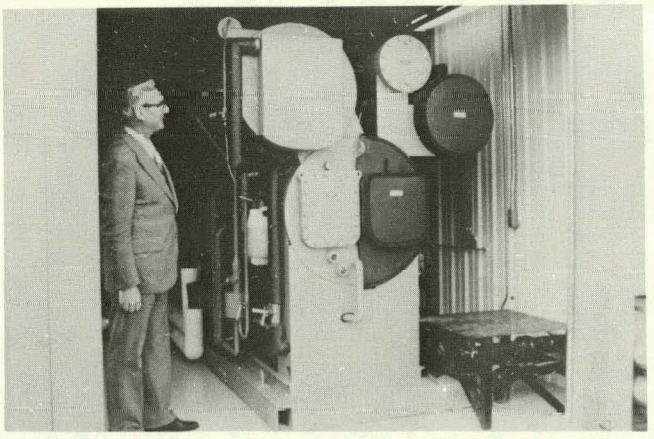


FIGURE 4. MACHINERY ROOM, BIG EDDY SITE. PHOTO: COURTESY BPA.

TECHNICAL ACCOMPLISHMENTS

- A low generator temperature absorption chiller concept has been completed and proven in laboratory and site testing.

- First generation unitary solar packaging has been demonstrated at two widely differing installations.

- An evaluation will be made of an inexpensive industrial type microprocessor applied to solar system control.

- A simplified and inexpensive approach to collecting operational data will be evaluated.

FUTURE ACTIVITIES

- Negotiations are in progress to sell several of the unitary solar packages or solar absorption chillers.

- A "second generation" solar package aimed at further simplification and cost reduction has been included as part of the SOLERAS program and will become operational in the Spring of 1981.

- A scaled up version of the low temperature chiller will supply 700 kW (200 tons) of cooling at the Frenchman's Reef Engineering Test Site at St. Thomas, A.V.I. under NASA sponsorship.

This machine will be built on a commercial production line and may be regarded as one step closer to commercialization for solar, geothermal and energy recovery applications.

DEVELOPMENT OF SOLAR DRIVEN ABSORPTION AIR CONDITIONERS AND HEAT PUMPS*

K. DAO, M. WAHLIG, E. WALI, J. RASSON AND E. MOLISHEVER

LAWRENCE BERKELEY LABORATORY

1 CYCLOTRON ROAD

BERKELEY, CALIFORNIA 94720

OBJECTIVE AND APPROACH

The objective of this project is the development of absorption refrigeration systems for solar active heating and cooling applications.

The approaches being investigated are those using air-cooled condenser-absorbers and those leading to coefficient of performances (COP) that increase continuously with heat source temperature.

This is primarily an experimental project, with the emphasis on designing, fabricating and testing absorption chillers in operating regimes that are particularly suited for solar energy applications.

SUMMARY

The first phase of this project has been concluded and has experimentally demonstrated that the conventional single-effect ammonia-water absorption cycle can be used (with minor modifications) for solar cooling[1]. The optimum operating temperature ranges for this kind of system are:

Heat source	:	200 to 230°F
Cooling air	:	95°F
Leaving chiller water	:	50° to 40°F
COP	:	0.65 to 0.72

The second phase of this project explores the commercial potential of the single-effect (SE) NH_3/H_2O absorption air conditioner. A completely new 3-ton SE unit was engineered and designed to achieve high performance and low cost[2,3]. The key components of this new unit are tube-in-tube heat exchangers for high effectiveness and low cost, and a pair of piston drivers and pumps for the recuperation of the mechanical energy from the returned strong absorbent.

The success of the SE unit will not obviate the need for development of more efficient advanced chillers that can improve significantly the economics of solar cooling. These advanced air-conditioners are designed to achieve high COP at high heat source temperatures compatible with recently developed collectors. Accordingly, the third phase of this project is the development of advanced absorption cycles whose COP increases with temperature, maintaining a relatively constant fraction (about 0.6) of the Carnot COP over a wide range of operating conditions[4,5]

TECHNICAL ACCOMPLISHMENTS

The design and fabrication of the SE ammonia-water absorption air conditioner to be developed in the second phase of this project has been completed. Design characteristics and performance have been reported in references (2) & (3). This experimental unit has been installed and its "debugging" phase has been started. The performance testing phase of this basic single-effect air-conditioner should be completed by August 1980.

Detailed computer analysis of a new advanced absorption cycle (called the Double-effect Regenerative Absorption Refrigeration cycle or cycle 2R) has been completed and has served as the basis for the design of the components of the "2R chiller".

The engineering and detail design of all components of the 2R chiller have been completed. Fabrication of the critical new component, the multi-stage pump, has just been completed. This pump will be subjected to extensive tests before being integrated with the rest of the 2R chiller. Fabrication of other chiller components will begin as the working drawings are completed.

The configuration of the 2R chiller is shown in Fig. 1. More details on the conceptions of cycle 2R can be found in reference (4). Essentially, the cycle 2R is constructed by adding a boiler, a multi-stage pump with its driver (labeled DM in Fig. 1.), and a recuperator to the basic conventional single-effect cycle which consists of the generator, the pre-heater, the rectifier, the absorber, the condenser and the evaporator.

All heat exchangers of this 2R chiller are of the tube-in-tube configuration. The design rated capacity is 3 tons. Other design conditions are:

Heat source temperature	:	280°F
Heat sink (cooling air)	:	95°F
Cold source (chilled water	:	45°F
Net COP	:	0.87

The off-design performance is summarized in Fig. 2. The net COP (shown in Fig. 2) is defined here as the COP obtained after deduction of the amount of high pressure vapor used to run the pump drivers DM and DV.

FUTURE ACTIVITIES

The fabrication of the 2R chiller should be completed by June 1981, and its performance testing and evaluation should be completed by May 1982.

Investigation of another possible advanced absorption cycle (cycle 1R reported in reference (5)), that has the potential for better performance and

lower cost than the cycle 2R, will continue in 1980. The search for high temperature refrigerant-absorbent pairs suitable for this advanced cycle is continuing. The search consists of subcontracting the measurement of a minimum set of key properties of a number of pre-selected pairs. From the key properties all other mixture properties of these pairs can be approximated for use in cycle calculations. Selection of the best pair will be done by comparative performance analyses. Following the selection of the working pair, the design and fabrication of the experimental cycle 1R chiller will proceed.

FOOTNOTE AND REFERENCES

* This work has been supported by the Active Building Systems Branch, Systems Development Division, Office of Solar Applications, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

1. "Performance of an Experimental Solar-Driven Absorption Air-Conditioner", K. Dao, M. Simmons, R. Wolgast, and M. Wahlig, Lawrence Berkeley Laboratory Report LBL-5911, Jan. 1977.

2. Solar Energy Program, Annual Report 1977, Energy & Environment Division, Lawrence Berkeley Laboratory, Report Pub-248, pages 13-16.

3. Solar Energy Program, Annual Report 1978, Energy & Environment Division, Lawrence Berkeley Laboratory, Report LBL-9630, pages 15-18.

4. K. Dao, "Conceptual Design of an Advanced Absorption Cycle: The Double-effect Regenerative Absorption Refrigeration Cycle", Lawrence Berkeley Laboratory Report LBL-8405, Sept. 1978.

5. K. Dao, "A new Absorption Cycle: The single-effect Regenerative Absorption Refrigeration Cycle", Lawrence Berkeley Laboratory, Report LBL-6879, Feb. 1978.

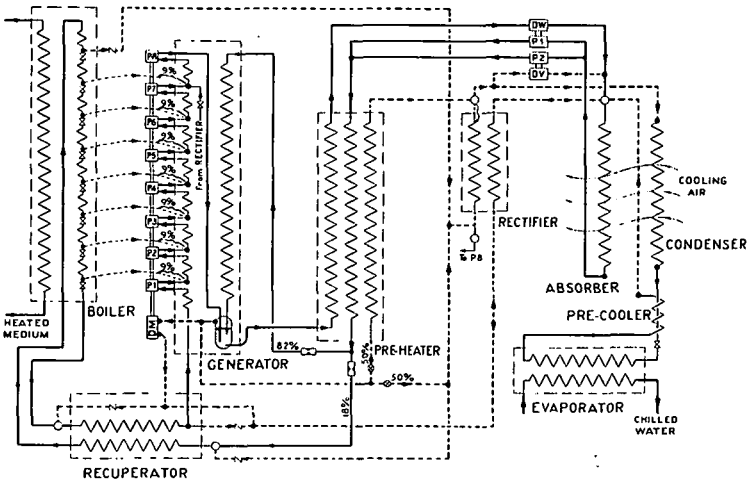


Figure 1. Schematic flow diagram of the "2R chiller"
The dotted lines are vapor paths.
The solid lines are liquid paths.
DM: multistage pump driver, driven by high pressure vapor.
DW: main circulation pump driven by strong absorbent.
DV: main pump driven by high pressure vapor.
—⋈— restrictors
—▸|— check valves
zig-zag lines are tube-in-tube heat exchangers.
small wavy lines are bleeded liquid to rectify the vapors.

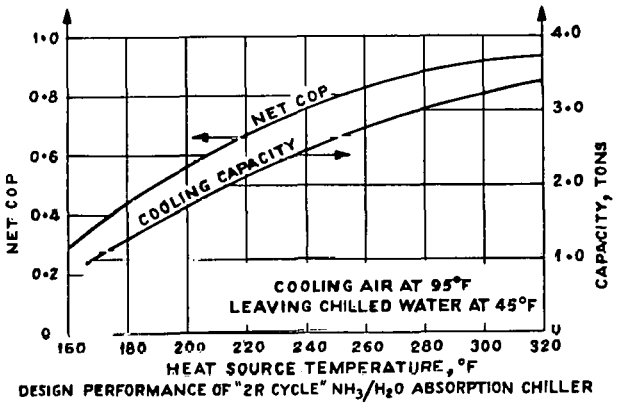


Figure 2. Design performance of "Cycle 2R" chiller. The dots on the curves are rated design points.

MULTIPLE EFFECT ABSORPTION CYCLE ANALYSIS

CENTER FOR ENERGY STUDIES, THE UNIVERSITY OF TEXAS AT AUSTIN

DOE DE-AC03-79F10540

GARY C. VLIET

PERIOD OF CONTRACT: SEPT. 1, 1979 to AUG., 31, 1980

OBJECTIVE

There appears to be potential for application of double effect absorption cycle cooling with solar-thermal input, because of an improved cycle co-efficient of performance (C.O.P.). The primary objective of this project is to develop a numerical model of the double effect absorption cycle which is then to be used to examine the effect on cycle performance (C.O.P., capacity and limits of operation) of varying the several system input and design parameters. Specifically hot, cooling and chilled water temperature effects will be examined, in addition to the size and location of heat exchangers in the system. Secondary objectives are to consider the magnitude of the corrosion problem, to project costs of double effect systems manufactured in quantity and to examine the feasibility of refrigerant/solution storage within the double-effect cycle.

CONCEPT AND BACKGROUND

The double effect absorption cycle involves the addition of a second stage of regeneration to the more common single effect cycle. The result is an enhanced C.O.P. because the refrigerant vapor produced in the first effect is condensed in the second effect to produce additional refrigerant vapor. Another advantage is the smaller cooling water requirement per ton of cooling. The schematic is illustrated in Figure 1

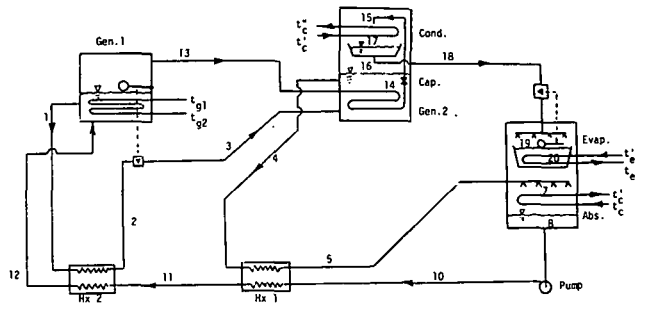


Figure 1. Double Effect Absorption System Schematic

which also defines the system being modelled in the present study. The penalties for obtaining the increased C.O.P. is an additional regeneration effect and a higher required temperature for regeneration. This requirement is imposed on the source, and in the case of solar input will undoubtedly require a more costly and/or lower efficiency collector. However, the overall system C.O.P. may be improved, and the cost of the solar collector array, a major cost of the solar cooling system, may be reduced. The double effect absorption cycle concept has been fairly well developed and units are commercially available in moderate to high tonnage units. They were however designed and built for other than solar applications in mind and on the basis of much lower energy costs than exist today.

The purpose of the current investigation is not to examine the solar/absorption system overall performance. Rather, the principal objective of the study is to examine in detail the double effect cycle performance as influenced by the several operating and system design variables, so that the solar/double effect absorption system may be evaluated at a later date.

SUMMARY

A numerical model is being developed to dynamically simulate the performance of a double effect absorption cycle with the water/lithium bromide system. It is structured to permit examination of the cycle performance as affected by the various operating and design parameters for the cycle. The model has been developed and used to obtain preliminary results of the affect on cycle performance of several of these parameters. Currently, the model is being refined to improve the treatment of the physical processes occurring in some of the cycle components.

TECHNICAL ACCOMPLISHMENTS

- A numerical model (Figure 1) of the double-effect absorption cycle has been developed to simulate dynamically the performance of the water-lithium bromide system. The performance parameters include: capacity, coefficient of performance and limits of operation. The operating and system design parameters of interest include the flow rates and temperatures of the hot, cooling and chilled water streams; the sizes (effectiveness), locations, and configurations of heat exchangers, and system control.
- Preliminary results have been obtained for the affect on cycle performance of several of these parameters (fluid flow rates and temperatures; and sizes of the two recovery heat exchangers). These results have suggested model improvements.
- The model is currently being refined to improve the treatment of physical processes occurring in some of the cycle components. For all heat exchangers the areas will be specified and overall coefficients calculated internally (as opposed to specifying effectiveness). Better physical models are being incorporated in the case of mass transfer or phase change, with the absorber model being given special consideration. The need to incorporate pressure differences between adjacent components is being reviewed for possible implementation. Different options for

solution circulation flow rate control are being incorporated.

- A trip to La Crosse, Wisconsin was made to consult with the Trane Company personnel on system design characteristics, systems controls, aspects of corrosion and projections of unit cost. Valuable information on all of these subjects were obtained which will benefit the work on this contract.

FUTURE ACTIVITIES

Contract Activities. Refinements will be completed on the current numerical model. The model will subsequently be used to conduct a performance sensitivity analysis of each of the operating and design parameters for the cycle, with the sensitivity analyses referenced to a "nominal" cycle configuration. Further effort on corrosion will be minimal. Using data supplied by Trane as well as data being solicited from other manufacturers, unit cost projections will be made. The use of refrigerant/solution storage in double effect systems will be assessed.

Post Contract Activities. It is hoped that the results of this study will be used by interested manufacturers to better optimize double effect system configurations. Further, it is anticipated that this model and results will be used either in an extension of this contract, or in an independent contract to assess the feasibility of solar powered double effect absorption cycle cooling.

PUBLICATIONS

None to date.

III DESICCANT SOLAR COOLING SYSTEMS

NATIONAL SOLAR DESICCANT COOLING PROGRAM

DOUGLAS W. HOOKER AND FRANCES H. ARNOLD
SOLAR ENERGY RESEARCH INSTITUTE
GOLDEN, COLORADO

ABSTRACT

This paper briefly describes the concepts under development by Department of Energy desiccant cooling contractors, the status of these efforts and the work remaining, and the efforts underway in SERI's desiccant cooling research program. The desiccant cooling programs at Zeopower Co. and the University of Wisconsin—Madison are not described here because they are discussed in separate papers for this review meeting.

BACKGROUND

Contractors for the U.S. Department of Energy (DOE) are performing R&D on residential-size solar cooling systems using desiccation processes. Four contractors are developing solar cooling systems which use open-cycle adsorption processes: AiResearch Manufacturing Co., Illinois Institute of Technology (IIT), Institute of Gas Technology (IGT), and University of Wisconsin—Madison. These projects are in various stages of completion, ranging from basic research and analysis to cooling system development and prototype testing. One contractor, Zeopower Co., is currently working on a closed-cycle adsorption system using natural zeolites as the desiccant material; prototypes are being constructed and will be laboratory tested late in FY80. Colorado State University (CSU) recently began to evaluate analytically and experimentally an open-cycle absorption system using a packed tower concentrator. The Solar Energy Research Institute (SERI) has DOE program management responsibilities for national solar desiccant cooling programs and is continuing its own research program.

The open-cycle adsorption process is receiving most of the effort in the current DOE desiccant cooling program. The major, unique component in these systems is the dehumidifier bed, which removes moisture from the process airstream. These systems usually can operate in one of two modes: ventilation or recirculation. The ventilation system configuration is shown in Fig. 1. In the supply stream, ambient air is adiabatically dehumidified, sensibly cooled, evaporatively cooled, and then introduced into the conditioned space. In the regenerating stream, air removed from the conditioned space is evaporatively cooled, then heated as it cools the supply stream, heated again by solar energy, cooled and humidified in the dehumidifier, and finally exhausted to the ambient air (see Fig. 2; the numbers correspond to the bulk airstream conditions at the numbered system locations shown in Fig. 1). The AiResearch and IGT systems follow this basic process.

In the recirculation system configuration the supply and regenerating airflow streams are separate. The supply stream air is removed from the conditioned space, adiabatically dehumidified, sensibly cooled, evaporatively cooled, and then reintroduced into the conditioned space. In the regenerating stream, ambient air is evaporatively cooled, then heated as it cools the supply stream, heated again by solar energy humidified and cooled as it regenerates the dehumidifier, and exhausted to the ambient air.

IIT is developing a dehumidifier in which a portion of the heat of adsorption is removed by a cross-cooling air stream. This improves desiccant performance but requires additional parasitic power to provide the cross-cooling.

The liquid desiccant cooling process of open-cycle absorption, under investigation at CSU, is shown schematically in Fig. 3. This cycle is similar to its closed-cycle counterpart except that the weak absorbent solution is regenerated by evaporating refrigerant (water) to the atmosphere instead of recovering it in the condenser. The dilute solution is heated

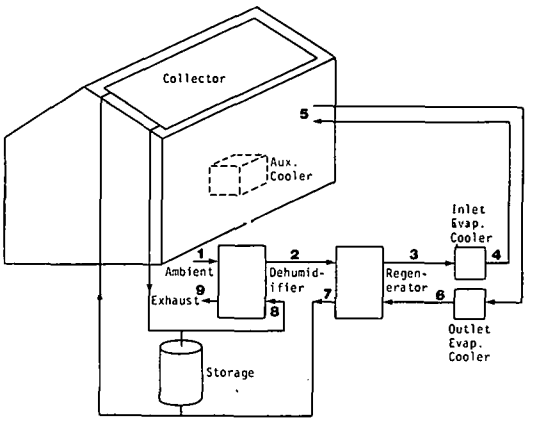


Figure 1. VENTILATION SYSTEM CONFIGURATION

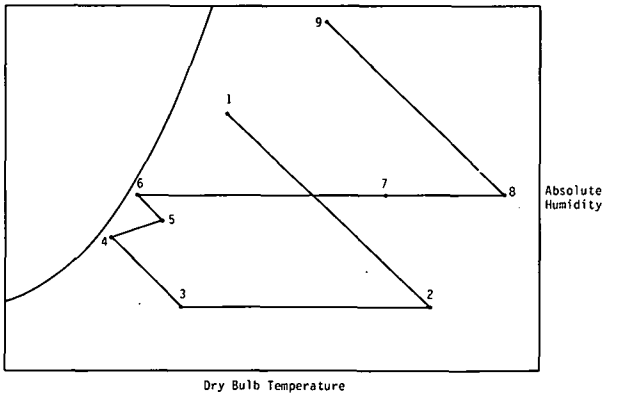


Figure 2. VENTILATION MODE PSYCHROMETRIC DIAGRAM

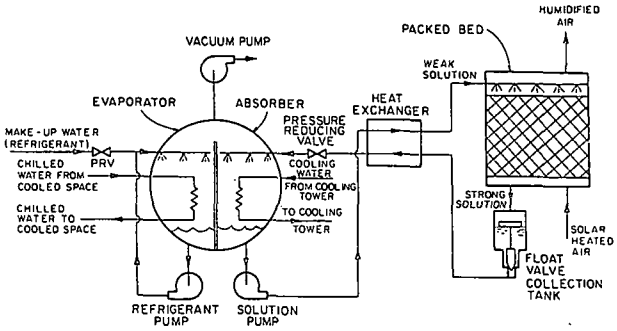


Figure 3. OPEN-CYCLE ABSORPTION SYSTEM SCHEMATIC

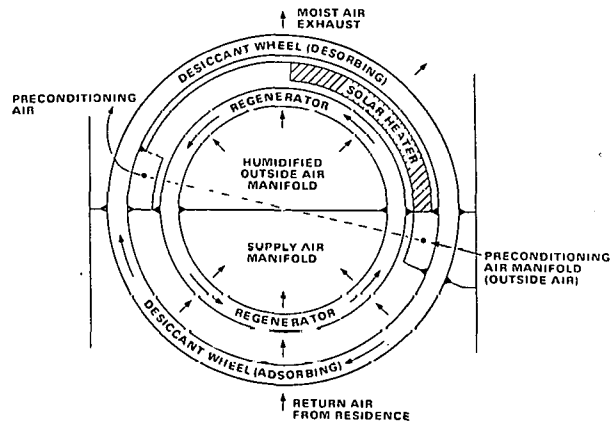


Figure 4. AIRESEARCH ROTARY RADIAL OUTFLOW DEHUMIDIFIER

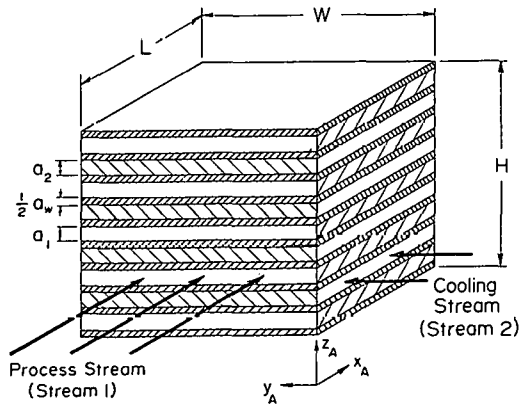


Figure 5. IIT CROSS-COOLED DEHUMIDIFIER

and regenerated using an air collector system and a packed-tower concentrator. The strong, regenerated solution leaves the concentrator and passes through a valve in which pressure is reduced from atmospheric levels. The solution passes through a regenerative heat exchanger and then to the absorber, where the solution absorbs water from the evaporator, maintaining the reduced pressure required by the evaporator. The heat of absorption for the water-absorbent solution is removed by a cooling tower loop. In the evaporator, water from an external source is evaporated at reduced pressure with the heat supplied from the cooled space. The resulting weak solution is pumped from the absorber back to atmospheric pressure through the regenerative heat exchanger and to the concentrator, completing the cycle. A vacuum pump deaerates the solution after it has been exposed to the atmosphere. The useful output of the CSU system is the evaporation of water. For every pound of water evaporated in the concentrator, one pound of water can be evaporated in the evaporator and absorbed in the absorber. Thus, the water evaporation rate from the concentrator determines cooling system performance.

AIRESEARCH MANUFACTURING COMPANY

AiResearch is developing a solar desiccant cooler which features a rotary radial outflow configuration [1,2,3]. The design is intended to reduce parasitic power requirements by increasing the face areas of the dryer and regenerative heat exchanger and reducing their airflow length. The desiccant bed and the regenerator are two counter-rotating concentric drums. The desiccant material is silica gel, and the regenerator matrix is a fine screen of galvanized steel. A top view of the dehumidifier along the axis of rotation is shown in Fig. 4. The prototype dehumidifier drum is 86 cm (34 in.) high, and 86 cm in diameter, has a 3-cm (1.15-in.) thick airflow length through the desiccant, and rotates at 5 rph. The system was designed for 5.3-kW (1.5-ton) cooling capacity, a COP of 0.52, and parasitic power input at full flow of 0.6 kW.

Fabrication of the prototype was completed in June 1979, and the unit was installed in a controlled atmosphere chamber for testing in September 1979. Preliminary tests indicated that the prototype unit cooling capacity was 4.2 kW (1.2 tons) with a COP of 0.43, a performance lower than expected. Further investigations revealed defects in the desiccant drum. Variations in the desiccant drum thickness caused flow maldistributions through the desiccant material, decreasing the system performance. The prototype test program was halted while the desiccant drum was rebuilt. The new drum has been installed in the prototype, and the system is ready for further tests. This effort is scheduled to be completed by May 1980.

ILLINOIS INSTITUTE OF TECHNOLOGY (IIT)

IIT is developing a solar desiccant cooling system that uses silica gel in a cross-cooled dehumidifier [4]. The dehumidifier is constructed of paper-like sheets of silica gel in a Teflon matrix. (See Fig. 5 for schematic representation.) The cooling system consists of two cross-cooled dehumidifiers of equal size with evaporative coolers. One dehumidifier removes moisture from the process air while the other is regenerated by solar energy.

Much of the work to date on this concept has been basic R&D, including the development of mathematical analysis methods, production and testing of silica gel sheets, and testing of a small model of the cross-cooled bed. However, a prototype dehumidifier equivalent to approximately 2.6-kW (0.75-ton) cooling capacity has been built and is being laboratory tested.

The small dehumidifier (15 x 15 x 15 cm, or 6 x 6 x 6 in.) was built and tested under periodic steady-state conditions [5]. The major parameters affecting system performance were studied (process stream flow rate, temperature, and humidity; cross-cooling stream flow rate and temperature; regeneration stream flow rate, temperature, and humidity). These tests indicated that cross-cooling could improve dehumidifier performance about 40%.

The system currently undergoing laboratory testing includes a 0.6 x 0.6 x 0.6 m (2 x 2 x 2 ft) dehumidifier. Inlet conditions to the system are controlled and held constant

Table 1. EFFECT OF REGENERATION TEMPERATURE ON CAPACITY AND COP

ENERGY INPUT TYPE	CONDITIONS DB/DP, °F OUTDOOR	INDOOR	THIRD STREAM FRACTION	REGEN'R EFFECT. %	REACT., TEMP., °F	ENERGY INPUT BTU/HR	FRACTION SOLAR INPUT, %	COOLING CAPACITY TONS	COP	EER
S+G	93.8/67.5	79.6/60.0	0.28	96.1	194	70310	44.8	2.52	0.43	22.4
S+G	94.2/66.7	79.6/60.6	0.27	95.7	195	64580	46.5	2.60	0.48	23.1
S+G	96.0/67.3	80.7/59.3	0.27	97.7	204	65570	50.9	2.58	0.47	22.9
S+G	94.8/67.1	79.9/59.5	0.18	92.4	211	67820	49.9	2.38	0.42	21.2
S+G	95.8/67.5	80.4/60.5	0.22	94.5	209	67890	50.0	2.42	0.42	21.5
G	95.4/67.9	80.9/60.2	0.23	95.0	251	76005	0	3.09	0.49	27.5

during each run. For an air flow rate of 0.22 kg/s, the system has shown a cooling capacity of 2.1 kW (0.6 ton) and a COP of 0.50.

Future work will aim to completely characterize the performance of the prototype dehumidifier through laboratory testing, refine and improve dehumidifier performance modeling, and model the total cooling system. In addition, a total cooling system will be built, complete with solar collectors and two dehumidifier beds, to test the system performance under outdoor operating conditions with solar energy input. Construction of this system will be completed by May 1980, and testing will be conducted during the summer.

INSTITUTE OF GAS TECHNOLOGY (IGT)

IGT is developing a solar desiccant cooling system which uses a molecular sieve rotary dehumidifier wheel and a natural gas-fired burner to supplement the solar energy input [6]. As shown in the SOLAR-MEC III schematic in Fig. 6, the rotary desiccant wheel is divided by a partition into two balanced-flow segments, one for moisture removal and the other for passage of the high-temperature reactivation air stream. These two streams flow in opposite directions. Considerable design and testing efforts were conducted at IGT on the SOLAR-MEC cooler previous to the current DOE-funded program. Two units were field tested, and the results of these tests provide the basis for the present program.

The SOLAR-MEC III, showing results from the current DOE program, includes several improvements over previous versions in the following areas: air seals, wheel support and drive mechanisms, air distribution and fans, and rotary heat exchange wheel. Two significant design changes include staged regeneration of the desiccant wheel and unbalanced flow operation of the heat exchange wheel. Table 1, resulting from laboratory tests of SOLAR-MEC III, illustrates the effect of regeneration temperature on system cooling capacity and COP. The parasitic power consumption of SOLAR-MEC III is 1.35 kW, whereas the early version used 2.31 kW.

IGT also developed a mathematical model and computer program for the SOLAR-MEC and, in conjunction with AB Carl Munters of Sweden, developed a nonasbestos-substrate desiccant wheel to replace the asbestos-substrate wheel. The computer model was used to help determine optimum system design, part load operation, and seasonal performance of the SOLAR-MEC. The nonasbestos desiccant wheel (using a LiCl desiccant) was recently incorporated into the SOLAR-MEC III and initial laboratory tests show satisfactory performance.

Future work in this program will include laboratory testing of the SOLAR-MEC III with the nonasbestos desiccant wheel and refinement of the seasonal simulation model. Numerous laboratory tests will be performed to completely characterize the SOLAR-MEC III performance over expected operating ranges. These tests will be conducted with regeneration energy input from solar energy alone and from the solar/natural gas combination. The seasonal simulation model will be revised to include an allowance for air leakage and a detailed parasitic power calculation.

COLORADO STATE UNIVERSITY (CSU)

CSU began an experimental investigation of an open-cycle lithium chloride absorption cooler (Fig. 3) in February 1980. The major purpose of the work is to measure the heat and mass transfer characteristics of a packed tower containing Raschig rings and Berl saddles over the potential operating range of the cooling system. Results will be compared with previous CSU theoretical analyses of the reconcentration of lithium chloride in a packed column [7,8].

The apparatus being assembled for the experiments is shown in Fig. 7. Heated air will be supplied from a fuel-fired heater to the packed column. The lithium chloride solution will be circulated through the column, diluted, and cooled in a heat exchanger to the desired supply temperature. The humidity and temperature of the air supply will be controlled. Based on the results of these experiments, CSU will design a complete 3-ton cooling system.

SOLAR ENERGY RESEARCH INSTITUTE (SERI)

A large part of the in-house work of the SERI Desiccant Cooling Program has been aimed at comparing the performance of desiccant machines with that of absorption, Rankine, and vapor-compression machines [9]. SERI is developing a universal, desiccant-bed heat- and mass-transfer

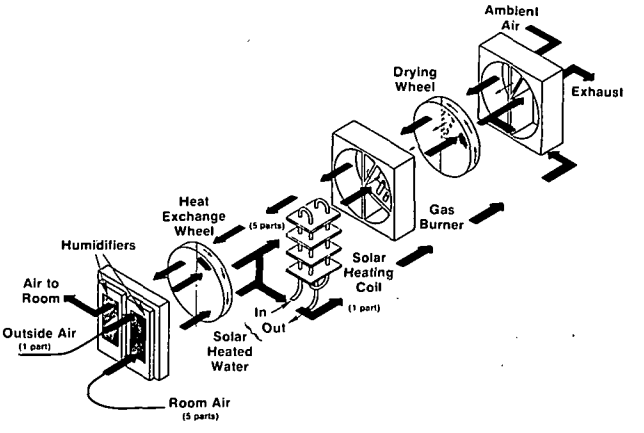


Figure 6. SOLAR-MEC III FLOW SCHEMATIC-VENTILATION MODE

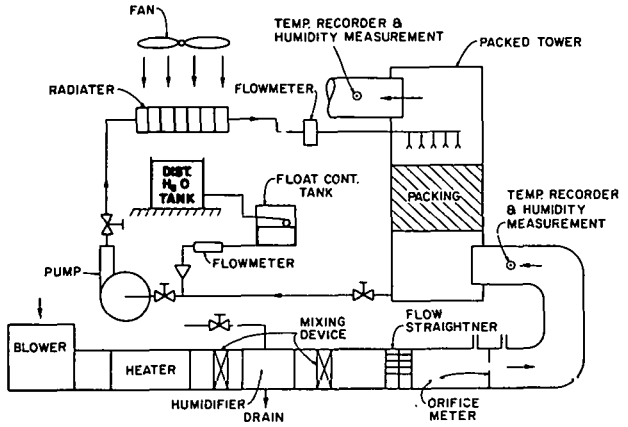


Figure 7. CSU EXPERIMENTAL APPARATUS

model that will allow simulation of solar desiccant machines and generation of tools for their proper design.

Consultants from the Colorado School of Mines are providing SERI with experimental data (equilibrium capacities of desiccants as a function of concentration and temperature) as well as expertise in adsorption modeling. Once the mass transfer and diffusion coefficients are determined, breakthrough curves (solute concentration in the effluent stream vs. time) can be obtained from the equilibrium capacities by solving the energy and mass balances in the bed. From these curves and the mass- and heat-transfer model, rates of adsorption, bed exhaustion times, and degree of regeneration can be predicted. The SERI model will be used to generate this information for the numerous desiccant materials described by the Radke-Prausnitz isotherm.

The analytical model will be validated in the SERI desiccant laboratory and with a specially designed gas chromatograph [10]. The desiccant laboratory can supply 17 m^3/min (600 cfm) of air at 121°C (250°F) and a wide range of humidities to full-scale drier beds. Effluent humidity is measured with an optical dew-point hygrometer and plotted as a function of time to give breakthrough curves. Ambient conditions and solar regeneration can also be simulated to verify the predictions of the model. The gas chromatograph records breakthrough curves and equilibrium data (adsorption isotherms) by means of perturbation chromatography. Diffusion coefficients for the bed can be measured directly, and diffusion coefficients within a single particle of desiccant material can be predicted from the breakthrough curves [10].

SERI is also exploring the role desiccants can play in meeting the latent cooling load in passive buildings. A desiccant machine, such as the IGT or AiResearch device, used for dehumidification only will be modeled. The heat- and mass-transfer model will be extended to include these systems, and the materials characterization work will include desiccants such as natural zeolites, which are particularly interesting for passive applications. Design tools will be generated using the heat- and mass-transfer model and the desiccant laboratory. In particular, parametric studies will evaluate the trade-offs among bed efficiency, parasitic energy, bed geometry and packing, thermodynamic strategy for cooling, and economics.

The investigation of solid-to-solid phase-change energy storage materials is a third SERI research task. A class of simple organic compounds with tetrahedral structure exhibits reversible solid-to-solid structural transformations with large enthalpy changes. One such compound is pentaerythritol ($C_5H_{12}O_4$), a chemical mass-produced for use in paint resins. Pentaerythritol can reversibly store 77 cal/g at 188°C in a solid-to-solid transformation. This and related low-cost compounds are being studied as candidate materials for direct-contact storage/heat exchangers to help level the temperature of regeneration air entering desiccant coolers.

SERI is also exploring the possibility of combining an open-cycle absorption chiller with a solar-assisted heat pump for summer cooling and winter heating. For this task, the thermal effectiveness of open-flow collectors (the salt-solution working fluid flows over the collector in direct contact with the atmosphere) is being analyzed. If the salt solutions (LiCl and $CaCl_2$) do not freeze or lose water in the winter, the same collectors which evaporate refrigerant to the atmosphere in the summer can be used to supply energy to a vapor-compression heat pump for winter heating. The vapor-compression heat pump is normally needed for backup cooling in any case. Computer models of the refrigeration system for the cooling season are being adapted to winter conditions for candidate cities.

REFERENCES

1. Gunderson, M. E.; Hwang, K. C.; Railing, S. M. 1978 (31 March). Technical Progress Report-Development of a Solar Desiccant Dehumidifier. 78-14957. Torrance, CA: AiResearch Manufacturing Co.

2. Gunderson, M. E.; Hwang, K. C.; Railing, S. M.; Rousseau, J. 1978 (10 November). Second Technical Progress Report-Development of a Solar Desiccant Dehumidifier. 78-15444. Torrance, CA: AiResearch Manufacturing Co.

3. Gunderson, M. E. 1979 (12 June). Third Technical Progress Report-Development of a Solar Desiccant Dehumidifier. 79-16042. Torrance, CA: AiResearch Manufacturing Co.

4. Illinois Institute of Technology. 1978 (10 June). First Semi-Annual Progress Report (Nov.-May 1978) on Development of a Solar Desiccant Dehumidifier. Chicago, IL: IIT.

5. Illinois Institute of Technology. Milestone Report—Test of Cross-Cooled Dehumidifier Model. Chicago, IL: IIT.

6. Wurm, J.; Kinast, J. A.; Rush, Jr., W. F.; Zawacki, T. S.; Maariss, R. A. 1979 (October). SOLAR-MEC Development Program—Annual Progress Report. COO-4495-15. Chicago, IL: Institute of Gas Technology.

7. Leboeuf, C. M. 1979. Solar Driven LiCl Open Cycle Absorption Cooling With Packed Bed Absorbent Reconcentration. MS Thesis. Ft Collins, CO: Colorado State University.

8. Leboeuf, C. M.; Löf, G. O. G. 1978 (October). 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. COO/4546-1. Ft. Collins, CO: Colorado State University.

9. Shelpuk, B. C.; Hooker, D. W.; Jorgensen, G. J.; Bingham, C. E. 1979 (June). Simulation and Economic Analyses of Desiccant Cooling Systems. SERI/TR-34-090. Golden, CO: Solar Energy Research Institute.

10. Pitts, R.; Czanderna, A. 1980 (February). Design for a Gas Chromatograph for Characterizing Desiccant Material. SERI/RR-334-550. Golden, CO: Solar Energy Research Institute.

DEVELOPMENT OF A SOLAR DESICCANT DEHUMIDIFIER

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

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

J. ROUSSEAU

PERIOD OF CONTRACT: SEPTEMBER 1977 to MAY 1980

OBJECTIVE

This program is aimed at the design and development of a 1-1/2-ton solar desiccant air conditioner (SODAC) for residential application.

CONCEPT

A schematic of the system is shown in Figure 1, and the arrangement of the desiccant bed and regenerator is depicted in Figure 2. The system, by comparison to 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. Thermal energy thus recovered results in a 25 percent increase in COP.

(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.

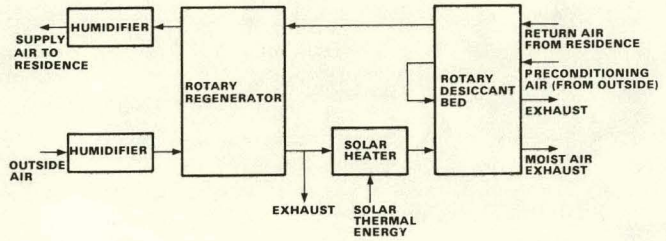


Figure 1. System Schematic

TECHNICAL ACCOMPLISHMENTS

• Design data. The COP of the unit optimized under this program is 0.52 at standard rating conditions and a solar heat source of 200°F. Overall dimensions are 60 in. wide by 41 in. deep by 56 in. high (see Figure 3). The cost of the SODAC in yearly production quantities of 25,000 is estimated at $2,000 (list price).

• Economic feasibility. 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.

• Preliminary testing. The system shown in Figure 3 was instrumented and installed in a controlled atmosphere chamber at the Dunham-Bush Harrisonburg facility. Preliminary performance runs were made to verify design point selection in terms of airflow rates and drum speeds. The test data revealed abnormalities in the desorbing airstream temperature. Upon close examination, the desiccant drum was found to be damaged with variations in thickness as high as 25 percent. The test program was interrupted and the drum was rebuilt.

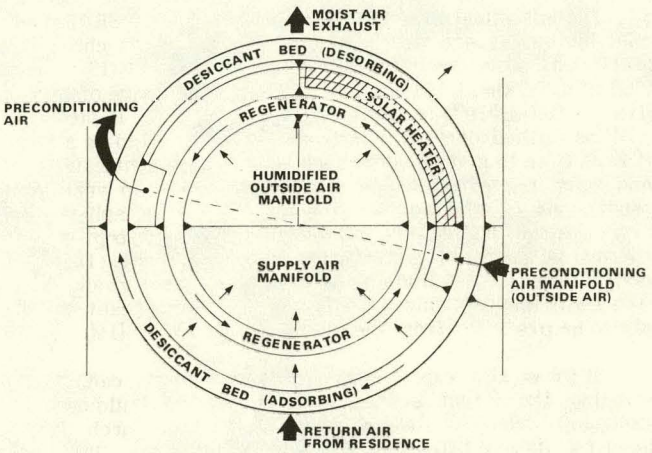
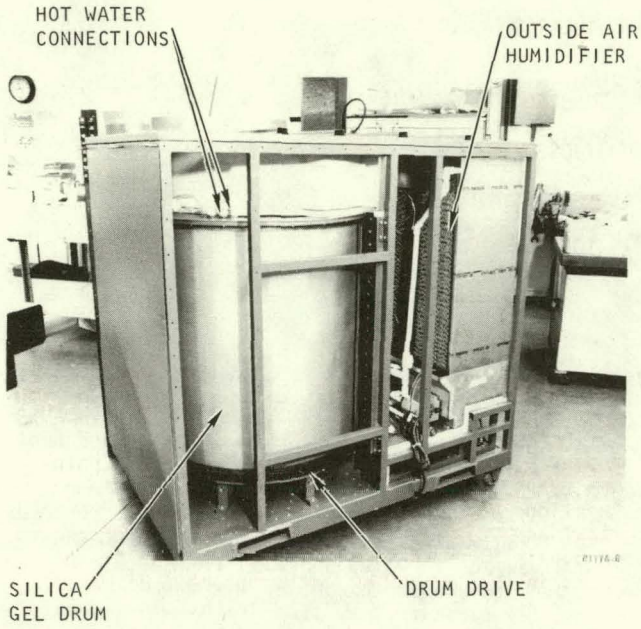


Figure 2. Dehumidifier Cross Section

FUTURE ACTIVITIES

The preliminary data obtained with the damaged drum is very encouraging, and it is anticipated that predicted performance will be achieved. Currently the system is ready for installation in the test chamber.

Following successful testing in the test chamber, the next phase of the program will involve SODAC evaluation in a test house as part of a complete solar system.



- 1.5-TON CAPACITY
- CONDITIONED SPACE AIRFLOW: 830 CFM
- OUTSIDE AIRFLOW: 950 CFM
- PARASITIC POWER 0.6 KW (FULL FLOW)
  0.23 KW (HALF FLOW)
- WATER USE: 5 GAL/HR AT 1.5 TONS
- OVERALL DIMENSIONS: 60 IN. X 41 IN. X 56 IN. HIGH
- SYSTEM COP: 0.52

F-31693

Figure 3. SODAC Package

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 (awaiting DOE approval).

Third Technical Progress Report, Development of a Solar Desiccant Dehumidifier, June 12, 1979 (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.

F-31698

OPEN CYCLE LITHIUM CHLORIDE SOLAR COOLING

SOLAR ENERGY APPLICATIONS LABORATORY, COLORADO STATE UNIVERSITY

CONTRACT NUMBER DE-AC03-79CS30206

PRINCIPAL INVESTIGATOR GEORGE O.G. LOF

CONTRACT PERIOD 15 SEPTEMBER 1979 TO 31 JANUARY 1981

OBJECTIVE

The specific objective of the project is the measurement of mass transfer (water vapor transfer) rates in packed columns in which lithium chloride solutions are reconcentrated by vaporization into a heated air stream. This information is needed for design of open cycle lithium chloride absorption cooling systems in which solar heated air provides the energy for operation.

CONCEPT

The numerous advantages of solar air heating systems do not include a present capability for cooling. An attractive possibility based on a theoretical analysis of energy supply from solar air collectors to an open cycle lithium chloride absorption cooling system is therefore being experimentally investigated.

The theoretical analysis and the present experimental investigation are based partially on a successful open cycle lithium chloride absorption chiller operated in the Soviet Union for several years. In that system, chilled water is produced by vacuum evaporation of water in an evaporator/absorber vessel, water vapor from the evaporator being absorbed in lithium chloride solution. The diluted lithium chloride is reconcentrated by circulation across a roof exposed to the sun, make-up water being added to the system in the evaporator. Different climatic conditions in the United States preclude the reconcentration of the solution by trickling across an open roof, but the theoretical analysis shows that regeneration can be effected in a small packed column through which solar heated air is supplied. Figure 1 shows the principal features of this system.

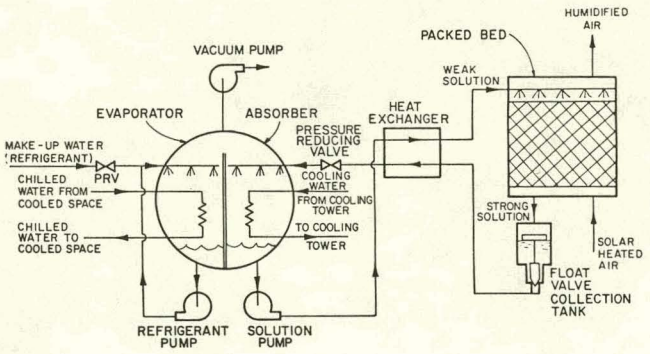


Fig. 1. Schematic of the open cycle absorption air conditioning system

BACKGROUND

There are no data on the mass transfer and heat transfer characteristics of lithium chloride solutions evaporating into an air stream, so certain assumptions and inferences are necessary in the theoretical analysis. A typical set of computed results is shown in Fig. 2. The principal purpose of the present investigation is the measurement of mass transfer and heat transfer coefficients in a packed tower containing Raschig rings and Berl saddles, under various conditions of temperature and flow rate of liquid and air streams. Humidity of the heated air is also an important variable. The results will be used in determining more precisely the design requirements and expected performance of complete solar cooling systems of this type.

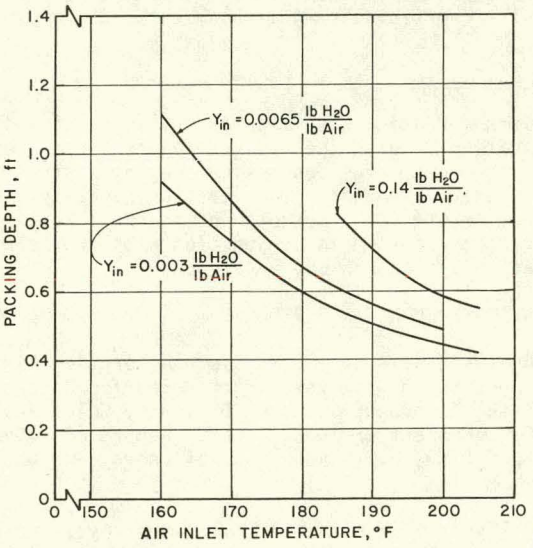


Fig. 2. Required tower height as a function of air inlet temperature for a 3-ton air conditioning capacity. Packing type: 1.5 inch Berl saddles, $K_G a_M$ = 800 lb H_2O/hr·ft^3·(ΔY)

SUMMARY OF PROJECT ACCOMPLISHMENTS

Equipment for experimental determination of mass transfer coefficients in a packed column in which lithium chloride solution is reconcentrated by contact with heated air is now being assembled. The work, which started in February 1980, was preceded by a theoretical analysis and design of a regeneration system for evaporating the water absorbed by lithium

chloride solution in an open cycle lithium chloride cooling system.

The experimental apparatus being assembled for determination of mass transfer and heat transfer coefficients in this system is shown in Fig. 3. Heated air will be supplied from a fuel-fired heater to the packed column, and the lithium chloride solution will be circulated through the column, diluted for reuse, and cooled in a heat exchanger to the desired supply temperature. Humidity and temperature of the air supply will be controlled, and flow rate will be measured.

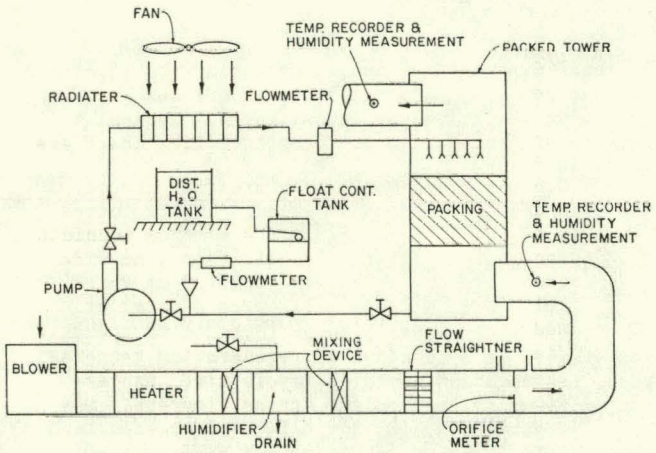


Fig. 3. Experimental apparatus for measuring mass transfer coefficients in lithium chloride solutions

FUTURE ACTIVITIES

Plans for use of the results developed in this investigation involve the design of a complete open cycle lithium chloride absorption cooling system of approximately three tons refrigeration capacity, the construction of such a system, and the full-scale testing of the system in conjunction with the solar air-heating systems in CSU Solar House II.

PUBLICATIONS/REPORTS/REFERENCES

"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", C.M. Leboeuf and G.O.G. Löf. Report COO/4546-1 prepared for the U.S. Department of Energy, October 1978.

"Analysis of a Lithium ChlorideOpen-Cycle Absorp- Air Conditioner Utilizing a Packed Bed Regenerator and Solar Heated Air", C.M. Leboeuf. Colorado State University (Department of Mechanical Engineering) M.S. thesis, summer 1979.

PROJECT TITLE: DEVELOPMENT OF A SOLAR DESICCANT DEHUMIDIFIER

NAME OF CONTRACTING ORGANIZATION: ILLINOIS INSTITUTE OF TECHNOLOGY, CHICAGO, IL 60616

CONTRACT NUMBER: EG-77-C-03-1589

PRINCIPAL INVESTIGATORS: Z. LAVAN AND D. GIDASPOW

PERIOD OF CONTRACT: SEPTEMBER 30, 1977 - SEPTEMBER 30, 1980

OBJECTIVE

The principal objectives are design, construction, testing and mathematical simulation of cross-cooled dehumidifiers and desiccant sheets.

CONCEPT

The novel aspect of the system is a cross-cooled dehumidifier constructed from aluminum and paper-like sheets of silica gel made by a unique process developed under this contract. This dehumidifier, shown in figure 1, has a number of distinct advantages. 1) Low regeneration temperatures (~150°F). 2) Low pressure drop (high EER). 3) Better sorption dynamics. 4) Higher cooling capacity. 5) Higher COP.

SUMMARY

In two and a half years, we were successful in transforming a theoretical concept into a working prototype unit. Desiccant sheets were manufactured. Their superior performance was established. A cross-cooled model was built and tested. Mathematical simulation models were developed. A prototype dehumidifier was built. The COP is about 0.5 verses a calculated value of 0.7. A complete prototype cooling system is being constructed and modeled.

TECHNICAL ACCOMPLISHMENTS

- Successful silica gel sheets were made and tested [1].
- A Graetz-type analysis was applied to the silica gel sheet data [2,3]. Nusselt numbers for the channel and sheet were calculated [2]. (See figure 2).
- A diffusion model for the sheet that takes into account transfer of water in the micro and macropores was developed. Figure 3 shows a comparison between the channel data and the model. The major unknown parameter is the diffusion coefficient of water in the micropores. The curve fit produced a diffusion coefficient in the micropores typical of diffusion in liquids.
- A small cross-cooled dehumidifier was designed, constructed and tested [2,4]. The dehumidifier performance increases significantly with moderate cross-cooling.
- A computer program has been developed to predict the performance of cross-cooled dehumidifiers under periodic steady state conditions. The effect of diffusion in the desiccant is included by assuming a linear moisture distribution in the desiccant. The experimental data of the dehumidifier model are in good agreement with this model [4]. (See figure 4).

Rational dehumidifier design criteria were developed and the performance sensitivity to off-design operating condition was investigated. Typical results presented in a psychrometric like chart are shown in figure 5.

- A 0.6 ton cross-cooled dehumidifier prototype has been designed and constructed. The prototype shown in figure 1 is 0.6 x 0.6 x 0.6 m and consists of 80 process and cooling channels each 2 mm wide. The process channels are lined with 1.5 mm thick silica gel sheets on both walls with a total of 64 m^2 of exposed sheet area. The performance of the unit was studied as a function of regeneration temperature, regeneration humidity, cycle time, process stream flowrate and cooling stream flowrate. One set of results showning the effect of regeneration temperature is shown in figure 6.

FUTURE ACTIVITIES

Contract activities. Testing of the prototype dehumidifier will be completed and results will be compared to the computer model. An outdoor cooling system that uses two dehumidifiers will be installed and tested. The desiccant cooling system will be simulated. A detailed desiccant sheet optimization study will be conducted.

Post-contract activities. Testing of the complete cooling system and modeling of the desiccant sheets will be completed. Improvements will be incorporated into new designs for field testing. Such testing will be done together with industrial partners. An attempt will be made to increase the coefficient of performance considerably beyond unity by use of a two stage system that uses the principle of latent heat recovery.

PUBLICATIONS/REPORTS

1. "Development of a Solar Desiccant Dehumidifier," 13th Intersociety Energy Conversion Engineering Conference, October 1978. San Diego, California.

2. "Development of a Solar Desiccant Dehumidifier Part II," IECEC, August 1979, Boston.

3. "Gas-Phase and Desiccant Resistances in a Solar Powered Silica Gel Dehumidifier," AICHE, November 28, 1979, San Francisco, California.

4. "Cross-Cooled Dehumidifier Model, Test Results and Computer Simulations." (NTIS).

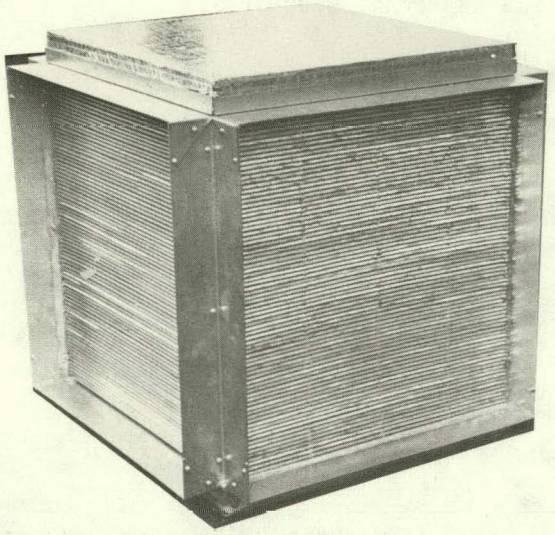


Figure 1. Cross-Cooled Dehumidifier Prototype

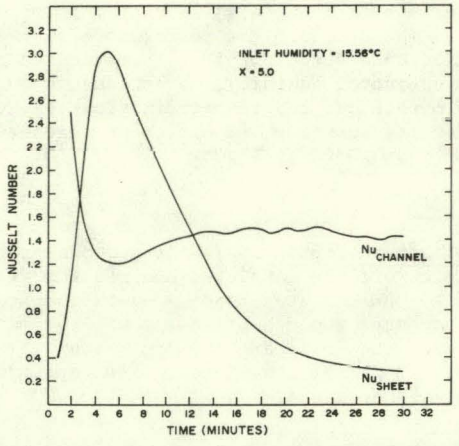


Figure 2. Dimensionless Mass Transfer Coefficients

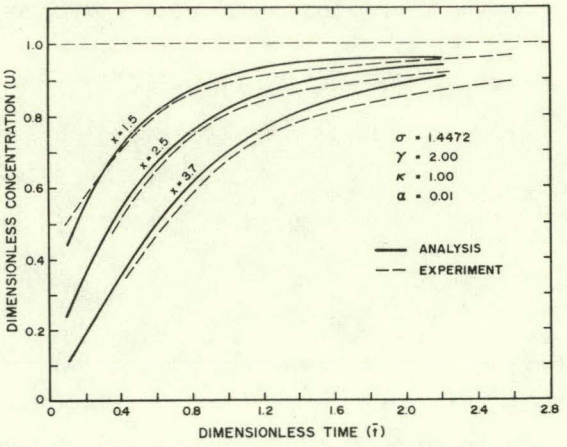


Figure 3. Micro-Macro Diffusion Model

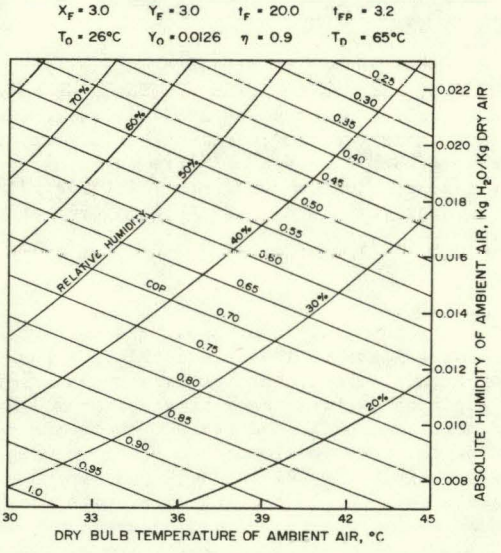


Figure 5. Predicted Performance

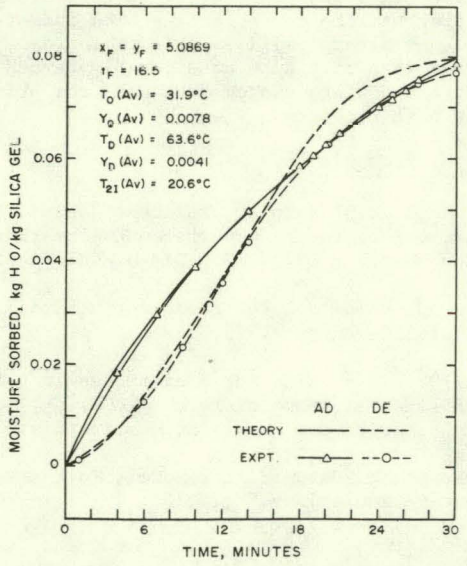


Figure 4. Performance of Dehumidifier Model

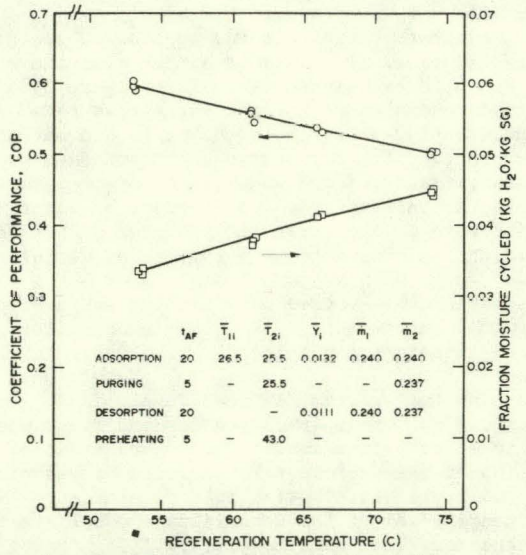


Figure 6. Performance of Prototype Unit

SOLAR-MEC® DEVELOPMENT

INSTITUTE OF GAS TECHNOLOGY

DE-AC03-77CS34495

Robert A. Macriss and Jaroslav Wurm

September 1, 1977 – February 29, 1980

OBJECTIVE

IGT is currently developing under contract to DOE an "advanced" version of the SOLAR-MEC open-cycle solar desiccant heating/cooling system, for engineering field testing and ultimate commercialization. The advanced features of this residential-size unit (SOLAR-MEC III) are staged desiccant reactivation, unbalanced flow heat exchange, non-asbestos desiccant moisture exchanger, and new burner and seal systems.

BACKGROUND

The basic SOLAR-MEC heating/cooling machine is an open-cycle system based on the principle of adsorption. When operating in a cooling mode, ambient air or air from a room is dried to very low moisture levels by a desiccant. After removal of the heat of condensation, this air is adiabatically rehumidified to produce cold air of the same quality produced by conventional air conditioners. This air is then delivered to the room being cooled. The cycle is complete when the desiccant is regenerated. This is accomplished by heating an equivalent amount of air from the room or of ambient air to drive the absorbed moisture from the desiccant. Figure 1 shows a schematic diagram of the basic SOLAR-MEC system. A typical cooling mode of the unit working on ambient air (ventilation or fresh air mode) is shown on the psychrometric chart of Figure 2 and is self-explanatory.

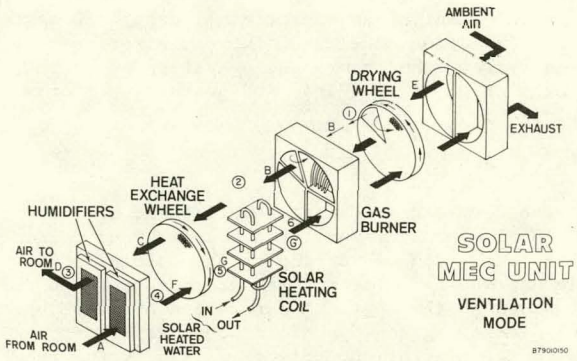


Figure 1. SOLAR-MEC I LAYOUT

Between 1967 and 1977, first as a gas-fired machine and, since 1974, as a gas-augmented, solar heat-energized heating-cooling system, the basic SOLAR-MEC (System I) has undergone gradual development from exploratory and conceptual design, to laboratory testing and evaluation, to field testing of two breadboard prototypes. These activities, over the years, have been supported by the Gas Developments Corporation, the National Science Foundation, the American Gas Association, with additional support by Southern California Gas Co., Consolidated Natural Gas Service Corp., ENSERCH, Inc., and the Consumer Gas Co. (Toronto).

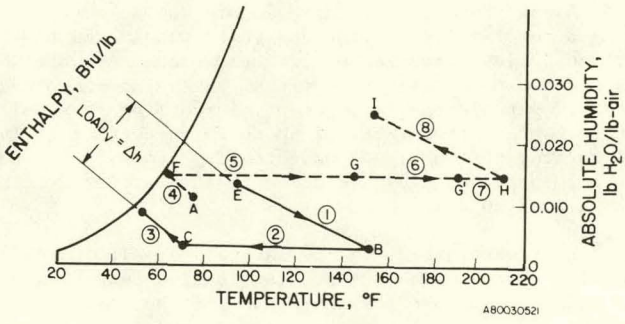


Figure 2. SOLAR-MEC PSYCHROMETRIC CYCLE (Ventilation Mode)

Solar and solar/gas cooling performance obtained with an early laboratory and two field test units (in Los Angeles and Toronto, Canada) demonstrated the need to improve overall performance of the system. It should be noted here that both the Los Angeles and Toronto field units and installations are operating at present, with the Los Angeles unit having accumulated over 3 years of continuous operation, and the Toronto unit having logged about a year of continuous operation. The overall performance of these laboratory and field prototypes indicated also sufficient promise for this device to warrant further development work and indicated the direction in which that development work

should proceed. The objectives of the current (ongoing) program derive from the results of the field test program.

SUMMARY

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

1. Improvement of the overall seasonal performance factor (SPF) for cooling and reduction of parasitic power by "advanced" process design modifications.
2. Assembly and preliminary testing of an "advanced" SOLAR-MEC unit (System III) which utilizes staged reactivation mode and unbalanced flow design of the sensible heat exchanger.
3. 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.
4. Replacement of the desiccant asbestos substrate by a novel, non-asbestos matrix for testing and evaluation.
5. Development of an operational, dynamic seasonal system simulation model used for optimization of preferred system embodiments and operating schedules, and for simulation of part-load, and seasonal performance simulation.

TECHNICAL ACCOMPLISHMENTS

One very significant accomplishment of the current phase of the program was the development of data relating to the dynamic drying of the molecular sieve desiccant wheel.[1] These data were necessary to define the values of the physical parameters of a computer model simulating the dynamic process of air drying and desiccant regeneration. Figure 3 illustrates the comparison of desiccant wheel performance simulation with the model to actual data obtained.

With the desiccant model completed and verified, we undertook and completed the mathematical description (model and computer program) of the component processes of the SOLAR-MEC system (namely, desiccation, heat exchanger, and evaporative cooling) and of the total system. We used the model to evaluate improvements to increase efficiency and unit capacity.

Among these design improvements, we selected staged reactivation of the desiccant wheel[2] and unbalanced flow operation of the heat exchanger wheel,[3] as the two most relevant options. With these improvements, we projected improvements in cooling seasonal performance factor (SPF) of up to 20 percent (relative to earlier designs), and unit cooling capacity increases over 20 percent, again relative to the earlier design shown in Figure 1.

We investigated, in the laboratory, air leakage levels, sources and causes, distribution and resultant parasitic power penalty therefrom (of the early vintage units) and on this evidence, we redesigned the air-seals (Figure 4), wheel support and drive mechanisms, (Figure 5), and air distribution and fans, in order to achieve projected parasitic power decreases of the order of 40 percent, relative to the field test units. In addition, we investigated the long-term stability of the rotary heat exchanger wheel performance and found it excellent. However, we also evaluted a low-cost alternative matrix (corrugated instead of the costlier expanded structure) and found it also satisfactory.

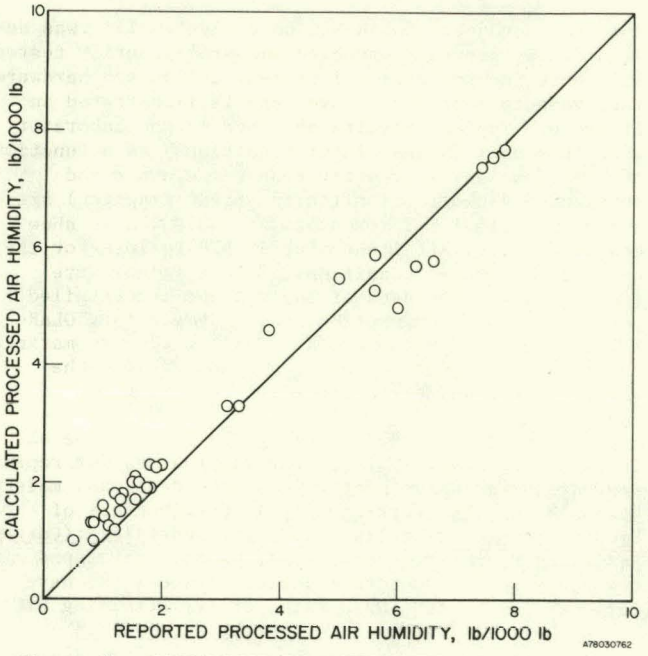


Figure 3. COMPARISON OF DRYER WHEEL SIMULATIONS WITH MEASURED DATA FOR THE MOLECULAR SIEVE WHEEL

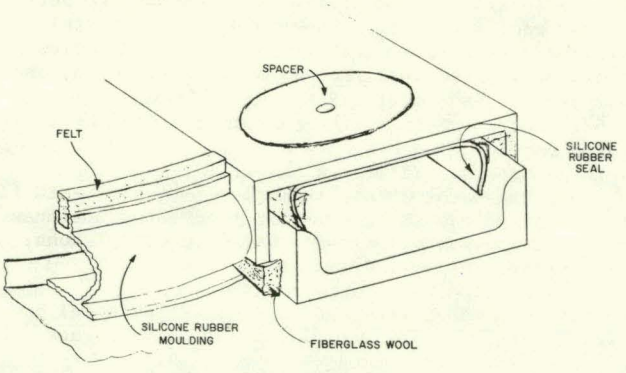


Figure 4. DESIGN OF POINT OF CONTACT BETWEEN THE RADIAL AND PERIPHERAL SEALS

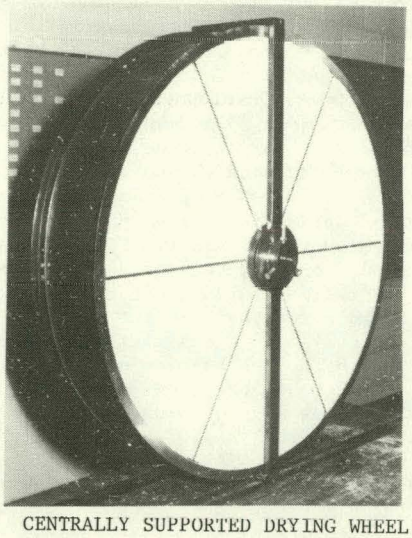


Figure 5. CENTRALLY SUPPORTED DRYING WHEEL ASSEMBLY

An "advanced" SOLAR-MEC unit (System III) was designed, engineered, assembled and preliminarily tested. This unit incorporates all process design and hardware improvements mentioned above, and is illustrated in Figure 6. Typical results obtained in the laboratory with this unit (at ARI input conditions) as a function of solar/gas energy reactivation temperature and unbalanced flow fraction (third stream fraction) are shown in Table 1. The results of Table 1 also show measured Energy Efficiency Ratio (EER) values for the unit, at ARI rated conditions. These values were computed using the data of Table 1 and the detailed parasitic power consumption measured with the SOLAR-MEC III unit. For comparison, Table 2 also summarizes the parasitic power consumption measured with the earlier field units (Figure 1).

During the current phase of the program, we also investigated several alternative approaches for replacement of the asbestos substrate of the desiccant moisture exchanger wheel. Working with AB Carl Munters of Sweden, and their wholly owned U.S. subsidiary (Cargocaire, Amesbury, Massachusetts), we have developed a new non-asbestos substrate desiccant wheel and have successfully tested one version of it, utilizing LiCl as the desiccating agent.

We have also developed and partially verified (using data from the unit such as shown in Table 1) a seasonal system simulation model and computer program. Although not yet fully refined, we have used the program to simulate variable SOLAR-MEC III performance for a reference house and variable total (sensible and latent) load for six selected cities (Santa Maria, New York, Apalachicola, Ft. Worth, and Phoenix) very successfully.

FUTURE WORK

- Intensive laboratory testing of the SOLAR-MEC III unit incorporating a new, non-asbestos desiccant support substrate to produce data for seasonal system model verification
- Refinement of the seasonal simulation model by the inclusion of actual residual air leakage and model for parasitic power.

PUBLICATIONS

1. Wurm, Kinast, Rush, Jr., Zawacki, Macriss, "SOLAR-MEC® Development Program — Annual Progress Report," COO-4495-15, October 1979.
2. Rush, Wurm, Dufour, "Air Conditioning Process," (assigned to Gas Developments Corporation), U.S. Patent 4,113,004 (1972) September 12.
3. Weil, "Three-Stream S-Wheel and Cooling Mode Operation" (assigned to Gas Developments Corporation) U.S. Patent 3,880,224 (1975) April 29.

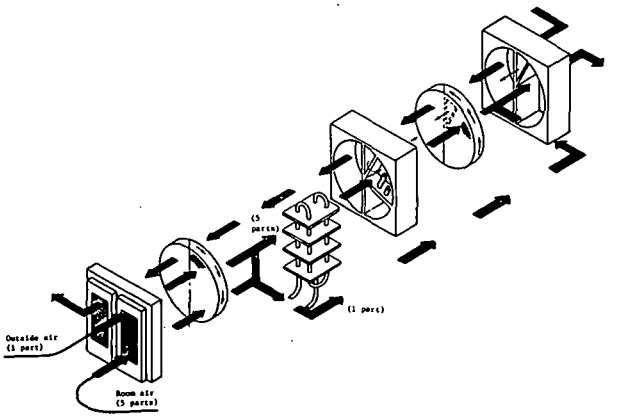


Figure 6. SOLAR-MEC III LAYOUT

Energy Input Type	Conditions DB/DP, °F Outdoor	Indoor	Third Stream Fraction	Regen'r Effect. %	React. Temp., °F	Energy Input Btu/hr	Fraction Solar Input, %	Cooling Capacity tons	COP	EER
S+G	93.8/67.3	79.6/60.0	0.28	96.1	196	70310	44.8	2.52	0.43	22.4
S+G	94.2/66.7	79.6/60.6	0.27	95.7	195	64580	46.5	2.60	0.48	23.1
S+G	96.0/67.3	80.7/59.3	0.27	97.7	204	65570	50.9	2.58	0.47	22.9
S+G	94.8/67.1	79.9/59.5	0.18	92.4	211	67820	49.9	2.38	0.42	21.2
S+G	95.8/67.5	80.4/60.5	0.22	94.5	209	67890	50.0	2.42	0.42	21.5
G	95.4/67.9	80.9/60.2	0.23	95.0	251	76005	0	3.09	0.49	27.5

Table 1. EFFECT OF REGENERATION TEMPERATURE ON CAPACITY AND COP AT CONSTANT 3RD STREAM FRACTION (SOLAR-MEC III)

Power Components	SOLAR-MEC I	SOLAR-MEC III
	Parasitic Power, Watts	
Process Stream Fan-Motor	595	365
Reactivation Stream Fan-Motor	1040	604
Burner Fan	-	40
Wheel Drive Motors		
Desiccant	118	100
Heat Exchanger,	183	155
Water Pumps (2)	190	86
Total	2316	1350

Table 2. PARASITIC POWER CONSUMPTION OF EARLY UNITS (SOLAR-MEC I) AND CURRENT DESIGN (SOLAR-MEC III)

SYSTEMS EVALUATION STUDY OF SOLAR DESICCANT COOLING SYSTEMS

UNIVERSITY OF WISCONSIN-MADISON
CSIRO, MELBOURNE, AUSTRALIA
CONTRACT DE-AC03-79SF10548

J.A. DUFFIE AND J.W. MITCHELL

AUGUST 1, 1979 TO JULY 31, 1981

OBJECTIVES

The objective of this project is to develop reliable and useful models of the components of solar desiccant air conditioning systems. The performance predicted by these models will be validated with experimental results. Simulation methods will be used to evaluate various system configurations in a variety of applications.

SUMMARY

The major accomplishments of the project to date have centered around the development of component models for desiccant air conditioning systems. This has involved models for rotary and fixed bed dehumidifiers, sensible heat exchangers, evaporative coolers, and building sensible and latent loads. The results from simplified analogy models have been compared to those from detailed mechanistic models. The effect of desiccant properties, and the properties of an ideal desiccant have been considered. Preliminary simulations of the performance of three candidate system types (ventilation mode, recirculation mode, and Dunkle cycle) have been explored. The project is in the early stages and definitive conclusions on system viability can not be drawn at this time.

TECHNICAL ACCOMPLISHMENTS

Desiccant properties. The determination of the set of desiccant properties that are most appropriate for the systems is under way. This includes an evaluation of the characteristics of an ideal desiccant from a thermodynamic viewpoint, and a comparison of actual properties against this ideal. Discussions have been carried out with the co-investigators at the Division of Mechanical Engineering, CSIRO, Melbourne, Australia. These discussions have led to the conclusion that ideal desiccants have characteristics along constant wet bulb and relative humidity lines. Preliminary system simulations with these characteristics have been performed. The results are somewhat anomalous, and further study into the properties of ideal desiccants is continuing. The simplified curve fits to the characteristics (F_1, F_2) for silica gel were refined and extended over a greater temperature and humidity ratio range.

Rotary dehumidifiers. A series of models have been developed for predicting the performance of rotary dehumidifiers. These models are 1) a very simple model that uses the F_1 - F_2 analogy theory and constant effectiveness, 2) an analogy model that uses variable desiccant properties (1) and 3) a finite difference models that solves the governing differential equations for heat and mass transfer with variable properties. The results of these models have been compared against each other.

The desiccant properties for silica-gel and lithium chloride have been included in the models as appropriate.

- Performance results from the analogy method and finite difference method of dehumidifier analysis were compared. It was found that the two methods generally showed very good agreement. Instances which showed poor agreement were restricted to those processes with very large differences in inlet state relative humidities. The lack of agreement is attributed to improper selection of average desiccant properties over the range of temperature and humidity sensed by the matrix. The finite difference program has been simplified to accommodate analysis of these average properties and reduce run time. Investigation of various averaging techniques is underway.

- The predictions from the analogy method models have been compared to those from the finite difference models to establish the ranges of validity of the analogy solutions. The analogy methods are found to be satisfactory for system simulations especially for desiccants with well behaved properties such as silica gel.

Other component models. TRNSYS compatible models of sensible heat exchangers of rotary and periodic flow fixed bed configuration have been developed. The sensible heat exchanger models use correlations of Kays and London's Compact Heat Exchangers to obtain effectiveness. Modifications to the correlations for rotary heat exchangers have been made to accommodate low rotation speeds.

Transient analysis of sensible heat regenerators has been started. A computer program to investigate the effects of a step change in the flow inlet conditions of a rotary sensible heat regenerator is being developed to allow evaluation of transients on performance.

- The components needed for system models have been developed. The components include an evaporative cooler model, a collector-storage model for moist air, controls, and a building load model that accounts for sensible and latent loads.

- A control model for the ventilation cycle with variable temperature of the auxiliary supply has been written. This incorporates control logic to limit auxiliary input when the system is in a bypass mode. These features allow system capacity and COP to be maximized during simulation. This model has been extended to include the other system configurations.

System simulations. The development of the component models has allowed system models to be con-

structed. Seasonal simulations are then feasible. The accomplishments in this area are described below.

• System models of ventilation, recirculation and Dunkle cycles have been completed. These models have been incorporated into TRNSYS.

• Performance maps showing the sensible and latent capacities for the ventilation, recirculation, and Dunkle cycles have been developed for a wide range of systems parameters. These maps provide insight into system operation and the control strategy necessary to achieve effective cooling. They also provide information needed for the design requirements for the system and the sizes of the various components.

On the basis of these steady state, or design point analyses, it was concluded that in order to maximize the system COP, a variable temperature auxiliary is required. The regeneration temperature is controlled by monitoring the bypass air flow rate; the auxiliary temperature is incremented only if the system can meet the load without requiring bypass mixing. Thus, in general, the regeneration temperature during periods when the latent load is large compared to the sensible load is higher than when the sensible load is higher than when the sensible load is large compared to the latent load. Using the maps of system COP as a function of ambient temperature and humidity, it was shown that for systems with nominal effectiveness components, this control strategy does not necessarily optimize COP, while for systems with high effectiveness components, it will.

The maps show that desiccant systems will require high effectiveness components in order to meet nominal residential loads without excessively large air flow rates. For example, to meet the 2.5 ton Miami design load described below, a ventilation system with high effectiveness components and a regeneration temperature of 100C must be able to supply on the order of 3000 kg/hr (6 air changes/hr) to the living space. These cycles require large mass flow rates to meet typical latent and sensible loads.

As a basis for future work in system simulation design and simulation, a set of baseline parameters were chosen to characterize the cooling load. These parameters were selected to yield a 2.5 ton (8792W) load in Miami at 5% design conditions with the latent load approximately 20% of the sensible load.

The operation of the various systems during the month of July in Miami, Florida, and Fort Worth, Texas were simulated. Several trends indicated by the simulation results are discussed below.

• The relative system performance is affected by component parameters. If low effectiveness components are employed in the system, the Dunkle cycle has the greatest capacity and COP. The recirculation system with low effectiveness components performs better than a ventilation system with equivalent components in the Miami climate, while in the Fort Worth climate the performance of these two cycles is approximately equal. If systems with high effectiveness components are compared, the recirculation cycle performs worst in both climates, while in Miami, the vent system is superior to the Dunkle cycle, and in Fort Worth, the performance of the Dunkle cycle is somewhat better than the ventilation cycle.

• The COP and fraction of the thermal energy supplied by solar energy is sensitive to the effectiveness of the components in all of the cycles. The system capacity is very sensitive to component effectiveness in the Miami climate, but is only modestly affected by similar variations of component parameters in Fort Worth. In both climates, the capacity and COP of the ventilation system are the most sensitive to component effectiveness and regeneration temperature.

The variation with climate and component parameters of system performance for solar-only operation of the various cycles is also pronounced. In this mode of operation, there is no thermal auxiliary. All of the cycles operating in this mode with low effectiveness components have unacceptably low capacity and COP. If high effectiveness components are employed, the capacity and COP of the solar-only cycles approach those of cycles with thermal auxiliary available. For example, over the month of July, a solar-only mode ventilation cycle operating in Miami provided about 80% as much cooling as did a ventilation cycle which allowed auxiliary regeneration of the dehumidifier at 80C, yet performed with the same COP. In Fort Worth, the solar mode ventilation cycle had 93% of the total capacity of a ventilation system with an 80C auxiliary, and the solar mode cycle operated with a higher COP. In this latter case, the solar-only mode COP was ≈ 1.2, while in the Miami example, the COP was ≈ .97.

• The preliminary simulation results indicate that the use of high effectiveness components is essential in the design of a desiccant cooling system for residential use with 7-11 kW (2-3 ton) capacity. Since the recirculation system performs significantly worse than either the ventilation or the Dunkle cycle under these circumstances, this indicates that the development of the recirculation system should not be actively pursued. The superior thermal performance of the Dunkle cycle in hot and dry climates such as Fort Worth may be offset in an econmic sense by the increased initial and operating cost associated with the additional sensible heat exchanger. Thus, these preliminary results suggest that the ventilation cycle may be the preferred system configuration.

• The latent capacity of all cycles is much greater than the sensible capacity. In residential applications, the latent load is a small fraction of the total load, while in commercial or industrial applications, the ratio is greater. These cycles seem more appropriate for commercial or industrial applications than residential.

FUTURE ACTIVITIES

Contract activities. The major activities remaining are:

1. To complete system simulations of the various cycles in a variety of climates for typical building loads.

2. To evaluate these systems for their technical and economic viability.

3. To construct component models and to compare predicted performance to that experimentally determined.

4. To compare predicted system performance to that determined experimentally.

REFERENCES

(1) Nelson, J.S., W.A. Beckman, J.W. Mitchell and D.J. Close, "Simulation of the Performance of Open Cycle Disiccant Systems Using Solar Energy," Solar Energy, 21 , 4, 273-278 (1978).

(2) Banks, P.J., "Coupled Equilibrium Heat and Single Adsorbate Transfer in Fluid Flow Through a Porous Medium - I: Characteristic Potentials and Specific Capacity Ratios," Chem. Engr. Sci., 27, 5, 1143-1155 (1972).

(3) Maclaine-Cross, I.L. and P.J. Banks, "Coupled Heat and Mass Transfer in Regenerators - Prediction Using an Analogy With Heat Transfer," Int. J. Heat Mass Transfer, 15, 6, 1225-1242 (1972).

INTEGRATED SOLAR ZEOLITE COLLECTOR

THE ZEOPOWER COMPANY

DE-AC03-78CS32117

DR. DIMITER TCHERNEV

Begin SEPTEMBER 25, 1978 End SEPTEMBER 24, 1980

OBJECTIVES

The goal of the first year effort is to design, construct and test an integrated 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. The specific objectives are: (1) To develop zeolite collector units that provide maximum heating/cooling capability at minimum cost; (2) To construct and test prototypes of such collectors. The goal of the second year effort is to evaluate the performance of the integrated solar zeolite collector under different climatic conditions in different parts of the USA. The specific objectives are: (3) To construct a sufficient number of operating zeolite collectors that provide maximum heating and cooling capability; (4) To install and instrument such collectors at a number of different geographic sites in the United States and to collect data on their operating performance under a variety of weather conditions.

CONCEPT

Zeolites are ideally suited for solar heating and cooling because they provide the unique combination of two properties. (1) Due to their cage-like structure and consequent high internal surface area, they are capable of adsorbing large quantities of a variety of refrigerant gases, ranging from water vapor and ammonia to carbon oxides and freons in the vicinity of room temperature. For most of these gases the amount sorbed is about the same - 30wt.%. Since the heat of vaporization of water is the largest of any common refrigerant and about ten times larger than that of freons, the zeolite-water vapor combination can provide the most efficient system and requires the smallest quantity of zeolite for its operation. (2) The adsorption process is extremely temperature sensitive, so that the amount of vapor adsorbed decreases drastically when the temperature is increased over a rather narrow range not far above room temperature. In addition, zeolites are chemically inert, abundant, and inexpensive.

The operating principles of heating and cooling systems utilizing the adsorption properties of zeolites are illustrated in Fig. 1. The system takes advantage of the day-to-night variation in solar insolation to achieve gas pumping action without the use of mechanical compressors or other moving parts. The left side of Fig. 1 shows the day cycle, which lasts about 8 hours. During this period the zeolite collector panel, its surface coated with a black absorber, is heated by the sun. The heated zeolite desorbs water vapor that had been adsorbed during the night. The desorbed vapor is then condensed, liberating its latent heat of vaporization, and stored as liquid in the condensate tank. The condenser operating temperature determines the water vapor pressure in the collector-condenser system, which is ∿ 1 psia for a condenser temperature of 100°F. During the night cycle, shown on the right side of Fig. 1, the zeolite cools down and can readsorb water vapor. In cooling systems this vapor is supplied by injecting water from the condensate tank into the evaporator, whose pressure is maintained at ∿ 0.1 psia. At this pressure, evaporation occurs at about 35°F, and the water's latent heat of vaporization is absorbed from the surroundings. When the vapor from the evaporator is readsorbed, low-grade heat is generated and continuously rejected from the zeolite panel to the atmosphere.

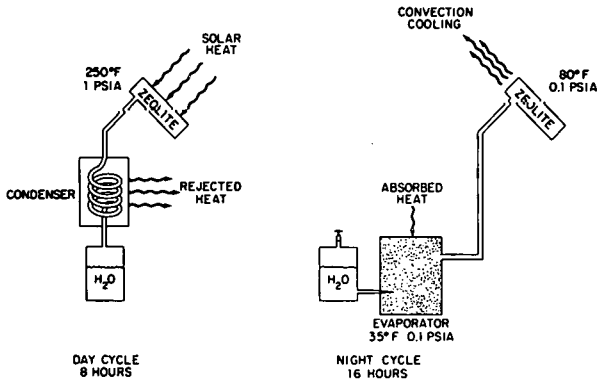


Figure 1. Schematic diagram illustrating day and night cycles for the zeolite-water system.

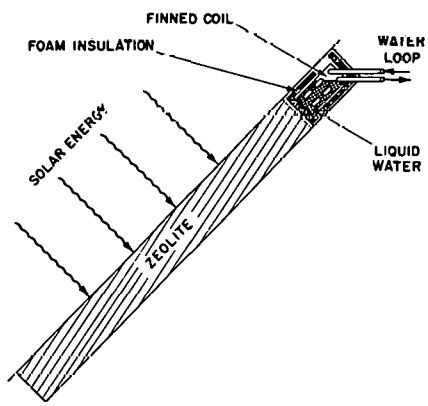
Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting March 1980

Since the operating pressure of the zeolite collector changes from ∿ 1 psia during the day to ∿ 0.1 psia at night, the basic system of Fig. 1 acts as a 1-cycle-per-day compressor with a 10:1 compression ratio. Like a heat pump, it can be used for both heating and cooling. The heat from the condenser can be used to provide domestic hot water throughout the year. During the heating season, this heat is also used to produce hot water for space heating, with excess hot water being stored for use during the night and on cloudy days. During the cooling season, heat from the condenser that is not needed for domestic hot water can be rejected to the atmosphere.

At night, water from the condensate tank is readsorbed by the zeolite panels. During the cooling season, the water is first passed through the evaporator at 35°F, where it is converted into vapor at ∿ 0.1 psia. The heat required for evaporization could be absorbed from an external water loop, producing chilled water for cooling. During the heating season, when chilled water is not desired, liquid water from the condensate tank is pumped directly into the zeolite panel, bypassing the evaporator. In contrast, conventional heat pumps always require the use of an evaporator, whose operation necessitates an external source of heat even during the winter. Throughout the year, readsorption of water by the zeolite during the night results in the production of low grade heat, which is continuously dissipated to the atmosphere.

Since the zeolite system can be used for both heating and cooling, such a system will permit a much shorter period for repayment of capital costs than a single-application system, making the combined system more attractive to potential users.

If the condenser and evaporator of Fig. 1 are combined with the water condensate storage tank and the whole combination is integrated with the zeolite panel, we arrive at the integrated zeolite collector shown in Fig. 2. In this diagram a finned coil heat exchanger is immersed in the water storage tank and the whole flooded type evaporator/condenser is made an integral part of the zeolite collector. In this manner the collector can be assembled, tested, evacuated and sealed in the factory and it will not be necessary to make vacuum-tight joints at the construction site. The only connections needed at the construction site will be the regular plumbing joints to the external liquid loop, which can be made by any person trained in the installation of conventional solar collectors.



INTEGRATED ZEOLITE PANEL
WITH FLOODED TYPE EVAPORATOR-CONDENSER

Figure 2. Schematic diagram of the integrated solar zeolite collector.

While in Fig. 2 the flooded evaporator/condenser is physically located at the top of the collector, it was discovered during the development portion that this unnecessarily reduces the collector aperture and the useful area for the collection of solar energy. Therefore, the flooded evaporator/condenser was relocated behind the zeolite while still being an integral part of the panel and the vacuum tight container.

SUMMARY

During the first year of the contract, two integrated solar zeolite collectors were designed, constructed, instrumented and tested. They performed as expected and the actual experimental data is very close to the computerized prediction of performance done with a simple mathematical model. The total daily cooling efficiency, defined as the total cooling produced by a square foot of collector divided by the total daily solar input, was measured to be over 25%. The total daily heating efficiency was over 35%, in close agreement with published data on other flat plate collectors. During the second year, 10 more integrated collectors were constructed and are presently undergoing vacuum testing.

TECHNICAL ACCOMPLISHMENTS

The design of the integrated solar zeolite collector was accomplished on time. The optimum zeolite loading was found by computer simulation to leave a broad maximum which extends from about 5 lb/ft^2 to about 25 lb/ft^2. A number of experiments confirmed this result experimentally. It was therefore concluded to specify for this design a loading at 8 to 10 lb/ft^2 requiring a panel depth of 2 inches. The finned coils for the heat exchanger were commercially available and most other parts used were readily available. A large number of different zeolites were tested and a chabazite from Bowie, Arizona was found to give the highest potential overall efficiency and was therefore chosen for the job.

Based on the design above, two collector panels of 16.4 ft^2 area each were constructed from copper. They were filled with zeolite at about 9 lb/ft^2 loading and sealed. The finned coil heat exchanger was installed behind the zeolite and thermally insulated from it. The heat exchanger was provided with a manual freeze-protection valve, which permits all liquid water from the heat exchanger to be drained back into the zeolite whenever the temperature of the liquid water drops below 35°F. This valve remains open during the heating season thereby allowing the panel to operate as a heat-pipe.

Both panels were tested under pressure and under vacuum and exhibited no leaks. The collector panels were then painted with flat black paint. The collector frame was constructed from aluminum and two different insulations were used on the two panels: Foam glass and high-temperature isocyanurate trymer. At first the collectors were tested with 3/16" window glass while later low-iron glass was used for the double glazing. Standard gaskets were used for weather sealing.

The panels were instrumented with automatic BTU-meters and high accuracy mercury thermometers for manual readout of input and output temperatures. Pumps, flowmeters and fan-cooled finned coils completed the external fluid loop. Solarimeters and integrating recorders measured the instantaneous and total solar energy incident on the collectors. The collectors were tested on numerous occasions for 3 to 5 days and nights with data taken every 15 minutes. During the rest of the time only total daily input and total daily cooling and heating outputs were recorded.

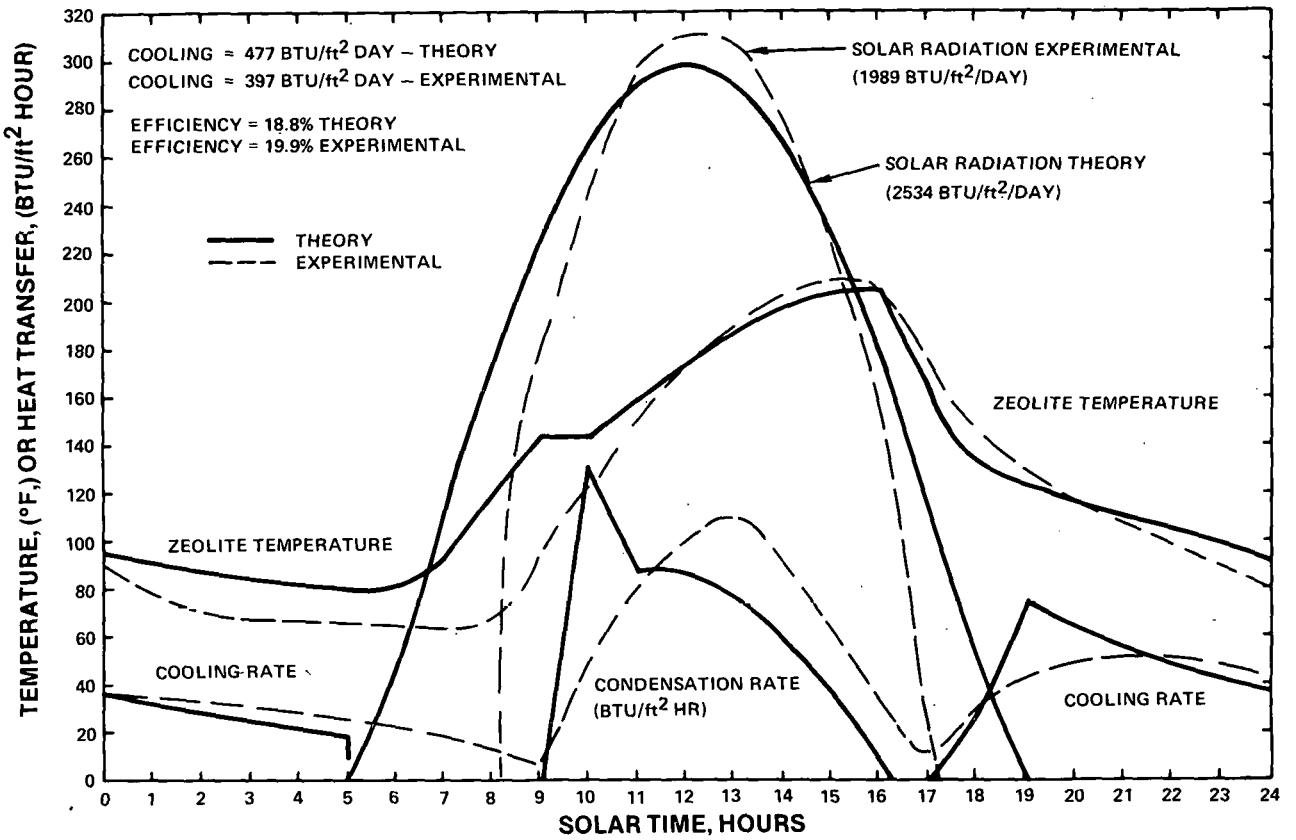


Figure 3. Comparison of the theoretical computer prediction with the actual experimental results.

The detailed experimental data was compared to the computerized prediction done by the University of Arizona and the agreement was better than expected. The computed and measured data is shown in Fig. 3. While the effect of buildings (shadows and reflections) affected the solar input in early morning and late afternoon, the overall fit of theory to experiment is remarkable. Fig. 4 presents the total daily overall cooling efficiency (total daily cooling output divided by total daily solar input) as a function of total daily insolation. On clear sunny days with over 2000 BTU/ft^2 day input the cooling output of the collector is over 500 BTU/ft^2 day, and the efficiency is 25 to

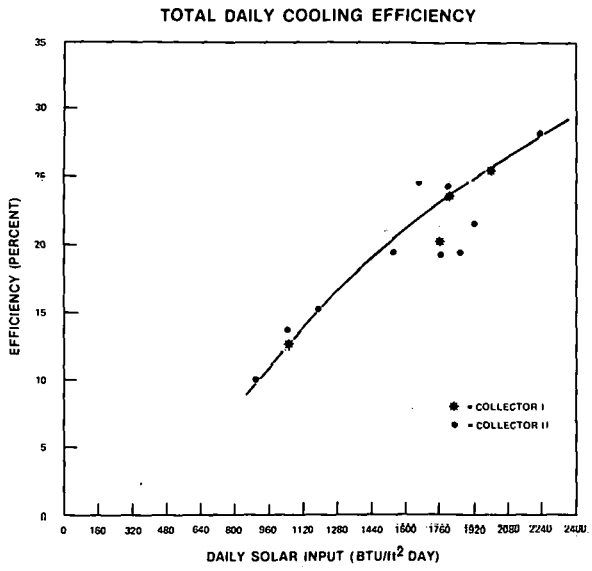


Figure 4. Total daily cooling efficiency as a function of total daily solar input.

28%. Fig. 5 presents the heating efficiency as a function of total daily solar input. In indicates that the collector performs like a regular flat plate collector in the heating mode. In general, we can conclude that on days with less than 400 BTU/ft^2 day solar input, no useful cooling or heating output can be observed while the efficiency increases to 10% at 950 BTU/ft^2 day.

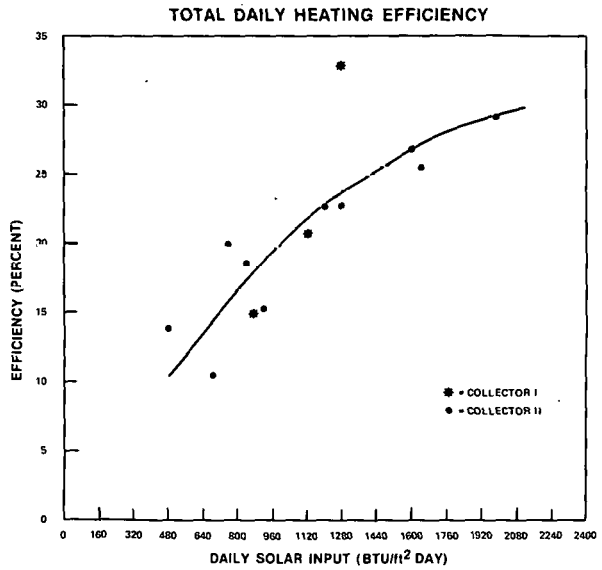


Figure 5. Total daily heating efficiency as a function of total daily solar input.

Construction of 10 more integrated solar zeolite collectors was completed. Five of them have been sealed and are undergoing vacuum testing. Samples from the new shipment of zeolites were compared to samples from previous shipments and their properties appeared identical.

FUTURE ACTIVITIES

Contract activities. After completing the vacuum testing of all collectors, the final assembly with the frames, insulation and glazing will be completed. The collectors will then be tested for performance and efficiency to qualify each panel under actual operating conditions at the plant. At least two collectors each will be installed and instrumented at each of at least four different geographic sites in the USA and data collected on their operating performance under a variety of weather conditions. The data for a period of at least one month will then be evaluated.

Post-contract activities. A residential building of over 2000 ft^2 floor space will be constructed with private funds in the Denver, Colorado area. This structure will be equipped with 600 ft^2 of integrated solar zeolite collectors and the proper system elements, including storage, pumps, controls, etc. This will be the first full-scale test of the operation of a complete system utilizing the zeolite collectors. The results of this test will hopefully accelerate marketing acceptance and commercialization. Further efforts will be directed also at reducing the cost of the collector in mass production by a factor of two or more.

PUBLICATIONS

(1) D.I. Tchernev, In "Natural Zeolites, Occurrence, Properties, Use", Pergamon Press Ltd., 1978, pp. 479-85.

(2) D.I. Tchernev "Solar Refrigeration Utilizing Zeolites." In Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, Vol. 2, pp. 2070-2073.

IV SOLAR HEAT PUMP SYSTEMS

SOLAR ASSISTED HEAT PUMP PROGRAM OVERVIEW AND SUMMARY OF WORK AT BROOKHAVEN NATIONAL LABORATORY*

JOHN W. ANDREWS
SOLAR TECHNOLOGY GROUP
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

PROGRAM OBJECTIVE

The objective of the solar assisted heat pump program is to produce an energy efficient HVAC system utilizing solar energy and electric powered heat pumps which will be optimized according to the following criteria of merit:

1. Cost: When first cost, maintenance cost, and energy cost are considered, the system must be competitive with air-to-air heat pumps.
2. Performance: The system must provide a comfortable living space and adequate hot water.
3. Reliability: The system must have a low failure rate and acceptable system life.
4. Utility impact: Widespread use of the system must not impair, and should improve, the load factor of the electric utility serving the community. This consideration can affect considerably the cost calculations specified in the first criterion.

PROGRAM BACKGROUND

It is possible to view much of the work of the last two years on solar assisted heat pump (SAHP) systems as an attempt to address a single fundamental question: What does one do when the sun isn't shining and storage is depleted? Studies based on the assumption that electric resistance is used as the backup heat source have generally concluded that the SAHP is not a good idea. However, it is now possible to identify four generic paths which have been taken to avoid this difficulty. These are:

1. Bimodal SAHP systems
2. Direct-expansion solar collector/heat pump systems
3. Volume-dominated ground-coupled systems
4. Area-dominated ground-coupled systems

Each type of sysem has its own special characteristics. These are described below.

Bimodal System. I use the term bimodal to describe a system in which the heat pump processes solar-derived heat from storage as long as the storage temperature is above a preset minimum, and some type of backup heat source takes over when the storage temperature falls below this minimum. This is the basic SAHP system, with the proviso that the backup heat source need not be electric resistance, with a coefficient of performance (COP) equal to 1, as has been assumed by most previous studies of SAHP systems.

Recent study[1] has shown that a backup heat source with a COP of 1 (electric resistance) is a poor backup to a SAHP system. It has also been shown that a relationship exists between the COP of the backup and the optimum temperature at which solar energy should be collected and used; this temperature can be controlled by setting the minimum storage temperature below which the system goes to auxiliary. Backup with a COP greater than 1 can be achieved either by using the heat pump to process an alternate source of low-grade heat, or, on a primary energy basis, by using a fossil-fueled burner. The numbers at the left of Fig. 1 show the relationship between optimum storage temperature and backup COP. For this example, which was done for Madison, Wisconsin, an auxiliary COP of 2 results in optimum storage temperatures of from -5 to 11°C in midwinter, the range depending on collector characteristics. If the auxiliary has a COP of 3, the optimum storage temperature is 21 to 39°C. In the first case, a heat pump is needed to process the heat to the load; in the second case the optimums are close enough to what is required for direct heating that is probably pays to go to direct heating. Thus, the optimum system configuration can depend in detail on what is used as backup. A second result seen from Fig. 1 is that as the efficiency of the auxiliary increases, the energy which can be saved by the SAHP system decreases relative to use of the auxiliary only. There are two reasons for this. First, with a more efficient auxiliary there is simply less room for conservation since the auxiliary is now by itself relatively energy efficient. Second, the SAHP, in order to compete with the auxiliary, must operate at higher source temperatures in order to provide COP's that are attractive relative to the auxiliary. Operating at higher source and collection temperatures, the SAHP system will now collect and use less solar energy than before.

Fig. 1 may also be used in a slightly different way. One can compute an economic COP of the auxiliary based on the ratio of the cost of energy provided by the backup to the cost of electricity used to run the SAHP. Then the operating temperatures would be optimized with respect to cost and the vertical axis would represent dollars saved rather than Btu's. In this case off-peak electric resistance supplied at 1/2 the on-peak rate would have a COP of 2. Natural gas costing $4/million Btu (after conversion) would have a COP of 5 relative to electricity costing $20/million Btu. In the first case the SAHP could provide substantial operating cost savings relative to use of the off-peak resistance alone, whereas in the second case the SAHP could not compete.

Bimodel systems can be of interest to electric utilities because they avoid the impact of everyone going to on peak electric resistance at the same time during very cold ambient conditions, as can happen

* Work performed under the auspices of the Systems Development Division, Office of Solar Applications, U. S. Department of Energy.

with air-to-air heat pumps. Of course, bimodal air-to-air heat pump systems with fossil fueled backup are also possible and the bimodal SAHP must compete with them.

Direct-Expansion Solar Collector/Heat Pump. In this type of system, exemplified by the Sigma Research, Inc. system described elsewhere in these proceedings, the collector itself is used as the heat pump evaporator. Refrigerant in the vapor compression loop is passed through finned tubes exposed to the sunlight; absorbed solar energy evaporates the refrigerant directly, without intermediate storage or heat exchangers. These systems are seen as especially suited for areas such as the Pacific Northwest, with high humidity and rainfall, moderate winter temperatures, and relatively low insolation rates.

Volume-Dominated Ground-Coupled SAHP. In this system concept a large volume of water thermally coupled to the ground is used as the storage element in the SAHP system. Examples of this type of system are the Kaman Sciences systems, using large uninsulated buried tanks, which are described elsewhere in these proceedings, and systems which use a swimming pool as the storage element. Advantages of this type of system are:

1. The cost of storage in dollars per gallon is much less than that of conventional insulated storage. In the case of the swimming pool whose cost is justified by its recreational value, the cost of storage is close to zero.

2. The potential for long term storage (weeks to months) of low grade heat exists. Energy collected at times when the solar collectors are underutilized may be saved for times when they are overworked. The extent of this potential is still under investigation.

3. The system can be designed so that no electric resistance backup is required. This has great advantage to the load factor of the electric utility which is coupled to the system, since heat is always supplied by the heat pump at a high COP, meaning that more customers can be served by the same electric power generating capacity.

Area-Dominated Ground Coupled SAHP. In this system a relatively small amount of heat-transfer fluid is spread out to present a large area, relative to its volume, to the ground. The typical configuration is a serpentine coil of buried plastic pipe, although others are possible. Here the ground is used as a source of heat (or heat sink during the cooling season). Such systems have been installed both in the U.S. and Europe and have performed well. Even without solar input such systems have provided seasonal performance factors in the heating mode in the range 2.5 to 3.0. In colder climates the heat-transfer water which is passed through the pipes must contain antifreeze, and during the depths of winter the ground will be frozen. Minimum source temperatures to the heat pump of $\sim -5°C$ are encountered. If the heat pump and ground coil are sized to meet the design heating load at the minimum ground source temperature, high seasonal performance factors are obtained by avoiding the energy-consuming defrost cycle and the need for supplemental resistance heating, both of which seriously degrade the performance of ait-to-air heat pumps.

If it is desired to add solar energy to such a system to improve performance further, it must be done in such a way that the added cost of the solar components is justified by the additional energy saved. Since the nonsolar ground coupled system is already quite efficient, this is a far more severe test than competing with electric resistance. There are, however, at least three different avenues to coupling solar energy to such a system, and there is hope that one or more will prove competitive. These are:

1. Use of an active solar system to provide space heat and hot water, with the ground coupled heat pump used as backup and for cooling. The solar derived heat could be provided directly to the load; it could be processed through the heat pump at lower source temperatures; or it could be used to preheat the incoming room air, with the ground coupled heat pump boosting the temperature of the air stream to the service value.

2. Use of the most inexpensive passive solar concepts in the building design, with the ground-coupled heat pump providing backup heat, hot water, and cooling.

3. Use of photovoltaics to provide electricity to drive the ground-coupled heat pump.

SUMMARY OF WORK AT BNL

Work at BNL has proceeded in three areas related to SAHP systems - heat pump development, ground coupling, and low-cost collectors for use with such systems together with necessary analysis work to enable these components to be combined into optimal systems. The heat pump work will be described by E. A. Kush in the following paper. The remaining work is described below.

Study of Ground Energy Coupling Techniques and Their Effect on Solar Assisted Heat Pump Systems. There are presently nine solar ground coupling heat flow experiments in operation at Brookhaven National Laboratory (BNL), including 5 "fields" of serpentine nominal size 1 1/2 in. polyethylene pipe, and 4 buried tanks made from precast concrete rings. The fields, three of which contain an antifreeze solution, are buried at depths of from 2 ft to 12 ft with lengths from 300 ft to 900 ft. The tank volumes are 2200 and 3600 gallons. The experiments are arranged in a circle and connected to a central hub where heat pumps and hot water heaters are used to remove heat from or add heat to the experiments, as dictated by computer simulations of ground coupled solar heat pump systems. Thus the value of various control strategies including summer storage of solar heat for winter use, space cooling heat rejection to the ground, and summer daytime storage of heat for nocturnal rejection, are experimentally tested.

Heat flow rates, water flow rates, experiment temperatures and ground temperatures are all measured. Soil property experiments have been conducted to determine soil heat capacity, density, moisture content, thermal diffusivity, and (indirectly) thermal conductivity. Additional advanced heat flow and soil property experiments are planned.

One important research effort at BNL has been the development of a validated model of ground coupling. A flexible, 3-dimensional finite element computer program called GROCS has been written to model ground coupling devices. GROCS was subsequently integrated[2] with the solar system simulation program

TRNSYS so that complete ground coupled solar heat pump systems can now be simulated. The GROCS-TRNSYS program with documentation is publicly available. Papers which describe the design, construction and operation of these experiments,[3] computer simulation results,[4] experimental results,[5] and experimental versus computer model comparisons are available.[6]

Heat Pump Impact Upon Solar Collector Design and Cost. This project has involved a program of analysis to determine appropriate cost and performance goals for collectors used in the systems under study at BNL. A companion effort to develop low-cost collectors which, if successful, will meet these cost and performance goals was also initiated.

The flat-plate solar collectors under development depart radically from conventional designs.[7] High-performance thin-film plastics (0.001 to 0.010 in.) are used in the glazing and absorber portions of these collectors in order to reduce cost. These plastic films are attached to a light rigid frame by means of a pressure-sensitive adhesive or other sealer which functions as both fastener and weather seal. The attached films form a set of stressed membranes that contribute to the overall strength of the panel. this monocoque construction provides a complement of physical properties which reduces material requirements and lowers fabrication costs.

In this solar collector design water is used as the liquid heat-exchange medium. It enters the absorber through manifolding integrated into the frame. The water enters the collector from the top manifold and flows between the two absorber films. A layer of aluminum foil laminated to the upper plastic layer in the absorber provides good lateral heat transfer from unwetted to wetted areas. Solar-heated water flows to the bottom of the collector and then out through manifolding similar to that at the top, but with larger porting to ensure adequate drainage.

The solar collectors made with thin plastic films have several advantages over conventional flat-plate collectors:

1. A reduction in material costs;
2. A large reduction in collector weight and bulk, which make installation easier and less expensive;
3. Potentially enhanced performance because of good-to-excellent physical properties such as high glazing transmissivity (to 96%) and good thermal heat transfer;
4. Potentially high reliability and good production yield because the absorber requires essentially no internal pressurization and the construction is uncomplicated;
5. Tolerance of the absorber to freezing temperatures without the addition of antifreeze agents.

The major factor limiting the use of thin plastic films in a solar flat-plate collector is their environmental tolerance. The glazing films must be able to withstand high temperatures, weather, corrosive agents, and ultraviolet light for an extended period. The absorber, which is somewhat protected from weather and ultraviolet, must be resistant to the effects of fluid flow and of long-term exposure to high temperatures under conditions of thermal stagnation.

TECHNICAL ACCOMPLISHMENTS

The following major technical accomplishments can be listed:

1. The ability of the vapor compression cycle to provide the high predicted COP's at high source temperatures has been confirmed. See the following paper by E. A. Kush for details.
2. The ability of a ground-coupled pipe coil to provide acceptable rates of heat transfer has been demonstrated. Rates of $\sim$ 2 Btu/°F-hr-ft pipe are consistent with results elsewhere; the temperature difference is taken between the ground coupling device and the temperature of undisturbed ground at the same depth and time of year (far-field temperature).
3. A low-cost collector using thin-film plastics in both the absorber and glazings has been constructed and tested. Fig. 2 shows predicted performance curves for single and double glazed collectors, together with test data for a double glazed model.
4. A computer model of ground coupled systems (both area-dominated and volume-dominated) has been developed and integrated into TRNSYS.
5. A simplified analysis method for optimizing SAHP systems has been developed. Fig. 1 was one of the results of this analysis.

FUTURE ACTIVITIES

Activities in the following major categories will be pursued:

1. Upgrading of the solar heat pump simulator, continued evaluation of vapor compression cycle performance, and testing of the Northrup prototype heat pump (see dollowing paper for details).
2. Continued collection and analysis of ground coupling data and use of these results to validate and improve ground heat flow models. In conjunction with other projects monitored by BNL, a first generation of design guidelines will be developed.
3. Further development of the low-cost collector and investigation of suitable polymeric materials.
4. Simplified analyses as required to integrate system components and to make possible proper program direction.

PUBLICATIONS/REFERENCES

1. Andrews, J. W., Optimization of Solar Assisted Heat Pump Systems Via a Simple Analytic Approach, Proc. of the Second Annual Systems Simulation Conf., BNL 27316, San Diego, CA, January 23-25,1980.

2. Andrews, J. W., A TRNSYS-Compatible Model of Ground-Coupled Storage, BNL 51061, September 1979.

3. Metz, P. D., Design, Construction and Operation of the Solar Assisted Heat Pump Ground Coupled Storage Experiments at Brookhaven National Laboratory, Proc. of 4th Annual Heat Pump Tech. Conf., BNL 25908, Oklahoma State Univ., Stillwater, OK, April 9-10, 1979.

4. Andrews, J. W. and Metz, P. D., Computer Simulation of Ground Coupled Storage, Proc. of 1979 Int. Solar Energy Soc. Cong., BNL 26216, Atlanta, GA, May 28 - June 1, 1979.

5. Metz, P. D., Experimental Results from the Solar Ground Coupling Research Facility at Brookhaven National Laboratory, Proc. of 1979 Int. Solar Energy Soc. Cong., BNL 26219, Atlanta, GA, May 28 - June 1, 1979.

6. Metz, P. D., Experimental Results from the First Year of Operation of the Solar Ground Coupling Research Facility at Brookhaven National Laboratory, Proc. of 2nd Int. Conf. on Alternative Energy Sources, BNL 27137, Miami Beach, FL, December 10-13, 1979.

7. Andrews, J. W. and Wilhelm, W. G., Thin-Film Flat-Plate Solar Collectors for Low-Cost Manufacture and Installation, BNL 51124, March 1980.

8. Metz, P. D., Kush, E. A., and Andrews, J. W., The Use of Earth Coupling in Solar Assisted Heat Pumps, Proc. of Nordic Symposium on Earth Heat Pump Systems, BNL 26748, Chalmers Univ. of Tech., Göteborg, Sweden, October 15-16, 1979.

9. Andrews. J. W., Heat Pump Impact Upon Solar Collector Design and Cost, Proc. of 1979 Int. Solar Energy Soc. Cong., BNL 26217, Atlanta, GA, May 28 - June 1, 1979.

10. Kush, E. A., The Series Solar Heat Pump and Energy Conservation, Proc. 2nd Int. Conf. on Alternative Energy Sources, BNL 27012, Miami Beach, FL, December 10-13, 1979.

11. Kush, E. A., Performance of Heat Pumps at Elevated Evaporating Temperatures - with Application to Solar Input, Proc. of ASME 1979 Winter Meeting, BNL 26772, December 3-7, 1979.

12. Kush, E. A., Experimental Performance Study of a Series Solar Heat Pump, Proc. of 1979 Int. Solar Energy Soc. Cong., BNL 26220, Atlanta, GA, May 28 - June 1, 1979.

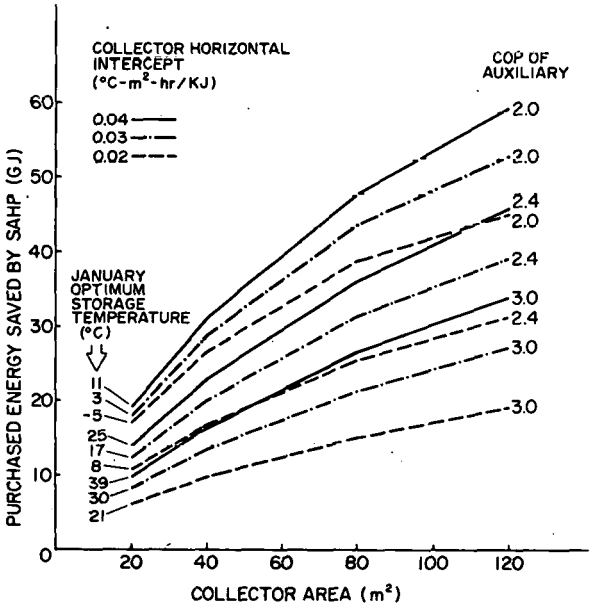


Figure 1. Purchased Energy Saved by SAHP Relative to Use of Auxiliary Only, Without SAHP

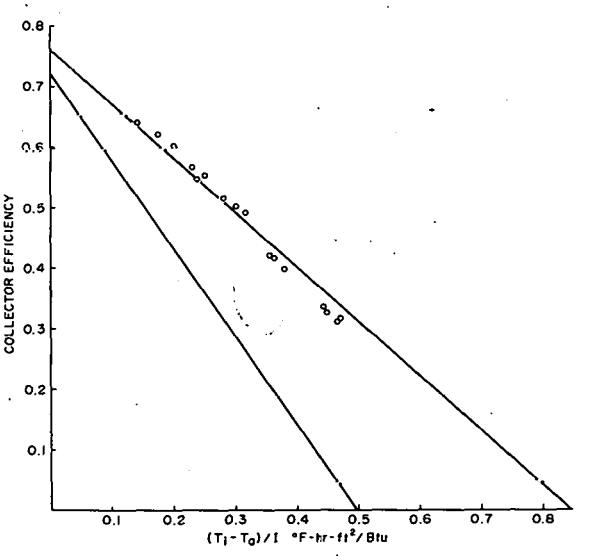


Figure 2. Calculated Efficiency Curves for BNL Low-Cost Collector, Single and Double Glazed, with Test Data Points for Double Glazed Collector

SOLAR ASSISTED HEAT PUMP STUDIES - HEAT PUMP HARDWARE AND EXPERIMENTS, SIMULATIONS, EARTH COUPLING CONTRACTS AND SUPPORTING CONTRACTS*

EDWARD A. KUSH
SOLAR TECHNOLOGY GROUP
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

ABSTRACT

Combining solar energy with an electrically driven heat pump is one of the more attractive techniques for providing space heating that is energy conserving and potentially cost competitive for a large portion of the U.S. A program to identify the most appropriate means of effecting this combination and to develop needed hardware and strategies to expedite implementation of practical solar/heat pump systems is being carried out - with consideration to total heating (DHW included) load, effective space cooling, and load management/utility interaction. Single family residential application is stressed with multi-family and light commercial (to 25 tons) applications also considered. Principal emphasis has been placed on the series type of system because of its energy saving potential (high SPF) and ability to use low temperature, inexpensive collectors. Contractual efforts by manufacturers to develop heat pumps which can realize the thermodynamic potential of high COP provided by solar input while functioning in overall energy effective systems are being supported and some significant progress has been made. In-house experimental studies at BNL have demonstrated the viability of very high COP's and investigated the associated details of the vapor compression cycle.

Because of the need in most heating climates for a back-up heat source caused by periods of solar depletion, methods of alternate heat supply (other than resistance heat) are being studied extensively; and since a heat pump is already present, heat sources processed through it are of most interest - with earth coupling identified as highly promising. A systematic experimental/analytic study of earth-coupling configurations suitable for heat pump supply is being conducted at Brookhaven National Laboratory (BNL), and four contractors around the U.S. are studying specific configurations experimentally. The earth coupling studies address use of the earth heat source for backup per se and also as a means of storing active solar heat for partial retrieval, as well as a sink for reject in cooling season; and buried coils, buried tanks, and wells are included.

This report summarizes the status of the heat pump hardware development contracts, the results to date of the BNL in-house heat pump experiments, the progress of the contractual effort in earth coupling, and the activities of various supporting contracts. An accompanying paper by J. Andrews describes the BNL earth coupling experiments and BNL collector development and gives an overview of the Solar Heat Pump Program.

* Work performed under the auspices of the Systems Development Division, Office of Solar Applications, U. S. Department of Energy.

BACKGROUND

BNL has been support laboratory for solar heat pumps since 1977. Early in the program it was realized that of the two principal methods of combining solar with a heat pump, i.e. (1) the parallel configuration whereby solar heats directly and the heat pump is an independent backup and (2) the series system which supplies solar heat to the evaporator, the series system provides the most potential for energy conservation and for use of low cost collectors while bearing the most needs for development. The parallel system uses direct heating collectors of the generic type already under extensive study elsewhere in the DOE program and privately and a conventional heat pump - thus requiring little special development. The series system, as a long term candidate, required special heat pumps to provide the high COP performance thermodynamically available from solar input, simple low temperature, low-cost collectors and a means of reserve heat supply other than resistive heating (which at a COP of 1 serious degrades seasonal performance). Thus these three aspects were addressed.

Heat Pump. An RFP was issued in 1977 and resultant awards given to Northrup, Lennox and General Electric to develop high COP residential size capacity-controlled heat pumps and to conduct accompanying systems performance and in-depth marketing/commercialization studies; and a Solar Heat Pump Simulator was constructed at BNL to study series heat pump hardware resulting from the contractual projects. In 1979 a Dunham-Bush project to develop a multi-slide helical screw compressor which allows matching of pressure ratio to source and load conditions for high efficiency and can provide two-level source and delivery temperatures was added to address capacities in the 25 ton range (down to 10 tons with adaptations).

Collectors. In-house studies and an investigation of candidate configurations inside and out of the DOE program were undertaken.

Back-Up Heat Source. Earth coupling potential was identified and a systematic series of experiments was constructed at BNL and contractors added to the program to study varied configurations in different climates. Oklahoma State University began coil and well experiments in 1978, the existing Kaman Sciences buried tank project was enlarged and incorporated into the Heat Pump Area in 1979, and an E-Tech project of installing ground coils at six existing solar heat pump houses was also added in 1979. In 1980 FAFCO has been added to study buried plastic heat exchangers. All earth-coupling experiments are aimed at establishling the viability of the ground as short-term back-up and also determining whether summer/fall solar collection can be stored for heating season use; and

most include evaluating cooling season advantages of air-conditioning reject to the earth. An RFP to be issued in Spring 1980 will be directed at further experiments installed in diversified geographic regions and at specific technology studies.

Continuing in-house and contractor computer simulations and analyses have been carried out to assist in evaluation of the many possible solar/heat pump combinations and variations - including how best to use the high COP performance available and the trade-offs between collector area (cost) and back-up device (e.g. ground coil) or no solar at all. A contractual effort by Singer (denoted SAHP-2) has provided assistance in these areas since 1978, conducting comparative studies of solar heat pumps and conventional systems as a function of region and economic parameters.

SUMMARY

In the approximately eighteen months since the last Contractors' Meeting, there has been important progress in each of the three areas, though the advances have proceeded at a moderate rate. The ability of heat pump hardware to achieve high COP's at high source temperatures has been demonstrated by the Northrup project and the BNL laboratory studies. Northrup has developed a packaged water-to-air heat pump employing rolling piston rotary compressors which can obtain COP's on the order of 6 at 90°F source and also perform well at earth coupled or ground water source temperatures; and the manufacturer feels they will be able to bring it to the marketplace quickly. The BNL Laboratory Heat Pump experiments on the simulator have obtained monotonically increasing COP's reaching as high as 9.7 (without parasitics included) at source temperatures from 50 to 120°F and compiled extensive accompanying details of cycle and component performance - with no factors prohibitive to concept viability encountered. Lennox compressor testing has shown good performance of their 2-speed hermetic reciprocating machine at high suction temperatures and is moving ahead with detail design of water source high COP prototypes which will be capable of short term commercialization.

System performance and economic simulations using TRNSYS, proprietary, and specially developed computer codes by contractors (Lennox/Honeywell, G.E., Singer) and in-house have been conducted for a number of climatic regions comparing parallel, series, and dual source solar heat pumps, solar heating alone, conventional heat pumps, and fossil fuel heating. The general results indicate that the three types of solar heat pumps are not now, nor in the immediate future, cost competitive with conventional, but can become so when electric rates reach the order of $0.10/kW-hr, with neither parallel or series systems showing a clear-cut edge toward being competitive first; and all of the solar heat pump systems outperform a straight solar heating system with resistance back-up (while also providing cooling capability). The series system shows the greatest energy conservation in most heating climates and is severely handicapped by use of resistance back-up (used in all the simulations), clearly defining the need for alternate, higher COP, backup. General Electric simulations demonstrated that the performance of parallel systems can be substantially improved by use of the solar as a preheat boost to the high side of the heat pump when storage is in the range above 70°F but below direct heating temperature (approximately 105 to 110°F).

The ground-coupling experiments at Oklahoma State have shown that either a coil or vertical well can supply required short-term back-up without prohibitive cost and those at Kaman Sciences have achieved good performance with buried uninsulated tanks. The other contractors' projects are not yet at a stage of yielding data. The quite encouraging BNL experiments are reported in the J. Andrews paper herein.

TECHNICAL ACCOMPLISHMENTS

Heat Pump Hardware.

Northrup, Inc. Hutchins, Texas - In Phase III, Fabrication and Test, of the three phase SAHP-1 contract.

- o Studied many heat pump configurations in arriving at optimum configuration for a marketable high COP, water source machine.
- o Performed calorimeter tests of a number of compressors at high saturated suction temperatures (to 100°F) and selected Fedders rotary piston type as best performing for their design (gives very good motor unloading).
- o Constructing and testing prototypes of packaged water-to-air high COP heat pump employing two Fedders compressors (for capacity control) and specially selected heat exchangers. Cooling mode uses cold storage and simple mechanical seasonal changeover. Design can also perform well at earth source conditions.
- o Detailed presentation by A. Ecker appears in these proceedings.

Lennox Industries, Inc. Carrollton, Texas - Has proceeded reservedly in the conceptual design phase and received a one year extension to the original 2-year contract and are now in Phase II - Detail Design stage of three phase contract, with major portion of funding remaining.

- o Conducted simulation studies of various solar heat pump systems (with subcontractor Honeywell) and determined that dual-source (air/solar) is most attractive but too complicated for short term development. Proceeding with straightforward series SAHP design.
- o Tested their two-speed compressor at high evaporating temperatures (to 80°F) and found very good COP performance.
- o Conducted marketing analysis to determine most attractive heat pump sizes for commercialization, arriving at 2-1/2 and 3 tons (cooling) as best choices.

Dunham-Bush, Inc. West Hartford, Ct. - In Phase 1 of 25-ton helical screw compressor development for high performance at solar source temperatures.

- o Carrying out thermodynamic and mechanical design of 4-slide, 2-speed helical screw compressor which matches compression ratio to available solar source temperature and load requirement, while providing for multi-level input (e.g. solar plus earth coupling) or output.
- o Tested existing 4-slide prototype to optimize slide positions using upgraded test loop.
- o Carried out preliminary performance estimates, showing high COP potential.
- o Detailed paper by D. Shaw appears in these proceedings.

BNL In-House Studies

- o Completed construction of residential size solar heat pump simulator in water-to-water configuration

with high accuracy instrumentation and control. Water-to-air simulating mode under construction.

- o Designed and constructed baseline Laboratory Model Heat Pump using off-the-shelf components and carried out comprehensive test program to determine performance at high evaporating temperatures typical of solar source (50 to 100°F). An open-type reciprocating compressor driven by a 2-speed (4/8 pole) motor and a 2-speed Lennox hermetic (2/4 pole) reciprocating compressor have each been used in the heat pump.
- o Showed that by using capacity control, suitably large heat exchangers, and proper choice of expansion device, that monotonically increasing heating COP's following the Carnot trend can be obtained with increasing source temperature in the range from 50 to 115°F. A maximum COP of 9.7 was obtained (without parasitics), and representative results are shown in Figure 1, with nominal parasitics accounted for as noted.
- o Compiled data on the characteristics of the vapor cycle at high evaporating temperatures for a range of parameters. Also tested at typical earth coupled heating and cooling conditions.
- o Disseminated results via technical publications and presentations.
- o Carried out analyses to determine best ways to utilize series solar input in a practical energy conserving system.

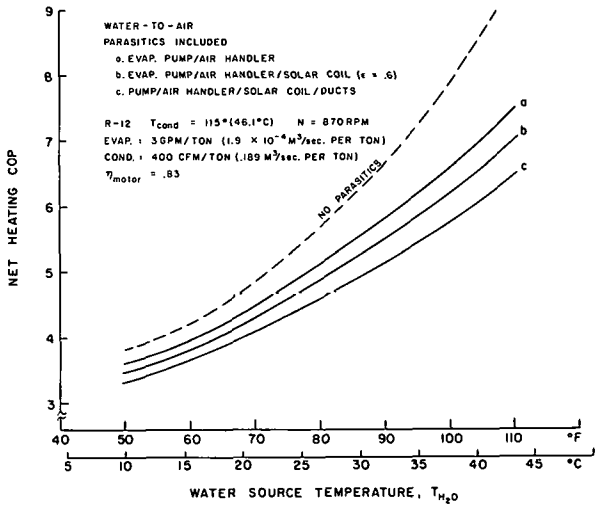


Figure 1 Representative Laboratory Test Data Adjusted for Nominal Parasitics

Earth-Coupling Contracts.

Oklahoma State University - Carrying out a set of instrumented field experiments to evaluate horizontal earth coils and vertical coil/wells for application to SAHP systems. August 1978 - July 1980.

- o Constructed and tested a 1000 ft horizontal earth coil of 4 inch PVC pipe at 4 ft depth, compiling data for operation connected to a heat pump for both heating and cooling seasons.
- o Established that the earth can supply sufficient heat for approximately a 2-1/2 ton load with this coil and that solar input to the earth can be effective for short term performance but not carried over from summer to heating season with this configuration and local soil conditions. Found cycling and coil thermal history affect heat transfer rates.
- o Constructed and operated a 240 ft deep vertical coil (well) which is a sealed 5 inch PVC pipe with heat pump water discharged at either top or bottom and established guidelines of required well depth for heating and cooling under local conditions. Found that well temperatures rise and fall more rapidly than for the coil and the well has greater temperature recovery potential, while both well and coil (in these sizes) obtain approximately the same U-value.
- o A detailed presentation will be given by J. Bose, in these proceedings.

Kaman Sciences Corporation (KSC) Colorado Springs, CO - Has studied buried, uninsulated tanks used with a SAHP in the Phoenix House in Colorado Springs since 1974 and this project was brought into the Solar Heat Pump Program in June, 1979 (through June 1981) and only developments since then, which include installations at two other locations, are included here.

- o Upgraded the Phoenix House with a new water-to-air heat pump and installed additional instrumentation to detail the earth properties and thermal behavior. No backup heating required in December.
- o Constructed ground coupled SAHP at industrial building in Middletown, Ohio with buried large tri-tank stratified storage and large single tank storage. System has both standard double glazed and low cost plastic collectors.
- o Constructed ground coupled SAHP at office building in Albuquerque, New Mexico with buried tri-tanks and buried plastic HX plates and low cost plastic collectors.
- o Found the low cost plastic collectors performed better in the SAHP system than double glazed collectors.
- o Formulated plans for commercializing SAHP systems.
- o Detailed presentation by D. Jardine in these proceedings.

E-Tech - Atlanta, Georgia - April 1979 to September 1980.

- o Retrofitted ground coils in total of 6 existing solar heat pump houses in Atlanta (2), Baltimore (2), Tallahassee and Charleston. Instrumentation included for heat flows and earth temperatures. DHW included.
- o In cities with two installations, two earth-coupled configurations are being compared - (A) earth coil and solar tank, (B) earth coil, no tank, solar heat to ground, each pair of houses being nearly identical. Third house in Atlanta used for comparison has air coil (dual source) instead of earth coil.

FAFCO Incorporated - Menlo Park, California

- o Beginning one year contract to study the performance of extruded polymer ground coupled heat exchangers. Project also includes a technical and marketing assessment of the use of plastic solar collectors with SAHP's.

Supporting Contracts.

Singer, Corporate R&D Laboratory, Fairfield, NJ - Has just completed a two-year contract (SAHP-2) to analyze the market potential of solar heat pump systems versus conventional heating systems and direct solar for the various climatic regions of the U.S.

- o Carried out technical and economic comparison of parallel, series, and dual source solar heat pump, and electrical resistance heating systems using regionally optimized versions of each system, carefully selected economic parameters, and a life cycle costing (LCC) methodology.

- Found that on LCC basis, solar heat pump systems are not now cost competitive with conventional air/air heat pumps or fossil fuel, but become so at an equivalent electric rate of approximately $0.13/kW-hr (1979) dollars for New York City. At this point the series system becomes most economical (even with resistance back-up) if credited with low cost collectors, the crossover point coming sooner if a high performance heat pump is used. Direct solar has higher LCC than any heat pump (0.36/kW-hr crossover with stand-alone heat pump). Results qualitatively similar for other locations with significant heating.
- Developed computer code based on analytical expressions (rather than numerical simulations) and simplified weather which performs rapid system comparisons with reasonable annual agreement with TRNSYS. Code optimizes system on marginal basis then evaluates LCC.

General Electric - Corporate Research Center, Schenectady, New York - Performed Phase I Conceptual Design portion of SAHP-1, then withdrew from hardware phases because of decision that SAHP was not appropriate product for G.E. at present.

- Compiled two six-month reports with extensive performance and cost analysis of solar and conventional heat pumps.
- Showed that theoretically the performance of a parallel system can be substantially improved by using solar heat as preheat to the heat pump when storage is between 70 and 110°F, (can run on low speed more often).

Sigma Research Inc., Richland, Wash. - Studying the use of unglazed solar collectors as the evaporator of a series heat pump with particular application to cloudy climates such as the Pacific Northwest.

SEEC, Ft. Collins, CO - Instrumenting an existing series heat pump demonstration project in Denver, Colorado to assess performance.

SAI/Albuquerque, NM - Beginning a small support effort to BNL to survey existing earth-coupling heat transfer computer codes and their applicability to solar heat pumps and to identify low cost collector installations suitable for study.

FUTURE ACTIVITIES

- Finish development of high performance heat pump prototypes and evaluate them through manufacturer testing and BNL simulator tests
- Continue current earth-coupling experiments, consolidate and evaluate data, and prepare interim design manual for engineering field tests. Expand data base with RFP.
- Plan experimental installations of complete SAHP systems with high performance heat pumps, low cost collectors, and earth-coupling or other suitable back-up. Include provisions for extension to engineering field tests.
- Continue evaluation of options for most appropriate regional designs with accompanying commercialization studies.
- Further evaluate dual source concepts.

PUBLICATIONS - [Listed in order of contracts as presented in text.]

1. Ecker, A. (Northrup, Inc.), "Optimal Refrigerant Compressor For Low Pressure Ratio Applications," Proc. of ASHRAE Conv., Los Angeles, February 1980.

2. Lennox Industries Inc., "Development of Marketable Solar Assisted Heat Pumps" (a) First 6-month Progress Report, June 1979.* (b) Second 6-month Progress Report, February 1980.*

3. Kush, E., "Experimental Study of a Series Solar Heat Pump," Proc. of 4th Annual Heat Pump Conf., Oklahoma State Univ., Stillwater, OK, April 1979. Also Proc. of ISES 1979 Congress, Atlanta, May 1979.

4. Kush, E., "Performance of Heat Pumps at Elevated Evaporating Temperatures-With Application to Solar Input," Proc. of ASME 1979 Winter Annual Meeting, Paper No. 79-WA/Sol-19, New York, NY, December 1979.

5. Metz, P. D., Kush, E. A., and Andrews, J. W., "The Use of Earth-Coupling in Solar Assisted Heat Pumps," Proc. of Nordic Symposium on Earth Heat Pump Systems, Göteborg, Sweden, October 1979.

6. Bose, J. W., Ledbetter, C. W., and Partin, J. R., "Experimental Results of a Low-Cost Solar-Assisted Heat Pump System Using Earth Coil and Geothermal Well Storage," Proc. of 4th Annual Heat Pump Conf., Oklahoma State Univ., Stillwater, OK, April 1979.

7. Bose, J. E., Ledbetter, C. W., and Partin, J. R., "Field Test Results of Solar-Assisted Heat Pumps Using Earth Coil Coupling and Storage," Proc. of the Nordic Symposium on Earth Heat Pumps Systems, Göteborg, Sweden, October 15-16, 1979.

8. Bose, J. E., "Design and Field Testing of Solar Assisted Earth Coils," Oklahoma State Univ. Annual Report, August 1, 1978 - July 31, 1979.*

9. Jardine, D. M., and Jones, D. W., "Phoenix/City of Colorado Springs Solar Assisted Heat Pump Project (Phase II)," Kaman Sciences Corp., Final Report, April 1979.

10. Estes, R. C. and Kahan, W. (Singer), "Optimization and Comparison Strategies for Solar Energy Systems," Proc. of ASME 1979 Winter Annual Meeting, Paper No. 79-WA/Sol-26, New York, NY, December 1979.

11. Kahan, W., "Analytical Selection of Marketable SAHP Systems," Singer Final Report, SAN/1467-1 (to be published).

12. General Electric Company, Corporate Research and Development Center, "Solar Assisted Heat Pumps for the Heating and Cooling of Buildings," (a) Six-month Technical Report, November 1978, SRD-78-175, (b) Six-month Technical Report, May 1979, SRD-79-042; H. Jaster, Principal Investigator.

13. Bessler, W. F., and Huang, B. C., (GE) "Performance of SAHP Heating Systems for Residential Applications," Proc. of Joint ASME/AIChE 18th National Heat Transfer Conf., San Diego, CA, August 1979.

*Currently available on a limited basis through BNL Solar Technology Group, Building 701, Upton, NY 11973.

MULTIPLE SLIDE SCREW COMPRESSOR

DUNHAM-BUSH, INC.

DE-AC03-79CS30035

DAVID N. SHAW, P.E.

BEGIN OCTOBER 1979; END MARCH 1982

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 ratio as high as 6.5. The compressor must have the capability to efficiently and continuously adjust to the widely varying inlet flow requirements as dictated by the operating conditions of the Series Solar Heat Pump System.

Further to the above, the capacity of the developed compressor will be nominally 25 tons of heating when utilizing Refrigerant 22. The compressor shall be the helical screw type with multiple slides in order to accomplish the stated objective.

CONCEPT OR BACKGROUND

Figs. 1, 2 and 3 should be studied when considering the compression concepts developed herein. Following is a listing of the basic concepts involved:

- Positive displacement compression, only two rotating parts.
- No intake or discharge valves.
- Flow and head independently variable.
- Allows near-ideal liquid expansion process.
- Allows bi-level intake and bi-level discharge.
- Highest efficiency and system flexibility.
- Simultaneous earth and solar coupling allowable.
- Two condensing levels allowable simultaneously.
- 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.

The volume ratio slide as shown on the top of the diagram can be moved axially along its axis as can be imagined from the diagram. If the volume ratio slide is moved to the left, further compression of the pumped gas will take place. If the volume ratio slide is moved to the right, less compression of the pumped gas will take place.

The ejection slide as shown carries a port which is exposed to the interlobe area of the right hand rotor as shown. This port allows gas to be tapped at any point along the compression process. There are various advantages associated with bi-level discharge.

A phantom injection slide is shown receiving moderate pressure intake vapor. After the low pressure intake process has been completed and the gas compression has started as the rotors rotate, the interlobe volume with initiated compression is exposed to the port in the injection slide. This injection slide can be moved along its axis as indicated and therefore allows the moderate-pressure intake vapor to be delivered at the ideal point during the compression process in order to maximize compression efficiency.

- Explanation of Fig. 2. Fig. 2 demonstrates one of the advantages of the injection slide. 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 slide, 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. Obviously, 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. Obviously, this increase in refrigeration effect

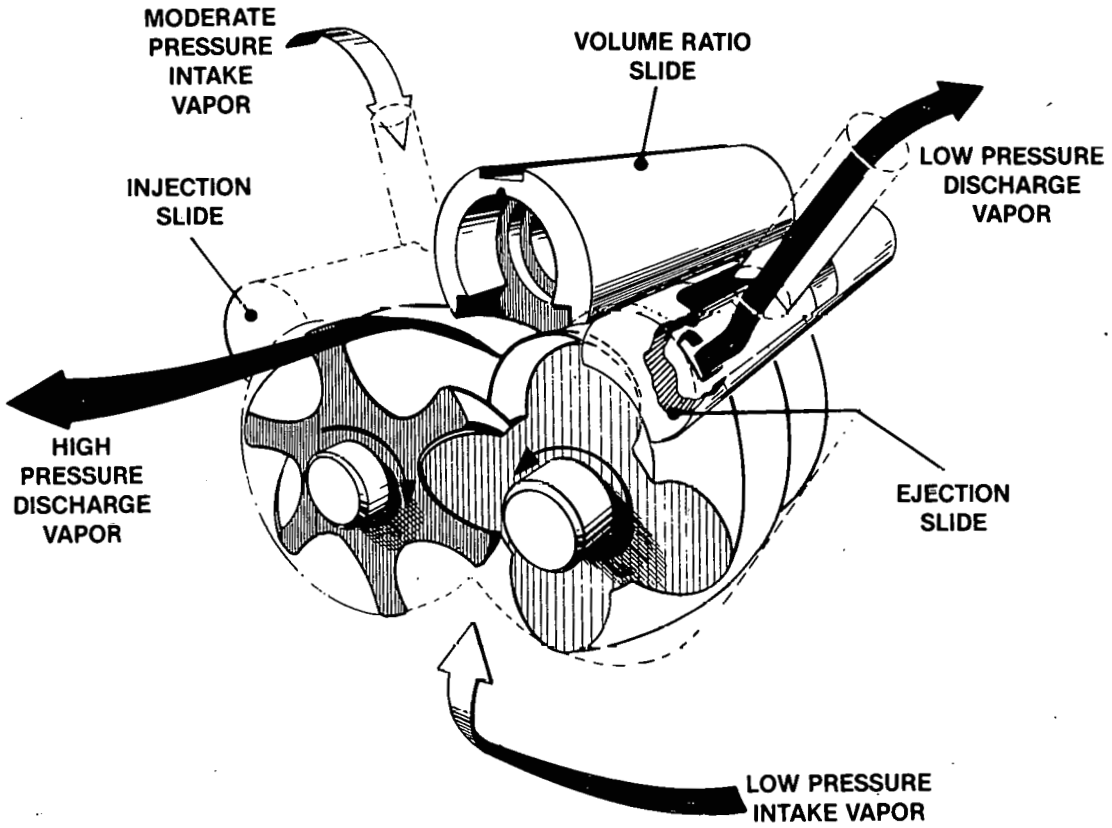


FIGURE 1. MULTIPLE SLIDE SCREW COMPRESSOR - ROTORS & SLIDES

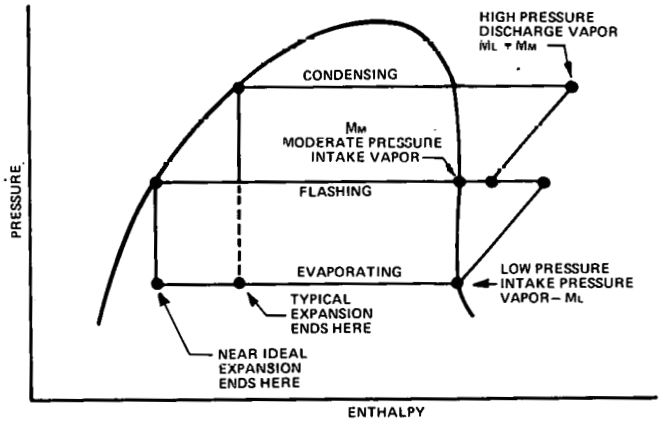


FIGURE 2. NEAR IDEAL LIQUID EXPANSION PROCESS

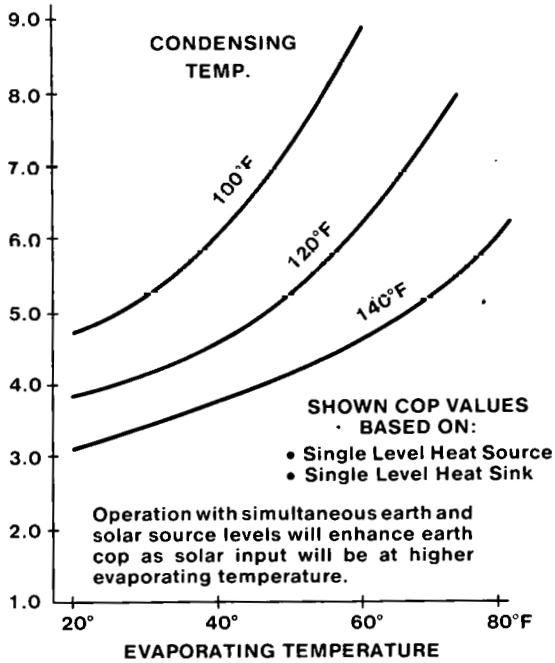


FIGURE 3. EXPECTED HEATING COP

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 only one of the thermodynamic cycle advantages that can be enjoyed by the utilization of the multi-slide screw compressor.

The multi-slide screw compressor is a fully modulating device capable of operating at any inlet flow 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 both 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 demands 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 over-pulling them. The potential capacity of such a compressor is significantly enhanced through utilization of the basic compressor displacement twice.

Various advantages can also be identified through the use of the intermediate ejection process. As an example, two levels of heating could be carried out simultaneously. Hot water heating could be accomplished with the high pressure discharge, whereas warm air heating could be accomplished with the low pressure discharge. This obviously could improve the effectiveness of the associated heat exchangers as they could be used more of the time thus reducing the necessary heat exchange per unit of time.

Fundamentally, the multiple-slide screw compressor is potentially the best compressor for Series Solar Systems in that it allows the highest possible compression efficiencies at all operating conditions, allows a near-ideal liquid expansion process, and allows bi-level intake and bi-level discharge. Some or all of the features can be utilized, whatever is shown to be the best compromise for given situations.

SUMMARY

Significant effort in the performance of this contract comenced during January of 1980. However, it should be pointed out that Dunham-Bush had built a four slide multiple-slide screw compressor research machine at Dunham-Bush expense in order to investigate the variables affecting the design of a more production-oriented machine. Intense testing of this research machine has been under way for the past two months.

Significant accomplishments since inception of the project are as follows:

- A theoretical data base is now well under way.

- The selection of variables and ranges of those variables to be investigated has been completed.

- Significant progress has been made on the research machine pertaining to optimized vapor injection testing.

- Various modifications necessary on the research machine and its associated test loop have been completed.

TECHNICAL ACCOMPLISHMENTS

A necessary theoretical data base is now well under way. This theoretical data base will allow actual machine performance to be properly judged under all necessary operating conditions including bi-level intake, bi-level discharge, and the near-ideal liquid expansion process. An entire paper could be written pertaining to this theoretical data base itself.

- The identification of all variables related to compressor performance has been accomplished. The ranges through which these variables will be investigated have also been identified and charted.

- Significant progress has been made pertaining to optimized vapor injection. As an example, if a cycle is idealized pertaining to the near-ideal liquid expansion process, and the moderate pressure intake vapor mass identified as a ratio of the low pressure intake vapor mass (see Fig. 2), the testing of the research machine has now confirmed that the secondary vapor injection capability of the compressor significantly exceeds that which is necessary for the near-ideal liquid expansion process alone. What this means is that the compressor is capable of dealing with the near-ideal liquid expansion process simultaneously as it deals with a significant level of moderate pressure intake vapor from a secondary evaporator as well. This, of course, is all in addition to the low pressure intake vapor being generated by the low pressure evaporator. This was a significant question as we are obviously dealing with a dynamic situation with limited flow passages, high surface speeds, etc. In effect, the vapor injection slide is performing very well and

by all indications appears to be an extremely desirable feature.

• Various cycle modifications have been made pertaining to the test loop for the research machine. The test loop is now capable of dealing with the higher evaporating conditions associated with Series Solar Heat Pump Systems. The research compressor has been equipped with a two-speed motor as well. It is expected that results from the modified compressor and test loop will be available during the month of April, 1980.

• The design of the 25 ton compressor has been started. Work is now commencing in the various areas not affected by information that is still required to be obtained from the research machine. However, it is expected that data obtained from the research machine will time phase properly with the design of the 25 ton compressor in order that all variables indeed will be optimized and the best possible compressor developed.

• The expected heating COP based on a single level heat source and a single level heat sink is included as Fig. 3 of this report. It is believed that a study of this curve will help indicate the potential of the multiple-slide screw compressor in Series Solar (SAHP) applications.

FUTURE ACTIVITIES

Contract activities. The major tasks to be completed on this contract are as follows:

• Testing of first generation prototype -- results from this research machine are expected to greatly influence the design of the 25 ton multiple-slide compressor.

• Performance estimating of the second generation prototype -- this is the 25 ton compressor and as the estimated performance is developed based on input from the first generation prototype, the delivered data base will be enhanced.

• Design of the second generation prototype -- this task, of course, will result in the completed design of the 25 ton machine.

• Procurement/building of second generation prototype -- this task will result in a second generation 25 ton prototype ready for test.

• Testing of the second generation prototype -- it is expected that this task will bear out the estimated performance predictions pertaining to this 25 ton compressor.

Post-contract 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 Heat Pump Systems.

GROUND COUPLED SOLAR ASSISTED HEAT PUMP FIELD PERFORMANCE

Sam V. Shelton

E-Tech, Inc.
3570 American Drive
Atlanta, Georgia 30341

OBJECTIVE

This program is designed to collect field data on residential ground coupled solar assisted heat pump systems in four different geographical areas. Two concepts are being evaluated using low temperature solar collectors, an earth heat exchanger, and a water to air heat pump.

CONCEPT

The first concept (an A House) utilizes a water source heat pump with a solar heated storage tank and a ground coil as parallel heat sources. The solar heat is always added to the storage tank. If the tank is above 45°F, the water source heat pump draws heat from the tank. If not, water is circulated through the earth heat exchanger and then to the water source heat pump. The second concept (a B House) utilizes the solar heat in series with the earth heat exchanger, eliminating the need for a storage tank. The water source heat pump always draws heat directly from the ground. In this way, the solar heat replaces the heat extracted from the ground in order to maintain its temperature.

Both systems operate identically for air conditioning. Heat is added to the water at the condenser of the water source heat pump. This warm water is circulated through the earth heat exchanger to transfer heat to the ground.

The earth heat exchanger is a 1-1/2 inch plastic pipe (approximately 1000 ft. for a 3-1/2 ton system) buried four feet deep in the ground through which water is circulated. When the water that is circulated is colder than the ground, heat is transferred to the water. In the summer, when it is warmer, heat is transferred from the water.

Seven systems in 4 geographical regions (listed below) are being studied. One of them has an outdoor water to air heat exchanger in place of the earth heat exchanger and is used as a control house. These are listed below.

Atlanta, GA - 1 A House, 1 B House, Control House

Baltimore, MD - 1 A House, 1 B House

Harleyville, SC - 1 A House

Tallahassee, FL - 1 A House

Each system is instrumented with 5 BTU meters, 2 kwhr meters, 3 hour meters, 1 pyranometer and integrator, and a 12 channel digital temperature recorder.

The purpose of each is as follows:

BTU Meters

Solar Heat Input - On the HXP to measure the total solar heat input.

Heat Pump Heating - On the Carrier Heat Pump to measure the total heat removed from the water during the heating season.

Heat Pump Cooling - On the Carrier Heat Pump to measure the total heat added to the water during the cooling season.

Ground Coil Heating - (A House only) On the ground coil to measure the total heat removed from the ground during the heating season.

Domestic Water Heating - On the hot water supply to measure the heat added for domestic hot water use.

Kwhr Meters

These measure the total electricity consumption of the Carrier Heat Pump (labeled Heat Pump kwhrs) and the Water Heating Heat Pump (labeled domestic water heating kwhrs.)

Hour Meters

- Installed on the emergency heat to measure the total number of hours that the resistance heater is used.

- Installed on the collector relay to determine the total hours the collectors run.

- Installed on the Carrier unit to determine how long it runs.

Temperature Recorder

This device records the temperature at various points throughout the system at hourly time intervals. The following tem-

peratures are being monitored:

1. House temperature
2. Outdoor temperature
3. Main tank (A House Only)
4. Water entering ground coil
5. Water leaving ground coil
6. Ground coil pipe temperature at 25% of its length
7. Ground coil pipe temperature at 50% of its length
8. Ground coil pipe temperature at 75% of its length
9. 1 foot above the ground coil pipe
10. 1 foot below the ground coil pipe
11. Between the pipes at close spacing
12. Undisturbed temperature of the ground at same depth as the ground coil.

Pyranometer and Integrator

This device measures the total solar heat that is incident on the collectors in BTU's/square foot.

SUMMARY

All systems were instrumented and operating as of 1 February 1980. Operating data is presently being collected and will be analyzed to determine the solar heat collected, solar heat utilized, earth heat extracted and added, and heat pump heating and cooling coefficient of performance. Earth heat exchanger temperatures relative to undisturbed temperatures will allow computation of its performance.

The results will yield performance data on ground coupled solar assisted heat pump systems operating in both the parallel and series modes over a geographical range from Baltimore, Maryland to Tallahassee, Florida. This information will be used in optimizing the design of ground coupled solar assisted heat pump systems. The cost effectiveness of such optimum systems against alternative systems can then be evaluated.

PHOENIX/CITY OF COLORADO SPRINGS SOLAR ASSISTED HEAT PUMP PROJECT - PHASE III

KAMAN SCIENCES CORPORATION

DE-AC03-79-C5-34511

D. M. JARDINE, P.E.

JUNE 1979 TO JUNE 1981

OBJECTIVE

The objective of this project is to stimulate the development of a preferred ground coupled solar assisted heat pump system through improving the performance and design data base for this system by conducting Engineering Field Tests for the system on different types of building applications in different climatic regions of the United States.

CONCEPT OR BACKGROUND

The technical feasibility of employing ground coupled solar heat pump with massive thermal capacitance steel ground coupling devices was developed and proven in the first two phases of this project which started in 1974.

Figure I gives an overview of Phase III project activities. The Engineering Field Tests on this project are concerned with proving the operational success of low cost system components in the system in a broad range of building and climatic applications which are:

- Residential buildings, high ratio of annual heating to annual cooling loads (Colorado Springs, Colorado system),
- Commercial buildings, high ratio of annual cooling to annual heating load (Albuquerque, New Mexico system),
- Industrial buildings, low ratio of annual heating to annual cooling load (Middletown, Ohio system).

There are four important areas of concerted effort on this project which are as follows:

- Water source heat pumps utilized for space and water heating, and space cooling.
- Three types of ground coupled thermal storage equipment consisting of enhanced stratification unit, no stratification unit, and no stratification direct bury plastic plates unit which act as annual infinite heat sinks for the heat pump condenser and the solar collectors, and an annual infinite heat source for the heat pump evaporator with storage temperatures maintained in an optimal temperature band for the heat pump,
- Proving the suitability of low cost - low temperature plastic collectors for use with the Ground Coupled Solar Heat Pump.
- Instrumentation packages which produce data showing system performance and energy balances, and electric utility interface data suitable for supporting electric power cost of service studies regarding the system for rate hearings by regulatory bodies to provide class of service rates and tariffs for these systems in commercial use within the spirit and intent of the Public Utility Regulatory Policies Act (PURPA) of 1978 (PL95-617).

Special instrumentation has been installed in the ground coupled storage unit to obtain data relating to the following:

- Thermal gradient activities in the ground around the ground coupled storage unit during the annual cycle of storage temperatures and heat injection and withdrawal from the ground,
- Moisture migration in the ground resulting from annual ground coupled storage temperature variations,
- Further confirmation of previously modeled and empirical U factors (Btu/HR-FT^2-°F) for use in sizing the storage unit and selecting proper heat pump capacities to handle connected peak loads during minimum and maximum storage temperatures,
- Optimization of conductivity enhancement in the protective envelope for the Ground Coupled Storage Unit.

SUMMARY

All three test sites had operational systems at the end of December 1979, and a sufficient operational history and reliable data flow was produced on two of the systems to show the following significant accomplishments:

- Low Cost Solar Collectors:

At the Ohio test site, the low cost plastic collectors have demonstrated their compatibility with the ground coupled thermal storage units by producing significantly more thermal energy per unit of collector area than the double glazed metal absorber plate collectors under equal operating conditions during December, 1979.

- System Performance:

At the Colorado Springs test site, the system demonstrated the ability to handle all the space and water heating without any space heating backup energy requirements for space heating which shows the annual characteristic of the ground coupled storage unit. Here are the performance factors of this system for the month of December 1979:

- Heat Pump COP (space and water heating) = 3.59
- Total System COP = 2.78
- Collector Efficiency = 37%
- Peak System Electric Demand = 5.8 KW
- Load Factor for Electric Utility = 0.58

TECHNICAL ACCOMPLISHMENTS

- Low Cost Solar Collectors:

The low cost plastic collectors averaged an average monthly outlet temperature minus inlet temperature value of 7°F higher than the double glazed metal absorber plate collectors. Both collectors are of equal area, operated the same duration during the month with equal flow rates, and served ground coupled storage units of equal ground contact areas with equal heat pump evaporator loads. The low cost collector unit raised its thermal storage units 4°F higher than the double glazed metal absorber plate collector raised its storage unit during the month of December 1979. Both collector units started up on December 1st against ground temperature storage units. All instrumentation data recorders were not in service in December so energy balance data is not available.

- System Performance:

Here is the energy balance data for the system operation at the Colorado Springs test site:

Energy Parameters	KWH
Solar Energy on Collectors	10,637
Thermal Energy from Collectors	3,936
Stored Heat to Heat Pump Evaporator	4,511
Thermal Energy Withdrawn from Annual Storage	575
Space Heating Load Served	6,390
Hot Water Load Served	352
Total System Thermal Load	6,742
Compressor and Fan Power Used	1,879
I^2R Hot Water Auxiliary Power	37
Parasitic Power (Pumps and Controls)	509
Auxiliary Space Heating (I^2R) Used	-0-
Total Power Used	2,425

- Ground Thermal Gradients:

Sufficient data was collected from ground instrumentation to show the value of using the proper thickness of the noncohesive envelope around the ground coupled storage device at the Colorado Springs test site. Further data is being evaluated to provide an in-depth report on this important area.

FUTURE ACTIVITIES

Contract Activities. The major activities left on Phase III of this project are:

- Performance and Life Cycle Cost Evaluation of the Three Systems and Applications,
- Final Design Formulations for Market Field Test Systems,
- Reporting.

Post-Phase III Contract Activities. Confidence in the commercial potential for this system is now very high due to the positive experience gained installing the systems and early system operations in the engineering field tests. Plans for Market Field Tests for this system are being made now. The Market Field Tests are the last step prior to full scale commercialization. Here are the objectives of the planning steps for the Market Field Tests:

- Market Field Sites:

Define and arrange for a test site owner's participation in the Market Field Testing (Phase IV). The test site owner should own and operate standardized facilities on a nationwide basis with a high degree of public visibility and access, and should have the interest and capability to move forward as a member of the commercialization team.

- Definition of Geographic Commercialization Areas:

The criteria for these areas are high heating energy costs and/or visible future shortages, a suitable mix for new and retrofit applications, and utility interest. Assessment of market potential will be made in those areas.

- Marketing and Supply Chain:

Formalize marketing and supply chain approaches and logistics, establish warranty conditions, scope direct capital requirements and formalize sources.

- Manuals:

Develop installation, operation, and maintenance manuals and develop dealer, installer, and maintainer training programs.

- Public Information:

Develop a public information program (advertising campaign) which will be used in the market test areas to encourage customer interest and order subscriptions.

- Marketing Vehicle:

Develop marketing vehicles in the form of marketing plans for utility ownership, leasing, and private ownership of the system for single and multi-family, small and large commercial, institutional, industrial, and other applications in both new buildings and retrofit situations.

PUBLICATIONS

Jardine, D. M. , Jones, D. W., "Phoenix City of Colorado Springs Solar Assisted Heat Pump Project (Phase II) Final Report. April 1979.

Jardine, D. M., Jones, D. W., "Phoenix House: Solar Assisted Heat Pump System Evaluation", Final Report, EPRI ER-712, March 1978.

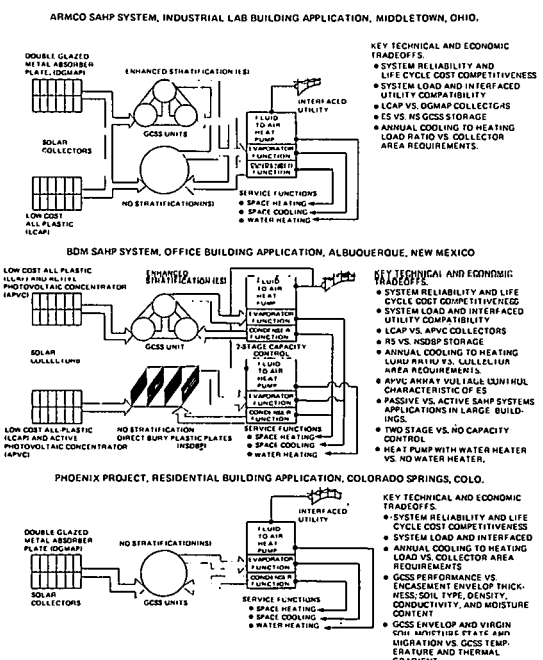


FIGURE I. PHOENIX PHASE II PROJECT OVERVIEW

DEVELOPMENT OF MARKETABLE SOLAR ASSISTED HEAT PUMP

LENNOX INDUSTRIES INC.

DE-AC-03-78-CS3-1720

ROGER HUNDT

FEBRUARY, 1978 - MAY, 1981

Lennox Industries Inc. has completed Phase I, which had as an objective to identify a conceptual design and solar heat pump arrangement that would be marketable in quantity. This was accomplished with the assistance of Honeywell by simulating various arrangements in various areas of the country. Figure 1 is typical of results from this simulation study.

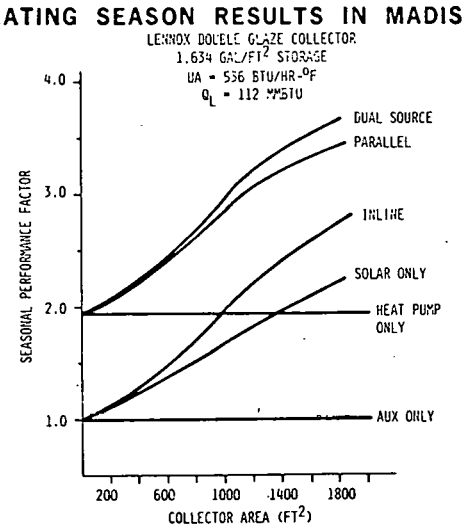


Figure 1

As shown, the study led to the conclusion that a dual source approach, shown in Figure 2,

BASELINE DUAL SOURCE SAHP

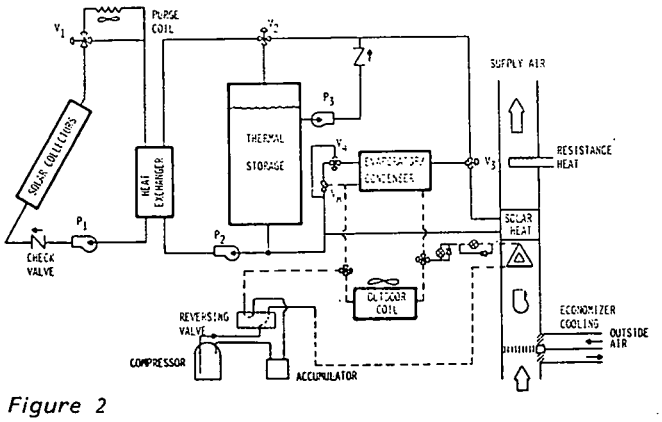


Figure 2

would be the most efficient way of utilizing solar energy with the heat pump. However, because we can get to the marketplace faster with the in-line approach (adding solar energy directly to the evaporator on the heat pump as shown in Figure 3),

INLINE SAHP

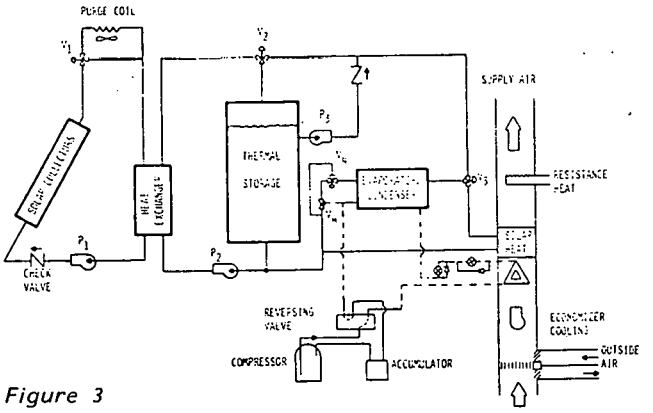


Figure 3

we have chosen that route for Phases II, detailed design, and III, fabrication and test.

Problems that would delay us should we elect to pursue dual source at the present time are as follows:

1. With dual source, there must be at all times an inactive evaporator. We foresee a great deal of experimental effort in preventing refrigerant from migrating to the inactive evaporator and rendering the active system short of refrigerant charge. It has been our experience that even tightly sealing solenoid valves cannot prevent the migration of refrigerant over long periods of time.

2. Figure 4 depicts the control strategy for a dual source solar assisted heat pump. Such a strategy can be applied only with microprocessor technology, which in itself will require a lengthy development timetable. Development of this technology is going on right now, of course, but results will not suit the Phases II and II schedules that Lennox intends to complete.

3. Solutions to the first two problems mentioned would likely cause production costs to exceed what we would need to be able to market the product. Time can change this situation, but Lennox feels that it

is out of time for developing and marketing a water source heat pump.

OPTIMAL CONTROL STATEGY

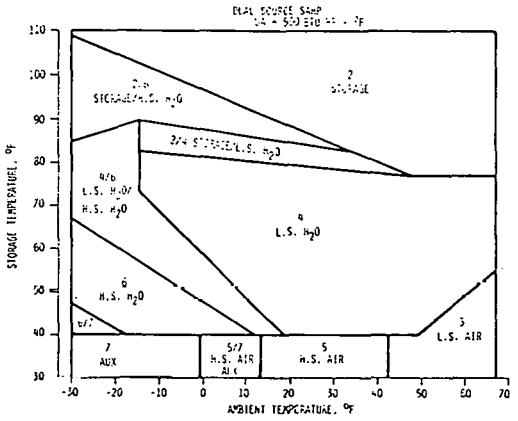


Figure 4

Perhaps it should be stated as a matter of record that Lennox does not intend to depart from a dual source approach. We will pursue this approach for the long range future and outside of the 1720 project.

There is at least one possible disadvantage with the in-line approach. This has to do with suction valve stresses in the compressor. Lennox has developed and proven proprietary equations for predicting dynamic stresses in reed suction valves. These stresses are related to a number of factors, but one of the most important is evaporating temperature. The equations show that Lennox compressor designs should not be applied with evaporating temperatures higher than about 54°F, with condensing temperatures as low as 100°F. However, the equations were derived for two-pole motor speed (3500 rpm), and for the 1720 project, high source temperatures leading to 80°F evaporating temperatures would only require low speed (1750 rpm) operation of the compressor. We have effected life tests in our Fort Worth laboratory for low speed operation of a Lennox compressor having 100°F condensing temperature and 80°F evaporating temperature. It is hoped that low speed operation will allow us to utilize high source temperatures without endangering the reliability of the heat pump compressor.

Tests with high evaporating temperatures have been conducted with Lennox compressors as part of the 1720 program. These tests revealed that for every compressor there is a point where input drops with increased evaporating temperature. There is a theoretical answer to this phenomena. Energy supplied to the compressor motor depends mostly on the following equation:

$$W_{ki} = \dot{m}\,\Delta h_i$$

where,

W_{ki} = *ideal work required for pumping refrigerant.*
$\dot{m}$ = *mass rate of flow of refrigerant handled by compressor (dependent on volumetric efficiency of compressor at operating conditions)*
Δh_i = *change in enthalpy of refrigerant during compression process if the process were isentropic.*

In the normal evaporating temperature operating range (-10F to 50F), with a given condensing temperature, an increase in evaporating temperature will cause an $\dot{m}$ increase higher, proportionally, than a Δh_i decrease -- meaning higher input values for the compressor. However, higher source temperatures leading to evaporating temperatures of, say, 60-80F, can cause the $\dot{m}$ quantity to increase less than the Δh_i decreases. Figure 5 depicts the efficiency characteristics of a typical Lennox two-speed compressor, and the advantages of high evaporating temperatures are readily seen.

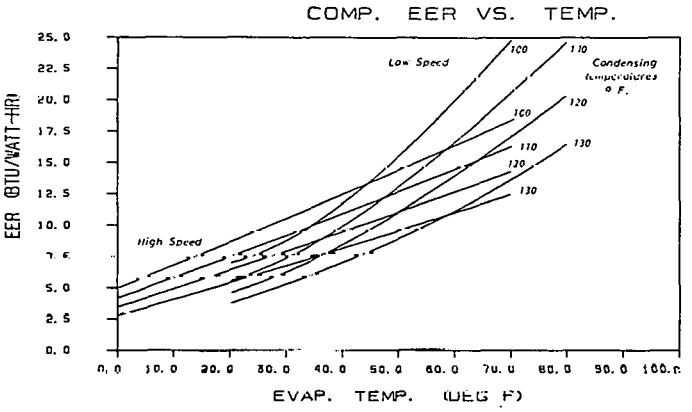


Figure 5

Figures 6 and 7 are schematics of the two system configurations that Lennox will be detailing for Phase II. With system performance maps and additional simulation, we will choose the most cost-effective in-line system for Phase III.

WATER SOURCE HEAT PUMPS

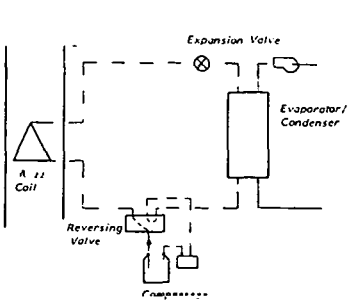


Figure 6

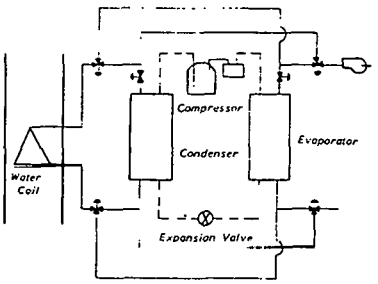


Figure 7

In addition to the technical investigation discussed in preceeding paragraphs, the Marketing department of Lennox has conducted an investigation to determine the capacity of solar assisted heat pumps (SAHP) that could potentially find the greatest marketability. Inasmuch as Lennox has committed to do detail design on two capacities of the SAHP, it was desirable to determine the capacities that would find the greatest acceptance in the marketplace.

At the end of 1977, there were 80.7 million housing units in the United States. Of these, 41.0 million had warm air furnaces, 14.5 million utilized hydronic heating, 5.3

million utilized built-in direct element electric heat, and 1.1 million utilized heat pumps. The remainder utilized various types of room heaters and other non-central systems. A total of 41.5 million housing units were served by utility gas and 15.6 million used fuel oil with an additional 4.1 million using liquified petroleum gas.

It was our purpose to identify what portion of this existing and new construction residential sector represents the largest number of units of a given capacity.

Since utility natural gas service represents the largest single group of housing units, and, further, since the best statistical data is available from gas utility sources, this particular group was studied in the greatest detail. Our methods of analysis reveal that the two largest categories of natural gas users for space heating are those with a requirement of 80 cubic feet per hour representing 8.32 million users and those with 100 cubic feet per hour input representing a total of 8.52 million based on this method of quantification. The most popular sizes of 80 and 100 cubic feet per hour input result in outputs of 52,000 and 65,000 BTU per hour respectively.

We have merely converted the heating output of 65,000 BTU per hour for the most popular group of 8.5 million units to the equivalent for heat pump with a heating COP of 6.0. As calculations indicate, the heat pump for this most frequent probable size of unit would be 30,163 BTU per hour. However, to achieve maximum annual energy conservation utilizing night-time setback, a 20% oversizing factor should be used in order to achieve morning pickup during periods of design outdoor weather conditions. This calculation results in an indicated capacity of 36,200 BTU per hour or essentially a 3 ton nominal capacity for the heat pump during the greatest cooling cycle.

Obviously, energy conservation in both renovated and new homes will reduce the most popular size requirement for the system. Utilizing an anticipated 15% reduction in peak load requirements, the unit for this application results with a nominal capacity of 2.5 tons.

This study therefore indicates that it is desirable to detail design a 2.5 ton unit with a 3.0 ton unit. These two units could be used as the prototype for extensions both upward and downward in nominal capacity since smaller units would be required for garden and other low-rise type apartments while larger capacity machines would be needed for larger homes in the Northeast sector where oil heat is presently utilized extensively.

Although no detailed market assessment can be made until the conclusion of econometric studies as a part of Contract 1720, it is important to recognize the number of new and replacement HVAC systems that were installed in the single family residential sector during 1978. Of these systems, 0.323 million were oil furnaces and boilers, 1.7 million were gas furnaces and boilers, 0.56 million were heat pumps, and over 0.6 million were other types of electric systems. Obviously, all of the electric systems are candidates if a cost effective system evolves from the SAHP project. This situation should receive foremost consideration during the subsequent phases of the contract project.

DEVELOPMENT OF A SOLAR ASSISTED HEAT PUMP FOR THE HEATING AND COOLING OF BUILDINGS

NORTHRUP, INCORPORATED

EG-78-C-03-1718

AMIR L. ECKER

FEBRUARY 1978 - APRIL 1980

OBJECTIVE

The hardware development of optimized high efficiency vapor compression cycle heat pumps for use in conjunction with solar assisted heat pump (SAHP) systems was the primary focus of this development program. While the overall scope of the design effort included the formulation of SAHP system designs for residential, multi-family and commercial building schemes, the principle effort was directed towards the residential application. A systematic development approach consisting of several distinct program phases including system design and evaluation, heat pump detailed design, hardware fabrication and testing were undertaken. In addition, a marketing analysis and plan for commercializing these systems was assembled.

The goal of the program was to develop the hardware for SAHP systems which offer increased performance with minimal cost impact. With the concomitant energy savings that accrue from the use of these systems, the impetus is thus provided for the marketing of SAHP systems, on a broad basis, as an economically justifiable alternative to conventional space conditioning equipment.

BACKGROUND

As a result of the seemingly formidable cost barriers attendant with an active solar heating system, which serves to retard market penetration of these systems even in light of the increasing cost of fossil fuels, alternate approaches of combining an active solar system with heat pump technology are envisioned. Among the design approaches available are series, parallel and dual source (hybrid) solar-heat pump systems configurations

Of particular interest in this program was the development of a high efficiency vapor compression cycle heat pump to be utilized in (series) solar assisted heat pump systems. Since the heat pump is one of the few devices which can effectively utilize low grade thermal energy, the union of solar energy in series with the heat pump appears to be a viable marriage. Single glazed collectors with less rigid technical specifications can be incorporated into the system to provide economical solar boost for high collection temperatures are not required to source the heat pump. By incorporating capacity modulation means and by eliminating the deleterious effects of the defrost cycle, the performance and reliability of the heat pumps are further improved. Through the introduction of thermal ground coupling which can be achieved by a variety of schemes, a heat source can be provided to the heat pump to obviate the reliance of the SAHP system on expensive electrical resistive elements during periods of low solar insolation and high heat loss. In addition, ground coupling can favorably impact the economics of SAHP systems as it significantly reduces the collector area requirements.

From a performance standpoint, the heat pump is by far the most crucial element in a SAHP system. Fundamentally, the heat pump must exhibit substantially increased efficiency as the source temperature is raised, by either solar assist or ground coupling, for the solar assisted heat pump to become a viable system approach. Heat pumps for comfort conditioning have not been previously designed to operate at evaporating temperatures (suction) above 45°F primarily because no such applications existed prior to the emergence of the solar heat pump system concepts. The design effort concentrated on these aspects as well as providing a synergistic means of interfacing the heat pump with the solar collection and thermal storage elements in such a way to minimize the total energy required to satisfy the thermal demands of a given structure.

SUMMARY

At the onset of the program, the evolution of the high efficiency heat pump proceeded in two distinct directions: system development and component development. While there exist a wide variety of solar collector designs, thermal storage systems and ground coupling schemes in various stages of development, Northrup decided to divorce the heat pump design from a specific collection and storage approach. Instead, the efficient utilization of a thermal source, both ambient air and storage, to condition the load with an electrically driven heat pump became the research target. Even with this simplification, a multitude of SAHP configurations, including both series and hybrid types, were designed - each having its own peculiar advantages and disadvantages. Concurrently, the analysis, testing and evaluation of heat pump components was undertaken so that data could be obtained when operating at conditions typical of a SAHP system.

Resulting from the system and component development, Northrup has designed a preferred solar assisted heat pump system shown schematically in Fig. 1. The system is comprised of the following:

- o a solar subsystem including collectors and a heat transfer module
- o a storage subsystem including a pumping module
- o an air handler with a water-to-air heat

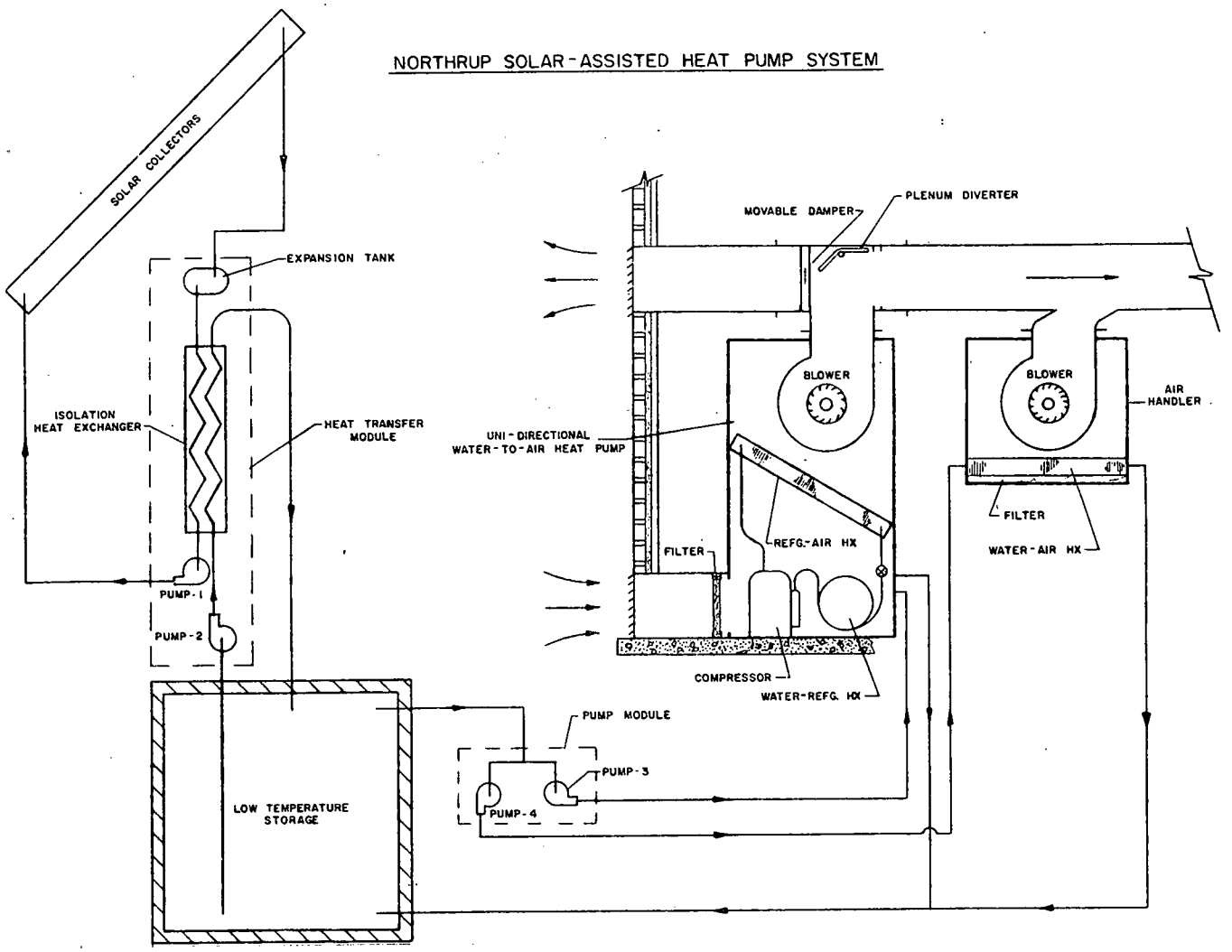


FIGURE 1: Northrup Solar Assisted Heat Pump System

exchanger
- o a uni-directional variable capacity water-to-air heat pump with suitable means for dampering the air stream

Excluding the solar subsystem mode, this SAHP system can function in the following modes:

Heating
- o Direct solar heating from storage
- o Water source heat pump at three different capacity levels
- o Simultaneous operation of the above
- o Economizer

Cooling
- o Direct cooling from storage
- o Chilling off-peak or nocturnally at two different capacity levels
- o Economizer

As shown, this system incorporates a damper changeover system which can be either manual or automatic. Economizer operation is available and the thermal storage tank is utilized year-round - both of which improve the SAHP system economics. The high efficiency water source heat pump developed by Northrup can operate efficiently and reliably over an inlet water temperature from 38° to 120°F with a coefficient of performance (COP) ranging from 3.2 to 8.1.

This particular system approach appears to have tremendous merit as a result of the following facts:

- o Highest heat pump performance possible
  - three capacity levels provided with the use of parallel rotary compressors
  - optimized heat exchangers
  - flooded evaporator with an electric thermal expansion valve
  - rotary compressors can achieve highest performance possible at low pressure ratio conditions
- o Lowest heat pump cost
- o Compact design
- o Versatile capabilities
  - can be used for SAHP systems
  - can be used for off-peak cooling systems
  - can be used for heating-only WSHP systems

- o Best heat pump reliability
  - no refrigerant reversing valves
  - single package system, optimally charged with little oil return problems

TECHNICAL ACCOMPLISHMENTS

o Developed numerous SAHP system configurations including both series and dual source system designs. In particular, Northrup's dual source SAHP system is characterized by a high degree of simplicity as additional refrigerant control valves are noticeably absent from the design.

o Discovered a significant compressor performance phenomenon at high suction, low pressure ratio operating conditions typical of a SAHP system. Were it not for this discovery, the near term availability of a heat pump suitable for integration in a solar assisted heat pump system would have been severely jeopardized. The relevance of this accomplishment will be explained in further detail.

As previously stated, the crux of the hardware development task was the design of a heat pump capable of capitalizing upon the tremendous performance improvement possible when operating at elevated suction conditions as dictated by thermodynamic principles. The refrigerant compressor is the fundamental performance related component in a heat pump system so the proper selection of this device is of paramount importance. Fig. 2 presents a compressor operating map and indicates typical envelopes for a heat pump (using refrigerant 22) operating under SAHP conditions. Of particular concern in this program was the performance of hermetic refrigerant compressors at high suction conditions and low pressure ratios occuring during the heating mode.

Off-the-shelf hermetic refrigerant compressors are designed and optimized for operation at the ASRE-T compressor rating condition since this design point correlated in the past to the operating condition of a compressor in air cooled equipment at the ARI system rating point. Note from Fig. 2 the ASRE-T rating condition relative to the SAHP heating and cooling envelopes. Selecting a compressor to operate efficiently within the low pressure ratio heating envelope posed a severe problem since no published performance data was available above evaporating temperatures of 55 F. In fact, reciprocating compressor manufacturers place strict limitations on the use of compressors above this temperature because of reliability problems.

After performing a polytropic analysis of compressor performance at the low pressure ratio conditions, it was determined that a refrigerant compressor should be capable of operating with the desired performance as long as the isentropic compression efficiency did not diminish. Because of the unavailability of compressor data at these low pressure ratio conditions, a heat pump simulator utilizing a hot gas bypass system was constructed. An accurate assessment of the performance of candidate compressors was performed over an extensive range of suction and head conditions.

Two basic types of compressors were evaluated: reciprocating and rotary. Of these two, the reciprocating units are by far the most refined and popular type of compressor; however, the results of the experimental investigation were astonishing.

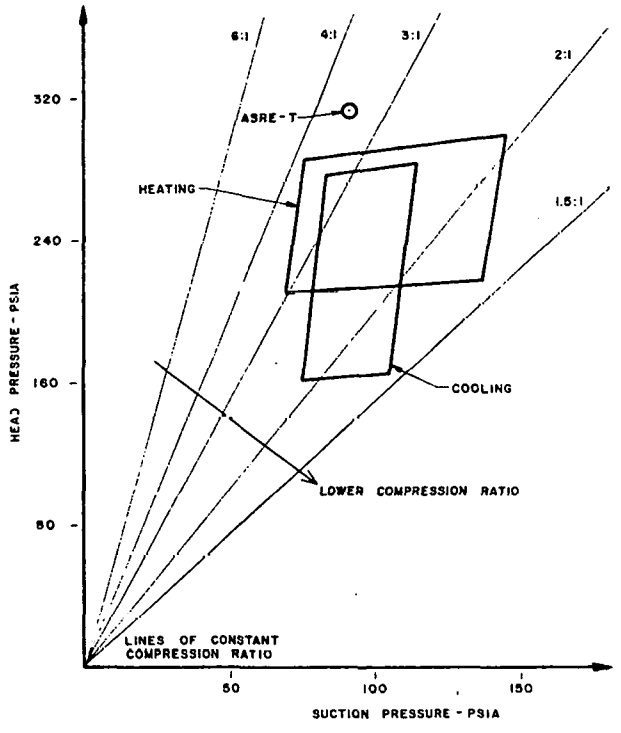


FIGURE 2: Compressor Operating Map

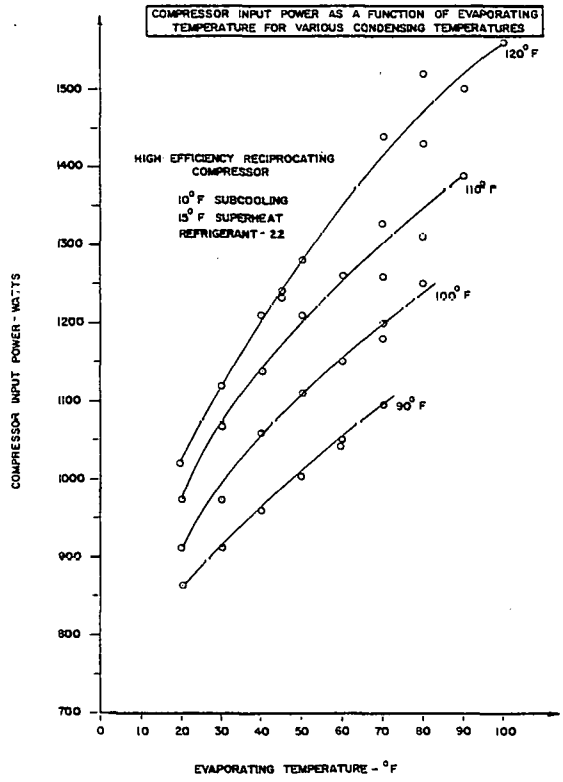


FIGURE 3: Reciprocating Compressor Performance

Fig. 3 depicts the calorimeter test results for a high efficiency reciprocating compressor. In this figure, the compressor input power as a function of evaporating temperature is graphed. As shown, the compressor power requirement increased monotonically as the suction temperature was raised. The results for an identically sized rolling piston rotary compressor are shown in Fig. 4. Remarkably, an entirely different response to high suction conditions is exhibited by the rotary as the compressor input requirement peaks and then begins to diminish at higher back pressures.

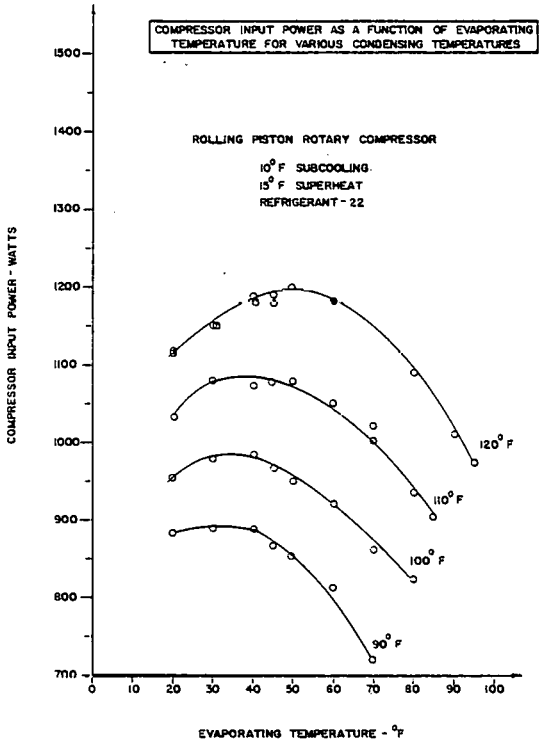


FIGURE 4: Rotary Compressor Performance

The variance in the response of these compressors to a high suction low pressure ratio environment is ultimately manifested in Fig. 5 which displays the heating coefficient of performance as a function of evaporating temperature. In comparison to the reciprocating machine, an increase in performance by as much as 70% can be achieved with a rotary compressor.

o Developed a product line of vertical water source heat pumps, sized from 1½ to 3 tons, which exhibit superior performance over conventional equipment in both the heating and cooling modes.

o Developed a unique water-to-refrigerant heat exchanger configuration, especially designed for ground coupled systems, which allows optimization of the coil for both the evaporating and condensing modes.

o Developed a new heat exchanger construction concept for double wall heat exchangers to be utilized in glycol to potable water heat transfer. This new design improves both the cost and performance

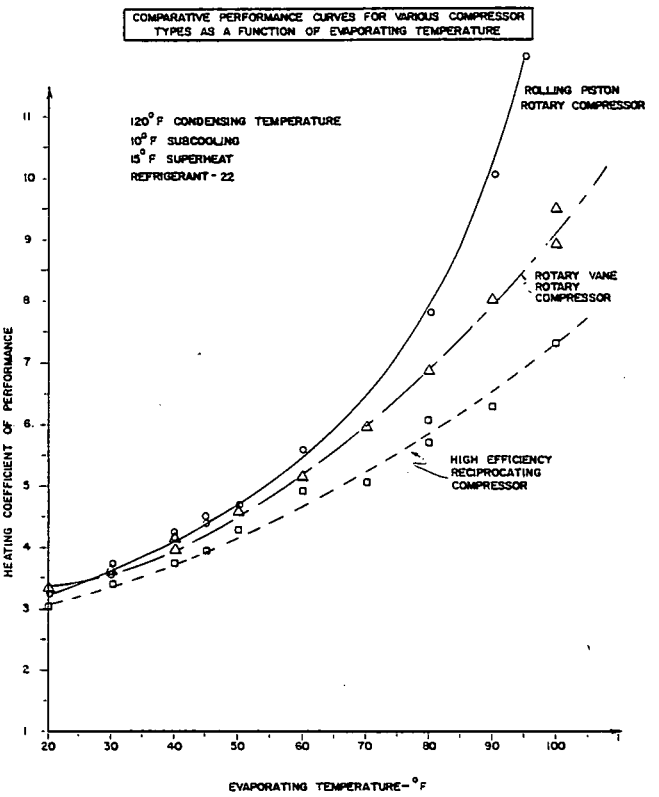


FIGURE 5: Comparative Compressor Performance

characteristics over currently available devices.

o Developed a key component for Northrup's dual source SAHP systems called an Accu-Vap heat exchanger. With this unit, the refrigerant circuitry and control is simplified.

o Developed a uni-directional variable capacity water source heat pump, nominally rated at 2½ tons, utilizing two parallel rotary compressors for achieving capacity modulation. This heat pump can maintain an extremely high level of efficiency over an inlet water temperature range from 38°F to 120°F.

FUTURE ACTIVITIES

The program is nearing conclusion with further laboratory testing of the variable capacity water source heat pump remaining. A final technical report documenting the activities performed during this contract is being prepared. Resulting from this heat pump development program, a line of vertical water source heat pumps having superior performance over conventional equipment is currently available in the marketplace. This heat pump line will be modified in a few months to incorporate a new water-to-refrigerant heat exchanger which will allow operation of these units down to 38°F entering water temperature. The variable capacity WSHP will be available on a trial basis after April 1980.

PUBLICATIONS

A. L. Ecker, "Optimal Refrigerant Compressor for Low Pressure Ratio Applications" ASHRAE Transactions, 1980, Vol. 86, Part 1, N.Y.,N.Y.

DESIGN AND FIELD TESTING OF SOLAR-ASSISTED EARTH COILS

OKLAHOMA STATE UNIVERSITY

DE-AS03-79CS30210

JAMES E. BOSE

1 AUGUST 1978 - 31 JULY 1980

OBJECTIVE

The objective is to design and operate a set of instrumented field experiments to obtain engineering information and data needed for optimum design of ground energy coupling devices for use in solar-assisted heat pump systems. The field experiment addresses energy coupling configurations for both horizontal pipes in trenches and vertical coils or geo-thermal wells. Procedures are to be developed to determine the proper balance between what is collected and stored in the ground, rejected to the ground, and extracted from the ground by the heat pump.

CONCEPT/BACKGROUND

Existing heat pumps are not presently designed to optimally utilize evaporator temperatures between 40°-110°F. Present heat pump development programs address this problem and improved heat pumps are expected to be available for these source temperatures by 1980. These heat pump systems will not be stand-alone machines and must be carefully integrated into a system. This system can expect excellent market potential if the costs of the remaining components of the system (collectors, storage, and controls) can be kept to a minimum. Target costs for solar collectors are $3-$5 per square foot and storage costs of $700-$1200 per million of BTU's.

The geographic location determines the balance between heating and cooling requirements and, thus, dictates the heat pump/solar system overall design. In climates where cooling loads dominate, heat rejection during the summer season must (1) replace the energy that was absorbed from the storage system in the winter, (2) must generate domestic hot water, and (3) must be temperature bounded so that sufficient cooling of the condenser is achieved. In warmer geographic areas, there is sufficient waste heat energy from cooling requirements to replace the previous winter's heating and domestic hot water requirements. During the summer season, what must be controlled is the maximum storage temperature that will occur during extreme cooling demands. Vertical unglazed solar panels used for cooling condenser water before circulating back to the geo-thermal storage are proposed to limit the maximum inlet condenser water desired.

In areas where heating demands dominate, storage systems with lower bounds of 40°F. are desired. Depending on average solar insolation, the geo-thermal storage system must maintain this lower temperature limit for extended periods of overcast or cloudy weather. Vertical geo-thermal wells or horizontal earth coils buried at depths below the frost line are capable of limiting lower temperature. Glazed solar collectors on properly-sloped surfaces would be required in winter to supplement or elevate storage temperatures and used in the summer season to replace and store energy for the heating season and domestic hot water requirements.

SUMMARY

A field demonstration laboratory using unprepared earth as a heat sink/source device has been under development at Oklahoma State University since June, 1977. The demonstration laboratory consists of a 1,000-foot horizontal earth coil and two vertical heat exchangers. The horizontal heat exchanger is a 4-inch PVC pipe buried in a serpentine pattern at a depth of four feet. Undisturbed temperatures at this depth are cyclic and depend on latitude, moisture content, and soil type.

The first of two vertical heat exchangers consists of a 240-foot vertical heat exchanger fabricated from a 5-inch PVC pipe placed in the earth using a conventional water well drilling rig. Undisturbed temperatures at these depths are constant and depend to a large part on yearly mean temperatures.

The second vertical heat exchanger consists of a 300-foot vertical, 6-inch iron pipe. A loop heat exchanger inside the steel pipe is filled with an antifreeze solution to prevent evaporator icing and thus allowing lower operating temperatures in the pipe.

Overall heat transfer values for both the horizontal and vertical heat exchangers have been experimentally determined. The overall heat transfer value depends on cycle time and the past source/sink history. Temperature measurements taken the the earth near the horizontal heat exchanger are presented as well as water temperatures inside the pipe down its length.

TECHNICAL ACCOMPLISHMENTS

Two types of earth coils have been designed, constructed, and are operational on the Oklahoma State University campus. A 1,000-foot, 4-inch PVC coil buried in a serpentine pattern, as shown in Fig. 1, has been the heat source/sink for two commercial heat pump systems.

Integral to the earth coil is a 1,000-gallon uninsulated storage tank in which solar energy from 200 ft^2 of solar collectors can be added directly to the heat pump or circulated through the 1,000-foot earth coil system.

The earth coil system in this study is a 4-inch PVC pipe with approximately 0.65 gallons of water and 1.0 ft^2 of surface per linear foot.

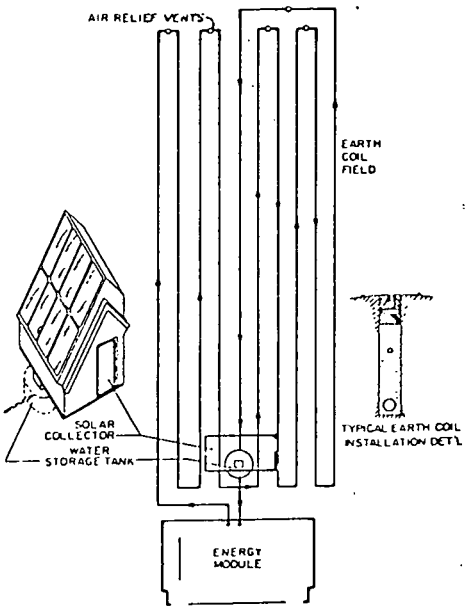


Figure 1. Earth Coil Configuration.

Fig. 2 is a plot of earth and water temperatures during a continuous (8-hour) run of the heat pump system.

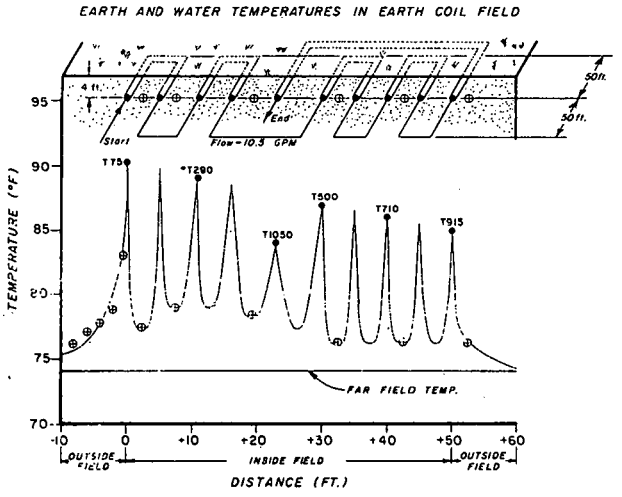


Figure 2. Earth and Water Temperatures Around Earth Coil

Fig.-3 shows overall U values for nine-hour test periods for two different time periods. From this plot it can be seen that the earth field temperature gradually increases during the day as well as over the season.

Earth coil performance during the 1978/79 winter heating season is shown in Fig. 4. Fig. 4 is a profile of the water temperature down the length of the 1,000-foot earth coil along with the corresponding far field temperature.

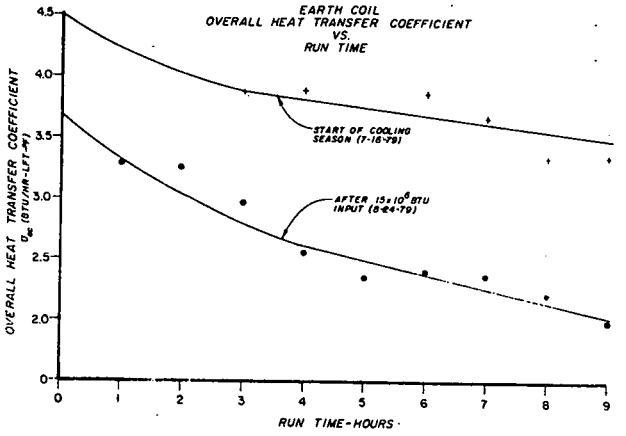


Figure 3. Thermal Conductivity versus Run Time.

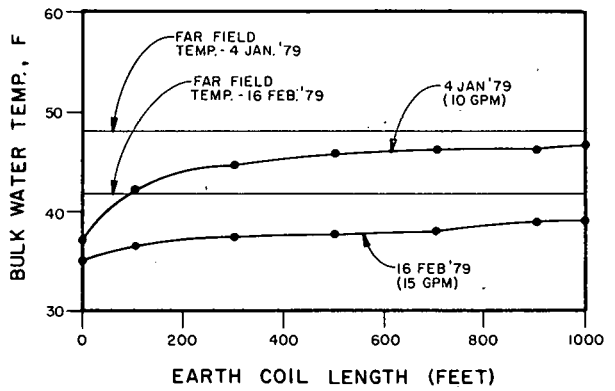


Figure 4. Earth Coil Test Data During 1978/79 Winter Season.

Several conclusions are apparent, after the initial earth coil testing (horizontal field):

1. Summer heat cannot be carried forward to the heating season with the single-layered earth coil as designed and built at Oklahoma State University.

2. Without solar assist, earth coils long enough to prevent evaporator freezing must be approximately 400 feet per ton of capacity if anti-freeze solutions are not used.

3. Heat transfer rates depend upon cycle time and earth coil past history.

4. Solar assist would reduce temperature drawdown in the earth coil during long, sustained operation, thus reducing supplementary heating requirements.

5. Installed costs for earth coils at the four-foot level are approximately $2.00 per foot when placed under septic laterals and $3.00 per foot when the total trench cost is charged to the earth coil.

6. Approximately 300 feet of pipe per ton of heat pump capacity are required to reject the summer cooling load. The use of supplementary heat and/or solar assist will determine if additional footage is required for the heating season. These numbers are

valid only for this region and do not represent extension to other areas. The use of antifreeze mixtures in the pipe during winter periods would also influence coil lengths.

The second type of earth coil under study is a vertical coil approximately 240 feet in length, as shown in Fig. 5. Placement of the coil is with a conventional water well drilling machine. The vertical heat exchanger consists of a 5-inch PVC pipe which is capped at both ends and pressurized at approximately 15 psig. This sealed and pressurized heat exchanger allows a low-power pump to circulate water through both the heat pump and vertical heat exchanger system.

Depending upon the type of test being studied, the water may be discharged to the top or bottom, and the discharge tube may be insulated.

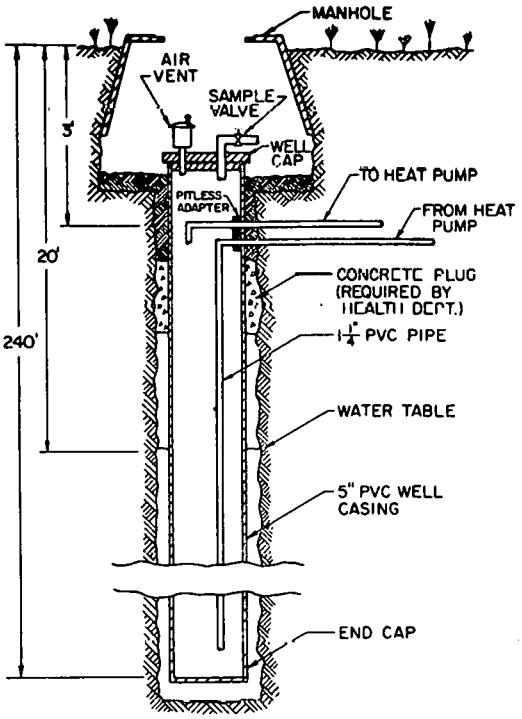


Figure 5. Geo-Thermal Well Design.

Tests have been run to determine overall U values, recovery profiles, and the use of insulated discharge tubes to limit the heat transfer loss as water is circulated in the well bore. Overall U values for this set of tests using the uninsulated dip tube are given in Fig. 6.

Long-term, steady-state values for the well will be around 2.0 Btu/(Hr - ℓft - °F) with 50 per cent cycle time values approaching 4.2. With solar assist, the value will depend on system sizing and solar gain availability.

The rate of heat gain/loss in the vertical heat exchanger is dependent upon past well performance. Fig. 7 is a plot of three tests showing the well performance as a heat sink (August, 1979), a solar storage device (January, 1980), and a heat source for the heat pump in January, 1980. The test data taken during August, 1979, indicate that the earth has been heat saturated from rejected heat during

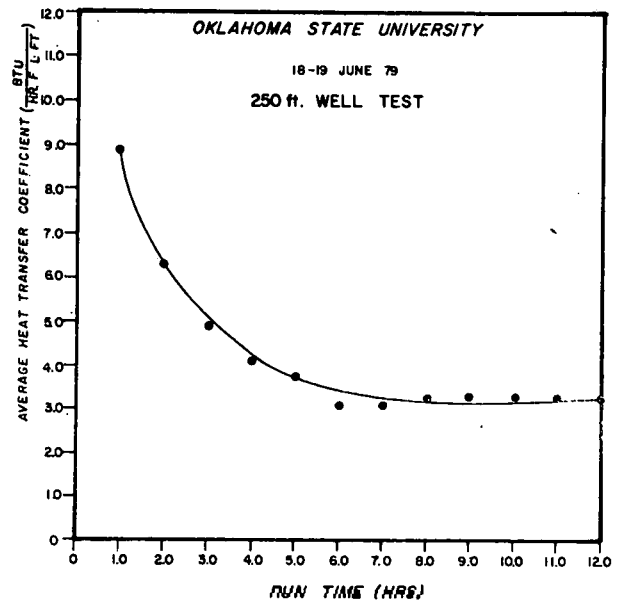


Figure 6. Thermal Conductivity (Well) versus Run Time.

the cooling cycle. The January, 1980, test data indicate that the earth around the heat exchanger has "cooled" and the ability to store or retain heat is less than that occurring in August of 1979. The

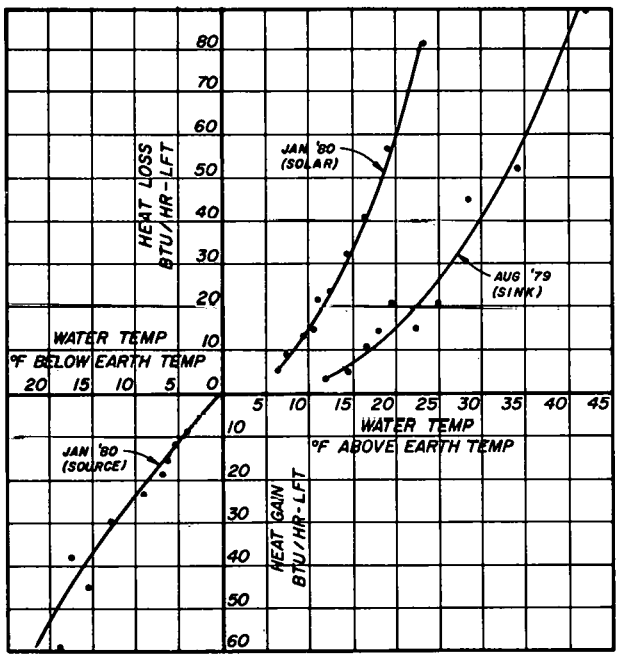


Figure 7. Heat Flow As A Past Function of Well History.

same generalized statements can be made about the well as a heat source. The effect of solar is to rotate the "source" curve counterclockwise, which has the effect of increasing the heat gain per degree Fahrenheit and increasing the average well temperature. Further testing will define the physical parameters which dictate curve placement as a function of heat gain/loss history.

The geo-thermal well study has resulted in the following conclusions:

1. In comparison to long earth coils, the geo-thermal well temperatures rise and fall more rapidly with both systems exhibiting approximately the same U values for both cycling and steady-state operation.

2. The average yearly temperature of 62°F offers a distinct advantage when considering solar assist. Without solar assist and using the length ratio as proposed, both systems approach the same temperature during periods of heavy demand. The well has higher temperature recovery potential than the earth coil, which is beneficial to climates with cyclic winter patterns.

3. Costs for the vertical heat exchanger are approximately $6.50 per foot. These costs were determined from six residential systems operating in the local area. There is a high degree of variability among contractors.

4. Approximately 100 feet of wetted pipe per ton of capacity is required for summer heat load rejection. This is a typical value for residential systems in this area. Water temperatures during the heating season will depend upon solar gain availability and/or cyclic behavior.

FUTURE ACTIVITIES

Future activities include a study of the effects of moisture content and migration together with a study of the effects of solar addition to the earth coils. Analytical modeling of both the horizontal and vertical earth coils has been initiated with very promising results being provided by the GROCS model developed by Dr. Phil Metz at BNL. Other models are being developed to determine near-time transient behavior due to heat pump cycling and solar addition.

Approximately sixty (60) earth-coupled, heat pump systems have been installed in the local area. Of this total, three are solar assisted and all use the vertical geo-thermal well as the earth coupling device for the heat pump system. The installed systems are sealed and pressurized and use small wattage (185 watts) circulating pumps. The earth coils are buried at the four-foot level and use from 200 to 300 feet of earth coil per ton of heat pump capacity, and 100 feet of wetted pipe per ton of capacity for the vertical heat exchanger. All systems have incorporated domestic hot water preheaters.

PUBLICATIONS/REPORTS/REFERENCES

1. Bose, J. E., "Design and Field Testing of Solar Assisted Earth Coils," Annual Report, 1 August 1978 - 31 July 1979, for the U. S. Department of Energy, Office of the Assistant Secretary for Conservation and Solar Applications, Washington, D.C.

2. Nordic Symposium on Earth Heat Pump Systems, Chalmers University of Technology. S-41296, Goteborg, Sweden. October 15-16, 1979.

3. Bose, J. E., Ledbetter, C. W., Partin, J. R., Cason, G., "Earth Coupled and Solar Assisted Heat Pump Systems," paper to be presented at the Heat Pump Technology Conference, Engineering Energy Laboratory, Division of Engineering, Technology and Architecture, Oklahoma State University, Stillwater. April 14 & 15, 1980.

4. Andrews, John W. and Metz, Philip D., "Computer Simulation of Ground Coupled Storage in a Series Solar Assisted Heat Pump System." Brookhaven National Laboratory, Building 701, Upton, New York 11973.

5. Andrew, John W, "Heat Pump Impact Upon Solar Collector Design and Cost." Brookhaven National Laboratory, Building 701, Upton, New York 11973.

LOW-COST HEATING AND COOLING USING A DIRECT-EXPANSION SOLAR COLLECTOR AND HEAT PUMP

SIGMA RESEARCH, INC.

DE-AC03-79SF10542

E. W. SAASKI

BEGIN: AUGUST 16, 1979 END: JUNE 14, 1980

Development of an analytical model and construction of a solar-assisted heat pump system have been pursued. The model and test unit have been used to evaluate the various factors affecting system performance and economics. The results of these analyses and tests have been used for model verification and control development. The final goal is to develop and demonstrate an optimized collector and control system.

The high cost of solar heating systems has led to the design and testing of a novel direct-expansion solar collector system that is low-cost, lightweight, and thermally efficient. In this new design, solar energy absorbed by exposed panels directly vaporizes a refrigerant fluid. The resulting low-temperature vapor is pumped to a high temperature and pressure and then condensed to release the heat absorbed in the vaporization process. The solar panels at most times operate at or below ambient temperature, resulting in a significant reduction in heat loss to the environment and eliminating the need for glass covers and expensive insulation around the collectors.

This new collector is particularly suited for heating in locales that experience large amounts of cloud cover and rainy weather because the panel continues to absorb energy by convection and radiation in the absence of solar input. In addition, condensation can provide significant thermal input to the collector under the proper meteorological conditions.

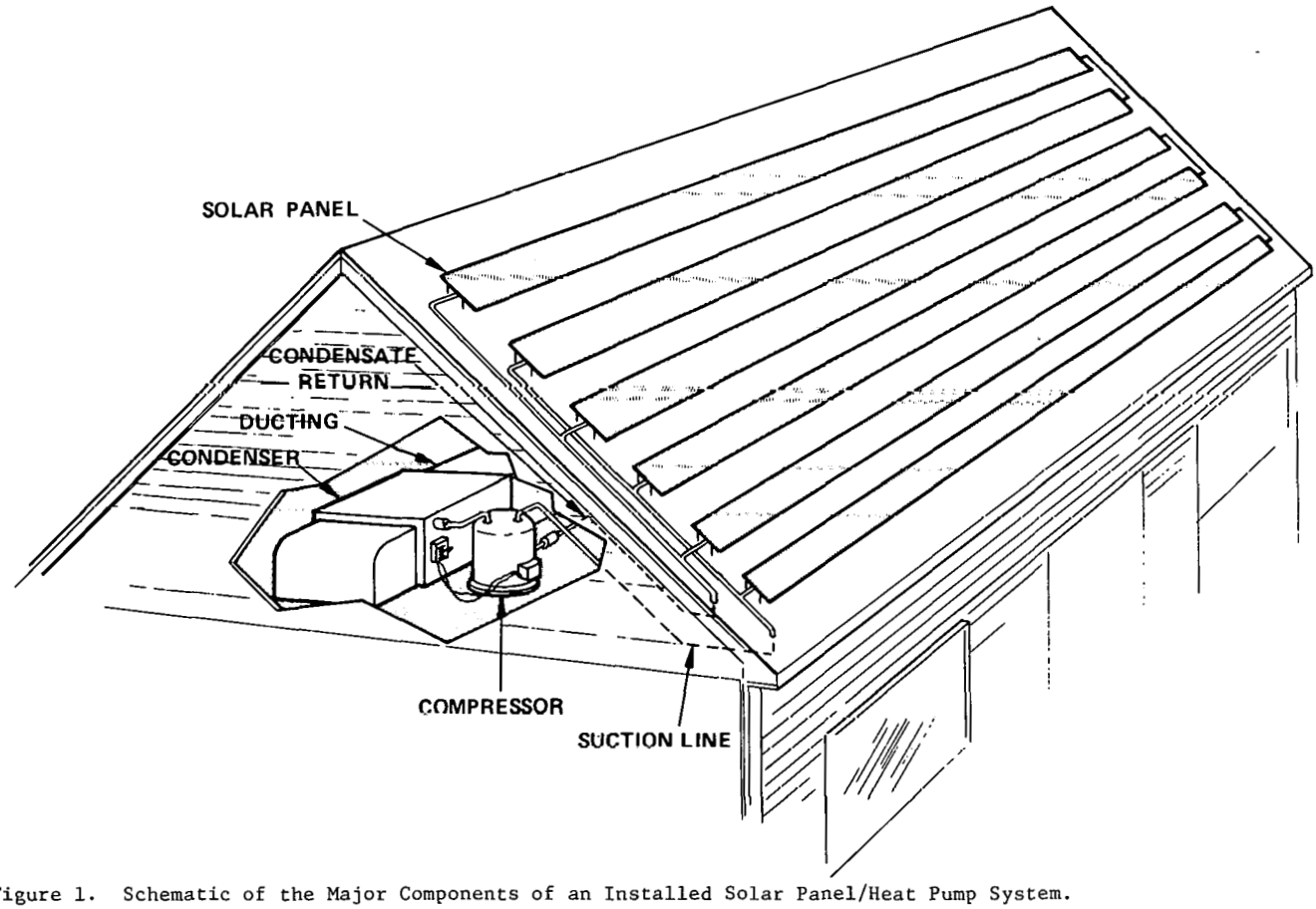


Figure 1. Schematic of the Major Components of an Installed Solar Panel/Heat Pump System.

An estimate of the average contributions of insolation, condensation, and convection to the thermal input to a collector of this type on a March day in Seattle, Washington, shows the utility of this design for regions not normally considered for solar energy collection

$$\text{Insolation} = 2.7\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)} - \text{day}}\right) = 49\%$$

$$\text{Condensation} = 0.7\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)} - \text{day}}\right) = 13\%$$

$$\text{Convection} = 2.1\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)} - \text{day}}\right) = 38\%$$

$$\text{Total} = 5.5\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)} - \text{day}}\right)$$

The average contributions on a July day in Seattle are estimated to be

$$\text{Insolation} = 4.1\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)day}}\right) = 38\%$$

$$\text{Condensation} = 3.1\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)day}}\right) = 29\%$$

$$\text{Convection} = 3.5\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)day}}\right) = 33\%$$

$$\text{Total} = 10.7\left(\frac{\text{kW-hr}}{\text{m}^2\text{(fin)day}}\right)$$

Convection and condensation are a large portion of the total input to the collector and together can provide an energy resource comparable to direct insolation, thereby doubling collector energy output. At solar noon on a sunny spring day typical percentage contributions in the Seattle area are

Insolation ——→ 68%

Condensation ——→ 13%

Convection ——→ 19%

Use of a microprocessor to control the heat pump system is being examined. This is expected to improve the average coefficient of performance (COP) of the system and extend compressor life. The microprocessor will examine temperature throughout the system and control the compressor speed and perhaps the expansion valve to insure optimum performance. The microprocessor will also control system start-up, thus reducing the possibility of compressor damage by entrained liquid.

The solar-assisted heat pump provides efficient utilization of available solar energy with a collector of minimal cost. In addition, the system provides significant heat output on cloudy days and during the night. These features coupled with the system's high COP make it very attractive for use in marginal solar heating areas.

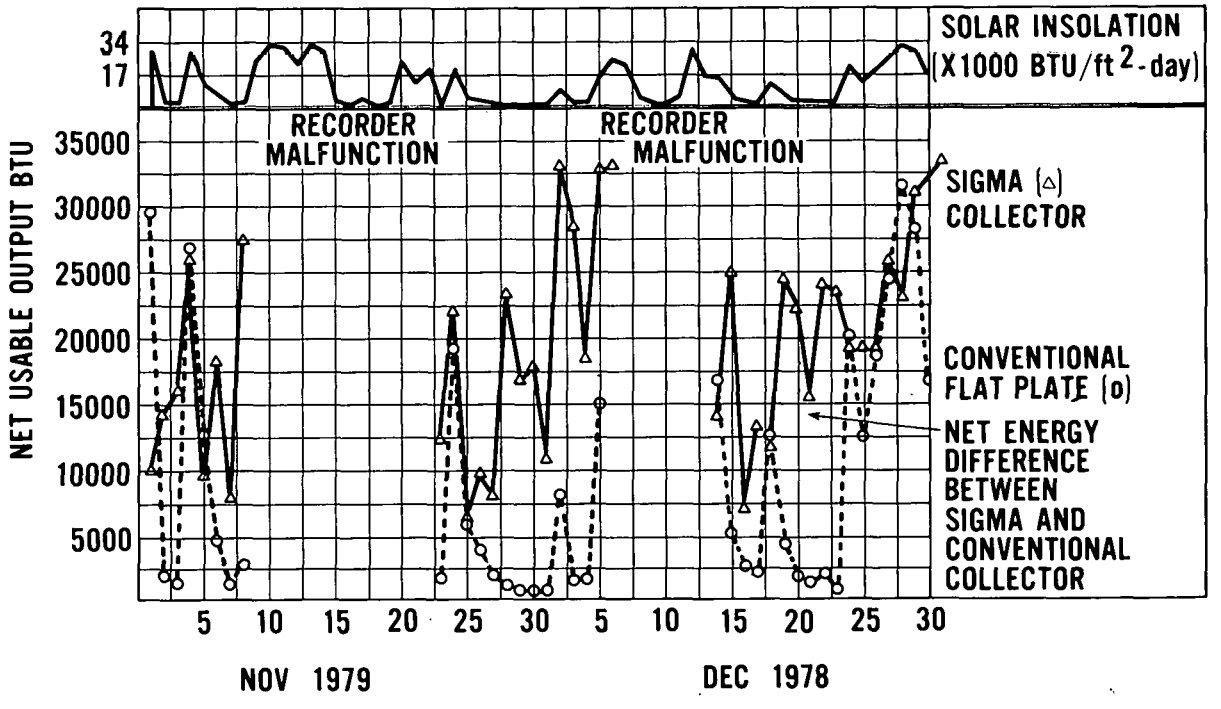


Figure 2. Performance Comparison Between Sigma and Conventional Flat Plate Collector Installations in Seattle, Washington.

SAHP-2 ANALYTICAL SELECTION OF MARKETABLE SAHP SYSTEMS

THE SINGER COMPANY

Contract No. EG-77-C-03-1467

Principal Investigator: Wm. Kahan

September 1977 to January 1980

OBJECTIVE.

The program objective is to identify the configurations of solar assisted heat pump (SAHP) systems and associated components that have the best market potential for the various climate regions of the United States, the primary criterion for best marketability being lowest life cycle cost relative to alternative systems. To achieve the program objective, an efficient analytical model is used to compare the thermal and economic performance of the following competing six systems: 1) an all electric resistance heating system, 2) a stand-alone heat pump system, 3) a stand-alone solar energy system, 4) a series SAHP system, 5) a parallel SAHP system, and 6) a dual source SAHP system. For each system (where appropriate) the collector area and storage volume are sized by means of the model to yield an economically optimum system. Thus, optimized systems are compared and ranked according to their marketability. This comparison is to be performed in a number of U.S. climates to assess the dependence of system rank on climate.

BACKGROUND.

Two systems that have been extensively developed to conserve energy used in space conditioning are a heat pump system and a flat plate collector solar energy system. Each has its merits and drawbacks.

Heat Pumps. Although a heat pump can provide space cooling and conserve energy in providing space heating, it has a number of drawbacks. Its heating capacity decreases as the source temperature decreases so that it provides the least heat when heat is needed most. The heat pump's capacity deficiency usually cannot be overcome by selecting a larger unit because cooling requirements determine the proper heat pump size. An overly large unit does not remove sufficient amounts of moisture when it cools the living space and produces a clammy and uncomfortable environment. In addition to losing capacity as the source temperature decreases, the heat pump also loses its energy saving characteristics. Its coefficient of performance (COP, the ratio of power provided for space heating to the power consumed by the heat pump) diminishes with falling outdoor temperatures. Another detriment to the efficiency of popular air source heat pumps is the need to defrost the outdoor evaporator coils at regular intervals to provent ice build up from impeding proper heat transfer.

Flat plate solar energy systems. Solar energy systems provide solar heating at a much lower operating cost than heat pumps. However, the solar energy systems have far greater initial costs, and must therefore be sized very carefully to be cost effective. Although an oversized system can provide more solar energy than one properly sized, its larger, more costly components will not be fully utilized during warmer portions of the heating season, and consequently such poorly deployed capital would not be economically justified. Depending upon the size of the system components, the size of the load, and weather conditions, solar energy systems designed for residential space heating typically provide between 20% and 80% of the heating load, the remainder being provided by conventional fuel sources.

A drawback of solar energy systems that leads to increased cost is the requirement to heat fluids to temperatures high enough for space heating. Collectors producing high temperature effluent during cold weather are well insulated and expensive; cheaper collectors suffer a large degradation in efficiency as the ambient temperature falls below that of the effluent.

Another drawback of solar energy systems is that they cannot provide cost effective cooling. Where cooling is required, a refrigerator must be installed and auxiliary energy must be consumed for its opeation.

SAHP systems. Can a heat pump and a solar energy system be combined into a solar assisted heat pump system that overcomes some of the drawbacks discussed above and that is more cost effective than either stand-alone systems? If so, in which climate region would SAHP systems be most effective? What would their price/performance characteristics be? How large would the market be for these SAHP systems? These are the basic questions addressed by the present program.

SUMMARY.

The program was organized into two major efforts:

- a Technical-Economics Study
- a Marketing Study

These efforts were conducted in parallel to optimize the use of the planned time period.

The prime thrust of the Technical-Economics Study centers around the development and use of an analytical model that predicts the thermal and economic performance of the competing systems. The results of the study clearly show that, of the active solar energy systems studied, SAHP systems are by far more economically attractive than a stand-alone solar energy system in the foreseeable future. This was found to be true in five different U.S. climate regions. Furthermore, it was found that if regulated natural gas is not available, the most cost effective space heating system at present and near future costs of electricity

is the air-to-air heat pump. At higher fuel prices, the series SAHP system has the lowest life cycle cost.

A major accomplishment of the Marketing Study was the collection and collation of systems and energy cost distribution data, as well as relevant characteristics of single family housing in the U.S. In addition to their use as inputs to the analytical model study, these data were used in a multiple variable correlation analysis to determine the factors that influence system marketability.

TECHNICAL ACCOMPLISHMENTS.

Program accomplishments are here reported for five areas of efforts.

1. Economic Constraint Analysis. The performance of a generic active solar energy system was analyzed to determine under which conditions the system costs less than the energy it saves over its lifetime (Ref. 1).

- Maximum economical system purchase prices (expressed per unit of collector area) were computed for SAHP and for stand-alone solar energy systems used for space heating as well as for domestic hot water. Results were obtained for 19 U.S. cities between latitudes of 26°N and 48°N.

- The sensitivity of V_o, the maximum economical system purchase price, to changes in assumptions regarding the annual worth of money, the annual fuel escalation rate, and the system lifetime was elucidated. It is noteworthy that the spectrum of reasonable assumptions for these quantities is broad enough to yield values of V_o that differ by a factor of 4.

- It was demonstrated that if stand-alone solar energy systems are less cost effective than stand-alone heat pump systems, then parallel SAHP systems are also less cost effective than stand-alone heat pump systems.

2. Analytical Model Development. For rapid analysis of the thermal and economic performance of competing heating systems, there were developed models based on closed form solutions of first order, linear differential equations that describe generic forms of the systems (Ref. 6).

- The models were implemented by means of an interactive FORTRAN program on a minicomputer. The annual performance of a typical system is computed (with TMY weather data) in less than two minutes.

- The Analytical Model was validated for all six competing systems, air and hydronic solar energy systems, for New York, NY, Fresno, CA, and Boston, MA, climates by comparing the energy savings over electric resistance heating as predicted by the Model against those predicted by TRNSYS. In 3/4 of the 20 systems analyzed, the compared values differed by less than 8%. In all but one case, the difference was less than 11%.

- Economic analysis capability was incorporated into the computer program so that it can be used to optimize systems, that is, to size system parameters for minimum system life cycle cost. This is accomplished by locating the parameter value at which the incremental benefit derived from a change of that parameter equals the incremental cost of effecting that change.

3. Thermal-Economic System Analysis - Results. The program combining thermal and economic analysis capability was used to select the most economical system from those previously optimized on a life cycle cost basis. This system was then identified as the most marketable one.

- The life cycle costs of the six competing systems were calculated for five U.S. locations. For each location calculations and comparisons were made for a large range of C_F, the cost of fuel at the time the system is installed. Furthermore, for each value of C_F the collector area and the storage volume (where appropriate) were sized to yield a minimum life cycle cost system. Thus, optimized vying systems were compared against each other. The system comparison for New York City climate is shown in Figure 1.

- The above comparisons show that where climate and fuel costs clearly justify an active solar energy system, the one with the lowest life cycle cost is the series SAHP system.

- The comparisons were made assuming an annual fuel escalation rate, F, of 4.5% and an annual worth of money, I, of 2%. The sensitivity of the results to these assumptions was evaluated by comparing optimized series SAHP systems against a stand-alone heat pump and electric resistance heat using F=2.5%, I=2%, and F=2.5, I=1%. The results are shown in Figure 2.

- The above analyses show that the system with the lowest life cycle cost and hence, according to the program assumption, the system that is most marketable, depends critically on C_F, the cost of fuel at the time the system is installed. Four broad intervals of C_F can be identified, and since C_F is expected to increase faster than inflation, these intervals correspond to four time epochs.

  - Epoch I. At the very low values of C_F, such as those of controlled natural gas, no energy conserving system has a lower life cycle cost than a gas furnace, even if the latter is only 50% efficient.

  - Epoch II. At values of C_F between 3¢/kWh and 8¢/kWh, the air-to-air heat pump system has the lowest life cycle cost.

  - Epoch III. At values of C_F significantly above 10¢/kWh (1979 dollars), the series SAHP system has the lowest life cycle cost.

  - Epoch IV. At values of C_F high enough for a stand-alone solar energy system to be more cost effective than a stand-alone air-to-air heat pump, the annual uniform cost of providing heat to a typical single family house is so high (> $5000, 1979

dollars) that drastic changes in life style are dictated.

4. Market Study. The program study was based on the premise that a system's marketability is determined, primarily, by its life cycle cost (LCC) relative to those of competing systems. Accordingly, a portion of the program was devoted to the collection and collation of system and energy cost distribution data. However, in order to obtain realistic SAHP data for LCC comparisons, it was necessary to design several SAHP systems in sufficient detail that their component costs could be obtained and that extensive computer simulations (TRNSYS) of them could be performed so that their thermal and economic performance could be ascertained. One important result of the LCC analyses was that, presently, factors other than LCC influence the marketability of systems that have low LCC but high initial costs, such as the SAHP and heat pump systems.

- Designs for four different (series) SAHP systems were developed. Basically the systems are: - an all air system; - an all water system; - an air collector and water storage system; and - a water collector and rock storage system. The systems were configured in detail with considerable flexibility so that many sub-systems can be derived from each one. Furthermore, control algorithms were specified for each of the systems and each was successfully simulated with TRNSYS. The results were made available to other DOE contractors.

- The program focused on the single family home as the largest, most homogeneous market to which to relate its assessment of system marketability. A considerable amount of data on the characteristics of such dwelling units was collected from all 50 states and utilized in a unique way to develop annual home heating costs by fuel source and system type for subsequent use in comparing SAHP systems with heat pumps and conventional systems.

- To check the correlation between life cycle cost (LCC) and marketability and to illustrate the effects of local variations of such significant factors as fuel cost and availability, detailed LCC data were collected and analyzed for newly constructed houses in three cities: Fort Worth, TX; Dallas, TX; and Madison, WI, for gas, oil, electric resistance, and heat pump heating systems. It was found that heat pump sales were not directly related to their LCC.

- Although heat pump sales are not correlated to a single independent variable, a multivariate correlation analysis showed that they are reasonably well correlated (correl. coef. = 0.85) to eight marketing variables, including the number of new single family starts and the number of new gas heating services. A similar study is required for SAHP systems when that market begins to develop.

5. Domestic Hot Water Heating, Addendum. In addition to the thermal and economic analysis of SAHP and competing space heating systems, the Analytical Model was used to assess the effects of collector tilt on the system's life cycle cost.

- The results of this study showed that the energy savings, accrued when changing the collector tilt from vertical (south facing) to that of the latitude, justify an incremental installation cost of approximately $7 per square foot in New York, NY, climates and approximately $4 per square foot in Forth Worth, TX, climates.

FUTURE ACTIVITIES.

Contract Activities. The only remaining major task is the publication of the final report. Presently a draft of this report is being reviewed by the cognizant autnorities.

Post-Contract Activities. A number of post-contract research areas have been identified. They include:

- o Collector parameter study. A study, by means of the Analytical Model to evaluate the consequences of the availability of collectors with improved performance and higher costs as well as those with inferior performance at lower cost. This study will help identify and select collector development projects that can significantly accelerate the market penetration of solar energy systems.

- o Dual source SAHP control algorithm. A study, with a modified form of the Analytical Model Program, to aid in formulating and assessing superior algorithms for selecting which of the two evaporators will be used at any time. The study will provide an indication of the inherent capabilities of dual source SAHP systems and will thereby aid in encouraging the development of cost effective SAHP systems.

- o Analytical model of a ground coupled heat pump. A project to devise an analytical model of a ground coupled heat pump that will yield an improved understanding of 1) the capability of the ground to provide short and long term storage, and 2) the interaction between the near and far ground fields. This effort will also enhance the development of control strategies that optimize system performance.

PUBLICATIONS/REFERENCES.

1. "A SAHP System Analysis Model", Systems Simulation and Economic Analysis for Solar Heating and Cooling, 175, U.S. DOE (1978).

2. "The Economic Constraints on Solar Energy, Heat-Pump, and Solar Assisted Heat Pump Systems". Proc. 1978 Annual Meeting Amer. Sect. Int. Sol. Energy Soc., 2.1, 288, Ed. K. W. Boer and G. E. Franks (1978).

3. "SAHP-2: Analytical Selection of Marketable SAHP Systems", 3rd Annual Solar Heating and Cooling R&D Contractors' Meeting, U.S. DOE (1978).

4. "Analytical Selection of Marketable SAHP Systems", Solar Energy and Conservation Symposium-Workshop, 41, Ed. T. N. Veziroglu, Univ. of Miami (1978).

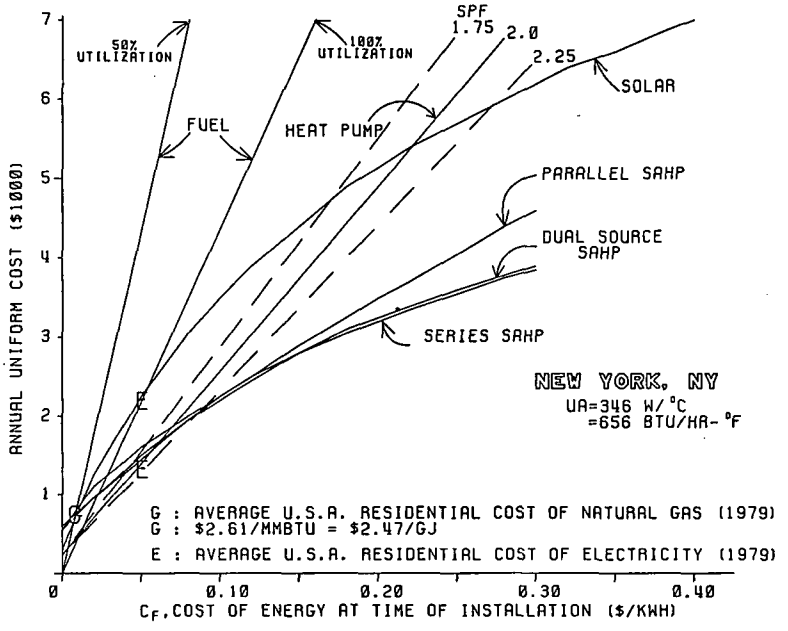
5. "Economically Optimum Thermal Storage Size via

Marginal Analysis", Proc. 1979 Convention Int. Sol. Energy Soc. (1979).

6. "Optimization and Comparison Strategies for Solar Energy Systems", Amer. Soc. Mech. Eng., Winter Annual Meeting, 79-WA/Sol-26, New York, NY (1979).

7. "Analytical Selection of Marketable SAHP Systems", in Vol. I, Chap. 6 of Solar Energy and Conservation, Ed. T. N. Veziroglu, Pergamon Press (1980).

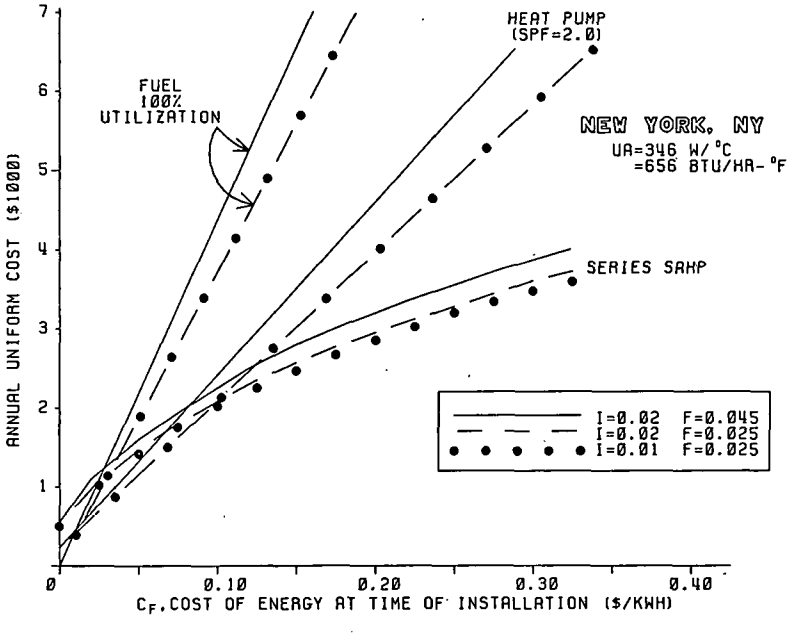
FIGURE 1



COMPARISON OF COMPETING SPACE HEATING SYSTEMS IN NEW YORK, NY, CLIMATE

The figure shows the Annual Uniform Cost (AUC) in 1979 dollars, of heating a single family house in a New York City type climate as a function of C_F, the cost of fuel at the time the system is installed. The AUC is the annual cost of owning and operating the system and is directly related to the total life cycle cost (LCC). For the assumptions used here (annual worth of money = 0.02 above inflation, fuel escalation rate = 0.045 above inflation, system lifetime = 15 years), each $1,000 of the present value of the LCC is equivalent to $77.83 of AUC. Where appropriate, the collector area and storage volume have been sized at each value of C_F to minimize the AUC of the system.

FIGURE 2



SENSITIVITY OF AUC TO

-F, ANNUAL FUEL ESCALATION RATE
-I, ANNUAL WORTH OF MONEY

Three sets of curves depict the Annual Uniform cost of owning and operating three types of heating systems:

- 100% efficient, conventionally fueled systems
- heat pump systems with SPF=2
- series SAHP systems

versus C_F, the cost of fuel at the time the systems are installed. All systems are used to heat a single family house in a New York City type climate. For all curves, the system lifetime is 15 years and the values of F and I are above inflation.

INSTRUMENTATION AND MONITORING OF THE TWIN CROWN REALTY BUILDINGS IN DENVER, COLORADO

SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INC.

DE-AC03-79CS-30115

DAVID K. HAYS

JUNE 11, 1979 - DECEMBER 11, 1980

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 & 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}).

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 favorably 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.

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.

V SOLAR SPACE HEATING SYSTEMS

OVERVIEW OF SOLAR COLLECTOR AND MATERIALS R&D FOR ACTIVE BUILDINGS

MATERIALS, ENGINEERING, AND COLLECTOR DEVELOPMENT FOR SPACE AND WATER HEATING

Charles A. Bankston
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

This paper presents a brief overview of the activities and accomplishments of the 100 projects that constitute the solar collector and materials R&D program. The program includes basic studies in collector engineering and materials as well as the development of collectors for heating, cooling and heat pump applications. Part 1 covers the engineering and materials R&D projects as well as the development of collectors for space and water heating applications.

BACKGROUND

The National Program for Solar Heating and Cooling Research and Development was established by ERDA in 1976 based in large measure on the directed research and development plan contained in the publication ERDA-77-144 (now available as DOE/CS-0008). Solar collector and materials R&D was one element of the original component and technology oriented national program. The program was initially managed by Dr. Stephen L. Sargent, a program manager in the Research and Development Branch of the Office of Solar Applications, then headed by Dr. Frederick H. Morse.

The majority of the 100 projects that have comprised the collector and materials element resulted from a series of solicitations issued in the spring of 1977. These solicitations identified needed R&D work in nearly 60 categories, but the broad areas of emphasis were as shown in Table I.

TABLE I

SOLAR COLLECTOR AND COLLECTOR MATERIALS R&D PROGRAM

	No. of Projects	
COLLECTOR DEVELOPMENT		
Nonconcentrating Air Heaters	14	
Low Temp., $T < 120^{o}F$		4
Med. Temp., $120 < T < 170^{o}F$		8
High Temp., $T > 170^{o}F$		2
Funding Through FY-79: $1500K		
Nonconcentrating Liquid Heaters	17	
Low Temp., $T < 120^{o}F$		1
Med. Temp., $120 < T < 170^{o}F$		9
High Temp., $T > 170^{o}F$		7
Funding Through FY-79: $3379K		
Concentrating Collectors	15	
Low Temp., $T < 120^{o}F$		0
Med. Temp., $120 < T < 170^{o}F$		4
High Temp., $T > 170^{o}F$		11
Funding Through FY-79: $3468K		
COLLECTOR STUDIES	24	
Funding Through FY-79: $4374K		
MATERIALS R&D	29	
Absorbers		6
Glazings and Coatings		11
Fluids/Corrosion		7
Insulating Materials		3
Sealants		2
Funding Through FY-79: $4037K		
PROGRAM SUPPORT	1	
Funding Through FY-79: $1230K		
TOTAL PROJECTS: 100		
TOTAL FUNDING: $17988K		

Table I also shows the number of projects associated with each of these areas. Approximately 1/2 of the early emphasis has been on development and improvement of collectors that are primarily for building applications. The balance of the program involves collector engineering and materials research and development, which is intended to augment the technological base. The program plan called for much of the collector engineering and materials work to be done before embarking on the collector development work, but due to funding considerations and procurement realities, the order was actually reversed. The program is presently heavily slanted toward technology-base activities.

In 1979, the Office of Solar Applications reorganized, under Fred Morse's leadership, along applications rather than technology lines. This has lead to a subdivision of the collector and materials research program into parts that are most supportive of Active Building Systems, Agricultural and Industrial Process Heat, and Passive/Hybrid applications. This is realistic, to some degree, with the collector development projects, because the characteristics of the collector often dictate its application. The collector studies and materials research and development, however, generally apply more or less uniformly to all three areas. We have, therefore, not made any arbitrary distinction between these projects. Figure 1 shows the program matrix.

Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting
March 1980

SOLAR COLLECTOR PROGRAM MATRIX

FIGURE 1

	ABSORPTION	AGRICULTURAL & INDUSTRIAL PROCESS HEAT	PASSIVE/HYBRID
COLLECTOR DEVELOPMENT	• HIGH TEMPERATURE (COOLING) • MEDIUM TEMPERATURE (HEATING) • LOW TEMPERATURE (SOLAR ASSISTED HEAT PUMPS)	• TRACKING • STATIONARY - EVACUATED SOLAR COLLECTORS (ESC) - PONDS	• AIR HEATERS • THERMOSIPHON
MATERIALS AND ENGINEERING	• MATERIALS - ABSORBERS - GLAZINGS - FLUIDS/CORROSION - INSULATION - SEALANTS • ENGINEERING STUDIES - HEAT TRANSFER - APPLICATIONS - ENGINEERING	• MATERIALS - ABSORBERS - GLAZINGS - FLUIDS/CORROSION - INSULATION - SEALANTS • ENGINEERING STUDIES - HEAT TRANSFER - ENGINEERING	• MATERIALS - ABOSRBERS - GLAZINGS - INSULATION - SEALANTS
SUPPORT	• DIRECT SPACE AND WATER HEATING	• MASS PRODUCIBLE COMPONENTS • ESC AND PONDS	

The current programmatic and technological emphasis in the collector program is shown in Figure 2. For hot water systems, flat-plate liquid heaters have become standard and are commercial. The industry and, to a great extent, government, have turned their attention to the market place. Additional research and development technology needs to be accomplished, however. In terms of components, the long-term durability and reliability are vital issues--assuring durability and reliability is largely a matter of proper selection and application of materials and engineering design practice without adding excessively to the cost. The greatest market barrier is first cost, and cost reduction is, therefore, an area of technological emphasis; the development of inexpensive or low-mass, long-lived materials again holds the key. Evacuated collectors are promising for hot water applications because they are made from low-cost materials and, in large volume, may be produced quite inexpensively. Although their high temperature capability is not needed, their ability to operate efficiently in cold weather and with very little insolation is an attribute.

Both air and liquid heating flat-plate collectors are available for direct space heating applications, supplied by more than 300 manufacturers. At the component level, the collector emphasis is essentially the same as for the hot water application--durability, reliability, and lower cost through improved materials and processes. Space heating systems, on the other hand, are not nearly so well standardized as hot water systems, and much development and integration remain to be done. There are benefits to be derived from improved integration of the solar collectors with the other solar components and with the building envelope as well. In the case of air heating systems, the need is especially acute. Air systems frequently operate at performance levels well below their potential because of inadequate design and installation practices and ill-suited system components. Building integrated, perhaps site-built, collectors represent a promising approach.

Salt-gradient stabilized solar ponds and tracking collectors are candidates for building heating as elements of large or small solar utilities or district heating systems. Such systems are receiving increasing attention in Europe and elsewhere and do look very attractive when integrated with long-term thermal energy storage. Solar ponds are in an early stage of development and require major research attention in order to understand the destabilizing influences and how to control them. Tracking collector development has been supported for a number of years by solar thermal applications and has reached an advanced stage of technical development. Cost reduction is a major requirement and, once again, the technological emphasis is on low-cost material and improved production methods.

Solar assisted heat pumps are one of the more controversial applications of solar energy. There is no universal agreement on their cost effectiveness in relation to unassisted heat pumps or alternative system configurations. There is general agreement, however, that in order to compete economically, any solar heat pump system must utilize very low-cost solar collectors. Thus, the emphasis for collector development has been placed on achieving low cost through the use of light weight construction and low-cost materials. As an example, very low mass collectors may be made by laminating several sheets of thin plastic film in a high-speed process. Development of suitable materials and processes is certainly the key issue for collector technology in this application.

Current solar cooling technology is not cost competitive, and its energy effectiveness is marginal. Two avenues to improved thermal/mechanical performance are the development of far more efficient low source temperature chillers to work

FIGURE 2
SOLAR COLLECTOR PROGRAM EMPHASIS

APPLICATION	COLLECTOR TECHNOLOGY	PROGRAM EMPHASIS	TECHNOLOGY EMPHASIS
HOT WATER	FLAT PLATE-LIQUID	MARKETING	DURABILITY/RELIABILITY, COST
	ESC	DEVELOPMENT	PERFORMANCE, PRODUCTION
DIRECT SPACE	FLAT PLATE-LIQUID	SYSTEM DEVELOPMENT	DURABILITY/RELIABILITY, COST
	FLAT PLATE-AIR	SYSTEM DEVELOPMENT	SYSTEM DESIGN AND INTEGRATION
	ESC	DEVELOPMENT	PERFORMANCE, PRODUCTION
	PONDS	R & D	PERFORMANCE, COST, APPLICATIONS
HEAT PUMPS	FLAT PLATE-LIQUID	DEVELOPMENT	MATERIALS (PLASTICS)
COOLING	ESC	DEVELOPMENT	PERFORMANCE, PRODUCTION
	TRACKING	DEVELOPMENT	COST, DURABILITY/RELIABILITY

with present collectors or the development of simple, reliable, and safe high-temperature collectors for building cooling. Non-tracking collectors are currently capable of operating at temperatures up to about 250-300°F at reasonable efficiencies without seasonal adjustment. Higher temperatures usually require 3 to 12 tilt adjustments per year. The technological challenge is to develop collectors that are capable both of producing high temperatures efficiently and of operating in a simple, safe, durable, and nearly maintenance-free condition. Tracking collectors, of course, are capable of much higher temperatures. Large tracking collectors can be used for building cooling as part of a solar utility where proper maintenance and repair could be assured.

Collectors for industrial application must be made more cheaply because of industry's stringent requirement for a high rate of return on investment. In addition to the development of low-cost materials and processes, the engineering of large module collectors that lend themselves to low-cost mass production and installation becomes increasingly important.

Passive or hybrid applications also benefit from work contained in the collector program. Low-cost materials developed for collector applications are often highly suitable for use in passive applications. Polymers for glazing, thermal insulation, and sealing or gasket compounds are also examples. In addition, the increasing interest in hybrid heating systems may bring with it a requirement for special air heating collectors that are optimized for use in natural convection systems rather than forced air systems.

In the following sections the projects that comprised the program as of the end of FY-79 are described and some of the major accomplishments are listed. Many of the projects are presented in more detail in the proceedings. The materials R&D and collector engineering projects are presented in this part of the paper along with the medium temperature collector development work. The development of high temperature collectors for cooling and low temperature collectors for heat pump application are discussed in Parts 2 and 3 in the cooling and heat pump sections of these proceedings.

ACCOMPLISHMENTS

Materials R&D - Absorbers, Glazings and Coatings

Objectives. This program subelement's general objectives are those of assessing, developing, testing, and evaluating materials and processes for passive, heating and cooling, and AIPH applications. The present range of operating conditions and environments for the various materials is wide and varied. Each application or operating range requires that the cost/performance/durability parameters be quantified for each class of conditions.

The projects covered in this program subelement represent the attempt being made to encompass the broad spectrum of solar materials so desperately needed.

PROJECT/AMOUNT	DESCRIPTION	TERM
Honeywell AR $184K	Low-Cost AR Coatings on Glass	7/78-9/79
Honeywell IR $132K	Development of IR Selective Coatings	8/78-10/79
Hughes $162K	Development of New Polymeric Materials	7/78-7/79
IITRI $445K	Solar Exposure Testing & Evaluation	3/77-4/79
Owens-Illinois $265K	Develop Improved AR Coatings for ESC	9/78-5/80
RTI $154K	Investigate Silicone Glazings	9/78-9/80
Springborn $178K	Evaluate Polymers for Glazings & Coatings	9/78-9/80
Tufts University $73K	Study of Optics of Indium Oxide Films	6/78-5/80
U. Wisconsin $248K	Study of Inhibition of Photodegradation	6/78-5/80
Berry $148K	Develop Commercial Electroplated Selective Surfaces	9/78-9/80

PROJECT/AMOUNT	DESCRIPTION	TERM
Honeywell $142K	Improve Black Chrome Electroplating	6/78-11/79
Honeywell $116K	Develop Inexpensive Selective Paints	6/78-11/79
Lockheed $125K	Evaluate Commercial Selective Coatings	9/78-12/79
Penn State $67K	Evaluate Black Germanium Selectivity	9/78-6/79
Sperry-Univac $64K	Develop Fluid for Absorbing Liquid Collector	9/78-12/79
Telic $83K	Investigate Selective Sputter Coatings	8/79-3/80

Project Activities and Accomplishments

• Honeywell has provided technical assistance to Norell, Inc., a small glass processor in Minneapolis, Minnesota, in the development of effective processes for etching several low-iron glasses used in solar applications. These additional glasses include ASG Water White, ASC Solatex and CE Heliotherm brand glasses. When the program is completed, collector manufacturers will be able to purchase a wide range of glasses having an overall transmission of 95% or greater owing to the antireflective properties of the etched surface.

• Hughes Aircraft Company has developed two new copolymers which have the potential of becoming effective solar glazing polycarbonates. Again, the search for durable, cheap, weatherable, lightweight glazing materials engages many other solar researchers.

• Illinois Institute of Technology Research Institute has conducted a three year program to determine the effects of solar irradiation and environmental exposure on the mechanical and optical properties of materials used in solar collectors. The results of this effort have been compiled and will soon be published in handbook form.

• Owens-Illinois has investigated the use of AR coatings in evacuated solar collectors and has developed improved selective absorber surfaces for their all-glass collectors.

• Research Triangle Institute has determined that silicone glazing materials are potentially cost-competitive with glass. All of the commercially available organosilicone materials have been obtained or fabricated and are undergoing weathering in EMMA, EMMAQUA, and on south-facing racks. Samples are removed periodically for evaluation. Detailed investigations of uv degradation are underway. In addition, the problem of dust and dirt retention is being studied.

• Springborn Laboratories is conducting a survey and evaluation of plastic materials for collector glazing and housing applications. They are also developing procedures for laminating different plastics in order to obtain composite films that are stronger and more uv resistant than the individual sheets. This work could have important implication for the development of low-cost collectors.

• Tufts University has developed two methods for precise index of refraction measurements. Two measuring methods, the Brewster/Ables and the Prism-Coupled Optical Waveguide techniques, have been developed to precisely measure the refractive index at 633 mm. wavelength. The measurements are being utilized to evaluate two refractive index models, which are currently yielding good predictability for Fe-, B-, Al-, Sn-, Zr-, and combined (B- + Sn-) doped indium oxide films. Changes in the refractive index associated with oxidation, reduction anneals are also being evaluated.

Indium oxide has potential applications as a heat mirror but has high visible reflectivity due to its high index of refraction. Learning to modify its refractive index could lead to greater utility in collector systems.

• University of Wisconsin has demonstrated the ability of cerium ions to down-convert uv radiation to less damaging frequencies. If practical means of implanting the ions on the surface of plastic films could be found, it could prove to be a very effective means of controlling photodegradation.

• Berry's work on process control has permitted the reduction in price of electroplated black chrome to $0.80/ft^2. While the actual objective of the project is to investigate means of improving selective surfaces on copper, aluminum and stainless steel, the reduction in cost of this process benefits the entire solar program.

• Honeywell has made significant progress in the development of inexpensive optically selective paints for solar collectors and other applications. Two application techniques are being developed - very thin paint films applied to metal foils which may then be bonded to absorber surfaces, and paints containing metal particles which may be applied in thick coatings by conventional painting techniques such as brush, spray, or roller. Extremely thin "thickness sensitive" coatings, have been produced with solar absorptances of 0.90 and infrared emittances of 0.10. The metal flake "thickness insensitive" concept has resulted in solar absorptances of 0.90 and emittances of 0.30. Manufacturing costs to produce the thickness sensitive system including an adhesive backing might be as low as 6¢/ft^2. Material cost of the thickness sensitive paint could be as low as 1¢/ft^2.

• Lockheed has evaluated fourteen selective absorbers and reported on the results. A few additional coatings have been added for the final, longer-duration testing. All the coatings tested to date had relatively good stability.

• Penn State University has completed a study of black germanium as a solar selective absorber surface. Although the coating does exhibit moderately selective properties and could probably be produced at low cost, it is quite fragile. This problem was not addressed and would probably limit its suitability for low temperature solar collector applications.

• Sperry Univac has developed a superior black liquid for plastic collectors. This leaves plastic material selection as the last remaining problem for black liquid collector commercialization. The black liquid is a carbon suspension using Zanflo, and Xanthan gum derivative, to provide excellent re-suspension qualities for the carbon particles. Fluid was successfully tested outdoors as well as in the laboratory.

• Telic successfully carried out their Phase III task of continuously sputtering a cermet film on aluminum foil. This work establishes the potential for producing useful quantities of selective surface coated foil by a low-cost process.

Materials R&D - Heat Transfer Fluids and Corrosion

Objectives. The principal objectives of these projects are (1) to survey and evaluate the characteristics of superior, cost-effective liquid coolants; (2) to elucidate the corrosion problems and their cures for aqueous coolants with inhibitors and anti-freezes in multi-metallic collectors and systems, and (3) to enumerate the various techniques of freeze protection and their costs.

PROJECT/AMOUNT	DESCRIPTION	TERM
Battelle $206K	Study Corrosion by Aqueous Coolants	9/78-9/79
Dow Corning $120K	Identify Superior Liquid Coolants	9/78-12/79
EIC $202K	Develop Electro-deposited Polymer Films	5/78-11/79
U. of Florida $50K	Investigate Vegetable Oil Coolants	9/78-3/80
Giner $183K	Develop Corrosion Inhibitors for AL	6/78-7/80
Monsanto $156K	Survey Heat Transfer Fluids	8/78-4/80

Project Activities and Accomplishments

• Battelle Memorial Institute has completed two important reports. The first is a thorough annotated bibliography of the corrosion literature applicable to solar energy - this should be a valuable resource to those engaged in corrosion research. The second report presents an in-depth analysis of the current status of technology in the prediction and prevention of corrosion for combination of metals and fluids used in solar systems. The latter report should be of interest to system and component designers.

• Dow Corning selected four fluids for a comparative evaluation: Syltherm TM 444, Uniroyal PAO-LV, Ethylene Glycol/H_2O, and Propylene Glycol/H_2O. These fluids were subjected to extended stagnation testing in solar collectors at New Mexico State University. Olin Metals Research Laboratories did the corrosion evaluation of the absorber panels from those collectors. D.C. did physical property measurements, toxicity testing and stability testing on these fluids. Based on life-cycle costing, the propylene glycol water system is the most expensive and the Syltherm TM 444 silicone is the least expensive. A final report on this study is due early in 1980.

• EIC has succeeded in getting protective films to form on AL, Fe and Cu, and the films did inhibit corrosion. These coatings are electrochemically deposited polymers. Although adhesion of the films and pinholes remain problems, this work has demonstrated that electrochemical deposition of films to inhibit corrosion is possible.

• University of Florida has completed its study of vegetable oils as possible solar coolants. The thermo-physical properties of several natural oils were obtained in order to evaluate their use in high temperature solar applications. Cost and performance evaluation for the use of these oils were established. The materials are: cottonseed oil, corn oil, peanut oil and soybean oil.

• Giner, Inc. has demonstrated that zinc particles in glycol-water solutions provide protection against pitting corrosion for aluminum panels at temperatures up to 160°C. The work is continuing in order to better define the mechanism and to identify the most practical means of implementing the protection. This is an important finding for the manufacturers of aluminum collectors since it may extend their utility to higher temperatures and a greater variety of fluids.

• Monsanto Research Laboratory has completed the first phase of a survey of fluids for use in solar energy systems and has compiled the physical, thermal and transport properties of over 50 commercially available fluids. This compilation is available in their final report and should be valuable to component and system designers.

Materials R&D - Insulation

Objectives. The general objective of this program subelement is to provide the solar industry with insulation materials and the pertinent information that is necessary to design cost-effective solar heating and cooling systems that must use insulation on a number of the components.

The first objective is to establish the criteria for the insulation on the various components since properties other than the heat transport characteristics often dictate the choice of material. For example, consider the insulation requirements for flat-plate collector housings: maximum temperature 204°F, temperature cycling endurance between -29°C and 121°C, and thermal conductance less than 0.57 $W/M^2{}^oC$. If binders are used in the insulation, they must not outgas and deposit on the cover plate. Freon-blown materials release products that form acids and corrode the selective coatings, etc. The usual basis for a useful technological assessment of industrial thermal insulation materials is the temperature, a necessary, but not sufficient measure of value.

PROJECT/AMOUNT	DESCRIPTION	TERM
Dow Corning $141K	Develop Foamed Silicone Insulation	9/78-9/79
Solar Turbines $132K	Develop Polyimide Foam Insulation	8/78-1/80
Versar $116K	Survey Insulation for Solar Collectors	9/78-1/80

Project Activities and Accomplishments

- Dow Corning has produced and characterized silicone elastomeric foams (in a range of densities) for use as solar collector insulation. One selected foam was stagnation tested by DSET Lab. This foam matched fiberglass insulating efficiency and meets HUD performance requirements. Economic analysis indicates that use of the most expensive silicone insulation has very small impact on the total cost of the solar system.

- Solar Turbines International has produced and evaluated polyimide foam insulation for solar applications. Flexible foams with densities of 1.3 to 1.5 lb/ft^3 and rigid foams with densities of 10 to 70 lb/ft^3 were produced. All foams have good insulating and thermal and environmental stability, and in addition, are non-burning and non-smoking. Their higher cost may be justified in applications where fire safety is important.

- Versar has completed their survey and evaluation of existing insulation materials for use in solar systems. Survey of insulation manufacturers is complete. Data from the survey and from the literature have been tabulated and evaluated. Insulation materials and applications for both active and passive systems were documented. Multi-function uses of insulation were investigated. Collector manufacturers will now have a single document to consult to determine the properties of insulation currently on the market.

Materials R&D - Sealants

Objective. The objective of this facet of the materials R&D program is to survey and evaluate pertinent characteristics of a variety of sealants for use in solar collectors and to develop improved sealing materials and methods for collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
Products R&C $71K	Develop Sealants for 400°F Service	9/78-8/79
Westinghouse $186K	Evaluate Collector Sealants & Breathing	9/78-12/79

Project Activities and Accomplishments

- Products Research and Chemical has identified fluorocarbons and some silicones for sealant use at high temperatures. They have documented, through extensive testing, the best available sealants for solar use. Sealants were examined for compatability and use in solar collectors by testing in the following areas: corrosion, compression set, hydrolytic stability, ultraviolet light exposure, ozone and fungus exposure, thermal aging, outgassing products and chemical degradation. The final report should be very useful to collector designers and manufacturers.

- Westinghouse has documented through extensive testing the best available sealants for solar use. Sealants were examined for compatability and use in solar collectors by testing in the following areas: corrosion, compression set, hydrolytic stability, ultraviolet light exposure, ozone and fungus exposure, thermal aging, outgassing products, and chemical degradation. These data are also important to designers and manufacturers of solar collectors.

Collector Studies - Applications

Objectives. Projects in this program element seek to identify the best type of collectors for specific applications or to determine the heat applications for certain collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
American Helio. $98K	Heat Pump Applications Study	9/18/78-4/17/80
Altas $59K	Hail Risk Studies	7/10/78-11/30/79
InterTech. Corp. $107K	Mirror & Lens Concentrators	8/1/78-11/30/79
Trident Engineering $128K	Survey and Evaluation of ESC	8/7/78-9/30/79

Project Activities and Accomplishments

- American Heliothermal is studying the use of low-cost solar collectors in various heat pump systems. Their work will include economic and technical assessments. A second phase of the projects involves experimental determination of the heat transfer from large area unglazed collectors such as might be appropriate for heat pump applications.

- Altas has developed the methodology for predicting the probability of collector arrays of a given size being hit by stones of a given diameter from the meterological information including the yearly number of hail days in a given location and some general information about the size spectrum. The capability to produce nationwide hail damage and economic risk assessment for nearly all parts of the country now exists. This is important for designers, owners and insurers of solar collector installations.

- InterTechnology has completed a study of mirror and lens concentrators for building application. The study includes tracking and stationary concentrators, but emphasizes the lower concentration ratio types. The final report contains both performance and economic comparisons of commercially available concentrators for various heating loads and solar fractions.

- Trident Engineering has completed a comprehensive study of all available and proposed evacuated solar collectors. Their final report includes details of the collector design, application and cost data, comparison of four commercially available collectors in a hypothetical 2000 ft^2 system

simulated in Albuquerque and Boston, a survey of development work, a compilation of systems employing ESC, and an extensive reference list. The report should be of considerable interest to designers of heating and cooling and AIPH systems.

Collector Studies - Engineering

Objectives. The general objective of the projects that constitute this program element is to provide the engineering methods, data, and guidelines needed by designers of collectors or collector arrays.

PROJECT/AMOUNT	DESCRIPTION	TERM
EG&G $93K	Survey Tracking Mechanisms and Joints	8/78-8/79
Honeywell $156K	Study Requirements for Mirrors and Lenses	9/78-12/79
U. of Penn. $80K	Collector Array Studies	9/78-2/80
Solar Resources $91K	Study Use of Reflectors with F.P. Collectors	9/78-9/79
Texas A&M $133K	Structural Requirements for Wind Loads	6/76-8/80

Project Activities and Accomplishments

• EG&G has completed their project to survey tracking mechanisms and rotary joints for coolant piping. The final report contains the following: the tracking problem is thoroughly analyzed analytically and families of curves generated to predict performance of various collector systems, both single and dual axis. Typical performance specifications and daily operational requirements are established. Various actuators, error detectors and interface amplifiers are analyzed. Fluid couplings and heat transfer fluids are investigated. Several alternate conceptual design approaches are presented.

• Honeywell has completed their survey of mirrors and lenses for concentrating collectors, and an assessment of the accuracy requirements for their reflecting or refracting surfaces. Eleven tracking and non-tracking concentrator designs were selected for detailed evaluation. Results for the eleven concentrators are contained in the final report, presented in graphic form. A survey data base was established on the effect of environmental exposure on the optical degradation of mirrors and lenses.

As a part of this work a flexible Monte Carlo ray trace computer program has been developed and is presented in the final report along with a guide to its use. Both the survey and the computer program should be valuable to designers of optical elements for concentrating collectors.

• University of Pennsylvania is continuing its development of computer methods and experimental data to assist in the design and optimization of collector arrays. The calculations take into account array optics such as shading, the hydraulic and thermal losses associated with the interconnecting piping, the influence of flow distribution on array efficiency, and the economics. Sensitivity and parametric calculations are performed.

• Solar Resources is studying the use of planar reflectors to augment the performance of flat plate collectors.

• Texas A&M has completed a three-year study of wind loads on solar collectors and their supporting structures. The investigation was conducted in three major parts: wind tunnel tests to define loads; full-scale collector tests for comparative data; and structural analysis to define design procedures. A final report summarizing the results of the investigation, which should be of value to system designers, has been issued. An ongoing program extending the study to investigate dynamic effects has begun.

Engineering Studies - Heat Transfer

Objectives. The general objective of this group of projects is to provide detailed information and engineering data on the internal and external heat transfer processes in various types of solar collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
Northrop $40K	Study of Air Heat Transfer Augmentation	9/78-6/79
U. of Penn. $139K	Analysis of Free Convection	9/78-9/80
Purdue U. $142K	Study of Forced Convection	9/78-9/80
Tenn. Tech. $71K	Study Effects of Wind	9/78-10/79
Virginia Poly. $40K	Heat Transfer at Low Pressure	8/78-7/80

Project Activities and Accomplishments

• Northrop Services, Inc. performed a solar collector systems analysis to evaluate various techniques for enhancing the heat transfer between the absorber and the air stream. One solar collector design providing ducted cooling air on the absorber shaded side was selected for detailed study. A transient heat transfer analysis of a complete collector was used to demonstrate that an optimum absorber-to-air heat exchanger design could be provided with several "interrupted" fin configurations. Analyses were performed to establish that the maximum energy collected per unit pumping power was realized for a Reynolds number range of 1000 to 2000. This Reynolds number range was used to establish a theoretical design limit curve for all "interrupted" fin designs as published in the open literature. Heat and momentum transfer empirical relationships were defined for scaling the state-of-the-art high conductance fin designs identified from a "compact" configuration to the less compact designs needed for solar collectors.

• University of Pennsylvania project has the ultimate objective to develop correlating equations which can be used to design or to predict the heat losses from absorber plates in flat plate collector--both air and liquid cooled. The first step was to

modify an existing computer program in order to obtain detailed flow patterns and temperature profiles in the various air gaps (for different heater configurations) as a function of aspect ratios, inclinations and rotations for both isothermal and non-isothermal surfaces. The reduction of the data into appropriate heat loss correlations will be started when the theoretical results have been verified.

• Purdue University has completed a two-dimensional analysis of a flat plate air heating solar collector. This analysis considers multiple cover plates with air flow above, below and both above and below the absorber plate. This is a realistic analysis of a general class of flat plate collectors.

This project is also obtaining information on forced and natural convection in air-heating solar collectors through theoretical, experimental, and technological studies. These convective heat transfer and fluid mechanics relationships are applicable to several different collector configurations. The surveys of the literature and technology have been completed. The first phase of the analysis and experimentation was devoted to flat plate and louvered collectors in various configurations (5 total).

• Tennessee Tech has completed a study of the effect of winds on heat losses from collectors and collector arrays. Their final report presents improved equations for calculating the convective heat transfer from the collector cover and includes the effects of collector orientation, array configuration, adjacent buildings, etc. This information should be of value to system designers and researchers.

• Virginia Polytechnic Institute has confirmed approximate theoretical models showing that initial pressures of 10^{-4} to 10^{-3} Torr would reduce conduction losses to 1 to 10% of radiation losses in evacuated collectors at 150°C.

A literature search was carried out to determine the availability of previous calculations and data needed to develop a quantitative model for heat conduction effects. Work to develop pertinent models of heat flow in parallel plate and tubular collectors is complete. Coincidence of this work with parallel experimental work at Owens-Illinois has provided the chance to compare the model with observed behavior for helium in a tubular collector. This project is now waiting for experimental results from Owens-Illinois.

Medium Temperature Collectors for Hot Water and Space Heating

Objective. The general objective of this program element is to foster the development by industry of solar collectors that are suitable and cost-effective for direct space and hot water heating applications within the residential and light commercial market sectors. The appropriate temperature range is generally considered to be 120 - 170°F.

PROJECT/AMOUNT	DESCRIPTION	TERM
UCLA $115K	Develop Transpired Solar Air Heating Collector	9/30/77-9/30/80
Solaron $148K	Develop Evacuated Cover System for Air Heaters	9/15/78-4/30/80
TEA $142K	Write Handbook for Site-Built Solar Collector	9/30/77-2/29/80
Westinghouse $306K	Develop Low-Cost Evacuated Tube Air Heater	8/1/78-12/31/79

Project Activities and Accomplishments

• UCLA has tested a number of collector configurations employing combinations of honeycomb glazing and solid or transpired absorber plates. In their quarterly report for December they report preliminary results for a collector using a honeycomb glazing of glass cylinders and Teflon film and a porous absorber. The performance of this configuration was encouraging, but further development is needed to overcome some mechanical difficulties.

• Solaron is investigating the use of evacuated fluorescent tubes as covers for flat plate air heating collectors. GTE Sylvania is the subcontractor for the evacuated tubes.

• TEA has been developing a comprehensive handbook dealing with site-built collectors for air-heating systems. The manual will provide detailed instructions for fabricating effective, economical and reliable air-heating collectors and for integrating them into a building's roof, wall structure and heating system. The handbook is being written for the builder or home owner and should receive wide distribution. It is expected to have considerable influence on small builders.

• Westinghouse has completed design and analysis of an evacuated tube air heating collector.

Stationary Collectors - Ponds

Objective. The primary objective of this program element is to conduct the research necessary to understand the physical processes that control the stability and efficiency of salt gradient solar ponds and utilize this information to design ponds that will be stable, effective, and economical.

PROJECT/AMOUNT	DESCRIPTION	TERM
Argonne National Laboratory $80K	Develop Numerical Models of Solar Ponds	10/79-9/80
DRI $97K	Investigate Saturated Ponds	9/79-4/81
ITC $24K	Evaluate Salts for Saturated Ponds	9/79-5/80
Los Alamos Scientific Lab $80K	Theoretical Studies of Salt-Gradient Ponds	10/79-9/80

PROJECT/AMOUNT	DESCRIPTION	TERM
Mound Lab. $80K	Instrument and Monitor Miamisburg Pond	5/78-5/81
UNM $156K	Study Stability of Solar Pond	9/77-8/80
Ohio State $225K	Conduct High-Temperature Research Pond	9/77-1/80

Project Activities and Accomplishments

- Argonne is developing a modified version of its two-dimensional, incompressible fluid dynamics code, COMMIX-SA-SP, to investigate various salt pond phenomena. The program and models will be validated and documented.

- Desert Research Institute has found that precipitation of borax during cooling of the saturated pond left a white coating on the pond bottom. This, in turn, caused loss of bottom heating and loss of the gradient. This experiment proves the need for vanes or other mechanisms to assure a dark surface on the bottom of the pond during cooling.

- InterTechnology Corporation is investigating the use of carbonate-sodium bicarbonate in saturated ponds.

- LASL has initiated theoretical studies of various aspects of solar ponds behavior.

- Mound monitors the pond that supplies heat to a swimming pool-recreational complex at Miamisburg, Ohio. During the fall of 1979 workers discovered a leak in the pond liner. The leak was located and temporary repairs were made without draining the pond.

- University of New Mexico has written two reports on all facets of solar pond operation. One report contained a stability analysis allowing for varying temperature and salinity gradients. This lead to a technique of using measured temperatures and salinity profiles to ascertain proximity to layer instability.

  The first report covers pond operation, heat extraction, layer behavior, stability and filling techniques. The second report covers salt diffusion, the Soret effect, and an investigation of salts suitable for a saturated pond. Progress was made in thermal modeling. The pond was covered and heat loss compared to calculation. Observed losses were higher.

- Ohio State University has completed construction of their new pond. Fencing for the new pond was completed in September, 1979. Salt was added during October and November. The installation of the data acquisition system is underway. Progress was made on the writing of a microcomputer program to average radiation input and do energy balance calculations. The new pond is now operating. The principal investigator is visiting India and Israel, under other funding, to exchange information on ponds.

FUTURE ACTIVITIES

Much of the work discussed above is in progress and is expected to be completed during FY 80. Every effort will be made to see that the important results from these projects are reported and disseminated quickly to the solar community. Final reports will be distributed through the Technical Information Center (and in some cases through special mailings), and technical papers will be prepared for presentation at meetings and for publication in professional journals.

The technical program support staff at LASL has initiated an effort to compile, evaluate and select information and engineering data generated by the 100 collector projects over the past four years and prepare a solar collector design handbook. Program generated information will be supplemented with information from the solar, engineering design, materials science, thermal science and manufacturing literature in order to provide collector designers and manufacturers with a single comprehensive and authorative data source for all their needs. At the same time, the handbook will represent the essence of the multi-year, 18 million dollar collector and materials R&D program.

The continuing collector and materials program is expected to emphasis technology base building through engineering studies and materials R&D and some the development of collectors for the more demanding applications.

REFERENCES

A listing of completed solar collector projects whose final reports are to be distributed through TIC was prepared and distributed at the conference. A complete publications list of all major reports and papers generated by the participants in the solar collector and materials program is in preparation and will be available from LASL.

SOLAR SPACE HEATING SYSTEMS USING ANNUAL HEAT STORAGE

UNIVERSITY OF TORONTO

DE-AC02-76CS32939

F.C. HOOPER

MARCH, 1979 to MARCH, 1980

OBJECTIVE

The objectives of this project are generally to investigate solar space heating systems utilizing annual storage of solar heated water and carry on research to establish the relationship between the primary weather variables and the optimum system configuration. The primary objective is to develop a simple algorithm allowing calculation of the optimum system.

CONCEPT

An annual storage solar heating system incorporates a much larger thermal storage unit than the corresponding short term system. This permits collection of available solar energy throughout the year, greatly increasing the solar system efficiency, defined as the annual heat load supplied by solar divided by the annual solar energy incident on the collector array. Because of the high thermal capacity of the system, short term variability in the weather can be ignored and systems can be designed to provide 100% of the building heat demand from the solar source for a typical year. The annual storage temperature cycle typical for such systems is shown in Figure 1 for a designed community of two 100-unit apartment buildings in Madison, Wisconsin, sharing a common storage tank and collector system.

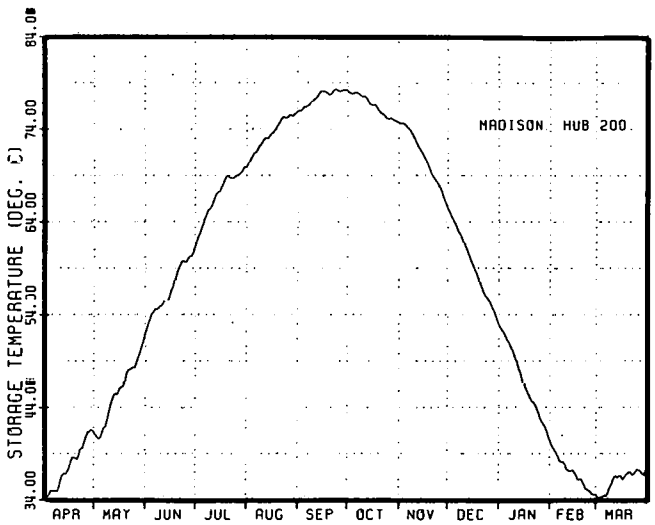


Figure 1. Annual Storage Temperature Cycle for a Designed Community of Two 100-unit Apartment Buildings in Madison, Wisconsin.

SUMMARY

An hourly Annual Storage solar Energy Program (ASTEP) has been developed to predict the performance of annual storage solar heating systems. This has allowed the determination of optimum configurations given certain cost assumptions. The hourly computer simulation performance predictions are in general agreement with measured data from two operating annual storage systems. The general usefulness of this program was shown in a recent project with SERI, in which a preliminary sensitivity analysis was performed to examine significant correlations of parameters for annual storage design.

This led to the development of methods for the initial approximation of optimum system configurations for any location or building type.

TECHNICAL ACCOMPLISHMENTS

- From our analysis we can say that for buildings of more than about 10,000 square feet of floor area, and for the insolation conditions typical of the northern states, annual storage systems providing 100% of the space heat requirement from the solar source appear to be more cost effective than shorter term storage systems supplying their optimum proportion of the load (usually about 60%). Small district heating systems where a single storage is shared by the community appear to offer the most cost-effective means of solar heating for smaller buildings (i.e.

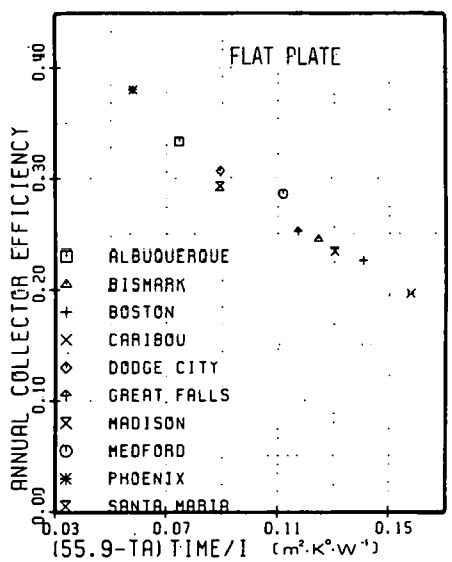


Figure 2. The Annual Operational Collector Efficiency as a Function of the Annual Incident Insolation and the Average Ambient Air Temperature During Daylight Hours for a Typical Flat-Plate Collector.

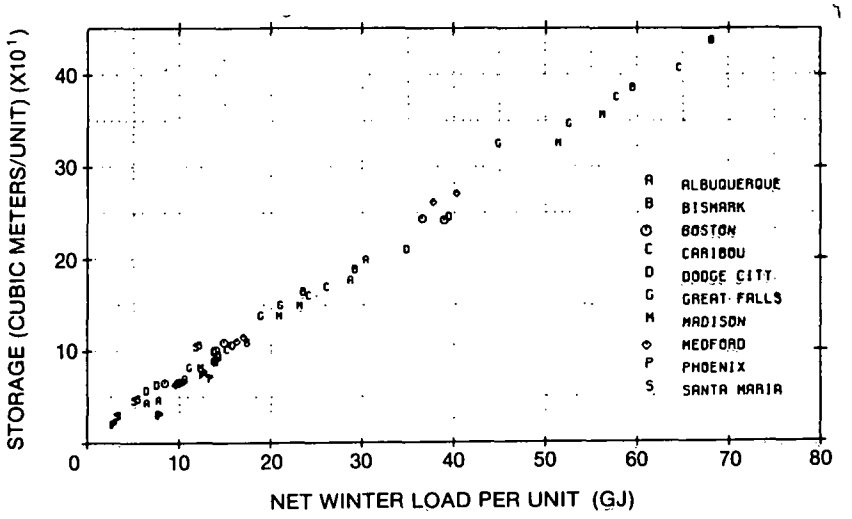


Figure 3. Storage Size vs. Net Winter Load (NWL) Correlation. NWL = Σ (Monthly Load-Monthly Gain)$^+$

single family residences) in insolation conditions typical of the northern states.

• Annual storage systems sized for unconstrained performance (no heat rejected, and design maximum and minimum storage temperature reached once per year) have been found to effectively minimize the solar acquisition cost, provided the solar fraction of the total load is large.

• Ideas have been developed for a generalized method of storage-collector sizing for unconstrained annual storage systems. Initial sizing approximations are based on an annual operational collector efficiency (see Figure 2) for determining collector area, and the net winter load (see Figure 3) for describing the amount of stored energy required to carry over the winter heating season. The annual operational collector efficiency has been found to be location specific, but independent of building type.

FUTURE ACTIVITIES

Performance data, where available, will be reported on the existing annual storage installations. A users guide to the hourly simulation program (ASTEP) will be prepared with appropriate design data.

It is anticipated in the future that we will be able to prepare a design handbook for annual storage solar heating systems based on the current development of a generalized method of storage-collector sizing. Examination of the various system efficiencies should provide an analytically based method for annual storage design which would complement existing design methods for short term systems. The handbook would include design guidelines for minimizing storage construction and operating costs over a range of site conditions.

PUBLICATIONS/REPORTS

1. Report COO-2939-1. "Solar Space Heating Systems Using Annual Storage". Progress Report for Period July 1, 1976 to December 31, 1976.
2. Hooper, F.C. and C.R. Attwater. "Optimization of an Annual Storage Solar Heating System Over It's Life Cycle". DOE Report No. COO-2923-2.
3. Hooper, F.C. "Seasonal Heat Storage for Solar Space Heating Systems in Cold High Latitude Locations". Presented at the Conference of Solar Energy in Cold Climates, University of Detroit, June, 1976.
4. Hooper, F.C. and C.R. Attwater. "A Design Method for Heat Loss Calculation for In-Ground Heat Storage Tanks". DOE Report No. COO-2923-3. Presented at the Conference on Heat Transfer in Solar Energy Systems, sponsored by ASME, Atlanta, Ga., November, 1977.
5. Report COO-2939-4. "Solar Space Heating Systems Using Annual Storage". Progress Report for Period January 1, 1977 to June 30, 1977.
6. Hooper, F.C. "The Effects of Collector Tilt and Orientation on Solar Heating Performance". Presented to Solar Energy Update '77, Solar Energy Society of Canada 3rd Annual Meeting and Conference, August 22-24, 1977.
7. Report COO-2939-5. "Solar Space Heating Systems Using Annual Heat Storage". Progress Report for Period July 1, 1977 to December 30, 1977.
8. Report COO-2939-6. "Solar Space Heating Systems Using Annual Heat Storage". Progress Report for Period January 1, 1978 to September 30, 1978.
9. Williams, G.T., C.R. Attwater and F.C. Hooper. "A Design Method to Determine the Optimal Distribution and Amount of Insulation for In-Ground Heat Storage Tanks". DOE Report No. DOE-CS-32939-7. Presented at the International Solar Energy Society Silver Jubilee Congress, Atlanta, Ga., May, 1979.
10. Hooper, F.C. and J.D. McClenahan. "Effect of Latent Heat on Frost Penetration in Moist Soil". DOE Report No. DOE-CS-32939-8. Presented at the Seventh Canadian Congress of Applied Mechanics, Sherbrooke, Quebec, Canada, May 27, 1979 to June 1, 1979.
11. Hooper, F.C. and A.P. Brunger. "A Model for the Angular Distribution of Sky Radiance". DOE Report No. DOE-CS-32939-9. Presented at the Joint ASME/AIChE 18th National Heat Transfer Conference, San Diego, Calif., August 6-8, 1979.
12. Hooper, F.C. and J.D. Cook. "Design of Annual Storage Solar Space Heating Systems". DOE Report No. DOE-CS-32939-10. Presented at the 72nd Annual AIChE Meeting, San Francisco, Calif., November 25-29, 1979.
13. Hooper, F.C., J.D. McClenahan, J.D. Cook, F. Baylin, R. Monte and S. Sillman. "Analysis of Community Solar Systems for Combined Space and DHW Heating Using Annual Cycle Thermal Energy Storage". No. DOE-CS-32939-11. 2nd Systems Simulation and Economics Analysis Conf., San Diego, Jan. 23-25, 1980.

DEVELOPMENT OF A SITE-FABRICATED BUILDING-INTEGRATED AIR SOLAR HEATING SYSTEM

TOTAL ENVIRONMENTAL ACTION, INC.

DE-FG04-77CS34123 MOD A002

PETER L. TEMPLE

BEGIN 9/30/77 END 4/30/80

OBJECTIVE

The general goal of this project was the development of a cost-effective, durable, site-fabricated solar air heating system. The specific objectives of the study were: (1) Development of a site-fabricated solar air heater design with performance comparable or superior to presently available manufactured systems, but which can be installed at only one-half the cost of the manufactured systems. (2) Development of the air heater design so that it can be cost-effectively integrated into building structures in the majority of potential building situations with a minimum of construction problems. (3) Development of sufficient technical and economic data, drawings, and other information to promote the application of the design.

CONCEPT

The purpose of this project was to significantly lower the cost of active solar systems by: (1) designing a collector which shares several of its components with the building, reducing duplication of materials, and (2) developing a low-cost delivery and storage system. Since commercially available active systems have only been marginally cost-effective in residential applications, TEA believed the introduction of an effective low-cost design would fulfill a tremendous need. In the predicted growth of residential solar applications there was clearly a definite role for economical active systems, even though passive solar systems prove an attractive option for much new construction. It was felt that for many buildings a combination of active and passive solar systems would be the best solution, while for others, only one or the other system-type would be appropriate.

Any new building design should be influenced by the principles of passive solar, at least to the extent of having some direct gain windows on the south wall. In cases where it might be difficult to integrate a passive system requiring a large aperture area on the wall, (for example, when a traditional house design is desired), the best option may be an active roof collector. In addition, in many climates the only way of achieving a high solar fraction is by combining both passive wall systems and active roof systems. Active collectors also have the advantage of permitting a large aperture area over a fully insulated wall or roof. This means the rate of heat loss or gain of the building is not increased--a particularly important consideration in cold climates which do not have a great deal of sun, and in climates which experience hot summers.

In retrofitting existing buildings for solar, active becomes an even more likely option. Existing buildings often do not have a large wall area with a solar exposure, but do have a well exposed roof. Then a large roof collector and a complete storage system is the best way of achieving a sizeable solar heating fraction. Even if there is a wall with good solar exposure, the plan of the house may not allow for the use of passive systems--for example, the south wall may be the garage wall. In these situations an active wall collector can be very useful, delivering the heat wherever it is most needed. If the collector area is not large, no storage is required (the collector being run only when heat is needed) and costs are dramatically reduced. Thus, there are many retrofit and new construction situations where active systems are a more attractive option than passive systems, or at least more attractive than the sole use of passive systems.

The decision to develop an air system, rather than a liquid design, was based on the consideration of a number of issues. Air collectors are simpler to build on-site for those without plumbing skills, and the collector materials are usually less expensive. The collectors are not subject to catastrophic freezing, and long-term corrosion is not a problem. The only long-term degradation problem is air leakage. The MODEL-TEA collector is initially assured to be air-tight by incorporating a smoke test into the construction process; at anytime thereafter the collector can be retested and recaulked if leaks are suspected. Liquid collectors have the distinct advantage of potentially higher heat removal efficiency factor (F_R). In addition, the liquid delivery and storage systems occupy much less space than those for air. Altogether the advantages and disadvantages of the two types of systems seem fairly equal. TEA's decision to develop an air system was influenced by the belief that it could produce a design which cost less, did not leak, and could be easily integrated (including duct work) into most buildings.

The final design had to fulfill many criteria. In order to promote widespread use, it had to be low-cost, simple, and easy to build using conventional techniques. Visual appearance was very important; the collector had to be considered an attractive addition to homes, or at least not a detractive one. But at the same time the system had to perform well, be reliable, and maintain long-term durability under very demanding conditions of extreme temperature variations and weathering. This set of requirements established a very challenging project goal.

SUMMARY

The specific accomplishments were: (1) Survey of existing site-fabricated solar air heaters. (2) Assessment of materials for site-fabricated collectors. (3) Evaluation of alternative collector designs and selection of best design. (4) Optimization of selected design based upon theoretical performance study. (5) Experimental testing of collector modules and comparison with theoretical predictions. (6) Experimental testing of site-built glazing systems for roof collector applications. (7) Development of design for site-built Air-handling and Control Systems. (8) Development of Rock Bin storage design. (9) Creation of design for low-cost innovative air-handling system utilizing one-way rock bed. (10) Preparation of Construction Manual for MODEL-TEA Solar Heating System. (11) Dissemination of final air solar system design.

TECHNICAL ACCOMPLISHMENTS

- TEA began the project by conducting a nationwide survey of existing site-fabricated solar air heaters. A questionnaire was developed to obtain information on materials used, costs, design specifications, detailed construction drawings and procedures, collector performance, and problems and solutions. A list of approximately 40 names and addresses of builders of site-fabricated air collectors was compiled from Shurcliff's Solar Heated Buildings: A Brief Survey, TEA's contacts with collector builders and component suppliers, and referrals from site builders. Of these, 27 were contacted and agreed to complete the questionnaire; 20 questionnaires were returned. Description information relating to materials, construction, and problems was very complete, but quantitative information on performance was sketchy.

- The next accomplishment of the project was an extensive review of all materials available for site-fabricated air collectors. Information was gathered primarily from manufacturers, but many independent sources such as testing laboratories and actual builders were incorporated as well. Glazing materials, absorber plates, collector paints, sealants, fasteners, and structural materials were evaluated with respect to available sizes, physical properties, and cost. The review and selection of materials was perhaps the single most critical aspect of the collector design development. The material requirements of the delivery and storage systems were somewhat familiar, but the collector provided a very challenging set of demands. In choosing these materials, the most important considerations are usually performance, durability, cost, and attractiveness. But for a site-fabricated collector, materials must also be readily available and easy to handle and fabricate. Ideally, a site-built collector should be constructed from standard building materials which are familiar to the builder. However, a collector is a much more demanding application of materials than normal building construction. The collector materials are subject to extreme temperature variations over a twenty-four hour period, and large daily temperature differences between inner and outer layers. They must endure intense ultra-violet radiation and high temperatures for at least twenty years, while still maintaining all their desirable physical properties and retaining the air-tight and water-tight joints. It is a difficult problem, because on the one hand the materials should be standard, familiar, inexpensive, and commonly available, but on the other hand they must perform outstandingly well in an application which is far more exacting than standard construction. The final choices for the TEA design were the result of an extensive assessment of all materials available for site-built solar systems.

- The evaluation of alternative collector designs was the third major accomplishment. Six collectors were designed based on the results of the questionnaire, the materials survey, and TEA design experience. Collector parameters were theoretically determined for each design, collector efficiency curves were calculated, and annual performance was determined in two cities using F-chard. Material and labor costs were established for each design, and construction simplicity, ease of building integration, reliability, durability, and aesthetics were evaluated. Through this process the project staff selected the best design of the six.

- The fourth major accomplishment was the optimization of this selected design. The effects on collector performance of: (1) air mass flow rate, (2) collector plate length, (3) collector channel configuration, (4) paint emissivity, (5) insulation, and (6) glazing alternatives were studied. In addition, procedures were developed to determine the optimum air flow rate, collector path length, and channel size for various specific applications.

- To pursue the study of this optimum design, five collector test modules were constructed and tested according to strict industry test procedures (ASHRAE 93-77 standards and the HUD 30-day stagnation test). A standard, commercially manufactured air collector was tested on the same equipment for direct comparison. This allowed not only a direct check of the site-fab design vs. the manufactured, but also allowed a comparison with testing results on the manufactured collector obtained by another nationally recognized independent testing laboratory. The overall purpose of the testing program was to provide basic performance numbers for comparison with the theoretical predictions, and to allow a direct evaluation of the collector modules regarding such considerations as durability, ease of construction, weathering, and aesthetics. The modules differed in the types of glazing material, absorber surface, and amount of caulking material.

The testing program produced a wealth of valuable information. The measured efficiency of the basic design showed excellent agreement with TEA's theoretical calculations, and the TEA design performed at least as well as the commercially manufactured collector. In addition, after more than 30 days of summertime stagnation, the collector efficiency did not decrease. The test modules showed no degradation due to weathering or high temperature stagnation. All the collector modules were tested for leakage, and the results demonstrated that eliminating leaks is probably the most critical aspect of site-building an air collector. As a result of these tests, TEA has specified a smoke test as an integral part of the construction process, and it has been demonstrated in actual installations that the collector can readily be made air-tight.

One of the most valuable results of this testing program concerned glazing materials. Although the project staff was seriously considering glass, due in large part to aesthetic considerations, three types of plastic glazing materials were tested on the modules.

One type was a total failure, and the other showed serious problems, making glass the ultimate choice.

• The search for a method of fastening the glass to the collector arrived at three alternatives, and to assist in choosing among these, another testing program was begun. A full scale mock-up of a 60° tilt roof was constructed, and the three glazing systems were mounted side-by-side. The test provided information about the ease of installation and weathering characteristics of each system. For the roof collector, it was essential that the glass and glazing system be easy to handle and install under difficult conditions. The three glazing systems tested were a standard greenhouse system, an EPDM extrusion system, and a system consisting of 2 layers of flat EPDM strips with an outer aluminum bar. The third option was selected for the final design.

• The seventh major accomplishment was the development of the air-handling systems. After surveying current designs, TEA began work on a simple low-cost design which could be integrated into existing buildings or used in new construction. For small collectors (usually on walls) only a very simple system was required, as no storage would be employed. In these applications a fan and ductwork would deliver the heated air from the collector directly to the living space whenever there was both demand for heat and sufficient sunshine. But for larger collectors a storage rock bin would be used, and a more complicated air-handling system would be required. It was important that this system not depend on any particular building configuration, since it had to be adaptable to either new construction or retrofit.

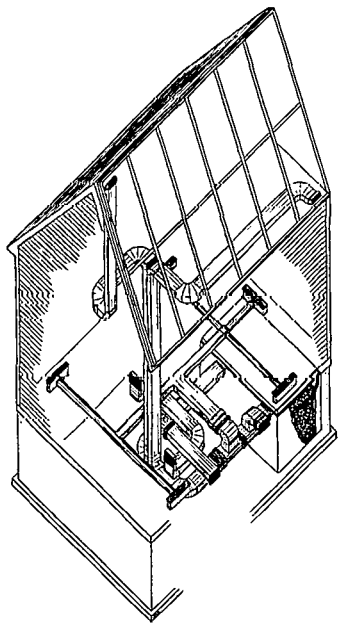


Figure 1: Air Solar Heating System

Based on TEA's research, and its experience with design and installation of solar air heating systems, a final design was completed which uses two fans and three standard low leakage dampers. In existing buildings this system is installed independently of the present conventional heating system (in parallel). This enables a straightforward installation, no matter what type of heating system is present. In new construction the solar system replaces a conventional heating system. Auxiliary heating is accomplished by inserting the heater in the ductwork so it is in series with the solar system, resulting in beneficial preheating by solar even when the latter cannot carry the entire load. This series installation is possible in new construction since the auxiliary can be carefully integrated with the design of the solar system, and since new buildings do not require an extensive heat distribution system, due to their high level of insulation. Thus, a properly designed new building can result in a substantial savings due to the synthesis of the solar and auxiliary heating systems.

• The next major accomplishment was the development of a rock bin storage design which could be easily and inexpensively built from standard materials, would perform well, and could be readily integrated into most building situations. The design is a two-way rock bin which employs a U-shaped air flow path allowing both inlet and outlet duct connections to be made at the top of the bin, and limiting the overall height. These are important features when retrofitting rock bins into existing basements where space may be tight. Rocks can usually be dumped into the bin on a chute through a basement window. For houses on slabs, the rock bin must be integrated into a space on the first floor. The rock bin is constructed on site from standard framing lumber, and lined with plywood and Gypsum board. Joints are carefully caulked and taped to prevent air leakage, and the bin is fully insulated.

• TEA also developed an innovative air-handling system which utilized a one-way rock bed. This system can be built at a significantly lower cost, but it is more critically dependent upon precise sizing and engineering, and requires extensive integration with the building design. For this reason, this system is only suitable for new construction, where the designer can carefully integrate the system needs with the building design. The one-way rock bed allows a much simpler air-handling system, and thorough building integration permits major savings in ductwork. The system has two modes. In the first mode, collection mode, air is drawn from the house to the collector, heated, blown through the rock bed and returned to the house. In the second mode, storage to house, air is drawn from the house to the rock bed, heated, and delivered back to the house. Air flow through the rock bed is in the same direction in both modes. The auxiliary heater is located in series between the rock bed and the living space, and whenever the solar-heated air cannot meet the house heating demand, the auxiliary boots the air temperature. The rock bed can be integrated into a wall or under a floor.

• The tenth major accomplishment was the preparation of a Construction Manual on the "MODEL-TEA Solar Heating System." The manual provides complete plans, photographs, and step-by-step instructions for the entire solar system--collector, air-handling, controls, and storage. It also contains a wealth of information on the development of the design, solar basics, materials analysis, and engineering of solar systems. Complete cost information is presented which shows that although the MODEL-TEA performs as well as manufactured systems, it costs less than one-half as much. Using this manual, the MODEL-TEA can readily be constructed by a local building contractor, or a homeowner who is well-acquainted with construction techniques.

• The final accomplishment of the project is the dissemination of the design. A vigorous program is being implemented to inform builders, contractors, developers, designers, and architects about the design. TEA is teaching MODEL-TEA workshops to homeowners, builders, and other professionals. In addition, TEA is working with other organizations such as the National Association of Solar Contractors to assist in disseminating the design.

FUTURE ACTIVITIES

Contract activities. TEA is presently completing the final task, Dissemination of the Design, and will submit the final technical report by April 30, 1980.

Post-contract activities. Site-built solar systems should play a major role in solar space-heating applications. TEA believes that there are many projects which can be effectively pursued to develop and promote successful designs, and the staff hopes to be very active in this area. The current project has resulted in an active solar system which performs at least as well as typical commercially manufactured systems and yet costs less than one-half as much. Still, TEA feels that there are some innovative ideas which, if successful, could increase the effectiveness of site-built active solar systems.

PUBLICATIONS/REFERENCES

"Development of a Site-Fabricated Building Integrated Air Collector", First Quarterly Report, January 20, 1978; Interim Report, April 28, 1978; Third Quarterly Report, July 31, 1978.

Construction Manual: MODEL-TEA Solar Heating System, March, 1980 (P. Temple, J. Adams)

"Evaluation of Six Designs for a Site-Fabricated, Building Integrated Air Heater. Part 1: Theoretical Performance," Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Vol. 2.1 (September, 1978) (J. Coleman, J. Kohler, P. Sullivan, P. Temple).

"Evaluation of Six Designs for a Site-Fabricated, Building Integrated Air Heater, Part II: Cost, Seasonal Performance, Building Integration, Reliability and Aesthetics," Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Vol. 2.1.(September, 1978) (J. Coleman, J. Kohler, P. Sullivan, P. Temple).

"Development of a Site-Fabricated, Building Integrated Air Collector, Part 1: Evaluation of Alternative Collector Designs," Proceedings of the First Annual New England Site-Built Collector Conference, December, 1978 (J. Coleman, J. Kohler, P. Sullivan, P. Temple).

"The MODEL-TEA Site-Fabricated Building Integrated Air Collector, June, 1979. ASHRAE Annual Meeting (J. Kohler, P. Sullivan P. Temple).

"Choosing a Glazing Material for a Site-Fabricated Solar Collector," Proceedings of the 1979 Solar Glazing Conference sponsored by Mid-Atlantic Solar Energy Association, June, 1979 (P. Temple).

VI SOLAR HOT WATER SYSTEMS

dup of 5.1

OVERVIEW OF SOLAR COLLECTOR AND MATERIALS R&D FOR ACTIVE BUILDINGS

MATERIALS, ENGINEERING, AND COLLECTOR DEVELOPMENT FOR SPACE AND WATER HEATING

Charles A. Bankston
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

This paper presents a brief overview of the activities and accomplishments of the 100 projects that constitute the solar collector and materials R&D program. The program includes basic studies in collector engineering and materials as well as the development of collectors for heating, cooling and heat pump applications. Part 1 covers the engineering and materials R&D projects as well as the development of collectors for space and water heating applications.

BACKGROUND

The National Program for Solar Heating and Cooling Research and Development was established by ERDA in 1976 based in large measure on the directed research and development plan contained in the publication ERDA-77-144 (now available as DOE/CS-0008). Solar collector and materials R&D was one element of the original component and technology oriented national program. The program was initially managed by Dr. Stephen L. Sargent, a program manager in the Research and Development Branch of the Office of Solar Applications, then headed by Dr. Frederick H. Morse.

The majority of the 100 projects that have comprised the collector and materials element resulted from a series of solicitations issued in the spring of 1977. These solicitations identified needed R&D work in nearly 60 categories, but the broad areas of emphasis were as shown in Table I.

TABLE I

SOLAR COLLECTOR AND COLLECTOR MATERIALS R&D PROGRAM

	No. of Projects	
COLLECTOR DEVELOPMENT		
Nonconcentrating Air Heaters	14	
Low Temp., $T < 120^{o}F$		4
Med. Temp., $120 < T < 170^{o}F$		8
High Temp., $T > 170^{o}F$		2
Funding Through FY-79: $1500K		
Nonconcentrating Liquid Heaters	17	
Low Temp., $T < 120^{o}F$		1
Med. Temp., $120 < T < 170^{o}F$		9
High Temp., $T > 170^{o}F$		7
Funding Through FY-79: $3379K		
Concentrating Collectors	15	
Low Temp., $T < 120^{o}F$		0
Med. Temp., $120 < T < 170^{o}F$		4
High Temp., $T > 170^{o}F$		11
Funding Through FY-79: $3468K		
COLLECTOR STUDIES	24	
Funding Through FY-79: $4374K		
MATERIALS R&D	29	
Absorbers		6
Glazings and Coatings		11
Fluids/Corrosion		7
Insulating Materials		3
Sealants		?
Funding Through FY-79: $4037K		
PROGRAM SUPPORT	1	
Funding Through FY-79: $1230K		
TOTAL PROJECTS: 100		
TOTAL FUNDING: $17988K		

Table I also shows the number of projects associated with each of these areas. Approximately 1/2 of the early emphasis has been on development and improvement of collectors that are primarily for building applications. The balance of the program involves collector engineering and materials research and development, which is intended to augment the technological base. The program plan called for much of the collector engineering and materials work to be done before embarking on the collector development work, but due to funding considerations and procurement realities, the order was actually reversed. The program is presently heavily slanted toward technology-base activities.

In 1979, the Office of Solar Applications reorganized, under Fred Morse's leadership, along applications rather than technology lines. This has lead to a subdivision of the collector and materials research program into parts that are most supportive of Active Building Systems, Agricultural and Industrial Process Heat, and Passive/Hybrid applications. This is realistic, to some degree, with the collector development projects, because the characteristics of the collector often dictate its application. The collector studies and materials research and development, however, generally apply more or less uniformly to all three areas. We have, therefore, not made any arbitrary distinction between these projects. Figure 1 shows the program matrix.

SOLAR COLLECTOR PROGRAM MATRIX

FIGURE 1

	ABSORPTION	AGRICULTURAL & INDUSTRIAL PROCESS HEAT	PASSIVE/HYBRID
COLLECTOR DEVELOPMENT	• HIGH TEMPERATURE (COOLING) • MEDIUM TEMPERATURE (HEATING) • LOW TEMPERATURE (SOLAR ASSISTED HEAT PUMPS)	• TRACKING • STATIONARY - EVACUATED SOLAR COLLECTORS (ESC) - PONDS	• AIR HEATERS • THERMOSIPHON
MATERIALS AND ENGINEERING	• MATERIALS - ABSORBERS - GLAZINGS - FLUIDS/CORROSION - INSULATION - SEALANTS • ENGINEERING STUDIES - HEAT TRANSFER - APPLICATIONS - ENGINEERING	• MATERIALS - ABSORBERS - GLAZINGS - FLUIDS/CORROSION - INSULATION - SEALANTS • ENGINEERING STUDIES - HEAT TRANSFER - ENGINEERING	• MATERIALS - ABOSRBERS - GLAZINGS - INSULATION - SEALANTS
SUPPORT	• DIRECT SPACE AND WATER HEATING	• MASS PRODUCIBLE COMPONENTS • ESC AND PONDS	

The current programmatic and technological emphasis in the collector program is shown in Figure 2. For hot water systems, flat-plate liquid heaters have become standard and are commercial. The industry and, to a great extent, government, have turned their attention to the market place. Additional research and development technology needs to be accomplished, however. In terms of components, the long-term durability and reliability are vital issues--assuring durability and reliability is largely a matter of proper selection and application of materials and engineering design practice without adding excessively to the cost. The greatest market barrier is first cost, and cost reduction is, therefore, an area of technological emphasis; the development of inexpensive or low-mass, long-lived materials again holds the key. Evacuated collectors are promising for hot water applications because they are made from low-cost materials and, in large volume, may be produced quite inexpensively. Although their high temperature capability is not needed, their ability to operate efficiently in cold weather and with very little insolation is an attribute.

Both air and liquid heating flat-plate collectors are available for direct space heating applications, supplied by more than 300 manufacturers. At the component level, the collector emphasis is essentially the same as for the hot water application--durability, reliability, and lower cost through improved materials and processes. Space heating systems, on the other hand, are not nearly so well standardized as hot water systems, and much development and integration remain to be done. There are benefits to be derived from improved integration of the solar collectors with the other solar components and with the building envelope as well. In the case of air heating systems, the need is especially acute. Air systems frequently operate at performance levels well below their potential because of inadequate design and installation practices and ill-suited system components. Building integrated, perhaps site-built, collectors represent a promising approach.

Salt-gradient stabilized solar ponds and tracking collectors are candidates for building heating as elements of large or small solar utilities or district heating systems. Such systems are receiving increasing attention in Europe and elsewhere and do look very attractive when integrated with long-term thermal energy storage. Solar ponds are in an early stage of development and require major research attention in order to understand the destabilizing influences and how to control them. Tracking collector development has been supported for a number of years by solar thermal applications and has reached an advanced stage of technical development. Cost reduction is a major requirement and, once again, the technological emphasis is on low-cost material and improved production methods.

Solar assisted heat pumps are one of the more controversial applications of solar energy. There is no universal agreement on their cost effectiveness in relation to unassisted heat pumps or alternative system configurations. There is general agreement, however, that in order to compete economically, any solar heat pump system must utilize very low-cost solar collectors. Thus, the emphasis for collector development has been placed on achieving low cost through the use of light weight construction and low-cost materials. As an example, very low mass collectors may be made by laminating several sheets of thin plastic film in a high-speed process. Development of suitable materials and processes is certainly the key issue for collector technology in this application.

Current solar cooling technology is not cost competitive, and its energy effectiveness is marginal. Two avenues to improved thermal/mechanical performance are the development of far more efficient low source temperature chillers to work

FIGURE 2
SOLAR COLLECTOR PROGRAM EMPHASIS

APPLICATION	COLLECTOR TECHNOLOGY	PROGRAM EMPHASIS	TECHNOLOGY EMPHASIS
HOT WATER	FLAT PLATE-LIQUID ESC	MARKETING DEVELOPMENT	DURABILITY/RELIABILITY, COST PERFORMANCE, PRODUCTION
DIRECT SPACE	FLAT PLATE-LIQUID FLAT PLATE-AIR ESC PONDS	SYSTEM DEVELOPMENT SYSTEM DEVELOPMENT DEVELOPMENT R & D	DURABILITY/RELIABILITY, COST SYSTEM DESIGN AND INTEGRATION PERFORMANCE, PRODUCTION PERFORMANCE, COST, APPLICATIONS
HEAT PUMPS	FLAT PLATE-LIQUID	DEVELOPMENT	MATERIALS (PLASTICS)
COOLING	ESC TRACKING	DEVELOPMENT DEVELOPMENT	PERFORMANCE, PRODUCTION COST, DURABILITY/RELIABILITY

with present collectors or the development of simple, reliable, and safe high-temperature collectors for building cooling. Non-tracking collectors are currently capable of operating at temperatures up to about 250-300°F at reasonable efficiencies without seasonal adjustment. Higher temperatures usually require 3 to 12 tilt adjustments per year. The technological challenge is to develop collectors that are capable both of producing high temperatures efficiently and of operating in a simple, safe, durable, and nearly maintenance-free condition. Tracking collectors, of course, are capable of much higher temperatures. Large tracking collectors can be used for building cooling as part of a solar utility where proper maintenance and repair could be assured.

Collectors for industrial application must be made more cheaply because of industry's stringent requirement for a high rate of return on investment. In addition to the development of low-cost materials and processes, the engineering of large module collectors that lend themselves to low-cost mass production and installation becomes increasingly important.

Passive or hybrid applications also benefit from work contained in the collector program. Low-cost materials developed for collector applications are often highly suitable for use in passive applications. Polymers for glazing, thermal insulation, and sealing or gasket compounds are also examples. In addition, the increasing interest in hybrid heating systems may bring with it a requirement for special air heating collectors that are optimized for use in natural convection systems rather than forced air systems.

In the following sections the projects that comprised the program as of the end of FY-79 are described and some of the major accomplishments are listed. Many of the projects are presented in more detail in the proceedings. The materials R&D and collector engineering projects are presented in this part of the paper along with the medium temperature collector development work. The development of high temperature collectors for cooling and low temperature collectors for heat pump application are discussed in Parts 2 and 3 in the cooling and heat pump sections of these proceedings.

ACCOMPLISHMENTS

Materials R&D - Absorbers, Glazings and Coatings

Objectives. This program subelement's general objectives are those of assessing, developing, testing, and evaluating materials and processes for passive, heating and cooling, and AIPH applications. The present range of operating conditions and environments for the various materials is wide and varied. Each application or operating range requires that the cost/performance/durability parameters be quantified for each class of conditions.

The projects covered in this program subelement represent the attempt being made to encompass the broad spectrum of solar materials so desperately needed.

PROJECT/AMOUNT	DESCRIPTION	TERM
Honeywell AR $184K	Low-Cost AR Coatings on Glass	7/78-9/79
Honeywell IR $132K	Development of IR Selective Coatings	8/78-10/79
Hughes $162K	Development of New Polymeric Materials	7/78-7/79
IITRI $445K	Solar Exposure Testing & Evaluation	3/77-4/79
Owens-Illinois $265K	Develop Improved AR Coatings for ESC	9/78-5/80
RTI $154K	Investigate Silicone Glazings	9/78-9/80
Springborn $178K	Evaluate Polymers for Glazings & Coatings	9/78-9/80
Tufts University $73K	Study of Optics of Indium Oxide Films	6/78-5/80
U. Wisconsin $248K	Study of Inhibition of Photodegradation	6/78-5/80
Berry $148K	Develop Commercial Electroplated Selective Surfaces	9/78-9/80

PROJECT/AMOUNT	DESCRIPTION	TERM
Honeywell $142K	Improve Black Chrome Electroplating	6/78-11/79
Honeywell $116K	Develop Inexpensive Selective Paints	6/78-11/79
Lockheed $125K	Evaluate Commercial Selective Coatings	9/78-12/79
Penn State $67K	Evaluate Black Germanium Selectivity	9/78-6/79
Sperry-Univac $64K	Develop Fluid for Absorbing Liquid Collector	9/78-12/79
Telic $83K	Investigate Selective Sputter Coatings	8/79-3/80

Project Activities and Accomplishments

• Honeywell has provided technical assistance to Norell, Inc., a small glass processor in Minneapolis, Minnesota, in the development of effective processes for etching several low-iron glasses used in solar applications. These additional glasses include ASG Water White, ASC Solatex and CE Heliotherm brand glasses. When the program is completed, collector manufacturers will be able to purchase a wide range of glasses having an overall transmission of 95% or greater owing to the antireflective properties of the etched surface.

• Hughes Aircraft Company has developed two new copolymers which have the potential of becoming effective solar glazing polycarbonates. Again, the search for durable, cheap, weatherable, lightweight glazing materials engages many other solar researchers.

• Illinois Institute of Technology Research Institute has conducted a three year program to determine the effects of solar irradiation and environmental exposure on the mechanical and optical properties of materials used in solar collectors. The results of this effort have been compiled and will soon be published in handbook form.

• Owens-Illinois has investigated the use of AR coatings in evacuated solar collectors and has developed improved selective absorber surfaces for their all-glass collectors.

• Research Triangle Institute has determined that silicone glazing materials are potentially cost-competitive with glass. All of the commercially available organosilicone materials have been obtained or fabricated and are undergoing weathering in EMMA, EMMAQUA, and on south-facing racks. Samples are removed periodically for evaluation. Detailed investigations of uv degradation are underway. In addition, the problem of dust and dirt retention is being studied.

• Springborn Laboratories is conducting a survey and evaluation of plastic materials for collector glazing and housing applications. They are also developing procedures for laminating different plastics in order to obtain composite films that are stronger and more uv resistant than the individual sheets. This work could have important implication for the development of low-cost collectors.

• Tufts University has developed two methods for precise index of refraction measurements. Two measuring methods, the Brewster/Ables and the Prism-Coupled Optical Waveguide techniques, have been developed to precisely measure the refractive index at 633 mm. wavelength. The measurements are being utilized to evaluate two refractive index models, which are currently yielding good predictability for Fe-, B-, Al-, Sn-, Zr-, and combined (B- + Sn-) doped indium oxide films. Changes in the refractive index associated with oxidation, reduction anneals are also being evaluated.

Indium oxide has potential applications as a heat mirror but has high visible reflectivity due to its high index of refraction. Learning to modify its refractive index could lead to greater utility in collector systems.

• University of Wisconsin has demonstrated the ability of cerium ions to down-convert uv radiation to less damaging frequencies. If practical means of implanting the ions on the surface of plastic films could be found, it could prove to be a very effective means of controlling photodegradation.

• Berry's work on process control has permitted the reduction in price of electroplated black chrome to $\$0.80/ft^2$. While the actual objective of the project is to investigate means of improving selective surfaces on copper, aluminum and stainless steel, the reduction in cost of this process benefits the entire solar program.

• Honeywell has made significant progress in the development of inexpensive optically selective paints for solar collectors and other applications. Two application techniques are being developed - very thin paint films applied to metal foils which may then be bonded to absorber surfaces, and paints containing metal particles which may be applied in thick coatings by conventional painting techniques such as brush, spray, or roller. Extremely thin "thickness sensitive" coatings, have been produced with solar absorptances of 0.90 and infrared emittances of 0.10. The metal flake "thickness insensitive" concept has resulted in solar absorptances of 0.90 and emittances of 0.30. Manufacturing costs to produce the thickness sensitive system including an adhesive backing might be as low as $6¢/ft^2$. Material cost of the thickness sensitive paint could be as low as $1¢/ft^2$.

• Lockheed has evaluated fourteen selective absorbers and reported on the results. A few additional coatings have been added for the final, longer-duration testing. All the coatings tested to date had relatively good stability.

• Penn State University has completed a study of black germanium as a solar selective absorber surface. Although the coating does exhibit moderately selective properties and could probably be produced at low cost, it is quite fragile. This problem was not addressed and would probably limit its suitability for low temperature solar collector applications.

• Sperry Univac has developed a superior black liquid for plastic collectors. This leaves plastic material selection as the last remaining problem for black liquid collector commercialization. The black liquid is a carbon suspension using Zanflo, and Xanthan gum derivative, to provide excellent resuspension qualities for the carbon particles. Fluid was successfully tested outdoors as well as in the laboratory.

• Telic successfully carried out their Phase III task of continuously sputtering a cermet film on aluminum foil. This work establishes the potential for producing useful quantities of selective surface coated foil by a low-cost process.

Materials R&D - Heat Transfer Fluids and Corrosion

Objectives. The principal objectives of these projects are (1) to survey and evaluate the characteristics of superior, cost-effective liquid coolants; (2) to elucidate the corrosion problems and their cures for aqueous coolants with inhibitors and antifreezes in multi-metallic collectors and systems, and (3) to enumerate the various techniques of freeze protection and their costs.

PROJECT/AMOUNT	DESCRIPTION	TERM
Battelle $206K	Study Corrosion by Aqueous Coolants	9/78-9/79
Dow Corning $120K	Identify Superior Liquid Coolants	9/78-12/79
EIC $202K	Develop Electrodeposited Polymer Films.	5/78-11/79
U. of Florida $50K	Investigate Vegetable Oil Coolants	9/78-3/80
Giner $183K	Develop Corrosion Inhibitors for AL	6/78-7/80
Monsanto $156K	Survey Heat Transfer Fluids	8/78-4/80

Project Activities and Accomplishments

• Battelle Memorial Institute has completed two important reports. The first is a thorough annotated bibliography of the corrosion literature applicable to solar energy - this should be a valuable resource to those engaged in corrosion research. The second report presents an in-depth analysis of the current status of technology in the prediction and prevention of corrosion for combination of metals and fluids used in solar systems. The latter report should be of interest to system and component designers.

• Dow Corning selected four fluids for a comparative evaluation: Syltherm TM 444, Uniroyal PAO-LV, Ethylene Glycol/H_2O, and Propylene Glycol/H_2O. These fluids were subjected to extended stagnation testing in solar collectors at New Mexico State University. Olin Metals Research Laboratories did the corrosion evaluation of the absorber panels from those collectors. D.C. did physical property measurements, toxicity testing and stability testing on these fluids. Based on life-cycle costing, the propylene glycol water system is the most expensive and the Syltherm TM 444 silicone is the least expensive. A final report on this study is due early in 1980.

• EIC has succeeded in getting protective films to form on AL, Fe and Cu, and the films did inhibit corrosion. These coatings are electrochemically deposited polymers. Although adhesion of the films and pinholes remain problems, this work has demonstrated that electrochemical deposition of films to inhibit corrosion is possible.

• University of Florida has completed its study of vegetable oils as possible solar coolants. The thermo-physical properties of several natural oils were obtained in order to evaluate their use in high temperature solar applications. Cost and performance evaluation for the use of these oils were established. The materials are: cottonseed oil, corn oil, peanut oil and soybean oil.

• Giner, Inc. has demonstrated that zinc particles in glycol-water solutions provide protection against pitting corrosion for aluminum panels at temperatures up to 160°C. The work is continuing in order to better define the mechanism and to identify the most practical means of implementing the protection. This is an important finding for the manufacturers of aluminum collectors since it may extend their utility to higher temperatures and a greater variety of fluids.

• Monsanto Research Laboratory has completed the first phase of a survey of fluids for use in solar energy systems and has compiled the physical, thermal and transport properties of over 50 commercially available fluids. This compilation is available in their final report and should be valuable to component and system designers.

Materials R&D - Insulation

Objectives. The general objective of this program subelement is to provide the solar industry with insulation materials and the pertinent information that is necessary to design cost-effective solar heating and cooling systems that must use insulation on a number of the components.

The first objective is to establish the criteria for the insulation on the various components since properties other than the heat transport characteristics often dictate the choice of material. For example, consider the insulation requirements for flat-plate collector housings: maximum temperature 204°F, temperature cycling endurance between -29°C and 121°C, and thermal conductance less than 0.57 $W/M^2{}^oC$. If binders are used in the insulation, they must not outgas and deposit on the cover plate. Freon-blown materials release products that form acids and corrode the selective coatings, etc. The usual basis for a useful technological assessment of industrial thermal insulation materials is the temperature, a necessary, but not sufficient measure of value.

PROJECT/AMOUNT	DESCRIPTION	TERM
Dow Corning $141K	Develop Foamed Silicone Insulation	9/78-9/79
Solar Turbines $132K	Develop Polyimide Foam Insulation	8/78-1/80
Versar $116K	Survey Insulation for Solar Collectors	9/78-1/80

Project Activities and Accomplishments

- Dow Corning has produced and characterized silicone elastomeric foams (in a range of densities) for use as solar collector insulation. One selected foam was stagnation tested by DSET Lab. This foam matched fiberglass insulating efficiency and meets HUD performance requirements. Economic analysis indicates that use of the most expensive silicone insulation has very small impact on the total cost of the solar system.

- Solar Turbines International has produced and evaluated polyimide foam insulation for solar applications. Flexible foams with densities of 1.3 to 1.5lb/ft^3 and rigid foams with densities of 10 to 70 lb/ft^3 were produced. All foams have good insulating and thermal and environmental stability, and in addition, are non-burning and non-smoking. Their higher cost may be justified in applications where fire safety is important.

- Versar has completed their survey and evaluation of existing insulation materials for use in solar systems. Survey of insulation manufacturers is complete. Data from the survey and from the literature have been tabulated and evaluated. Insulation materials and applications for both active and passive systems were documented. Multi-function uses of insulation were investigated. Collector manufacturers will now have a single document to consult to determine the properties of insulation currently on the market.

Materials R&D - Sealants

Objective. The objective of this facet of the materials R&D program is to survey and evaluate pertinent characteristics of a variety of sealants for use in solar collectors and to develop improved sealing materials and methods for collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
Products R&C $71K	Develop Sealants for 400°F Service	9/78-8/79
Westinghouse $186K	Evaluate Collector Sealants & Breathing	9/78-12/79

Project Activities and Accomplishments

- Products Research and Chemical has identified fluorocarbons and some silicones for sealant use at high temperatures. They have documented, through extensive testing, the best available sealants for solar use. Sealants were examined for compatability and use in solar collectors by testing in the following areas: corrosion, compression set, hydrolytic stability, ultraviolet light exposure, ozone and fungus exposure, thermal aging, outgassing products and chemical degradation. The final report should be very useful to collector designers and manufacturers.

- Westinghouse has documented through extensive testing the best available sealants for solar use. Sealants were examined for compatability and use in solar collectors by testing in the following areas: corrosion, compression set, hydrolytic stability, ultraviolet light exposure, ozone and fungus exposure, thermal aging, outgassing products, and chemical degradation. These data are also important to designers and manufacturers of solar collectors.

Collector Studies - Applications

Objectives. Projects in this program element seek to identify the best type of collectors for specific applications or to determine the heat applications for certain collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
American Helio. $98K	Heat Pump Applications Study	9/18/78-4/17/80
Altas $59K	Hail Risk Studies	7/10/78-11/30/79
InterTech. Corp. $107K	Mirror & Lens Concentrators	8/1/78-11/30/79
Trident Engineering $128K	Survey and Evaluation of ESC	8/7/78-9/30/79

Project Activities and Accomplishments

- American Heliothermal is studying the use of low-cost solar collectors in various heat pump systems. Their work will include economic and technical assessments. A second phase of the projects involves experimental determination of the heat transfer from large area unglazed collectors such as might be appropriate for heat pump applications.

- Altas has developed the methodology for predicting the probability of collector arrays of a given size being hit by stones of a given diameter from the meterological information including the yearly number of hail days in a given location and some general information about the size spectrum. The capability to produce nationwide hail damage and economic risk assessment for nearly all parts of the country now exists. This is important for designers, owners and insurers of solar collector installations.

- InterTechnology has completed a study of mirror and lens concentrators for building application. The study includes tracking and stationary concentrators, but emphasizes the lower concentration ratio types. The final report contains both performance and economic comparisons of commercially available concentrators for various heating loads and solar fractions.

- Trident Engineering has completed a comprehensive study of all available and proposed evacuated solar collectors. Their final report includes details of the collector design, application and cost data, comparison of four commercially available collectors in a hypothetical 2000 ft^2 system

simulated in Albuquerque and Boston, a survey of development work, a compilation of systems employing ESC, and an extensive reference list. The report should be of considerable interest to designers of heating and cooling and AIPH systems.

Collector Studies - Engineering

Objectives. The general objective of the projects that constitute this program element is to provide the engineering methods, data, and guidelines needed by designers of collectors or collector arrays.

PROJECT/AMOUNT	DESCRIPTION	TERM
EG&G $93K	Survey Tracking Mechanisms and Joints	8/78-8/79
Honeywell $156K	Study Requirements for Mirrors and Lenses	9/78-12/79
U. of Penn. $80K	Collector Array Studies	9/78-2/80
Solar Resources $91K	Study Use of Reflectors with F.P. Collectors	9/78-9/79
Texas A&M $133K	Structural Requirements for Wind Loads	6/76-8/80

Project Activities and Accomplishments

• EG&G has completed their project to survey tracking mechanisms and rotary joints for coolant piping. The final report contains the following: the tracking problem is thoroughly analyzed analytically and families of curves generated to predict performance of various collector systems, both single and dual axis. Typical performance specifications and daily operational requirements are established. Various actuators, error detectors and interface amplifiers are analyzed. Fluid couplings and heat transfer fluids are investigated. Several alternate conceptual design approaches are presented.

• Honeywell has completed their survey of mirrors and lenses for concentrating collectors, and an assessment of the accuracy requirements for their reflecting or refracting surfaces. Eleven tracking and non-tracking concentrator designs were selected for detailed evaluation. Results for the eleven concentrators are contained in the final report, presented in graphic form. A survey data base was established on the effect of environmental exposure on the optical degradation of mirrors and lenses.

As a part of this work a flexible Monte Carlo ray trace computer program has been developed and is presented in the final report along with a guide to its use. Both the survey and the computer program should be valuable to designers of optical elements for concentrating collectors.

• University of Pennsylvania is continuing its development of computer methods and experimental data to assist in the design and optimization of collector arrays. The calculations take into account array optics such as shading, the hydraulic and thermal losses associated with the interconnecting piping, the influence of flow distribution on array efficiency, and the economics. Sensitivity and parametric calculations are performed.

• Solar Resources is studying the use of planar reflectors to augment the performance of flat plate collectors.

• Texas A&M has completed a three-year study of wind loads on solar collectors and their supporting structures. The investigation was conducted in three major parts: wind tunnel tests to define loads; full-scale collector tests for comparative data; and structural analysis to define design procedures. A final report summarizing the results of the investigation, which should be of value to system designers, has been issued. An ongoing program extending the study to investigate dynamic effects has begun.

Engineering Studies - Heat Transfer

Objectives. The general objective of this group of projects is to provide detailed information and engineering data on the internal and external heat transfer processes in various types of solar collectors.

PROJECT/AMOUNT	DESCRIPTION	TERM
Northrop $40K	Study of Air Heat Transfer Augmentation	9/78-6/79
U. of Penn. $139K	Analysis of Free Convection	9/78-9/80
Purdue U. $142K	Study of Forced Convection	9/78-9/80
Tenn. Tech. $71K	Study Effects of Wind	9/78-10/79
Virginia Poly. $40K	Heat Transfer at Low Pressure	8/78-7/80

Project Activities and Accomplishments

• Northrop Services, Inc. performed a solar collector systems analysis to evaluate various techniques for enhancing the heat transfer between the absorber and the air stream. One solar collector design providing ducted cooling air on the absorber shaded side was selected for detailed study. A transient heat transfer analysis of a complete collector was used to demonstrate that an optimum absorber-to-air heat exchanger design could be provided with several "interrupted" fin configurations. Analyses were performed to establish that the maximum energy collected per unit pumping power was realized for a Reynolds number range of 1000 to 2000. This Reynolds number range was used to establish a theoretical design limit curve for all "interrupted" fin designs as published in the open literature. Heat and momentum transfer empirical relationships were defined for scaling the state-of-the-art high conductance fin designs identified from a "compact" configuration to the less compact designs needed for solar collectors.

• University of Pennsylvania project has the ultimate objective to develop correlating equations which can be used to design or to predict the heat losses from absorber plates in flat plate collector--both air and liquid cooled. The first step was to

modify an existing computer program in order to obtain detailed flow patterns and temperature profiles in the various air gaps (for different heater configurations) as a function of aspect ratios, inclinations and rotations for both isothermal and non-isothermal surfaces. The reduction of the data into appropriate heat loss correlations will be started when the theoretical results have been verified.

• Purdue University has completed a two-dimensional analysis of a flat plate air heating solar collector. This analysis considers multiple cover plates with air flow above, below and both above and below the absorber plate. This is a realistic analysis of a general class of flat plate collectors.

This project is also obtaining information on forced and natural convection in air-heating solar collectors through theoretical, experimental, and technological studies. These convective heat transfer and fluid mechanics relationships are applicable to several different collector configurations. The surveys of the literature and technology have been completed. The first phase of the analysis and experimentation was devoted to flat plate and louvered collectors in various configurations (5 total).

• Tennessee Tech has completed a study of the effect of winds on heat losses from collectors and collector arrays. Their final report presents improved equations for calculating the convective heat transfer from the collector cover and includes the effects of collector orientation, array configuration, adjacent buildings, etc. This information should be of value to system designers and researchers.

• Virginia Polytechnic Institute has confirmed approximate theoretical models showing that initial pressures of 10^{-4} to 10^{-3} Torr would reduce conduction losses to 1 to 10% of radiation losses in evacuated collectors at 150°C.

A literature search was carried out to determine the availability of previous calculations and data needed to develop a quantitative model for heat conduction effects. Work to develop pertinent models of heat flow in parallel plate and tubular collectors is complete. Coincidence of this work with parallel experimental work at Owens-Illinois has provided the chance to compare the model with observed behavior for helium in a tubular collector. This project is now waiting for experimental results from Owens-Illinois.

Medium Temperature Collectors for Hot Water and Space Heating

Objective. The general objective of this program element is to foster the development by industry of solar collectors that are suitable and cost-effective for direct space and hot water heating applications within the residential and light commercial market sectors. The appropriate temperature range is generally considered to be 120 - 170°F.

PROJECT/AMOUNT	DESCRIPTION	TERM
UCLA $115K	Develop Transpired Solar Air Heating Collector	9/30/77-9/30/80
Solaron $148K	Develop Evacuated Cover System for Air Heaters	9/15/78-4/30/80
TEA $142K	Write Handbook for Site-Built Solar Collector	9/30/77-2/29/80
Westinghouse $306K	Develop Low-Cost Evacuated Tube Air Heater	8/1/78-12/31/79

Project Activities and Accomplishments

• UCLA has tested a number of collector configurations employing combinations of honeycomb glazing and solid or transpired absorber plates. In their quarterly report for December they report preliminary results for a collector using a honeycomb glazing of glass cylinders and Teflon film and a porous absorber. The performance of this configuration was encouraging, but further development is needed to overcome some mechanical difficulties.

• Solaron is investigating the use of evacuated fluorescent tubes as covers for flat plate air heating collectors. GTE Sylvania is the subcontractor for the evacuated tubes.

• TEA has been developing a comprehensive handbook dealing with site-built collectors for air-heating systems. The manual will provide detailed instructions for fabricating effective, economical and reliable air-heating collectors and for integrating them into a building's roof, wall structure and heating system. The handbook is being written for the builder or home owner and should receive wide distribution. It is expected to have considerable influence on small builders.

• Westinghouse has completed design and analysis of an evacuated tube air heating collector.

Stationary Collectors - Ponds

Objective. The primary objective of this program element is to conduct the research necessary to understand the physical processes that control the stability and efficiency of salt gradient solar ponds and utilize this information to design ponds that will be stable, effective, and economical.

PROJECT/AMOUNT	DESCRIPTION	TERM
Argonne National Laboratory $80K	Develop Numerical Models of Solar Ponds	10/79-9/80
DRI $97K	Investigate Saturated Ponds	9/79-4/81
ITC $24K	Evaluate Salts for Saturated Ponds	9/79-5/80
Los Alamos Scientific Lab $80K	Theoretical Studies of Salt-Gradient Ponds	10/79-9/80

PROJECT/AMOUNT	DESCRIPTION	TERM
Mound Lab. $80K	Instrument and Monitor Miamisburg Pond	5/78-5/81
JNM $156K	Study Stability of Solar Pond	9/77-8/80
Ohio State $225K	Conduct High-Temperature Research Pond	9/77-1/80

Project Activities and Accomplishments

- Argonne is developing a modified version of its two-dimensional, incompressible fluid dynamics code, COMMIX-SA-SP, to investigate various salt pond phenomena. The program and models will be validated and documented.

- Desert Research Institute has found that precipitation of borax during cooling of the saturated pond left a white coating on the pond bottom. This, in turn, caused loss of bottom heating and loss of the gradient. This experiment proves the need for vanes or other mechanisms to assure a dark surface on the bottom of the pond during cooling.

- InterTechnology Corporation is investigating the use of carbonate-sodium bicarbonate in saturated ponds.

- LASL has initiated theoretical studies of various aspects of solar ponds behavior.

- Mound monitors the pond that supplies heat to a swimming pool-recreational complex at Miamisburg, Ohio. During the fall of 1979 workers discovered a leak in the pond liner. The leak was located and temporary repairs were made without draining the pond.

- University of New Mexico has written two reports on all facets of solar pond operation. One report contained a stability analysis allowing for varying temperature and salinity gradients. This lead to a technique of using measured temperatures and salinity profiles to ascertain proximity to layer instability.

The first report covers pond operation, heat extraction, layer behavior, stability and filling techniques. The second report covers salt diffusion, the Soret effect, and an investigation of salts suitable for a saturated pond. Progress was made in thermal modeling. The pond was covered and heat loss compared to calculation. Observed losses were higher.

- Ohio State University has completed construction of their new pond. Fencing for the new pond was completed in September, 1979. Salt was added during October and November. The installation of the data acquisition system is underway. Progress was made on the writing of a microcomputer program to average radiation input and do energy balance calculations. The new pond is now operating. The principal investigator is visiting India and Israel, under other funding, to exchange information on ponds.

FUTURE ACTIVITIES

Much of the work discussed above is in progress and is expected to be completed during FY 80. Every effort will be made to see that the important results from these projects are reported and disseminated quickly to the solar community. Final reports will be distributed through the Technical Information Center (and in some cases through special mailings), and technical papers will be prepared for presentation at meetings and for publication in professional journals.

The technical program support staff at LASL has initiated an effort to compile, evaluate and select information and engineering data generated by the 100 collector projects over the past four years and prepare a solar collector design handbook. Program generated information will be supplemented with information from the solar, engineering design, materials science, thermal science and manufacturing literature in order to provide collector designers and manufacturers with a single comprehensive and authorative data source for all their needs. At the same time, the handbook will represent the essence of the multi-year, 18 million dollar collector and materials R&D program.

The continuing collector and materials program is expected to emphasis technology base building through engineering studies and materials R&D and some the development of collectors for the more demanding applications.

REFERENCES

A listing of completed solar collector projects whose final reports are to be distributed through TIC was prepared and distributed at the conference. A complete publications list of all major reports and papers generated by the participants in the solar collector and materials program is in preparation and will be available from LASL.

DEVELOPMENT OF A GAS BACKUP WATER HEATER PROPERLY INTEGRATED WITH SOLAR HEATED DOMESTIC HOT WATER STORAGE TANKS

Altas Corporation
Santa Cruz, California

Contract No. EM-78-C-02-4696

Principal Investigator: Dennis J. Morrison

Period of Contract: March 1978 - March 1980
California Congressional District No. 16
Congressman: Leon Panetta

Funding Schedule
FY 1978 - $ 29,274
FY 1979 - 124,810
FY 1980 - 41,729
FY 1981 - -0-

OBJECTIVE

The current contract aims at the development of engineering prototype hardware for an efficient gas-fired backup heater for solar DHW systems. Current designs are inadequate. Electrical backup heaters are not a viable answer in areas in which gas is available.

CONCEPT AND BACKGROUND

Solar DHW systems need conventional backup systems if the consumer is to be assured a constant hot water supply despite variations in demand or insolation. In areas in which gas is unavailable, electrical (resistance heated) backup systems are needed, and it is easy to produce an efficient solar-backup combination. It is wasteful to use electrical backup heaters when one can use gas. The current gas heaters, however, are not suited for solar backup service. Their central flue leads to constant and large losses, and their large height makes it impossible to mount them on top of the solar tank so as to use solar energy to compensate for parasitic losses. Another disadvantage is that the backup tank normally does not contribute to the solar storage. The current contract aims at solving this problem through development of a compact gas fired backup heater mounted on top of the solar tank. Gas heat is supplied with a one-way (gravity condensate return) heat pipe, using an electronic pilot for gas ignition. Provisions are included for transferring excess solar heat to the upper tank. This not only allows the use of solar heat to compensate for parasitic losses; it also makes the backup tank an integral part of solar storage. A sketch of the device is shown in Figure 1.

SUMMARY

All the major technical problems involved in the heater design have been solved satisfactorily so that a viable engineering prototype can be delivered. A significant follow-on is underway to develop production prototypes, so as to get the heater concept closer to the marketplace. This is funded by the Gas Research Institute.

TECHNICAL ACCOMPLISHMENTS

- Commercialization activities are underway with a Gas Research Institute follow-on contract (Contract No. 5014-343-0279) for $323K for the development of production prototype hardware. The current DOE contract was for the development of engineering prototype hardware, stressing the development of understanding of the physics but not yet of cost optimization of the hardware.

- A compact combustion chamber has been developed, ignited by an electronic pilot, with an 83 percent (typical) firing efficiency at 50,000 Btu/hr, operating with natural draft. The flame tips are no further than 1/2 inch from the heat exchanger surfaces, a single bank of finned tubes containing the heat pipe fluid (H_2O). Water was chosen because it is non-toxic. Frost protection is provided by having the finned tubes only partially full. The use of water made it necessary to use a copper heatpipe configuration. The engineering prototype being built at present is all copper.

- It proved necessary to separate the upflowing vapor and the downflowing condensate in the heatpipe for the heatpipe to operate stably. In the beginning of the project (before the streams were separated) the boiling section of the heat pipe ran dry on numerous occasions, particularly under cold startup conditions under which the heat pipe operated at low saturation temperatures with correspondingly large vapor velocities. To avoid "burnout" it proved necessary additionally to use a slow ignition sequence, involving roughly 30 seconds to get to the full firing rate. The electronic pilot used has provisions to do this with no modifications.

- A detailed computer model has been made of the complete system, so as to be able to determine the optimum design for individual components, and to be able to determine the overall performance of the unit analytically.

- Parametric correlations obtained with the above model have been used to produce a TRNSYS subroutine.

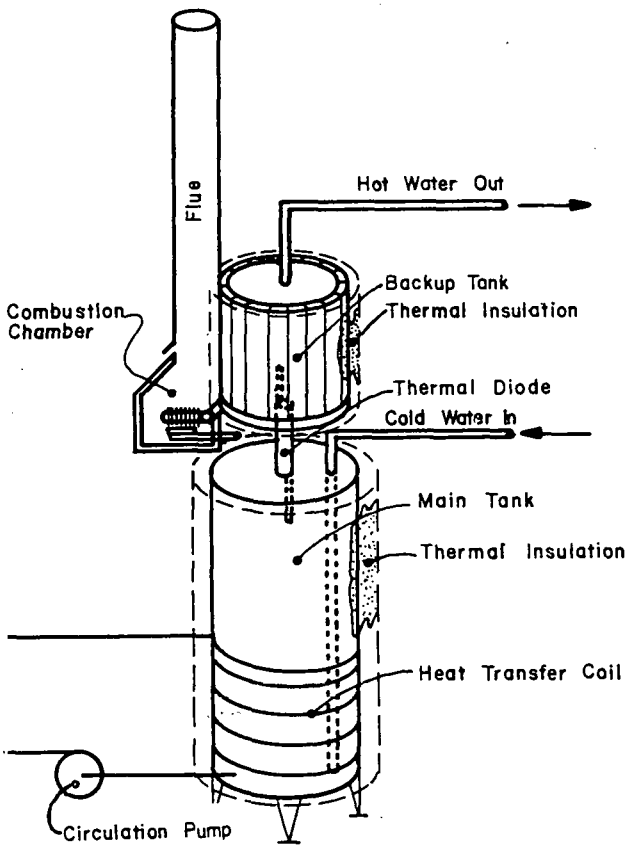


Figure 1. Heat Pipe Concept Applied to Solar Backup Heating

This TRNSYS subroutine can be used to determine the optimum system size and configuration based on cost versus solar fraction tradeoffs. The work to date has been with perfectly mixed tanks. This subroutine is being modified to accept stratified tanks for use in the GRI follow-on work.

- A novel thermal diode has been developed to transfer excess solar heat to the top tank with a minimum temperature difference between the tanks. The diode is shown in Figure 2.

  It is easy to derive an approximate relationship for the behavior of such devices. Downward conduction is easy to describe and to keep negligible. By equating buoyancy and pressure drop terms for upward convection, one can show that for steady state solar heating above the thermostatic set point temperature of the top tank, the temperature lag of the top tank with respect to the lower tank can be derived with a simple equation accurate to within about 10-20 percent. In typical tests, this diode reduces the temperature lags by an order of magnitude over the case with no diode.

- It was found by computer simulation that the thermal performance of this thermal diode connecting the two tanks had virtually no effect on the solar fraction, in solar DHW systems which were modestly sized, and in which the hot water consumption was identical day in day out. This is really quite logical, since under such conditions there is never any excess solar heat of any significance to transfer up into the backup tank. The question is; is this realistic? Since the answer clearly seems to be no, at Altas some work is planned in this area.

- The final engineering prototype, to be a deliverable item, is virtually completed. It has an 80 gallon solar preheat tank with heat exchanger coil ready to be hooked up to a collector system, topped by the 25 gallon, 50,000 Btu/hr gas backup heater. It will be submitted to qualification testing and then prepared for shipment. Three labs are presently being considered for final testing.

- It should be noted that this unit is an integrated system, needing only a water supply, and connection to a collector and to a hot water requirement. No other assembly work is needed on-site.

- It should also be noted that having the backup heater above the solar tank saves a significant amount of floorspace, typically worth \$30/ft^2 in the modern American home.

FUTURE ACTIVITIES

Contract Activities

The contract is now being wrapped up, having met all

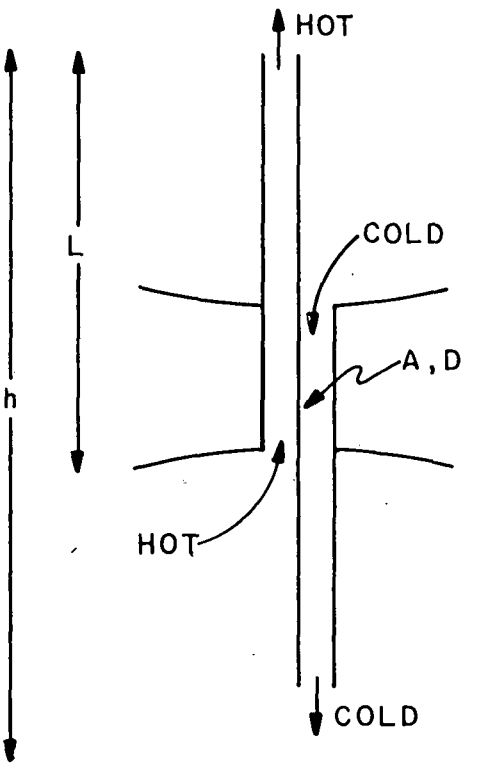


Figure 2. Convection Assembly Used in Thermal Diodes Between Tanks

contract objectives within the proposed time and cost estimates. The contract ends March 31, 1980. Currently final assembly work is continuing on the deliverable engineering prototype. This includes the gas backup heater and the associated solar storage tank with heat exchanger and associated plumbing ready to be hooked up to a real or simulated collection system. The solar tank has a volume of about 80 gallons, the backup heater about 25 gallons. Upon completion of construction, the unit will be run through checkout test and held pending DOE shipping instructions.

The only other remaining contract activity involves preparation of the final report.

Post Contract Activities

A modest DOE-funded follow-on is contemplated to complete the research aspects in this program by performing detailed modeling on the stratification behavior of the water with the Argonne computer program COMMIX-SA-1. This will give some final guidance on a number of design choices and parameters:

- determination of optimum thermostat placement
- determination of heat transfer coefficients from tank walls
- determination of optimum coil and condenser placement and configuration

In addition, this may include detailed testing on the deliverable prototype heater prior to shipment to DOE.

These results, numbers and criteria are particularly important for the continuing commercialization work on this heater concept, being done at Altas under sponsorship of the Gas Research Institute (GRI). GRI recently awarded Altas a 2 year, $323K contract (Contract No. 5014-343-0279) to extend the DOE contract (which had been aimed at developing an engineering prototype) to produce production prototype hardware. The GRI program is mainly aimed at solving problems with materials, manufacturing techniques, and design optimization through parametric analysis and through experimental work. It includes testing on stratification behavior but does not include funds for the detailed computer modeling on stratification behavior that the Argonne computer code makes possible.

In addition to the GRI involvement in commercializing the heater, a contract is expected from the Copper Development Association (CDA) for development of optimum fabrication techniques and for the delivery of several prototypes for demonstration work. The CDA interest is based on the likelihood that the heater will involve extensive use of copper and copper alloys.

Publications

1. D.J. Morrision et al: "Development of a Gas Backup Water Heater Properly Integrated with Solar Heated Domestic Hot Water", Annual Progress Report (July 1978–June 1979) on DOE Contract No. EM-78-C-02-4696. A000, Santa Cruz, July 31, 1979.
2. F. de Winter, "A Gas heater for Domestic Hot Water Particularly Suited to Solar Backup Service." Proceedings of the August 28-31, 1978, Annual Meeting of the A.S. of ISES, Volume 2.1 pp. 594-598.
3. P.R. Armstrong et al: "Simulation Models Applied to the Design of a Novel Domestic Water Heater", Proceedings of the ISES May 1979 Conference, Volume II p. 982.
4. F. de Winter: "The Development of a Gas Backup Heating Water Tank Properly Integrated with Solar Heated Domestic Water Storage Tanks", Proceedings of the 3rd Annual Solar Heating and Cooling R&D Branch DOE Contractor's Meeting, Washington September 24-27, 1978, pp. 173-174.

SOLAR HOT WATER SYSTEM TEST PROGRAM

NATIONAL BUREAU OF STANDARDS

EA-77-A01-6010

A. HUNTER FANNEY, STANLEY T. LIU, AND JAMES E. HILL

OCTOBER 1, 1978 - MARCH 31, 1980

OBJECTIVE

Several computer codes are being widely used to predict the thermal performance of solar domestic hot water (SDHW) systems. However, they need to be validated with experimental data to justify their wide use. One objective of this project is to conduct controlled experiments on typical state-of-the-art solar domestic water heaters and to determine the extent to which existing computer programs can accurately predict their performance. A second objective is to investigate alternate methods of testing the systems for the purpose of rating and to support the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in developing a standard test procedure.

BACKGROUND

Three computer codes are currently experiencing high level usage in the design of solar domestic hot water systems: TRNSYS [1], F-CHART [2], and SOLCOST [3]. These computer codes need to be validated with experimental data to justify their current level of usage. In addition, although there are now industry-adopted test standards for the two major components in any solar heating and cooling system, solar collectors and thermal storage devices [4,5], there is no adopted testing standard for solar domestic water heaters which are now being sold as packaged systems.

The staff of the National Bureau of Standards began a multi-year project in fiscal year 1978 to provide experimental data required for the validation of computer programs and to support the development of an industry test standard for solar domestic hot water systems.

During fiscal year 1978, a laboratory apparatus was designed around the typical components simulated in TRNSYS. Detailed short-term experimental data which were used to calculate the performance of these components were collected and the results compared with the predictions of TRNSYS for the same conditions. Good agreement was found between the program and the experiment when comparing the degree of temperature stratification in the preheat storage tank and heat loss from the tank. A summary of the results are given in reference [6].

A theoretical study was also completed during fiscal year 1978 to determine how experimental data might be collected on operating SDHW systems over a relatively short period of time (1 week to 1 month) and then used to establish a performance curve for the system that could be used for rating. It was found that the thermal performance of typical one and two-tank pumped systems utilizing flat-plate collectors could be satisfactorily described by a plot of solar fraction versus a combination of variables which include the primary thermal characteristics of the collector, the incident solar irradiance, ambient air temperature, water main temperature, and hot water load. However, the requirement for relatively long periods of testing was judged to make the technique unattractive as a basis for an industry rating method. The results of the study are given in reference [7].

SUMMARY

During fiscal year 1979 and the first half of 1980 (period covered by this report), detailed performance data was gathered on six heavily-instrumented SDHW systems at a field site at NBS in Gaithersburg, Maryland. The experimental results over a 12-month period were compared to the predictions of the computer programs over the same time period and for the same operating conditions. The six systems were then modified and data collection is now underway for a second 12-month period. During this reporting period, NBS staff members also participated in the development of ASHRAE Standard 95 for the testing and rating of SDHW systems (currently in draft form). Test equipment was designed and built at NBS in accordance with the Standard and preliminary validation experiments were completed.

TECHNICAL ACCOMPLISHMENTS

o Six SDHW systems were fabricated with associated instrumentation and put into operation on a continuous basis in April, 1978. Data collection began in June and continued for 12 months. Of the six systems used during the first year of the experiment, three were double-tank and three used only a single tank. Three different methods of freeze protection were utilized among the systems: (1) water-ethylene glycol mixture in the collector loop with a wrap-around heat exchanger on the preheat tank, (2) drain down using solenoid valves to dump the water from the collector and isolate the collector from the rest of the system, and (3) air-heating collectors and an air-water heat exchanger between the collectors and preheat tank. One system operated on the thermosyphon principle while the other five required electric power for fans or pumps. All five of the all-liquid systems utilized two or three modules of the same single-glazed collector with a selective surface on the absorber. The air system used double-glazed collectors with a flat-black-coated absorber. The two tanks used with wrap-around heat exchangers were

commercial products designed for solar hot water systems and contained 7.6 cm (3.0 in) of glass fiber insulation. The remaining tanks were all conventional electric water heaters with 5.1 cm (2.0 in) of glass fiber insulation. All systems ran continuously side-by-side and provided approximately 0.265 m^2 (70 gal) of hot water per day at 49°C (120°F).

Results of the first eight months of the comparison of experimental results with computer program predictions were presented at the International Congress of the International Solar Energy Society (ISES) in Atlanta, Georgia in May, 1979 [8]. Operational results for the first 12 months were presented at the Second Annual Solar Heating and Cooling Operational Results Conference in Colorado Springs, Colorado in November, 1979 [9]. A paper describing the first year's comparison of results with computer program predictions was presented at the Semi-annual meeting of the The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in Los Angeles, California in February, 1980 [10]. It was found that all the major programs now in use (F-CHART-3, TRNSYS-9.2, and SOLCOST-2.0) predicted the first year's fractional energy savings* within ± 11 percentage points for all the systems modeled. The agreement was within ± 6 percentage points for the double-tank systems.

After the completion of the first 12-month's data collection (June, 1979), modifications were made to the systems in preparation for a second 12 months of test. An evacuated-tube, air collector system was installed in place of the flat-plate air collector system. A preheat storage tank with internal coil heat exchanger was used in place of the tank with the wrap-around heat exchanger in the double tank indirect system. An additional collector panel was added to the single tank direct system so its collector area is now identical with the other liquid systems, and the tanks for the double tank direct system were replaced by two energy saving storage tanks. Also, mixing valves at the hot water outlet were removed from all the six systems to make the system configurations more closely resemble those assumed in the computer programs. A seventh system consisting of a conventional electric hot water heater was installed as a reference system. All the modifications were completed by the end of September, 1979 and data collection and analysis is now ongoing for the second year of operation.

o NBS staff members participated on ASHRAE Project Committee 95P and assisted in developing a proposed standard test procedure for SDHW systems. The procedure requires that the entire system be assembled in the laboratory and that the system be subjected to specific diurnal variations of the environmental conditions controlling the system performance, such as incident solar irradiance and ambient temperature, while the system supplies hot water at specified temperature, times, and draw rate throughout the day. The test continues until the system performance is near-identical for successive days. It is proposed that the rating be the daily fractional energy savings under this quasi-steady-state condition. The actual collector array can be used and irradiated with a solar simulator. Alternately, the collector module comprising the array can be tested separately following ASHRAE Standard 93-77, the results used to compute the thermal output of the array under the specified system test conditions, and this thermal output supplied to the system during the system test using a conventional energy source (simulated collector array).

A written draft of the Standard was completed by the project committee in April, 1979 and approved by the ASHRAE Standards Committee for public review. The public review period ended November 30, 1979 and based on comments received, the Standard is now being revised and will be subjected to a second public review.

Two test loops designed in accordance with the proposed Standard were fabricated at NBS in April, 1979 to validate the technique which requires the use of a simulated collector array. All components in both loops (including the piping configuration) are identical with the exception of the solar collector array. One loop consists of a complete solar hot water system and utilizes two actual solar collector modules exposed outdoors to solar radiation while the second loop utilizes a simulated collector array in the laboratory. A number of experiments are planned to evaluate alternate techniques of controlling the simulated collector array. One set of experiments was completed during August and September, 1979 and the results were presented at the ASHRAE Semi-annual meeting in Los Angeles, California in February, 1980 [11]. The system which utilizes the actual collector modules was allowed to operate in its normal manner for several days including days having both clear sky conditions and intermittent cloud conditions. The performance of the system was determined by making appropriate measurements and all environmental conditions were monitored continuously. The system with the simulated collector array was then operated in a similar manner but with the collector output simulated by the auxiliary heater that was manually adjusted every five minutes throughout the test day. The adjustments were made based on a continuous measurement of the entering water temperature to the simulated collector array (auxiliary heater), known environmental conditions (measured during the previous tests), and using the governing equations for the actual collector module (determined from separate Standard 93-77 tests) which were programmed into a programmable calculator. It was found that daily collector output could be reproduced in the laboratory within 4% even on intermittently cloudy days and that the daily fractional energy savings of the two systems was within two percentage points for all the days tested.

FUTURE ACTIVITIES

Data will be collected and processed on all six operating SDHW systems through the summer of 1980 to obtain the second 12 months of data. The same type of comparison will be made with the predictions of the three computer programs as was done for the first 12 months. A comparison will also be made between the experimental data of the first year and second year to ascertain the effect of modifications made to the systems. Consideration will be given to a third year of testing in order to gather data on

* The fraction of the energy used by a 0.2 m^3 (52 gal) electric water heater meeting the same load that is saved as a result of using the solar system.

other generic types of systems. Those under consideration include ones using (1) an evacuated tube collector with a liquid heat transfer fluid, (2) integral collector and storage design, (3) a heat pump, (4) oil in the collector loop, and (5) alternate types of double-wall heat exchangers.

Validation experiments of proposed ASHRAE Standard 95 will continue. Alternate experimental techniques will be investigated for simulating the solar collector array. In addition, experimental studies will be undertaken to determine to what extent the method of using a simulated collector array is valid for systems other than the conventional pumped one and two-tank systems with flat-plate collectors. This is particularly important due to the current use of thermosyphon systems and those with concentrating and/or evacuated tube collectors.

REFERENCES

1. "TRNSYS, A Transient Simulation Program," Engineering Experiment Station Report 38, Solar Energy Laboratory, University of Wisconsin, Madison, October, 1977.

2. Beckman, W.A. and J.A. Duffie, Solar Heating Design by the F-CHART Method, John Wiley & Sons, Inc., 1977.

3. Connolly, M., Giellis, R., Jensen, C., and R. McMordie, "Solar Heating and Cooling Computer Analysis - A Simplified Design Method for Non-Thermal Specialists," Proceedings of the Joint Conference of the American Section of the International Solar Energy Society and the Solar Energy Society of Canada, held in Winnipeg, Canada, August 15-20, 1976.

4. "Methods of Testing to Determine the Thermal Performance of Solar Collectors," ASHRAE Standard 93-77, ASHRAE, 345 E. 47th St., New York, New York, 10017, 1977.

5. "Methods of Testing Thermal Storage Devices Based on Thermal Performance", ASHRAE Standard 94-77, ASHRAE, 345 E. 47th St., New York, New York, 10017, 1977.

6. Liu, S.T., Shih, K., and B.D. Wood, "Experimental Validation of the Solar Simulation Program TRNSYS for a Solar Domestic Hot Water Heating System," Proceedings of the DoE Conference on System Simulation and Economic Analysis for Solar Heating and Cooling, held in San Diego, California, June 27-29, 1978.

7. Liu, S.T. and J.E. Hill, "A Proposed Technique for Correlating the Performance of Solar Domestic Water Heating Systems," ASHRAE Transactions, Vol. 85, Part I, pp. 96-109, 1979.

8. Fanney, A.H., and S.T. Liu, "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, held in Atlanta, Georgia, May, 1979.

9. Fanney, A.H., and S.T. Liu, "Performance of Six Domestic Hot Water Systems in the Mid-Atlantic Region", Proceedings of the Second Annual Solar Heating and Cooling Operational Results Conference, held in Colorado Springs, Colorado, November, 1979.

10. Fanney, A.H., and S.T. Liu, "Comparison of Experimental and Computer - Predicted Performance for Six Solar Domestic Hot Water Systems," presented at the ASHRAE Semi-Annual Meeting in Los Angeles, California, February, 1980, to be published in ASHRAE Transactions, Vol. 86, Part I, 1980.

11. Hill, J.E., and A.H. Fanney, "A Proposed Procedure of Testing for Rating Solar Domestic Hot Water Systems" presented at the ASHRAE Semi-Annual Meeting in Los Angeles, California, February, 1980, to be published in ASHRAE Transactions, Vol. 86, Part I, 1980.

INSTALLATION AND CHECKOUT HANDBOOKS FOR SOLAR DOMESTIC HOT WATER SYSTEMS

SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INC. (SEEC)

SUBCONTRACT NO. AH-9-8189-1 UNDER PRIME CONTRACT NO. EG-77-C-01-4042

C. BYRON WINN

JUNE 1, 1979 - MAY 31, 1980

OBJECTIVE

The objective of this effort includes the preparation of two separate handbooks. The first is a Domestic Hot Water (DHW) Systems Checkout Handbook, which will contain procedures for checking the operation of an installed DHW system. The second is a Controls Handbook for Designers and Installers of Solar Domestic Hot Water Systems, which will contain guidelines for the design and installation of DHW control systems. A third task covers technical support to SERI in the overall Systems Analysis and Testing Program.

BACKGROUND

The results of studies of HUD Demonstration Program projects, as well as independent studies of privately funded solar systems, have shown numerous problems in the installation and operation of residential solar heating systems. These problems include:

- Uninsulated pipes, ducts, and preheat tanks.
- Differential thermostat not properly set.
- Various phases of operation not checked after installation. (Systems installed for over a year, but did not function owner unaware.)
- Air flow rates at 40% of required for optimum performance.
- Operating procedures not provided to homeowner.
- Poor installation resulting in excessive air leakage.

In many cases, systems are not operating properly and the homeowner is not even aware of the problem. Most of these problems could be avoided if the system were properly installed and checked out. Installation and checkout handbooks will increase the proficiency of the installer and therefore be a major step toward reduction of consumer dissatisfaction.

SUMMARY

The intent of this contract is to produce guidelines for the proper installation and checkout of residential solar domestic hot water systems. The scope is limited to domestic hot water because these systems are being installed in the largest numbers and are the least complicated from a design and operation viewpoint. DHW systems represent an ideal starting point for this effort.

Many designs of solar domestic hot water systems are available, utilizing different principles and types of components. The differences and novelty of these many systems have been a problem to most system installers who do not completely understand the principles of each system's operation. Installers generally possess technical and not analytical skills; therefore, most installed systems cannot be checked by the installer for proper operation. Most system manufacturers provide only installation and not "checkout" instructions. However, checkout procedures for the large number of systems are somewhat general and the most basic characteristics of a properly installed DHW system can be described in one installation handbook. The tools needed for an inspection of a domestic hot water system are both readily available and relatively inexpensive.

TECHNICAL ACCOMPLISHMENTS AND FUTURE ACTIVITIES

Drafts of both handbooks have been provided to SERI for review. SEEC has received recommended changes and modifications from SERI which are being incorporated into the handbooks for delivery by May 31, 1980. Alternative methods for marketing the handbooks are being reviewed by SERI.

PUBLICATIONS

Two handbooks will be deliverables under this contract.

1. System Checkout Handbook for Solar Domestic Hot Water Systems.
2. Controls Handbook for Designers and Installers of Solar Domestic Hot Water Systems.

CONTROLS AND INSTALLATION AND CHECKOUT HANDBOOKS FOR SOLAR DHW SYSTEMS

SOLAR ENVIRONMENTAL ENGINEERING COMPANY, INC. (SEEC)

C. BYRON WINN, KEITH SHARP, JIM LEFLAR AND THOMAS KENT

OBJECTIVES

The objectives of this project are to:

- Provide system checkout and service procedures that may be used to quickly determine the thermal performance of solar DHW systems.
- Provide design and installation guidelines for designers and installers of DHW control systems.

HOT WATER HANDBOOK

Results that have been obtained from the SEEC/SERI Reliability Assessment Team have indicated that the major deterrents to achieving desired system performance in solar DHW systems have been improper design and installation. Shown on Fig. 1 are results that have been obtained from inspections of 12 systems by the Reliability Assessment Team. It is apparent from the results shown in this figure that approximately 75% of the problems have been design or installation problems, the remaining being component or O and M type problems. The large number of problems incurred does not agree with the premise that solar DHW systems have immediate market potential. This apparent contradiction may be resolved by restating the premise. That is, one should state that properly designed and properly installed solar DHW systems have immediate market potential. At the present time there still are numerous solar DHW systems that are being offered to the public on a commercial basis that are not representative of properly designed solar DHW systems. For example, a perusal of the Solar Products Specifications Guide will reveal the fact that there are solar DHW systems presently available commercially that incorporate features such as concentrating and tracking collectors used with a single tank system having gas auxiliary. In order that solar DHW systems realize their market potential, it is necessary that systems be reliable and designed to fit the needs.

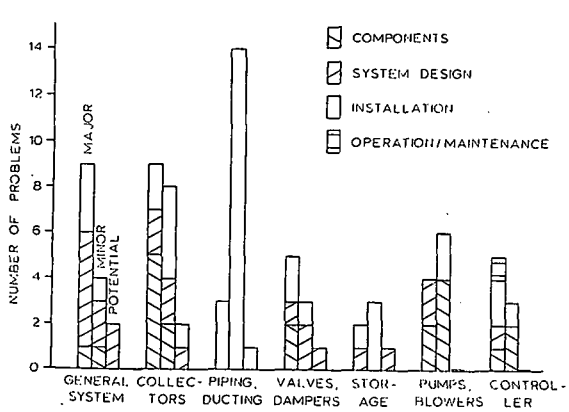


Figure 1. Summary of Problems

There are essentially two approaches that may be used in order to realize a viable solar DHW industry. The first is to let the marketplace serve as a filter, thereby eliminating those systems that do not have adequate market potential. The second is to attempt to circumvent the problem by education of designers, installers and purchasers. The first approach is a long term approach and can be shortened by the process of education.

There are presently available numerous sources of information, both for design and installation of solar DHW systems. For example, in the design area, there are handbooks, textbooks and many articles in the professional and trade literature dealing with the design of solar DHW systems. Also, in the installation area, there are handbooks, workshops, vocational technical programs, and programs and material prepared by professional/trade organizations. There is, however, a gap in the presently available material. That gap relates to inspection and performance evaluation. To recognize that this gap exists, all we need to do is realize that good design and proper installation are necessary, but not sufficient, conditions to ensure proper operation. This is because of the fact that components may be ineffective or may fail in unexpected modes. That has been seen in a number of installations. Another situation that arises is that, at present, one does usually not know if a system is functioning properly once it has been installed. The problem is that the industry has tended to rely on customer satisfaction as a measure of system performance. This is not a satisfactory approach since it has been shown that some customers have been satisfied with poorly performing systems, while others have been dissatisfied with systems that perform quite satisfactorily.

The objective, therefore, of this contract is to provide system checkout and service procedures that may be used to quickly determine system performance.

RESULTS

- Starting with 18 solar DHW systems, these were reduced to eight generic systems which are covered in the handbook.
- The handbook contains three major sections:

- General Information

  This section contains an explanation of the basic principles of operation of solar water heating systems.

- System Inspection and Performance Evaluation

  The Systems section contains a logical performance evaluation and troubleshooting procedure for each of the eight generic systems that are described in the Introduction. These are the procedures that the installer should use in inspecting the system and evaluating its performance.

- Component Inspection

  The Components section contains the most detailed information regarding specific problems.

- The Handbook Also Contains Three Appendices:

  - Appendix A is written for the owner.

    Simple procedures using inexpensive instruments are described which will enable the owner to determine whether or not the system is operating as it should, although not necessarily at its maximum efficiency.

  - Appendix B is written for the installer.

    It contains a description of test equipment that the solar service person should use for thorough system performance evaluation. The cost of the equipment is low and the time required to completely check the system is short. The extra expense and effort should be rewarded by better system performance, greater system reliability and a more satisfied solar customer.

  - Appendix C is written for the designers.

    It contains a description of recommended taps, plugs and other hardware that should be included in the system design in order to expedite the task of system performance evaluation.

FUTURE ACTIVITIES

- Disseminate the handbook through SERI, the RSECS, conferences and workshops, and professional and trade organizations.

PUBLICATIONS/REPORTS/REFERENCES

1. Oral presentation at DOE Contractors' Meeting, Lake Tahoe, Nevada, March 1980.

2. Oral presentation at the Solar Fair at North Lake College, Irving, Texas, April 1980.

3. Sharp, Keith, Leflar, Jim and Winn, Byron, "Solar Domestic Hot Water System Inspection and Performance Evaluation Handbook," June 1980.

CONTROLS HANDBOOK FOR SOLAR DHW SYSTEMS

A tabular summary of some results that have been obtained by the SEEC/SERI Reliability Assessment Team is shown in Table 1. From this information we see that approximately 10% of the problems have been due to the controllers themselves. However, if we consider the controls system to include pumps or fans and valves or dampers, then the problems due to the controls system represent approximately 33% of the total system problems. Additional information that has been obtained from surveys of installed solar systems indicates that the median control system cost represents approximately 8% of the total system cost. Therefore, we have the situation where a small percent of total system cost is being spent on portions of the system that represent a large percent of total system problems.

The objectives, therefore, are to provide design and installation guidelines for designers and installers of controllers for solar DHW systems.

TABLE 1

	COMPONENT						
	GENERAL SYSTEM	COLLECTORS	PIPING/ DUCTING	VALVES/ DAMPERS	STORAGE	PUMPS/ BLOWERS	CONTROLLERS
MAJOR PROBLEMS	9	9	3	5	2	4	5
MINOR PROBLEMS	4	8	14	3	3	6	3

PROBLEMS DUE TO CONTROLLERS = 10%

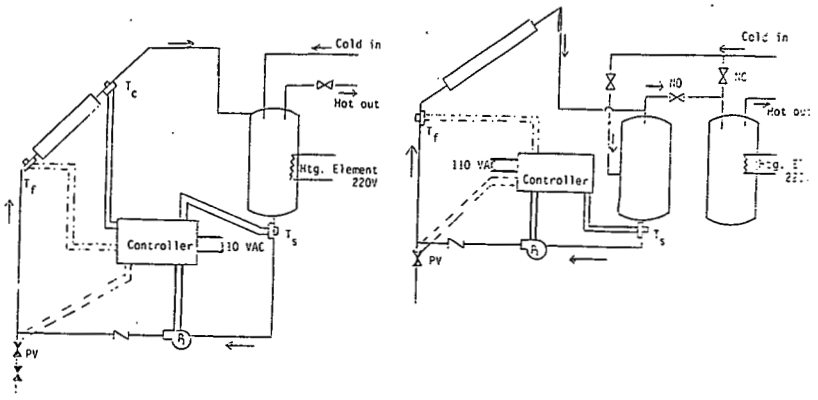
PROBLEMS DUE TO CONTROL SYSTEM = 33%

MEDIAN CONTROL SYSTEM COST = 8% OF TOTAL SYSTEM COST

RESULTS

- Started with 18 system types
- Reduced these to 8 generic systems
- Defined three basic controllers
  - One pump, direct
  - One pump, indirect
  - Two pump, indirect
- Defined added features
  - High temperature protect
  - Freeze protect
- Defined control functions
- Defined hardware
  - Sensors
  - Logic
  - Output
- Defined installation and checkout procedures

Samples of material from the handbook are shown in Fig. 2 and Table 2.



ONE TANK

TWO TANKS

WIRING

- Line Voltage
- Control Voltage
- Special Feature Line Voltage
- Special Feature Control Voltage
- Pump
- Heating Element (220 V)
- Check Valve
- Manual Valve MV
- Powered Valve PV
  NO - closed on power input
- Temperature Probe
  - T_c = Collector Probe
  - T_s = Storage Probe
  - T_f = Freeze Probe

CONTROL LOGIC

Collection Pump: $P_1 = T_c >> T_s$

Optional Features:

Recirculating Freeze: $P_1 + T_c > 40^0, T_f$

Drain Down Freeze: $PV_1 = (T_c > 40^0) + P_1 \cdot \overline{Power}, T_f + \overline{P_1}$

Drain Back: $PV_1 = \overline{P_1} + \overline{Power}$

Storage High Limit: $\overline{P_1} = T_s >$ High Limit

Heating Element Inhibit: $\overline{P_2} = T_s >$ Set Point, P_1

START-UP TEST

Collection	On/Off Auto	Test	Output
1	On	—	Pump on
2	Auto	Short T_c, open T_s	Pump on
2a	Off	Short T_c, open T_s	Pump off
3	Auto (if no freeze protect)	Short T_s, open T_c	Pump off
3a	On (no f.p.)	" " "	Pump on
Freeze Protect			
4	Auto	Open T_c (and T_f)	Pump on
4a	Auto	Short T_c (open T_f)	Pump on
Storage High Limit			
5	Auto	Short T_c and T_s	Pump off

Figure 2. Open Loop System

TABLE 2. CONTROLLER MODULE FAILURE DIAGNOSTIC

	FAILURE MODE	DIAGNOSTIC/DISCUSSION	RECOMMENDED ACTION	
			FIELD	SHOP
1. Output Relay	Relay doesn't close	Disconnect coil leads from controller and apply voltage to test. (If relay operates coil, look to the logic diagnostics. The controller will probably have to be returned to the manufacturer.) Look for noisy input power.	Replace controller	Replace relay
2. Relay continuously open	Welded contacts	Visual inspection. Look for shorted pump motor.	Replace controller	Replace relay
	Logic driver "on"	Disconnect controller power. If relay doesn't close, replace relay and test. If relay closes, look to the logic diagnostic. The controller will probably have to be returned to the manufacturer. Look for chattering relay or noisy power input.	Replace controller	Return to manufacturer
3. Output triac continuously on	Triac shorted	A very common failure mode due to several causes: too much current, high inductive loads, shorted output, etc.	Replace controller	Return to manufacturer
4. Relay chattering	Noisy relay followed by burned out pump	If unit pases start up test on bench, then fluctuating voltage and/or noise on the line causes failure.	Replace	Open offset and hysteresis in logic module
5. Half cycle triac failure	Excessive motor overheat	Triac acting like a pulsing DC source.	Replace controller	Return to manufacturer
6. Input power	Non-functional logic or relay	Test controller transformer with a load to design voltage. Look to chattering relay or high ambient temperature as cause.	Replace controller	Replace transformer
7. Logic failure	Continuous on or off operation	Use "Start-up" test after investigating outputs. If logic has failed, the source will generally be due to too high an ambient environment or large voltage line spikes.	Replace controller	Return to manufacturer
	Intermittant ON-OFF	Use "Start-up" procedure to test. If unit passes, it points to either large line voltage spikes, a fast system thermal time constant or drift with ambient temperature.	Replace controller	Open offset and hysteresis in logic module

FUTURE ACTIVITIES

- Disseminate the handbook through SERI, the RSECs, conferences and workshops, and professional and trade organizations.
- Develop a controls handbook for controllers for solar space heating systems.

PUBLICATIONS/REPORTS/REFERENCES

1. Oral presentation at DOE Contractors' Meeting, Lake Tahoe, Nevada, March 1980.
2. Sharp, Keith, Leflar, Jim, Winn, Byron and Kent, Thomas, "Handbook for Controllers Used in Solar Domestic Hot Water Systems," January, 1980.

VII SPECIAL PROJECTS

PHOTOVOLTAIC/THERMAL HYBRID PROJECTS

EDWARD A. KUSH
BROOKHAVEN NATIONAL LABORATORY
UPTON, NY 11973

ABSTRACT

Systems which utilize a combination of photovoltaic and thermal collection in the same solar collectors (PV/T Systems) can have advantages over PV or thermal only systems in that the cost effectiveness of the collectors and their support structure may be improved, active cooling may allow the cells to run at lower temperatures-hence higher conversion efficiency, and space limitations on side by side collectors can be avoided. Evaluation of such systems requires formulation and assessment of collector concepts, power conditioning, storage, and control strategies, and their interactions when combined into a total system. Three projects to accomplish this are currently in progress. Two of them, at MIT/Lincoln Laboratory (MIT/LL) and Brown University address systems with flat plate PV/T collectors and vapor compression heat pump driven by the photovoltaic electric output. The third, at Arizona State University, is studying PV/T concentrating collectors and their potential applications, particularly to solar driven absorption chillers.

BACKGROUND

MIT/LL was brought into the Active Cooling program of the (then) R&D Branch for Solar Heating and Cooling in late 1977 to study PV-driven heat pumps because of the need for potentially cost competitive solar-activated cooling at residential level. They have studied PV/T heat pump systems, with emphasis on liquid collectors, since then under combined funding from CSA and ET. Brown University was requested to submit a proposal for the same type of work, with emphasis on air systems, and did so in 1978, and was funded after some iteration in July 1979. Arizona State University submitted an unsolicited proposal to study a PV/T collector/solar absorption chiller system based on results of an MIT/LL regional study which showed this system as having potential for a hot, dry climate (Phoenix); and this project was also funded in July 1979.

SUMMARY

MIT/LL studies of PV and PV/T-Heat Pump Systems have included a performance simulation and economic analysis to arrive at what they feel is an optimum system for northern climates. That system is composed of PV/T collectors, an air-air (parallel system) heat pump, and a utility interactive inverter for power conditioning (no electric storage). They have installed an experimental system of this type at the University of Texas at Arlington (UTA) Solar House which uses side-by-side thermal and PV collectors from which some limited data has been obtained thus far. A second system has been designed and is being installed at MIT/LL and will use an array of PV/T collectors to be procured by RFP. MIT/LL has also tested prototype flat plate PV/T collectors (both liquid and air) which resulted from a Sandia RFP, found them to be quite poor in performance, and identified some methods of improving both thermal and electrical efficiency.

Brown University is in Phase I-Conceptional Design and has been studying air PV/T collector concepts in detail, and investigating power conditioning, storage and heat pump options for systems to be constructed in Phase II. A number of methods of adapting silicon cells to serve as effective absorbers are being explored and interactions with cell manufacturers to determine the most appropriate cells for PV/T are underway. Both Brown and MIT/LL have been active in formulating PV/T standards within the Photovoltaics program.

Arizona State University is adapting their existing absorption chiller test simulator for PV/T testing, investigating existing PV/T concentrating collector configurations for use in the test system, and carrying out TRNSYS simulations of PV/T-absorption chiller performance. The simulations utilize PV/T collector and other component models developed at ASU for use with TRNSYS.

TECHNICAL ACCOMPLISHMENTS

MIT/Lincoln Laboratory

- Performed TRNSYS (modified for PV/T system calculations) simulation for New York climate to compare a PV/T - Parallel Heat Pump, PV/T - Series Heat Pump (resistance backup), and PV-only heat pump. Accompanying economic analysis showed PV/T-Parallel HP system to have lowest life cycle cost under the assumptions used.

- Found that utility-interactive AC systems meet a greater percent of total energy for the New York case than storage battery systems, and are more cost effective for a .5 utility energy buy-to-sell ratio.

- Installed Phase I (quasi-series) and Phase II (parallel, Carrier Solaround with 2-speed compressor, Tri-x coil) heat pump experiments at UTA. Side-by-side collectors; PV drives heat pump. Have limited data.

*Work performed under the auspices of the Systems Development Division, Office of Solar Applications, U.S. Department of Energy.

- Designed and constructing heat pump test facility at MIT/LL (Hanscom Field) with similar Carrier air-to-air arrangement. Existing PV array will drive HP. PV/T collectors to be purchased. Both systems employ line-stuffing inverters. Design of system seeks to take advantage of using thermal storage to "store" electrical output via heat pump.

- Interacted with BNL and Heat Pump program. Have incorporated "solar preheat" mode and solar defrost into heat pump installations.

- Tested prototype PV/T collectors, both liquid and air, made by manufacturers who were successful respondents to Sandia RFP. Found them to be very poor in performance, identified the reasons, and made recommendations for improved PV/T collectors.

Brown University

- Carrying out Phase I design study of PV/T air collectors, power conditioning, storage, and heat pump to arrive at appropriate PV/T-Heat Pump System to be built in Phase II. Designing for adaptability of heat pump configuration (parallel, series, variable speed drive etc.)

- Studying methods to tailor silicon PV cells for good thermal absorption (and possible low emissivity) and effective heat transfer to the coolant. Investigating appropriate encapsulation and mounting/bonding techniques, contact configuration, and back surface treatment for long term optimized PV/T collectors. Designing four prototype collectors.

- Designing modular building to hold collector array, simulate loads, and house heat pump and other equipment. Selected installation site on campus.

Arizona State University

- Prepared revised version of TRNSYS-plus-PV/T for system simulations incorporating ASU models. Carried out studies of hot side vs cold side storage with LiBr absorption chiller - PV/T system.

- Adapting existing LiBr abosrption chiller simulator to PV/T system tests.

- Investigating PV/T concentrating collectors for use in test system.

- Studying best method of using PV portion of PV/T collection to drive chiller parasitics.

FUTURE ACTIVITIES

- Continued assessment of PV/T systems for performance and cost potential.

- Establish if high performance can be obtained with PV/T collectors and what specific cell configurations would be required (and whether they are consistent with any of those being developed in the PV program).

- Investigate synergism potential between compressor drive and PV array output.

- Incorporate developments from Heat Pump program to update decisions on system configuration, e.g. ground coupling with PV/T-Series Heat Pump is candidate for study.

- Identify best applications for PV/T concentrators.

PUBLICATIONS

1. Russel, M. C. and Kern, E. C., "Optimization of Photovoltaic/Thermal Collector Heat Pump Systems", Proc. of ISES 1979 Congress, Atlanta, GA, May 1979.

2. Russel, M. C., "Solar Photovoltaic/Thermal Residential Systems", COO-4577-9.

3. Sheldon, D. B., "Phase II Experimental Test Plan Solar Photovoltaic/Thermal Residential Experiment", COO-4094-65.

4. Hendrie, S. D., "Evaluation of Combined Photovoltaic/Thermal Collectors", Proc. of ISES 1979 Congress, Atlanta, GA, May 1979.

5. Kush, E. A., "Hybrid Photovoltaic/Thermal Systems With a Solar Assisted Heat Pump", Proc. of AS/ISES 1980 Annual Meeting, Phoenix, AZ, June 1980.

EXPERIMENTAL AND ANALYTICAL SYSTEM STUDIES ON A COMBINED THERMAL-PHOTOVOLTAIC RESIDENTIAL SOLAR SYSTEM

MECHANICAL ENGINEERING DEPARTMENT
ARIZONA STATE UNIVERSITY
DE-AC03-79CS30203

BYARD D. WOOD, DONOVAN L. EVANS, BARRY W. MCNEILL

JULY 1, 1979 - DECEMBER 31, 1980

OBJECTIVE

The objective of this study is to make combined photovoltaic/thermal (PV/T) solar cooling systems commercially viable by designing and carrying out integrated analytical and experimental systems studies to identify and evaluate overall system and component design criteria. Particular emphasis is placed on concentrator PV/T collectors and absorption cooling. Specifically, the contract is to establish a residential sized concentrator PV/T collector solar cooling test facility for: steady and dynamic system performance testing, in situ component testing, simultaneous model and experiment validation, optimization of control strategies to maximize system performance, minimization of thermal and electrical parasitic losses, and determination of an optimum split between electrical and thermal conversion from the collector array for various solar cooling systems and solar/meteorological regions.

BACKGROUND

Combined PV/T collectors which produce both electric and thermal power can be designed to provide greater energy savings throughout the year than if a solar thermal system is used. (1,2,3). In fact, Westinghouse Electric Corporation (1) concluded that a total energy residential power system provides the most cost effective match between the solar energy incident on the roof of the residence and its electrical and thermal loads. This research provides an additional technology path for solar cooling applications as identified in the National Program Plan for Research and Development in Solar Heating and Cooling (ERDA 76-144).

The research also is a natural extension of the solar research at Arizona State University, which has had extensive experience in solar thermal systems, photovoltaic power systems with sunlight concentration, and computer systems simulation (e.g., 4, 5, 6, 7, 8, 9, 10). Evans (10) has developed a number of photovoltaic system models which are compatible with TRNSYS, a solar system simulation algorithm (11). His model for a PV/T collector is based upon the work of Florschuetz (12), who developed a model similar to the Hottle-Whillier-Bliss model. The PV/T model is applicable to collectors where the solar cell output can be assumed to decrease linearly with local cell temperature. Unfortunately there has been very little experimental validation of PV/T system models. It is anticipated that this contract will provide valuable system performance data for PV/T systems.

SUMMARY

A PV/T system test facility has been designed and is currently being constructed in several phases so that subsystem performance tests can be started for preliminary evaluation of system design and computer model validation. For example, the absorption chiller is operational in conjunction with hot storage, cold storage and programmable load. Computer simulation models with several system design options have been developed for a concentrator PV/T collector and a three ton lithium-bromide/water absorption chiller for a Phoenix residence. Preliminary simulation runs have been made to evaluate the effect of hot and cold storage volumes on system on/off cycling. Cold storage does indeed reduce the number of on/off cycles but the overall impact on system efficiency needs further study.

TECHNICAL ACCOMPLISHMENTS

System Test Facility Design Decisions. In line with the overall objective of the project is a design decision that the test facility be of "residential size" and be highly flexible. "Residential size" means that it should consist of components that might be found in such a system within certain practical and economic constraints. Only the PV/T collectors deviate significantly from this decision. For economic and flexibility reasons, only a fraction (1/3 to 1/2) of the anticipated array field will be purchased. The balance of the array field will be simulated with heat exchangers operating in parallel with the PV/T collectors (see Fig. 1).

Also in terms of flexibility, it is desirable to be able to test components or subsystems even when part of the system is not operating. For example, the collector field simulator is large enough to replace the complete field and is controlled by a minicomputer. Thus, the chiller (or a heat engine) can be tested even if the PV/T collectors are not operating. To further enhance the flexibility, system layout permits relatively easy replacement of components, e.g., the absorption chiller could be easily replaced with a Rankine cycle engine/vapor compression unit or a heat pump.

System Test Facility Construction. Work in designing, procuring, fabricating and constructing the PV/T system test facility, shown in Fig. 1, is essentially on schedule. Aside from the possibility that the PV/T collector/absorbers may not be available by summer 1980, it seems quite reasonable to expect that a secondary goal of having an operating system by August 1980 can be met.

The absorption chiller, thermal storage tanks (hot and cold), and cooling towers are in place and operating. The thermal simulator for the collector array has been designed and the control components procured. The final stages in the design of the collector field loop are being completed and collector field prime pump controller specifications will be drawn up. The PV/T concentrator collectors and absorber will probably come from either BDM, Albuquerque, NM or E Systems, Dallas, TX. Only enough collectors to give approximately 1 kW peak electrical will be purchased. 1 kW of electrical power is enough to permit the test facility to include a D.C. motor and battery storage which satisfies the primary design goal of having real components whenever possible. The design of the D.C. electrical side has not been finalized but will consist of either batteries plus an inverter or batteries plus a D.C. motor. The final selection on the D.C. side will be made by the end of March.

The design of the instrumentation and control for the facility has been specified. The system has been designed with a number of automatic control components in order to make system testing possible. Thus, automatic flow control is provided for both the collector field and the flow to the chiller. Further, a large number of electrically actuated on/off valves has been employed to permit operating in a number of different modes.

Experimental Results. Absorption chiller on/off cycling data have been completed, some of which have been reported in Ref. 6. An example of the transient data is shown in Fig. 2. Fig. 3 shows the results of new experimental on/off cycling tests. The temperature of the heat transfer fluid, piping and heat exchangers external to the absorption chiller were preset at their respective final steady state values in order to measure the time response of the chiller alone. Comparing these data with previous system response measurements suggest that the transient response of the whole system must be taken into account rather than looking at the chiller alone.

Solar Cooling System Simulation Modeling. The initial simulation studies underway at the present time involve concentrator PV/T collectors used with absorption refrigeration machines. Later simulations will also be run using other types of photovoltaic arrays (e.g., flat arrays) as well as other cooling techniques (e.g., vapor compression machines).

The simulations are presently being carried out using improved versions of the collector, solar cell, battery and inverter models that first appeared in Ref. 10. These models are compatible with the executive routines and component models of TRNSYS. The major components of the system being studied are:

(1) a single zone house with 186 sq m floor area, R-12 insulation in the walls and R-30 insulation in the ceiling. Since this work got underway, DOE has issued its latest version of the Building Energy Performance Standards and in the location being studied (Phoenix, AZ), these standards call for more thermal resistance; hence, the residence is currently being upgraded to meet these standards.

(2) a three ton lithium-bromide/water absorption air conditioner whose start-up and shut-down properties are modeled with separate time constants (13).

(3) a concentrator (CR = 20) PV/T collector array. The model presently being used suffers from the exclusion of the mass of the absorber tube assembly and the coolant. The effect of this simplification will be studied.

(4) a hot storage tank.

(5) a cold storage tank.

(6) the circulation pumps and controllers necessary for operating the system.

The simulations are being done using SOLMET data for Phoenix for May through November of 1968.

The intent of cold storage is two-fold. First, it should and does reduce the on/off cycling of the absorption chiller. This is desirable since the COP under intermittent use can be reduced from its steady state value. The improvement in COP with cold storage is shown by the solid curves of Fig. 4.

For example, with hot storage only (3 cu m or 0.1 cu m per sq m of collector) the chiller cycles on about 600 times during a fixed period of time and operates at an average COP of 0.75. The addition of cold storage (3 cu m) reduces the number of cycles to about 250 and improves the average COP to 0.78 during this same period of time.

The second reason for considering cold storage is that the availability of cold storage may make it possible to generally operate at a collector coolant temperature that is somewhat below that for a system with only hot storage. This would mean that the photovoltaic cells would operate at a generally lower temperature and, thus, higher efficiency. This indeed is the case, but unfortunately, an extra pump is required in the chilled liquid loop. The additional parasitic power consumption of this pump (assuming 200 watts) is more than the gain in output of the cells, as shown in the dotted curves in Fig. 4. The solar electric fraction shown there is the percent of the system pump and air handler fan loads (2.3 kW estimated) supplied by the PV output.

REFERENCES

1. Pittman, P.F., "Conceptual Design and Systems Analysis of Photovoltaic Power Systems, Final Report," ALO-2744-13, Westinghouse Corporation Research and Development Center, April 1977.

2. Kern, E.C., Jr. and M.C. Russell, "Hybrid Photovoltaic/Thermal Solar Energy Systems," COO-4577-1, Massachusetts Institute of Technology, Lincoln Laboratories, Lexington, MA March 1978.

3. "Conceptual Design and Systems Analysis of Photovoltaic systems, Final Report," ALO-3686-14, General Electric Space Div., March 1977.

4. Rauch, J. and B. Wood, "Steady-State and Transient Performance Limitations of the ARKLA Solar Absorption Cooling System," Proceedings 1976 AS/ISES Meeting, Winnipeg, Manitoba, 1976.

5. Evans, D., and B. Wood, "Solar Heating and Cooling and Energy Conservation Potentials for Commercial Buildings," 1976 ASME Winter Annual Meeting, New York, NY, 1976.

6. Froemming, J., B. Wood, J. Guertin, "Dynamic Test Results of an Absorption Chiller Residential Solar Applications," ASHRAE Transactions, 1979.

7. Backus, C., D. Evans, L. Florschuetz, D. Jacobson, B. Wood, "Considerations for Using Solar Concentrations in Photovoltaic Systems," 12th Intersociety Energy Conversion Engineering Conference, Washington D.C., August 1977.

J. Backus, C., B. Wood, D. Jacobson, B. McNeill, "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Arizona State University, August 1977.

9. Williams, R. and B. Wood, "Passive Cooling for Linearly Concentrated Solar Cell Arrays," 13th Photovoltaic Specialist Conference, Washington, D.C., 1978.

10. Evans, D., W. Facinelli, R. Otterbein, "Combined Photovoltaic/Thermal System Studies," SAND78-7031, Arizona State University, August 1978.

11. "TRNSYS, A Transient Simulation Program," Engineering Experiment Station Report 38, University of Wisconsin, 1979.

12. Florschuetz, L., "Extension of the Hottle-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors," Solar Energy Vol. 22, No. 4, 1979.

13. Blinn, J.C., "Simulation of Solar Absorption Air Conditioning," M.S. Thesis, University of Wisconsin, Madison, WI, 1979.

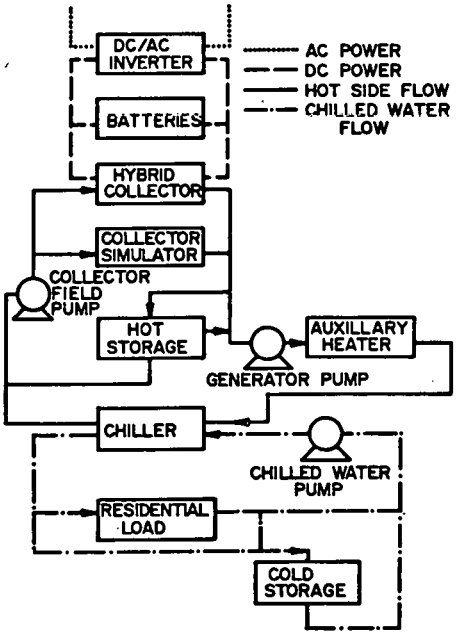


Fig. 1 Schematic of the Arizona State University PV/T solar cooling system test facility

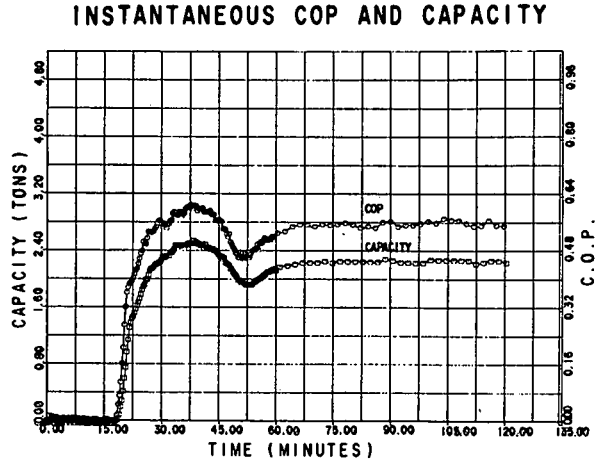


Fig. 2 Cold start-up instantaneous values of COP and cooling capacity for 90.6C (195F) hot water inlet, 35C (95F) cooling water inlet, and 7.2C (45F) chilled water outlet.

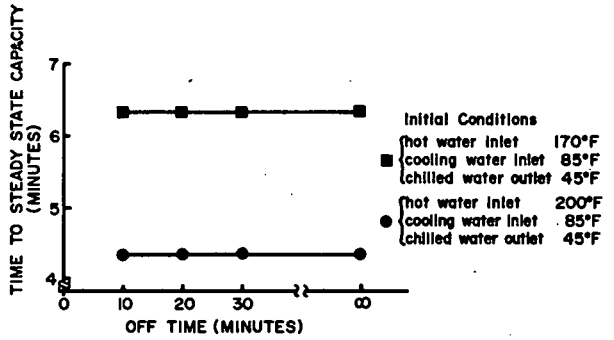


Fig. 3 Transient Performance of ARKLA Chiller. Time to regain steady state capacity for various off times. Generator hot water supplied from 4.5m³ (1200 gal) storage tank.

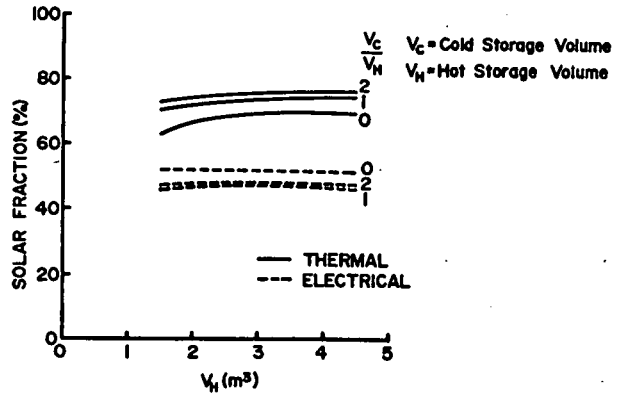


Fig. 4 Fraction of energy supplied by a 30m² combined PV/T collector to cool a residence with an absorption chiller. Computer simulation using Phoenix, AZ weather data May-Oct 1968.

COMBINED SOLAR THERMAL-PHOTOVOLTAIC SYSTEMS DEMONSTRATION-PHASE I

DIVISION OF ENGINEERING, BROWN UNIVERSITY, PROVIDENCE, RI 02912

CONTRACT NO. DE-AC03-79CS30205

PRINCIPAL INVESTIGATOR, PROFESSOR JOSEPH J. LOFERSKI

PERIOD OF CONTRACT PHASE I: JULY 1, 1979-MARCH 31, 1980

Participants: T. Russell, J. Beall, J. Shewchun, J.J. Loferski, B. Roessler, R. Dobbins
R. Beckman and H. Yarme (REDE, Inc.); P. Levine (Solarfern)

OBJECTIVE

The objective of the first phase of this contract is to produce a conceptual design of a combined photovoltaic/thermal (PV/T) solar energy system for a small single-family residence. Except for the combined PV/T panels themselves, the design should utilize "off-the-shelf" components, since the whole system is intended for commercialization when the price of photovoltaic cells drops to the levels envisioned by the DOE PV goals for the mid-1980's. The PV/T panels will use air as the heat transfer fluid. The electricity produced by the photovoltaic cells will be interfaced with the electrical utility via a synchronous inverter. This electrical energy will be used mainly for space conditioning; most of it will be used to run a conventional air-to-air heat pump. However, a portion will supply the standard electrical needs of the building. Because PV/T collectors are not commercially available as yet, a principal objective of this program is the design and modelling of optimized PV/T collectors followed by the construction and testing of a few prototypes. The thermal energy provided by the collector will be used to heat the building through a standard solar thermal configuration. The ultimate goals of this project are the construction of the system, its incorporation into a building, monitoring its performance and comparing the performance with predictions based on a model of the system.

BACKGROUND

Since this is the first report on our project, it is appropriate to offer a rationale for combined photovoltaic/thermal systems before describing the particular features of the Brown University project.

The principal objective of the DOE Photovoltaic Program is to bring the price of photovoltaic cells down to such a level that the cost of electricity produced by PV cells will be competitive with the cost of electricity produced by nuclear and fossil fuel power plants. The cost of electricity is a function of both the price of the PV cells and of balance-of-system (BOS) costs. The balance-of-system costs are determined by the intended application.

The DOE has sponsored economic studies of various proposed systems incorporating PV cells in order to determine the extent to which economic goals for photovoltaic cells may be affected by the system in which they are used. These studies can be broadly classified as distributed and centralized systems(1). The distributed systems have been further subdivided into photovoltaic-only and combined photovoltaic/thermal systems. Some of these economic studies conclude that combined photovoltaic/thermal systems have an economic advantage over photovoltaic-only systems for individual residential buildings. There are a number of reasons for this advantage. First of all, a photovoltaic array and a solar thermal panel have a number of components in common. Both must have a transparent cover; both must have a substrate, and combining them in the same panel reduces the overall cost. Secondly, by combining the photovoltaic and thermal collector components in the same panels, the total area on the roof of the building which must be covered by solar devices is reduced. Thirdly, the efficiency of solar photovoltaic cells decreases as the temperature increases and, therefore, it is desirable to provide for cooling the cells. This can be conveniently accomplished in a combined panel which carries heat away from the cells and puts that heat to beneficial use. Finally, the combined panel results in a higher solar energy conversion efficiency than a photovoltaic-only panel, since the latter is presently limited to an efficiency of about 12% for standard commercial solar cells.

The first PV/T panels under DOE sponsorship were constructed about one year ago. These panels were tested by the MIT Lincoln Labs group; the reported performance of these panels was disappointing(2). The conversion efficiency of the photovoltaic cells was substantially below 10%, and the performance of the combined panels as solar thermal collectors was not satisfactory. Consequently, the first and most important task for combined PV/T projects is the design and modelling of improved collectors based on the experience gained with the first-generation collectors. The first step in this process is to establish the causes for the shortcomings of the first-generation collectors. This, in turn, requires a good knowledge of how solar cells work and how the properties of these cells can be changed in a direction which would make the cells more effective in combined PV/T collectors. The Brown University group is a reservoir of substantial expertise on solar cells gained over the twenty-five years since the invention of the solar cell in 1954, a period during which members of the group have made important contributions to solar cell research and development. It was this long-term commitment to ultimate commercialization of photovoltaic solar power and the conviction that distributed combined PV/T systems will play an important role in such commercialization which prompted the Brown group to undertake this project.

The design of combined PV/T collectors also requires expertise in the technology underlying solar thermal collectors. Such expertise is provided for the project by Brown's fluid mechanics faculty and by the chief engineer of Solarfern, Incorporated, a manufacturer of solar thermal collectors in which air is used as the heat transfer fluid.

As noted above, the Brown group decided to use air collectors because such collectors seem to be

more compatible with certain features of solar cell assembly procedures and because of certain perceived advantages of air collectors in small residence heating systems. With respect to solar cells, the light receiving surface of solar cells must be protected from dust, abrasion, etc. To afford such protection, it is common practice in the industry to bond several tens of solar cells to a single glass panel cover having dimensions of several square feet. Since the glass is an electrical insulator, the system designer is free to interconnect the cells in such series-parallel combinations as may be desired. An obvious way to extract heat from cells mounted on such a glass panel is to pass the heat transfer fluid over the exposed back surface of the cells and, therefore, air is a preferred heat transfer fluid. It is an objective of the design of PV/T collectors that the temperature of the cells should not be higher than the temperature of the absorber plate in the collector. If, alternatively, the cells are bonded to a metal plate, the plate must be covered by an electrical insulator to allow freedom in series-parallel interconnections of cells. The cement used to bond the cells to this metal absorber plate adds to the thermal resistance between the cells and the absorber surface. The metal absorber plates used in thermal collectors are likely to be made from thin, flexible sheets; this can also generate problems since solar cells bonded to such a sheet may themselves experience flexing which could lead to cell fracture or to de-lamination. Cells bonded to a glass cover clearly avoid these difficulties. Finally, cooling the cells during the summer when the thermal energy is not needed by the building is simplified in air collector systems; it is only necessary to vent the air to the atmosphere to maintain the cells around the ambient temperature.

The Brown group has, therefore, focused its attention on thermal collector designs in which the heat transfer coefficient between cells mounted on a glass cover plate and the air is maximized.

As regards the advantages of air systems for heating of a small residence, a substantial fraction of single-family dwellings in the United States use air heating systems because they are less expensive. Central air conditioning of small residences is accomplished relatively simply in houses equipped with ducts needed for air heating. Air-to-air heat pumps for small buildings are available off-the-shelf, and they can be readily incorporated into such air-heated buildings.

The use of electrical energy storage in this project has been considered but has been deferred, in part, because it is not clear that storage batteries can be economically ready by the mid-1980's and, in part, because studies of the impact of photovoltaic systems on utilities indicate that the utility can serve as the "storage system" if the total amount of power contributed by PV systems is of the order of 5 to 10% of the total power demand (3).

The Brown system will include a microprocessor to control the system and to allow exploration of various modes of operation.

These considerations have resulted in the PV/T system shown schematically in Fig. 1. A computer model of the system has been developed from precursor models of such systems (4,5), and the system performance is being studied with the help of this model. Based on this modelling, we anticipate that the system will produce between 3 to 5KW of electrical energy and between 30 and 40KW of thermal energy on a typical sunny day in the winter of Rhode Island.

SUMMARY OF TECHNICAL ACCOMPLISHMENTS

Our main effort has been devoted to the design and modelling of PV/T air collectors. We have identified modifications of the cells themselves which can lead to improved performance and are exploring modifications of the thermal collectors which would improve the thermal performance. We have designed in collaboration with REDE, Incorporated, a Providence-based architectural design firm, a simple, inexpensive structure having a floor area comparable to that of a single-family residence on which the PV/T system will ultimately be incorporated. This building will be sited on the flat roof (having a larger area than the residence) of an existing building on the Brown campus. This arrangement emphasizes the experimental nature of the project and provides security and a convenient work environment.

TECHNICAL ACCOMPLISHMENTS

- We have devised methods for increasing the absorptance of solar cells by blackening the metallization (which normally reflects about 10% of the incident light) and by reducing reflection losses. The optical properties of such cells which are "customized" for PV/T collectors have been measured.
- We have identified three methods for improving heat transfer from the cells to the air and are in the process of constructing prototype panels based on these methods. The first of these methods involves attachment of "fins" to the back surface of the cells; a schematic representation of such a cell and the calculated performance of such a panel are shown in Fig. 2. The second design is based on jet-impingement cooling. The third involves constriction of the airflow channel. The true overall efficiency of such PV/T panels including parasitic losses have been calculated and will be taken into account for the design.
- Virtually all other components of subsystems to be used in the system (heat pump, microprocessor, etc.) have been identified. Preliminary design of the residential building has been completed, and a site has been selected.

FUTURE ACTIVITIES

Contract Activities. The prototype PV/T collectors must be constructed and tested. The availability and price of PV cells poses a problem. We are presently evaluating potential suppliers of cells. We have not yet identified a PV/T panel assembler and do not exclude the possibility that they will be assembled at Brown. During Phase II of the contract scheduled to begin in April 1980, the system will be constructed and monitoring will begin.

Post-contract Activities. We anticipate that the PV/T collectors we are now designing are second-generation panels which will eventually be displaced by more advanced panels. Some of the anticipated advances like those currently being pursued for thermal panels by the Brookhaven National Laboratory (BNL) Solar Group should lead to reduced cost, since they substitute plastics and other inexpensive materials for those used in today's conventional panels. Other advances would result in improved photovoltaic performance of the panels by the incorporation of higher efficiency solar cells customized for PV/T collectors according to procedures currently being developed at Brown and elsewhere. The residential heating/cooling system will benefit from work on higher coefficient of performance heat pumps like that being pursued at

BNL. The requirements on microprocessors for such PV/T systems will be established so that the cost of the controls can be minimized. The thermal storage portion of the system could eventually be changed to utilize a eutectic salt storage system. In short, the building with its PV/T system will serve as a test site for improvements in PV/T systems.

REFERENCES

(1) P.F. Pittman, E.F. Federman, R.R. Ferber and C.R. Chowaniec, "Conference Record of the 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, LA, November, 1976," p. 681; M. Wolf, Energy Conversion, 14, No. 2, 55 (1975).

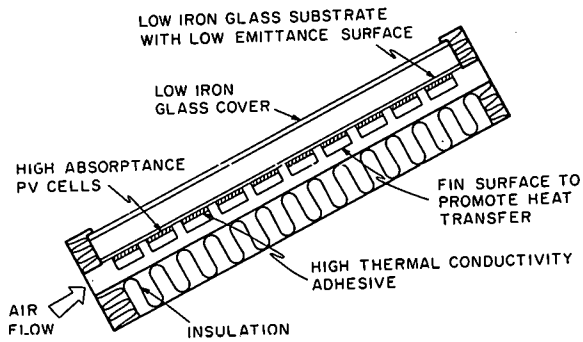
(2) S.D. Hendrie, "Evaluation of Combined Photovoltaic/Thermal Collectors," Presented at the International Solar Energy Society Conference, 28 May-1 June, 1979, NTIS No. COO-4577-8.

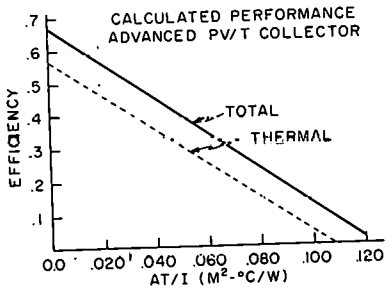
(3) W.D. Marsh, EPRI Contract Report on Contract No. RP651-1, General Electric Company, Schenectady, New York.

(4) L.W. Florscheutz, "Extension of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors, Solar Energy, Vol. 22, pp. 361-366.

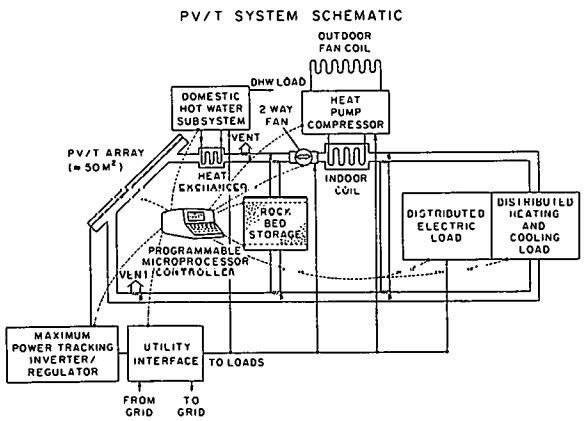
(5) D.L. Evans, W.A. Facinelli, R.T. Otterbein, "Combined Photovoltaic/Thermal System Studies," Arizona State University, SAND78-7031, Sandia Labs, Contract P.O. 05-6012.

ADVANCED PV/T AIR COLLECTOR CONCEPT





PV/T SYSTEM SCHEMATIC



STUDIES OF HEAT TRANSFER AND WATER MIGRATION IN SOILS

COLORADO STATE UNIVERSITY

DE-AC02-79CS30139

WYNN R. WALKER

MAY 1, 1979 TO JUNE 30, 1980

PROJECT OBJECTIVE

The principal objective of this research is the investigation of thermal properties of partially saturated soil surrounding subsurface heat storage reservoirs and heat exchange piping. Four specific objectives or tasks are planned.

(1) To study the thermal conductivity of soil materials in relation to mineralogical composition, water content, and bulk density. The purpose of this objective is to provide guidelines for using available in situ soil materials around buried heat reservoirs and heat exchange piping;

(2) To study the rates of soil drying around heated surfaces, particularly the width of the dry layer and its change in thermal conductivity. The purpose of this objective is to evaluate a soil's self-insulating capacity;

(3) To study the water vapor permeability of water barriers which might be used as reservoir or heat exchange boundary materials. The purpose of this objective is to determine the feasibility of managing thermal properties of the soil surrounding heated or cooled buried surfaces; and

(4) To study the heat exchange from in-ground piping. The purpose of this objective is to establish criteria for pipe spacing and flow rates.

BACKGROUND AND CONCEPT

The cost of residential solar energy systems is generally high because peak winter heating demands occur when available solar radiation is minimal. Providing a long-term storage capability is one means of reducing the capacity and thereby the cost of solar heating systems. The soil materials in the first 10-100 meters of the earth's surface are one alternative thermal storage site. The feasibility of in situ soil heat storage and exchange first requires an effective understanding of soil thermal properties and methods for their optimal control. This project is intended to yield additional information on the influence of soil properties on potential heat storage and extraction facilities.

The simple one-dimensional theory of heat flow in a partially saturated porous medium illustrates the essential concepts encompassed by this research. Soil heat flux is described by:

$$Q_h = -\lambda \frac{\partial T}{\partial x} \quad (1)$$

in which,

Q_h = heat flux, cal $cm^{-2}sec^{-1}$;

λ = thermal conductivity, cal $cm^{-1}sec^{-1}{}^{\circ}C^{-1}$;

T = temperature, °C; and

z = distance, cm.

The thermal conductivity is highly dependent on soil water content as well as soil material composition, bulk density, and pore size distribution. The storage of heat in soil or the withdrawal rates, are described by:

$$\frac{\partial Q_h}{\partial z} = - C \frac{\partial T}{\partial t} \quad (2)$$

where,

C = heat capacity, cal $gm^{-1}\ {}^{\circ}C^{-1}$; and

t = time, sec.

The heat capacity of an average soil can be approximated by the relation:

$$C = 0.46\ X_m + 0.60\ X_o + X_w \quad (3)$$

in which,

X_m, X_o, X_w = volumetric fraction of soil minerals, organic matter and water, respectively.

A plot of λ and C for a typical soil is given in Figure 1.

A major component of the thermal conductivity is the movement of water vapor in response to a temperature gradient. From Figure 1, the effect is seen to be approximately an order of magnitude. Heat capacity changes much less with increased water content. These

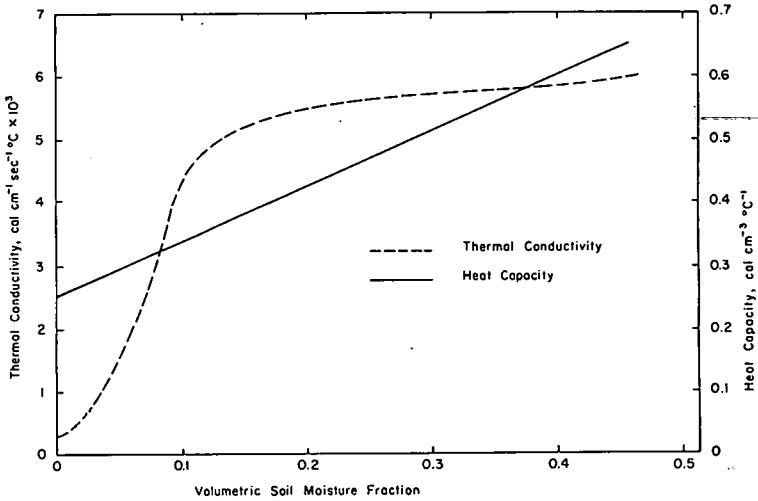


Figure 1. The influence of soil water content on thermal conductivity and heat capacity of a partially saturated soil.

processes can be managed in such a way that a soil volume can act as both a heat reservoir and an insulator around the reservoir. The concept is illustrated in Figure 2 and is the subject of at least two patent applications (Kemper and Walker, 1978).

A moist soil is contained within an impervious barrier and heated or cooled with exchange piping. The thermal gradients around the reservoir cause a dry layer to form which tends to insulate the reservoir. Internally, the water barrier prevents the drying of soil around the exchange piping thereby maintaining a high exchange efficiency. Experiments are being made as part of this project to determine how the exterior insulating process and the interior storage and exchange efficiencies can be maximized.

SUMMARY

A small field reservoir has been constructed and heated. Thermal gradients and heat flux measurements have been taken within and outside the reservoir to study the storage and heat exchange properties. A mathematical model of the physical processes has been developed from literature sources and is being verified with extensive laboratory data. Extrapolations of laboratory and model predictions to the observations are indicating satisfactory agreement. Laboratory experiments are being designed to evaluate the water and heat movement around underground piping.

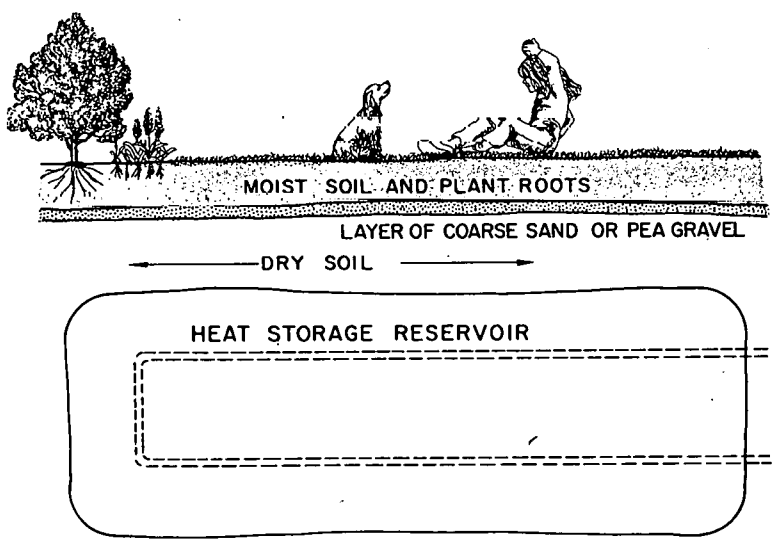


Figure 2. The basic concept for low cost underground storage of heat (after Kemper and Walker, 1978).

TECHNICAL ACCOMPLISHMENTS

At the time of this report, the project is toward the middle of both laboratory and field data collection activities. Accomplishments in three areas will be reported: (1) field heat storage reservoir test; (2) formulation of a soil water and heat flow model; and (3) laboratory measurement of the thermal conductivity of various soils.

As a field scale method of verifying the basic concept, a heat storage reservoir depicted in Figure 3 was constructed near Colorado State University's Solar Village. A circular pit was excavated to a depth of 18 feet. The excavated soil was then spread over an area of approximately 1/4 acre and allowed to dry. Periodic stirring of the soil with agricultural cultivation equipment was undertaken to breakup large aggregates and ensure equal drying. After drying the excavated soil was completed, a 3 foot layer of the dry soil was replaced in the pit and a dual wall plastic cylinder was supported above the fill with a light frame and then filled with wet soil in 1.5 foot intervals. A plastic pipe soil was placed between each layer in order to heat or cool the reservoir. Concurrent backfilling with dry soil around the outside of the reservoir protected the shape of the plastic container. Another 5.5 feet of dry soil was placed over the reservoir and then separated from the 1.5 feet of top soil by a thin gravel layer in order to prevent downward movement of precipitation.

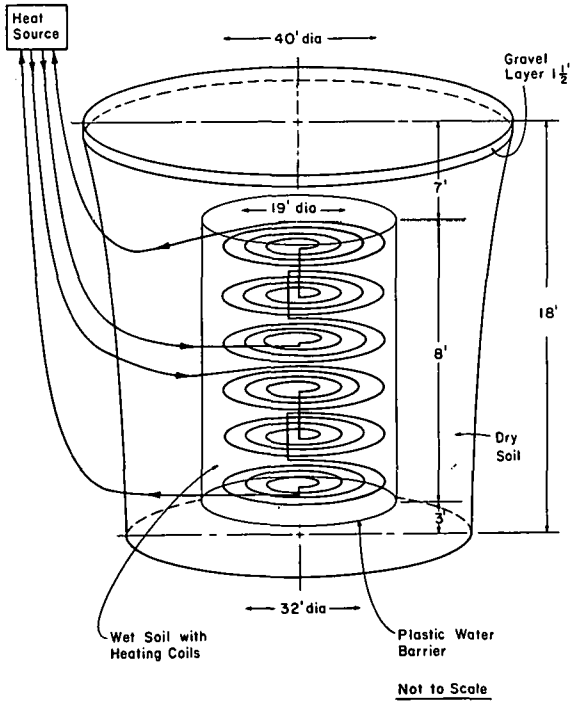


Figure 3. Schematic diagram of the underground heat storage reservoir.

Throughout the field system, instrumentation was located to measure water, temperature, and heat flux. Figure 4 shows a side view of the reservoir with the location of the monitoring points. The water content in the soil outside the reservoir is checked with a neutron probe. A multiple junction thermocouple plate was developed to measure heat flux around the reservoir exterior, and temperature measurements are recorded with copper-constantan thermocouples.

The reservoir has been heated approximately 90 days using a propane water heater and calibrated water circulating system. Heat losses into the surrounding soil are approximately 80,000 BTU/day which has been equalized with the rate of heat input as a check. Total heat storage, taken as the difference between starting and final reservoir temperature, is 5 million BTU. Thus, heat losses are approximately 1.6% per day. This heat loss rate is somewhat higher than expected although the reservoir has a relatively large surface area to volume ratio. Thermal conductivity measurements on the materials surrounding the reservoir are consistant with the heat losses being observed.

• The range of soil and heating conditions that are encountered are far to broad to study individually. A more cost-effective approach is to sample the range of conditions and use the results to calibrate and verify a general mathematical representation of the system. The thermal regime in soils has been the subject of extensive study in soil science. A model proposed by DeVries (1963) is widely utilized, but is known to be inaccurate with regards to the effects of temperature and water vapor flux. Two major modifications were discovered in the literature which correct the problems. The revisions to the original heat and water flow analysis given by Kemper and Walker (1978) is nearing completion and will be tested against laboratory data. It appears that a usable heat flow model in partially saturated soil will be an important part of this project.

• Laboratory measurements of the soil's thermal and hydraulic properties is a major problem without large investments in specialized equipment. An unwritten objective of the investigators has been to develope the means to make such measurements on various partially saturated soil materials quickly and inexpensively. Two procedures have been developed. The first is a multiple junction thermocouple plate formed by winding a constantan wire around a plexiglas plate and electrocoating half of the winds with copper. The plate is then placed at the bottom of an insulated cylinder filled with a material of known thermal conductivity. The cylinder is placed on a heated surface of known temperature and the temperature gradient in the filler recorded with time. When the system has reached steady state, the heat flux can be calculated and correlated with the flux plate voltage reading. These type of sensors were installed with the field reservoir as indicated earlier.

A problem with the multiple junction thermocouple heat flux plates was found when the calibrating procedure used a liquid filler. Literature sources stated that a bentonite slurry or glycerol would not develop convection currents, but in reality do when exposed to a heated surface in the range of temperatures used in this study. Thus, it is suggested that solid materials be used as the filler material when calibrating this type of instrumentation. To overcome this problem, another heat flux plate was developed by enclosing a spiral of known resistance wire between two thin plexiglas plates. By flowing a measured current through the spiral or measuring the voltage

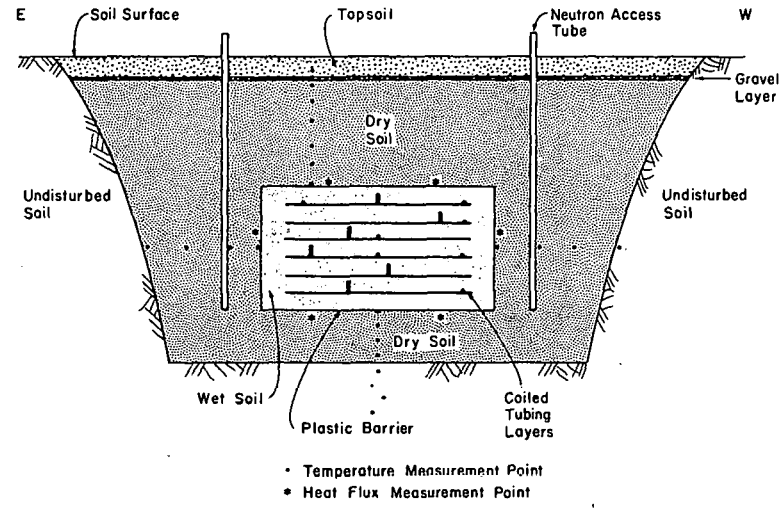


Figure 4. Side view of the field heat reservoir indicating water, temperature, and heat flux plates.

across the spiral, the heat generated can be accurately determined. The spiral is then placed in the middle of the test sample as shown in Figure 5. Temperature gradients in both directions are allowed to stabilize and then used to calculate the thermal conductivity in both directions. The two measurements can be averaged to yield the sample's thermal conductivity.

FUTURE ACTIVITIES

Data collection, model testing, and report preparation will occupy most of the remaining project interval. The study of heat flux around underground pipes in the laboratory has not yet reached the data gathering stage, but should be started in the near future. Preliminary efforts have been made regarding objectives 2 and 3 and will be expanded. The field reservoir heating cycle is concluded. For a period of about two weeks, no heat will be added in order to monitor the natural cooling of the reservoir. Then it will be reheated and then cooled by extracting the heat by circulating a cooled water flow.

REFERENCES

DeVries, D. A. 1963. Thermal Properties of Soils. In Physics of the Plant Environment, W. R. VanWijk (Ed.). North-Holland Publishing Co., Amsterdam, The Netherlands.

Kemper, W. D. and W. R. Walker. 1978. Trans-Seasonal Storage of Solar Energy. Report COO/4546-3, Solar Energy Applications Laboratory. Colorado State University, Fort Collins, Colorado. October.

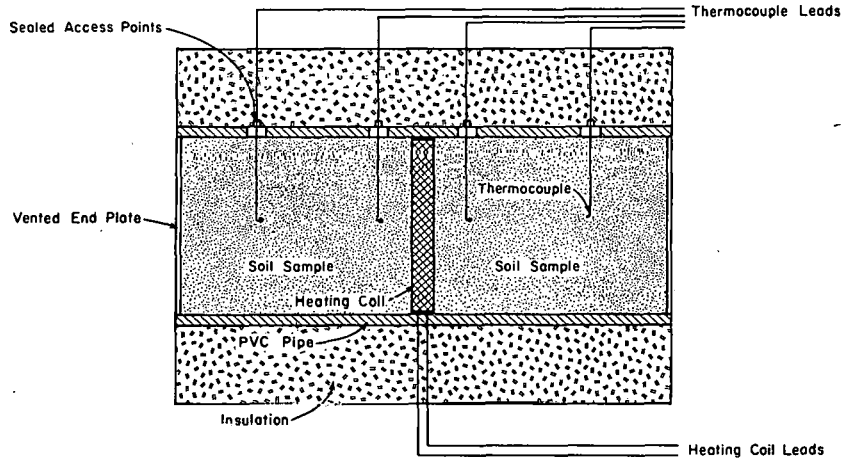


Figure 5. Illustrative view of the mid-sample thermal conductivity measuring apparatus developed for soil testing.

DIRECT CONTACT LIQUID-LIQUID HEAT EXCHANGER FOR SOLAR HEATED AND COOLED BUILDINGS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
EY-76-S-02-2867.A008

SUSUMU KARAKI

JANUARY 1, 1979 to APRIL 30, 1980

OBJECTIVE

The objective of the current phase of the project is to establish the technical feasibility and economic practicability of using direct contact liquid-liquid heat exchangers in solar heating and cooling systems.

BACKGROUND

In a direct contact liquid-liquid heat exchanger, thermal energy from solar collectors is transferred to water storage by direct contact of droplets of collector fluid with water in the storage tank. A dense liquid which is heavier than water and immiscible in water is circulated through the collector array and the heated fluid is dispersed through the storage vessel in the form of small droplets. The transfer of thermal energy is rapid from the collector fluid to water because the droplets are small and the total surface area created by the droplets is large. A schematic representation of the direct contact heat exchange/ storage tank is shown in Figure 1.

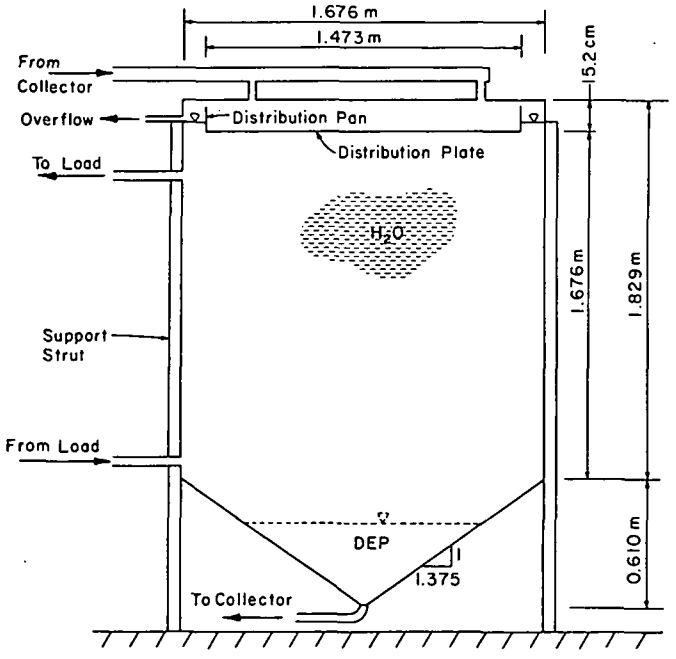


Figure 1. Direct Contact Heat Exchanger/Storage Tank

The distribution pan in Figure 1 has small 1-mm diameter holes spaced at 1.5 cm centers. The collector liquid streams through the small holes and breaks up into droplets at the top levels of the tank. The droplets collect at the bottom of the tank, which is conically shaped to minimize the volume of collector fluid, and the fluid is recirculated to the collector.

Dimensions of the tank are shown on the sketch. The liquid capacity is 4250 liters, of which 450 liters is the collector liquid. Experimental work at CSU with this heat exchange/storage system has involved the use of collector fluids heavier than water. Fluids lighter than water were considered before designing the bench (pilot) and prototype scale equipment, and a heavy liquid was chosen for testing on the basis of comparative evaluation of chemical and physical properties of the different liquids [1]. The collector liquid selected for the experiments is diethyl phthalate (DEP), which has a specific gravity varying from 1.05 at 100°C to 1.13 at 0°C, viscosity which is about three times greater than a 50 percent mixture of ethylene glycol and water and specific heat which is about one-half the value of a 50 percent mixture of ethylene glycol-water solution or four-tenths the value of pure water. The freezing and boiling points are -40°C and 298°C respectively.

Prior to constructing the full-scale direct contact/ storage unit, a small scale bench (pilot) facility was constructed to evaluate the concept and to conduct some basic experiments to study the mechanics of droplet formation, heat transfer mechanisms and to determine fall velocities of droplets and total retention volume of DEP in the storage vessel. Theoretical and experimental work for the pilot experiments are described in a previous report [2].

The advantages of the DCLLHE concept, using a non-freezing, non-boiling, non-corrosive liquid as the collector heat transfer fluid compared to a dual-fluid conventional liquid solar system are: (1) elimination of the need for heat exchanger hardware as well as an additional pump with corresponding reduction in parasitic electrical energy consumption (2) elimination of freezing problems in the collector with use of a low freezing point collector fluid, (3) prevention of boiling in the collector with the use of a high boiling point liquid, and at the same time, preventing boiling of water in storage by use of limit controls to stop circulation, (4) prevention of galvanic corrosion and allowing use of dissimilar metals in the collector fluid circuit because the collector liquid is non-aqueous and (5) increases collection efficiency by eliminating a positive temperature difference between the fluid at the inlet to the collector and the storage medium.

The disadvantages of a DCLLHE system compared to a conventional dual-liquid system using a counterflow heat exchanger are: (1) DEP is more viscous than ethylene glycol and the pressure drop across the collector is greater for DEP at the same capacitance flow rate as water or ethylene glycol-water solutions, (2) special handling of a collector fluid such as DEP is necessary during filling and draining processes, and (3) there is some additional cost for the

collector liquid compared to water, or ethylene glycol-water solutions.

Based on the results of experiments with a bench model, a full-scale unit was assembled in a portable trailer and during a short period of the 1977-78 winter, the unit was attached to an evacuated tube collector system on CSU Solar House III. Results of tests with the full-scale solar system were reported at the Third Annual Solar Heating and Cooling R&D Contractors' Meeting (September 1978), [3]. System performance during April 1978, with the DCLLHE, was compared to performance results obtained with conventional heat exchanger/storage unit using the same collectors, but operated during February 1978. There was little difference in measured solar collection efficiency but with the DCLLHE system there was some reduction in parasitic power consumption per unit of useful solar energy collected.

The goals of the project during the current contract period are to collect and evaluate performance data of a solar system with a DCLLHE unit to assess technical feasibility, and to establish whether the DCLLHE unit is economially practicable in a solar heating and cooling system. As expected, a solar system equipped with low-loss collectors, such as evacuated tube collectors, would not benefit substantially from a DCLLHE unit as was shown by the performance data collected the previous year. Performance data for this contract period is obtained from a flat-plate collector system.

SUMMARY

The direct contact heat exchanger/storage unit is a technically viable alternative to a dual-liquid solar collection/storage unit which uses ethylene glycol solution in the collector loop and a heat exchanger to separate the antifreeze solution from water in storage. Data collected during February, March and April 1979 (heating season) and August and September 1979 (cooling season) indicate daily collection efficiencies of 23 to 37 percent during winter and 26 and 34 percent for August and September, respectively. These performance measures by themselves, however, do not indicate the technical merits of the DCLLHE unit in the system.

Comparisons of measured daily collection efficiencies of the DCLLHE system with an identical flat-plate, dual-liquid collector system using a heat exchanger are not available for the same period and same loads. However, comparing the performance with a second system using a standard heat exchanger in the collector loop, with the same load profile, showed that the system with the DCLLHE collected on average about 17 percent greater thermal energy for the months of February, March and April 1979. To quantitatively establish the benefits of a DCLLHE unit against a standard heat exchange system, the collector, volume of storage, and heating load profiles must be the same. To achieve this comparison, the TRANSYS simulation program is being used, and the data collected from the experimental systems are being used to validate the formulation of the numerical models. By comparing the DCLLHE system with standard systems for the same period at the same location and with the same loads, the technical and economic benefits may be evaluated.

TECHNICAL ACCOMPLISHMENTS

- A full-scale DCLLHE unit in a solar heating and cooling systm was tested during 1979.
- Performance data obtained for the winter months are tabulated in Table 1.

Table 1. Monthly Mean Daily Performance

No.	Item	Units	Feb.	Mar.	April
1	Total Solar Insolation	MJ/(m²·day)	74.93	21.05	24.33
2	Insolation While Operating	MJ/(m²·day)	10.46	12.64	19.34
3	Useful Heat Collected in Storage	MJ/(m²·day)	5.50	4.90	8.48
3a	Useful Heat Collected in Storage	MJ/day	266.60	237.50	411.50
4	Daily Collection Efficiency	3/1	0.37	0.23	0.35
5	Collection Efficiency	3/2	0.53	0.39	0.44
6	Total Load	MJ/day	491.90	410.30	468.60
7	Total Solar Contribution	MJ/day	266.60	237.50	411.50
8	Total Auxiliary to Load	MJ/day	225.30	172.80	75.10
9	Solar to Space Heating	MJ/day	231.40	200.60	353.50
10	Solar to DHW	MJ/day	35.20	36.90	58.00
11	Auxiliary to Space Heating	MJ/day	152.00	87.60	54.70
12	Auxiliary to DHW	MJ/day	73.30	85.20	20.40
13	Heat Loss from Tank in (9)	MJ/day	47.00	47.30	60.40
14	Electrical Energy for Collection	MJ/day	5.95	5.08	8.44
15	Collection COP	3a/14	44.80	46.80	48.80
16	Fractional Loss From Storage	13/3a	0.18	0.20	0.15
17	Number of Days of Useable Data		11	22	19

- Performance characteristics of the DCLLHE unit used in a solar cooling system during August and September are shown in Figure 2.

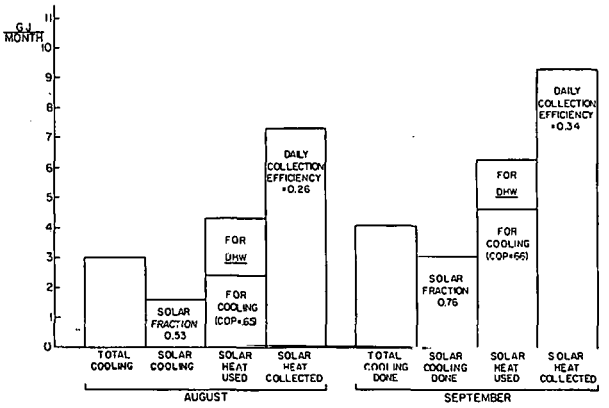


Figure 2. Energy Totals for Direct Contact System, Solar House I, 1979

FUTURE ACTIVITES

Contract Activities. The final task of this project is to make a technical and economic assessment of the practicability of the DCLLHE unit in a solar heating and cooling system. Performance comparisons of the DCLLHE and conventional heat exchanger systems are being made for 5 locations in the United States; Boston Massachusetts, Madison, Wisconsin, Charlotte, North Carolina, Dodge City, Kansas, and Phoenix, Arizona.

An economic assessment of the DCLLHE unit in a system is being made. The differences in capital and operating costs of the DCLLHE unit compared with a standard heat exchanger/storage tank subsystem are

being evaluated, and weighed against performance and other advantages, as well as disadvantages, of the two subsystems.

Post-Contract Activities. The unit tested is an experimental system and operated thus far under strictly ontrolled conditions. It is highly desirable to nstall a DCLLHE unit in a demonstration system to operate for a full year, with experimental interruption, to better assess the operational and maintenance characteristics of the system. Even if this is not done, the results of the full-scale experiment will be made available to the public through publishing of papers and technical reports. Also, the design, installation and (experimental) operational characteristics of the DCLLHE in a solar heating and/or cooling system will be included in Manuals for Design and Installation of Solar Systems prepared by Colorado State University and used in many educational programs.

PUBLICATIONS/REPORTS

1. Buchan, R. M., J. R. Majestic, and R. Billau (1976) "Toxicological Evaluation of Liquids Proposed for Use in Direct Contact Liquid-Liquid Heat Exchangers for Solar Heated and Cooled Buildings". Topical Report prepared for the U. S. Energy Research and Development Administration, COO-2867-1, September.

2. Ward, J. C., W. Loss and G. O. G. Löf (1977) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings: Pilot Plant Results". Annual Progress Report, Prepared for the U. S. Energy Research and Development Administration, COO-2867-2, September.

3. Loss, W. M., (1978) "Direkt-Kontakt-Warmeaustauscher-Speicher in Sonnenhäusern". Presented at the Second International Solar Forum, Hamburg, West Germany., July 12-14. Proceedings., Volume 2, pages 149-159, COO-2867-3.

4. Ward, J. C., and W. M. Loss (1978) "Direct Contact Liquid-Liquid Heat Exchanger: Pilot Plant Results". Proceedings, AS/ISES Annual Meeting, Volume 2.1, pages 413-419, COO-2867-4, August.

5. Ward, J. C., (1978) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings". Proceedings, Third Annual Solar Heating and Cooling R&D Contractors' Meeting, COO-2867-5, September.

6. Karaki, S., (1979) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings". Annual Progress Report for the period 1977-78, COO-2867-6, October.

7. Karaki, S., W. M. Loss and P. Brothers (1979) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings". Progress Report for the period January 1979 through November 1979, COO-2867-7, December.

REFERENCES

1. Buchan, R. M., J. R. Majestic, and R. Billau (1976) "Toxicological Evaluation of Liquids Proposed for Use in Direct Contact Liquid-Liquid Heat Exchangers for Solar Heated and Cooled Buildings". Topical Report prepared for the U. S. Energy Research and Development Administration, COO-2867-1, September.

2. Ward, J. C., W. M. Loss, and G. O. G. Löf, (1977) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings: Pilot Plant Results". Annual Progress Report for the period February 1976 through July 1977. Prepared for the U. S. Energy Research and Development Administration, COO-2867-2, September.

3. Ward, J. C., (1978) "Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings". Prepared for the Third Annual Solar Heating and Cooling R&D Contractors' Meeting, COO-2867-5, September.

SELF CONTROLLING, SELF PUMPING HEAT CIRCULATION SYSTEM STUDY

FRANKLIN RESEARCH CENTER, PHILADELPHIA, PA 19103

CONTRACT NO. EG-77-C-02-4484

PRINCIPAL INVESTIGATOR: G. P. WACHTELL

PERIOD OF CONTRACT: BEGIN AUGUST 1, 1977, END JULY 31, 1978

This report describes the work performed by the Franklin Research Center (FRC) in a one-year study of self controlling, self pumping heat circulation systems for solar applications (Ref. 1). The purpose of self pumping is to transport heat from solar collectors to the thermal energy storage (TES) or point of use without using utility power. If the TES is located above the solar collectors, natural convection (thermosyphoning) will suffice. This study was therefore concerned only with the *downward* transport of heat.

It was assumed that low temperature flat plate collectors with outlet temperature in the 120 to 160°F range are used, because schemes that can function with low temperature collectors can also be made to work with higher temperature collectors. Self pumping incurs a performance penalty, δT, an increase in the amount by which the average collector temperature must exceed the average TES temperature. It was assumed that the loss in collector efficiency due to a δT of up to 10°F can be tolerated.

Self pumping schemes that were evaluated are: power cycles for moving air or liquid or for use in vapor/liquid (latent heat) systems, vapor bubble lift (liquid), vapor expansion (liquid), entrainment of condensate by vapor (latent heat), injector (liquid), pulsejet (liquid), fluidyne (liquid), osomotic pumping (latent heat), capillary pumping (latent heat), negative thermal expansion coefficient for downward thermosyphoning (gas and condensed phase), magnetic forces on ferrofluids (liquid), and electrostatic forces on dielectric fluids (liquid).

In addition, some schemes that are not strictly self pumping were considered. They are: photovoltaic power (air, liquid, and latent heat), methods employing small amounts of utility power to return condensate in latent heat systems, and optical ducting of solar energy directly to the TES.

The principal findings of the study are as follows: power cycles are either external or internal power cycles (Ref. 2). An external power cycle (Figure 1) uses heat exchangers to draw heat from the circulant after it has been heated by the collector and to reject heat to the circulant after it has been cooled by the TES. The external power cycle is then used to drive the circulator. An internal power cycle uses the circulant as its working fluid, and uses the circulator as the pump or compressor of the power cycle.

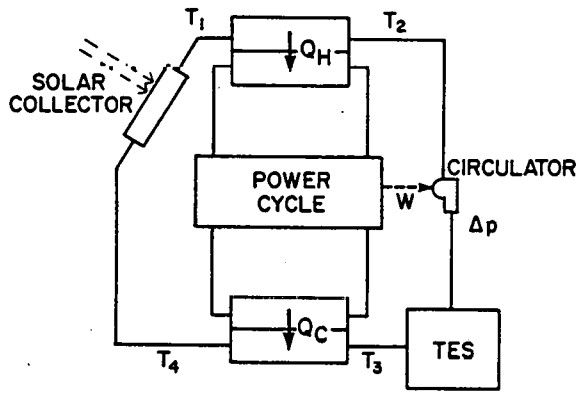


Fig. 1. External Power Cycle

Depending on the pressure drop in the system with air as the circulant, the relative efficiency of the external power cycle ($\eta_{Rel} = \eta/\eta_{Carnot}$) must must be at least 0.2 or 0.3, including the effect of heat exchanger temperature drops and other losses, in order to incur a penalty of $\delta T < 10°F$. A smaller value of η_{Rel} can be tolerated for external power cycles with water.

Feasible external power cycles for air are Rankine and Stirling (for systems with minimal pressure drop). These external power cycles are also feasible for circulating water. The Brayton gas cycle is not feasible as an external power cycle for air.

The internal power cycle is not feasible for circulating air or water. However, external and internal power cycles are feasible for latent heat transport, in which vapor is generated by the collected heat and is condensed upon delivering heat to the TES, using water or other volatile liquids. Condensate may be returned to the boiler by means of a small pump powered by a small vapor driven actuator.

Of the many schemes studied (Ref. 1) that do not employ power cycle apparatus, three are recommended for development and demonstration. They are:

1. *Bubble pump* (Figure 2). Vapor bubbles lift collector-heated water into an elevated reservoir

from which the water flows by gravity through the TES into a condenser. Vapor flows directly from the reservoir to the condenser, where it is condensed by the TES-cooled water. Water flows by gravity from the condenser to the solar collector.

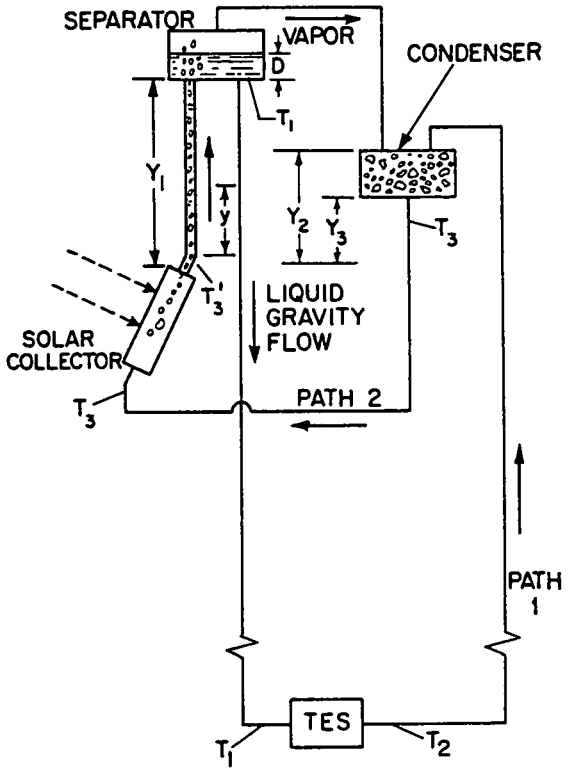


Figure 2. Vapor Bubble Pump

2. *Latent heat transport with condensate return by entrainment in vapor stream* (Figure 3). The vapor flows down from the boiler to the point where condensate joins it by gravity flow from the TES-cooled condenser, then up to a liquid separator, then down again to the condenser where it delivers the heat. The separated liquid flows by gravity into the boiler. This method of condensate return may be difficult with water because of the low density of water vapor, but should work well with liquids having denser vapors.

3. *Injector* (Figure 4). Although this requires either a higher temperature than that supplied by a flat plate collector or a more volatile liquid than water, its simplicity makes it attractive.

References

1. Wachtell, G. P., "Self Controlling, Self-Pumping Heat Circulation System Study," Final Report, COO-4484-07.

2. Wachtell, G. P., "Self Pumping by Means of Power Cycles," Second National Passive Solar Conference, Philadelphia, March 15-19, 1978, Vol. 3, Page 514, COO-4484-01.

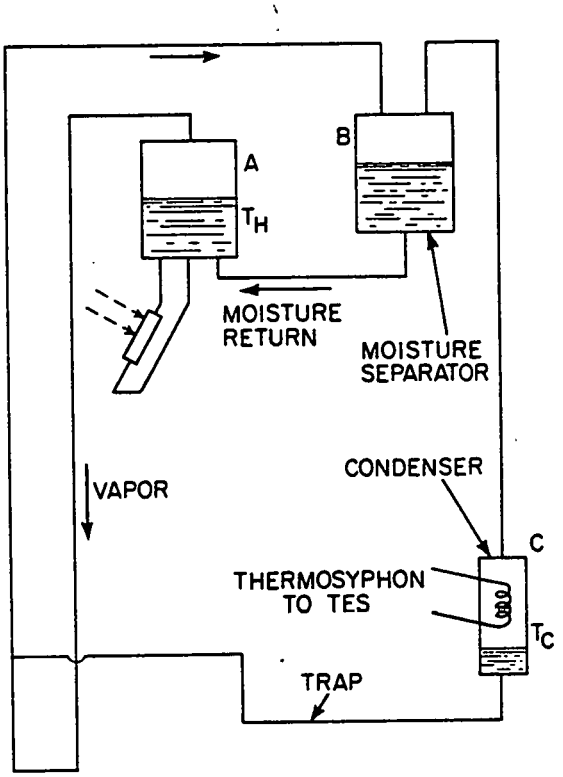


Fig. 3. Latent Heat System with Condensate Entrainment

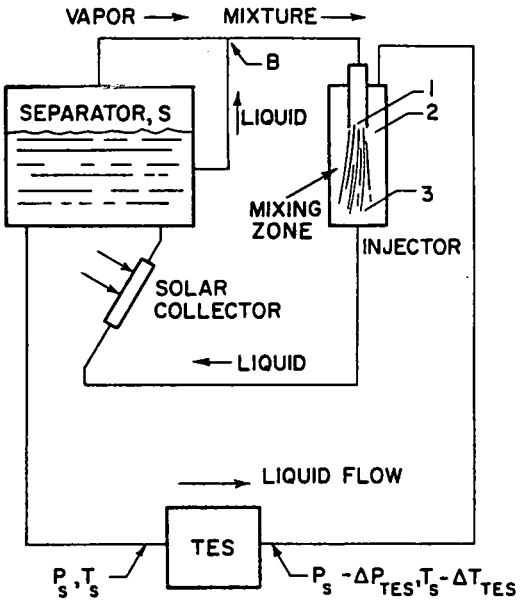


Fig. 4. Injector Self Pump

SOLAR HYBRID ENERGY PROJECT

MIT LINCOLN LABORATORY

DE-AS02-77CS34577

MILES C. RUSSELL

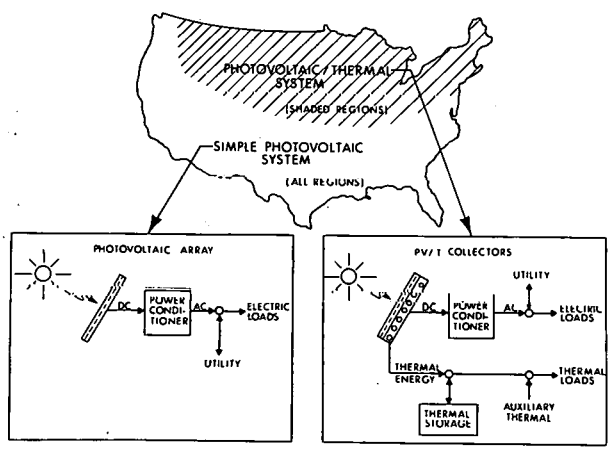
PERIOD OF CONTRACT: BEGIN 10/1/79 END 12/31/80

INTRODUCTION

Under sponsorship of the Department of Energy's Photovoltaic Program, MIT Lincoln Laboratory (MIT LL) has undertaken the task of developing residential solar photovoltaic energy systems. This activity includes the design and testing of both photovoltaic components and residential systems.

RESIDENTIAL SYSTEM DESIGNS

During the first phase of activity, PV systems appropriate for various climatic and economic regions of the country were studied. One system identified as being potentially economical in all regions consists of a roof-mounted photovoltaic array and a utility-interactive power inverter. In this system photovoltaic power in excess of the immediate residential electrical demand can be routed to the electric utility grid and "stored" for use at a later time. A typical installation of this PV system will include power conditioning equipment to maximize the photovoltaic array power output. This system is shown in Figure 1.



RESIDENTIAL PHOTOVOLTAIC SYSTEM
Figure 1.

A second system identified utilizes combined photovoltaic/thermal (PV/T) collectors which, in a single unit, convert sunlight to both thermal and electrical energy. A fundamental PV/T collector consists of PV cells attached to the absorber plate of a solar thermal collector. Systems employing collectors of this type are predicted to be economical in cold climate regions.

COMBINED PHOTOVOLTAIC/THERMAL COLLECTOR TESTING

Testing of several prototype PV/T collectors is ongoing at MIT LL. To date, detailed thermal and electrical performance data have been measured in accordance with the ASHRAE 93-77 specifications. The test facility at MIT LL can accommodate two liquid and two air-cooled PV/T collectors. The maximum solar-to-thermal and solar-to-electrical conversion efficiencies measured for an air-type PV/T collector are 43% and 6.2%, respectively. The corresponding conversion efficiencies for the liquid-type PV/T collector are 32% and 6.6% .

Experimental measurements of the various surface temperatures within the PV/T collectors have been made to calculate the convection heat transfer coefficients and energy flows of these collectors. Analytical modeling of the collectors from first principles has been done and verifies that improved bonding of PV cells to the thermal collector would result in much improved thermal efficiencies.

Experimentation is continuing to measure the performance of a commercially available low concentration PV/T collector.

ADVANCED PV/T COLLECTOR DESIGNS

Improved collectors are being designed, which are based upon the detailed experimental measurements done for the prototype PV/T collectors. Several design improvements have been developed which are expected to yield increases in the thermal and electrical efficiencies of as much as 10% and 4%, respectively.

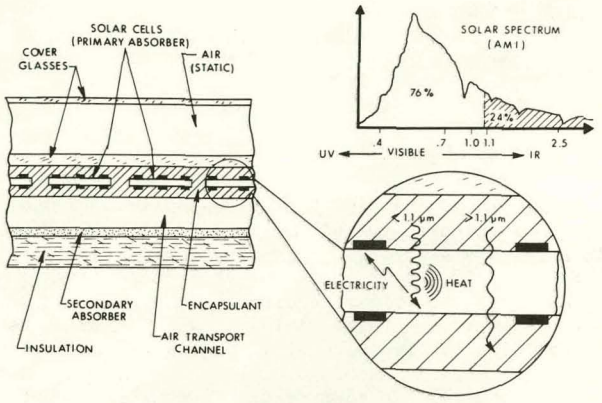
One area where improvements can be made is in the PV cell-to-absorber bonding. Rough, gapped, uneven bonding was found on both the liquid- and air-type prototype PV/Ts, causing poor thermal conductivity between the PV cell and absorber. A carefully applied, thin, uniform bonding layer would significantly improve collector thermal efficiency. A second design improvement is in the back surface metallization of the PV cells. Traditionally, PV cells have a metallized grid pattern on the "sun side" and are solder-dipped on the back side. Long wave radiation in the solar spectrum will be transmitted through the silicon, reflected off the metallized back surface, and lost in a cell of this design. Applying a grid pattern on the back as well as the front surfaces of the PV cell will allow infrared radiation to pass through the cell

*This work was sponsored by the U. S. Department of Energy.

**Presented at the U. S. Department of Energy's Annual Active Solar Heating and Cooling Contractors' Review, Lake Tahoe, 26-28 March 1980.

+The U. S. Government assumes no responsibility for the work presented.

and be absorbed in the substrate material (see Figure 2). To realize this improved utilization of the solar spectrum requires increasing the doping levels in the cell to avoid increasing the series resistance and thereby reducing the solar-to-electric conversion efficiency.



ADVANCED PV/T COLLECTOR

Figure 2.

HEAT PUMP TESTING AND DEVELOPMENT

In addition to the ongoing PV/T component development activity, a major effort in testing of heat pumps is also underway. Part of the MIT LL project is to identify promising heat pump configurations and control strategies for residential PV applications. Consequently, a solar research facility at the University of Texas at Arlington (UTA) has been equipped by MIT LL with a modified Carrier Corporation Solaround System. This system is being used to determine how well the Tri-X Coil system, which is the system's unique feature, contributes to reducing the residence's utility energy consumption. The Tri-X Coil makes possible four operational modes which will be examined in detail in the course of the UTA work:

1. Off-Peak Cooling. Water chilled during the night, when lower utility rates apply, is used to cool the residence.
2. Simultaneous Heating of Residential Return Air. Residential air is simultaneously heated by the heat pump and energy extracted from the thermal storage tank.
3. Utilization of the Heat Pump's Excess Capacity. The heat pump is used to transfer energy from the ambient atmosphere to the thermal storage tank. This is done when the ambient temperature rises above the balance point of the heat pump and the temperature of the water in the thermal storage tank is below about 100°F.
4. Utilization of Storage Thermal Energy to Defrost the Outdoor Coil. Utilizing energy stored in the thermal storage tank to defrost the outdoor heat pump coil obviates extracting energy directly from the residence.

To date, publications describing Lincoln Laboratory's PV/T activity are as follows:

COO-4577-1 Kern, E. C., "Hybrid PV/Thermal Energy," American Section of the International Solar Energy Society, San Francisco, CA, 15-17 February 1978, Technical Report, 27 March 1978.

COO-4577-2 Kern, E. C., "On Photovoltaic/Thermal Collectors and Heat Pumps," American Section of the International Solar Energy Society, Denver, CO, 28-31 August 1978.

COO-4577-3 Kern, E. C., and Russell, M. C., "Combined Photovoltaic and Thermal Hybrid Collector Systems," 13th IEEE Specialists' Conference, Washington, DC, 5-8 June 1978.

COO-4577-4 Kern, E. C., "On Air-Conditioning with Photovoltaics," ASME International Gas Turbine and Solar Conference, San Diego, CA, 12-15 March 1979.

COO-4577-5 Darkazalli, G., "A Description of the University of Texas at Arlington Solar Energy Research Facility PV/Thermal Residential System," 16 March 1979.

COO-4577-6 Kern, E. C., "Phase One Experiment Test Plan, SPV/Thermal Residential Experiment," 15 March 1979.

COO-4577-7 Russell, M. C., and Kern, E. C., "Optimization of Photovoltaic/Thermal Collector Heat Pump Systems," ISES Silver Jubilee International Solar Exhibition, Atlanta, GA, 28 May to 1 June 1979.

COO-4577-8 Hendrie, S. D., "Combined Photovoltaic/Thermal Collector Performance," ISES Silver Jubilee International Solar Exhibition, Atlanta, CA, 28 May to 1 June.

COO-4577-9 Russell, M. C., "Photovoltaic/Thermal Residential System Designs," December, 1979.

EVALUATION OF SOLAR POND PERFORMANCE

MONSANTO RESEARCH CORPORATION

DE-AC04-76-DP00053

LAYTON J. WITTENBERG

June 1978 - Continuing

OBJECTIVE

This project is directed toward data collection and evaluation of the thermal performance and operational characteristics of the largest, functional, salt-gradient solar pond in the United States. Also, firsthand experience is being obtained regarding the maintenance, adjustments and repairs required of a large, operational solar pond facility. This evaluation will provide engineering knowledge for the future design of similar large ponds in the U. S.

BACKGROUND

The City of Miamisburg, Ohio, constructed during 1978 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. This solar pond, which occupies an area of 2020 m^2 (22,000 sq. ft.), was designed from experience obtained at smaller research ponds located at Ohio State University, the University of New Mexico and similar ponds operated in Israel.

The solar pond (shown schematically in Figure 1) 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/ sq. ft.). 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 amortized over ten years, the cost of this heat will be only 1.8¢/kWH (\$5.45/million BTU).

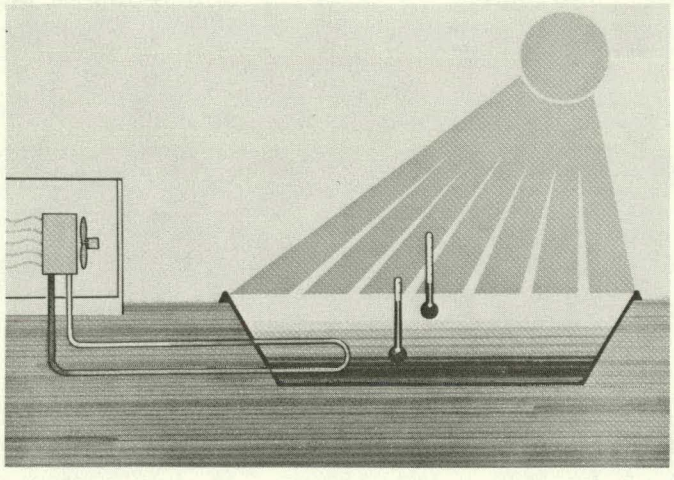


Figure 1. A schematic representation of the salt-gradient solar pond. The darker shading near the bottom of the pond represents higher salt concentrations and, consequently, higher water temperatures.

SUMMARY

During the summer of 1979, the initial heat (40,000 kWH, 136 million BTU) was withdrawn from the solar pond to heat the outdoor swimming pool. All of the data collection systems were installed and functioned as designed so that operational data were obtained. The observed performance of the pond was compared with several of the predicted models for this type of pond.

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 ∿80°F. Because of very poor solar insolation during August 1979 and some readjustments required to the solar pond, the test of heat extraction for space heating during the winter of 1979-80 could not be conducted.

- Instrumentation was installed to measure the total solar insolation, the solar radiation penetration into the water, air temperature, wind speed and direction, 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. The seasonal variation in the temperature of the storage layer is illustrated, Figure 2.

- A simple heat flow model was constructed for the pond and tested by comparison between the observed and predicted temperature for the storage layer during each month of 1979. These predicted values were in good agreement with the observed values except for March and April when a large amount of heat is probably consumed to heat the ground. 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 5-6 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 become severe. All of the original solder joints, composed of 95% tin-5% antimony, were subsequently refabricated with a brazing alloy of high silver content.

- A 25 cm length along one seam of the plastic liner in the pond separated and some of the saline water leaked from the pond. This seam was successfully patched under eight feet of water.

FUTURE ACTIVITIES

Contract Activities Continuous data collection from all the installed instrumentation will continue. This information will be used to improve the thermal performance model of the pond, which will permit greater reliability in the prediction of pond performance. Several maintenance operations will be instituted to improve or maintain water clarity, acidity and salinity of the various layers of the pond. Corrosion tests of metallic specimens will be initiated to determine the preferred materials for the construction of the heat exchanger. Several techniques will be tested to locate small leaks in the large pond of water. Analytical and experimental studies will be conducted to improve the thermal efficiency of the solar pond.

Post Contract Activities No current plans exist for marketing this system. The cost and performance information derived from this project will be given wide circulation, because it is the largest, functional pond 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.

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. 1979 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. Wittenberg, "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.

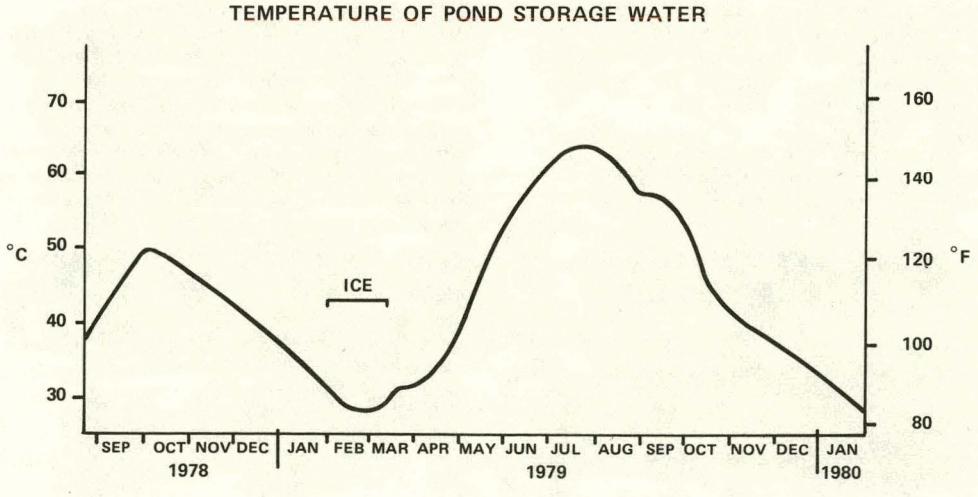


Figure 2. The seasonal variation in the temperature of the storage layer of the solar pond since its completion in August 1978.

SOLAR POND STUDIES: PHASE III

THE UNIVERSITY OF NEW MEXICO

EG-77-S-04-3977

H. C. BRYANT

APRIL 1, 1977 - AUGUST 30, 1980

OBJECTIVE

Our objective is to continue to investigate the physics of a full-scale, salt-gradient solar pond now entering its fifth season of operation on the UNM north campus. We are continuing, with the aid of an on-line computer, to add to the data base on full-scale ponds. We are doing theoretical, numerical and experimental studies of pond behavior, which should lead to suggestions for improved pond design.

BACKGROUND

The UNM solar pond project began in July, 1975, under a grant from the New Mexico Energy Resources Board (BEF-161). In the fall of 1975, the pond pit, a smooth frustum of a cone, was prepared, lined with 3-ply, 45-mil Hypalon, and the filling begun. By the end of the summer of 1975, the pond had been filled to capacity. The top diameter of the pond is 15 m; its depth is 2.5 m; the bank angle is 34°. The total capacity of the pond is 230 m^3, with the average storage volume in the bottom convective layer being 130 m^3. Reference (1) gives an overview of the UNM pond project. For a complete discussion of the solar pond effort at UNM up until the spring of 1979, see ref. (2). Fig. 1 shows the UNM solar pond compound as it was in October 1977. There is essentially no change in its appearance to date. The circular solar pond occupies the center of the photograph. The two rectangular ponds on the lower left are evaporating ponds used to concentrate surface water from the solar pond for reinjection into the bottom convecting layer at a salt concentration of better than 20%. The trailer on the right is used as a field station housing a RAMP (KAYE) data logger with 64 channels and other field equipment. Thermocouples and outputs from other transducers (pyranometers, conductivity probes) feed into the RAMP data-logger, which then transmits the data into the Physics and Astronomy research building to a MIK 11 computer. In addition to the field work, laboratory studies have been done on model saturated ponds. Since April 1, 1977, this project has been operated under the auspices of the U.S. D.O.E.

SUMMARY

The UNM solar pond has reached its fifth year of operation, and its demise is being contemplated. Studies of the UNM pond have led to progress in understanding the stability of solar ponds and problems of heat and salt transport. The pond has served as a real-life example by which to check computer models of the thermal behavior of ponds. Theoretical analysis has led to the discovery of the importance of the Soret effect in the transport of salt in the solar pond, and laboratory studies have established the very promising nature of saturated ponds using KNO_3.

TECHNICAL ACCOMPLISHMENTS

• The UNM pond has been monitored continuously since operation began in the fall of 1975. Fig. 2 illustrates its thermal history through four complete years. In August, 1977, with no heat load, the pond reached the highest temperature ever recorded for NaCl ponds: 93°C. The pond was able to supply 71% of the hot water and space heating needs of a 2,000 ft^2 Albuquerque home during the year November 1977 to November 1978, the heat being withdrawn to match the natural gas usage of the home. For this heat-withdrawal schedual, the average collecting efficiency was 9% over the year. For further details, see ref. (2).

• As a diagnostic of the thermal behavior of the UNM pond we "turned off" the sun for a period of eight days (August 20 - August 28, 1979) by covering the pond with sheets of 8-mil black polyethylene, reducing the solar input to essentially nil. During this period the temperature of the storage layer dropped linearly with time from 86°C to 75°C, or 1.4°C per day. Using the results of our heat transport program we predicted that the rate of temperature drop should have been only 0.6°C per day. This is based on a thermal conductivity of the soil to be .0048 W/cm°C as measured

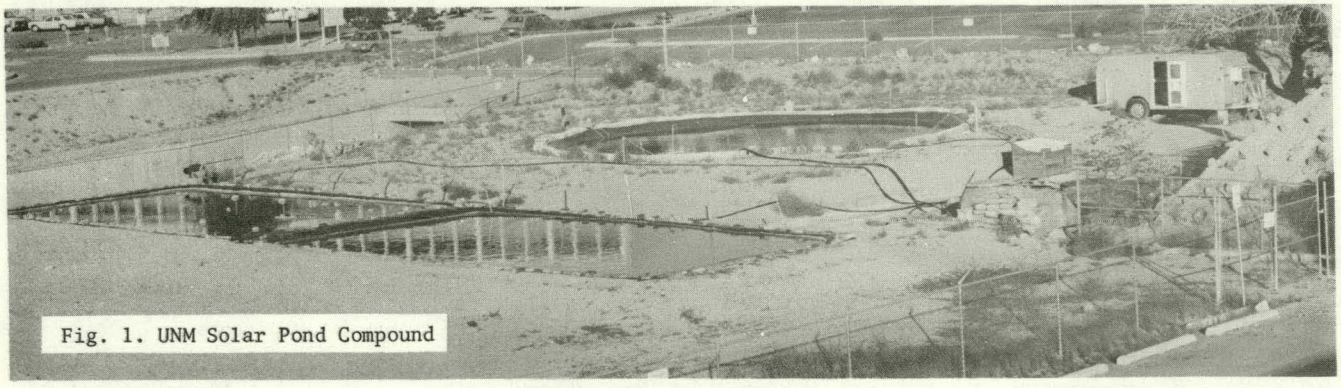


Fig. 1. UNM Solar Pond Compound

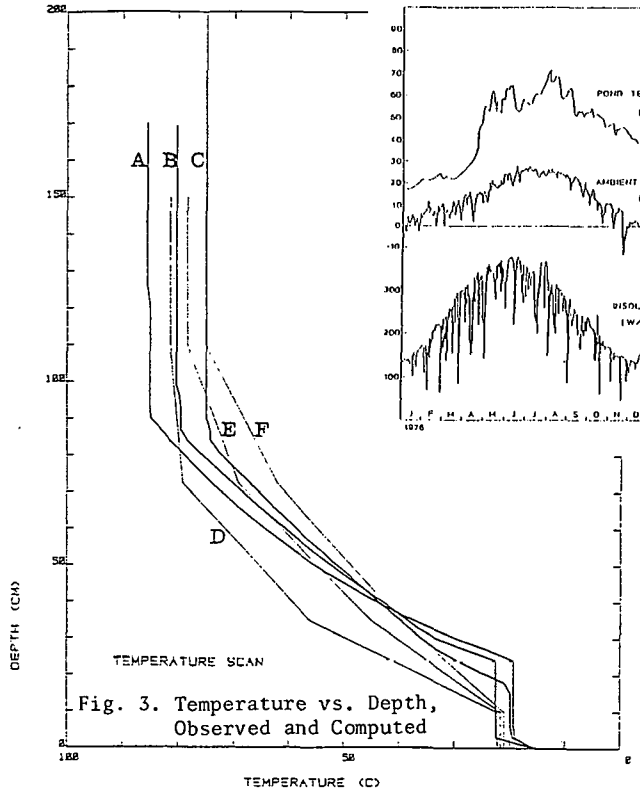


Fig. 3. Temperature vs. Depth, Observed and Computed

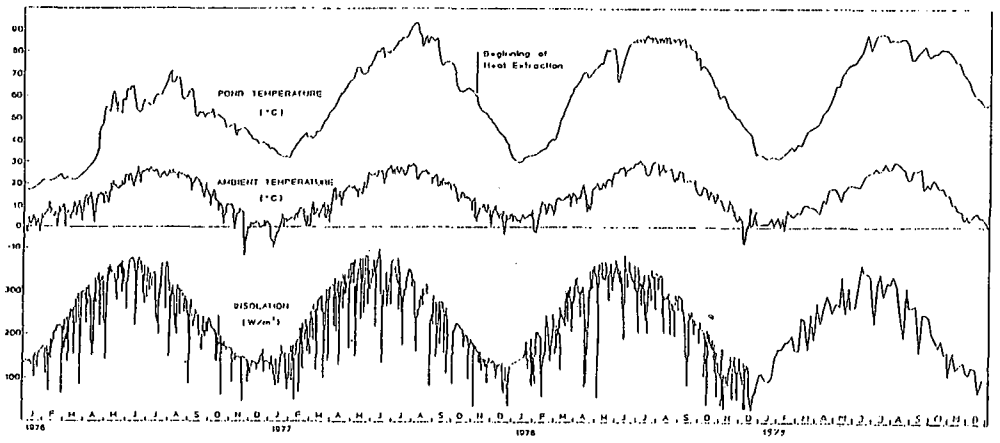


Fig. 2. Thermal History of the UNM Pond

for soil from the pond bottom. The most likely explanation for this discrepancy is heat transport along sloping walls. Fig. 3 illustrates these results. Curves A, B, and C show the temperature vs. depth into the pond (measured from the top surface) taken during the covered pond episode (August 20, 24, and 28, 1979, respectively). Curves D, E, and F show the results of a computer simulation of a similar episode on the 0th, 5th and 10th days, respectively.

• Since the "covered pond" episode in August, 1979, no heat has been extracted from the UNM pond, with the exception of the inadvertant withdrawal of 29.3 m^3 of 20% salt water at 62°C from the storage layer on October 29, 1979. (A cap had broken on a syphon when it fell from its support.) as of the date of this writing (March 6, 1980) the lowest temperature of the storage layer this season is 48.3°C on January 22, 1980.

• A finite element heat transport program has been modified to model the thermal behavior of a cylindrically-symmetric, salt-gradient pond of the UNM type. A report describing sample results, including daily variations, annual variations and the "covered pond" episode, described above, is in preparation (3).

• A theoretical analysis of salt transport in the UNM pond led to the discovery that neglect of the Soret effect (salt diffusion driven by a thermal gradient) is not justified (as has always been done in the past), and can amount to as much as a 73% discrepancy in a realistic solar pond (4,5).

• A laboratory model of a saturated solar pond using KNO_3 has been studied. The conclusion from this study is that KNO_3 can support a thermal gradient of more than 2°C/cm. For details, see ref. 4.

FUTURE ACTIVITIES

Contract Activities. We shall continue to operate and monitor the pond through the spring lof 1980.

We are attempting to measure the rate of transport of salt to the surface. In late spring we shall probably conduct another "covered pond" exercise. Later in the summer, we are thinking of terminating the NaCl pond by allowing the temperature of the storage layer to rise to the boiling point (about 104°C) at which time we expect the gradient to overturn with subsequent rapid cooling. We think this solar pond death and subsequent post-mortem should be of considerable interest to the solar pond effort, although it should not be as dramatic as Three Mile Island.

Post-Contract Activities. Disposing of the large quantity of brine from the dead solar pond may be a problem. The best solution would be to use this brine for a new pond (with vertical walls!) that would actually be used to heat a building on the UNM campus. Interest among students in the UNM Physics and Astronomy Department seems to warrant trying to continue solar pond work, perhaps in the area of saturated ponds and in pond design for special circumstances, such as for the deserts of Saudi Arabia.

REFERENCES

1. F. Zangrando and H. C. Bryant, "A Salt-Gradient Solar Pond," Solar Age, Vol 3, No. 4, April, 1978.
2. F. Zangrando, "Observation and Analysis of a Full-Scale Experimental Salt Gradient Solar Pond," Ph.D. Dissertation, UNM, May, 1979. Available from the NTIS as Report DOE/EG-4-3977-4.
3. K. Dhingra and H. C. Bryant, "Thermal Model of a Cylindrically Symmetric Solar Pond," in preparation.
4. M. K. Rothmeyer, "Saturated Solar Ponds. Modified Equations and Results of a Laboratory Experiment." M.S. Thesis, UNM, December, 1979.
5. M. Rothmeyer, "The Soret Effect and Salt-Gradient Solar Ponds," preprint, available on request.

SALT-GRADIENT SOLAR POND DEVELOPMENT

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

DE-AC04-77CS34155

CARL E. NIELSEN

SEPTEMBER 30, 1977 TO AUGUST 31, 1980

OBJECTIVES

This project has two major objectives. The first objective is to obtain accurate experimental energy balance data from an operating salinity gradient solar pond for comparison with calculations from a numerical model. Given agreement between observation and computation for this one case, it becomes possible to predict with some confidence the performance to be anticipated for a range of environments and operating conditions. The second objective is to develop improved methods of observation for pond monitoring and to develop pond management procedures that will insure reliable pond operation.

CONCEPT AND BACKGROUND

A salinity gradient solar pond is a pond of salt water containing a non-convective zone of substantial thickness that is maintained non-convective by a downward increase of density. This non-convective zone transmits a part of the incident solar energy to a convective storage zone beneath where it is converted to heat and removed for use or stored. Solar ponds combine the functions of collection and storage. Even annual storage is feasible (1,2). (For a more detailed discussion, see Refs. 3 and 4.)

One of the major tasks of the project has been the construction of a research pond designed to facilitate measurement of all heat transfers, as required for determination of energy balance and efficiency. This pond is circular, 22.8 m in diameter, and at normal operating level is 1.5 m deep at the perimeter, 4.5 m deep at the center. The area is 408 m^2. The walls are of vertical timbers alternately 4 cm and 9 cm thick. Foam insulating panels added inside the timbers make the total wall thickness 21 cm. These panels are 5 cm thick styrofoam except for the inside layer which is high temperature urethane foam 2.5 cm thick. Mean wall conductance is calculated to be 0.18 W/m^2K (corresponding to R31). This placement of insulation was chosen on the basis of numerical computations indicating that wall insulation would reduce peripheral heat loss to about half of the value for an uninsulated pond. Further reduction could be accomplished by insulating the floor adjacent to the wall, but this did not seem practically feasible. The pond is lined with a high temperature-resistant plastic coated fabric "XR-5" supplied by Shelter-Rite and installed by Plastisteel Corporation.

The pond is surrounded by a moat to be filled with fresh water approximately to the pond surface level. The purpose is to provide a well-defined temperature boundary condition for the wall and for the earth outside the pond. The moat also will trap some of the leaves and dirt that might otherwise blow into the pond. A 5 cm thick layer of styrofoam insulation extending out 3 m from the pond wall is to be placed at the bottom of the moat. This will reduce somewhat the heat flux out of the pond through the earth and also will facilitate measurement of the magnitude of that heat flux. For measurement of heat exchanges with the earth, an extensive array of 169 thermocouples is located at 31 sites under the pond and under the moat outside of the pond. These are located on east-west and north-south lines and are buried to a maximum depth of 2.5 m under the pond.

The vertical distribution of temperature in the pond is determined by a scan using a sensor moved at a constant rate, typically 10 cm/min, as in our previous pond experiments. Instead of a thermistor or thermocouple we are now using a platinum resistance sensor for better stability and precision. In addition to the scanning sensor we have several fixed sensors giving more precise measurement of the time variation of temperature at fixed points for use in calculating radiation absorption calorimetrically.

Radiation incident is measured by a conventional black and white pyranometer. Radiation penetration is measured by a submersible black and white pyranometer of our own design and construction. Information from the submersible pyranometer is combined with the absorption calculation based on temperature data.

Major requirements for good pond operation are maintenance of adequate transparency, limitation of the thickness of the surface mixing zone, and maintenance of an adequately thick gradient zone. We have studied methods for meeting these requirements both in the Farm Science Review pond operated since 1975 and in a variety of small experiments.

SUMMARY

(a) The research pond has been completed. The salt was added in November 1979, and the warm up is now underway.

(b) A submersible pyranometer suitable for scanning radiation penetration has been designed, constructed, and used in our ponds.

(c) Calculation and preliminary observation have indicated that calorimetric determination of radiation absorption from temperature data is feasible.

(d) Laboratory studies have established that suspended particles are responsible for the transmission loss in our ponds. Pond cleaning procedures have

restored good transparency.

(e) Additional information on zone boundary equilibrium has been obtained.

(f) A controlled injection procedure for modifying salinity gradient and controlling zone boundary position has been developed and tested.

TECHNICAL ACCOMPLISHMENTS

• Research pond. The research pond is now completed and operating. The insulating of the floor of the moat and filling it are still to be done. The leads from the thermocouples and other sensors have been brought into the instrument trailer, but are not yet connected to the digital data acquisition and processing system. Temporarily we are taking selected essential data manually and on chart recorders. We look forward to obatining a full year of performance data in 1980.

• Submersible pyranometer. Radiation penetration into ponds has seldom been very well determined. Commercially manufactured submersible pyranometers have had a rather poor survival record in solar ponds, and moreover their equilibration to sudden change in environmental temperature tends to be slow. Several years ago we made and used pyranometers sufficiently leak resistant and corrosion resistant for submersion in ponds, but it was not until last year that we succeeded in constructing one having short equilibration time. With this new design the transients associated with sudden change in environmental temperature are negligible after about two minutes. This performance results from a construction of metal, glass and alumina (no plastics of low thermal conductivity) with a symmetry such that the environment transfers heat at an approximately equal rate to the black and white segments.

• Radiation absorption from temperature data. It is evident from the expression for energy conservation that in steady state, with constant radiation input and constant pond temperature, the energy absorbed per unit volume at any depth in the non-convective zone is just proportional to the curvature of the temperature profile T(z) at that depth. Where the radiation and pond temperature are variable the situation is much more complicated. It can be shown however, that if the temperature profiles are known at times t_1 and t_2 between depths z_1 and z_2 in the non-convective zone, if the time variation of temperature at z_1 and z_2 is known between times t_1 and t_2, if the radiation incident is known between t_1 and t_2, and if the radiation absorption per unit volume at any z is constant between t_1 and t_2, then the absorption at any z can be calculated. We have made observations of the time variation of temperature at various fixed depths z, and it appears that data of sufficient accuracy are obtainable to permit useful calculations of radiation absorption. It would be a substantial simplification if special submersible pyranometer data could routinely be replaced by calculations from temperature data.

• Water transparency. In situ measurements of radiation penetration in a pond cannot be replaced by laboratory transmission measurements using a water sample in an absorption cell. The reason is that the relative contribution of scattering is completely different in the laboratory. It is possible however to get useful information about the relative quality of water samples from laboratory transmission data. We used transmission through a 20 cm cell to study the effect of filtering on poorly transmitting pond water samples. The attenuation, relative to that of distilled water, was always much greater at the blue-u.v. end of the spectrum. By using fine pore filters we were able to increase the transmission of even the most absorbing samples to within a few percent of the distilled water value. We found that an appropriate quantity of alum was effective in coagulating and settling the suspended particles in a laboratory sample, and accordingly we added alum to the convective zones in the Farm Science Review pond in September 1979 with excellent results. At the present time the transparency in both ponds is good, objects at a depth of more than 2 m being clearly visible.

• Zone boundary equilibrium. Studies of the boundary between gradient and convective zones in laboratory tanks have continued. For some time there has been an inconsistency between data from larger laboratory tanks (0.75 m diameter, 1.15 m deep) and earlier data (3) from smaller laboratory tanks (0.56 m diameter, 0.40 m deep), which agreed with data from the Farm Science Review pond. The discrepancy has now been eliminated with the installation of a temperature-controlled guard cylinder around the insulated walls of the larger tanks that reduces the temperature difference across the insulation and gives a better approximation to one dimensional heat flow. The points representing the equilibrium relation between temperature gradient and specific gravity gradient now fall close to the line found earlier, increasing confidence in the essential correctness of that line. The unexpected result that the larger tanks gave poorer data initially is probably to be explained by the fact that the gradient zone in the smaller tanks was quite thin, making wall losses relatively less important.

• Controlled injection. Injection of water or brine has been used in the past to move gradient zone boundaries or to eliminate convection zones within the gradient zone (5,6). In general this injection has been at a high rate for a short time. Since the process involves a combination of uncontrolled factors it has been impossible to predict exactly the distribution of salinity that will result. By laboratory experiments we have established the conditions under which a relatively slow injection changes the salinity at a precisely specified level (specified within about 1 cm). It is thus possible by using injection distributed appropriately in depth to make controlled changes in the salinity profile over a few days, and also to move the boundary of the gradient zone. We have tested this new injection procedure in the Farm Science Review pond. It is also possible, as proposed at the Atlanta meeting, (7) to use continuous very slow injection to maintain a salinity profile different from the diffusion profile and thus to alter the position of the stationary zone boundary.

FUTURE ACTIVITIES

Research pond. This year we are collecting the experimental data required for calculation of pond energy balance and efficiency. During the summer we shall begin construction of the tracking reflector designed to explore the utility of reflectors with small solar ponds. Later in the year after a body of data has accumulated we shall compare experimental

performance with numerical computation. Since one year is far too short for the pond to reach a stationary state relative to the earth, experimental observations should be continued and compared with computation for additional years after 1980.

Pond monitoring. While we believe we have made significant progress in development of instruments and procedures for pond monitoring, we consider this work far from completed. We shall continue to work toward simpler procedures for reliable measurement of radiation input and pond transparency, and for determining heat losses from the pond. Present methods for measuring temperature and salinity distribution in the pond appear adequate, but a method for accurate salinity measurement less laborious than withdrawing and weighing samples would be welcome.

Pond operation. Data from operation of the research pond will provide needed information on energy loss to the earth. The other most important matters requiring continuing study are the behavior of gradient zone boundaries and the effect of surface influences on the surface mixing zone. Laboratory experiments on zone boundary behavior, which have already yielded important information, will be continued. The effect of surface influences, which has thus far been explored to only a limited extent, will be studied actively. This will include both laboratory and small outside pond experiments on the effects of wind, surface evaporation, and diurnal variation of heat loss from the surface. Apparatus for wind and evaporation experiments is already constructed and ready to use. It may be noted that the operating temperature of a pond decreases approximately 10°C for every 10 cm increase in surface convective zone thickness . (See Ref. 4) Limitation of surface zone thickness is thus of the greatest practical importance.

PUBLICATIONS

Publications since the inception of this contract are the references numbered 2-4, 7-10.

REFERENCES

1. A. Rabl and C. E. Nielsen, Solar Ponds for Space Heating, Solar Energy 17, 1-12 (1975).

2. C. E. Nielsen, Annual Storage Using Salinity Gradient Solar Ponds. Proc. Solar Energy Storage Options, San Antonio, TX, v.2, 38-44 (CONF-790328-P3) (March 1979).

3. C. E. Nielsen, Salt Gradient Solar Pond Development. Paper presented at Solar Heating and Cooling Contractors' Meeting, U.S. Dept. of Energy, Washington D.C., Sept. 1978.

4. C. E. Nielsen, Nonconvective Salt Gradient Solar Ponds, chapter in Solar Energy Handbook, edited by W. C. Dickinson and P. N. Cheremisinoff, to be published by Marcel Dekker, Inc. 1980.

5. C. E. Nielsen, Experience with a Prototype Solar Pond for Space Heating. Proc. Joint Conf. Am. and Can. Solar Energy Societies, Winnipeg, Canada, v.5, 169-182 (1976).

6. F. Zangrando and H. C. Bryant, A Salt Gradient Solar Pond. Solar Age 3 No. 4, 21 (April 1978).

7. C. E. Nielsen, Control of Gradient Zone Boundaries. Proc. Congress International Solar Energy Society, Atlanta, GA, (May 1979).

8. C. E. Nielsen, Conditions for Absolute Stability of Salt Gradient Solar Ponds. Proc. Congress International Solar Energy Society, New Delhi, India, v.2, 1176-1180 (Jan. 1978).

9. C. E. Nielsen, Equilibrium Thickness of the Stable Gradient Zone in Solar Ponds. Proc. Am. Sect. International Solar Energy Society, 2.1, 932-935 (Denver 1978).

10. C. E. Nielsen, Salinity Gradient Solar Ponds for Passive Storage. Proc. 4th National Passive Solar Conf., Kansas City, MO, 541-545 (Oct. 1979).

"A MARKET ASSESSMENT OF ACTIVE SOLAR HEATING AND COOLING PRODUCTS - CATEGORY B
A SURVEY OF DECISION-MAKERS IN THE HVAC MARKETPLACE"

OR/MS DIALOGUE, INC.

DE-AC03-79CS-30209

PAUL E. JOHNSTON and GARY L. LILIEN

BEGIN: SEPTEMBER 28, 1979 END: MARCH 28, 1980

OBJECTIVE

The objective of the project is a comprehensive evaluation of the market for solar heating and cooling products, both for new construction and replacement/retrofit markets. The project's focus is on identifying decision makers and evaluating their solar knowledge, attitudes and behavior. The data collected during the course of the study is analyzed to identify the prime determinants of market acceptance of solar products. This information will aid both government and private decision making in programs designed to accelerate the commercialization of active solar systems.

BACKGROUND

Experience with new product marketing and in particular with solar energy marketing leads to two inescapable conclusions:

- A major cause of commercial failure among technically successful new products is a lack of appreciation for how customers actually perceive and evaluate those products. Buyers, whether industrial or consumer, do not always act "economically" (rationally). Extensive research in measuring and modeling the impact of non-economic factors in purchase decisions forces this conclusion. An understanding of these factors is thus a prerequisite to a successful commercialization program.

- Ultimate product success is most likely when information from the marketplace is integrated with product development and marketing plans.

The project methodology reflects the importance of these two points. Methodologies of recent past studies are assimilated into approach. Product/market combinations have been chosen as those highest in market potential for detailed survey work and analysis.

The analytical approach employs state-of-the art models of consumer and industrial purchasing decisions. New techniques such as a decision matrix and a measurement procedure, "disjoint measurement", as well as factor analysis and preference regressions, have been refined to provide insight into both the adoption of new products by large organizations and the purchase choice of individual consumers.

SUMMARY

The initial task in this project was to select for study those products and market segments which appeared to have high potential for early solar commercialization. The study is therefore directed primarily at solar space and water heating using flat plate and concentrating collector techniques. In addition, solar cooling technologies are considered to a lesser degree. Five key market segments have also been selected: residential consumers, home builders, industrial firms, HVAC and AE consulting engineers and commercial businesses.

Specific methodology was developed to collect and analyze data in each of these segments. The methodology included "pilot" studies in each major segment undertaken to refine the data collection and analysis procedures.

To date the pilot studies in each of the five segments have been completed, each resulting in minor modifications to the original approach. In addition, the home builders data has been completely collected, and is now under analysis. Final data collection activities are under way in the residential, HVAC/AE and commercial segments.

TECHNICAL ACCOMPLISHMENTS

- Residential Segment - Interview protocols, the prime data collection method in this segment, have been developed (and customized for each of 48 states). A pilot test has been completed with a sample of homeowners. The pilot test studied retrofit solar water heating. The protocols have been modified based on analyses of the pilot test results. The main data collection effort in this segment now underway.

- Builder/Developer Segment - Interview protocols were designed and tested, and discussions with home builders were held at the 1980 NAHB convention in Las Vegas, Nevada. A description of data obtained from these individuals is complete; analyses are now underway.

- HVAC/AE Segment - Interview protocols have been designed and tested and a pilot test with HVAC and AE professionals has been completed. A description of pilot test data is completed. Protocols have been modified based on the test and the main data collection effort is underway.

• Industrial Segment - Preliminary conversations have taken place. Analysis of the data and interview protocol revisions are underway.

• Commercial/Institutional Segments - Initial discussions have been conducted in four segments: low-rise motels, hospitals, car washes, and laundries. These discussions continue at this time, and are expected to be completed in about a month.

FUTURE ACTIVITIES

Future activities involve the completion of discussion and interviews in each of four market segments, analysis and interpretation of the assembled data, and reporting.

PUBLICATIONS/REPORTS/REFERENCES

As the completion of this project, Dialogue will provide DOE with the following reports:

• A series of regional guides to residential markets for active solar products that reflect major differences on solar economics, prevalent building styles, and general consumer orientation from one area of the country to another.

• A set of guides directed at specific commercial, industrial, and institutional submarkets identified as holding the most potential for widespread commercialization of solar.

• A final technical report to provide market-based input to government solar commercialization programs.

SOLERAS COOLING PROJECTS

SOLAR ENERGY RESEARCH INSTITUTE

Richard E. Davis

ABSTRACT

The jointly funded $100 million five-year international agreement (SOLERAS) between Saudi Arabia and the United States was undertaken to promote the development of solar energy technologies of interest to both nations. This paper describes five engineering field tests of active solar cooling systems funded under the SOLERAS agreement for installation and operation in the U.S. southwest.

BACKGROUND OF THE SOLERAS PROGRAM

The Saudi Arabian-United States Program for Cooperation in the Field of Solar Energy (SOLERAS) is administered as part of the United States-Saudi Arabian Joint Commission on Economic Cooperation, a unique program because it is equally funded by both nations. The program is directed by an Executive Board consisting of four United States officials from the Departments of Energy and Treasury, and four Saudi Arabian officials from the Ministry of Finance, universities, and the Saudi Arabian National Center for Science and Technology (SANCST). A Project Selection Committee, consisting of United States and Saudi Arabian representatives, is responsible for reviewing proposed projects for recommendation to the Executive Board. The Operating Agent is the Solar Energy Research Institute (SERI) in Golden, Colorado, and is responsible for overall technical and financial management of the SOLERAS program.

THE SOLAR COOLING PROJECTS

Carrier Corporation (Water-cooled Absorption)

The solar cooling package is designed to be set into place on a concrete slab. The package base is 1.4 m x 3.9 m and will contain the standard carrier 47 kW solar absorption machine (SAM) which uses the lithium bromide cycle. The package will also contain all necessary pumps, controls, valves, and electrical elements to be self contained. The package will have nine pipe stubs. These will be connected to the collector, fan coil, cooling tower, and storage. The rating point will be 47 kW of cooling using 82°C water from the collectors and 29.5°C condensing water. For responding to higher condensing temperatures, the controls allow the hot water to rise with the condensing water so that a constant difference of 5°C between hot water and condensing water is maintained.

The solar heat collector system selected for this engineering field test is a linear Fresnel lens concentrating solar collector developed by E-Systems, Inc. of Dallas, Texas. Ten of the 91 cm x 244 cm collector modules are mounted in a common support structure to form an array assembly. A single roll-axis drive controlled by an active sun-sensing tracking system rotates the ten modules in unison to provide the diurnal, east-to-west tracking function. This field test will ground mount 6 of the 10 unit modules for a total aperture area of 133.8 m^2.

The storage subsystem consists of two fiberglass reinforced high temperature resin tanks. The larger tank of about 7500 ℓ will be used to store collected energy beyond what is necessary to operate the chiller at design. The second smaller tank, about 2000 ℓ, will provide thermal inertia to minimize "short cycling" of the chiller. The tank is sized only to hold the excess heat of midday until it is needed later in the afternoon or early evening. Antifreeze addition is not anticipated.

Key to this project is the use of the thermostatically controlled diverter valve which will divide the hot fluid stream from the collector array into two streams (if it is above the desired use temperature), one of which is diverted to storage where it displaces a like amount of cooler fluid to combine with the undiverted stream. The collector pump will run as long as energy is being collected at an acceptable rate. When the collector pump is running, hot fluid continually passes through the absorption chiller generator (which is empty unless the solution pump is running). Since there is no energy drain, the temperature of the ballast tank continues to rise until a control sensor near the bottom indicates a "turn on" temperature. At this point a relay is closed, turning on the absorption chiller and chilled water circulation pumps.

The site selected for the engineering field test is the Phoenix distribution center for BDP Company, a division of Carrier Corporation, located in Phoenix, Arizona. It is an existing and operating 3700 m^2 structure consisting of office space and a warehouse area. The present cooling system for the office and parts department consists of three 17.5 kW roof mounted packaged units with supply and return air ducts feeding each zone. The present system will act as the backup system.

Carrier Corporation (Air-Cooled Absorption)

The solar cooling unit will consist of two 18 kW absorption chillers mounted and piped for parallel flow to provide 36 kW of cooling. The overall chiller package will be approximately 1.2 m x 3.6 m x 2 m high including the ballast storage tank. Included on this base will be all of the pumps, valves, and electrical equipment to support the system. Seven pipe stubs will serve the collectors, storage, and chilled water loops. The chillers use a lithium

bromide mixture that is different from the basic water-cooled chiller. This mixture, designated "Carrol" by Carrier uses as an absorbent a mixture of lithium bromide and ethylene glycol, water as refrigerant and 1-aminononane as heat transfer additive. Lithium nitrate and lithium hydroxide is used for corrosion inhibition. The design rating point for the hot fluid (water) is 110°C.

The solar collection subsystems for this field test is similar to the previous Carrier installation. The two significant differences are that only four of the 10 unit E-Systems collectors will be utilized and they will be roof mounted.

The storage subsystems of this field test follows the concepts planned for the Carrier water-cooled unit. The storage tanks will be reduced in size since the air-cooled unit is lower in capacity.

The same controls and control logic for the water-cooled field test of Carrier will be repeated for this air-cooled test.

The project site is a new combination business and warehouse complex under construction for the Ware, Sigler and Faigen Corporation located in Phoenix, Arizona. A separate water coil will be installed in the plenum of the existing cooling unit. An interconnecting control system will actuate the standard air conditioner whenever the solar system is unable to meet the load conditions.

General Electric Company

The Rankine/electric air conditioner (REA-140) is a Rankine engine driven vapor compression air conditioning system designed to provide 49 kW cooling capacity at ARI standard rating conditions. The REA-140 is a split system, direct expansion, condensing unit having a nominal cooling capacity of 42 kW for an outdoor dry bulb temperature of 43°C. The REA-140 is an air-to-air cooling system with refrigerant R-22 being the air conditioner working fluid. The Rankine engine will use fluorocarbon FC-216 as the working fluid. The outdoor unit (ODU) is designed for roof top or ground level mounting. Its overall size is 205 cm x 279 cm x 173 cm high. All Rankine engine components are located in ODU. The Rankine engine, as well as the air conditioner, is designed for hermeticity - there are no shaft seals. The Rankine engine expander is a two-stage multivane expander which is coupled to a multi-piston vapor compressor by a permanent magnet drive and over-running clutch assembly. The expander and compressor run at synchronous speed. The magnetic drive provides hermeticity for the Rankine engine and for the refrigeration system. The over-running clutch self-engages when the Rankine expander starts to rotate.

This project will install 165 m^2 of the GE TC100 evacuated tube solar collector. The evacuated glass tube consists of two concentric glass cylinders which have been joined to form a "large thermosbottle." The space between the two cylinders is evacuated to minimize thermal losses. The tube is nested in a cusp-like reflector which improves performance at all insolation rates by concentrating the available energy on the absorber. The level of concentration is such that both diffuse and direct insolation are captured.

The thermal energy storage (TES) tank planned for this project will store energy between the design Rankine vapor generator input temperature of 138°C and its fully charged temperature of 160°C. The TES will be operated at a minimum pressure of 310 KPa with transport fluid of 35% Prestone and 65% deionized water.

The control strategy is to collect solar energy when the insolation level is above the control level. The collected solar energy is either delivered to the solar cooling unit or to storage. Solar energy is used to satify load demands if sufficient solar energy is available either directly or from storage. Only when solar energy is not sufficient is the electric drive mode used. At the system level the operator/control interface is a two stage thermostat plus a power on/off switch.

The site selected for this engineering field test is the Administration/Engineering Building of the General Electric Edwards Flight Test Center Operation. The building is located in Mojave, California, and is a single floor wooden construction building with asphalt siding. The building duct system is presently set up as independent systems for each wing. The solar cooling system will be installed to provide the necessary cooling for a wing of the building.

Honeywell, Inc.

The Rankine driven air conditioning system for this project is composed of a radial inflow 39,500 RPM turbine using R-113 with a design inlet temperature of 149°C and a condensing temperature of 54°C. This turbine drives a 46 kW 5 cylinder R-12 compressor designed for 52°C condensing while supplying a direct expansion (DX) coil operating at 16°C evaporating temperature. The Rankine unit has electrical generating capability, and during a no-load (or satisfied load) state, the compressor is decoupled, and the unit generates power to the utility grid. Power can also be generated when the output of the turbine exceeds the cooling demand.

The collector selected for the 200 m^2 field is the Energy Design Corp. model XE-300, having a CPC nontracking reflector. Each module contains six rows of horizontally arranged, concentrating (1.33:1) reflecting troughs with evacuated tubular glass absorbers and copper-tube flow channels.

The storage subsystem will consist of a vertically mounted unlined ASME-rated 7500 ℓ tank. The water-glycol transport fluid will be pressurized with a nitrogen gas blanket to permit operation up to 163°C.

The control subsystem design philosophy is the use of direct solar energy first and then use of stored thermal energy, and finally, optimum use of auxiliary conventional energy. The system has six modes of operation: direct cooling from collectors, cooling from storage, electric motor auxiliary cooling, storage charging, Rankine electrical power generation, and purge excess energy.

The field test site for this solar cooling system is a new service facility being constructed by the Arizona Public Service (APS) Company in suburban Phoenix, Arizona. The structure will be a one-story office and laboratory building that will be partially cooled by the proposed solar cooling system.

United Technologies Research Center

The water chiller module comprises a Rankine-cycle power loop which provides shaft work directly to a vapor-compression cooling loop. The radial in-flow turbine receives nearly saturated R-11 vapor which has been generated in a shell and tube vapor generator. The exhaust from the turbine condenses inside the tubes of an air-cooled condenser and is subsequently pumped back into the vapor generator. The vapor generator receives hot water (150°C) from the hot water storage tank. The compressor impeller is of the double-entry design and is mounted directly on the turbine shaft. R-11 is compressed and delivered to an air-cooled condenser. The condensate is throttled in an expansion valve and is then admitted into a flooded-type evaporator which also acts as the water chiller. The prototype water chiller module has been tested in the laboratory and has developed 60 kW of cooling with a thermal COP = 0.6.

This system will be powered by approximately 160 m^2 of tracking parabolic trough collectors installed with north-south axis.

Storage will consist of both hot and cold water tanks. The hot water tank will store 11,300 l of 160°C water while the cold tank will hold 3800 l of 7°C water. Both tanks will be buried.

Control of the solar cooling system is "on-off" without modulation of flow rates through valves or pumps. The solar cooling system will be activated so long as the cold and hot storage tank temperatures are sufficient to maintain the building temperature within predetermined limits. Excessive hot water tank temperatures (and pressures) will be avoided by either venting the tank or by defocusing the collectors.

The site selected for this project is the Phoenix, Arizona headquarters of Hamilton Test Systems. The building is a single story 650 m^2 office type building.

OPERATIONAL DATA

The data to be collected from each of the five engineering field tests will be directed toward determining three general aspects of the installation. How the cooling unit performs will be established in such areas as COP, EER, control functions and durability. Data will be utilized to validate the computer models used in the original simulations and design of the installation. Energy balance information will be established from the data collected to determine overall system thermal performance and addressing the overall economic benefit to be expected from the system, in terms of non-renewable energy saved. Each contractor is also expected to gather additional data to assist in future engineering modifications to the cooling unit as well as to help in identifying potential system configuration design improvements.

CONCLUSION

The five cooling engineering field tests are the first major projects to be conducted in the United States under the SOLERAS program. The tests will provide valuable information to the entire international solar energy community. The application of solar energy to building cooling functions promises to be an appropriate match of technologies for widespread regions of the United States.

The installation of the systems is scheduled to be completed to permit operational study beginning with the summer cooling season in 1981. The systems will be operated by SOLERAS for a minimum of two cooling seasons before the facility owners assume complete system responsibility. Before the SOLERAS program concludes in 1983, analysis of the system designs and operational evaluations will be distributed.

A companion project also being conducted by SOLERAS is the construction and operation of cooling test facilities at four Saudi Arabian universities. The test facilities will provide research capabilities for investigating both system and component concepts of solar cooling using both active and passive approaches.

Other major projects which are sponsored by SOLERAS include a 350 kW photovoltaic power system project for two villages in Saudi Arabia, a solar energy water desalination system study and pilot plant test, a controlled environment agriculture project for demonstrating the feasibility of combining solar energy with agricultural technologies, and a program for university research of solar energy.

SOLERAS is funded jointly by both Saudi Arabia and the United States at a total program budget of $100,000,000. The program activities began in 1979 and will conclude in 1983. A key objective of the program is to advance the development of solar energy technology. The engineering field tests will achieve this objective by bringing solar cooling systems closer to commercial competitiveness.

VIII ADMINISTRATION/MANAGEMENT SUPPORT

ACTIVE HEATING/COOLING SYSTEMS SUPPORT

CHARLES J. BISHOP

SOLAR ENERGY RESEARCH INSTITUTE
1617 COLE BLVD., GOLDEN, CO 80401

ABSTRACT

Support to the active heating and cooling program involves many varied activities including analysis, testing, validation, engineering handbook development/dissemination and management. This paper addressses work performed by the Solar Energy Research Institute (SERI), its subcontractors, and other laboratories/institutions in the area of systems support since the last review meeting, held in September 1978.

BACKGROUND

In late FY78, the Solar Energy Research Institute (SERI) accepted the responsibility for the development and management of the Systems Analysis and Tests (SAT) Program, a major program element of the National Solar Heating and Cooling Program within the Systems Development Division, Office of Conservation and Solar Applications, U.S. Department of Energy (DOE). Reference 1 discusses the early work performed in this program, and Refs. 2 and 3 summarizes FY79 activities.

The overall objectives of the Systems Analysis and Testing Program are to:

- provide overall integration and direction to the Systems Development Divison R&D effort;
- focus these efforts on the most effective aspects of product development/improvement; and
- provide the solar industry and others with methods to predict the performance of and to design/install/operate optimum solar systems.

Specific objectives of the Systems Analysis and Testing Program are to:

- identify and consistently rank solar technologies/systems which are optimized to the intended end use;
- identify cost/performance goals for various solar technologies/systems which make them competitive with conventional systems;
- develop and validate system simulation models, design tools, and handbooks for various user sectors;
- develop improved control strategies and control systems to increase solar system performance;
- coordinate/conduct system tests to evaluate, verify, and optimize system economic and performance behaviors; and to develop data to use in the validation process;
- provide technical and management support, including planning assistance of a national scope; and
- disseminate the developed data and tools to the user community.

SUMMARY

Major accomplishments since the last conference include definiton of a set of standard assumptions to be used in systems analyses to establish consistency in such work; an objective analysis of solar hot water systems where both net thermal performance and economics are considered; development of cost/performance goals for heat pumps and solar cooling systems; development of handbooks for domestic hot water systems, including controls; analyses which point to the near-term viability of solar ponds; and the development of an integrated active/passive solar system analysis capability.

These projects, and others funded as part of the SAT program, are discussed in the bulk of this paper. Both in-house effects and subcontracted work will be discussed. Work performed in support of the heating/cooling program by the National Bureau of Standards, Science Applications Inc., University of Wisconsin, Colorado State University, and Vitro Labs will not be discussed here as they have been reported elsewhere in this document. Also, controls work, which is in the process of being consolidated with the SAT program, is discussed as a separate element within this document.

TECHNICAL ACCOMPLISHMENTS

This section addresses the technical and programmatic accomplishments achieved by the various organizations involved over the time period covered.

Technical/Management Support

Because of SERI's lead role responsibility in the support area, a major concern is the coordination and implementation of the overall support program element. Programmatic activities accomplished since the last review meeting include the development of a draft SAT Program Plan which is currently being reviewed by DOE, and a Management Plan (Ref. 4).

The national program in heating and cooling includes the development of many advanced components and subsystems. To coordinate the testing and utilization of these components and subsystems, an Integrated Test Plan was developed (Ref. 5). The plan also addresses model validation. The test plan objective is to identify whether all the proper systems are being tested, to define data needs, and to develop an approach to testing systems. It is also meant to identify additional needs for new test facilities and to schedule future system testing within the Systems Development Division in DOE. The approach taken in developing this plan was first to identify the generic systems within the categoires of domestic hot water, space heating, space cooling, and agricultural and industrial process heat. Second, an attempt was made to identify whether these systems have been or are being tested within the context of the U.S. solar energy program. Also, if they are being tested, are they being instrumented and are test data being collected that would be useful in the validation process? The report addresses the present test facility capabilities in both government and private sectors, the components and subsystems that are emerging from the R&D program, and the scheduled availability.

SERI has also provided technical support to DOE in the areas of Building Energy Performance Standards (BEPS) by reviewing technical documents and providing backup analyses; Residential Conservation Service (RCS) where assistance was

provided to develop the solar portion of the audit procedure; and in the development of an integrated Analysis and Design Methods Plan which will address the development of methods for the analysis of active, passive and confined active/passive (hybrid) systems. This latter plan will be available in draft form in mid-1980.

Systems Analysis

The goal of this activity is to perform objective, consistent systems analyses of various solar systems and technologies. The development and dissemination of new simulation models for systems and components are an important part of this activity. Major analytical studies are presently being performed by SAI, as a subcontract to SERI, on heat pumps and solar cooling systems. This work, which is aimed at defining cost/performance goals, is discussed in a separate paper. Other current activities within the Systems Analysis area are described below.

(1) Reevaluation of Thermosyphon Domestic Hot Water Systems: Side-by-side testing of six domestic hot water systems by the National Bureau of Standards had implied that thermosyphon systems are significantly out-performing other active systems being tested. As a result, SERI undertook a task to reevaluate the thermosyphon hot water system to assess its potential for offering significant cost and performance benefits over active systems.

Findings of this study (Ref. 6), based on an intensive literature search to locate side-by-side performance comparisons of thermosyphon and active hot water systems other than the NBS test and a closer evaluation of the NBS tests, indicated that there was no significant thermal performance advantage in the use of thermosyphonic systems. There are, however, some definite advantages when parasitic power and system economics are considered. These advantages relative to other NBS-tested configurations are indicated in Table 1. The figures of merit presented in this table are normalized ratios of efficiency (best systems = 1.0) divided by initial system cost. Rankings corresponding to both thermal and net system (parasitic losses included) efficiencies are given.

The major difficulty perceived with thermosyphon systems to date has been the apparent problem of adequate freeze protection, as discussed fully in Ref. 6. A major finding of this analysis argues that a high-reliability drain-down capability could resolve this concern while allowing solar users to take advantage of the benefits of these systems. Also, recommendations for future development activity, including sound reliability analyses, high efficiency solenoid valves with high reliability, and different drain-down strategies are discussed.

(2) Solar Ponds: As part of the continuing need to evolve and identify new, promising concepts, SERI has undertaken a study of solar ponds that may have potential beneftis for both district and industrial process heat applications.

Solar ponds are conveniently classified as either salty (i.e., stratified) or saltless. The salty ponds contain a salinity gradient, which results in a density gradient, to reduce the heat loss by preventing convection within the water storage medium. Saltless ponds reduce heat loss by covering the pond's surface with transparent insulation. In some cases losses may be further reduced by additional night insulation. These are different from shallow solar ponds (developed by Lawrence Livermore Laboratory), which are water bag collectors with separate thermal storage. Water is pumped into the bags every morning and transfered to storage in the evening. The saltless ponds considered at SERI are deep ponds that combine the elements of storage and collection, thus avoiding the cost of elaborate plumbing and separate storage structure. They have high potential as low-cost, low-temperature, collector-storage systems.

Solar pond research at SERI has addressed the following areas: numerical modeling of stratified salty ponds; simplified analytical modeling of stratified salty and saltless ponds; salt availability; experimental program; and economics. A brief summary of results in each of the areas is described below. Five publications have resulted from the recent work (Refs. 7, 8, 9, 10, 11).

(a) Numerical Modeling of Stratified Salty Ponds: In order to investigate salinity-gradient solar pond performance under realistic weather and load conditions, a detailed numerical thermal simulation program was developed. This program (SOLPOND) models the solar energy absorption characteristics of the pond, and heat transfer and thermal storage within the pond and the surrounding earth (Ref. 8, 9). Finite element techniques have been used to describe conduction heat transfer through the pond, earth, and edges. Sensitivity studies of thermal performance with respect to geometry, load, and optical transmission have been calculated. This program will be available to the public through the SERI Code Center. Using this program, performance of solar ponds in differernt locations of the country also has been calculated.

(b) Simplified Analytical Modeling: Simple mathematical models are extremely useful in obtaining an idea of performance of solar ponds. At this stage of solar pond development, when there is scant experimental data, such simple tools may, in fact, be sufficient to predict performance of solar ponds and to size them. A generic mathematical model of solar ponds was developed by considering the system as a lumped parameter thermal network (Ref. 7). This model has been used to predict performance of salty and saltless ponds, and to predict maximum and minimum temperatures for different loads at different locations. It has also been used to size solar ponds for residential heating applications in 25 sites across the country. Because of the widely different climatic conditions in the two parts of the country, sizes of solar ponds in the Northeast tend to be two to three times larger than in the Southwest to supply the same residential heating load.

(c) Salt Availability: The cost of salt represents a sizeable fraction of the total initial investment for a salty solar pond. A typical pond may require 1/4 to 1/3 ton of salt per square meter of surface area. If the salt is to be bought at \$10-20/ton, the cost of salt is 25-50% of the total cost of the pond. Therefore, identification of suitable low cost salts is imperative. The SERI study has concluded that those salts which can be obtained as waste products offer substanital economic advantage for use in solar ponds. Magnesium chloride "bitterns" are available from plants that refine NaCl, and these sites are numerous in different parts of the country. Sodium sulfate has the potential for widespread availability in the next few years as a waste product from flue gas desulfurization (FGD) at coal-fired power plants. A 500 MW_e plant (burning approximately 0.2% sulfur coal) would produce approximately 250 tons of FGD waste per day. Thus, the potential for obtaining free sodium sulfate for use in solar ponds seems to be quite high in areas where power plants utilize the scrubbing process in which sodium sulfate is the waste product.

(d) Experimental Work: An experimental program was initiated in FY79 to support the analytical work. Small-scale experiments have demonstrated the predicted stability and salinity gradients of the ponds; several other experiments aimed at determining the feasibility of using low cost salts have been initiated.

(e) Saltless Ponds: Since saltless ponds have received little previous research attention, they are presently in the earliest stage of design. The Lawrence Livermore Laboratory's saltless solar ponds have demonstrated some performance success, and significant future design improvements may be realized. SERI investigations have centered on identifying potential areas for design improvements which include: reducing plumbing by eliminating separate thermal storage; reducing thermal losses with night insulation; and providing long-term storage with deep ponds.

(f) Economics: The economics for both salty and saltless ponds are encouraging. Preliminary results indicate the following findings.

- o There are potential sources of cheap salt as waste products in chemical processes in the salt industry and in the power industry.
- o Modeling and performance production indicate that a steady thermal load of 50 W/m^2, at a minimum temperature of 50° C, can be obtained from solar ponds of reasonable depth (approximately 1 m).
- o Salty ponds can provide low-temperature solar thermal energy for less than 1 ¢/kWh_{th} in many locations where salt is inexpensive.
- o Saltless ponds have the potential to provide low-temperature solar thermal energy for less that 1.5¢/kWh_{th} in places lacking an inexpensive local salt resource.

(g) District Heating: The concept of district heating on a neighborhood scale is currently being examined as a possible end use of energy supplied by a solar pond. This task includes several phases. First, SOLPOND, the thermal performance simulation code, was checked for accuracy by comparing its predictions with measured data obtained from the Miamisburg, Ohio pond (Ref. 8). This study indicated that SOLPOND is capable of very accurate predictions if the critical properties and parameters are known. Satisfied that the program is adequate for the district heating study, work has now begun on the sizing ponds for a variety of district sizes in a number of locations. Once complete, this information will be combined with specifications for the balance of the components necessary for district heating, such as pumps, piping, and heat exchangers; and to formulate an overall system design. System thermal and economic performance will then be studied, and the feasibility of ponds for district heating assessed.

(3) Standard Assumptions Document: Analyses of solar heating or cooling systems require as inputs meteorological data (i.e., temperatures, dew point, insolation, and wind) and well-defined building configurations to determine the load characteristics. In the past, researchers analyzing different systems generally have not modeled identical buildings in identical locations using the same weather data. Since these parameters greatly influence the performance of the system, it is difficult to make meaningful correlations among different systems or from differernt analysis methods. Furthermore, a common data set and a consistent performance basis are sorely needed in investigating the sensitivity of system operation to various components or the environment (climatic or economic).

To address these needs, a standard set of inputs, assumptions, analytical methods, and a reporting format for use in residential and commercial solar system analyses have been developed and published (Ref. 12). Significant inputs were developed by Science Applications Inc. and TPI as a part of subcontracted efforts to SERI. These standards should facilitate the comparison of results of analyses being performed by different investigators. By the common use of load data, meteorological data, economic parameters and reporting format, researchers examining, for example, two types of collectors may more easily compare their results. Only parameters not directly related to the energy system of a building are specified (with the exception of passive systems, in which the building is integral to the energy system) so that no biases are introduced into the analysis. In addition, a variety of climates are characterized that are typical of those found in the United States. Evaluating system performance in each of the locations can yield valuable information about the most promising location for immediate market penetration.

This document will require periodic updating to provide analysts with the most appropriate inputs and to assure that the results of systems analyses are based on the most meaningful information. Updating is especially important for rapidly changing information such as economic parameters. Subsequent revisions of this report will be available from SERI.

(4) Heat Pump Demonstration Analyses: The object of the heat pump demonstration analyses tank, a SERI FY80 activity, is to assess the performance of operating heat pump systems (both conventional and solar assisted) in the field. That assessment will include engineering and economic performance, including operation and maintenance aspects. Results of the assessment will be compared with the analystical studies being performed by SAI. The final result is expected to be a report which documents the status of heat pump performance, the prospects of solar-assisted heat pumps, R&D requirements for future focus, and cost/performance goals to guide and measure development efforts. Work to date has been the development of the work statement for the field assessment. Analytical results of the heat pump comparative results are discussed in the presentation by SAI, which is located elsewhere in this document.

(5) Analysis/Design Method User Requirements: To properly focus future developmental efforts of analysis/ design methods, a study was initiated to analyze and define user requirements/needs/abilities. The object of the study is to define the decision-making process in the residential building industry and define the needs/requirements for solar design and analysis tools. Large, medium and small builders will be studied and characterized. Their requirements for analysis/design methods will be defined in terms of content, complexity, ease of use, etc. The results of the study being performed by Booz, Allen, and Hamilton, will be used to guide future development of analyses/design methods.

(6) Integration of Active and Passive Analysis Capability: Until recently analytical capability for active and passive solar systems existed as separate entities. Comparative analyses of active and passive proved difficult, if not impossible. Perceived needs of the Residential Conservation Service (RCS) program dictated the development of a singular analysis method which would be capable of performing consistent analyses of active, passive and conservation techniques. As a

result, a contract was given to Booz, Allen, & Hamilton to integrate the Solar Load Ratio (SLR) method (Ref. 13), a simplified passive analysis technique, into the Residential Solar Viability Program (RSVP) (Ref. 14) analysis method. RSVP is based on the F-Chart method of analysis for active systems. The resultant program of this activity will be called PACE (Passive/Active/Conservation Evolution) Program. A working version of the program has been developed, implementing up to five passive sytems within a residence. An optimization sizing routine for the passive systems is being developed along with revised output formats. The latest version of F-Chart will be incorporated into this method. The program and documentation, including a User and Programmer Manual, will be delivered by July 1980.

(7) Handbooks: An important activity of the system support area is the development of appropirate engineering-oriented handbooks. Two efforts are currently underway in this area: the development of handbooks by ASHRAE on collector performance and solar domestic hot water; and the development of a solar domestic hot water inspection and performance evaluation handbook by Solar Environmental Engineering Company (SEEC). SEEC is also developing a handbook for controllers used in solar domestic hot water systems. That activity is described in the paper on controls which is located elsewhere in this document.

(a) Inspection and Performance Evaluation Handbook: The Inspection and Performance Evaluation Handbook is an outgrowth of an earlier study which showed that many systems in the field were not performing up to their potential and the users were unaware of this lack of performance. The objective of this handbook is to provide system startup and service procedures which may be followed by trained technicians so that system performance may be quickly estimated in the $\pm$ 10%, confidence level.

Procedures which should be followed upon the completion of any installation or during a service call are described in the handbook. Some test equipment not normally used by service personnel is required. The cost of the equipment is relatively small, as is the time required to completely check the system. The extra expense and effort should be rewarded by better system performance, greater system reliability and a more satisfied solar customer.

Eight generic domestic hot water systems are covered in this handbook. The handbook contains three major parts. Each part provides a different starting point for troubleshooting. The proper starting point depends upon the service person's knowledge of solar principles and his familiarity with the particular system being inspected.

Three appendices follow the text. Appendix A is written for the owner or prospective owner of a solar domestic hot water system who has little experience in the field. Simple procedures using inexpensive instruments are described which will allow the owner to determine whether or not his system is operating as it should, although not necessarily at its maximum efficiency. Test equipment that the solar service person should use for thorough system performance evaluations is listed in the second appendix. Recommended taps, plugs, and other hardware which expedite the task of system performance evaluation are described in the third appendix. Installation of this testing equipment should be considered by the designer so that service is easier. In this way, the life cycle cost of the system, including maintenance and repair, may be minimized.

(b) ASHRAE Handbooks: The intent of this effort is to develop two ASHRAE handbooks: a Solar Domestic Hot Water Handbook, and a Collector Performance Handbook. The DHW handbook is intended to cover all phases of design, installation, operation, and maintenance of solar hot water systems. A review of existing material is included in the contract to avoid duplication of effort.

The second handbook will cover the uses of the information determined from collector tests under ASHRAE standard 93.77. It will cover the prediction of collector performance under various conditions and will give information to aid the specification and design of collectors for varius applications.

The contract also covers an ASHRAE review of the Passive Solar Design Handbook (Ref. 13).

(8) Thermography: Thermography, or infrared photography, is used to illustrate and detect temperature differences in devices or structures. For instance, utilities use thermography to detect the overheating of line capacitators, and ASHRAE energy auditors investigate energy flows in buildings with infrared photography.

Thermography appears to have considerable merit as a solar system diagnostic tool. It can be used not only to assess the relative energy flows in passive structures, but also to identify temperature gradients in solar collectors of any kind. Such temperature gradients with active system collectors often are caused by flow imbalances, which can sometimes lead to damage of the systems and degraded system performance. Such a diagnostic tool can be extremely valuable to utilities, energy auditors, and solar firms in diagnosing whether a collector (or array) is functioning correctly.

SERI conducted a thermographic analysis of large solar collector arrays with expensive as well as low cost, hand-held units in Colorado and New Mexico at sites chosen from the National Solar Data Network, plus other instrumented locations. The systems examined included liquid and air flat-plate collectors, both selective and non-selective absorbing surfaces; evacuated tubes; passive houses; and compound parabolic collectors. The system sizes ranged from single family dwelling heating systems to the absorption cooling system on the Base Exchange at Kirtland AFB, which has 930 square meters of collectors. Plumbing configurations were series, parallel, and various combinations. The entire laboratory at Colorado State University was analyzed with its many varied systems and collector types.

The results of the thermographic analysis of the various collector systems were extremely interesting and valuable. Most systems showed temperature distributions which indicated balanced flow patterns both with the thermographs and with the hand-held unit. Subtle differences existed, but these differences were minor. In three significant cases, blocked or broken collector arrays were discovered. One situation was caused by an air blockage within a series-parallel combination of collectors. Thermographic analysis allowed the clearing of the blocked cluster by direct observation of the flow pattern as it was reestablished. Another system was discovered out of action due to a design problem with a drain-down valve. This was detected from a great distance on a very large collector system. The third case was one of a very large array system with a few broken glazings which were noted when examined from a utility-type bucket truck. All these discoveries had gone previously undetected and could be used to illustrate some of the practical applications of thermography as an analysis or operation and maintenance technique. Furthermore, when used correctly, low-cost hand-held units were

shown to have sufficient resolution capabilities to detect most commonly occurring problems.

A report on this work is in preparation (Ref. 15) and a paper has been accepted for presentation at the 1980 ASME Conference.

(9) Computer Code Development/Dissemination: Since SERI is rapidly becoming the national center for the evaluation and dissemination of solar simulation methods, evaluation of key solar computer codes was initiated in FY79. This is a first step in establishing a center of expertise and technical credibility in solar simulation methods. Two important, currently available, state-of-the-art, but relatively new, analysis methods (DOE-2 and DEROB) were chosen as a focus. Both of these codes have been brought online during the last quarter of FY79. DEROB is a passive code and will not be discussed here.

DOE-2 has the capability of analyzing the energy performance of large or small buildings. Developed by LASL and LBL, it has the potential to be a very versatile solar analysis tool. Further, it is a key evaluation tool for the Buildings Energy Performance Standards (BEPS) Program, and it is also being considered as an arbitration tool for California energy regulations. The solar portions of this code are relatively immature, but active, passive, and combined active and passive systems potentially can be analyzed. In FY79, analyses uncovered several minor problems, as well as some fundamental limitations to using the code for BEPS evaluation, particularly with respect to passive analysis. A paper on the capabilities of the component based simulator (CBS) solar portion of the program was presented at the SSEA Conference in San Diego in January 1980 (Ref. 16). In FY80, SERI's contribution will be to assist the developers in verifying the solar portions of the code and to provide a responsive, unbiased source of expertise on this method. Sensitivity studies and comparisons of the solar portions of DOE-2 with the more well established TRNSYS code have begun and will continue.

At the beginning of FY79 SERI was asked to take over the responsibility for the dissemination of F-Chart. Activities included the development of user-oriented literature describing the computational method and its capabilities (Ref. 17). More than 2000 copies of this brochure have been distributed. By working with the program authors and users, SERI has been able to identify needs and define problems that need correcting. SERI has responded to more than 500 technical inquiries regarding problems and the use of F-Chart.

Although SERI has no formal responsibility for SOLCOST, SERI has assisted Martin-Marietta Corporation, Solar Environmental Engineering Corporation (SEEC), and International Business Systems (IBS) in maintaining and disseminating this code. For example, SERI maintains configuration control of SOLCOST and coordinates development meetings for both Martin-Marietta and SEEC. In late FY79, SERI funded an activity to implement SOLCOST, Version 2.1, on the CYBERNET Network. SERI revised, printed, and disseminated the latest SOLCOST manual (Ref. 18). As with F-Chart, SERI has responded to more than 500 user inquiries about SOLCOST.

In FY78, SERI developed a user-oriented brochure on solar heating and cooling analysis methods (Ref. 19). The brochure was developed in response to many inquiries as to the most appropriate analysis and design methods. It lists available analysis and design methods and defines how they can be obtained. During the past eighteen months, SERI has updated that brochure to reflect new information generated by EPRI and others. More that 15,000 copies have been distributed to the public.

(10) SSEA Conference and Working Group Meetings: The Second Sytems Simulation and Economic Analysis (SSEA) Conference was planned by SERI and held January 23-25, 1980 in San Diego, California. More than 175 individuals participated and 75 technical and economic presentations were given during the 2-1/2 day meeting. Photovoltaics, wind, process heat, and thermal electic as well as solar heating and cooling systems were discussed. DOE's participation encouraged the direct and immediate assistance to industries and speakers were asked to address how their work met those needs. The meeting proved quite useful and successful in providing an open format in which the latest technical developments in solar systems analysis were subject to peer review and criticism. A number of issues were raised and discussed at the conference including validation, control strategies, and the unavailability of hybrid analysis methods. The papers along with these and other issues are discussed in detail in the proceedings which will be available in May of 1980.

In addition to the SSEA Conference, the SSEA Working Group met for two days each in May and November 1979. The May meeting addressed simulation model develoment, validation, and system testing. The November meeting focused on model issues as related to the Building Energy Performance Standards (BEPS) Program and, the Residential Conservational Service (RCS) Program; and the overall subject of validation, including status and methodologies.

Systems Test

Another major element of the SAT program is system testing, which has as an objective the coordination/conduct of system-level tests to evaluate, verify and optimize system economics and performance behavior; and to develop data to use in the validation process. Major programs are underway in the system testing area at Colorado State University, National Bureau of Standards, and Vitro Labs. These programs are discussed in other parts of this documents. Other test activities are discussed below:

(1) University of Texas: Funds were provided to the University of Texas at Austin to assist in instrumenting and monitoring performance of a solar heating/cooling demonstration on an apartment building. The system consists of an array of 1280 square feet of Northrup concentrating tracking collectors, a 5000-gallon hot water storage vessel, a 500-gallon chilled water storage vessel, a 25-ton Arkla Industries absorption chiller, and a two-pipe hydronic air conditioning system. The solar air conditioning equipment is installed in parallel with the existing conventional electric heating and cooling system, and the solar domestic water heating serves as preheat to the existing electric water heaters. The system was instrumented for monitoring with temperature, flow rate, electrical power, and meteorological sensors. It became operational in the summer of 1979.

Data taken in July/August 1979 indicate that 11.2% of the cooling load was met by solar. The reasons for these disappointingly low values are several. The concentrating solar collectors did not perform as well as represented by the manufacturer. In general, the measured collector efficiencies were approximately 60% of the manufacturer's suggested performance curves. This is in part due to a bank of collectors not performing as well as an accurately tracked single collector, which was the basis for the manufacturer's performance data. Also the collector performance is degraded for in-plane

but off-normal radiation. It was also found from tests of a single collector in the University if Texas laboraotry that the measured performance of a single collector fell approximately 30% below the manufacturer's recommended performance curve. Another factor influencing the low solar cooling fraction was that the thermostat (sensor in hot tank) turned the chiller on at too low a temperature. This caused excessive cycling of the chiller, which resulted in a poor average chiller C.O.P. Steady-state chiller operation exhibited a C.O.P. very close to the manufacturer's specified performance values.

During this monitoring period the daily average direct-normal radiation was 1166 Btu/ft^2-day and the daily average total horizontal radiation was 1657 Btu/ft^2-day. The direct-normal radiation is of primary importance since the collectors are concentrating/tracking. While the average direct-normal was 1166 Btu/ft^2-day, the maximums on "clear" days were approximately 2500 Btu/ft^2-day; in other words, the average direct-normal was a little less than 50% of that available on a "clear" day. In the late summer period of the year this is largely a result of partial (cumulus) cloud cover. The collector efficiency (based on the direct-normal) over this period was 32%, a somewhat lower average collector efficiency than expected.

Approximately six additional weeks of data were taken in the early fall 1979 after the solar domestic hot water was turned on and while solar cooling was still needed. To date, the data has not been reduced and evaluated because of problems with the mini-computer used for data processing. It is expected that this data will be processed and be made available in early 1980.

The evaluation of system performance, which to date is for the cooling season, indicates a lower performance than expected. However, it is felt that system performance in the cooling mode can be improved by better adjustment of the thermostats and controls.

Work in the future will include completion of analysis of data taken during the remainder of the 1979 cooling system (including domestic hot water); and continued data collection/analysis of heating season data. Control strategies will be modified in an attempt to increase system performance.

(2) University of Pennsylvania Row Home: Monitoring of the row house continued in FY79. Earlier results of the experiment are presented in Ref. 1. Data acquisition became fully operational in December 1978. Sixty-four channels of data are acquired at five minute intervals. Elapsed time meters were installed as a back-up system, to determine the total operating time of the collector loop pump, demand loop pump, warm air blower, warm air furnace burner, domestic hot water heater burner, and solar system solenoid valves. A detailed data reduction and analysis computer program was prepared, which produces the final system and component performance information in both tabular and graphic form.

At the end of summer 1979 the solar system's operation was stopped to (1) allow the examination of its components, (2) recalibrate the instruments, and (3) implement some minor modification. These activities are now complete and the system is operational again.

Reports have been prepared (or are in preparation) on: system and component performance; Philadelphia weather and solar data; data reduction and analysis computer program manual;system construction, operation and maintenance manual; anddurability of solar heating system components, and stability of instrumentation. Publications resulting from the work are cited in the reference section (Refs. 20, 21, 22).

Validation

A major concern in the solar community is whether solar analysis and design methods have been demonstrated to give valid results in realistic applications. During FY79, the SAT program initiated development of a validation methodology and coordinated validation expresses to test the various existing models.

(1) Methodology: In support of SERI, SAI was assigned to develop a validation methodology for solar water heaters (Ref. 23). The proposed SAI methodology compares a reference research code to constrained* experimental data, compares the design code to the research codes, and performs a sensitivity analysis of the design code to field-test data. The major concerns with such a methodology are its costs to implementation and its statistical validity because the uncertainty in the measurements required for the detail of data requested may be as large as, or exceed, the uncertainty in the parameters themselves.

A simpler global approach that would rely on simple, readily measured data appeared necessary. Such an approach was developed at SERI. The alternative methodology was established in an attempt to develop simple but statistically valid samples, and to measure variables obtainable with reasonable certainty and having meaning to the typical solar user (e.g., the amount of energy used with and without solar technology) (Ref. 26). These measurements are compared with computed predictions and statistical estimates for the expected uncertainties associated with simulations as compared to reality. The experimental results would be equally applicable to all codes which simulate the particular application being tested. However, the results are expected to have the most immediate applicability to design codes.

A proposed pilot study would identify the population of DHW systems in a region, and a group of systems would be selected according to statistical sampling theory. The sample would be instrumented as inexpensively as possible to determine a few integrated performance values. Design code predictions would be compared with measured performance. Correlated experimental and analytical results would pinpoint problems in the experiment design and confirm statistical parameters required for the larger experiment. In addition, results would provide initial guidance for improving analysis methods and refining the assumptions used in these methods. correlated experimental and analytical results would pinpoint problems in the experimental design and confirm statistical parameters required for the larger experiment. Funds, however, are not currently available to implement the proposed study.

(2) Validation Exercises: The SSEA Working Group is coordinating validation exercises. The approach has been to define various test problems in solar heating and cooling and have various individuals/groups attempt to independently predict performance of the system using their respective simulation methods. The group periodically meets to compare and

*"Constrained" refers to the fact that the experiment is under idealized conditions and is not necessarily representative of field experience.

resolve differences in their analyses. The exercises provide an opportunity both to study variations in answers when different codes are used, as well as operator variability when the same code is used. To date problems in liquid and in heating systems have been addressed. Most recently the group has begun addressing IPH (Ref. 2) and passive applications.

In addition to the SSEA sponsored validation problems the International Energy Agency (IEA) Task 1 group has addressed validation as part of their activities. The Task 1 group consists of approximately 25 experts in the field of solar system modeling and analysis from approximtely 12 different countries, who have met every six months for the last three years. The goup was chartered with the task of "establishing a common understanding and basis for the modeling and simulation of solar heating and cooling systems." To this end the group has defined a series of test problems in solar heating and cooling thermal and economic analysis, performed the analysis with the tools available to each of the participants, met to compare and discuss results, and published draft versions of a final report (Ref. 27). LASL, the University of Wisconsin, and Atlas Corp. has represented the United States the past several years.

Validation work consisted of comparing the TRNSYS and LASL simulation codes with the performance data from the LASL Study Center. In addition, five other codes from Europe and Japan were used. The results of this validation effort was presented at the recent SSEA conference (Ref. 28).

Additional work in an optimization subtask involved comparisons of the F-Chart program to the other IEA simulation codes; performance of an economic sensitivity study; development of a graphical optimization technique; and analysis of the economics of selected solar sytems in participating IEA countries (Ref. 29).

FUTURE ACTIVITIES

Work the remainder of FY80 is directed toward completion of the activities presented in the previous sections. All topics discussed will result in published reports/papers which will document the accomplishments made in each area.

The various systems analyses being performed on heat pumps and cooling systems will be used to focus and direct the R&D efforts in those areas. Cost/performance goals will be established and used within the technology programs to ensure that the products developed will be viable.

It is expected that the systems support activity will continue to assist DOE in defining cost/performance goals for other areas in the active heating/cooling program, using methodologies developed the past 18 months; as well as developing validated systems simulation and design methods for the solar community.

ACKNOWLEDGEMENT

This work was funded by the Systems Development Division, Office of Solar Applications, Department of Energy.

REFERENCES

1. Bishop, C. J. Systems Analysis/Validation for Solar Application (SAVSA), 3rd Solar Heating and Cooling R&D Contractors' Meeting, September 1978.

2. Bishop, C. J. Systems Analysis and Test (SAT) Program: Progress Report, October 1, 1978 - March 31, 1979. Golden, CO: Solar Energy Research Institute; SERI/PR-35-313; July 1979.

3. Murphy, L. M. System Analysis and Testing (SAT) Program Annual Progress Report: October 1, 1978 - September 30, 1979. Golden, CO: Solar Energy Research Institute; SERI/PR-351-419, November 1979.

4. Bishop, C. J.; Groome, L. Systems Analysis and Testing Program Management Plan. Golden, CO: Solar Energy Research Institute; SERI/MR-35-222; June 1979.

5. Benham, C. An Integrated Testing and Model Validation Program Plan for Advanced Solar Systems and Sub-Systems. Golden, CO: Solar Energy Research Institute; SERI/MR-34-079; March 1980.

6. Noreen, D.; Farrington, R.; Murphy, L. A Technical and Economic Performance Assessment of Six Generic Water Heating Systems. Golden, CO: Solar Energy Research Institute; SERI/RR-35-413; March 1980.

7. Edesess, M.; Henderson, J.; Jayadev, T. S. A Simple Design Tool for Sizing Solar Ponds. Golden, CO: Solar Energy Research Institute; SERI/RR-35-347; December 1979.

8. Henderson, J.; LeBoeuf, C. M. SOLPOND—A Simulation Program for Salinity Gradient Solar Ponds, 2nd Systems Simulation and Economic Analysis Conference; San Diego, CA, 23-25 January 1980. Golden, CO: Solar Energy Research Institute; SERI/TP-351-559; January 1980.

9. Jayadev, T. S.; Henderson, J. Salt Concentration Gradient Solar Ponds: Modeling and Optimization. Annual Meeting of the International Solar Energy Society (ISES); Atlanta, GA; May 28 - June 1, 1979. Golden, CO: Solar Energy Research Institute; SERI/TP-35-213; May 1979.

10. Edesess, M.; Benson, D.; Henderson, J.; Jayadev, T. S. Economic and Performance Comparisons of Salty and Saltless Solar Ponds. 14th Intersociety Energy Conversion Engineering Conference; Boston, MA; 5-10 August 1979. Golden, CO: Solar Energy Research Institute; SERI/TP-350-213; May 1979.

11. Jayadev, T. S.; Edesess, M.; Henderson, J. Solar Pond Concepts: Old and New. 14th Intersociety Energy Converison Engineering Conference; Boston, MA; 5-10 August 1979. Golden, CO: Solar Energy Research Institute; SERI/TP35-208; May 1979.

12. LeBoeuf, C. Standard Assumption for Solar Heating and Cooling, Systems Analysis. Golden, CO: Solar Energy Research Institute; SERI/TR-35-402; October 1979.

13. Balcomb, J. D.; Anderson, B. N. Passive Solar Design Handbook, to be published.

14. Groome, L. E. et al. Solar Economic Performance Model for Residential Applications. Annual Meeting of the International Solar Energy Society (ISES), Orlando, Fla, June 1977.

15. Eden, A. The Analysis of Solar Collectors Array Systems Using Thermography. Golden, CO: Solar Energy Research Institute; SERI/TR-351-494; January 1980.

16. Eden, A.; Simms, D. SERI-DOE-2 Solar Simulation Study. 2nd Systems Simulation and Economic Analysis Conference, San Diego, CA: 23-25 January 1980. Golden, CO: Solar Energy Research Institute; SERI/TP-351-501, January 1980.

17. Commercialization Division, Solar Energy Research Institute. F-Chart: An Interactive Program for Designing Solar Heating Systems. Golden, CO: Solar Energy Research Institute; SERI/SP-62-201; 1979.

18. SOLCOST Service Center. SOLCOST, Solar Energy Design Program for Non-Thermal Specialists: ANSI Standard FORTRAM, Version 2-1, A Users Guide. Fort Collins, CO: Solar Environmental Engineering Co.; June 1979.

19. Commercialization Division, Solar Energy Research Institute. Analysis Methods for Solar Heating and Cooling Applications. Golden, CO: Solar Energy Research Institute; SERI/SP-35-232; 1979.

20. Lepore, J. A.; Shore, S.; Lior, N. "Retrofit of Urban Housing for Solar Energy Conversion," Housing Science 2, 6, pp. 483-498, 1978.

21. Lior, H. "Instrumentation Principles for Performance Measurement of Solar Heating Systems," Energy, The International Journal, 4, pp. 561-573, 1979.

22. Jones, G. F.; Lior, N. "Optical Insulation for Solar Heating Systems," Energy, The International Journal, 4, pp. 593-621, 1979.

23. Knasel, T. M.; Kennish, W. J.; Cassel, D. Validation Methodology for Solar Heating and Cooling Simulation Models, (Draft), March 1979.

24. Cohen, J. Statistical Problems in Design Code Validation. Golden, CO: Solar Energy Research Institute; SERI/RR-35-377; forthcoming.

25. Morrison, L. Validation Approaches for Solar Heating and Cooling Models. Golden, CO: Solar Energy Research Institute; SERI/RR-35-404; forthcoming.

26. Freeman, T. L. A Comparison of the Predicted Performance of Several Solar Systems Simulations Codes for an Industrial Process Heat System, 2nd Systems Simulation and Economic Analysis Conference, San Diego, CA; 23-25 January 1980.

27. Jorgensen, O. (ed). Task 1: Investigation of the Performance of Solar Heating and Cooling Systems. A Modeling and Simulation Report on Subtask A. May 1978.

28. Hedstrom, J.; Freeman, T. L. Validaton of Solar Simulation Codes by the International Energy Agency, 2nd Systems Simulation and Economic Analysis Conference, San Diego, CA; 23-25 January 1980.

29. Freeman, T. L. Optimization of Solar Heating and Cooling Systems: Report on Subtask D. (Draft), September 1979.

Table 1: Relative Hot Water System Ranking

System	For Collector Cost of $\$81/m^2$		For Collector Cost of $\$162/m^2$	
	w/o parasitics	w/ parasitics	w/o parasitics	w/ parasitics
Thermosyphon	1.00	1.00	1.00	1.00
Single Direct	1.52	1.83	1.27	1.53
Single Indirect	2.02	2.18	1.71	1.85
Double Direct	2.07	2.60	1.77	2.22
Double Indirect	2.59	2.84	2.13	2.34
Air System	4.06	5.70	3.48	4.89

SOLAR COOLING SYSTEMS EVALUATION

HITTMAN ASSOCIATES, INC.

DE-AC03-79CS-30202

DR. H. M. CURRAN

1 APRIL 1979 TO 31 JANUARY 1980

OBJECTIVE

The project objective is to provide assistance to Lawrence Berkeley Laboratory in the management and evaluation of DOE solar cooling contracts, and to perform related research activities.

BACKGROUND

The Solar Group at Lawrence Berkeley Laboratory has the responsibility for technical monitoring of DOE solar cooling contracts. These currently involve the Rankine and absorption solar cooling technologies. The technical monitoring of DOE contracts in the desiccant solar cooling technology is under the direction of the Solar Thermal Conversion Branch of the Solar Energy Research Institute. The LBL and SERI solar cooling activities are closely coordinated.

SUMMARY

Contract activities included site visits, review of contractor reports, assistance to contractors in development of equipment test programs, initiation of development of an evaluation methodology, evaluation of unsolicited proposals, and research activities in support of solar cooling developments.

TECHNICAL ACCOMPLISHMENTS

The use of organic working fluids in Rankine engines in the U.S. and other countries was surveyed and the results documented in a report. A procedure for dynamic stability testing of organic working fluids was prepared. Performance test plans were developed for Rankine and desiccant cooling equipment. Technical input was provided to the DOE solar cooling commercialization readiness assessment.

FUTURE ACTIVITIES

Under a continuation contract the previous types of activities will be continued, the evaluation methodology task will be completed, and a new task on the use of thermal storage in cooling systems will be performed.

PUBLICATIONS

H. M. Curran, "The Use of Organic Working Fluids in Rankine Engines," report submitted to LBL, September 1979, and accepted for presentation at the 15th Intersociety Energy Conversion Engineering Conference, August 1980.

DOE/NASA SYSTEMS DEVELOPMENT

William F. Richardson
Chief, Systems Development Office
Solar Energy Applications Project
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

The DOE/NASA Development for Demonstration Program implementation was initiated in 1975 with the release of a series of five requests for proposals (RFP's). These were:

404 System Design and Development
405 Systems Integration of Subsystems
406 Systems with Additional Development
407 Subsystems with Additional Development
408 Marketable Subsystems

The contracts awarded under the 406, 407, and 408 series RFP's are mostly complete. Only minor "clean up" close-outs remain. Of the 34 contracts awarded, over 90% of the companies involved have hardware in today's solar marketplace. All were awarded to small businesses.

The contracts being reviewed today were awarded under RFP 404 "Systems Design and Development". These contracts are with Honeywell Incorporated, General Electric, and AiResearch. Reporting will be Steve Scarborough (Honeywell), Jim Graf (General Electric), and George McDonald (AiResearch). Following their reviews there will be a brief discussion of our operational test sites.

By way of overviewing these three reviews, it would be beneficial to describe their commonalities and their comparative uniqueness.

All three designs are Rankine cycle driven. All have an electric motor to provide auxiliary power. However, here the commonalities end.

The Honeywell system uses flat plate collectors. The boiler design temperature is 195^{o}F. The Rankine driver is a high speed turbine. The turbine drives a gearbox and thus the shaft is connected to a slow speed (1200 - 1800 rpm, depending on system size) compressor. A conventional motor is mounted between the gearbox and conventional compressor. This motor acts as a generator when surplus solar energy is available.

The General Electric system is totally a slow speed machine. The Rankine driver is a rotary vane expander, and coupled through a motor, drives the compressor. The system is powered by vacuum tube collectors; the design temperature is 300^{o}F.

The AiResearch system is totally high speed. The Rankine driver is a turbine, coupled through an electric motor to a centrifugal compressor. The system is powered by flat plate collectors at 185^{o}F.

So far as our operational test sites are concerned, these are sites that are geographically located throughout the continental United States. Locations range from Loxahatchee in southern Florida, to Togus, Maine. From Spokane, Washington, to San Diego, California. These sites are single family residences and multi-family residences. They are universities, national parks, and manufacturing plants. In short, they are real life, owner occupied buildings and the systems are being operated and data gathered in their true typical operating environment. These sites have numbered up to 43. Ten have been "closed out" - that is, the test period has been completed. Ten are now in the process of closing out. Thirteen more will complete testing by the end of this fiscal year. Nine will be operating in FY 81.

One site that shows excellent potential usage both from a standpoint of location and site owner desire to further the usage of solar is the Frenchman's Reef Motel at St. Thomas, Virgin Islands. This site now has 13,000 ft.^{2} of vacuum tube collectors that on a recent test day added some 9 million BTU's toward preheating the water for the steam-driven absorption chillers used for cooling the motel.

IX SOLAR COLLECTOR TECHNOLOGY GROUP

OVERVIEW OF SOLAR COLLECTOR AND MATERIALS R&D FOR ACTIVE BUILDING SYSTEMS

DEVELOPMENT OF LOW TEMPERATURE COLLECTORS FOR HEAT PUMP APPLICATIONS

Charles A. Bankston
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

This paper presents a brief overview of the activities and accomplishments of the 100 projects that constitute the solar collector and materials R&D program. The program includes basic studies in collector engineering and materials as well as the development of collectors for heating, cooling and heat pump applications. In Part 3 of this paper the development of low-temperature, low-cost collectors for heat pump applications is discussed.

SUMMARY

We are moving slowly in the development of plastic solar collectors. The basic problems are the limitations of the physical properties of the plastics; no single plastic appears to be ideal for use as a solar collector. The trend is toward constructing plastic collectors in composites or layers, taking advantage of the specific properties of each plastic; that is, outer layer UV resistant, middle layer inexpensive, inner layer resistant to the working fluid. The projects in the low-temperature plastic collector area use existing plastics for their collectors, and their success or failure will certainly depend on the material properties of the selected plastics. One should expect the quality of plastic collectors to increase as new plastics are developed. The success of the whole program element may well depend on continued basic polymer chemistry research.

Black liquid collectors may become commercial products in a year. Low-cost plastic laminate solar panels, like Acurex is developing, are at least two years away from commercialization and should be viewed as high risk, high payoff projects. Increased effort is necessary in this area to increase the probability of successful development.

Low Temperature Collectors for SAHP

Objective. To develop low-cost, low-temperature solar collectors through the use of lightweight or inexpensive materials and high-speed manufacturing techniques.

PROJECT/AMOUNT	DESCRIPTION	TERM
Acurex $147K	Further Development of a Low-Cost Solar Panel	9/28/79-9/30/80
Battelle Columbus $150K	Development of a Low-Cost Black Liquid Solar Collector	9/1/79-5/31/81
Monsanto $220K	Low-Cost Mirror Concentrators Based On Double-Walled, Metallized, Tubular Films	3/1/78-2/1/80

Project Activities and Accomplishments

- Acurex is developing the concept of a multi-layer laminated plastic collector in which several films of plastic are extruded and bonded together to form the absorber, flow passages and glazing in a single high speed process. Manufacturing and process development studies have been conducted and show that the concept could lead to very low cost collectors - perhaps $\$2.00/ft^2$ installed. Materials remain the major problem.

- Battelle Memorial Institute initially developed and tested two prototype all plastic black liquid collectors to demonstrate the technical feasibility of the approach. The current program focus on the material aspects of the collector development. Plastics are being evaluated for long term use under conditions that involve uv radiation, exposure to hot fluids, repeated thermal and mechanical stresses and other environmental stresses.

- Monsanto has evaluated low-cost aluminum-foil/plastic film laminates as alternatives to aluminized polyester reflectors. These materials were used to fabricate a prototype inflated concentrating collector of a truncated cylindrical design that reduced materials requirements. The collector is currently undergoing tests.

FUTURE ACTIVITIES

The activities described above will be completed and reported. It is clear that future development of low-cost collectors relies heavily upon the identification, evaluation, and/or development of suitable materials.

REFERENCES

A listing of completed solar collector projects whose final reports are to be distributed through TIC was prepared and distributed at the conference. A complete publications list of all major reports and papers generated by the participants in the solar collector and materials program is in preparation and will be available from LASL.

Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting
March 1980

OVERVIEW OF SOLAR COLLECTOR AND MATERIALS R&D FOR ACTIVE BUILDING SYSTEMS

DEVELOPMENT OF HIGH-TEMPERATURE COLLECTORS FOR SOLAR COOLING APPLICATIONS

Charles A. Bankston
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

This paper presents a brief overview of the activities and accomplishments of the 100 projects that constitute the solar collector and materials R&D program. The program includes basic studies in collector engineering and materials as well as the development of collectors for heating, cooling and heat pump applications. In Part 2, the development of high temperature collectors for Rankine cycle and absorption cooling is discussed.

SUMMARY

The efforts of the contractors in this area have been directed toward development of collectors that will make solar cooling cost effective. Some progress has been made; available collectors have been improved and some promising concepts or modifications have been studied. Unfortunately, no generally accepted cost/performance goals for collectors used in this application are available against which to measure progress.

ACCOMPLISHMENTS

High Temperature Collectors for Cooling

Objective. There are dual purposes to this program element: it is important to foster the development of solar collectors by industry that are 1) capable of operating at temperatures sufficient to drive absorption or Rankine-cycle chillers, and 2) sufficiently efficient and/or inexpensive to integrate with other components in systems that are cost-competitive. Unfortunately, at this time it is not possible to state the general objectives in terms of specific quantitative cost/performance goals. Generating such goals is an important objective of the ABS Program.

PROJECT/AMOUNT	DESCRIPTION	TERM
Chamberlain $334K	Develop 3X Nonimaging Concentrating Collector	5/1/78-8/31/79
Owens and Mayes $112K	Develop Marketable Nonimaging Collector	9/11/78-3/10/80
Owens-Illinois $131K	Determine Tube Vacuum Durability	9/1/78-3/31/80
Monsanto Research $220K	Develop Low-Cost Inflated Cylinder Collector	2/20/78-3/20/80
RCA $279K	Develop PT/PV Evacuated Collector	6/30/78-6/29/80
SET $86K	Develop Image Collapsing Concentrators	9/30/77-8/8/80
Thermacore, Inc. $219K	Heat Pipe Receivers for Evacuated Collectors	9/1/77-9/30/80

Project Activities and Accomplishments

- Chamberlain has been engaged in the development of a 3X non-imaging collector under DOE sponsorship, and a 1.8X collector under corporate funding for the past two years. Ten prototype collectors of the 3X configuration were fabricated and have been tested by ANL. Unfortunately, Chamberlain has recently decided to withdraw from the solar collector business. This means that neither collector will be commercialized.

- Owens-Illinois, in their project on vacuum durability, has determined through life cycle testing that the bakeout cycle can be shortened without affecting lifetime of the tubes.

  Earlier work on this project established the nature of the outgassing products and the suitability of the barium getter used to reduce the service outgassing. Subsequent work on this phase has aimed at reducing the bakeout cycle times or complexity. Tubes manufactured under these altered conditions have been undergoing aging at simulated stagnation temperatures. Besides periodic measurements on these life-cycle tests, current efforts are concentrated on thermal performance in tubes back-filled with known amounts of helium.

- Monsanto has built a prototype of their non-tracking, cylindrical, 3X mirror concentrator that utilizes inflation for shape generation and plastic materials to minimize cost. The target cost is $\$.50/ft^2$ for materials.

  The prototype has been built but testing is not complete. PVC material used on the prototype may be 9000, long-life material. Further testing of the collector may be necessary to determine overall economics.

• RCA now possesses the capability to deposit amorphous silicon coating on 48" glass tubes. This accomplishment hastens the development of another air-cooled evacuated tube collector, with the consequent benefits over liquid-cooled ETCs. In addition, this air-cooled ETC would have performance enhancement in the thermal area as a by-product of photovoltaic activity.

• Solar Energy Technology has designed and fabricated their Fresnel lens and image collapsing subreflector system. They have redesigned and tested the lens concentrator with prism facets on the inside.

The optical performance of this cylindrical Fresnel lens has been determined by analysis and ray tracing. Shaped subreflecting mirrors have been synthesized to concentrate the broad focal fields of the lens onto an absorber shelf area for elevation incidence in a 60^{o} zone and azmith incidence in about a 100^{o} zone. Energy distribution in the absorber area has been calculated. Progress has been made on cost analysis of the splics system and engineering work to accomodate the evacuated tubes for testing is proceeding.

• Thermacore completed prototype testing of their trimethylborate/steel heat pipe absorber in the GE TC100 evacuated collector. The trimethylborate pipe lowered the efficiency of the collector about 10% in these tests. However, system considerations indicate that significant reductions in manifold thermal losses, pumping power, manufacturing cost, and installation costs may be achieved through the use of heat-pipe receivers.

Thermacore is, therefore, proceeding with design and fabrication of water/alloy steel heat pipes and will test a second prototype this spring at GE. Due to the superior thermodynamic properties of water, the performance of the new collectors is expected to be indistinguishable from the standard in the noon efficiency test. If these tests, and concurrent lifetime tests, are successful, the heat pipe could be introduced into the market by 1981.

FUTURE ACTIVITIES

The activities described above will be completed and reported. The present program consists of a number of projects aimed at making incremental improvements in either efficiency or cost of collectors that are designed to operate with cooling equipment in the general temperature range from 200-250°F. Commercial collectors are already available for this range and their manufacturers are also pursuing incremental improvements. Although there is some progress in the government and private sectors, it is clear, even without definitive cost/performance goals for cooling, that systems operating in this temperature range are unlikely to become cost-effective without dramatic and improbable reduction in collector cost, improvement of chiller efficiency, or both. The future of solar cooling seems to depend upon the development of higher temperature collectors (300 - 350°F) that are acceptable for home and light commercial use. In many respects this is a materials problem, but we also need to address collector designs that are safe, reliable, durable, and nearly maintenance free.

REFERENCES

A listing of completed solar collector projects whose final reports are to be distributed through TIC was prepared and distributed at the conference. A complete publications list of all major reports and papers generated by the participants in the solar collector and materials program is in preparation and will be available from LASL.

TEST RESULTS ON VACUUM TUBE COLLECTORS

by
BERNHARD L. WIESENMAIER
CHIEF ENGINEER - SOLAR ENERGY APPLICATIONS PROJECTS
MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, AL 35812
(205) 453-5550

OBJECTIVES

The objectives of this in-house Marshall Space Flight Center (MSFC) test activity are:

- Evaluate the applicability of ASHRAE Standard 93-77 for testing vacuum tube collectors.
- Provide methodology for comparing vacuum tube collectors on an "apples and apples" basis.
- Relate experience to testing other collector types and improving collector standards.

These objectives derived from a need to know collector performance parameters in detail to assure proper application in system projects managed by MSFC.

BACKGROUND

MSFC interest in vacuum tube collectors began in late 1976 when Energy Research and Development Agency (ERDA) requested testing in the MSFC solar simulator to assess the integrity of the Owens-Illinois (O-I) Sunpak^{TM} collector for use in Demonstration Program projects. This work is reported in References 1 and 2 showing early problems to be due to metal, rubber, and plastic materials selection; lack of configuration control over design baselines; and lack of quality control over production processes rather than any weakness in the concept of using glass for a vacuum tube collector. Also, recommendations were made for more "applications" engineering to aid proper system design and installation of this high performance collector. Subsequent successful application of this collector demonstrates these early problems have been overcome.

Recent work, reported at this time, relates to performance correlation for three vacuum tube collectors used in system projects managed by MSFC. These are Owens-Illinois Sunpak^{TM}, General Electric TC-100, and Sunmaster collectors. Performance correlation, naturally, centers on the ASHRAE Standard 93-77, the current baseline for testing collectors. Overriding competition among manufacturers of vacuum tube collectors, there is a unified opinion that this standard produces an unfair performance picture and prevents wide acceptance of vacuum tube collectors by the user market. This was recently highlighted by the fact that no vacuum tube collectors were submitted for test in the National Collector Test Program commissioned by the Department of Energy (DOE). The following paragraphs show this concern to be justified. The discussion also identifies areas where user assessments of the applicability of the same type collector, i.e. vacuum tube, will be biased by only partial consideration of test information available via ASHRAE Standard 93-77.

RESULTS SUMMARY

Successful collection and application of test data derived using ASHRAE 93-77 requires understanding design configuration and operating characteristics of the vacuum tube collector. Key factors for the three vacuum tube collectors evaluated are shown in Table I. In particular, before "apples and apples" comparison

TABLE I. COLLECTOR CONFIGURATION DEFINITION

GE TC-100	Sunmaster	O-I (Series)
• Serpentine Flow	• Parallel Flow	• Series Flow
• Metal Fluid Loop	• Glass-Metal Fluid Loop	• Glass-Metal Fluid Loop
• Does Not Drain	• Drains When "OFF"	• Does Not Drain
• Pump Head Return	• Gravity Return	• Pump Head Return
• Cusp Reflector (8-Tube)	• Cusp Reflector	• Trapping Reflector
• "V" Reflector (10-Tube)		
• Accessory Manifold	• Integral Manifolds (Dec-8 And Dec-8A)	• Integral Manifold
• Soda Lime Glass	• Borosilicate Glass	• Borosilicate Glass
• Accessory Cover	• No Cover	• No Cover
• Tubes Shipped Separate	• Complete Module Shipped	• Shipped As Kit

of test results is valid, the accessory manifold and accessory cover effects must be determined for the GE TC-100 module and the test setup must assure the Sunmaster design drain/flow requirements are satisfied.

It is essential to know the often overlooked time constant requirement in ASHRAE 93-77 before attempts are made to obtain instantaneous efficiency or incident angle modifier data which are based on steady state measurements at 5-minute intervals around solar noon. This measurement interval is satisfactory when the time constant of a collector is less than 2 - 3 minutes, typical for a flat plate collector. However, time constants for the GE TC-100, Sunmaster, and O-I Sunpak™ collectors are 4.5, 12, and 20 minutes, respectively. With these long time constants any outdoor test results are suspect when test requirements demand steady state conditions. Hence, all testing at MSFC has been accomplished in the Solar Simulator where controls can assure steady state conditions.

Instantaneous efficiency data are derived and shown in Figure 1. For valid comparison, the GE TC-100 data must have the manifold losses considered. All data are referenced to gross area in accordance with the standard. Reference 3 contains data to show manifold losses reduce performance of the basic GE module 5 - 8 percent. Accessory covers, when used, reduce output another 5 percent. These constraints are not necessary with the Sunmaster and O-I Sunpak™ modules because of their integral manifolds and the tough borosilicate glass tubes not needing protective covers. Detailed data for these collectors are reported in References 4 and 5, respectively. Noteworthy, is the high temperature potential of vacuum tube collectors relative to a flat plate collector. This is very advantageous for cooling applications.

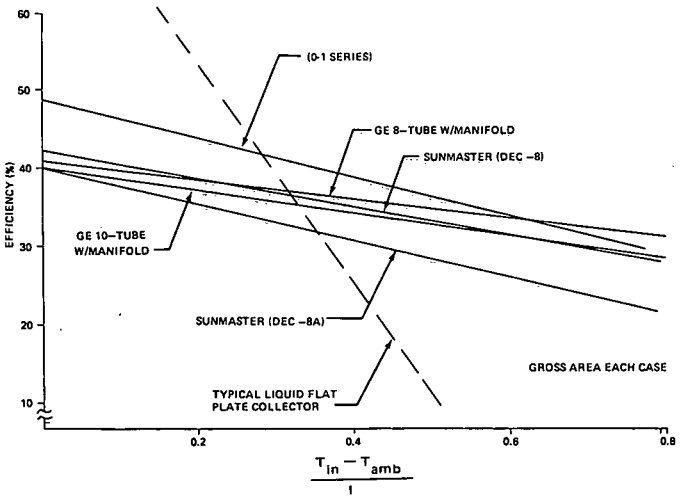


Figure 1. Instantaneous Efficiency Comparison.

The incident angle modifier data are compared in Figure 2. The gain, or loss, at higher incident angles must be applied to the instantaneous efficiency to obtain "effective" performance as the sun moves east to west during the day. Unfortunately, the ASHRAE Standard 93-77 does not dictate to the user of the test data; the incident angle modifier is neglected and many systems are sized with collector areas less than required. Even more concern exists when less than clear-day conditions prevail and the diffuse character of the insolation equates to a high incident angle condition. Figure 2 clearly shows the Sunmaster collector performs better in areas where less than clear-day conditions are frequent. To quantize this effect, direct/diffuse ratios should be correlated to the incident angle modifier and included in ASHRAE 93-77 requirements.

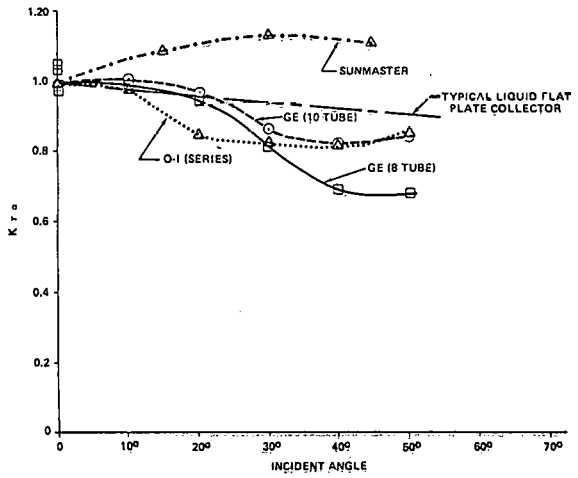


Figure 2. Incident Angle Modifier Comparison.

References 3 through 5 attempt to quantize incident angle modifier effects by adapting procedures from Reference 6 to calculate an all-day efficiency for a sample cooling application. Results are compared in Table II for each collector option. Normalizing the data relative to the lowest efficiency produces a factor that can be applied, inversely, to "cost per square foot" numbers to determine an "apples and apples" cost comparison of these collectors. Again, the GE TC-100 cost should include the manifold and applicable cover costs with the basic module cost when making cost comparisons with the Sunmaster and O-I Sunpak™ collectors. Rounding out any cost comparisons, Table III shows qualitatively other application factors that each user should address. These relate to installation and operation of the collector in a complete solar system.

TABLE II. ALL DAY EFFICIENCY COMPARISON

Factor	GE (W/Manifold-8 Tubes)			Sunmaster		Owen-Illinois
	Lexan Cover	Acrylic Cover	W/O Cover	DEC-8	DEC-8A	Series
Calculated All Day Efficiency*	26%	26%	26%	33%	29%	30.6%
Cover Loss	(-) 5%	(-) 5%	N/A	N/A	N/A	N/A
Net All Day Efficiency	21%	21%	26%	33%	29%	30.6%
Normalized Efficiency	1.0	1.0	1.24	1.57	1.38	1.46

*Reference NBSIR 78-1305 A; Cooling - 32°N Lat.-42° Tilt (will vary with application)

Note: Typical liquid flat plate calculated all day efficiency in cooling application is 15-20%

TABLE III. OTHER FACTORS IN APPLICATION

Factor	General Electric	Sunmaster	Owens-Illinois
Night Losses	Med	None	High
Pumping Power	High	Low	Med
Day Storage Losses	High	Low	Med
Installation Time	High	Low	High
Vandalism Risk Without Covers	High	Low	Mod
Diffuse-Day Losses	High	Low	High

CONCLUSIONS

Follow-on activities are planned to relate this experience to other collector types, provide missing data and quantize where possible, as well as update vacuum tube collector results if changes and improvements are made by the manufacturers selected to provide collectors for future system projects managed by MSFC. At this time, the following conclusions are offered:

- Standard for vacuum tube collector testing should be better defined.
- "Outdoor" test results are sensitive to direct/diffuse insolation ratios and collector design/operation characteristics.
- Experience needs to be retrofitted into flat plate collector testing and projected into concentrating/tracking collector test activities.
- Insolation data collection activities should expand to define direct/diffuse ratios.
- Incident angle modifier correlation with direct/diffuse insolation ratios by regions is necessary.
- Simpler, more practical, rating standard is possible.
- Reassessment of collector standards and test procedures is needed.

REFERENCES/REPORTS/PUBLICATIONS

(1) R. L. Nichols, "Owens-Illinois Liquid Solar Collector Materials Assessment", DOE/NASA TM-78163, March 1978.

(2) B. L. Wiesenmaier, "Final Report on MSFC Assessment of Owens-Illinois Sunpak™ Collector Problems", DOE/NASA TM-78179, July 1978.

(3) "Indoor Test for Thermal Performance of the GE TC=100 Liquid Solar Collector Eight- and Ten-Tube Configuration", DOE/NASA CR-161305, September 1979.

(4) "Indoor Test for Thermal Performance of the Sunmaster Evacuated Tube (Liquid) Solar Collector", DOE/NASA CR-161306, September 1979.

(5) "Results of Thermal Performance Evaluation of the Owens-Illinois Sunpak Liquid Solar Collector at Indoor Conditions", DOE/NASA CR-161189, October 10, 1979.

(6) "Provisional Flat Plate Solar Collector Testing Procedures: First Revision", NBSIR 78-1305A.

FURTHER DEVELOPMENT OF A LOW-COST SOLAR PANEL

ACUREX CORPORATION, MOUNTAIN VIEW, CALIFORNIA

CONTRACT DE-AC04-79L12032

ERIC V. NELSON AND TIMOTHY K. MULLER

SEPTEMBER 28, 1979 -- SEPTEMBER 30, 1980

OBJECTIVES

The overall objective of this program is to develop a single-glazed, liquid-heating, nonconcentrating collector which is cost-effective and can be rapidly commercialized. The primary applications for the collector will be space heating, water heating and process heat, at temperatures from 120°F to 170°F. The specific goal of the current 1-year contract is to fabricate, test, and gain operational experience on a full-scale prototype panel section, with emphasis on the unglazed version. The program also includes an assessment of alternate manufacturing methods and costs to take advantage of the experience gained in designing, fabricating, and testing these panels.

CONCEPT

The low-cost solar panel (LCSP) concept is based on using thin polymer materials which are combined in high-speed printing, laminating, and extruding processes to make a flexible absorber structure. An example of an unglazed prototype panel (absorber structure only) is shown in Figure 1. Good strength characteristics and resistance to environmental degradation are obtained by selecting the proper combination of materials. A cross section of the current absorber structure concept, nominally 12 mils thick, is shown in Figure 2. The outermost layers of the laminated structure are fiberglass or polyester (PET) scrims or fabrics, which have very good strength, creep resistance, and abrasion resistance. The scrim or fabric reinforcement and uppermost Hytrel layer are blackened and UV-stabilized to provide absorption of incident solar energy and long-term protection of the structure from ultraviolet degradation. The inner layers of the absorber are Hytrel, a DuPont polyester elastomer.

The Hytrel layers are bonded together by either of two prototype fabrication methods under investigation on this contract: adhesive lamination and heat sealing by dielectric heating. Adhesive lamination is accomplished by screen printing or using a template to apply the adhesive in a pattern which defines the water flow channels and supply and return manifolds. For heat sealing, the same flow pattern is photo-transferred onto a brass tool, which defines the local dielectric heating areas where fusion of the two Hytrel films will occur.

After bonding the two Hytrel layers together, the scrim reinforcement layers are adhesive laminated to form the absorber structure. A UV-stabilized polyester film (Martin Llumar) glazing is adhesive bonded to the absorber structure surface at only the outer edges.

The baseline prototype fabrication approach on this contract incorporates dielectric heat sealing

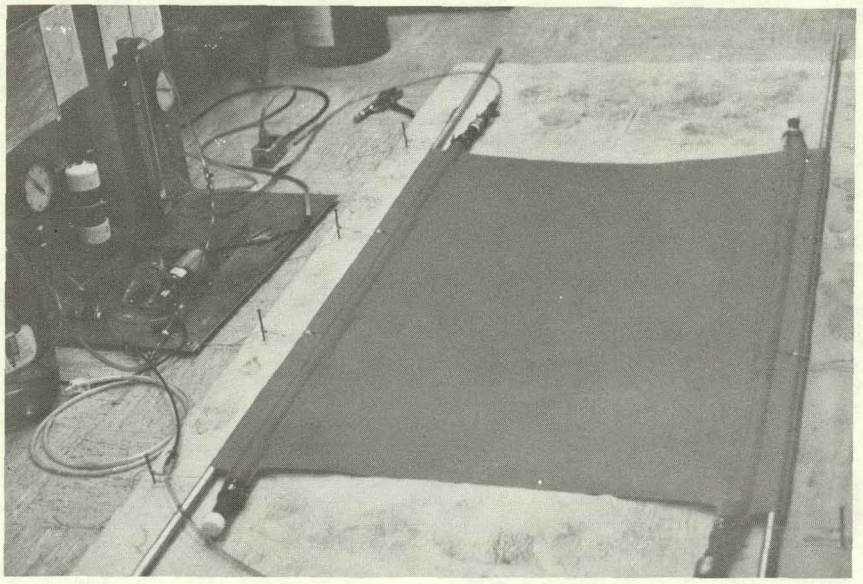


Figure 1. Low-Cost Solar Panel Prototype

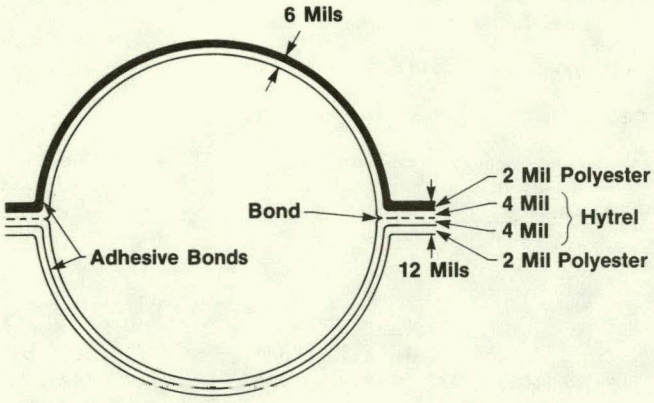


Figure 2. Cross Section of Absorber Structure

of a urethane-coated nylon fabric. Acurex has over 5 years of fabrication experience with these materials in producing liquid-heated and cooled garments for human comfort/protection in high- and low-temperature environments.

SUMMARY

The current project is nearly 60 percent complete. The design activities -- which included refinement of the flow configuration, materials selection, adhesive selection, and tooling design -- are all complete. Fabrication is currently underway including subscale and full-scale prototype panels assembled with adhesive lamination and heat sealing techniques. Heat sealed panels of the urethane-coated nylon fabric materials are complete. Subscale panel tests which include pressure drop, burst pressure, and flow distribution (dye injection), are complete, and good results are reported. Performance tests of a full-size panel are currently underway.

TECHNICAL ACCOMPLISHMENTS

- A mass producible prototype design is complete. Various materials were considered for the absorber structure; a Hytrel grade suitable for film casting was selected. This resin is also compatible with additives to reduce hydrolysis, and with carbon black for solar absorptance and resistance to UV degradation. A fiberglass scrim reinforcing fabric has been included for creep resistance and structural support at elevated temperatures.

- Several panel flow configurations were prototyped to define a pattern which resulted in minimum wrinkling and distortion of the inflated panel, good flow distribution, and low pressure drop. Each panel consists of a series of cells (repeat patterns) 18 inches in length and 4 feet in width.

- Panel layout and assembly sketches, photo-transfer patterns and tooling drawings are complete.

- Prototype panels fabricated of urethane-coated nylon fabric are complete. One-cell, 3-cell, and 12-cell (full-size) panels have been delivered for testing. Fabrication of Hytrel absorber structures by adhesive lamination and dielectric heat sealing is currently underway.

- Material screening tests of adhesives are complete. A urethane-based adhesive with a cross-linking cure agent has been selected. This adhesive is a high peel strength, flexible, structural adhesive suitable for use at elevated temperatures and compatible with Hytrel. This adhesive is also compatible with high-speed lamination equipment.

- Subscale 1-cell and 3-cell panel tests are complete. Pressure drop at design flowrate is less than 0.5 psi, with acceptably uniform flow distribution within flow passages of a single cell and from cell to cell. Panel burst pressures greater than 15 psig have been demonstrated.

- Performance testing of full-size prototype panels (12 cells and 20-foot length) has been initiated.

- A survey to compare design features, performance, and costs of conventional metal flat-plate collectors, commercially available plastic flat-plate collectors and prototype LCSP panels is complete.

- A manufacturing assessment to address production equipment and tooling requirements, production costs, and life-cycle energy cost has been initiated.

FUTURE ACTIVITIES

Contract Activities. It is anticipated that all contract objectives will be met on schedule and within budget. Performance testing of full size panels is already underway, with fabrication of scrim-reinforced Hytrel panels soon to follow. At the conclusion of fabrication, a high-speed production approach based on the prototype fabrication techniques will be formulated, and production costs estimated.

Postcontract Activities. Acurex is fully committed to commercialization and marketing of the LCSP as soon as practicable. Currently, private funds are being sought, and a business plan is being prepared; commercial product introduction is anticipated in 1981. Continuing support will be sought from DOE for completing the first generation panel development, developing manufacturing processes, and assessing the market. Greatly increased efforts (both by Acurex and others) in materials development and testing are recommended to support this development program.

EVALUATION OF HAIL PROTECTION NEEDS AND DEVICES FOR SOLAR FLAT PLATE COLLECTORS

ALTAS CORPORATION
Santa Cruz, California

Contract No: DE-AC04-78CS34291
(previously: EM-78-C-04-4291)

Principle Investigator: Francis de Winter

Period of Contract: June 1978-April 1980
California Congressional District No. 16
Congressman: Leon Panetta

Funding Schedule
FY 1978 - $11,688
FY 1979 - 39,393
FY 1980 - 8,364
FY 1981 - -0-

OBJECTIVE

To determine the incidence of potentially damaging hail on flat plate collector systems, and to develop guidelines for cost effective protection schemes to be used where necessary.

CONCEPT AND BACKGROUND

Away from coastal areas in regions between latitudes 30 (N or S) and 50 (N or S) one can expect hailstorms. In mountain areas, hailstorms are possible closer to the equator. Hail could be a serious barrier to solar energy implementation unless the risks and protective measures are understood. This contract addresses these questions. Hailpad data gathered in field experiments can be used to determine the incidence of potentially damaging hail in various locations. The "maximum probable hailstone size" can be used as a basis for performing tests on candidate geometries.

SUMMARY

A general hail risk model has been developed, based on hailpad data collected by the National Weather Service. The model is based on statistical distributions of hailstone size, number of hailstones per unit area per storm, and number of haildays per year in a given location. In addition, user-supplied parameters are the surface area exposed to hail and the number of years of exposure. The model is used to calculate the "maximum probable hailstone size" which is a convenient index for conducting impact testing. Altas has conducted tests on tempered glass, Fiberglass reinforced polyester (FRP), and screens as possible protection devices. The threat of vandalism to solar collectors has also been evaluated.

TECHNICAL ACCOMPLISHMENTS

- The probabilistic model described above has been used to calculate the "maximum probable hailstone size" in four locations in the "hail belt". These results have been used as a basis for conducting impact testing and for evaluating previously available simulated hail impact test data.
- The derivation and application of the probabilistic model is extensively documented in Refs [1] and [2] for use by others concerned with the incidence of potentially damaging hail. This is the most complete documentation on hail risk to date.
- The results from the hail risk model have allowed Altas to submit detailed assessments of developing standards and codes for solar equipment to withstand hail. The comments submitted by Altas to the DOE and to the Council of American Building Officials have hopefully averted a major blunder in the requirements for hail resistance in Ref [3].
- Altas's impact testing has shown that in very severe hail areas, 3/16" tempered glass is a more cost-effective hail-protection strategy than is the use of cover screens.
- The incidence of vandalism to flat plate collectors appears negligible at present.

FUTURE ACTIVITIES

Contract Activities

At present, both the statistical and testing work under the contract have been completed, and the final report is being prepared.

Post-contract Activities

Extensive work remains to be done in applying the hail risk model in different locations. A large set of hailpad data needs to be evaluated and incorporated in the model, in addition to the National Weather Service hailday data from approximately 200 weather stations. Further analysis will also allow improvement of the fit of the three statistical distributions used in the model.

More testing work can be done, and the testing work can be combined with the statistical analysis to determine realistic requirements for incorporation into solar equipment standards and codes. Based on the work done at Altas, Section B.108.2c of the Second

Draft of the Proposed Model Document for Code Officials on Solar Heating and Cooling of Buildings" [3] is entirely unacceptable as a requirement for solar equipment to withstand hail. Altas believes that if further work, codes, or standards are pursued in this area, the results should not be unjustifiable.

PUBLICATIONS/REFERENCES

1. M. Cox and P.R. Armstrong: "A Statistical Model for Assessing the Risk of Hail Damage to Any Ground Installation," Technical Report for the Period June 1978-March 1979 on U.S. DOE Contract EM-C-04-4291, dated September 1979.

2. M. Cox and P.R. Armstrong: "A Statistical Model for the Incidence of Large Hailstones on Solar Collectors," submitted to Solar Energy Journal, October 1979.

3. "Proposed Model Document for Code Officials on Solar Heating and Cooling of Buildings," Second Draft, available from the Council of American Building Officials, 2233 Wisconsin Avenue N.W., Washington, DC 20007.

EVALUATION OF SOLAR COLLECTORS FOR HEAT PUMP APPLICATIONS

AMERICAN HELIOTHERMAL CORPORATION

EM-78-C-04-5351

C. GARY SKARTVEDT

SEPT. 1978 - APRIL 1980

OBJECTIVE

1. Evaluate the potential utility of low-cost, flat plate solar collectors as the heat source/sink for solar assisted heat pump systems for space heating and cooling.
2. Conduct an experimental determination of effective night sky temperatures and convective heat transfer coefficients for surfaces with dimensions representative of flat plate solar collectors.

BACKGROUND

Heat pumps have been in use for heating and cooling buildings for many years. Because heat pumps can extract heat from low-temperature sources, the use of solar collectors in series with heat pumps (to collect energy at lower temperatures and correspondingly higher efficiencies), is an intuitively attractive idea. Numerous studies, however, have shown that in most applications, use of conventional glazed flat plate collectors as the sole energy source for a heat pump, is not as cost-effective as the use of the same collectors in parallel with a conventional air-to-air heat pump. This is particularly true if a large energy storage reservoir, such as a swimming pool, is not available to the solar-source heat pump.

Based on these results, the subject study was initiated to evaluate the potential utility of very low cost (possibly unglazed) solar collectors to provide both heat collection and rejection for a liquid-source heat pump.

The study approach consists of exercising a detailed analytical simulation of the complete heat pump/collector storage system against heating and cooling loads derived for typical single-family residences in eight U.S. cities. In addition to evaluation of collector options, the study includes consideration of buried pipe grids to provide earth-coupled thermal storage.

In order to determine the relative cost effectiveness of the solar-assisted liquid source heat pump systems against a conventional reference, their performance will be compared to that of an identical heat pump using a standard outdoor air coil as the heat source/sink.

In addition to the analytical tasks, the study includes an experimental determination of night sky temperature and convective heat transfer coefficients for solar collector size surfaces. It became apparent during the early phases of the system analysis effort that accurate estimation of the night-time heat rejection capability of solar collectors is highly dependent on sky temperature and convective film coefficients. Review of the literature indicated that the available correlations for convection coefficients were based on characteristic dimensions which were very small in comparison to typical solar collector dimensions. A correlation developed by Sparrow [1] does incorporate a characteristic length, but is based on wind tunnel tests using a thin 3" by 3" test article.

Because of the lack of experimental convection data for large surfaces, and the lack of extensive data of effective night sky temperature in the presence of clouds, a simple experiment was designed to characterize the radiative and convective losses from collector-sized surfaces. The initial experiment will be conducted in situ by placing the test apparatus on the roofs of houses in the Denver, Colorado area. If the Denver results appear useful, the hardware is designed such that the tests can easily be repeated in other climatic conditions.

SUMMARY

Hour-by-hour heating and cooling loads were calculated for typical single-family residences in eight U.S. cities. A detailed computer simulation model was developed for a solar-assisted liquid source heat pump system. The model includes provisions for ground-coupled thermal storage. Manufacturer's data and performance figures of merit were compiled for 20 commercially available collector configurations. System performance simulations were completed in four of the eight selected cities using a baseline unglazed plastic collector configuration and a typical glazed insulated collector.

Design calculations were completed for the night sky temperature/convection coefficient hardware. All materials and instrumentation equipment were purchased. Two identical test instruments have been fabricated and are ready for installation and checkout.

TECHNICAL ACCOMPLISHMENTS

- Construction and thermal characteristics were defined for single-family residences typical of current design and construction, in eight U.S. cities (Denver, Los Angeles, Miami, Atlanta, Baltimore, Boston, Minneapolis, and San Francisco).

  A computer model was developed to calculate hour-by-hour heating and cooling load profiles for the typical residence in each of the eight cities. The model includes transient response effects of walls and roofs, internal thermal mass, internal heat gains, and solar gains. The model uses

synthetically derived hourly and daily weather transients which match long term monthly averages.

- Detailed technical and cost data were solicited from the 110 manufacturers of flat plate solar collectors. Based on their responses, performance and cost, figures of merit were derived for 20 candidate designs. From these results a low-cost unglazed, uninsulated, synthetic rubber configuration was selected as the baseline collector for use in the initial system performance simulations.

- Six different conceptual designs of solar-assisted heat pump systems were defined and compared. These included various combinations of both single source (liquid) and dual source (air and liquid) indoor and outdoor coils. Based on qualitative evaluation of these systems, a liquid source configuration shown in Figure 1 was selected as the baseline configuration for the collector evaluation computer sumulations. As shown in the Figure, the system includes provisions for thermal storage in a conventional water tank and in the earth surrounding a buried pipe grid.

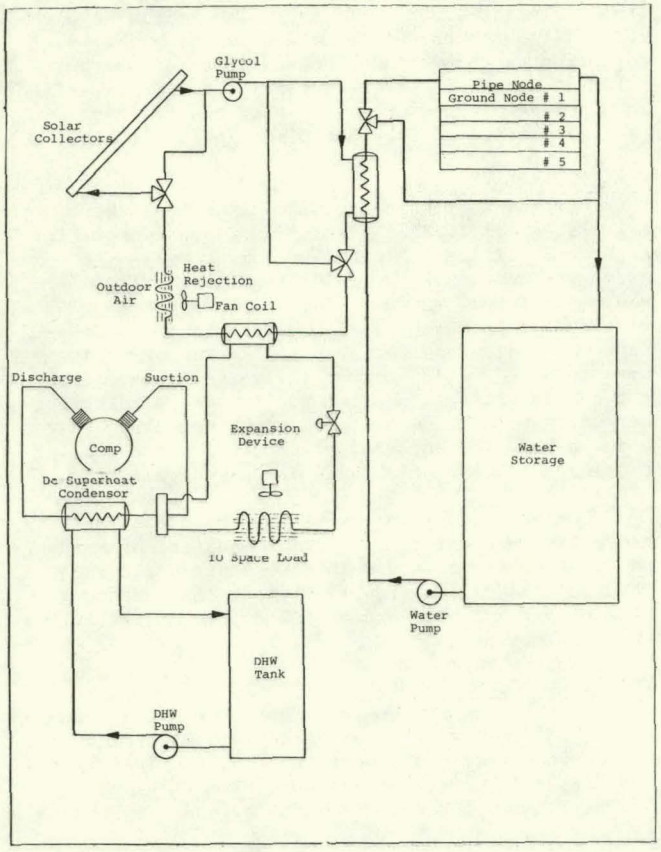


FIGURE 1. TYPICAL RESULTS FOR DENVER RESIDENCES

A computer model was developed for simulating the hour-by-hour annual performance of the selected liquid source, solar assisted heat pump system. The model includes detailed characterizations of the compressor, heat exchangers, controls, solar collectors, and psychrometrics of the air internal to the building. A single node water storage tank is included, and the ground-coupled storage is simulated by a one-dimension six-node model. The one-dimensional ground model was checked against a very detailed multi-node two-dimensional model with good agreement. The computer model was checked out and an initial series of parametric simulation runs were completed for Denver, Boston, Minneapolis, and Miami. Sample results showing the relative performance of glazed and unglazed collectors in Denver are shown in Figure 2.

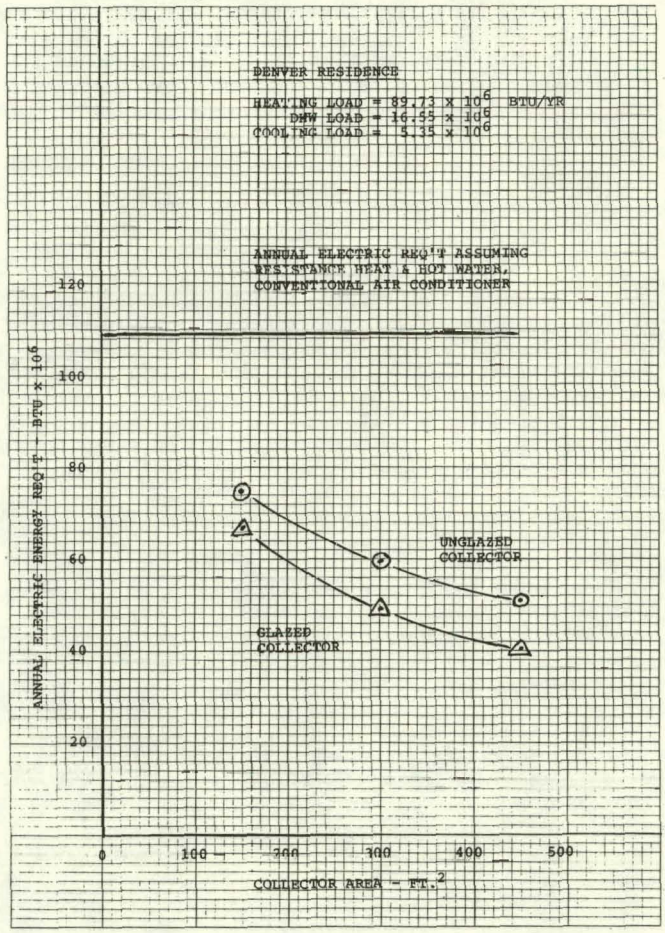


FIGURE 2. SYSTEM SCHEMATIC

- A survey was made of available data on night sky temperature and convection coefficients for large surfaces. These data are required for calculating the heat rejection capability of solar collector configurations. The survey revealed a lack of extensive sky temperature data in the presence of various cloud conditions, and indicated that available film coefficient correlations were based on test specimens with characteristic dimensions much smaller than those typical of flat plate solar collectors.[1] A simple experiment was conceived, consisting of heated plates of low and high emmissivity, to

measure effective night sky temperature and film coefficients for surfaces with dimensions typical of solar collectors.

A detailed design was completed for a test specimen and necessary instrumentation to measure effective night sky temperatures and convective film coefficients on large surfaces. Two identical test articles, suitable for "in situ" installation on the roof of a house, were fabricated and checked out.

FUTURE ACTIVITIES

Contract Activities. The remaining contract activities consist of completing the analytical system performance comparisons for the candidate solar collector/heat pump system configurations in the eight selected cities, and acquiring data from the sky temperature/convection coefficient test articles.

The solar assisted heat pump computer model will be modified to include a standard outdoor air coil so that the system can be run as a conventional air-to-air heat pump in both heating and cooling modes. This will provide a reference level of performance, achievable with commercially available hardware, against which the performance of the liquid-source heat pump, assisted by low cost collectors, can be measured. Through this approach, the end results of the analytical study should indicate which, if any, of the single-source solar-assisted heat pump configurations are competitive with conventional air-to-air units, and in which climatic areas.

The experimental part of the contract will consist of installing the two test articles on the roofs of two houses in the Denver area and recording data during periods of varying wind, temperatures and cloud cover conditions over a one-month period. The resulting data will be reduced and compared to determine if consistent correlations of night sky temperature and film coefficient can be obtained.

Post Contract Activities. At this point in the study, it does not appear than any of the candidate collector configurations provide a cost-effective heat source for a single-source heat pump in climate areas with significant heating demand. Potentially attractive system efficiencies have been achieved in an area with high cooling load (Miami), but at this time is is not clear if this is due to use of the unglazed collector in the rejection mode, or some other characteristic inherent in the system design. Additional analysis may be justified to optimize the system configuration if the high cooling efficiencies appear to be attainable and not due to some quirk in the analytical methodology.

If the experimental data produce consistent, highly correlated sky temperatures and film coefficients, consideration should be given to using the test articles to acquire data under different climatic conditions.

PUBLICATIONS/REPORTS/REFERENCES

1. E.M. Sparrow, "Journal of Heat Transfer", November 1977, Page 507.
2. Hittman Associates, "Residential Energy Consumption, Detailed Geographical/Analysis", Summary Report HIT-650-11, Contract H-2280R, May, 1977.

DEVELOPMENT OF COMPOUND PARABOLIC CONCENTRATORS FOR SOLAR HEATING AND COOLING APPLICATIONS

ARGONNE NATIONAL LABORATORY

W-31-109-ENG-38

K. A. REED

October 1, 1978 to September 30, 1979

OBJECTIVE

The objective of this project is the development and commercialization of improved collector systems for solar heating and cooling applications. The improvements sought include higher operating temperatures, increased thermal efficiency, lighter weight, and lower cost. The project builds on present day technology, identifying and developing those areas necessary for reaching the objective. The project combines basic collector and system design studies with fabrication and testing of engineering prototypes of the most promising designs. To promote early commercialization, intensive industrial interaction is encouraged in all phases of the project.

CONCEPT

Collector designs developed in this project are based on the principles of nonimaging optical concentration. By giving up the requirement that a concentrator form an image of the light source (i.e., the sun), one can gain a wide angular field of view. Unlike their focusing counterparts, for which finite-sized receivers are a compromise, nonimaging concentrators can be mated naturally to available flat and tubular absorbers. The most familiar class of nonimaging concentrators is known generically as the compound parabolic concentrator (CPC). Words such as "ideal" and "maximal" have been used to describe this class of mirror concentrators because theoretically its members can actually achieve the maximum concentration permited by fundamental physical principles for a given angular field of view.

A serious restriction of the CPC theory is the requirement that the mirror reflector touch the receiver at one or more points. The insulating gap between receiver and reflector that necessarily must be introduced, as well as the less than ideal properties of real materials frequently lead to mediocre collector performance. Argonne National Laboratory (ANL) has developed alternative nonimaging concentrators for tubular receivers, that give up some of the available angular field of view in order to obtain improved optical efficiencies in real collectors.

SUMMARY

Optical properties--reflectance and absorptance--have been determined for new candidate solar materials. The thermal loss as a function of absorber surface temperature has been measured and analyzed for four commercial and experimental evacuated tubular absorbers, and the effect of air leakage evaluated. The instantaneous thermal performance of three prototype concentrating collectors has been measured at temperatures up to 230°C. Two commercial CPC collectors are in the preliminary evaluation stage.

The computer ray trace program has been extended to include some non-CPC cases of nonimaging concentrators. It has successfully predicted the optical performance of a number of real collectors, has led to an understanding of anomolous effects, and has been used in numerous optimization studies. A new reflector design devised at ANL that allows a gap between reflector and absorber and that gives up some angular acceptance in order to avoid the attendant gap-loss has been refined using this program. In another study, the generation of process steam using CPC-collectors has been evaluated in terms of components needed and expected performance.

TECHNICAL ACCOMPLISHMENTS

Measurements of optical properties--reflectance and absorptance--continues as new candidate solar materials are obtained. The spectral measurements are taken as a function of angle of incidence, and then convolved with the solar spectrum of interest. The most striking finding is that the solar absorptance of the multilayer-on-glass coatings in commercial evacuated tubular receivers continues to be about 0.78 at normal incidence, in contrast to 0.9 or more for an electroplated black chrome-on-metal coating.

The thermal loss as a function of absorber surface temperature has been measured for two commercial evacuated tubular receivers (General Electric and Owens-Illinois) and two experimental evacuated receivers (Natural Energy and Corning). The commercial receivers had multilayer-on-glass absorber coatings, while the experimental receivers had electroplated black chrome-on-metal absorber coatings. The receiver loss data were analyzed in terms of an "effective" emittance calculated for the absorber's surface area. The emittances ranged from 0.05 to 0.20 depending on the coating (black chrome was higher), the temperature, and the given tube out of a batch. For the commercial receivers the effect of introducing known pressures of air into the vacuum space was also investigated.

The instantaneous thermal performance of three prototype collector modules has been measured at fluid inlet temperatures up to 230°C. Two of the collectors couple GE evacuated receivers to aluminum CPC-cusp reflectors: the geometrical concentration ratio of the ANL built collector is 1.5, and of the Chamberlain/GE built collector, 2.6. The third collector has a 5X CPC reflector coupled to experimental Corning evacuated receivers with a flat absorber strip inside a glass tube. The tests show that thermal losses can be successfully controlled with a good manifold material and evacuated receivers, but that the optical efficiency suffers from the gap-loss factor (typically, a 5-7% loss) and the low coating absorptance (typically, a 10-15% loss).

The computer ray-trace program has been refined and extended to include non-CPC cases of nonimaging concentrators. The program takes as input the parameters of real collectors, e.g., the physical dimensions of reflector, absorber, and gap, and the optical parameters such as transmittance, reflectance and absorptance, all as a function of angle of incidence, possibly. The program has successfully predicted the optical performance of a number of real collectors including their incidence angle modifiers. The program has led to an understanding of such "anomalies" as the enhanced optical efficiency that can arise from trapping of radiation reflected from the absorber. The program is now being used in design optimization studies.

A new nonimaging concentrating reflector design devised at ANL that allows a gap between reflector and absorber and that gives up some angular acceptance in order to avoid the attendant gap-loss has been refined using the computer ray-trace program. The CPC-cusp is replaced by a reflector that is "W" shape below the absorber tube and that curves smoothly up beyond. Compared to a CPC-cusp with the same reflector absorber gap, such a "gapless"-less concentrator can gain a 5-10% improvement in optical efficiency for light near normal incidence.

A system study which considers the generation of process steam using CPC-collectors has been completed recently. The study included consideration of the collector components, plumbing, and boiler required, and calculated steam generation rates for a particular layout.

FUTURE ACTIVITIES

Contract activities. The contract has been transferred to the Agricultural and Industrial Process Heat branch. Evaluation of the two commercial CPC-modules will be concluded as part of the activities for that branch.

Post-contract activities. The Solar Energy Group at ANL will continue to support manufacturers interested in commercializing collectors based on nonimaging optical concentration to ensure that designs are chosen which meet their needs and that refinements in the concentrator designs are correctly reduced to practice.

PUBLICATIONS/REPORTS

C. K. Hsieh, "Design of a System Using CPC Collectors to Collect Solar Energy and to Produce Industrial Process Steam," ANL Formal Report, ANL 79-102, available through NTIS.

W. R. McIntire, "Truncation of Nonimaging Cusp Concentrators," Solar Energy, Vol. 23, pp. 351-355, 1979.

W. R. McIntire, "Optimization of Stationary Nonimaging Reflectors for Tubular Evacuated Receivers Aligned North-South," Solar Energy, in press, 1980.

M. Collares-Pereira and A. Rabl, "Simple Procedure for Predicting Long-term Average Performance of Nonconcentrating and of Concentrating Solar Collectors," ANL Formal Report, ANL-78-67, available through NTIS.

K. A. Reed, "Application of Glass Technology to Novel Solar Collectors," Proceedings of the 23rd Symposium, American Society of Scientific Glass Blowers, 1979.

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

BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES

CONTRACT DE-AC04-79CS30171

D. K. LANDSTROM-PRINCIPAL INVESTIGATOR, S. G. TALBERT AND V. D. McGINNISS-TASK LEADERS

CONTRACT PERIOD OCTOBER 1979 to MAY 1981

OBJECTIVE

The primary objective of the Phase II program is to evaluate several candidate plastic materials and solar collector designs suitable for black liquid use, prior to specific development for commercial entry. Secondary objectives are:

- To obtain sufficient data to design a full-scale demonstration of the black liquid collector in a commercial application
- To team with a company willing to commercialize black liquid plastic collectors
- To recommend suitable plastics, coatings, 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.

BACKGROUND

The black liquid concept when applied to solar collector design offers some real potential advantages when compared to conventional collectors. The prime advantage is the projected low cost resulting from the essentially one-piece, extruded-type plastic construction, which eliminates much of the labor (soldering, welding, mechanical assembly, etc.) inherent in manufacturing conventional metal and glass collectors.

The theory behind the black liquid collector has been extensively covered elsewhere [1-3]. Basically, the concept involves direct absorption of the sunlight by a "black" fluid (absorbing across the entire solar spectrum) which replaces the conventional black metal absorber plate. Systems analyses have shown [3] that an all-plastic black liquid collector can be built to have an efficiency curve closely matching that for a conventional single-glazed, selective-surface collector. It is obvious that the plastic black liquid collector must be limited in temperature range, since the higher temperature stagnation region could cause excessive collector distortion, or even possible melting of some components. Use of a drain-back system that would activate when temperature limits are approached eliminates this problem, since the empty black liquid collector does not absorb appreciable solar energy and will remain cool. This feature also contributes to extended service life, since stagnation conditions leading to excessive deterioration will never be experienced.

Black liquid plastic collectors can be used effectively for swimming-pool heaters, domestic hot water, and space heating. Another major application is the combined use of the collector with a heat pump to supply supplemental energy and allow the heat pump to operate in a high coefficient of performance (COP) region. The series solar assisted heat pump system is a good candidate for use with the black liquid collector, since it can make good use of the lower temperature regions (where collector efficiency is high) and can be cost-effective when used with low-cost collectors. Operation in the low-temperature region means that many of the expensive solutions to reducing heat losses at higher temperatures can be minimized or eliminated.

Proper heat pump utilization of the black liquid collector (or any other low-cost collector) requires development of a high COP heat pump component capable of utilizing the higher temperatures available from the collectors as a source temperature. The U.S. Department of Energy (DOE) is presently sponsoring development of such heat pumps [4] and the coupling of the low-cost collector with the improved heat pump in a series system is a viable option for a cost-effective solar energy system.

The low-temperature, black liquid collector has two other features which should be mentioned: (1) collector will have high efficiency at the time of year when high efficiency is most needed for heat pumps, i.e., the winter months, since it will be operating with a small temperature difference between storage and ambient; (2) the black liquid collector can also produce temperatures in the summer which are suitable for heating domestic hot water (110-140 F), and the potential exists to produce higher temperatures with suitable choice of high-temperature plastics. These features are not unique to the black liquid collector; however, system cost would be considerably lower with the black liquid collector then that for conventional collectors designed to do the same job.

In the course of the previous work on black liquid systems, Battelle became aware of independent work being done by Ramada Energy Systems (Tempe, Arizona) on the development of a transparent collector system utilizing polycarbonate extruded panels and capable of being used as a black-liquid system. Subsequently, Battelle has worked closely with Ramada while they have been developing the manufacturing capability to produce quantities of extruded plastic collectors sufficient for experiment, evaluation, and eventual major market entry.

SUMMARY

Battelle's Columbus Laboratories has developed an efficient, low-temperature, low-cost, nonconcentrating black liquid solar collector and has demonstrated the feasibility of using this collector for a variety of solar applications [1-3].

The current program is designed to provide additional information about the long-term properties of plastic black liquid collectors through exposure/operation of collectors under varying experimental conditions and environments. In addition, other suitable plastic materials and collector designs are being tested with extensive investigation into proper test and exposure/evaluation procedures suitable for plastic materials when used in solar collectors.

Two automated test stands have been completed; one for use at Columbus, Ohio, the other in Phoenix, Arizona. Suitable samples of plastic materials have been incorporated into testing programs involving real-time outdoor exposure as well as accelerated testing to determine suitability for use in black liquid collectors. Battelle is working closely with Ramada Energy Systems to assist in developing plastic solar collectors which can be commercially marketed within a short time frame.

TECHNICAL ACCOMPLISHMENTS

- Introduction. To date, the major accomplishment of this program has been the design, constuction, and testing of two prototype black liquid solar collectors. These collectors fulfilled all design criteria and performed positively as predicted during field and laboratory tests [3].

It has also been determined that the black liquid collector has several potential advantages over the conventional flat-plate collectors for specific applications. Prime along these advantages is the low-cost, one-piece, extruded type construction which reduces much of the labor, materials, fabrication, and installation costs inherent in a conventional collector. Costs and weight are greatly reduced by employing suitable plastic materials instead of metal and glass components. Some of the demonstrated interdependent advantages are:

- No stagnation problems (collector will not collect appreciable energy when drained)
- All-plastic construction is possible
- No corrosion problems are encountered
- Drainback operation is possible
- Freezing problems are eliminated
- Extruded construction allows low-cost mass production
- Site assembly possible
- Lightweight, easily shipped
- Can be manufactured in many configurations (glazed, unglazed, temperature limiting, etc.) tailored to individual application
- Performance meeting or exceeding that of conventional collectors in the lower temperature range
- Potential for cost-effective use in solar-assisted series heat pump systems
- Applications to service water heating, direct space heating, industrial water heating, and possible agricultural uses
- Suitable for "do-it-yourself" construction and installation
- Repair and replacement easier than for conventional collectors
- Long life (15-20 years) appears possible with present data
- Distribution possible through building trades industry.

One important result of this program has been the realization that there is only limited information available about long-term materials problems certain to be associated with plastic materials in solar applications. Polymeric materials can exhibit long life under solar exposure. Conditions existing or required for use as 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. The present Phase II program is designed to investigate and answer some of the materials problems associated with black liquid collectors as well as the use of transparent polymeric materials in other types of collectors.

• Outdoor Solar Collector Test Facilities. Figure 1 is a photograph of an outdoor solar collector test facility in Columbus, Ohio. An identical unit will be used in Phoenix, Arizona by Ramada Energy Systems to cycle test their polycarbonate collector. These environments were chosen to provide two extremes for collector testing. Columbus provides a relatively cloudy environment, and freeze-thaw conditions, while Phoenix has a maximum of solar insolation and high ambient temperatures.

Figure 2 is a schematic flow diagram of the outdoor solar collector test facility as presently designed. This arrangement allows four modes of operation for evaluating various black liquids and solar collectors. The modes are briefly described as follows:

• Mode 1—a typical "daily temperature cycle" representative of a domestic solar water heater. Early in the morning, a timer activates the various valves and the pump to precool all of the liquid and components to city water temperature. When temperature sensors located under the collector and inside of the storage tank indicate that useful solar energy can be collected, the controller fills the collector and circulates the black liquid. Through proper selection of the liquid quantities, the collector temperature will increase to a maximum temperature each day, dependent on the availability of solar energy and ambient weather conditions. The integrating Btu/flow meter continuously records the total amounts of useful energy collected and the quantity of liquid circulated.

• Mode 2—a "constant low temperature" operation representative of swimming pool heating or a series heat pump application. Here, the temperature of the circulating liquid is maintained at a relatively low temperature all day by means of a temperature/flow control valve that modulates the flow of city water through the storage tank, thus simulating a heat load.

• Mode 3—a "constant high temperature" operation representative of process heating or air conditioning applications. This mode is achieved by a three-way temperature control valve which bypasses enough of the black liquid to the pump to maintain a relatively high collector inlet temperature. This mode might also be used to produce accelerated collector durability testing.

• Mode 4—a "stagnation temperature" operation, achieved by setting the 3-way proportioning valve at a temperature high enough to prevent fluid from being diverted through the heat exchanger in the storage tank. In this mode, the collector would reach a maximum temperature level each day, depending on ambient conditions. Mode 4 would create one of the most severe tests for plastic collectors. The temperature limits for certain plastics may prevent this mode of operation.

Figure 3 is a cross-section diagram of the Battelle acrylic black liquid collector constructed from an extruded Acrylite SDP™ acrylic sheet available from CY/RO Industries and equipped with an additional acrylic cover plate to reduce heat losses. The use of these commercially available components does not constitute endorsement, since the long-term liquid exposure effects on these materials have not been determined. It is likely that a protective coating will have to be applied to the liquid-wetted surfaces to minimize stress cracking and provide long life.

Figure 4 is a cross section of the Ramada extruded polycarbonate collector which can be used as a black liquid collector by passing the liquid through one or both of the bottom channels, or as a black-backed collector by providing a black backing to the plastic and passing clear water through the channels.

Figure 5 shows an exploded view of the prototype Ramada Collector, similar to the units to be tested in the solar collector test facility at Ramada's Phoenix, Arizona location. Battelle is planning long-term tests on a promising carbon-suspension black liquid developed by Sperry-Univac under a DOE contract [5]. This liquid will be used in both acrylic and polycarbonate collectors.

• Literature Review. Available information on materials/processing/collector performance obtained from the literature has been reviewed and evaluated. This included information that was generated by Battelle and Ramada for acrylic and polycarbonate collectors as well as other potential plastic materials. Throughout, major emphasis was placed on defining systems modifications/treatments to optimize long-term performance and on identifying information that could be utilized in applying the appropriate and effective aging tests for use in projecting service life of black liquid/transparent plastic collectors. This information is being prepared for publication. Specific items reviewed include:

- In-house and Ramada information
- Materials Properties
- Life-time evaluations
- Polymer degradation
- Bonding and adhesives
- Stress cracking
- Hydrolysis/hydration
- Pressure effects
- Staining
- Chemical reactions
- UV protection
- Black liquid exposure
- Accelerated versus real-time aging
- Failure analysis
- Temperature effects.

• Degradation and Solar Collector Performance. The loss of specific functions (efficiency, transmission, reflection, etc.) occurring up to any time during the lifetime of a plastic solar collector will provide a measure of any significant materials degradation that has taken place. This degradation may have occurred in one or a combination of the materials of construction for the collector, i.e., the polymerics, seals, or the black liquid itself. It may be due to materials processing and/or collector fabrication per se; and/or to exposure to the environment where ultraviolet, temperature, humidity (directly) and mechanical stress (indirectly) and their combinations may be causative. Other factors also may influence degradation, but these certainly are among the primary ones. Thus, it can be seen that collector degradation will be dependent on the individual and combined effects of (1) collector design, (2) materials of construction, (3) processing/fabrication methods, and (4) the environment(s) to which the array is exposed.

Solar collector design, independent of its effects on materials selection and processing/fabrication requirements, will influence the rate and extent of degradation in a number of ways. The access route of foreign penetrant gases and liquids will be dictated by the design features employed in the construction of the collector, by the thickness of the cover materials, by the method used in attaching the plumbing fixtures to the collector, etc. Also, design will determine the locations and magnitudes of stress localizations produced by high-wind loads, by temperature and humidity cycling, methods of hold-down, etc. Here again, design features such as component thicknesses, structural reinforcement, etc., will be critical to effective collector performance over the long term.

Another important factor in controlling collector performance is that of materials selection. Major requirements associated with mate-

rials selection, in addition to cost considerations, are optical and mechanical properties and the stability of these properties when exposed to hostile weathering environments for a prolonged time.

A third important factor determining system performance is collector fabrication coupled with the attendant problems of materials processing. If collector failure rate, in terms of some specified degradation level, is plotted against time, a trough-like curve generally results. It is characterized by a high initial failure rate, owing primarily to failures associated with processing/fabrication inadequacies, followed by a long period of stability with few failures, and finally by a return to high rates of failure when the collector begins to "wear out"

The failures associated with processing/fabrication, i.e., those occurring predominantly at an early stage in the exposure period, are likely to be primarily mechanical and chemical types and take the form of delaminations or leaks (ineffective bonding of one collector component to another), gas/liquid entrapment (associated with continued reactions of components or with residual volatiles in the polymeric components), etc. Minimization of such events, of course, will require implementing stringent quality-control procedures on incoming collector polymeric components and on fabrication procedures.

Finally, there is the environmental exposure factor. In the extreme, collector degradation can be essentially stopped if the collector is maintained in the dark at constant, moderate temperature and humidity. However, any solar collector must be exposed to the extreme sunlight with the accompanying environmental factors of heat, ultraviolet, moisture, wind, and air pollutants. With such exposure, various chemical reactions occur and continue to occur within the different materials that make up the collector, even though at times the rates of these reactions are infinitesimal. The combined effects of these reactions constitute the process of degradation.

• Application of Diagnostics to Solar Collector Materials Candidates. The effective utilization of diagnostic tools for measuring materials degradation early in the process(es) requires identifying most probable modes of degradation of candidate materials of construction of the solar collector exposed to specific types of environments. Such identification can be invaluable in reducing the number of materials properties at the molecular/morphological/macroscopic levels that require monitoring. This, in turn, also reduces diagnostic tool requirements.

Degradative-mode identification can best be illustrated using typical polymerics as an example, since these are the most degradation-sensitive class of materials used in solar collector construction. Comparison of acrylic (polymethyl-methacrylate-PMMA) and polycarbonate (PC) suggest that both will require protection from abrasion and chemical attack in order to function as solar collectors for long periods. This probably can best be accomplished through the use of a protective coating on the sheet applied when the solar collector is manufactured.

Further study of property comparison indicates that UV resistance will be a major bulk material weakness with PC, whereas with PMMA impact will probably be of major concern. With both of these materials, interfacial failures due to moisture penetration or to problems of bondability will be a problem. Moisture is likely to affect PMMA more, while bondability is more serious with polycarbonate.

Thus, from the standpoint of polymer diagnostics, optical property monitoring will be a key measurement of UV degradation for PC or from seal rupture that might result with both plastics from temperature cycling coupled with moisture penetration and/or poor initial adhesion. Obviously, then, with any system, a number of degradative events will be occurring simultaneously and, for service-life prediction, those that are precursors of system failure must be identified and the degradative action quantized.

• Materials-Aging Studies. Polymeric materials are being selected for acceleration/real-time aging studies for use in subsequent collector performance/durability evaluations. This includes:

- Adapting tests to determine failure modes of collectors
- Implementation of appropriate short- and long-term aging test procedures
- Statistical analysis of aging test data (stress levels, sample replication, etc.)
- Long-term exposure studies of selected materials
- Measurement of key properties as functions of aging conditions.

Typical accelerating environments to be used include ultraviolet exposures, isothermal aging, thermal cycling, high humidity exposures, and exposure to atmospheric contaminants. These environments could be tested independently or in various combinations, using a variety of materials. Other considerations would be static high-pressure/high-temperature environments to accelerate stress cracking and other reactions of the liquid with the interior walls of th collector. The testing program is designed around the Battelle facilities in Columbus, Ohio, and Daytona Beach, Florida, as well as Ramada Inns' facilities in Phoenix and Los Angeles.

Another concern is obtaining and projecting the relevant property measurements required to determine changes and degradation in the plastic materials. Both molecular scale and macro-scale measurements of environmental exposure conditions will be considered.

• Exposure Testing Methodology. Predicting service life for materials under multiple stress conditions is difficult in that many published weathering studies have not been done under carefully controlled conditions. The types and sizes of samples varied greatly between different experiments so that extrapolation from one set of test conditions to another has very little quantitative accuracy.

The term "weatherability", although commonly used in plastics technology, is a poorly defined concept, since it refers to long-term service under complex and variable conditions and because different properties of a plastic are affected to different degrees by a given environment. Improvement in the ability to predict weatherability therefore requires careful redefinition of the problem as well as a refinement of experimental technique. A review of the extensive literature on outdoor and artificial exposure of plastics shows that no simple correlation exists between these two modes of testing. Further, because the rates and mechanism of deterioration are different when produced by visible light, ultraviolet, heat, or moisture, an arbitrary "accelerated" weathering test will distort the balance of responses observed in the slower outdoor exposure of plastics.

In an ideal procedure, the effects of specific weathering parameters are established for specific properties of a given material using controlled artificial environments; the makeup of the weather at a given outdoor location is analyzed in terms of these parameters; and finally, by suitable mathematical models, the results to be expected on exposure of the material to this given composition of weather can be computed. While this approach is admittedly complex, its feasibility has been demonstrated. For routine studies where the mathematical approach may be impractical, it appears necessary to abandon the goal of a "universal" artificial weathering test unless only qualitative or screening comparisons are desired. Quantitative predictions, using present testing technology, will be most reliable if restricted to a comparison of materials that are fairly similar in composition.

FUTURE ACTIVITIES

• Contract Activities. A long-term program on actual black liquid collectors as well as selected black liquids and plastic components is planned to allow a full year of outdoor testing at Columbus, Ohio, and Phoenix, Arizona. In addition, accelerated testing is planned over a similar period, and an attempt will be made to correlate real-time and accelerated data. All this information will be used to further commercialization of black liquid collectors.

• Postcontract Activities. This contract is scheduled to be completed in May 1981. At that time it is expected that enough information will be available to design and build demonstration facilities utilizing black liquid collectors in heat pump, hot water, and space heating applications.

PUBLICATIONS/REPORTS/REFERENCES

[1] 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.*

[2] D. K. Landstrom, S. G. Talbert, and G. H. Stickford, Jr., "Development of a Low-Temperature, Low-Cost, Black-Liquid Solar Collector 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, September 24,27, 1978, Washington, DC.*

[3] 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.*

[4] Andrews, J. W., Kush, E. A., and Metz, P. D., "A Solar-Assisted Heat Pump System for Cost-Effective Space Heating and Cooling", Brookhaven National Laboratories, BNL 50819, U.S. Department of Energy Contract EY-76-C-02-0016, March , 1978.

[5] Jensen, S. O., Sperry-Univac, St. Paul, Minnesota, DOE Contract No. EG-78-C-04-5335.

*Publications/reports resulting from this study.

ACKNOWLEDGEMENT

This work is supported by the Solar Heating and Cooling Research and Development Branch, Conservation and Solar Applications, U.S. Department of Energy, under Contract No. DE-AC04-79CS30171. The assistance and contributions of Ramada Energy Systems and the following individuals are greatfully acknowledged: G. H. Stickford, R. E. Hess, J. A. Eibling, J. Evans, R. McAlister, R. Liden, and J. Krall.



Figure 1. Outdoor Solar Collector Test Facility

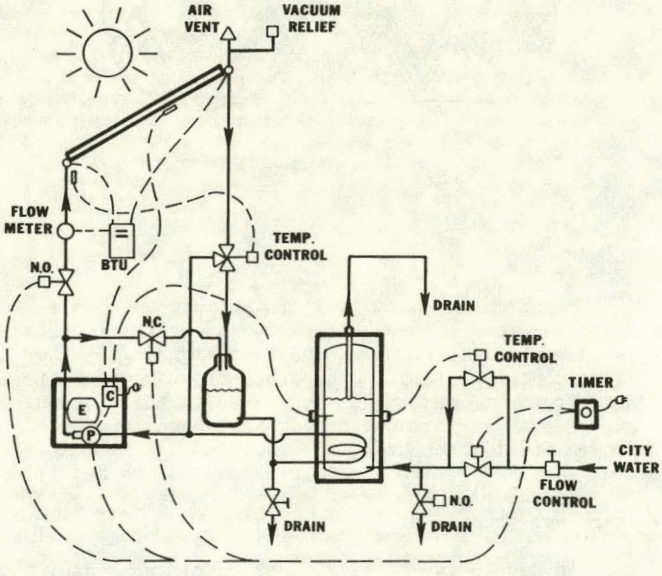


Figure 2. Schematic of Outdoor Solar Collector Test Facility

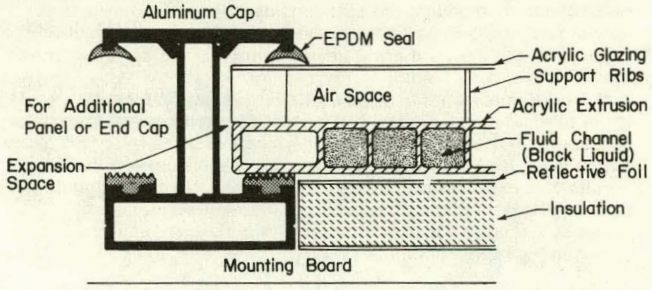


Figure 3. Battelle Acrylic Black Liquid Solar Collector Schematic

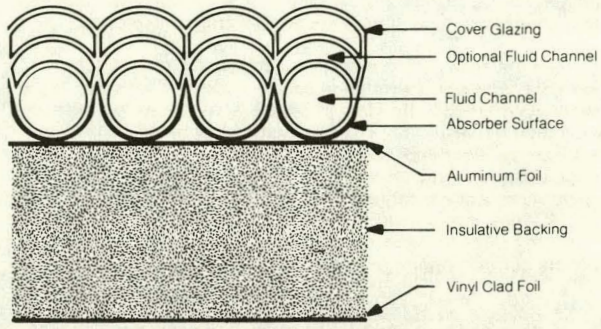
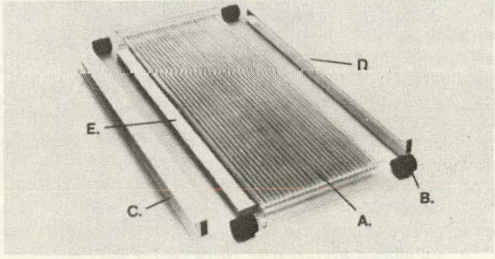


Figure 4. Ramada Polycarbonate Solar Collector Details



Exploded View of Collector Package

A. Polymer collector - transparent, UV protected extruded polycarbonate.
B. Collector connector - EPDM injection molded coupler specifically designed to allow for differential expansion and potential field misalignment.
C. Installation "H" rail - structural member for joining collectors.
D. Installation "C" rail - similar to the "H" rail, but only used along the outside edges of an array.
E. Insulation package - isocyanurate foam backing that has a tough 5 mil vinyl and aluminum covering.

Figure 5. Prototype Ramada Collector

TRANSPIRED SOLAR AIR HEATERS

UNIVERSITY OF CALIFORNIA, LOS ANGELES
SCHOOL OF ENGINEERING AND APPLIED SCIENCE
GRANT NO. DE-FG04-77C534088

H. BUCHBERG AND D. K. EDWARDS

PERIOD OF GRANT: 10/30/77 to 3/30/80

OBJECTIVE

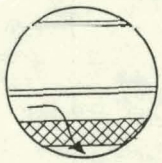
The objective of this investigation is to establish and prove the technical merit of two transpired solar air heater types: honeycomb, porous-bed absorber configurations and slotted flat and vee-corrugated selective black plate absorber configurations and to validate the performance of a full-scale experimental air heater representing the best concept of those studied.

CONCEPT OR BACKGROUND

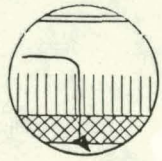
To achieve a high performance solar air heater two design problems need to be addressed: the heat exchanger design to minimize the temperature difference between the absorber and the hot air delivered and the top cover design to minimize the heat loss and thus maximize the useful energy collected. Accordingly this investigation focuses on the absorber-heat exchanger design and on cover systems in combination with selective black and nonselective black absorbers. All design concepts for solar air heaters are subject to the constraint of holding fan power consumption to an acceptable level.

The black porous-bed absorber provides a high transfer area per unit of volume for effective heat transfer to air. In combination with various honeycomb structures and glazings, as shown below, the porous-bed solar air heater has the potential for high performance by providing an extended heat exchange surface and by minimizing the net conduction-convection-radiation heat transfer from the solar absorber to the top coverglass.

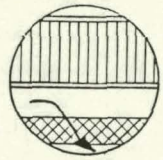
Reference Double Glazed Porous Bed



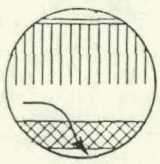
Single Glazed Transpired Glass Honeycomb



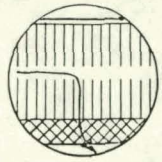
Double Glazed Honeycomb (Plastic & Glass)



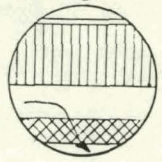
Single Glazed Honeycomb (Plastic & Glass)



Single Glazed Glass Plate Double Honeycomb

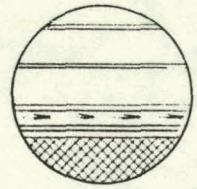


Double Glazed Glass Tube Honeycomb (Teflon Inner Glazing)

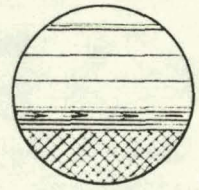


The performance of flat plate and vee-corrugated absorbers for solar air heaters, which have considerable promise for low manufacturing cost and high durability, can be improved by the use of a selective black absorbing surface to reduce re-radiation losses and by transpiring air through appropriately placed slots in the absorber plate. Various experimental flat and corrugated plate absorbers in combination with different cover systems are shown below:

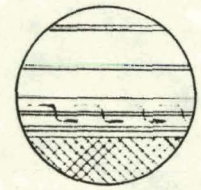
Reference Double Glazed Selective Black Flat Plate



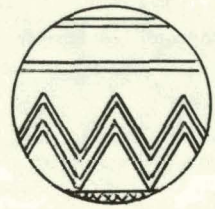
Triple Glazed (2 Teflon Inner Glazings) Thin Single Channel



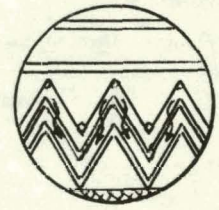
Triple Glazed Transpired Flat Plate, Teflon Inner Glazing



Double Glazed Corrugated Plate



Triple Glazed Transpired Corrugated Plate



(These two sections perpendicular to flow)

SUMMARY

Experimental 2 ft by 2 ft aperture solar air heaters were designed, assembled and tested in accordance with proposed NBS TN899 test standards. The experimental heaters included selective black plate and porous bed designs as described in the previous paragraph. Performance models have been formulated, programmed for computing and verified against experimental data. Design sensitivity studies to determine the influence of pertinent design and operating parameters were complted.

In developing a theoretical model to predict the performance of transpired solar air heaters it is

necessary to determine the rate of heat transfer from the working fluid to channel walls comprising a continuously or intermittently-porous plate (the absorber) and a rigid backup plate. It is advantageous to design the channel to achieve laminar flow. This two-dimensional flow and heat transfer problem was formulated in finite difference form and programmed, and numerical solutions were obtained.

TECHNICAL ACCOMPLISHMENTS

- The following porous bed (PB) and selective black (SB) experimental solar air heaters have been designed, assembled, and tested:

PB-I	Reference Double-Glazed Transpired Air Heater
PB-II	Double-Glazed Hexagonal Mylar Honeycomb Transpired Air Heater
PB-III	Double-Glazed Hexagonal Polycarbonate Honeycomb Transpired Air Heater
PB-IV	Single-Glazed Hexagonal Polycarbonate Honeycomb Transpired Air Heater
PB-V	Single Glazed Parallel-Plate Glass Honeycomb Transpired Air Heater
PB-VI	Double-Glazed Parallel-Plate Glass Honeycomb Transpired Air Heater
PB-VII	Single-Glazed Transpired Parallel-Plate Glass Honeycomb Air Heater
PB-VIII	Single-Glazed Transpired Double Parallel-Plate Glass Honeycomb Air Heater
PB-IX	Double-Glazed (Glass and Teflon) Tubular Glass Honeycomb Transpired Air Heater
SB-I	Reference Double-Glazed Air Heater
SB-IA	Optimized Spacing Double-Teflon-Single-Glass Glazed Air Heater
SB-IIA	Double-Glazed Transpired Slot Air Heater
SB-IIB	Double-Glazed-Transpired Micro-Perforated Flat Plate Air Heater
SB-III	Double-Glazed Corrugated Flat Plate Air Heater
SB-VI	Double-Glazed, Transpired, Slotted Corrugated Flat Plate Air Heater

The test results are shown as "best fit" performance curves in Figs. 1 and 2 where collector efficiency is plotted against the operating parameter Z, the ratio of average fluid temperature above ambient air temperature to the incident solar power.

- Performance models for air heater configurations PB-I, PB-IX, SB-I, SB-IA and SB-III have been formulated, programmed for computing and verified against experimental data.

- The hydrodynamic and thermal problem of two dimensional laminar entrance flow between a rigid and a continuously or intermittently porous plate has been coded for computer solution, and useful solutions have been obtained pertinent to the porous-bed and slotted plate air heaters.

FUTURE ACTIVITIES

A full-scale solar air heater incorporating the best features demonstrated during the course of the program will be designed, assembled and tested. The design decisions will be based on ease and cost of manufacture as well as the demonstrated technical merit of the features incorporated.

PUBLICATIONS

Several progress reports have been delivered to the Department of Energy, Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications as follows:

1. H. Buchberg and D. K. Edwards, "Transpired Solar Air Heaters", Technical Progress Report No. 1 covering the period November 1, 1977 to September 1, 1978, 4 pp, September 1978.
2. H. Buchberg and D. K. Edwards, "Transpired Solar Air Heaters", Technical Progress Report No. 2 covering the period September 1, 1978 to March 31, 1979, 73 pp, April 1979.
3. H. Buchberg and D. K. Edwards, "Transpired Solar Air Heaters", Technical Progress Report No. 3 covering the period April 1, 1979 to July 30, 1979, 37 pp, July 1979.
4. H. Buchberg and D. K. Edwards, "Transpired Solar Air Heaters", Technical Progress Report No. 4 covering the period August 1, 1979 to October 31, 1979, 36 pp, November 1979.

Copies of the progress reports can be made available at cost. An additional progress report, the final report, and open literature publications are pending.

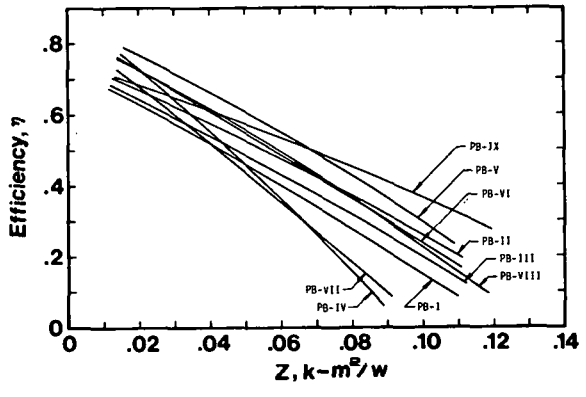


Fig. 1 Experimental "Best Fit" Performance Curves for Porous-Bed Solar Air Heaters

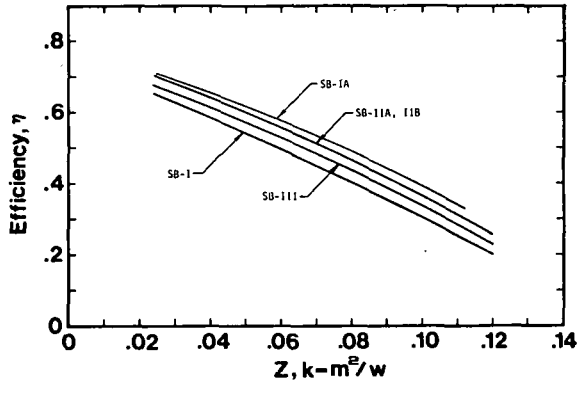


Fig. 2 Experimental "Best Fit" Performance Curves for Selective Black Flat Plate Solar Air Heaters With and Without Transpiration

STUDY OF ALUMINUM CORROSION IN ALUMINUM SOLAR HEAT COLLECTORS USING AQUEOUS GLYCOL FOR HEAT TRANSFER

GINER, INC.

DE-AC04-79CS31072

DAVID WONG, Ph.D.

JULY 30, 1979 - JULY 29, 1980

OBJECTIVES

The main objective of this program is to determine means whereby light gauge aluminum solar heat collector panels operating on aqueous glycol heat transfer fluids can be safely used over long periods of time without suffering from significant corrosion problems. The intermediate objectives are: (1) to investigate the characteristic changes of glycol solutions due to aging at elevated temperatures, (2) to determine the corrosiveness of these aged glycol solutions to aluminum, (3) to measure the critical pitting potential of aluminum in aqueous glycol media, and (4) to prepare a corrosion control manual.

BACKGROUND

Light gauge aluminum solar heat collector panels using aqueous ethylene or propylene glycol solutions for heat transfer appear to have considerable advantages vis-á-vis other presently available collector material and heat transfer medium combinations. These advantages include low cost, low density, high thermal conductivity and ease of fabrication of aluminum alloys, as well as low cost, ready availability, reasonably high heat capacity and combined antifreezing/antiboiling properties of aqueous glycol solutions. However, such a combination is presently hampered by the critical problem of aluminum corrosion.

Aluminum and its alloys are electrochemically active, capable of displacing hydrogen from water. In spite of this fact, aluminum is considered corrosion resistant in many aqueous environments where its protective oxide layer remains undisturbed. If this oxide film is disrupted and its healing prevented, very severe corrosion problems may result. Localized pitting corrosion is of particular concern since it has been identified as the major cause for corrosion perforation in many light gauge aluminum structures including solar heat collector panels.

In our previous work, under Contract No. EY-76-C-2-2934 (first with ERDA, later DOE), specific techniques were developed to obtain baseline aluminum corrosion data under conditions relevant to the operation of real solar heat collector systems. Once the extent of this corrosion problem had been quantitatively determined, the efforts were then directed to the development and evaluation of various corrosion control methods including the use of corrosion inhibitors and scavengers.

The present program deals specifically with the aging effects of glycol solutions since most of the major findings were based on data obtained from relatively short-term laboratory corrosion tests lasting for a two week period. The composition of glycol solution may change as a result of prolonged exposure to high temperatures. Thermal decomposition of the glycols, as well as breakdown of the inhibitors may take place as the aging process progresses. New product species aggressive to aluminum and its alloys may be produced.

Another area of research in this program is the determination of critical pitting potential of aluminum in aqueous glycol solutions containing chloride ions. This information is important to any type of corrosion protection methods used to prevent aluminum from pitting corrosion.

SUMMARY

Summary of Previous Work (Under Contract No. EY-76-C-2-2934; June 1, 1976-July 31, 1978).

The corrosion characteristics of four selected aluminum compositions (i.e. 99.9% Al, 1100, 3003 and 3004 series alloys) in a 35 vol % ethylene glycol and a 50 vol % propylene glycol solution have been obtained experimentally under a range of conditions relevant to the operation of a real solar collector system (A1-A4, B1). All aluminum compositions tested showed at least marginal corrosion resistance in *pure* glycol solutions to all types of corrosion including pitting. However, the presence of common impurities existing in any real system (such as Cl^-, Cu^{+2} and Fe^{+3} ions) significantly lowered this corrosion resistance to an intolerable level. Without the use of any corrosion control methods, an actual aluminum solar heat collector system is expected to suffer from corrosion perforation (most probably due to pitting) within days or even hours of operation.

Corrosion inhibitors similar to the ones found in commercial automotive coolants (consisting of nitrates, silicates, borates, phosphates and sodium MBT) are effective in stopping aluminum corrosion at temperatures below 100°C (A5-A7). For higher temperatures up to 160°C, we found that addition of 2 wt % zinc powder to this inhibited glycol solution provides corrosion protection. Zinc powder acts not only as scavengers for heavy metal ions, but also as a floating sacrificial anode which is capable of stopping aluminum from pitting corrosion even in a chloride ion containing aqueous glycol solution. This protection is achieved through the contact of zinc powder and aluminum which effectively lowers the open circuit potential of aluminum to below its critical pitting potential (B2) in that particular medium.

Summary of Present Work. Both inhibited and uninhibited ethylene glycol solutions are aged at 100, 140 and 190°C. Similar experiments are underway for propylene glycol based solutions at 100, 140 and 170°C. Aliquot samples are taken after every 1000 hours of exposure. Gas chromatographic analysis and pH measurement are performed to determine any characteristic changes in the composition of these glycol

solutions resulting from aging at elevated temperatures. All glycol solutions tested have been subjected to high temperatures for over 2000 hours to date. Results (A8) obtained so far showed that the values of solution pH decrease steadily (solution becomes more acidic) as aging process progresses, indicative of chemical composition changes. However, gas chromatographic analysis failed to reveal the presence of any new product species so far.

Critical pitting potential of 1100 series aluminum was determined using a step-by-step potentiostatic method (A8) in a 50 vol % ethylene glycol solution containing NaCl ranging from 10^{-4} to 1M at 25, 50, 70 and 100°C. The critical pitting potential was found to become more negative as the chloride ion concentration increases. For a fixed chloride ion concentration, it becomes more negative as the temperature of the solution rises. A plot of this critical pitting potential versus $[Cl^-]$ always yields a straight line at all four temperatures studied in this program

TECHNICAL ACCOMPLISHMENTS

Previous Work

- Development of laboratory techniques to measure aluminum corrosion in aqueous glycol environments, including linear polarization resistance method, thin foil method, circulation panel technique, etc.
- Development and verification of methodology to project pitting penetration depth in life size aluminum structures based on pit depth measured on laboratory corrosion coupons.
- Determination of the extent of corrosion problems expected in aluminum solar heat collector systems based on laboratory corrosion tests.
- Development and evaluation of effective corrosion inhibitor formulations to be used in aluminum solar collectors operating on aqueous glycol solutions at temperatures below 100°C.
- Discovery of a cathodic protection mechanism rendered by zinc powder in suspension to protect aluminum from pitting in aqueous glycol solutions containing chloride ions.
- Demonstration of the effectiveness of the combination of conventional corrosion inhibitors and zinc powder in totally stopping aluminum corrosion at temperatures up to 160°C.

Present Work

- Development of methodology to study the effects of glycol aging at elevated temperatures; including the thermal decomposition of glycol and the breakdown of inhibitors.
- Determination of critical pitting potential of aluminum in aqueous glycol solutions as functions of both chloride ion concentration and temperature.

FUTURE ACTIVITIES

Contract Activities. The aging effects of glycol solution are still in progress. More aged glycol samples are expected to be taken at 3000, 4000, 5000 and 6000 hours of exposure periods for chemical analysis and pH measurement. The corrosiveness of these aged glycol solutions will also be determined experimentally.

A corrosion control manual will be prepared and made available to solar heat collector builders and operators. This manual will describe procedures and methods developed in this program for minimizing corrosion damage in aluminum solar heat collector systems, including quantitative formulas for inhibiting agents, type and concentration of glycol to be used and a description of the design and principles of several implantable corrosion monitoring devices.

The discovery that zinc powder in suspension is capable of preventing aluminum from pitting in aqueous glycol solutions containing chloride ions has generated a great deal of interest and hopes that corrosion problems normally encountered in aluminum solar heat collector panels may be completely eliminated using this cathodic protection method. However, further development work in this area aiming at the optimization of such an approach must be carried out before any practical recommendations can be made.

REPORTS

A1. J. Giner, L. Swette and D. Wong, Quarterly Progress Report (COO-2934-1) for period June 1, 1976 - August 31, 1976.

A2. J. Giner, L. Swette and D. Wong, Quarterly Progress Report (COO-2934-2) for period September 1, 1976 - November 30, 1976.

A3. J. Giner, F. Cocks and D. Wong, Quarterly Progress Report (COO-2934-3) for period December 1, 1976 - February 28, 1977.

A4. J. Giner, F. Cocks and D. Wong, Annual Progress Report (COO-2934-4) for period June 1, 1976 - May 31, 1977.

A5. D. Wong, F. Cocks and J. Giner, Quarterly Progress Report (COO-2934-5) for period June 1, 1977 - August 31, 1977.

A6. D. Wong, F. Cocks and J. Giner, Progress Report (COO-2934-6) for period September 1, 1977 - March 31, 1978.

A7. D. Wong, F. Cocks, J. Giner and P. Majahad, Annual Progress Report (COO-2934-7) for period June 1, 1977 - July 31, 1978.

A8. D. Wong, F. H. Cocks and J. Giner, Semi Annual Technical Progress Report for period July 30, 1979 - January 31, 1980 (Contract No. DE-AC04-79CS31072).

PUBLICATIONS

B1. D. Wong, L. Swette and F. H. Cocks, J. Electrochem. Soc., 126, 11 (1979).

B2. D. Wong and F. H. Cocks, Corrosion, submitted for publication (1980).

SOLAR COLLECTOR STUDIES FOR SOLAR HEATING AND COOLING APPLICATIONS

InterTechnology/Solar Corporation

EM-78-C-04-5349

P. Nelson Brittle, Raju Yenamandra

1 August 1978 - 31 November 1979

OBJECTIVES

The objective of this study was to provide a survey of mirror and lens solar concentrator collectors suitable for space heating, cooling, and hot water applications. The survey, which continued through November 1979, has served two main purposes:

1) To provide DOE with detailed comparative design performance and delivered energy cost data which can be directly utilized in their R&D planning.
2) To provide the user community with this information presented in an understandable format so that the relative merits of each collector can be evaluated.

BACKGROUND

The scope of the survey included identification, analysis and comparison for all concentrating collector types for which prototypes and/or market models are or have been built for less than 10X concentration. The survey included greater than 10X concentration ratios for manufacturers marketing such collectors for space heating and/or cooling applications. To make the survey as complete as possible, collectors in the conceptual stage have been noted and their attributes and disadvantages identified.

Major topics discussed include energy collection, tracking, and comparative analysis among different collector types for various locations and heating load types.

ITC/Solar includes among its credentials preprogrammed analysis routines for the major concentrator types, survey experience, and experience in solar energy and systems analysis ranging from industrial process heat, residential, commercial and institutional case studies to HVAC, energy conservation, and solar total energy systems design.

SUMMARY

The overall project may be broken down into four tasks:

Literature Review. ITC/Solar conducted a thorough review of relevant literature and contacted known manufacturers and laboratories in order to provide a complete data base for the research effort.

Collector Performance Data Development. ITC/Solar performed system performance studies using solar heating, cooling, and hot water computer performance programs developed at ITC/ Solar.

a) Heating and cooling load tables were developed for three typical heating loads (standard insulated residence, office building, department store) to provide a basis for system modeling of the collectors.
b) Computer calculations were made of the performance including usable energy per square foot of aperture area for each collector as it would operate in complete systems. The thermal performance of each collector was computed, where possible, from data presented in the literature or data received from the manufacturer.
c) The above system studies were conducted for 12 climatic regions for each generic collector type, and in selected regions for all collectors meeting the required data base.

Data Analysis. The data developed in Task 2 was analyzed to determine:

a) The relative performance of each collector type under a consistent set of circumstances (geographical location, heating load type, etc.).
b) Which aspects of the collector design are inherently limited by physical laws (e.g., concentration ratio) and which are limited by the design itself.
c) The utility and durability of materials utilized in each collector (e.g., the deterioration of materials and coatings or breakage) including reasons why certain materials are used more frequently than others.

Comparison Chart and Graph Development. A series of comparison charts and graphs were developed to provide ready comparison of all collectors for the following aspects:

a) Delivered energy at a given solar fraction
b) Materials
c) System sizing
d) Economic factors

TECHNICAL ACCOMPLISHMENTS

The generic collector types covered in this report are tubular, parabolic trough, segmented mirror, fresnel lens, reversible vee-trough, and compound parabolic. The companies and laboratories manufacturing or studying each collector type are listed in Table 1. Tables 2 and 3 are summaries of collector properties for comparison.

Some collectors like the parabolic cylinder and the Fresnel lens must track the sun around at least one axis, that parallel or equal to the one formed by the absorber tube. There are two orientations available for doing this: the absorber tube oriented east-west and the absorber tube oriented north-south and tilted upward toward south at some fixed angle. The relative outputs of these two methods of tracking are illustrated in Figures 1 and 2.

COLLECTOR PERFORMANCE AND ECONOMIC ANALYSIS

Methodology. Performance of the collectors included in this survey were compared by plotting the following types of graphs: (a) Collector Area (net)/Load vs. % Load Supplied by Solar (b) Performance (Btu/ft^2-yr) vs. % Load Supplied by Solar.

Initially the performance of the collectors was to be obtained for twelve representative regions in the country and for three different building types. However a thorough analysis of the performance of two collector types (Beam Engineering's parabolic cylinder collector and Owens-Illinois tubular collector) for twelve regions and three building types showed that the performance of the collectors was not significantly different between certain regions. Hence the twelve regions were divided into three groups. Within a given group the performance of the collectors did not vary significantly and hence a representative region from each group was selected. The regions are Madison, WI; Washington, DC; and Charleston, SC.

Similarly the performance of the collectors did not vary significantly between the Typical Insulated Residence and the Small Office building types and hence the Small Office was dropped from the building types.

Performance data of the collectors (from eleven different manufacturers) was generated for the three regions and the two building types selected above and summarized in Table 4. These results show that the Del Manufacturing Company's parabolic cylinder collector has the highest rating among the tracking collectors and the Owens-Illinois' tubular collector fared the best among the non-tracking collectors. However, it should be noted that the data base on which the performance curves were generated was obtained directly from the manufacturers and was not verified by an independent testing agency except in the case of the Northrup collector.

These performance results do not mean that the collectors rated best are necessarily the most cost effective for a given building type in a given region. The above results are strictly on the basis of energy delivered and do not take into consideration the cost of the entire installed system. It is difficult to make a realistic cost estimate of a system in a generalized way which would accommodate any type of collector and any installation site. The cost of the system depends on, among several other factors, the extent of site preparation, local labor costs, site location, transportation costs, environmental factors and the inherent characteristics of the collectors themselves. For specific installations, the performance predictions may be combined with site-specific installed system cost estimates to choose the best design for the job.

Economic Analysis. A generalized economic analysis was performed for four energy costs and five installed system costs. By plotting the curves on a generalized basis, it is possible to compare different collectors. Installed system costs must be used for these analyses. Typically, installation costs including a minimum of support structure will run \$5 to \$10/ft^2. This does not include other major system components such as tanks, pumps, heat exchangers, controls/monitors, and long piping runs. These costs are site and system design-dependent and will increase dramatically with design temperatures and pressures.

A. Tubular
General Electric Company
KTA Solar Corporation
Owens-Illinois, Inc.
Energy Design Corporation

B. Parabolic Trough
Acurex Corporation
Albuquerque Western Solar Industries, Inc.
Beam Engineering, Inc.
Del Manufacturing Company
Solar Kinetics, Inc.

C. Segmented Mirror Solar Concentrator
Suntec Systems, Inc.
AAI Corporation
General Atomic Company

D. Fresnel Lens
Northrup, Inc.

E. Reversible Vee-Trough
Jet Propulsion Laboratory

F. Compound Parabolic Collector
Argonne National Laboratory

Table 1. Generic List of Concentrating Collectors

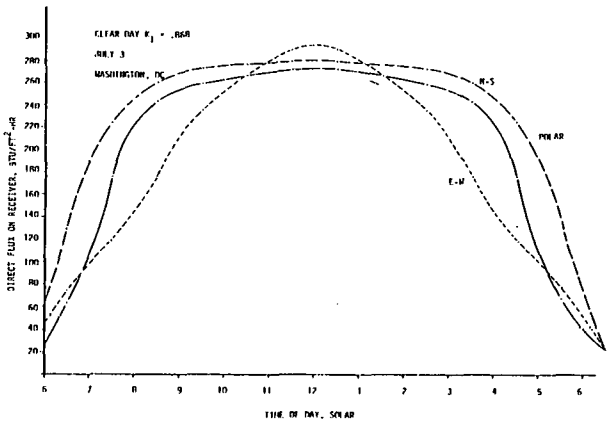


Figure 1. Orientation vs Output: July 3

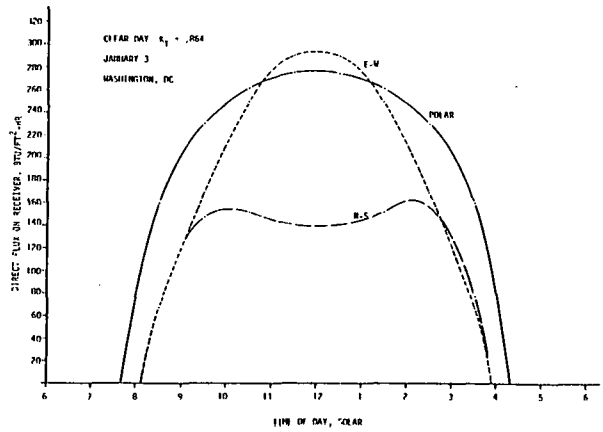


Figure 2. Orientation vs Output: Jan. 3

TUBULAR COLLECTORS

	O-I	GE	KTA	Energy Design Corporation
Module Inst. Area	32 ft² (14" x 81")	17.4 ft² (8 tubes) (52½" x 47-3/4")	19.21 ft² (63⅛" x 43-3/4")	34.3 ft² (104" x 47.5")
Module Collection Aperture Area	27.4 ft²	14.8 ft²	17.8 ft²	-
Module Weight				
Wet (filled)	185 lbs	62 lbs	80.1 lbs	
Dry	110 lbs	60 lbs	75 lbs	200 lbs
Receiver:				
τ of glass envelope	0.92	0.92	0.92	-
α of absorber	0.86	-	0.95	0.85 @ 212°F
ε of absorber	0.05	-	0.07	0.05 @ 212°F
Top cover plate, τ	No cover	optional	0.92	-
Recommended flow Rate in GPM/ft²	-	0.01486 @ 180°F	0.0125 to 0.04 GPM/ft²	-
Recommended heat transfer fluids	water	water/ethylene glycol	water, H_2O/glycol silicone oil	-
Cost, $/ft² of aperture area	22.5	-	-	-
Operating fluid temperature range	40°F to 240°F	100°F to 300°F	-	140°F to 100°F
Pr drop/ft of collector length	(min)	(min)		
Aspect ratio=L/W	2.00	1.10	1.44	-
Tracking	None	None	None	None
Recommended Applications	DHW space, H&C	DHW space, H&C	DHW space, H&C	DHW space, H&C
Expected life, years	-	-		-
Concentration ratio	1.0	1.3	-	1.3
η at ΔT/I=0	0.7180	0.5900	0.6700	0.5400
1st order coefficient	0.2360	0.00	0.3600	0.00
2nd order coefficient	0.00	0.1393	0.00	0.12

* Blanks represent information that could not be obtained from the manufacturer. Rest of the information is as given in the manufacturer's literature.

Table 2. Summary of Tubular Collector Properties

Manufacturer	Type of Collector	Concentration ratio	Aperture Area, ft²	A	B	C	Reflector/Lens ρ	Reflector/Lens τ	Receiver Cover τ	Receiver ε	Receiver α	Materials: Reflector	Materials: Receiver	Materials: Cover	Tracking
Acurex	Parabolic Cylinder	36.0	60.0 ft² (10' X 6')	0.63	0.11	0.00	0.75 to 0.80	N/A	0.90	0.15 @650°F	0.93	Coilzak™	Steel-Selective Coating	Pyrex glass tube	Shadow band sensor/ continuous tracking
Albuquerque Western	Shaped Reflector	5.0	14.67 ft² (8.' X 1.33')	0.70	0.29	0.75	0.88	N/A	0.90	0.95 @425°F	0.95	MYLAR	Copper - black paint	Tedlar glazing	continuous tracking
Beam Engineering, Inc.	Parabolic Cylinder	3.95	16.2 ft² (8.833' X 1.833')	0.70	-0.10	1.30	0.83 to 0.87	N/A	0.85	0.10	0.90	Coilzak™	Copper - black paint	Tedlar glazing	continuous tracking
Jacobs-Del Solar Systems, Inc.	Parabolic Cylinder	15.2	16.0 ft² (8' X 1')	0.72	0.05	0.03	0.90	N/A	0.90	0.25 @600°F	0.95	Back-Silvered Glass	Steel-black chrome coating	Pyrex glass tube	continuous tracking
Solar Kinetics	Parabolic Cylinder	48.0	40.0 ft² (10' X 4')	0.71	0.12	0.00	0.84	N/A	0.90	0.18 @500°F	0.95	Aluminized Acrylic film FEK-244™	Steel-black chrome coating	Pyrex glass tube	continuous tracking
*Northrup, Inc.	Fresnel Lens	10.64	9.72 ft² (9.8958' X 0.982')	0.55	0.46	0.03	N/A	0.92	N/A	0.12	0.95	N/A	Copper Selective coating	Cast acrylic plastic Fresnel lens	continuous tracking
Argonne Nat'l Labs.	CPC	5.0	4.5 ft² (8' X 0.5625')	0.65	0.34	0.23	0.85	N/A	0.91	0.08 @446°F	0.89	Silvered mirrors and Kinglux™	Aluminum - black chrome coating	Pyrex glass tube	12 tilt adjustments per year

A, B, and C are Coefficients in the η-equation
$\eta = A - B\left(\frac{\Delta T}{I}\right) - C\left(\frac{\Delta T}{I}\right)^2$

* Values of the Coefficients in the efficiency equation have been obtained from independent test results (Wyle Labs, Huntsville, Alabama) All the other information has been obtained from the manufacturers.

Table 3. Summary of Tracking Collector Properties

Region	Building Type	Collector Type	Performance Range @ 50% Load Supplied by Solar (10^3 Btu/ft^2-yr Collector Output)	Area/Load Range @ 50% Load Supplied by Solar (ft^2/10^6 Btu/yr Load)
Madison	Department Store	Non-Tracking	90-145	3.2-5.5
		Tracking	140-175	2.7-3.5
	Standard Residence	Non-Tracking	160-230	2.0-3.0
		Tracking	215-265	2.0-2.5
Washington	Department Store	Non-Tracking	65- 85	5.7-7.5
		Tracking	70- 90	5.6-6.7
	Standard Residence	Non-Tracking	190-280	1.7-2.3
		Tracking	175-310	1.6-2.0
Charleston	Department Store	Non-Tracking	65- 80	5.3-7.0
		Tracking	75-100	5.0-6.6
	Standard Residence	Non-Tracking	255-290	1.5-2.0
		Tracking	275-350	1.4-1.9

Table 4. Performance and Area/Load Data

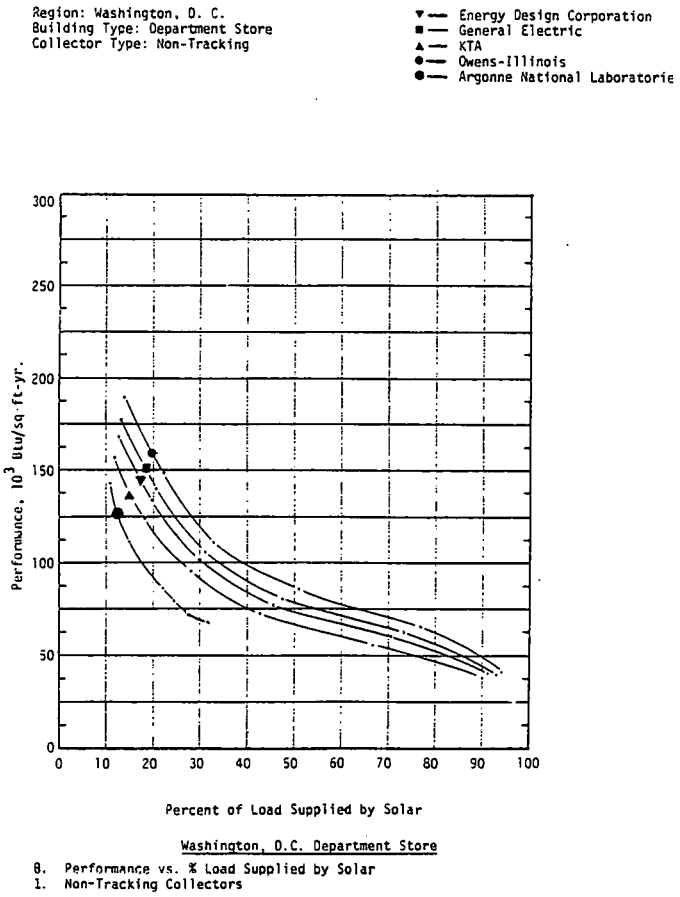


Figure 3. Sample Performance Analysis Output

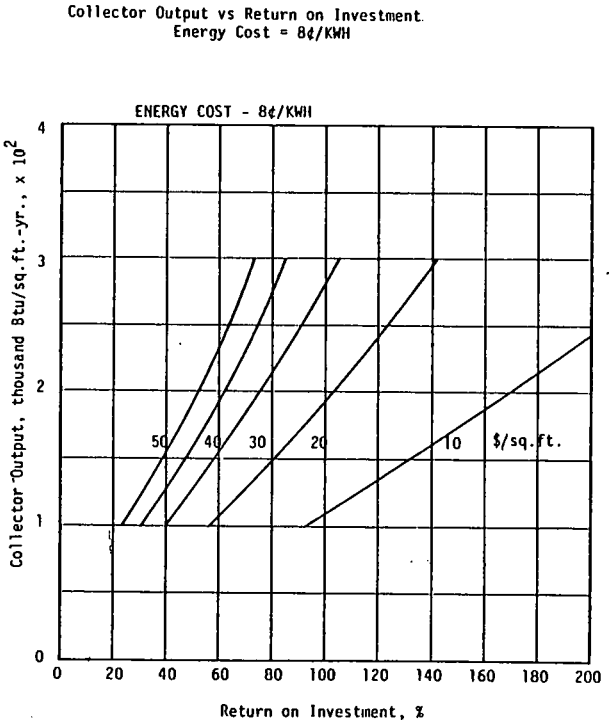


Figure 4. Sample Economics Analysis Output

ACTIVE SOLAR COLLECTOR AND MATERIALS RESEARCH*

LOS ALAMOS SCIENTIFIC LABORATORY

W-7405-ENG-36, D-496, D-501, D-526

D. A. NEEPER

PERIOD OF CONTRACT: Begin July 1, 1976, End Continuing

OBJECTIVE

In addition to providing technical support to DOE's management of collector R&D, the Los Alamos Scientific Laboratory (LASL) conducts its own testing and evaluation of collectors, collector materials, and active systems. Plans for this fiscal year include the testing of three commercial or near-commercial evacuated tubular collectors, the evaluation of selective absorbers for evacuated collectors, and publication of comprehensive analyses on each of three active systems that we have designed and operated. We are also initiating an investigation of the fluid dynamics of salt-gradient solar ponds.

SUMMARY

Construction of our high-temperature test loop with tracking collector mount is nearly complete. We have completed enough tests of Thermacore's heat pipe collector to eliminate concerns of instabilities in the heat pipe.

Projects at Honeywell and Telic show promise of developing selective surfaces that may be marketed on foils or films. We have evaluated a number of techniques for using these low-cost absorbers in tubular glass collectors.

We completed data acquisition in the National Security and Resources Study Center building, which is heated and cooled by a LASL-designed solar system. The building has performed reliably for about three years, with solar energy providing 70% of the heating and 95% of the cooling. However, parasitic power requirements in the cooling mode make such a system unattractive for purely cooling purposes.

Our review of previous R&D on nonconvecting solar ponds confirms that the lack of understanding of the mechanisms by which the various layer boundaries move is the major unsolved problem.

TECHNICAL ACCOMPLISHMENTS

- We have made side-by-side tests of Thermacore's heat-pipe collector and the General Electric TC-100 collector. Both collectors use the same evacuated shroud. Tests at G.E. indicated instability in heat flow from the heat pipe. Our tests show no such difficulty, so we believe the problem was in the test assembly at G.E.

- We have successfully electroplated black chrome selective surfaces on tubular glass substrates. The coatings initially showed $\alpha_s = 0.94$, $\varepsilon_T = 0.08$. Optical properties of the surfaces showed degradation after vacuum baking at 400 °C. This was traced, via electron and ion microprobe analysis, to diffusion of copper from the metallized glass through the black chrome, indicating the need for a diffusion barrier of nickel. The copper had been vacuum deposited on the glass.

- Attempts to metallize the glass tubes (prior to electroplating) by non-vacuum deposition processes resulted in coatings with poor adhesion. Fired-on organo-metallic resinates, using gold, were tried.

- We have examined numerous schemes for adhesion of absorber foils to glass tubes for evacuated collectors. Thus far, no method has proved both technically feasible and economically attractive.

- Our two-axis tracking test loop is nearly complete. It uses therminol 55 working fluid with a flow rate of 0 to 15 gallons per minute. In an open-loop mode, running from one tank and dumping into another, it can operate for five hours at one gallon per minute.

- We published two condensed reports of our studies on two of our active systems (see Publications).

- As part of an International Energy Agency subtask, we compared NBS data on several domestic hot water systems with the results of hourly numerical modeling. Behavior of some of the systems is not understood.

PUBLICATIONS

1. H. S. Murray, J. C. Hedstrom, and S. W. Moore, "Solar Heating Results for the Nambe Community Center," presented at the Second Annual Solar Heating and Cooling Systems Operational Results Conference, Colorado Springs, November, 1979.

2. J. C. Hedstrom, H. S. Murray, and J. D. Balcomb, "Solar Heating and Cooling Results for the Los Alamos Study Center," see Ref. 1.

*Work performed under the auspices of the U. S. Department of Energy, Office of Solar Applications.

3. S. R. Reisfeld and D. A. Neeper, "Solar Energy Research at LASL - 4/1/78 - 3/31/79," LASL Report, LA-8090-PR, February, 1980.

4. R. K. Collier, "A Simplified Technique for Comparing the Effectiveness of Collector Absorber Coatings," Solar Energy, Vol. 22, No. 5, 1979.

5. D. P. Grimmer and L. Bronisz, "Small-Scale Solar Simulator for Indoor Testing of Collector Modules and Materials," Proceedings of the 1979 Annual Meeting of the American Section of the International Solar Energy Society, Vol. 1, p. 413.

6. D. A. Neeper, "Analysis of Matrix Air Heaters," Proceedings of the 1979 Annual Meeting of the American Section of the International Solar Energy Society, Vol 1, p. 298.

7. R. K. Collier, "The Characterization of Crushed Glass as a Transpired Air Heating Solar Collector Material," Proceedings of the 1979 Annual Meeting of the American Section of the International Solar Energy Society, Vol. 1, p. 264.

LOW-COST MIRROR CONCENTRATIONS, BASED ON DOUBLE-WALLED, METALLIZED, TUBULAR FILMS

MONSANTO RESEARCH CORPORATION

DE-AC04-78AL04227

GEORGE L. BALL III, JAMES L. SCHWENDEMAN AND JAMES W. LEFFINGWELL

FEBRUARY 20, 1978 TO FEBRUARY 19, 1980

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 and moderate performance were to be emphasized.

CONCEPT/BACKGROUND

Concentrating solar collectors, needed to achieve higher temperature efficiently, are often expensive because of the need to precisely shape and align reflectors, and to track the sun throughout the day. An inflatable, circular cross-section, cylindrical concentrator fabricated from flexible metallized plastic film can solve many of these problems. First, an inflated cylinder assumes a circular cross-sectional shape on inflation, which precisely defines the reflector geometry. Second, with reasonably low reflector-to-absorber diameter ratios, actual concentration of about 3X with an acceptance angle of about 20° can be expected. With this acceptance angle capability, concentrator adjustment should be required only weekly to retain reasonable efficiency.

In this program the practicality of extending previous 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.

SUMMARY

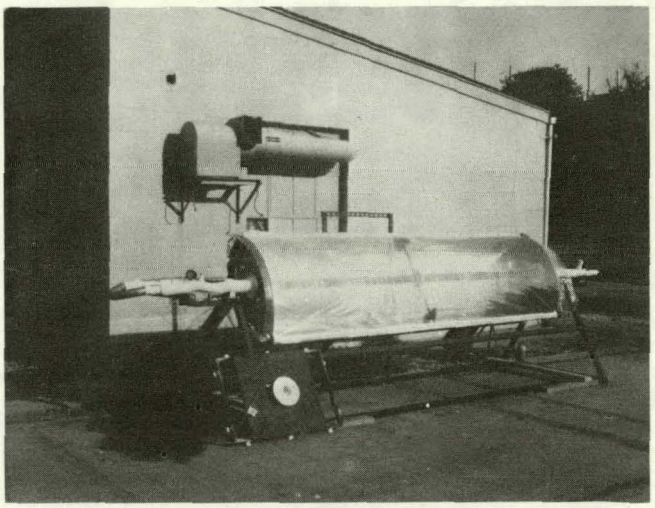
Low-cost, durable, reflective aluminum foil-plastic film laminates were evaluated as an alternative to relatively expensive aluminized polyester-type reflectors. These materials were used to build a truncated cylindrical designed unit which eliminates about 40% of both the cover and reflective surfaces of conventional cylindrical collectors. This 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 on the figure was fabricated in 1979 and is being tested.

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 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. The ultraviolet stabilizer XP 1029 was incorporated into the commercial PVC film by dissolving then reconstituting the film. Exposed to UV radiation in a Sun-lighter test chamber, the film containing XP 1029, 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 resulted in a savings of about 22% in land use.



- The absorber tube is the principal structural member of the concentration, supporting the entire concentration and providing the base for the end plates and transverse support which fixes the dimension and shape of the concentration.

- 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 suppo

• 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 sleve 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.

FUTURE ACTIVITIES

Outdoor testing of the efficiency of the concentrator around a black chrome absorber is planned for early 1980. A test site with adequate sun is needed. It is recommended that the truncated design and the suggested materials be further evaluated beyond the term of the present contract (March 1980).

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".

Final report on project should be completed in June 1980.

DEVELOPMENT OF STANDARD METHODS FOR TESTING SOLAR COLLECTORS

NATIONAL BUREAU OF STANDARDS

EA-77-A01-6010

JOHN P. JENKINS, ELMER R. STREED, AND JAMES E. HILL

OCTOBER 1, 1978 - MARCH 31, 1980

OBJECTIVE

The objective of this project is to develop standard testing procedures that can be used for testing and rating of solar collectors that are used in systems for heating, cooling, and heating of hot water in buildings.

BACKGROUND

Beginning in early 1974, the staff of the National Bureau of Standards (NBS) began the development of thermal test procedures for the two primary components of solar heating and cooling systems, solar collectors and thermal storage devices. A recommended procedure for testing solar collectors was published in December, 1974 [1] in a format consistent with standard test procedures of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). The procedure was later published with supplementary information explaining the rationale behind the procedure [2,3]. ASHRAE subsequently adopted Standard 93-77 [4] for solar collectors which is based substantially on the NBS procedure.

There has been a need to experimentally verify the applicability of this standard to state-of-the-art solar collectors and to examine alternate testing techniques that might be more accurate and/or easier to carry-out.

Three different test loops had been built in prior years at NBS in accordance with ASHRAE Standard 93-77 for testing both liquid and air collectors. During fiscal year 1978, tests and data analysis were completed on six different collectors which were tested outdoors in accordance with the Standard in order to verify its applicability to state-of-the-art flat-plate, evacuated-tubular, and concentrating collectors. The conclusions of the study and recommendations for modification of the Standard were presented in summary form at the ASHRAE Annual Meeting in Albuquerque, New Mexico in June, 1978 [5] and were published in an NBS Building Science Series report [6].

Data analysis was completed in fiscal year 1978 on a round robin collector testing program in which two collectors were tested by 21 different testing laboratories across the United States using the NBS-recommended procedure to determine thermal efficiency. A collector analytical model was used to show how much of the data spread could be attributed to different environmental conditions from facility to facility. The results were published in an NBS Technical Note [7] and summary form in Solar Energy [8].

An alternate testing procedure developed by BSE and consisting of indoor and outdoor tests has been investigated at NBS and several other laboratories [9]. The optical efficiency of the collector, or ordinate intercept of the efficiency curve, is determined by obtaining one efficiency test point outdoors with the average fluid temperature approximately equal to the ambient air temperature. A complete series of tests are then conducted indoors with no irradiation to determine the collector heat loss coefficient, $F'U_L$, as a function of the difference between the average fluid temperature and the ambient air temperature. With the two primary performance factors determined separately in this way, the collector efficiency can then be calculated for any combination of solar irradiance, ambient air temperature, and collector operating temperature.

During fiscal year 1978, and as an adjunct to the round robin program described above, heat loss measurements were performed by eight of the testing laboratories, including NBS, under both indoor and outdoor (non-irradiated) conditions on one of the collectors. The relationship between the heat loss coefficient obtained in this manner and that obtained from the slope of the efficiency curve as a result of the outdoor tests [7,8] was determined. The results indicated a relatively large spread in heat loss coefficient due to variations in environmental conditions (wind, sky temperature). The results were reported at the International Solar Energy Society (ISES) meeting in Denver, Colorado in August, 1978 [10].

SUMMARY

During this reporting period, an in-depth evaluation was made of the BSE collector testing procedure for five water heating flatplate solar collectors. The staff of NBS assisted ASHRAE in the development of ASHRAE Standard 96 for testing unglazed collectors. Two prototype reference heat source devices were designed and constructed for use with NBS test loops. Techniques for correcting collector test results for variations in fluids, flow rates, and test conditions were investigated.

TECHNICAL ACCOMPLISHMENTS

o Five different flat-plate water-heating collectors which had been previously tested in accordance with ASHRAE Standard 93-77 outdoors, were tested in accordance with the indoor heat loss procedure. The results were used to construct efficiency curves for the collectors which were compared with the curves previously established based on the outdoor (ASHRAE) tests. The collectors were selected to represent a

range of designs from single-glazed with poor thermal design of the absorber to a high-performance double-glazed collector. In addition, different experimental techniques were investigated for simulating sky temperature and wind effects indoors so that realistic eat loss characteristics could be obtained indoors. he results of the study were presented at the 1979 nternational Congress of ISES in Atlanta, Georgia in May, 1979 [11] and the 1979 Winter Annual Meeting of the American Society of Mechanical Engineers [12]. It was found that for the five collectors tested, the differences between the efficiency curves determined using the two test procedures was less than the uncertainity associated with the curve determined in accordance with the ASHRAE procedure.

o The staff of NBS assisted ASHRAE in the development of ASHRAE Standard 96 for testing unglazed collectors which are used predominately for heating of swimming pools. The Standard has been adopted but is not yet published. It is based substantially on ASHRAE Standard 93-77 with the following major differences:

a. Temperature difference measurement across the collector is required to be an order of magnitude more accurate than in Standard 93-77.

b. Efficiency data is required to be obtained under conditions when the inlet fluid temperature is cooler than the ambient air.

c. Wind velocity is required to be controlled to a low value (<1.3 m/s (3.3 mph)) and measured at several locations near the surface of the absorber (within 15 cm (6 in) and presumably with a hot wire anemometer).

During the period covered by this report, a test loop was conducted in accordance with the Standard and validation experiments were initiated.

o Difficulties in the measurement of liquid flow rates and the desirability to perform on-site calibration of complete collector test loops led NBS as well as several other laboratories to develop an electrical reference heat source. The thermally insulated heat source is located in the liquid collector test loop, either in place of the collector or in series with the collector, depending on the use. By measuring the amount of electrical energy dissipated by the heater and the temperature difference across the heater, a calorimetric type check of the test loop accuracy (in place of the collector) or of the solar collector output (in series with the collector) can be determined. The need for accurate knowledge of the fluid specific heat and fluid flow meter is thus eliminated (when placed in series with the collector) or the flow meter accuracy verified (when put in place of the collector) with the apparatus. Two prototype devices were designed and constructed for use with NBS test loops.

o Because of the range of environmental conditions allowable in ASHRAE Standard 93-77 during the test to establish the near-normal-incidence efficiency curve, considerable scatter in the data is possible. During the conduct of the round robin program, a correction technique was demonstrated [7,8] whereby each data point can be corrected to "standard environmental conditions" using a mathematical model of the collector. This is a potentially powerful tool for outdoor testing of collectors. During fiscal year 1978, an NBS Center for Building Technology University Grant was awarded to Virginia Polytechnic Institute and State University (VPI and SU) to experimentally verify the technique with extensive and controlled experiments on two flat-plate collectors. The basic objective is to develop a technique in the form of a set of nomographs or computer program that could be used by a commercial testing laboratory. Refinements in the program were made during this reporting period and completion of the study will occur during fiscal year 1980.

o Under a separate project from the one being reported on here, the staff of Wyle Laboratories, under contract from NBS, tested four generic types of water-heating flat-plate collectors for thermal efficiency using four different fluids and three flow rates and the NASA (MSFC) solar simulator. The results indicated that collector efficiency could be reduced by as much as 10 percentage points for the fluids and flow rates used compared to the use of pure water and the flow rate recommended in ASHRAE Standard 93-77 [13,14]. As part of this project, additional and similar tests were conducted on two flat-plate water heating collectors outdoors at VPI and SU using four different fluids and three different flow rates. Efficiency differences as large as 20 percentage points were obtained. The computer model described above was used to demonstrate that the test results could be corrected to "standard conditions" of using pure water and the flow rate recommended in ASHRAE Standard 93-77 and the major part of the efficiency differences eliminated [15]. All scatter was not eliminated due to measurement uncertainities and transients during the tests.

FUTURE ACTIVITIES

1. An evaluation of the BSE collector testing procedure will be made for evacuated tubular and unglazed collectors.

2. The electrical reference heat source will be evaluated in existing NBS test loops. Comparison of the apparatus with similar apparatuses in Canada and other U.S. test laboratories will be made. A report will be prepared and published describing the design, construction, calibration, and operation of these devices for solar collector testing.

3. The thermal performance of two types of unglazed collectors will be determined using ASHRAE Standard 96 and compared with results obtained using indoor heat loss measurements. The influence of environmental factors on test results, as permitted in the test method, will be evaluated. The results will be presented at the Annual Meeting of ISES to be held in Phoenix, Arizona in June, 1980.

4. The study of the feasibility of correcting collector test results to "standard conditions" will be completed.

REFERENCES/PUBLICATIONS

1. Hill, J.E. and T. Kusuda, "Methods of Testing for Rating Solar Collectors Based on Thermal Performance," NBSIR 74-635, December, 1974.

2. Hill, J.E., Streed, E.R., Kelly, G.E., Geist, J.C., and T. Kusuda, "Development of Proposed

Standards for Testing Solar Collectors and Thermal Storage Devices," NBS Technical Note 899, February, 1976.

3. Hill, J.E., and E.R. Streed, "A Method of Testing for Rating Solar Collectors Based on Thermal Performance," Solar Energy, Vol. 18, pp. 421-429, 1976.

4. "Methods of Testing to Determine the Thermal Performance of Solar Collectors," ASHRAE Standard 93-77, ASHRAE, 345 East 47th Street, New York, New York, 10017, 1977.

5. Hill, J.E., Jenkins, J.P., and D.E. Jones, "Testing of Solar Collectors According to ASHRAE Standard 93-77," ASHRAE Transactions, Vol. 84, Part II, pp. 107-126, 1978.

6. Hill, J.E., Jenkins, J.E., and D.E. Jones, "Experimental Verification of a Standard Test Procedure for Solar Collectors," NBS Building Science Series 117, January, 1979.

7. Streed, E.R., Thomas, W.C., Dawson, A.G., Wood, B.D., and J.E. Hill, "Results and Analysis of a Round Robin Test Program for Liquid-Heating Flat-Plate Solar Collectors," NBS Technical Note 975, August, 1978.

8. Streed, E.R., Thomas, W.C., Dawson, A.G., Wood, B.D., and J.E. Hill, "Results and Analysis of a Round Robin Test Program for Liquid-Heating Flat-Plate Solar Collectors," Solar Energy, Vol. 22, pp. 235-249, 1979.

9. "Guidelines and Directions for Determining the USABILITY OF SOLAR COLLECTORS, A. Efficiency Tests of Solar Collectors," Bundesverband Solarenergie, BSE, Kruppstrasse 5, 4300 Essen 1, Federal Republic of Germany, May, 1978.

10. Streed, E.R., "A Comparison of Flat-Plate Solar Collector Thermal Performance Data Obtained Indoors and Outdoors," Proceedings of 1978 Annual Meeting of the American Section, International Solar Energy Society, held in Denver, Colorado, August 28-31, 1978.

11. Jenkins, J.P., "A Comparison of Test Results for Flat-Plate Water-Heating Solar Collectors Using the BSE and ASHRAE Procedures," Proceedings of the 1979 International Congress of the International Solar Energy Society, held in Atlanta, Georgia, May 28-June 1, 1979.

12. Jenkins, J.P., and J.E. Hill, "A Comparison of Test Results for Flat-Plate Water-Heating Solar Collectors Using the BSE and ASHRAE Procedures," ASME Paper 79-WA/Sol-4, ASME Transactions, Journal of Solar Energy Engineering, Vol. 102, No. 1, pp. 2-15, February, 1980.

13. Youngblood, W.W., Schultz, W.E., Barber R., and E. Streed, "An Evaluation of the Influence of Heat Transfer Fluid Properties and Flow Rate on Flat-Plate Solar Collector Efficiency," Proceedings of the 1979 International Congress of The International Solar Energy Society, held in Atlanta, Georgia, May 28-June 1, 1979.

14. Youngblood, W.W., Schultz, W.E., and R. Barber, "Solar Collector Fluid Parameter Study," NBS Report NBS-GCR 79-184, October, 1979.

15. Thomas, W.C., "Effects of Test Fluid Composition and Flow Rates on the Thermal Efficiency of Sol: Collectors," VPI and SU Report No. 80-03, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, January, 1980.

EVALUATION OF HEAT TRANSFER ENHANCEMENT IN AIR-HEATING COLLECTORS

NORTHROP SERVICES, INC.
HUNTSVILLE, ALABAMA

CONTRACT NUMBER DE-AC04-78CS05352

DONALD L. MATTOX

September 5, 1978 to June 1, 1979

OBJECTIVE

The effort was to identify techniques for enhancing the heat transfer between the absorber and the air stream, develop methods of performance comparison for widely diverse designs, determine optimum Reynolds number flow regime for solar collector operation, develop theoretical prediction relationships for scaling state-of-the-art designs, and to make recommendations for further research. The objectives have been accomplished.

BACKGROUND

Introduction. If air collectors are to be commercially competitive with other energy sources they must have a high efficiency in converting solar energy to thermal energy with a minimum penalty in pumping power and manufacturing cost. This work was initiated to evaluate existing techniques for increasing the heat-transfer coefficient between absorbers and the air stream, and to offer new innovative approaches for accomplishing this task.

Statement of problem. The cross section of a proposed flat plate air-heating solar collector is shown in Figure 1. The collector consists of two transparent glazing covers, an absorber plate with attached air heat exchanger fins, an air flow passage, thermal insulation, seals, and support structure.

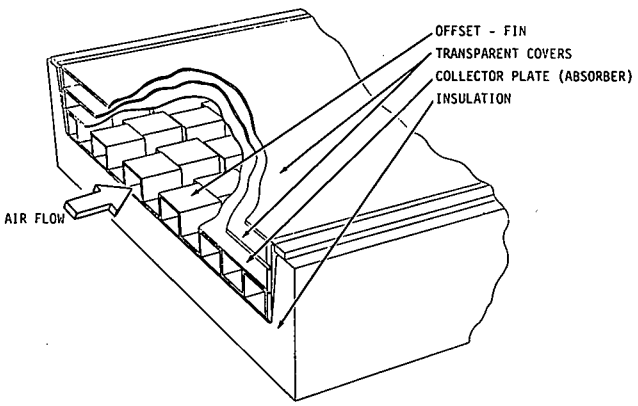


Figure 1. Proposed Air Heating Solar Collector

SUMMARY

The effort was completed and the final report submitted to DOE. Some of the more significant accomplishments were: (1) A solar collector systems analysis was performed to evaluate the impact, of various techniques for enhancing the heat transfer between the absorber and air stream, on overall thermal performance of the entire solar collector. (2) One solar collector design providing ducted cooling air on the absorber shaded side was selected for detailed study. (3) A transient heat transfer analysis of a complete solar air heating collector was used to demonstrate that an optimum absorber-to-air heat exchanger design could be provided with several "interrupted" fin configurations. (4) Analyses were performed to establish that the maximum solar collector thermal performance to required pumping power was realized for a Reynolds number range of 1000 to 2000. (5) A theoretical design limit curve for maximum thermal performance versus required pumping power was developed for all "interrupted" fin designs as published in the open literature. (6) Heat and momentum transfer empirical relationships were defined for scaling the state-the-art high conductance fin designs identified from a "compact" configuration to the less compact designs needed for solar collectors. (7) A proposal was submitted to conduct a research program including the design and fabrication of a miniature wind tunnel plus the design, test and evaluation of twelve air-heating solar absorber matrices.

TECHNICAL ACCOMPLISHMENTS

- The Northrop solar collector transient heat transfer analysis program was modified to include the new heat transfer techniques identified in the literature survey.
- The range of conductance area product (UA) values required for solar collectors was determined. A thermal model was developed that reproduced the experimental data measured by the University of Delaware for their collector. A parametric study, with UA as the main parameter, was performed using this same thermal model. The analysis was performed for a typical set of external environment, solar insolation and cooling air inlet temperature boundary conditions. A plot of thermal efficiency versus elapsed time after insolation exposure is provided (Figure 2). This figure presents data for several solar collectors. This data is provided in the form of instantaneous efficiency at any time after initial collector illumination with 947 w/m^2 of insolation. The Delaware collector has an efficiency of 41 percent after one time constant. At this same point in time the Solaron and smooth duct collectors have an efficiency of 25 percent and 17 percent, respectively.

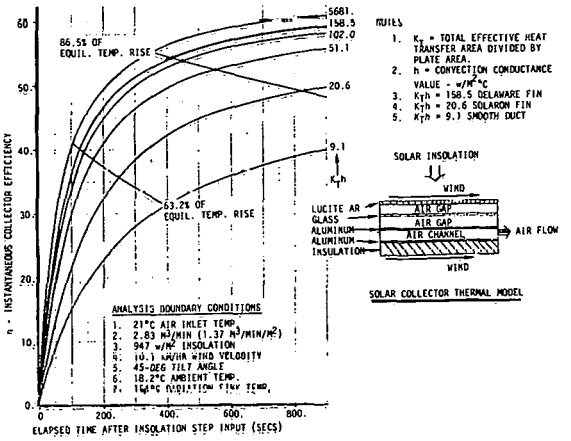


Figure 2. Collector Efficiency Time Histories

- Two merit indices were applied to determine the Reynolds number range where the ratio of solar thermal power to pumping power is a maximum. The merit indices were Stanton number cubed divided by friction factor and Stanton number divided by friction factor. The first merit indice is a measure of a solar collector thermal output per unit heat transfer area. The second is a measure of the thermal output per unit flow area. These merit indices were applied to a correlation of heat transfer and friction factor data for 22 different rectangular offset fin plate configurations. Both indices indicated that the optimum ratio of thermal power to pumping power was obtained at a maximum Reynolds number for laminar flow and a minimum Reynolds number for turbulent flow. This is the Reynolds number range of 1000 to 2000.
- Several fins were evaluated. A measure of the heat transfer enhancement exhibited by a particular absorber fin design was determined by comparing the fin induced conductance value to the fin required pumping power. Plots of fin thermal performance versus pumping power for Reynolds numbers of 1000 and 2000 were created for all available fin heat transfer and friction data. These plots identified potential state-of-the-art solar collector air heat exchanger designs. Comparison of these data with the best identified solar industry fin data reveals that the best solar industry fin design (Delaware fin) is not state-of-the-art.
- State-of-the-art "compact" fin designs can be scaled to that required for the solar industry using the fin running length in the flow direction and the distance between fins as the main scaling parameters. This phenomenon is characterized by the developing flow heat transfer and pressure loss expressions. Experimental absorber heat exchanger data was compared to developing and fully developed flow heat transfer and pressure loss expressions and was found to agree favorably both in the laminar and turbulent flow regimes with these theoretical predictions. A new expression for developing turbulent boundary layer duct flow, applicable over the solar collector fin Reynolds number range was developed as part of the present work.
- The "compact" heat exchanger fin designs were configured to remove the heat from one fluid stream and transmit it to another fluid stream in a very short flow path. Heat exchanger effectiveness was of major importance and pumping power was of secondary importance. A high effectiveness was obtained by creating a design with a large UA product in a small volume. The large conductance values are still mandatory for the solar industry but the heat transfer area can be provided over a much longer, flow path. The length of the air flow path being dictated by the required solar collector area.

FUTURE ACTIVITIES

An unsolicited proposal was submitted to request funding for a follow-on effort to the U.S. Department of Energy contract number DE-AC04-78CS05352 which Northrop Services, Inc. This proposal was submitted to the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications. The proposed effort would include additional theoretical analysis and an absorber heat exchanger test program to validate the performance of the fin designs selected and provide data to establish an optimum configuration.

PUBLICATIONS/REPORTS

- Mattox, D. L., "Evaluation of Heat Transfer Enhancement in Air-Heating Collectors", 3rd Annual Solar Heating and Cooling R&D Contractor's Meeting, September 1978.
- Mattox, D. L., "Evaluation of Heat Transfer Enhancement Air-Heating Collectors Final Report", Northrop Services, Inc., Huntsville, Alabama Technical Report 230-1968, June 1979.
- Mattox, D. L., "An unsolicited proposal for follow-on effort to Contract DE-AC04-78CS05352, "Solar Absorber Heat Exchanger Design and Test Program", Northrop Services, Inc. Unsolicited proposal to U.S. Department of Energy Office of Conservation and Solar Application, July 30, 1979.

ADVANCED HEAT TRANSFER STUDIES IN FLAT PLATE SOLAR COLLECTORS

UNIVERSITY OF PENNSYLVANIA
DEPARTMENT OF MECHANICAL ENGINEERING AND APPLIED MECHANICS

EM-78-04-5365

DR. STUART W. CHURCHILL, DR. NOAM LIOR, AND DR. HSUAN YEH

SEPTEMBER 1, 1978 TO SEPTEMBER 30, 1980

OBJECTIVE

The objective of our research is to study heat convection in solar collectors in order to understand how to reduce heat losses from water-heating and air-heating solar collectors. In particular, we are investigating the contribution of internal natural convection and external free convection to these losses and their coupling with irradiation, re-radiation, thermal conduction and convection to the working fluid.

BACKGROUND

The motivation for this work was the fact that the natural convection phenomena in the air layer which is customarily used to insulate solar collectors were so far studied only by two dimensional analytical (or numerical) models, and by limited experimental work, invariably utilizing simplified boundary conditions (such as uniform temperature or heat flux) and typically excluding radiative effects. In order to be able to reduce heat losses from collectors in an effective and systematic way, it was felt that more advanced studies need to be performed, which take into account the fact that the convection phenomena are 3-dimensional, and that realistic boundary conditions need to be applied, as well as the radiative interactions. Specifically, the conjugate problem of heat transfer and flow in the collector's absorber and insulating enclosed air space thus needs to be solved.

Previous studies by one of the principal investigators [1] indicated that heat transfer by natural convection in an enclosed fluid goes through a minimum at particular angles of inclination and rotation. The critical angle for this minimum depends on the aspect ratios of the enclosure and unfortunately occurs at inclinations far less than those of interest for solar collectors. It was postulated that this critical angle of inclination might be increased to a value of practical interest by controlling the temperature distribution on the collector plate through the orientation and spacing of the water passages.

To provide the necessary boundary conditions, a comprehensive model of flow distribution through the tubes in a collector's absorber (for an initial version see [2]), followed by a coupled heat transfer model, indicated the magnitude of the flow maldistribution in the tubes and its influence on the temperature profiles. Similarly, uncertainty was found in the magnitude of the external convective heat transfer coefficient on collectors, which required further study.

SUMMARY

The numerical model for computing 3-dimensional natural convection in enclosures [3,4] was adapted to allow such computations for nonuniform boundary conditions, and was made more time-efficient. The subsequent computations made revealed the influence of the boundary conditions on the circulation mode and on the overall heat transfer across the air-filled enclosure. The latter seems to be affected only slightly by the non-uniformity of the temperature on the boundaries. The improved understanding of the phenomena, however, introduced new possibilities for reducing the heat transfer coefficients and these are being now explored.

A 2-dimensional comprehensive model of flow distribution and of conductive-convective-radiative heat transfer in a collector's absorber was developed and solved, to be able to consider the conjugate problem of the absorber with natural convection in the air enclosure above it.

TECHNICAL ACCOMPLISHMENTS

- Review of the state of the art of natural convection in enclosures is near completion.

- The basic 3-dimensional numerical model, which was confirmed by experiments for uniform temperature boundary conditions (Fig. 1), was adapted to calculate natural convection for a variety of temperature distributions on one surface of an enclosure. These computations revealed that the temperature distribution on the collecting surface does directly affect the circulation pattern (upflow generally occurring over peaks in the temperatures and downflow over minima as seen in Fig. 2). However, the overall rate of heat transfer is virtually unaffected (Fig. 3). This result has two important consequences. An unfavorable consequence is that the temperature distribution on the collector plate, as controlled by the orientation and spacing of the water passages, apparently cannot be used to reduce heat losses significantly. Favorable consequence is that natural convection within the air space is effectively uncoupled from radiation, conduction, external free convection and forced convection to the boundary surfaces and hence can be calculated and correlated independently in terms of the aspect ratios, the average temperature difference and to a lesser extent with the temperature distribution on the side walls.

- Computer-graphic detailed flow and temperature distribution visualization of the 3-d convection in enclosures was obtained, and improved significantly the understanding of this phenomenon.

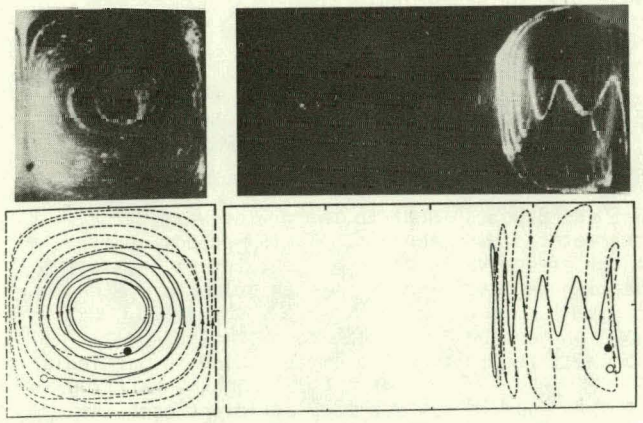


Fig. 1 3-Dimensional Natural Convection in an Enclosure [5]

Top: experiment Bottom: computation

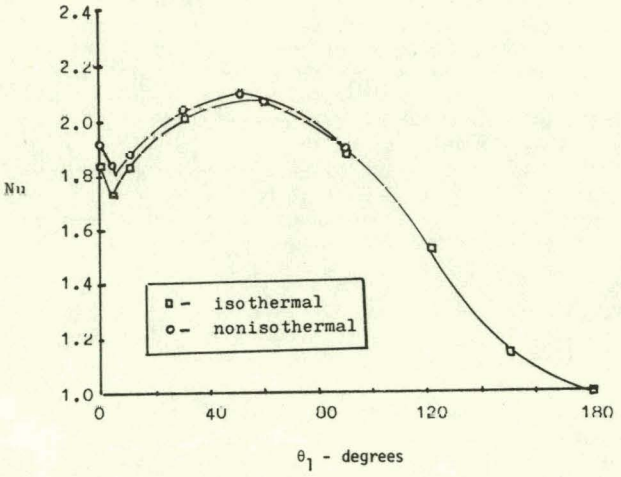


Fig. 3 Comparison Between Isothermal and Nonisothermal Hot Bottom Plate for the Inclination of the Short Dimension of the 2x1x1 Box

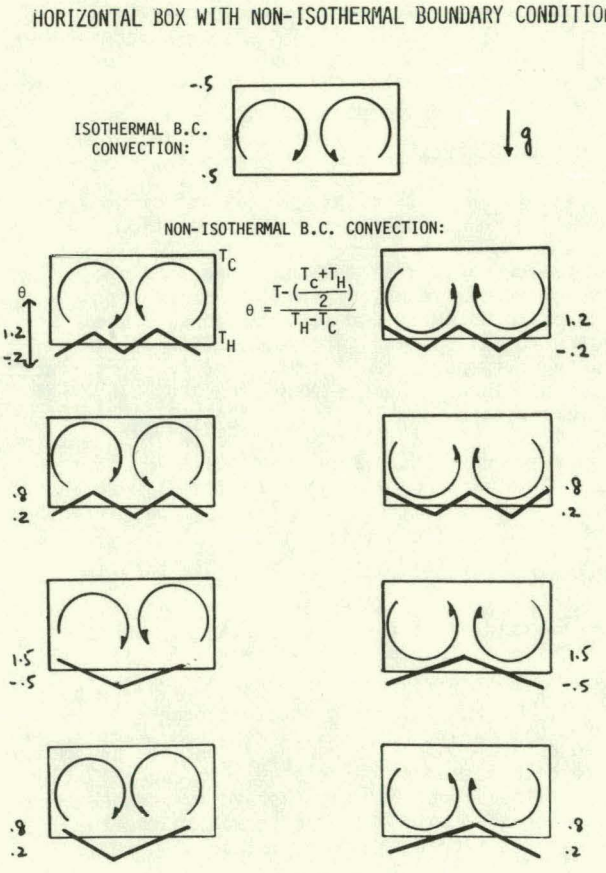


Fig. 2 The Effect of Bottom-Plate Temperature Non-Uniformity on the Mode of Circulation in a Horizontal Enclosure

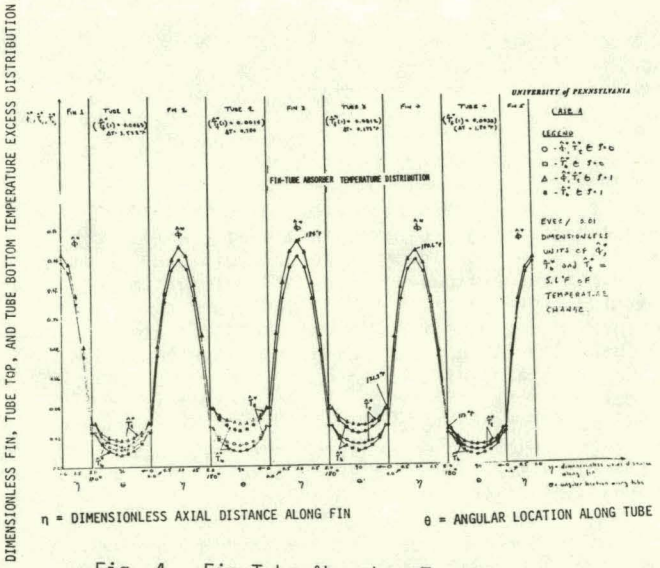


Fig. 4 Fin-Tube Absorber Temperature Distribution

- In consequence, an alternative method of reducing heat losses by natural convection in the air space is now being investigated. This is the use of partial baffles to control the circulation pattern. Honeycombs are known to be effective for his purpose but with the disadvantages of higher ost, reduced insolation of the collector plate due to shading and increased losses by thermal conduction and re-radiation. With partial baffles it may be possible to minimize these undesirable factors while still reducing natural convection significantly. Preliminary calculations are encouraging.

- A detailed analysis was developed to determine the flow distribution in piping systems comprised of two (inlet and outlet) manifolds connected by an arbitrary number of riser tubes, in parallel or reverse flow (this is the flow configuration in most liquid-heating collector absorbers). Flow maldistribution was determined for a large number of cases as a function of three dominant nondimensional parameters.

- A comprehensive two-dimensional conductive-convective-radiative heat transfer model of a liquid-heating collector's absorber was developed and results were obtained for heat transfer rates and temperature distributions, using the flow distributions calculated as described above. A typical temperature distribution on an absorber is shown in Fig. 4.

- A finite-difference model of turbulent flow and heat transfer on a flat plate at different angles of attack (inclined solar collector) is close to completion.

- A computer program was developed for a conventional heat analysis of an air-heating collector.

- An experimental facility for experimentation with air-heating collectors was designed and constructed [6].

- A small facility for the visual and heat transfer studies of natural convection in enclosures was designed.

FUTURE ACTIVITIES

Contract Activities

- 3-d natural convection calculations for larger enclosures

- Further investigation of the influence of baffles on natural convection in enclosures

- The incorporation of a more accurate flow and heat transfer model in the absorber's tubes

- The completion of analytical (numerical) solution of the turbulent heat transfer on plates at different angles of attack to the wind (external convection), and experimental verification.

- Studies of coupled natural forced convection in solar air heaters

- Experimental studies of natural convection in enclosures, without and with internal baffles

- Recommendations for the design of more effective solar collectors.

Post-Contract Activities

- The conclusions about the design of more effective solar collectors shall be disseminated to the solar energy industry and to other research establishment.

- Encouragement to the use of whatever theoretical and laboratory scale methods we find to be effective in reducing heat losses from air-heating and water-heating solar collectors.

- We hope to be able to extend our post-contract to additional geometries and in particular to the determination of optimal partial baffling. We also hope to develop more efficient computer algorithms which will permit us to extend our computations to larger aspect ratios than now possible.

PUBLICATIONS/REPORTS/REFERENCES

[1] H. Ozoe, H. Sayama and S. W. Churchill, "Natural Convection in an Inclined Rectangular Channel at Various Aspect Ratios and Angles - Experimental Measurements," Int. J. Heat Mass Transfer, Vol. 18, pp. 1425-1431, 1975.

[2] Gerard F. Jones and Noam Lior, "Isothermal Flow Distribuiton in Solar Collectors and Collector Manifolds," Proceedings of the Annual Meeting of the AS/ISES, 2.1, Denver, CO, Aug. 28-31, 1978, pp. 362-372.

[3] H. Ozoe, K. Yamamoto, S. W. Churchill, and H. Sayama, "Natural Convection Patterns in a Long Inclined Rectangular Box Heated from Below," Part II, Three-Dimensional Numerical Results, Int. J. Heat Mass Transfer, 20, pp. 131-139, 1977.

[4] H. Ozoe, and S. W. Churchill, et al, "Natural Convection in Doubly Inclined Rectangular Boxes," 6th Int. Heat Transfer Conf.,Toronto, 2,NC-19, p.293,1978.

[5] H. Ozoe, N. Sato, and S. Churchill, "Experimental Confirmation of the Three-Dimensional Helical Streaklines Previously Computed for Natural Convection in Inclined Rectangular Enclosures," International Chemical Engineering, Vol. 19, No. 3, pp. 454-462, July 1979.

[6] R. Fromberg, S. Miller and N. Lior, "The University of Pennsylvania Facility for Testing Air Heating Solar Collectors," Report to DOE, in print.

ACKNOWLEDGEMENTS

Major contributions to this work were made by University of Pennsylvania graduate students Paul Chao and Gerard F. Jones, and by Professor Hiroyuki Ozoe from Okayama University.

COLLECTOR ARRAY STUDIES

UNIVERSITY OF PENNSYLVANIA
DEPARTMENT OF MECHANICAL ENGINEERING AND APPLIED MECHANICS

DE-AC04-78C-35319

DR. NOAM LIOR AND DR. HSUAN YEH

OBJECTIVE

A. To determine the optimized configuration of collector rows as a function of available collector-mounting area, inter-row spacing, row orientation, collector inclination, collector height, wind effects, geographic location in the U.S., and system cost.

B. To determine recommended collector-array piping options (e.g., series, parallel, parallel-series) based on the determination of total system performance as a function of flow rate, collector efficiency, pumping power and system cost.

BACKGROUND

An important problem in the design of solar collector arrays is that of determining collector piping configurations, (e.g., series, parallel, series-parallel) which would optimize useful energy collection against system cost. The question of flow distribution (manifolding) through an array, or bank of solar collectors, has not been adequately addressed so far. The only attempt conducted till recently was the study by Dunkle and Davey (1970), which has indicated that poor flow distribution may easily occur in actual installations, and would lead to high local temperatures in parts of a single collector or in some of the collectors. This leads to significant reductions in collector efficiency, which could be avoided if the proper method for manifolding is known and implemented.

An important problem in piping design for solar collectors is also pumping power. Parallel flow through the collectors leads to the smallest temperature rise of the heated fluid, and thus to highest collection efficiency. On the other hand, it requires a significantly increased total flow rate when compared to a series, or parallel-series, flow configuration. Increased flow rates may lead to significantly increased demand in pumping power, as well as to more costly pumping equipment. Collector piping thus needs to be optimized as a compromise between collector efficiency (influenced by flow rate and flow distribution), pumping power, and cost of hardware. There exists practically no well-founded design information about piping collector arrays.

In relation to this it is being found with an increasing frequency that the pipes and manifolds associated with solar collector arrays also leads to significant thermal heat losses. Obviously this field required attention, by taking into account the techno-economical parameters and constraints which are specific to solar systems.

Another important element in the design of collector arrays is the inter-row spacing and collector inclination, orientation and height. Present solar engineering practice follows almost invariably the following rules for the configuration of solar collector arrays:

A. The spacing between rows is to be sufficiently large so that no mutual shading occurs at any time of day.

B. The collector tilt from the horizontal depends mainly on the geographic latitude, and is usually equal to (latitude + 15°) in the northern hemisphere, following essentially the recommendations by Tybout and Löf (1970).

C. The collector orientation is to solar south. The system performance is not too sensitive to the exact orientation, and actually some localities show peak terrestrial solar flux before or after noon, depending on prevalent local smog, fog, or cloud conditions. Calculations performed at the University of Pennsylvania (Lorsch and Niyogi 1971) showed that a 23° deviation of vertical collectors from exact southern orientation produces only a 5% energy penalty for December and January, and a 33° deviation a 10% penalty.

D. Collector height is dictated usually by the collector manufacturer's standard size or by local building or zoning codes.

These criteria could be modified to obtain better system efficiency and economics when (1) the collector mounting surface is small, and then the allowance of some mutual shading (through closer row spacing) in periods when the sun is lowest results in a higher amount of energy collected over the season, due to the increased area of collectors, and (2) the effect of wind on the collectors' efficiency is altered due to the geometry of the array.

The identification, modelling, and analysis of these problems initiated by the Principal Investigators (cf. Lior 1976, Lior et al 1977, Jones and Lior 1978), and the computer programs developed for that purpose, allowed the conduct of this project, with aim to provide practical design recommendations for the design of solar collector arrays.

SUMMARY

A computer program, SOLRAY, ("SOLar arRay") was developed to allow optimal design of solar collector arrays. Given the type of collectors and solar system, and the available collector-mounting area, the combination of collector spacing, inclination,

orientation, piping configuration (parallel, series, etc.) and diameters, and pump, which produce highest net useful energy collected or optimal system life-cycle cost can be determined either through the sensitivity analysis provided or through a scheme which determines the optimum only. Facilities for the experimental verification of the program's results were designed.

TECHNICAL ACCOMPLISHMENTS

- A method was developed and published, to allow the selection of optimal insulation for solar systems (Jones and Lior 1978, 1979a, 1979b). A typical design graph is shown in Fig. 1.

- The University of Pennsylvania computer program SOLSYS (cf. Lior et al 1977) for the analysis of solar heating components and systems was significantly improved, both to serve this project and to allow more in-depth analysis than presently used programs allow. A manual is near completion.

- A comprehensive computer program was developed to analyze isothermal flow distribution in collectors and collector arrays (cf. Jones and Lior 1978 for its initial version). Fig. 2 shows typical results for flow distribution in collector arrays.

- A numerical model to analyze the effects of turbulent wind on the thermal performance of collector arrays was developed.

- A facility for the experimental investigation of wind effects on the thermal performance of collector arrays was designed (incorporating the University of Pennsylvania wind tunnel) and is close to completion (cf. Fig. 3).

- A facility for the experimental investigation of flow distribution in piping systems consisting of two manifolds connected by risers was designed.

- An instrument was designed and built to determine flow distribution in manifolds by measuring the exterior temperatures of the risers, but it has not been tested yet.

- A computer program was developed to analyze the thermal performance of collector arrays as a function of flow configuration. The program was run for a large number of cases to obtain generalized results. A typical result is shown in Fig. 4.

- A present-value life-cycle economic model was developed to determine also the economically optimal array configuration.

- A formal optimization program, utilizing the pattern-search technique, was written to be able to determine optimal arrays directly.

FUTURE ACTIVITIES

Contract Activities. Apart from some small amount of experimental work, the work is essentially complete, and the final reports are in preparation.

Post-Contract Activities

- The results obtained shall be disseminated to solar designers and engineers to provide them with a quantitative method for optimal design of collector arrays, including thermal insulation, array geometry, and piping scheme.

- It is planned to extend the analysis and experimentation.

PUBLICATIONS/REPORTS/REFERENCES

1. N. Lior, J. A. Lepore, and S. Shore, 1976, "Residential Solar Heating Retrofit in the Urban Environment," Proceedings of the Joint Conference of the American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 4, pp. 36-52. Winnipeg, Manitoba, Canada.

2. N. Lior, J. O'Leary, and D. Edelman, 1977, "Optimized Spacing between Rows of Solar Collectors," Proc. Intern. Solar Energy Society Conference (U.S. Section), June 6-10, 1977, Orlando, Florida.

3. Gerard F. Jones and Noam Lior, "Isothermal Flow Distribution in Solar Collectors and Collector Manifolds," Proceedings of the Annual Meeting of the AS/ISES, 2.1, Denver, CO, Aug. 28-31, 1978, pp. 362-372.

4. Gerard F. Jones and Noam Lior, "Optimal Insulation for Solar Heating Systems," Proceedings of the Annual Meeting of the AS/ISES, 2.1, Aug. 28-31, 1978, pp. 187-197.

5. Gerard F. Jones and Noam Lior, "Optimal Insulation of Solar Heating System Pipes and Tanks, Energy, The Internat'l Jrnl, 4, pp. 593-621, 1979a.

6. Gerard F. Jones and Noam Lior, "Optimal Insulation of Pipes and Tanks for Solar Heating Systems," Topical Report, Feb. 1979b, U.S. Dept. of Energy No. ALO-5319-2.

ACKNOWLEDGEMENT

Major contributions to this project were made by the University of Pennsylvania graduate students G. F. Jones, S. Bassler and Y. Menuchin.

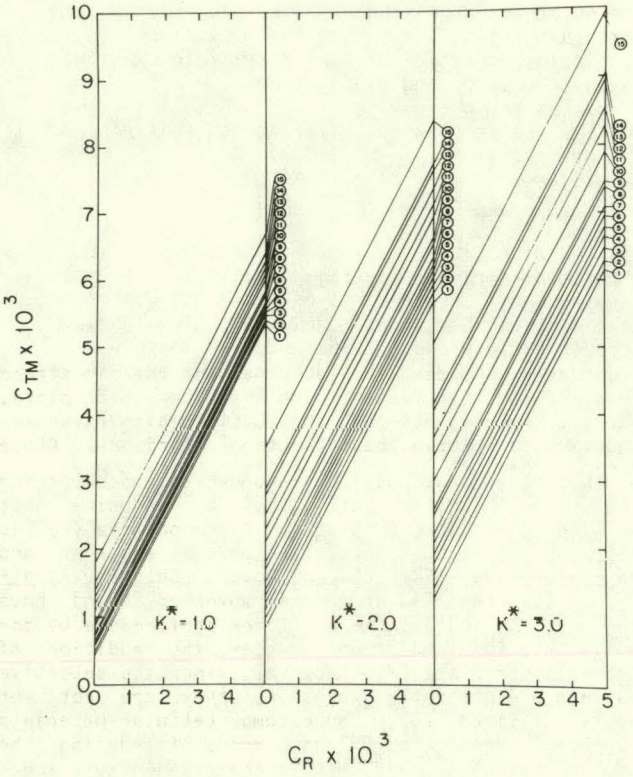


Fig. 1 Design Graphs for Optimal Insulation of Solar System Pipes and Tanks (Jones and Lior, 1979)

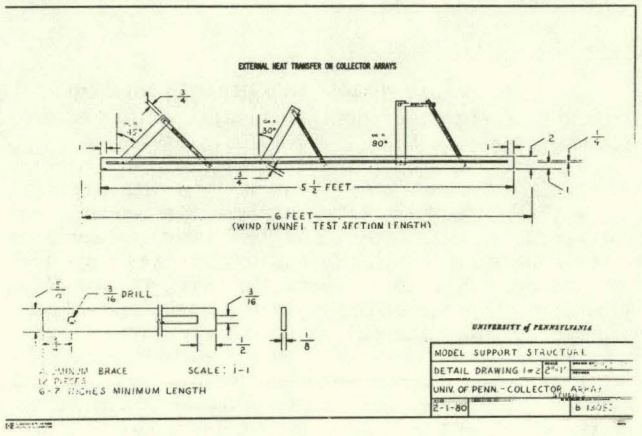


Fig. 3 Facility for Experimental Studies of External Heat Transfer Coefficients on Collector Arrays

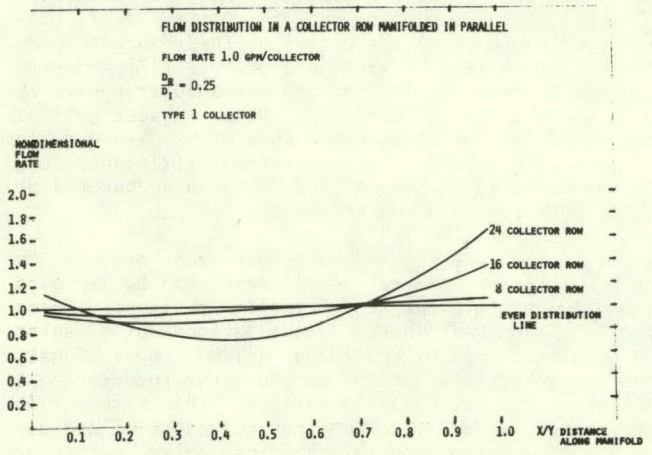


Fig. 2 Typical Flow Distribution in Parallel-Piped Collectors

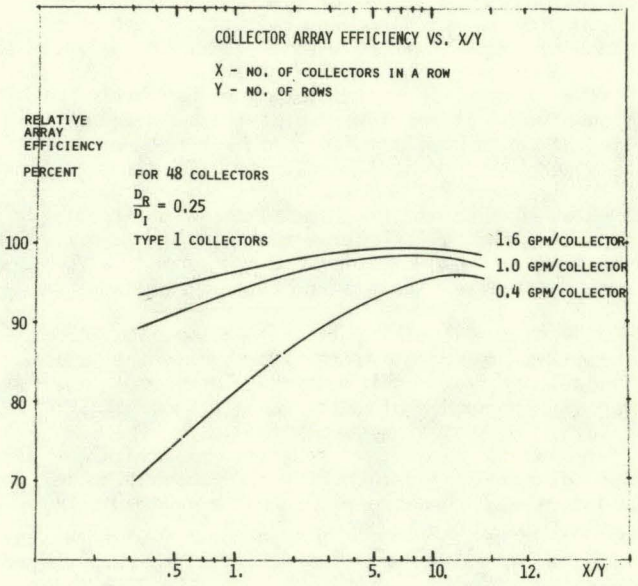


Fig. 4 Typical Sensitivity Analysis Results for Collector Array Energy Effectiveness (Compared to Arrays having Uniform Flow Distribution) as a Function of Array Configuration

FORCED AND NATURAL CONVECTION STUDIES ON SOLAR COLLECTORS FOR HEATING AND COOLING APPLICATIONS

HEAT TRANSFER LABORATORY
SCHOOL OF MECHANICAL ENGINEERING, PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA

CONTRACT NO. EM-78-C-04-5366

J. T. PEARSON

PERIOD OF CONTRACT: SEPTEMBER 11, 1978 THROUGH SEPTEMBER 10, 1980

OBJECTIVES

The work being performed is part of the national program for Research and Development in Solar Heating and Cooling. The overall objective is to stimulate the advancement of industrial, commercial, and professional capabilities for producing and distributing various solar energy systems. It is contemplated that the demand on fossil fuel supplies will be reduced through widespread use of solar energy (a) in the heating and possibly the cooling of residential and commercial buildings, (b) for heating service and process hot water, and (c) for the thermal needs of agricultural and industrial processes.

Specific objectives of this work are to obtain information on forced and natural convection in air-heating solar collectors through theoretical, experimental, and technological studies. Convective heat transfer and fluid mechanics relationships applicable to several solar collector configurations are being determined and will be documented in two primary areas. In Area 1, three absorber geometries are being considered: flat plate, flat plate with plane continuous and interrupted fins, and flat plate with corrugations. In Area 2, two permeable absorber geometries are considered: porous matrix and louvered surfaces.

The results will be presented in dimensionless form, whenever possible, as Stanton number or Nusselt number and friction factor as functions of Reynolds number and/or Rayleigh number with Prandtl number and geometry as parameters. In addition, simplified relations will be presented for air at 40°C.

The specific solar collector surfaces and geometries considered in these studies are those which, as a result of the literature survey, technology survey, and theoretical study, show the greatest potential for being efficient and cost effective in the most important applications.

Experiments are planned to test the critical aspects of the theoretical analysis. For each collector studied, the air flow rate per unit of collector face area is varied from about 0.1 to about 0.05 kg/m^{2}sec, while the radiative flux on the collectors is varied from about 100 to approximately 1500 W/m^2. The tilt of the collectors is varied from horizontal to vertical.

BACKGROUND

The basic design of an air-heating flat plate collector consists of a blackened absorber plate, one or more glass cover plates above the absorber, and insulation on the sides of and behind the absorber. Air is heated as it passes under and/or over the absorber plate. The major deficiencies in most air-heating collector designs are the relatively low heat transfer conductance between the absorber and the air stream and the large heat loss through the outer cover plate. Several improvements on the basic design have been suggested to improve the collection efficiency. Close [5]† has shown that passing air under the absorber increases the collection efficiency by reducing heat loss through the cover plates. A second advantage is the reduction of dust collection on the absorber and the under-side of the bottom cover. Selective coatings on the glass [6] or on the absorber [5,6] have been shown to improve the collector performance by approximately the same amount as does the addition of another cover plate [7]. However, since the selective coatings are presently expensive, they are not yet widely utilized [8]. Honeycomb cellular materials have been investigated [9] as a means of reducing the natural convection heat loss in the stagnant air space above the absorber. However, it was concluded that, for inclined collectors, the honeycomb material did not appreciably suppress natural convection. Applying a moderate vacuum in the air space above the absorber has also been suggested [10] as a means of reducing natural convection heat loss. Each of these design alternatives tend to result in increased cost of the air-heating solar collector. Consequently, future utilization of these suggested improvements should in most installations depend on the net cost of the energy savings derived.

Several researchers have modified the absorber plate geometry in the air-heating flat plate collector to obtain improved collection efficiency. Löf [11] utilized overlapped glass plates as the absorber in an air-heating collector. Buchberg et. al. [12] analyzed a porous absorber surface having rectangular honeycomb cells above a porous surface. Other investigations have used a porous absorber made of blackened guage [13] on screens [14]. The collection efficiency can also be improved by adding fins to the absorber [5] or using a corrugated absorber surface [15].

The works referenced above document methods by which collector thermal performance can be improved through more efficient heat transfer designs. These studies have contributed to the advancement of solar energy utilization by providing design, operational, and economic information to the solar industry on a variety of collector configurations. The objective of the present study is to continue to determine and document new and improved air-heating solar collector designs which have the potential of being efficient and cost effective.

† Numbers in square brackets refer to references, publications, or reports listed at the end of this report.

SUMMARY

The literature survey has been completed and the technology survey of air-heating solar collector manufacturers, designers, and users is being assembled.

Theoretical study has resulted in two papers [1,2] which are scheduled for publication this year.

The test facility for the project is now complete. The instrumentation has been selected, secured, and calibrated. Based on the theoretical study, results of four specific surfaces have been selected for experimental study. They are a flat plate surface which will be the base case of comparison, a flat plate absorber surface with corrugated convection channels attached to the back side, a louvered absorber surface, and a flat plate absorber with a finned channel on the back side.

Although not officially a part of the research objectives, the research activities being pursued led to participation in the Indiana Solar and Energy Exposition which took place in October, 1979.

TECHNICAL ACCOMPLISHMENTS

● Literature Survey. The literature applicable to forced and natural convection in channels and confined spaces and the literature on air-heating solar collectors relevant to the research being conducted have been collected and surveyed. The results to date from this survey are contained in the semiannual reports [3,4] on this project. The information obtained from the survey has been used in the detailed planning of theoretical and experimental work.

● Technology Survey. Information on currently manufactured air-heating solar collectors and the technology employed in their manufacture has been gathered from manufacturers and the open market. The objective of the survey is to identify the present technology for the production, distribution, and use of air-heating solar collectors and to determine the factors which encourage and discourage the present and future use of air-heating solar systems. In the spring of 1979, 264 questionnaires were mailed to companies and individuals involved in the design, production, distribution, and/or installation of air-heating solar collectors. Twelve percent of the questionnaires were completed and returned. The results have been tabulated and will appear in the April 1980 semiannual report.

● Test Facility. The test facility consists of three components: the radiative heat source, the solar collector, and the air-handling system. A photograph of the present test facility is shown in Fig. 1. The electrical controls are combined into a single control console that is located behind the facility. Details of the test facility design are shown in Figs. 2 and 3.

The radiative heat source, visible in Fig. 1, consists of 32 General Electric Model PS25-300 M/IF, 120 volt, 300 watt lamps arranged in a four by eight pattern. An extensive study was conducted to determine which manufactured lamps were best suited for this application, and it was found that these ordinary, inexpensive lamps are quite satisfactory because of their spectral distribution and their uniformity in directional intensity. The lamps are controlled in groups by eight autotransformers mounted on the control console. Each group of four lamps is symmetrically located around the center of the array. The lamps are cooled by ambient air drawn through an annular region at the base of the lamps and exhausted outside the building. The 40-inch space between the lamps and the collector is enclosed by five polished aluminum panel that reflect radiation onto the collector surface. In the view shown in Fig. 1, only the rear and top panels have been installed.

The solar collector shown in Fig. 2 consists of a 1/8" thick aluminum absorber plate and a single 3/16" Sunadex cover glass manufactured by ASG. The absorber is coated with 3M Nextel brand 101 black paint. The bottom of the collector is insulated with two inches of fiber glass insulation board. The sides of the collector are slotted so that any test collector between 2 inches and 10 inches deep can easily be installed without disturbing other portions of the facility. The entire facility can be tilted by a modified garage door opener to any inclination angle between 0° and 90°.

The air-handling system, shown in Fig. 3, circulates and conditions the air to provide steady-state operation. The system consists of a blower assembly, a heat exchanger, flow-metering nozzles, air mixers, thermocouples, and related duct work. The blower assembly is a Barry Series 70 centrifugal fan and motor. The fan is cushion mounted on air bellows vibration isolation mounts (Model No. SLM-1 manufactured by the Barry Wright Corporation) to reduce the transfer of vibration from the fan to the solar collector. A bypass damper helps control the air flow rate, which is measured as the air passes through a nozzle board consisting of five ASME flow nozzles located upstream

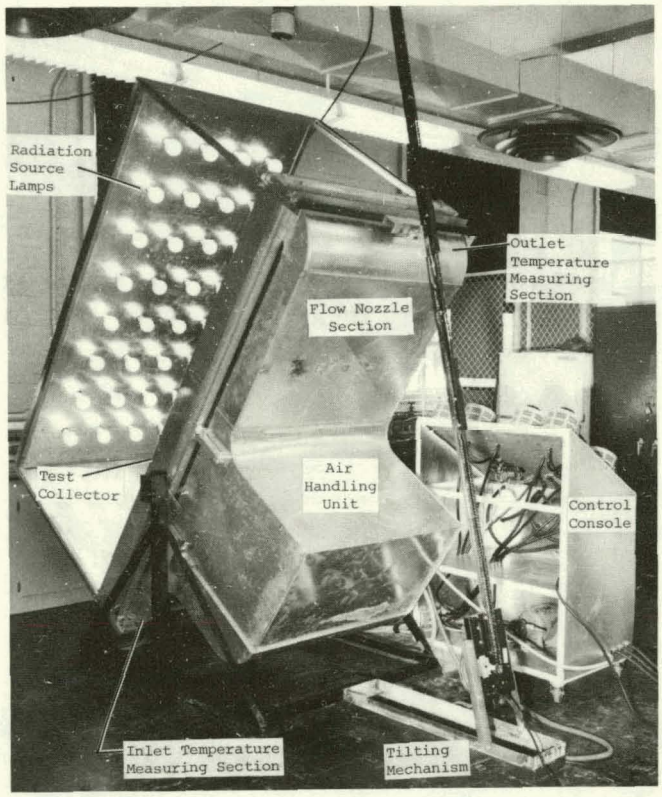


Fig. 1. Air-heating solar collector test facility with three radiation source side panels removed.

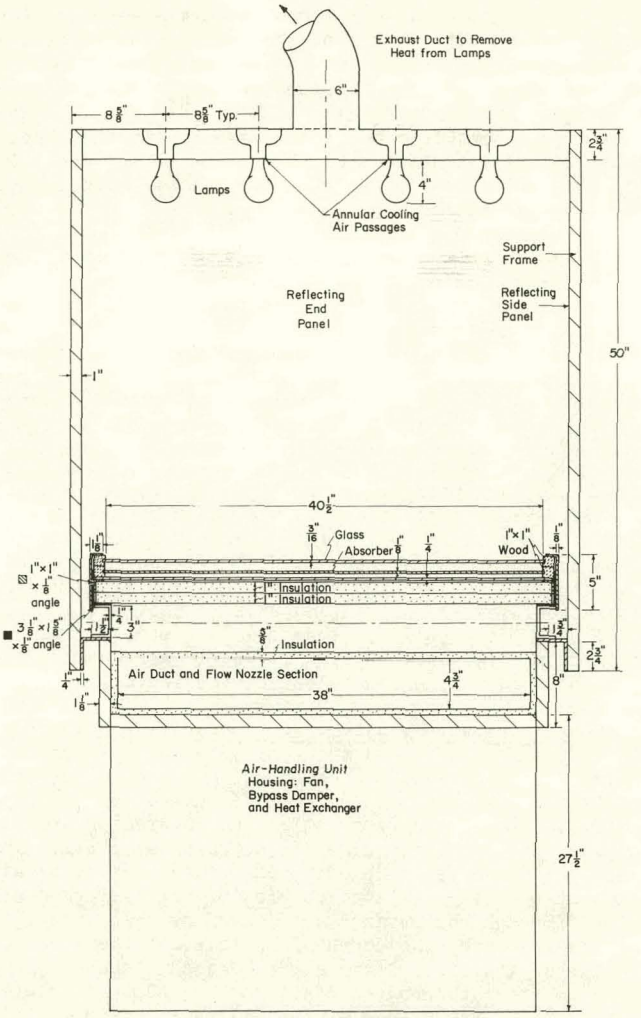


Fig. 2. Cross-sectional view of test facility with flat plate collector installed.

of the blower assembly. The inlet air temperature is controlled by the heat exchanger. The air temperature at the test collector inlet is measured by thermocouples located in the collector inlet region. A detailed view of the inlet region is shown in Fig. 4. Before the air temperature is measured, the air passes through an air mixer consisting of two 1/8" phenolic-impregnated linen sheets separated by 2" wide galvanized sheet metal baffle-supports. The air passes through ten 2" diameter holes in the lower sheet, around the baffle-supports, and through five 2 3/4" diameter holes in the upper sheet where nine thermocouples measure the air temperature. The air then flows into the collector and passes on both sides of the flat plate absorber illustrated. The temperature of the air leaving the collector is measured by thermocouples located downstream of another air mixer at the collector outlet.

● Instrumentation and Calibration. The following is a list of instrumentation selected for use in measuring the temperatures, flow rates, and other quantities in the collector.

1. Esterline Angus Model PD2064 Programmable, Data-Logging System, 62 Channels with paper tape printer.
2. Flow nozzle board having five 2" diameter flow nozzles.

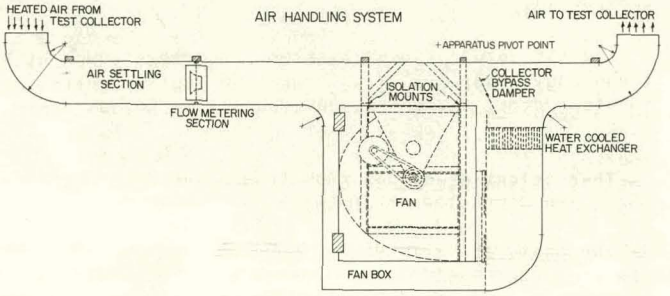


Fig. 3. Diagram of air-handling system for the air-heating solar collector test facility.

3. Flow nozzle board having two 1 1/2" diameter, two 1" diameter, and one 3/4" diameter flow nozzles.
4. Four precision 2" inclined micromanometers designed and built in the Heat Transfer Laboratory.
5. Omega Copper/Constantan thermocouple wire, Cat. No. NN-T-30, 30 B&S gage, nylon insulation.
6. Eppley Black and White Pyranometer Model 8-48.
7. Fisher and Porter Stabl-Vis No. 4H-60 Rotameter flowmeter.

The instrumentation used to measure the temperature distribution and the flow rate in the collector has been calibrated to the precision necessary for the project. The zero offset in the Esterline Angus data logger, which is used to record the thermocouple temperature readings, has been determined for each channel. Temperature measurements can now be made with a precision of ±0.1°C. Thermocouple arrays have been mounted downstream of the inlet and outlet air mixers,

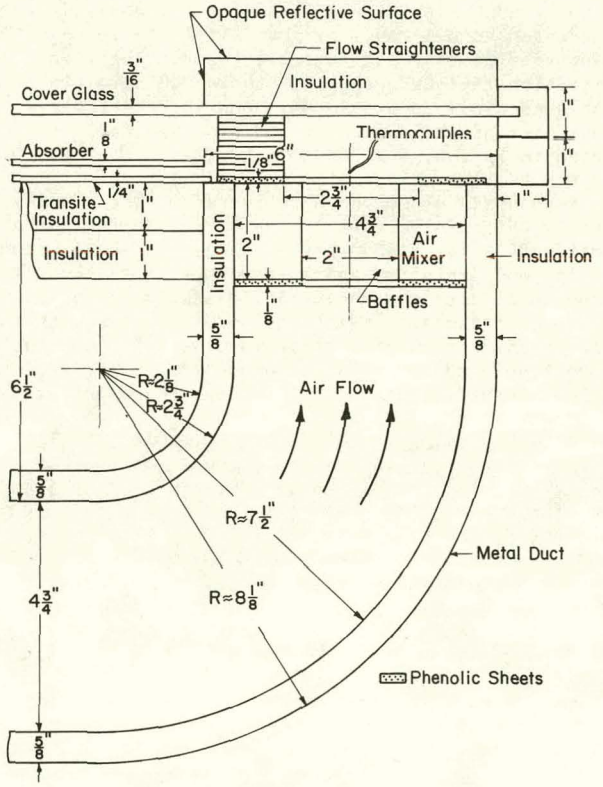


Fig. 4. View of inlet section to test collector showing air mixer and temperature probe locations.

designed in accordance with ASHRAE Standard 41.1-74, to measure bulk air temperatures. The thermocouple arrays have been adequately shielded from the radiation source. Flow nozzles, designed and instrumented in accordance with ASHRAE Standard 37-69, have been installed to measure the collector air flow rate. The coolant water flow meter has been fitted with a special float and has been calibrated to sufficient precision for use as a flow indicator.

The radiative flux from the radiation source apparatus has been fitted with a variable density grid filter to give a uniform flux at the test collector surface. The maximum variation in incident radiation flux at rated power has been reduced from 25% to less than 5%. Additional measurements at settings above and below rated power to the lamps are necessary to complete this calibration.

• Theoretical Analysis of Base-Case Collector. Analysis has indicated that in the case of air-heating flat plate collectors having impermeable absorbers, flow above the absorber, appears to be better from the standpoint of cost and thermal performance than arrangements with flow above the absorber or above and below the absorber [4, Ch 5]. Based on this study, no further consideration will be given to air-heating solar collectors having impermeable absorbers and air flow above the absorber.

• Incentive for Increasing Absorber to Air Conductance. An analysis has been conducted [4, Ch 5] to determine the incentives for increasing the UA product between the absorber and the air. The quantity U is the overall thermal conductance (based on A) between the absorber and the air, and A is the heated surface area in contact with the flowing air. It has been found that the collector efficiency, η, can be increased considerably by increasing the value of UA over that of the base case collector. Therefore, cost effective designs are being studied which will permit the desired increase in UA. One such arrangement being analyzed theoretically and experimentally is indicated in Fig. 5.

• Analysis of Louvered Collectors. The family of air-heating collectors illustrated in Fig. 6 having inclined louvered absorber surfaces has been studied using an analysis which accounts for conduction, forced convection, and thermal radiation exchange [2]. A two-band radiation exchange model describes the surface and material properties for the solar and thermal radiation bands. Louver shading effects are included, with the shaded portions of louvers being analyzed as

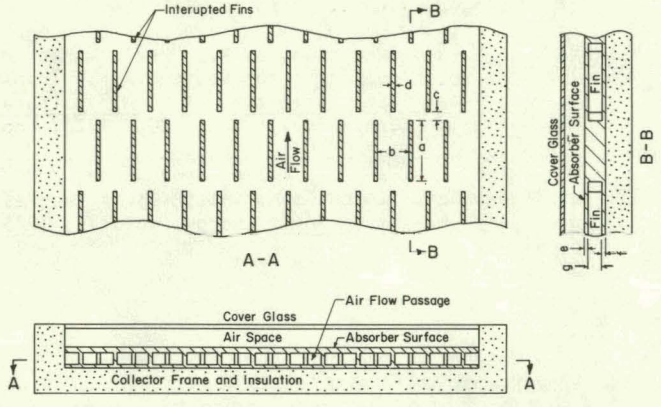


Fig. 5. Interrupted fin, flat plate solar air heater.

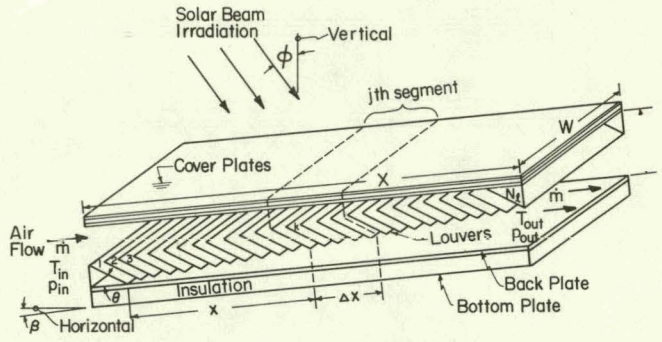


Fig. 6. Nomenclature for louvered air-heating solar collector.

fins. To facilitate the thermal analysis, the collector is divided into segments, with each segment having several convection/conduction nodes and several radiation surfaces. A system of simultaneous algebraic equations is derived for each segment and is solved by iteration. After calculating the steady-state temperature distribution, the pressure drop across the collector is determined by a model accounting for viscous, thermal, and gravitational effects.

• Experiments with a Corrugated Absorber Arrangement. An absorber configuration similar to a Solaron arrangement [16] is being investigated experimentally. The test apparatus is illustrated schematically in Fig. 7. A rectangular corrugated plate is bonded to the underside of the absorber plate. The absorber is heated by a uniform surface heat flux using blanket-type electrical resistance heaters. Air flows through the passageways formed by the underside of the absorber, the corrugated plate and the top side of the back plate. Because of a good thermal bond between the corrugated plate and the absorber plate, all surfaces are heated except the back plate. This arrangement increases the UA product between the absorber and the air, thereby increasing the thermal efficiency over that of the base case flat plate collector with flow behind the absorber. Air passageways 1 and 2 indicated in Fig. 7 are of different geometries and have different thermal boundary conditions. Therefore, the experimental apparatus is designed to measure the flow rates and heat transfer separately for each type of passage. Information from these experiments will make it possible to analyze the performance of this type of arrangement.

• Solar Course. As a result of this research project and due to the demands of engineering and physical science students, a series of three one-credit-hour courses on solar energy systems is being offered by Professors Viskanta, Pearson, and Koh. The topics emphasized are fundamentals of heating and cooling, and advanced applications. The three-course sequence was first offered in the fall of 1979. It is offered each semester, and the enrollment has been between 30 and 43 students for each course. The course sequence is taught at the senior level, but several graduate students also take the three course series under the ME 597 Selected Topics in Mechanical Engineering course for graduate credit. A higher level of performance is required from graduate students on homework and examinations.

• Solar and Energy Conservation Exposition. The Indiana Department of Commerce and the Indiana Solar Resources Advisory Panel sponsored the Solar and Ener

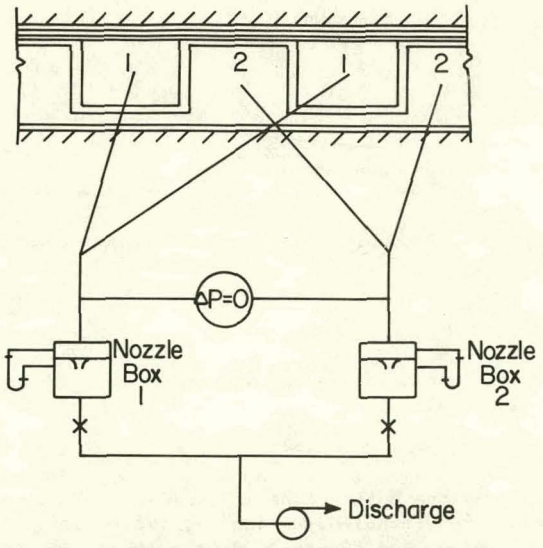


Fig. 7. Flow arrangement and configuration of a corrugated surface test section.

gy Conservation Exposition in Indianapolis on October 19, 20, and 21, 1979. Members of the research team of this contract took the initiative to organize a team of seniors and graduate students to help design and build displays and exhibits for the exposition. The Purdue exhibit covered the space of four 10 foot by 10 foot booths. The space of one booth was used for an exhibit on this research project.

FUTURE ACTIVITIES

Contract Activities

The contracted work is proceeding on schedule and will be completed in late summer 1980. The major tasks remaining to be done are the collection and analysis of experimental data on the several absorber configurations selected for study. As the experimental results become available, the interpretation and evaluation process will proceed such that a final report can be prepared in August.

Post-Contract Activities

Work on this project has shown that while air-heating collectors are major components requiring research and development, the other components of the system also require the development of sound design procedures in order to make it possible for designers, manufacturers, and installers to provide the public with efficient, cost-effective solar heating systems. At the present, a proposal is being prepared for research which should produce results useful to air-heating solar system designers and component manufacturers for the midwestern region of the United States.

PUBLICATIONS

1. Diab, R. M., Pearson, J. T. and Viskanta, R., "A Two-Dimensional Analysis of Flat Plate Air-Heating Solar Collectors," accepted for publication at the 1980 National Heat Transfer Conference, Orlando, July 28-30, 1980.

2. Christopher, D. M. and Pearson, J. T., "Parametric Analysis of Louvered Air-Heating Solar Collectors," accepted for publication at the ASME Winter Annual Meeting, Chicago, Nov. 16-21, 1980.

REPORTS

3. Pearson, J. T., "Forced and Natural Convection Studies on Solar Collectors for Heating and Cooling Applications," DOE Contract No. EM-78-C-04-5366, Semiannual Report, April 1979, 66 pp.

4. Pearson, J. T., "Forced and Natural Convection Studies on Solar Collectors for Heating and Cooling Applications, "DOE Contract No. EM-78-C-04-5366, Semiannual Report, October 1979, 72 pp.

REFERENCES

5. Close, D. J., "Solar Air Heater for Low and Moderate Temperature Applications," Solar Energy, Vol. 7, 1963, pp. 117-124.

6. Siebers, D. L. and Viskanta, R., "Thermal Analysis of Some Flat-Plate Solar Collector Designs for Improving Performance," Journal of Energy, Vol. 3, 1979, pp. 8-15.

7. DeWinter, Frances, "Solar Energy and the Flat Plate Collector: An Annotated Bibliography," ASHRAE, 1975.

8. Whillier, Austin, "Black-Painted Solar Air Heaters of Conventional Design," Solar Energy, Vol. 8, 1964, pp. 31-37.

9. Charters, W. W. S. and Peterson, L. F., "Free Convection Suppression Using Honeycomb Cellular Materials," Solar Energy, Vol. 13, 1972, pp. 353-369.

10. Eaton, C. B. and Blium, H. A., "The Use of Moderate Vacuum Environments as a Means of Increasing the Collection Efficiencies and Operating Temperatures of Flat Plate Solar Collectors," Solar Energy, Vol. 17, 1975, pp. 151-158.

11. Löf, G. O. G., "Performance of Solar Energy Collectors of Overlapped- Glass-Plate Type," MIT Solar Energy Symposium (1950) Open Space Heating With Solar Energy, MIT, 1954.

12. Buchberg, H., Lalude, C. A., and Edwards, D. K., "Performance Characteristics of Rectangular Honeycomb Solar-Thermal Converters," Solar Energy, Vol. 13, 1971, pp. 193-221.

13. Bliss, R., "Multiple Gauge Flat Plate Solar Air Heaters," Proceedings World Symposium on Applied Solar Energy, Phoenix, 1955, pp. 151-158.

14. Chan, K. V. and Henderson, S. M., "Performance of a Matrix Solar Collector for Heating Air," Trans. of the American Society of Agricultural Engineering, (Gen. Ed.), Vol. 20, 1977, pp. 552-561.

15. Satchunanathan, S. and Deonarines, S., "A Two-Pass Solar Air Heater," Solar Energy, Vol. 15, 1973, pp. 41-49.

A POINT FOCUSING FRESNEL SOLAR CONCENTRATOR FOR SOLAR HEATING AND COOLING: A NATURAL WHEN YOU CAN USE 250°F TO 750°F

RENSSELAER POLYTECHNIC INSTITUTE

EG-77-G-04-4161

William Rogers, David Borton

9/30/77-12/31/79

INTRODUCTION

When we began our development program six years ago, we recognized that to compete most successfully with conventional sources of energy in commercial and industrial markets, solar equipment had to be able to provide air conditioning and steam at industrial process temperatures. We also live in the rather harsh environment of upper New York State and know that a solar device must be able to collect as much sun as possible when it is out, and, more importantly, withstand the damaging effects of ice, snow and wind. In the past six years we've also come to appreciate many other aspects which make a solar collector compete as an energy source. This paper is an account of our perceived attributes of medium temperature collectors, and our progress in designing a system which fulfills a wide range of goals.

DEFINING THE PARAMETERS OF A SOLAR ENERGY SYSTEM

Initially we set out to design a solar collector in which the hardware implemented solutions to the following challenges:

1. **High performance in northern U.S.:** deliver 250° to 750°F, withstand 90 mph winds, protect mirrors from ice, snow and hail, and collect the maximum of available sunlight;
2. Low installed cost: minimize FOB cost, shipping costs, site specific design costs, and installation costs;
3. Low operating costs: maximize durability; minimize maintenance, and operate with low parasitic losses;
4. Adaptability: enhance ability to utilize the same collector for a variety of applications;
5. Reliability and safety: minimize consequence of failures and insure that the focal region cannot come below the receiver.

Two full years of research and development sponsored by the DOE Solar Heating and Cooling Branch built upon our success with three prior prototypes and addressed the above criteria. Although the overall goals of our development program have been lofty, we have succeeded in building a new generation of collectors which meet the above challenges during this contract period. Part of our success can be attributed to our having only four people involved in the entire effort. Communication problems did not arise since those who implemented goals in hardware were the same ones who designed, fabricated, assembled, and tested it. The full impact of one design problem was felt when unassembled drive subsystems had to be installed on top of a thirty foot structure during windy winter weather. Because the designers were the ones who froze their fingers, future designs immediately reflected the importance for preassembly of parts in a factory climate.

IMPLEMENTATION OF THE DESIGN

During the contract period we have successfully designed, manufactured, assembled, and interfaced a 70 KWth model (see figure 1) with a steam heating system and a steam fired absorption chiller. The unit has 80 square meters of reflective surface comprised of 864 one foot square mirrors mounted 8 per reflective column. Two drive trains provide the motion necessary to follow altitude changes of the sun. The entire unit rotates to track direction changes of the sun. Key features which enhance performance include:

1. Use of thin, low-iron, second-surface, silvered flat glass mirrors to provide maximum reflectivity and specularity,
2. Minimization of pointing inaccuracies due to structural deflections through a design which distributes the loads to the base of the structure and allows wind to pass through the concentrator,
3. Microprocessor control which insures a tight focus through use of sensors in the receiver and mirror protection, with automatic rainwash,
4. Use of a cavity receiver to minimize heat losses,
5. Minimization of power required to track the sun and operate the heat transfer loop when water is used in a boiler, and
6. Self-programmed tracking, when the sun is not out, which allows a very small motor to be used for the azimuth drive. (This feature also makes elaborate alignment procedures during setup unnecessary and does not require any precise shaft encoding system for position sensing.)

Lifetime cost factors include the selling price of the collector, installation costs, operating costs, parts replacement, and maintenance costs. The gamut of these costs has been thoroughly considered during the years of research and development. Features have been incorporated which allow the collectors to be operated safely without attention, make them relatively easy to assemble without injury, allow them to be made out of many identical pieces easily mass produced and handled by one person, incorporate reliable microprocessor controls and inexpensive drive components, and allow all parts to be easily maintained and replaced, if required.

For units using a boiler or high temperature heat exchanger, the receiver can be lowered, and the monotube heat exchanger (less than $100 of materials for current designs) replaced in less than an hour.

Optical alignment of the 108 reflective columns of the latest unit can be accomplished by two people in 10 minutes, once the structure has been aligned, a process which takes about an hour. This feature insures that the machine can be aligned in a very small

window in clouds or at a precise sun altitude for critical work.

Operating costs are low since the axis of rotation of each reflector column is through its center of gravity. Only friction need be overcome for column otation. One inch-ounce of torque per column has een adequate on designs implemented to date. Because the columns rotate so slowly during tracking, two small motors with correspondingly small power requirements are capable of moving the 108 columns. Likewise, a small motor is used for azimuthal tracking since only rolling resistance need be overcome.

Features of the electronic controls aid in preventive maintenance of the system by documenting operating parameters and recording modes of failure. An integral digital voltmeter allows the operator to "monitor" the control signals on the various channels.

There is no cumulative play in the column drive mechanism and, because of the minimal forces involved, the long moment arms and the very minimal motion per day, the plastic bushings of the drive linkage, which are not exposed to the UV of sunlight or weather, are expected to last the 25-30 year life of the machine with wear not exceeding tolerable allowances.

Adaptability has been achieved through use of a microprocessor control package. Heating with steam, hot water or air, and cooling with rankine or absorption air conditioning systems can be implemented using either water or a heat transfer oil as a medium. High intensity solar cells or a stirling engine can directly utilize the flux at the focus while allowing secondary use of the cooling fluids for heating.

Land use patterns and solar availability prevent the economic use of central power tower collection systems in the northeast. The use of modular collectors allows flexibility in system design and, as each unit is installed, its output can be used immediately. A small system can be augmented as experience and economics indicate. If a problem develops in a single unit, it does not affect the rest of the units.

To provide the reliability to withstand wind-loading when the reflector surface acts as a sail, a support structure has been designed which transmits the load through the space frame structure, wheels and central pivot to the distributed collector supports. Positioning the mirrors in the inverted stow position, except when the system is in operation or in rainwash, minimizes deterioration of the reflective surface due to dirt, ice, snow, and hail, or vandals. It also allows the wind to blow through the slats like open venetian blinds.

Without stringent control of the high energy flux at the focus, the concentrated solar radiation can become destructive and dangerous. To insure safety, electronic and mechanical limits as well as operational interlocks have been built into the system. The reflective columns remain stowed until conditions for safe operation have been met, and, in the case of an unsafe condition, they automatically return to stow. To prevent a wind blown projectile from damaging all the interconnected reflective columns, reflective columns are of a break-away design, so that, if one is torn out by force (three times greater than any normal snow or wind load), it breaks away leaving the remaining columns operational. The drive mechanism will include a similar feature for torque-induced break-away of single or groups of reflective columns.

The most important tool which allows development of a sophisticated inexpensive solar collector is the microprocessor. The control system is based on a microcomputer which provides flexible control for optimum energy collection. The control can be implemented by a "one chip" microcomputer in production quantities at about the cost and complexity of TV type games. Prototypes have been developed using a multiple chip approach. The control program firmware resides in read only memory, ROM. (The prototypes use EPROM which is erasable.) The program implements time-sharing of a real time clock, the control logic and a variety of other functions.

The microcomputer keeps track of sunrise and sunset times as well as collector position. During daylight hours the control "looks" to see if the sun is out. If the sun is out, the computer checks the azimuth and moves the collector east or west depending on the first level of azimuth sensors. When the shadowband senses azimuth is correct, the computer checks the elevation and rotates the mirrors until the focused solar power hits the receiver. When the microcomputer detects power at the receiver it uses the second level of sensors to optimize the position of the focus in the center of the receiver.

When the sun is out and power is being collected, the microcomputer stores the sun's azimuth value in memory, so that when the sun is not out, the collector can use this information to track the sun. The ability of the collector to follow the sun behind clouds allows the use of inexpensive low power drive motors because the collector does not have to quickly traverse a long way to "catch up" to the sun when it comes out.

The microcomputer stores the mirrors in an inverted position whenever the sun is not out for a programmed period of time or when high wind or other "stow" conditions occur. An exception to this is the sensed availability of rain (above freezing temperatures) of sufficient quantity to wash the mirrors. When this occurs, columns are positioned at an angle most appropriate for allowing rain to wash the mirrors.

Prototype controllers / data loggers have used both analog and digital sensor inputs. In the first case, the input is digitized by a multiplexing A/D converter attached to the computer data bus. In the other case, the electronics at the sensor convert the analog light inputs to digital signals that are input to parallel ports of the computer. At this time the analog system seems most cost effective and offers the bonus of a built-in user oriented digital voltmeter as a feature.

Since the controller time-shares the functions, a routine can easily be added to keep track of maintenance information such as hours of operation, number of motor or pump cycles, and any other information which indicates system wear or system performance.

The prototype controllers have time-shared routines that are keyboard selectable. These routines use displays to convey information to the collector operator. This information is currently available only at the microcomputer location. However, it could be made available to a remote status display station or to any other large or small computer.

The complete control system is flexible and can be adapted to a variety of applications. The control programs can also be expanded to handle other functions such as load and demand control. Because there are two levels of sensors, the collector can tolerate mechanical misalignment and small structural changes of the collector structure or the receiver support without any change in pointing accuracy.

PERFORMANCE AND COST

Tracking in two axes would allow any solar collector to make optimal use of available sunlight, eliminating cosine losses and the end losses of parabolic troughs. Concentration schemes by increasing

the energy flux, reduce the size of the heat exchange surface and at the same time reduce losses associated with the receiver. These benefits have their associated drawbacks. Tracking adds complexity and cost to equipment while concentrating optics above a ratio of 10 or so, eliminates the utilization of diffuse solar radiation. For six years we have been balancing these benefits with their associated costs in order to design a cost effective modular collector which is able to deliver heat in the 250°F to 750°F range efficiently, is simple to manufacture and practical to install and operate.

Loss ranges verified by operating performance associated with the collectors we have developed are as follows:

1. Cosine losses, shading by receiver and cables: 1-2% dependent on time of day and season;
2. Reflective surface losses: 5-20% dependent on glass iron content, silvering, surface dirt, and specularity;
3. Pointing errors: 1-10% dependent on mechanical tolerances, and off-axis effects; and
4. Scattering effects: 0-2% dependent on atmospheric conditions.

Optical efficiency, the result of the combination of the above factors, lying in the 66-93% range is typically above 88% with low iron glass, and average dirt and sun conditions. Thermal performances of receivers are difficult to quantify because of effects of shape, absorptive coatings, varying convective losses, and flux traps. A flat pancake type receiver, (see figure 2), without convection suppression, blackened with a non-selective black paint, delivers 85 to 92% of the energy incident at the aperture at 500°F.

Figure 3 shows collector cost per square meter as a function of size during the second year of production at 1000 units per year.

THE FUTURE

In order to pursue commercialization of this technology, we have formed a corporation, Power Kinetics, Inc. Further R+D in this and in application areas will be pursued jointly with Rensselaer Polytechnic Institute. The following are most important for future investigation:

1. Ease of manufacturing and speed of installation must be balanced against the cost of materials in one more iteration of design.
2. Since every near-term installation will require a monitoring subsystem, additional software will enable the system control package to provide the data-logging function.
3. Long term performance data will be acquired along with weather information in order to establish the actual economics of the system.
4. Further receiver development is essential for a full understanding of the parameters of the system.

ACKNOWLEDGEMENTS:

We are grateful to Dr. Frederick H. Morse and Dr. Steve Sargent who were sufficiently openminded and adventurous to take a chance on a totally new technology. Equal thanks also go to Dr. Charles Bankston and Dr. Kirk Collier for their continuing support, guidance and perception of the value of our work. Besides the above individuals from U.S. DOE Solar Heating and Cooling Program we would like to thank James Larocca, Chairman, and Dr. Rudolf Wiley, Manager-New Energy Technologies, of the N.Y.S. Energy Research & Development Authority, for their support.

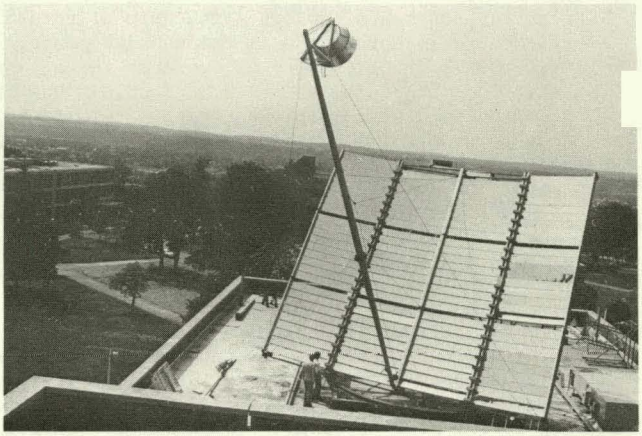


Figure 1

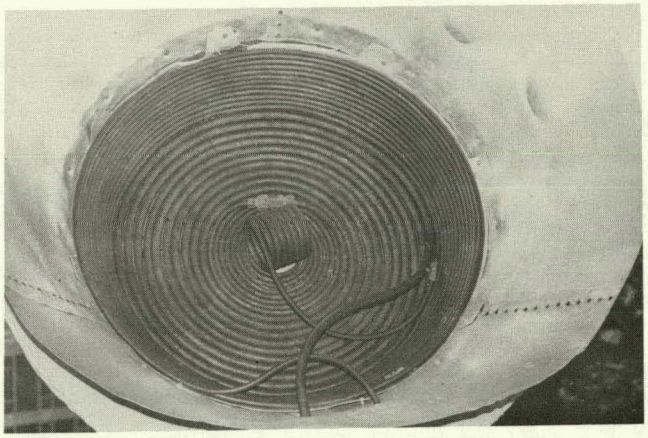


Figure 2

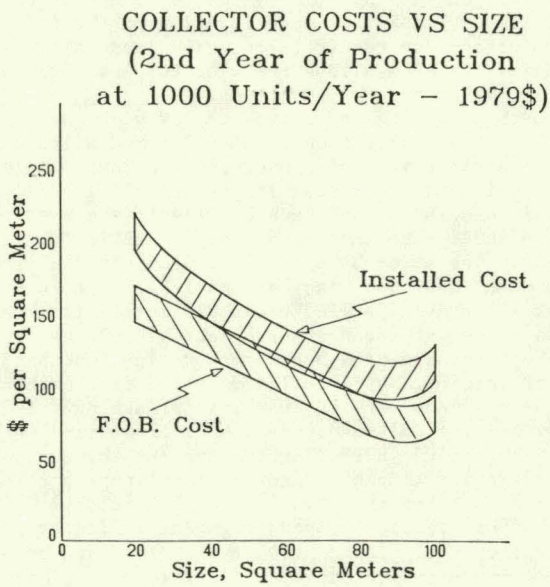


Figure 3

IMAGE COLLAPSING CONCENTRATORS

SOLAR ENERGY TECHNOLOGY, INC.

DE-FG04-77CS 34163

CARLYLE J. SLETTEN

OCTOBER 1977 to AUGUST 1980

OBJECTIVE

Develop and demonstrate new synthesis theories for the design of wide-angle Fresnel Lenses and accompanying Image Collapsing Subreflectors to maximize optical efficiencies and concentration ratios on non-tracking solar collectors. Construct a model collector and make thermal measurements on the new concentrator using vacuum and other selectively coated absorbers.

CONCEPTS

The cylindrical Stepped Prism Lens shown in cross section in Fig. 1 is designed to focus perfectly at $\pm$ 25° in the elevation angle plane and actually focuses very well over a 60° elevation arc. A typical elevation plane pattern is shown in Fig. 2. The lens also focuses well over a range of azimuth angle incidence from +60° to -60° but with focal shortening. The especially contoured mirror on the left side of Fig. 1 reflects nearly all the incident solar rays over these wide angular sectors onto a fixed absorber shelf shown between points F_o and P_o. The subreflecting mirror effectively collapses the broad focal image of the lens onto the shelf and corrects for focal shortening on oblique angle incidence resulting in a constant concentration ratio of approximately 3. Subreflector surfaces can be segmented to produce higher concentration ratios. These focusing wide-angle lenses can be used in tracking modes for very high concentration ratios, and the lens dimensions can be scaled to accommodate absorbers of different sizes.

SUMMARY

This research and development project has given to the solar technology community a new methodology for the design of wide-angle Fresnel Lenses and for the synthesis of subreflector contours to concentrate broad focal images onto small fixed strips. These new mathematical concepts have been verified on a model concentrator by analytical and laser ray tracing and by thermal testing. Based on thermal measurements made on the small collector section shown in Fig. 3, a full scale collector efficiency of greater than 50% is predicted over most of the 60° X 120° acceptance zone. Experimental work is underway with vacuum absorbers to determine Image Collapsing Collector characteristics with these improved absorbers. A cost analysis for the manufacture of these collectors is being conducted.

TECHNICAL ACCOMPLISHMENTS

- The new stepped lens synthesis procedure develops iteratively the prism face angles for the Fresnel steps beginning at the edge of the lens. By skillful use of analysis and computer techniques the center prism surfaces can be nearly vertical (see Fig. 1 and Fig. 4) and the unstepped lens surface can be closely approximated by a smooth circular arc. Step shadowing losses can be reduced to less than 12% for worse case solar incidence. Computer algorithms have been developed for stepped lens with facets on inside or outside surfaces.
- The subreflector contours are computed also by a new iterative synthesis technique that reflects the edge ray of the lens to an axial focal point (F_o in Fig. 1) of the subreflector while directing all other rays in the focused bundles onto the shelf between F_o and P_o. F_a is the on-axis focal point of the lens with azimuth and elevation angle incidence zero. Many subreflectors with different concentration ratios and optical efficiencies were synthesized by both incremental and envelope theory mathematics.
- SET, Inc. has carried out very thorough ray tracing analysis on these lenses and subreflectors. A new ray tracing technique was devised for ray tracing on the sack-like subreflector contours. Using these ray tracing methods the energy distributions on the absorber shelf were calculated for a wide range of solar incidence.
- A model concentrator was constructed using an acrylic stepped prism lens 30½ cms by 30½ cms in aperture with an image collapsing subreflector made of highly reflecting film. Thermal tests were made on the collector according to Bureau of Standards practices using an absorber made of black chrome coated copper tubes. This small collector section yielded results which, when corrected for avoidable losses, indicated that thermal efficiencies of 60% are possible.
- A detailed comparison of performances was made on a concentrator employing a nearly flat aperture lens with prism facets on its outside surface with the curved aperture lens of Fig. 1 having prisms on its inside surface.
- A patent application has been filed on an Internal Absorber Collector having about the same optical and thermal characteristics as the lens-subreflector collectors described above but with collector panel thicknesses of a ½ inch or less, thus reducing substantially the material costs in the construction of non-tracking collectors.

FUTURE ACTIVITIES

Vacuum absorbers will be installed in the SET, Inc. concentrator (Fig. 3) and tests made on temperatures and solar differences at the SET, Inc. roof top facilities. Tubular and flat absorbers will be used.

A study of fabrication costs in comparison with those of manufacturing compound parabolic concentrators is being conducted.

Post-contract activities. SET, Inc. is planning to develop and market this new technology primarily for space heating and air conditioning of homes.

REFERENCES

C. J. Sletten, F. S. Holt, S. B. Herskovitz, "Wide-Angle Lenses and Image Collapsing Subreflectors for Non-Tracking Solar Collectors," to be published in Applied Optics, May 1980.

1st Interim Technical Report, Image Collapsing Concentrators, May 1979,
and
2nd Interim Technical Report, Design and Comparison of Stepped Prism Lens and Image Collapsing Subreflectors, Jan. 1980, both under Grant DE-FG-0477CS 34163.

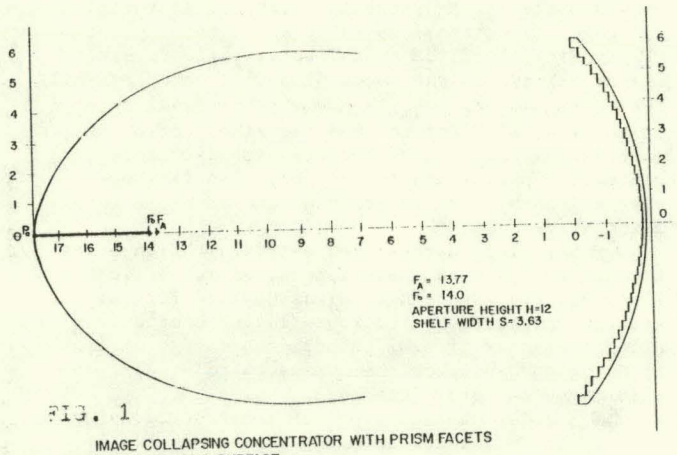
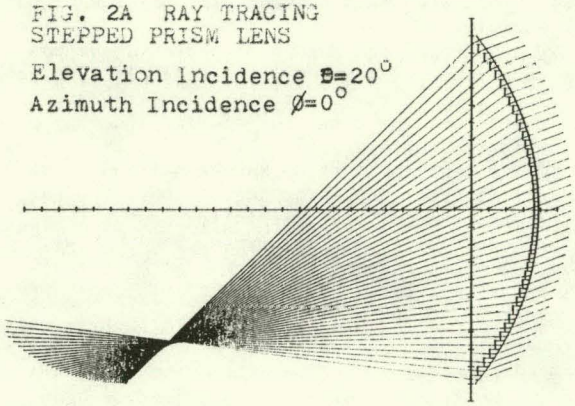
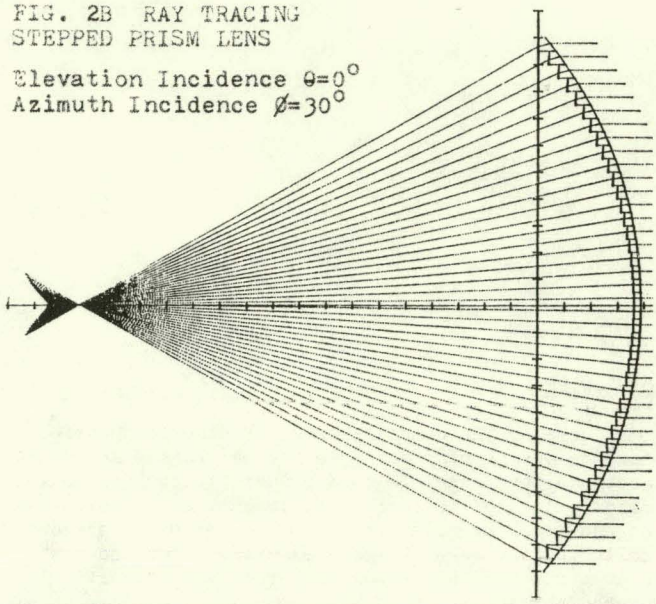


FIG. 1
IMAGE COLLAPSING CONCENTRATOR WITH PRISM FACETS ON INSIDE LENS SURFACE







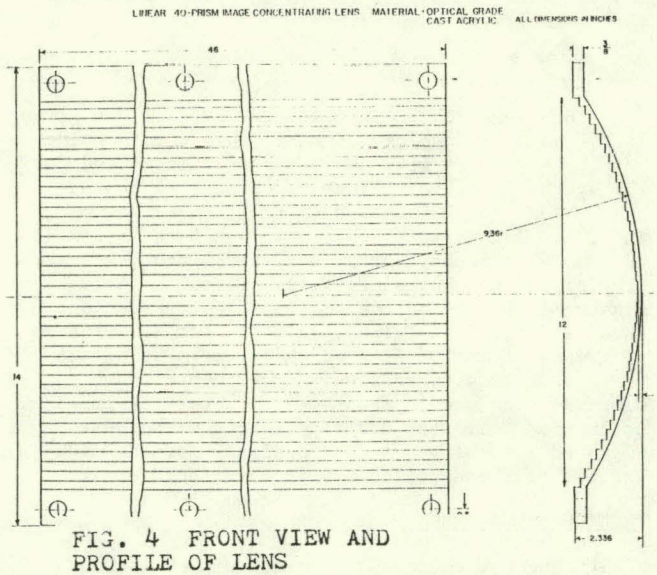


FIG. 4 FRONT VIEW AND PROFILE OF LENS

DEVELOPMENT OF A HIGH PERFORMANCE AIR HEATER THROUGH USE OF AN EVACUATED TUBE COVER DESIGN

SOLARON CORPORATION

DE-AC04-78CS 34193

DENNIS JONES

SEPTEMBER 1978 TO APRIL 1980

OBJECTIVE

The objective of this project is to develop a high-temperature (170-230°F) solar air-heater utilizing an evacuated fluorescent light tube array. The tubes are laid parallel in a close packed array to form a tranparent cover over the absorber plate.

BASIC CONCEPT

A close-packed evacuated-tube array is intended to reduce collector top loss by eliminating convective heat transfer across the inside of the tubes. Additionally top loss can be further reduced by coating the inside of the tubes with an infrared-reflective coating which reduces radiative heat transfer, but which also reduces solar transmittance

Since the tubes are made out of thin-walled non-tempered glass, the tube array serves as an inner glazing and a tempered glass plate is used as a protective outer glazing. The absorber surface may be either selective or non-selective and collected heat is transported by air flowing beneath the plate.

SUMMARY

Collector development has progressed from the basic concept through final design to prototype construction. Presently the collectors are on the roof being prepared for a thermal performance test series. Two intermediate test series included thermal conductance tests across the tube array and solar transmittance tests across the tube array.

TECHNICAL ACCOMPLISHMENTS

o The evacuated tubes were fabricated on conventional fluorescent light tube machinery by G.T.E. Sylvania. The tubes are uniform, dimensionally correct, and have shown no signs of vacuum degradation. Sixty each of the clear and coated tubes were manufactured. The I-R coating on the coated tubes did not appear to be uniform, with a heavier concentration of coating towards one end. A black getter coating on one end occupies about two inches of axial length.

o Solar transmittance tests were completed following quidelines of ASTM and ASHRAE test standards [4,5]. The transmittance test configuration is shown in Figure 1. The tests indicate that the clear tubes exhibit a normal transmittance of 0.87 as compared to a value of 0.83 for two sheets of low absorptance glass as shown in Figure 2. Furthermore the tube arrays exhibit less transmittance reduction with incident angle than flat glass plates. Test results are consistant with theory [1,2,6]. The I-R coated tubes have a significantly lower transmittance of 0.75.

o Thermal conductance tests were run on a guarded hot plate test apparatus. The clear tube array behaved similar to two flat glass sheets with an evacuated space in between, except the larger surface area on the outside surface of the tube array enhanced convection above and below relative to convection off flat sheets. The coated tubes exhibited an emittance of about 0.60 as compared to 0.88 for uncoated glass. The relative thermal conductance of various configurations may be predicted by EVAC, a Solaron. developed top loss coefficient model.

o Based on the results of the thermal conductance tests, final collector designs were set. Designs selected for fabrication and testing are:

1. Solaron Series-3000 baseline.
2. Modified Series-3000 with selective surface and no tubes.
3. Modified Series-3000 with selective surface and clear tubes.
4. Modified Series-3000 with flat black surface and coated tubes.

The thermal conductance tests indicated the optimal spacing between glazing elements in the collector. Figure 3 indicates the relative effects of spacing from which bottom spacing was set at 0.75 inches. The final configuration for collectors 3 and 4 is shown in Figure 4. The collectors do not represent production prototypes, but rather are designed to provide accurate test bids for comparison with competing concepts. Estimated thermal performance curves are shown in Figure 5.

o The four collectors have been fabricated and are presently being intalled on the collector test stand. A complete series of 93-77 tests will be run.

FUTURE ACTIVITIES

Thermal tests of the collectors should be completed in March. A detailed final report will be prepared including a cost analysis.

POST-CONTRACT ACTIVITIES

Solaron has no immediate plans for commercialization of the collector. The collector is designed for high temperature air heating for which there is presently little demand.

Critiquing the design, the evacuated tube effectively suppresses convection, but not thermal radiation which is the dominant mode of heat transfer at elevated temperatures. The I-R coated tubes are only marginally effective at stopping radiative heat transfer at the cost of reduced solar transmittance. The clear tube concept is hampered by the lack of an effective selective reflective coating.

REFERENCES

[1] Hollands, K.G.T., Raithby, G.D. and Unny, T.E., 1976. "Studies on Methods of Reducing Heat Losses from Flat Plate Solar Collectors". DOE Contract E(11-1)-2597 Final Report, June.

[2] Jones, D.E., Oonk, R.L., Shaw, L.E. and Löf, G.O.G., 1979. "Development of a High Performance Air Heater Through Use of an Evacuated Tube Cover Design". DOE Contract EM78-C-04-4193 Interim Report, May.

[3] Worek, W.M., 1977. "Performance of Cylindrical Glass Tubes Used as a Solar Collector Cover". Graduate Thesis, Illinois Institute of Technology, Chicago.

[4] "Method of Measuring Solar-Optical Properties of Materials", ASHRAE STANDARD 74-73, ASHRAE, 345 East 47th Street, New York, New York, 10017, 1973.

[5] "Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials", ASTM STANDARD E 424-71, ASTM, 1916 Race Street, Philadelphia, PA 19103, 1971.

[6] Duffie, J.A. and Beckman, W.A., 1974. "Solar Energy Thermal Processes". 1st ed., John Wiley and Sons, New York.

[7] Jones, D.E., Shaw, L.E., and Löf, G.O.G., 1979. "Development of a High Performance Air Heater Through Use of an Evacuated Tube Cover Design". DOE Contract EM78-C-04-4193 2nd Interim Report, August.

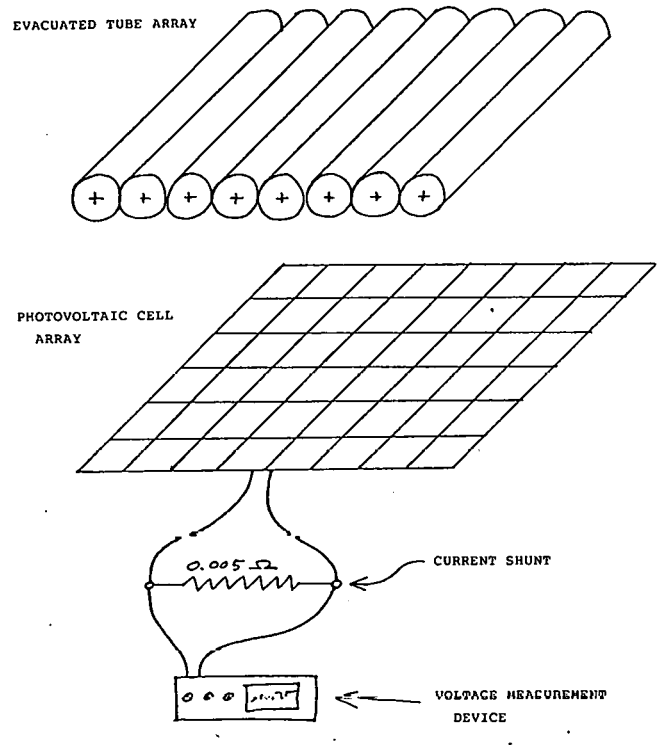


FIGURE 1
Transmittance Test Configuration

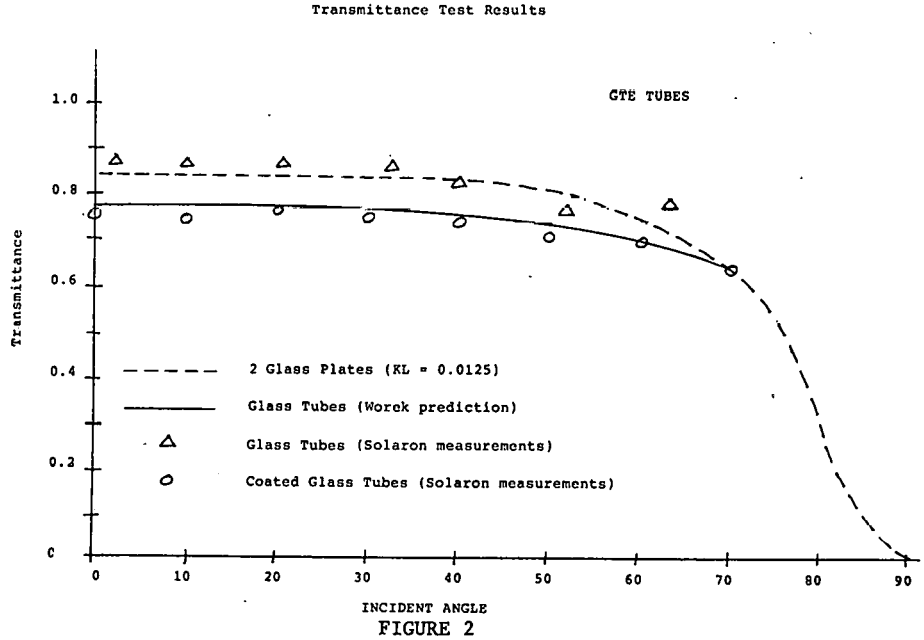


FIGURE 2
Transmittance Test Results

FIGURE 3
Dynatech Test Results for
Clear Tube Configuration

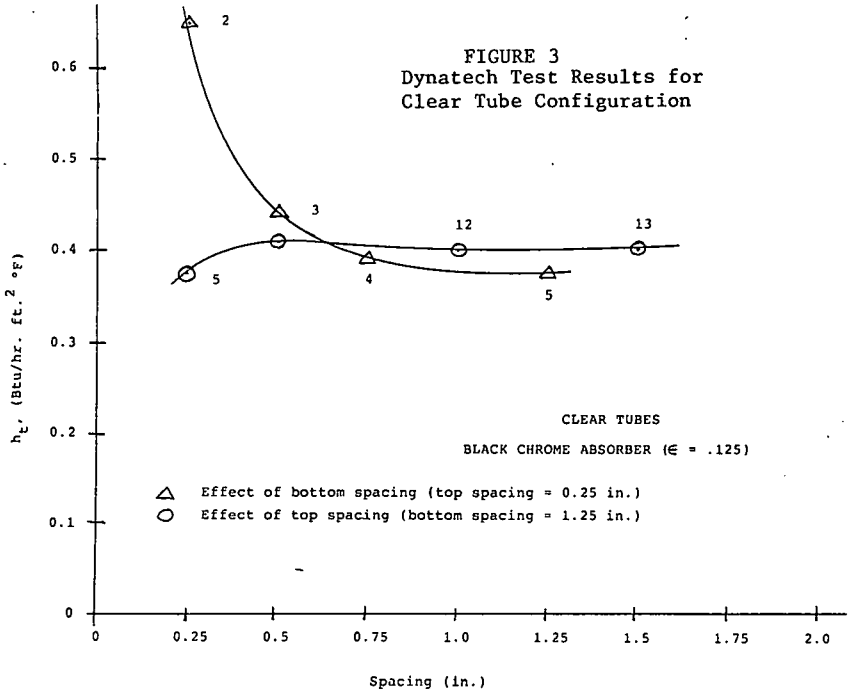
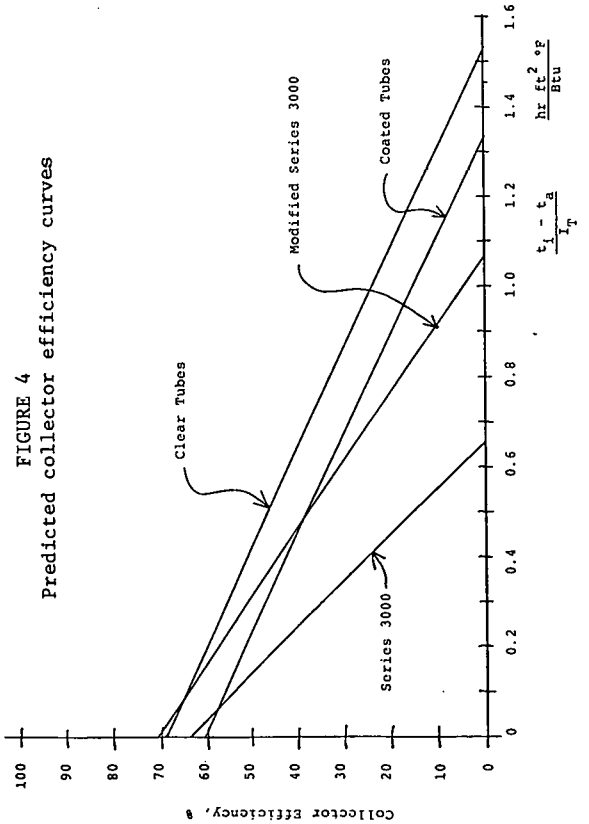


FIGURE 4
Predicted collector efficiency curves



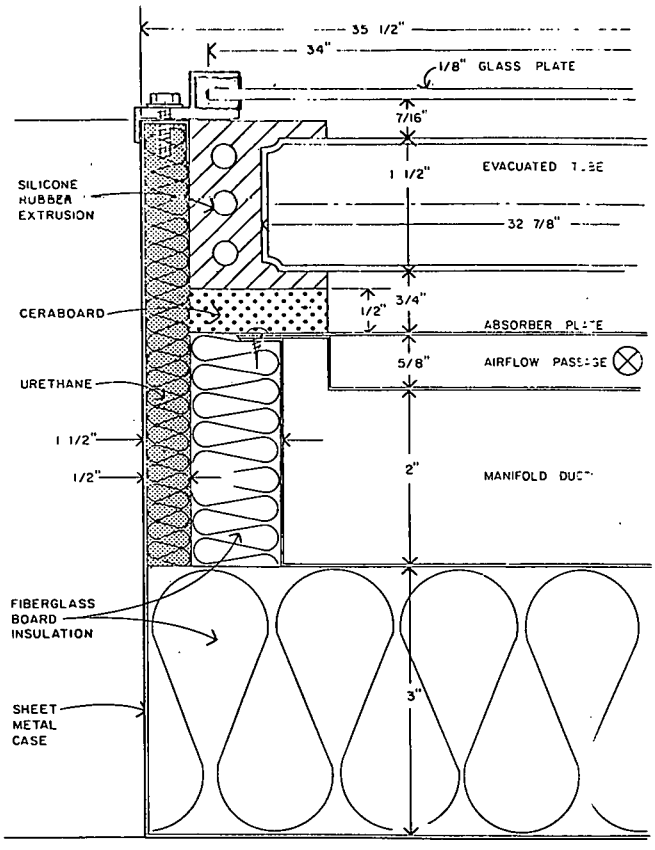


FIGURE 5
Collector Construction Detail

SOLAR COLLECTOR STUDIES FOR SOLAR HEATING AND COOLING APPLICATIONS

SPRINGBORN LABORATORIES, INC.

CONTRACT EM-78-C-04-5359

PRINCIPAL INVESTIGATOR: BERNARD BAUM

BEGAN 10/78 - END 10/80

OBJECTIVE

The project goal is the evaluation of 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. Surface etching processes and anti-reflective coatings to reduce reflection losses and increase transmission of plastic glazing will be investigated. Durable coatings and films for UV protection of plastics will be evaluated.

BACKGROUND

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, preferably in a stable binder such as acrylics, fluorocarbons, silicones, etc., to keep the ultraviolet energy from ever reaching the sensitive polymeric substrate.

Alternately, a film containing a high concentration of UV absorber could be bonded to the glazing to provide exterior protection. Such films are commercially available.

To allow the maximum percentage of solar energy to pass through to the collector, the plastic glazing must have minimum reflectivity. One way of achieving this is through use of an AR coating or etching of the plastic surface.

Springborn Laboratories, Inc. has extensive experience in the development of weather-resistant plastics and coatings. Related DOE contracts include: 1) JPL-Development of Solar Cell Encapsulants, 2) DOE-Sandia Livermore - Surface Modification to Facilitate Dust Removal from Heliostats, and 3) DOE-SERI - Protective Coatings for Glass and Plastic Heliostats and the Plastic Dome.

SUMMARY

A broad information search has been carried out to select (non-glass) materials for collector glazings and housings as well as UV protective coatings and antireflective coatings. A variety of housing materials and transparent plastic sheets are under exposure both by accelerated and outdoor weathering. Selected plastic glazings have been coated with an antireflective coating. Etching processes have been investigated to reduce surface reflection, so far without success. Acrylic and other coatings as well as UV screening films have been bonded to several plastic glazings.

TECHNICAL ACCOMPLISHMENTS

Twenty transparent plastics varying widely in structure - e.g., fluorocarbons, thermoplastic polyesters, thermosets, polycarbonates, acrylic, polyvinyl chloride, crosslinked ethylene/vinyl acetate copolymer and cellulose acetate butyrate - were chosen for both outdoor (Hazardville, CT) and accelerated weathering exposure on the Weather-Ometer. These samples have included commercial materials specifically designed for solar collectors - Llumar and National Metallizing thermoplastic polyesters, Filon 558 (Tedlar coated over acrylic modified FRP), Sunlite Premium II (modified thermoset polyester) and Flexigard 7410 (polyester/acrylic laminate). Tensile and optical properties are being measured after varying time periods. Based on weathering stability ten of the best materials have been selected for evaluation of critical - mechanical, thermal and optical - properties as well as for outdoor exposure by EMMAQUA (accelerated outdoor weathering) at DSET in Arizona.

Fourteen possible housing materials including wood composites, fiberglass reinforced polyester as well as other thermoset resins, crosslinked polyethylene, glass and talc filled thermoplastics, plastic foams and polyvinyl chloride compounds are under exposure in the Weather-Ometer. Tensile properties are being measured at varying time periods.

Methods of bonding UV screening polymer films to several transparent (glazing) polymer sheets have been developed. These composites are now under accelerated weathering exposure.

Acrylic and other coatings have been screened for bond strength and coating quality on several

possible glazing materials including acrylic, polycarbonate, crosslinked ethylene/vinyl acetate copolymer and thermoplastic polyester. The best coatings will be blended with UV absorbers to develop effective UV screening protection.

Magnesium fluoride AR coating improved the transmission of a variety of plastic sheets.

FUTURE ACTIVITIES

Contract Activities. Glazing materials have been selected for outdoor exposure by EMMAQUA. Glazing and housing materials which are promising after accelerated UV exposure will be evaluated for critical thermal, mechanical and optical properties. The durable acrylic coatings will be compounded with UV absorber systems and evaluated as protective coatings on selected glazings. Other antireflective coatings will be examined and finally cost studies will be initiated.

Post-Contract Activities. The information gained from these investigations can be used to develop low-cost glazing composites that would have 20 year outdoor life.

WIND EFFECTS ON COLLECTORS

TENNESSEE TECHNOLOGICAL UNIVERSITY

EM-78-C-04-5364

HUDY C. HEWITT, JR.

Began October 1, 1978; End October 1, 1979

OBJECTIVES

The primary objective of this study was to predict the effect of wind on the efficiency of a flat-plate solar collector. The problem was approached from five major aspects of the basic objective. These aspects must be considered individually to understand how they relate to the central objective.

BACKGROUND

The weather data currently available from reporting stations gives an hourly (or half-hourly) wind velocity and direction. The first problem to be considered was whether this data could be used to predict the wind velocity and direction at a location removed from the measuring station. This question was resolved by applying a cross-correlation test of data from three weather stations, and the same test was applied to data collected at two local recording stations.

Once the wind velocity and direction can be predicted in an unobstructed region, it is necessary to evaluate how this information can be used to predict the actual flow which will be present along the roof of a house. Since solar collectors will actually be located either on roofs or in an area where many potential obstructions will be present, the local free-stream wind velocity may not be directly related to the convective heat loss from the solar collector. The effect of obstructions on flow around model houses was studied in both the wind tunnel and the water table. The effect of an upstream house and upstream fences was studied.

The weather data presently available has three major disadvantages if it is to be applied to the heat loss from a solar collector surface. First it may not be possible to predict wind velocity and direction based on data collected fifty or one hundred miles away. Then, the data collected is averaged over a relatively long period. Finally, the unobstructed flow may not be easily adapted to the prediction of heat loss. Because of these limitations associated with currently available data, a study of possible additional weather sensors was made to establish a proof of concept. Two different detectors were tested to see if a system sensitive to convective heat transfer could be used to predict solar collector performance. A series of minature, model, solar collectors was tested along with a constant current thermistor circuit. The "mini-collectors" were compared with actual solar collector performance under controlled wind exposure.

The most commonly used model for the prediction of the convective heat transfer coefficient for solar collectors is in the form

$$h = A + BV \qquad (1)$$

where h = the convective film heat transfer coefficient, A and B are constants, and V is the wind velocity. Two questionable aspects of this equation are that there is some uncertainty of what velocity should be used at a given location and that there is no effect of the direction of flow in equation (1). A test of air- and liquid-cooled collectors was performed to attempt to partially answer these questions. This test involved an air-cooled collector and a liquid-cooled collector mounted side-by-side on a south-facing roof. A second roof had identical collectors and was located adjacent to the first roof. One roof was exposed to a forced air flow while the second was shielded. Wind from the south and from the north was possible for one system while all other environmental conditions were the same for both systems.

Finally, an experimental study of forced convective heat transfer from an inclined plate was made to evaluate the accuracy of equation (1). The effect of direction of flow on equation (1) was of particular interest since it would predict identical losses for flow from any direction

SUMMARY

Attempts to find meaningful correlation of speed and direction wind data between two separate weather stations were at best inconclusive. Generally, the correlation of wind speed near roofs to freestream speed did correlate fairly well. A sensor was developed which could be correlated with collector performance. The study of wind flow patterns around buildings did give some insight about how to relate freestream velocity to flow over a roof. Only very simple configurations were examined.

The experimental heat transfer data indicated that the model of equation (1) was approximately 10% too low at a velocity of 2.68 m/s and was approximately 20% too high at a velocity of 11 m/s. A wind from the north caused 10 to 20% less heat loss than one of the same magnitude from the south.

TECHNICAL ACCOMPLISHMENTS

Any effort to use wind speed and direction collected at one station for predicting their values at a station approximately one hundred miles away will probably be unsuccessful. An effort to find a direct time correlation between the three Tennessee cities of Nashville, Knoxville, and Chattanooga taken two at a time proved to be negative. There was no simple time delay in the wind patterns experienced by these cities.

The correlation of wind direction was extremely poor. Although speed correlation was better, it was not of a level acceptable for correlation.

Four wind direction and velocity units were used locally to measure and record data at a station in an open, unobstructed area. The sensor was located 30 feet above the ground. A second sensor was located 10 feet above the roof of a building which was 60 feet above the ground. These stations were approximately three hundred yards apart. The wind velocities and directions were quite different for the two locations. The critical factor in local wind velocity and direction is the field of obstructions present.

A "mini-collector" or a constant current thermistor system could be used to supplement weather data and provide information more important to collector performance than that presently available. Both of these sensors are sensitive to the convective heat loss over their outer envelope. Both sensors are immediately adaptable to integrating circuitry. The "mini-collector" was compared with the performance of actual collectors, and a correlation of actual performance was indicated by the "mini-collector." The project was a proof of concept, only. However, the potential is considered to be very promising.

All obstructions between a roof and the direction from which the wind is blowing will cause turbulence and separation around the roof. A study of simple obstructions such as houses and fences was completed. The obstruction of a fence in the wind path to a house was found to either enhance or reduce separation on the roof. This effect could be used to improve the performance of the flat-plate solar collector.

The equation most frequently used to determine the film heat transfer coefficient from the glass cover of a collector is the work of Jurges [1]

$$h = 5.7 + 3.8\ V \qquad (2)$$

where h is in W/m^2 C, and V is in m/s. Experimental data from this present experimental study from Drake [2], from Sparrow and Tien [3], and from equation (2) all differed from each other. References [2] and [3] gave values which were higher than the present results while the comparison with equation (2) is given in the previous section.

It is obvious that equation (2) would have to be modified to account for wind from some direction other than that orientation which is toward the inclined surface. This comparison in the second experiment revealed a reduction of from 10 to 20% when the flow is from the back of an A-frame roof.

The basic suggestion for a convective heat transfer coefficient should be in the form

$$h = C + D\ V^{\frac{1}{2}} \qquad (3)$$

where C and D are one set of constants when the direction on the wind is from the southerly direction and a second set of constants when the wind is from a northerly direction.

The error bounds relating actual collector performance to wind velocity gave a linear variation of the film heat transfer coefficient and wind velocity. However, an expression similar to equation (3) may also be appropriate. This was not determined from the data.

The actual collector tests indicated that wind from a northerly direction did not effect collector performance. It was expected that some smaller change would be experienced. However, the particular configuration tested did not result in a change.

FUTURE ACTIVITIES

Contract Activities. These activities have been completed at this time.

Post-Contract Activities. It is probable that a "mini-collector" sensor will be developed and extensively tested to provide weather data for predicting collector performance. This will still involve some design and a lot of testing.

PUBLICATIONS

One paper has been accepted for presentation at the ASME Century-Two Conference at San Francisco. This will be in August 1980. The paper is on the heat transfer to an inclined plate. Two other papers are being considered for other publications. These papers are on the air flow patterns and on the cross-correlation of weather data.

REFERENCES

1. McAdams, W. A. Heat Transmission, Third Edition, McGraw-Hill, New York, 1954, p. 249.
2. Drake, R. M., Jr. "Investigations of the Variation of Point Unit Heat Transfer Coefficients for Laminar Flow Over an Inclined Plate," Journal of Applied Mechanics, Vol. 71, 1949, pp. 1-8.
3. Sparrow, E. M., and K. K. Tien. "Forced Convection Heat Transfer at an Inclined and Yawed Square-Plate Application to Solar Collectors," TASME Journal of Heat Transfer, Vol. 99, November 1977, pp. 507-512.

STRUCTURAL INTEGRITY OF SOLAR COLLECTORS

TEXAS A&M UNIVERSITY

DE-AC04-79A111774

Howard L. Chevalier & Robert A. Wilke

Begin May 1976 End August 1980

OBJECTIVE

The objective of the project is to determine the structural load coefficients, in particular those due to wind loads, for solar panels and support structures. The data and analyses are based on reduced and full-scale models in steady and unsteady wind conditions. Both single and multiple panel configurations are considered in the project.

BACKGROUND

Problem Statement. During a review of design practices for solar panel installations, it was noted that the design practices were limited by a lack of knowledge of the wind loads on the installation. This deficiency in design information can be corrected by obtaining data and completing analyses that emanate from several tasks:

1) Wind tunnel tests to define steady wind loads.
2) Full scale tests of a solar collector system.
3) Analysis of the test data in steady wind.
4) Structural analysis of the support system.
5) Wind tunnel tests to define unsteady wind loads and pressure distributions.
6) Full-scale tests to define unsteady wind loads and pressure distribution.
7) Analysis of the unsteady test data.

Tasks 1 through 4 are complete and are described in the report entitled "Wind Loads on Solar Collector Panels and Support Structure," October 1979.

Tasks Completed. A study was completed using individual solar panels and panel arrays in a 7x10' cross section wind tunnel. The definition of wind loads on solar panels was made for steady wind conditions, where the approaching wind field was uniform and there was no significant turbulence. The effects of changes in aspect ratio, clearance ratio, inclination angle, and wind angle on the force coefficients were studied parametrically. Both isolated panels and panel arrays were considered.

A full-scale collector unit was mounted upon a rigid base and supported by a three axis load cell arrangement. This instrumented unit was installed on the roof of an aircraft hangar. The roof of the hangar is 45 feet above the ground and has clearance from obstructions on the hangar sides facing the prevailing winds. The first loads measurements were taken in moderate to low wind speeds (below 25 mph) so were taken as data in uniform wind conditions.

A structural analysis of the full-scale unit was completed using the wind tunnel data and full-scale data in a two-dimensional analysis.

SUMMARY

The project work to date has measured the force coefficients on single and multiple solar panel arrays in steady wind conditions. In addition, a theoretical analysis has been completed that will predict the steady wind loads and force coefficients on solar panels.

A full-scale solar collector structure was mounted on the roof of an aircraft hangar and instrumented to permit recording of the wind loads. The data recorded, at low velocities, were compared with the wind tunnel test results.

A structural analysis of the panel support frame was completed using a post and beam method and a finite element method. The structural members were found to be within design limits. However, the roof support connections were found to be critical design areas.

TECHNICAL ACCOMPLISHMENTS

The parametric studies of a single solar panel showed that the aspect ratio, clearance ratio, inclination angle, wind angle, and thickness-to-height ratio have a significant influence on the total force coefficient. The maximum total force coefficient, for a given panel area, was found to be less than 1.50.

The highest aspect ratio tested was 16; both theory and data (see Figure 1) show that the total force coefficient upper limit for large aspect ratios is approximately 2.0. Since most single solar panels have aspect ratios in the 1 to 4 range, the total force coefficient can be predicted fairly accurately.

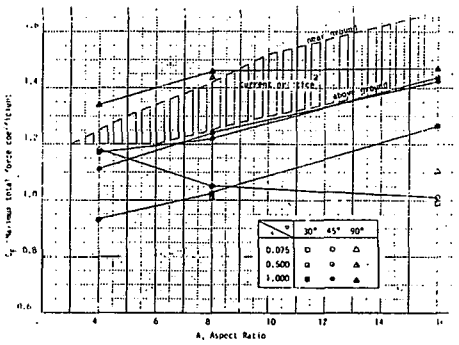


Figure 1. Total force coefficient for single panel.

The single panel total force coefficient, as well as other load coefficients, can be predicted

within ±10% through the application of a semi-empirical relationship that involves the geometric parameters listed above.

The lift coefficients for a single panel were found to be in the -.80 to .85 range. The drag coefficients were in the range of -.15 to .90.

Clearance ratio effects are complex and have a significant effect on the panel loads. As the clearance becomes very large the force levels change very markedly with changes in the wind angle. The negative downstream pressure is reduced by proximity to a ground plane because the plane suppresses large scale turbulence fluctuations.

The windward panel in a multiple array has a smaller total force than the equivalent single panel. The remaining panels have loads that are a function of the panel spacing ratio. For a spacing ratio of unity the successive panels have forces that are 1/5 of the windward panel loads. As the spacing becomes very large, theory and data show that the downwind panel loads approach those of a single panel. Both theory and experiments show that, because of flow separation and reattachment, the panel spacing ratios in the 5 to 10 range produce the maximum drag loads. Panel array designs should avoid this geometrical arrangement. The curves of Figures 2 and 3 may be used to obtain total loads for the design of solar panel arrays.

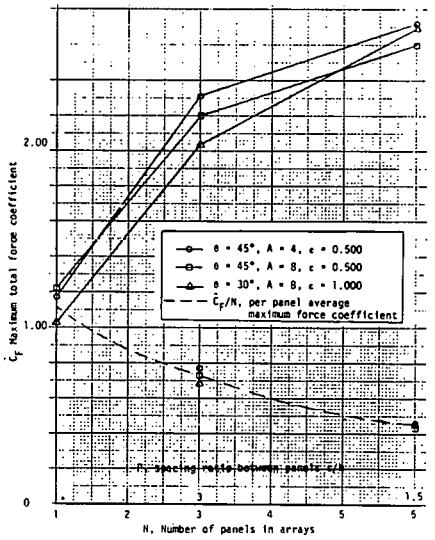


Figure 2. Panel array total force coefficient.

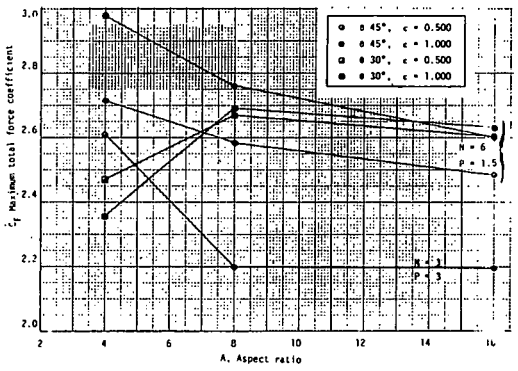


Figure 3. Effects of spacing and number of panels.

During the measurement of loads on the full-scale unit, mounted on the hangar roof, a lift coefficient of -.276 was obtained. This is less than the .47 predicted by the scale model study.

The full-scale drag coefficient was found to be 1.01. This is larger than the .64 value found in the model study. This difference, as well as the lift coefficient difference, is reasonable for the tests conducted and will be investigated further in nonuniform wind conditions. It is important to note that these values, measured and predicted, provide an initial insight into the full-scale loads. They provide an idea of the trends to be expected during unsteady wind conditions. The initial unsteady wind data suggest that the unsteady loads may be as much as 100% different from the steady loads.

The structural analysis of the full-scale support members showed that they are of adequate strength, but that the collector to building support links must use a different design than the procedures given in the building codes. The building codes do not adequately specify side forces. The support links must accommodate both the lift and side forces.

FUTURE ACTIVITIES

A single solar panel equipped with pressure transducers and static ports, shown in Figure 3, is scheduled for testing in the 7x10 foot wind tunnel. It will be tested in unsteady wind conditions with a mean dynamic pressure of 20 psf and an oscillating pressure of approximately ±5 psf. Three panel inclination angles and a range of wind angles from +90° to -90° will be used in the tests.

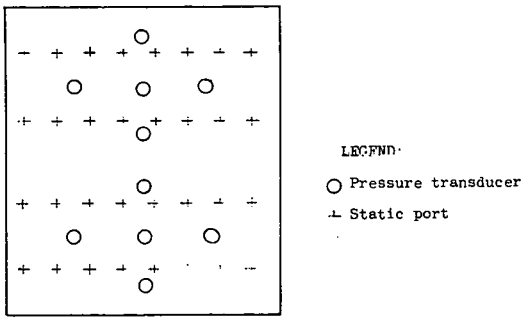


Figure 4. Panel geometry and instrumentation.

This panel, along with other panel types, including a tracking type panel, will be tested on the roof-mounted structure. The data obtained will be the wind direction, wind speed, panel pressure distribution, and support loads. The wind direction and speed will be gotten from a wind profile measured at locations in front of and at the unit.

REPORTS

1. The steady wind test results have been published in the report: Chevalier, H. L. and Norton, D. J., "Wind Loads on Solar Collector Panels and Support Structures," Texas A&M University, College Station, Texas, October 1979.

2. Current and future test activities that will define the unsteady wind load parameters will be included in the final contract report. It will be submitted within 30 days after the end of the contract period.

A SURVEY AND EVALUATION OF CURRENT DESIGN OF EVACUATED COLLECTORS

TRIDENT ENGINEERING ASSOCIATES, INC.

CONTRACT NO. DE-AC04-78CS05350

B. J. GRAHAM, Ph.D.

PERIOD OF CONTRACT: 8/7/78 through 9/30/79

OBJECTIVE

This report is to describe all of the evacuated collectors available, from those which had been tested extensively to others which were just in the stage of laboratory development. Where the information is available, the collectors are to be compared in performance and cost with a flat plate collector. A completed list of the sites using these collectors is to be compiled to show the variety and extent of use of evacuated collectors.

BACKGROUND

Evacuated collectors hold the promise of answering many problems posed by the utilization of solar energy. They have already shown that they can provide heat for a broader range of applications and with greater efficiencies than flat plate collectors. Recent developments indicate that the range of applications will be extended and, in some cases, evacuated collectors will compete with trough collectors. Currently there are some 100 sites using these collectors to study system and component improvements, the economics of this type of collector, and performance in a variety of situations.

Because of the lack of independent test facilities, only four of these collectors have been independently tested and made available to the market. However, there are some 30 of this type of collector in various stages of development. The manufacturers of evacuated collectors see their product as being competitive in cost, performance, and durability with the flat plate market, and in some specific applications with the market for tracking trough-like collectors.

SUMMARY

Some 30 evacuated collectors are described in the report, depending on the information available and the stage of development. In several cases, the same evacuated tube is considered for use in collectors of different modules or different heat delivery systems. Recent developments in evacuated collectors include utilization of CPC reflectors, both externally and internally with respect to the tube, use of air as a heat transfer medium, and the introduction of the heat pipe as a heat transfer device. A model system (2000 ft²) was used to compare performance and costs of evacuated collectors currently on the market with flat plate collectors. There were 97 sites identified which were using evacuated collectors of one type or another for applications which ranged from domestic hot water to industrial heat applications.

TECHNICAL ACCOMPLISHMENTS

- Description of Collectors

Even under the best of conditions, the heat energy per unit area contained in solar radiation is small. For this reason, it is important in the design of a solar energy collector to reduce to a minimum the heat losses from conduction and convection. Evacuated tube collectors achieve this by placing an insulating vacuum jacket about the absorber, and they reduce radiation losses by using selective coatings on the absorber surface. For a typical evacuated collector, the heat loss coefficient U_L is of the order of 2.10 to 2.40 W/m² °C, and the transmissivity-absorptivity product $\tau\alpha$ is 0.85 to 0.92. Values of the heat removal factor F_R vary with design, but these are generally high for evacuated tube collectors. As a consequence of these advantageous features, the minimum solar energy required for useful collection of energy for an evacuated tube collector at 50°C above the ambient temperature will be 0.13 to 0.15 kW/m². For a typical flat plate collector[1] this minimum solar energy is 0.25 to 0.30 kW/m². This improvement in performance means that, compared to flat plate collectors, evacuated tube collectors:

-- start collecting useful energy earlier in the morning and extend their collection until later in the day;

-- collect energy under less favorable operating conditions;

-- collect energy more days per year;

-- show substantial improvement in average daily collector efficiencies in regions of marginal availability;

-- collect energy at higher temperatures.

There are three fundamental designs of evacuated collector tubes:

Concentric tubes (Dewar). The Owens-Illinois SUNPAK[2] and the General Electric SOLARTRON[3] tubes in Figures 1 and 2 respectively typify this type of collector. An evacuated jacket about the absorber insulates the tube from reverse heat losses by convection and conduction. The wavelength selective coating on the absorber tube, which is protected from the environment by the evacuated jacket, minimizes losses by reradiation.

Single tubes. The majority of evacuated collectors are made of a single evacuated tube which contains an absorber element. This may be a U-shaped heat transfer tube like the copper tube in the Corning collector[4] (Figure 3); it may be a straight-through absorber tube like the Sanyo tube[5] (Figure 4); or it may contain a heat pipe like the Philips collector (Figure 5).

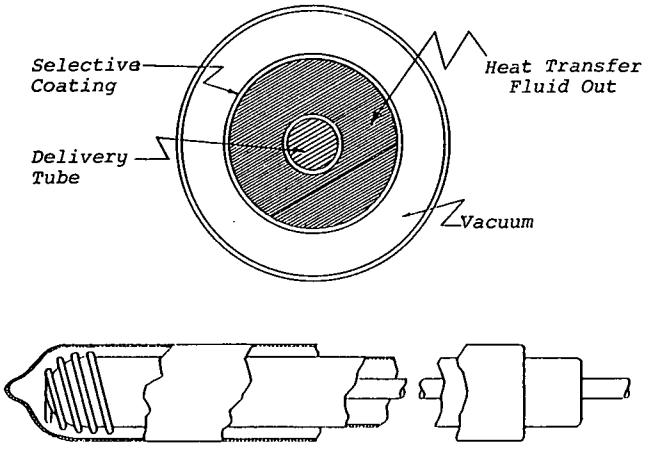


Figure 1. Owens-Illinois SUNPAK Tube

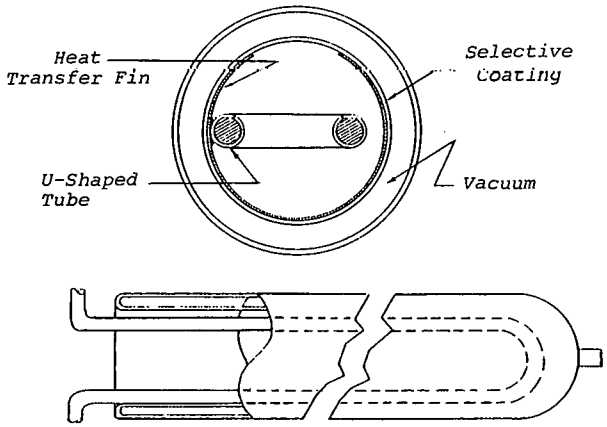


Figure 2. General Electric SOLARTRON Tube

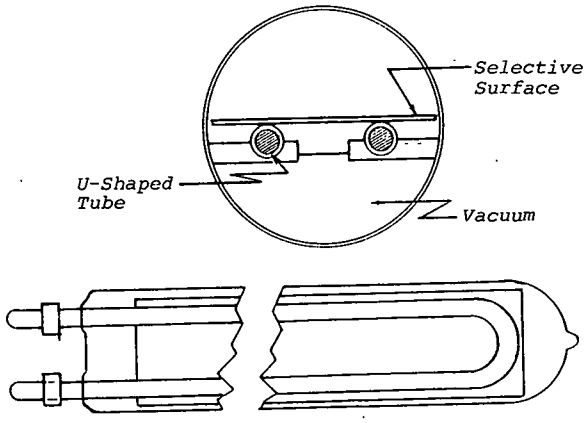


Figure 3. Corning Cortec

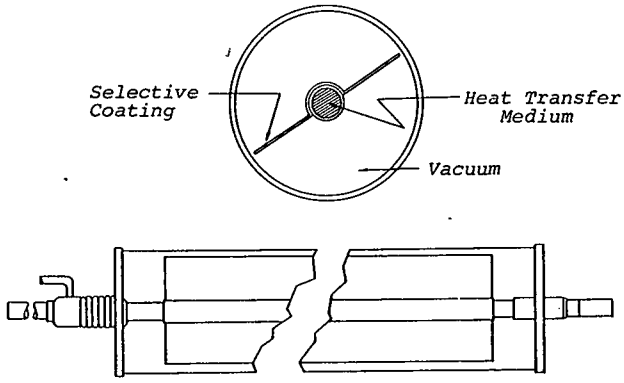


Figure 4. Sanyo Collector

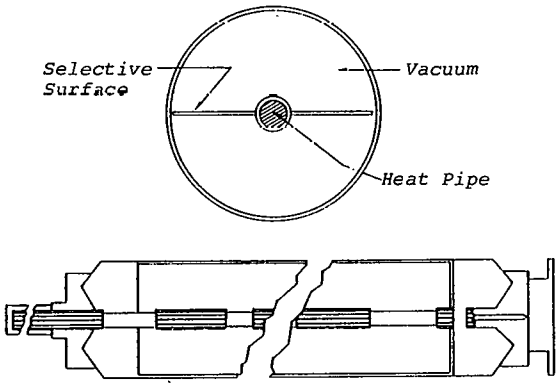


Figure 5. North American Philips Collector

Cover plate of tubes. The Philips Mark IV collector in Figure 6 and the proposed Solaron collectors[6] use evacuated tubes placed adjacent to each other to form an insulating cover for what is essentially a flat plate collector.

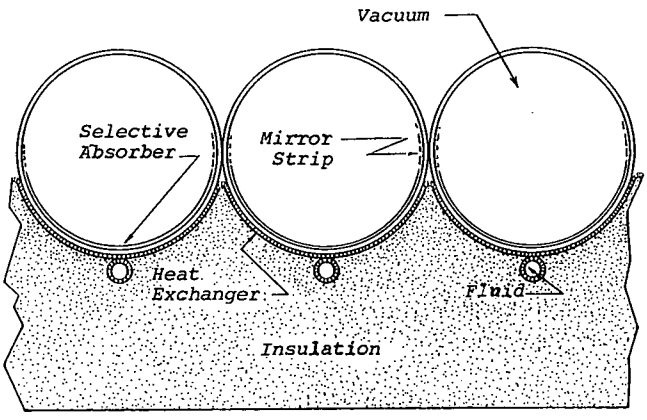


Figure 6. Philips Mark IV Solar Collector

- Performance

The performance of evacuated tube collectors can be appreciated by the curve in Figure 7 which shows an envelope that encompasses the efficiency curves for evacuated collectors for which there is reliable data. The efficiency curve for a double glazed, selectively coated, flat plate collector is also shown for comparison. One of the curves falling within this envelope is that of a module of evacuated tubes using air as a heat transfer medium. Independent data for collectors performing at $\frac{\Delta T}{I} > 0.6$ is not yet available; but it can be seen from the curves that at the higher temperatures even a well-engineered flat plate collector is a doubtful performer while some evacuated collectors may still be 50% efficient.

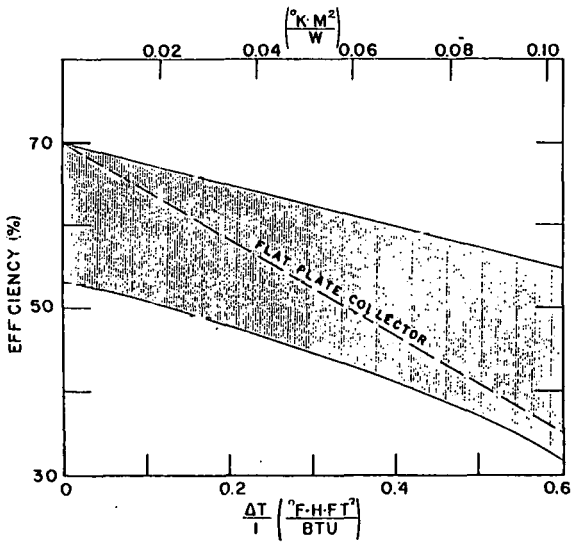


Figure 7. The shaded area shows the range of efficiencies for various evacuated tube collectors.

- Development Trends

Experience in the field is dictating some trends in the progressing development of these collectors. The following are developments which will make a significant impact on how evacuated collectors will be utilized.

-- The use of CPC reflectors has increased the efficiency of collector modules and has reduced the number of tubes required per module. Prototypes of CPC's (Figure 8) with a concentration of 5X requiring 12 tilt adjustments per year are expected to achieve an efficiency of the order of 50% at temperatures up to 570°F (300°C) even after parasitic losses are considered[7]. Corning has experimented with using a CPC reflector internally in the evacuated tube, as shown in Figure 9[8].

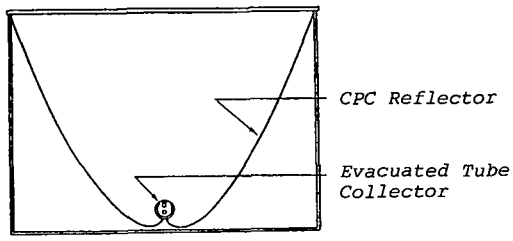


Figure 8. Compound Parabolic Concentrator (5X)

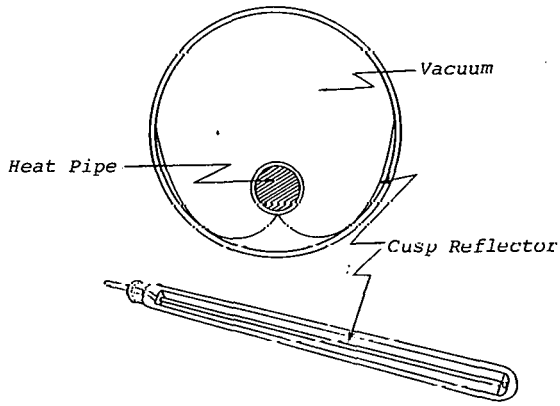


Figure 9. Corning Collector with Heat Pipe

-- Problems of freezing, stagnation temperatures, boiling water, and steam flashing make the use of air instead of water as the heat transfer medium appear attractive. Both the General Electric and the Owens-Illinois tubes have been used in modules using air, and they have reported good efficiencies for these modules. Westinghouse is in the developmental stage of an evacuated tube module which will use tubes from fluorescent tube production for a collector which is to use air.

-- Heat pipes used with evacuated collectors have the potential to improve performance by

- reducing the risk of thermal shock,
- maintaining a lower thermal capacity in the tube,
- reducing freezing and stagnation problems,
- allowing cheaper installation and maintenance.

Thermocore, Inc., and Grumman Energy Systems are developing heat pipes for use in the General Electric SOLARTRON tube, and North American Philips has developed a heat pipe to go with a collector tube of their own design (see Figure 5).

- Comparison of Collectors

There are four evacuated tube collectors which have been tested, used in demonstration sites, and developed for the market. A simple model system of about 2000 ft² of collector area was used to compare the performance of these four collectors and a flat plate collector. This includes costs for the support structure and piping for each system. It should be pointed out that some of the comparisons are not completely appropriate because evacuated collectors can

operate at temperatures at which a flat plate collector may produce no net energy at all. The system performance was considered for both Albuquerque ($\phi = 35° 03'$ N) and for Boston ($\phi = 42° 22'$ N); and the collector was tilted to 0.90 times the latitude angle. A comparison of performance and costs is given in Table 1 below.

TABLE 1

Heat Delivered per Year (MBTU/yr)				Investment Cost $/ft²		$/MBTU			
Albuquerque		Boston				Albuquerque		Boston	
SUNPAK	879	SUNPAK	411	Flat Plate	$56	SUNPAK	$ 85	SUNPAK	$186
Sanyo	719	Sunmaster	303	SUNPAK	$60	Flat Plate	$116	Sunmaster	$301
General Electric	678	General Electric	235	Sanyo	$70	Sanyo	$121	General Electric	$392
Sunmaster	669	Sanyo	226	Sunmaster	$71	General Electric	$133	Sanyo	$399
Flat Plate	608	Flat Plate	223	General Electric	$72	Sunmaster	$133	Flat Plate	$587

- Conclusions

Manufacturers, aware of the cost comparisons between flat plate collectors and evacuated collectors, are striving to enhance performance and costs by improvements in:

-- Production techniques for tubes and modules;
-- Packaging for shipping and handling, particularly at installation;
-- Module design which will,
  - facilitate installation and plumbing,
  - simplify the required control systems;
-- Long range reliability of tubes, insulation, connectors, reflectors, and module structure.

There are many installations using evacuated collectors, but these do not really represent the potential market. These are largely demonstration sites. Before manufacturers will be willing to make significant investments in the evacuated collector market, they must be motivated by an adequate and predictable market. To initiate such a market will require such things as appropriate legislation, tax incentives, and innovative programs like the TVA solar hot water project.

FUTURE ACTIVITES

This report concludes the project.

PUBLICATIONS

Graham, B. J., "Evacuated Tube Collectors", Solar Age, Vol. 4, No. 11, November 1979, pp. 12-17.

REFERENCES

1. Ward, D.S.; Duff, W. S.; Ward, J. C.; Löf, G. O. G., "Integration of Evacuated Tubular Solar Collectors with Lithium Bromide Absorption Cooling Systems", Solar Energy, Vol. 22, No. 4, 1979.

2. Beekley, D. C. and Mather, Jr., G. R., "Analysis and Experimental Tests of High Performance Tubular Solar Collector", paper presented at 1975 ISES Congress, Los Angeles, California, August 1975.

3. "Solartron™ TC-100 Vacuum Tube Solar Collector", General Electric Document No. 78SDS4215A, Advanced Energy Programs, Philadelphia, Pennsylvania, November 1978.

4. Ortabasi, U. and Buehl, W., "Analysis and Performance of an Evacuated Tubular Collector", paper presented at 1975 ISES Congress, Los Angeles, California, August 1975.

5. Hinotani, K.; Kanatani, K.; and Osumi, M., "An Evacuated Glass Tube Solar Collector and Its Application to a Solar Cooling, Heating, and Hot Water Supply System for the Hospital in Kinki University", Solar Energy, Vol. 22, No. 6, 1979.

6. Jones, D. E.; Oonk, R. L.; Shaw, L. E.; and Löf, G. O. G., "Development of a High Performance Air Heater Through Use of an Evacuated Tube Cover Design", Interim Report, Solaron Corporation, DOE Contract No. EM-78-C-04-4193, Denver, Colorado, June 1979.

7. Collares-Pereira, M.; O'Gallagher, J.; Rabl, A.; and Winston, R., "A Compound Parabolic Concentrator for High Temperature Solar Collector Requiring Only Twelve Tilt Adjustments per Year", Proceedings of the International Solar Energy Congress, New Dehli, India, January 1978.

8. Ortabasi, U. and Buehl, W., "An Internal Cusp Reflector for an Evacuated Heat Pipe Solar Thermal Collector", Proceedings of the 1977 American Section of ISES, Orlando, Florida, June 6-10, 1977.

HEAT TRANSFER IN PARTIAL VACUUM

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

DE-AC04-78CS35367

JAMES R. THOMAS, PRINCIPAL INVESTIGATOR

CONTRACT PERIOD: 8 AUGUST 1978 - 31 DECEMBER 1979

OBJECTIVES

1. Develop a rigorous theoretical analysis of gaseous conduction in evacuated solar collectors to determine the minimum partial vacuum necessary to eliminate conduction heat losses.
2. Assess the effect of helium penetration into the evacuated region on the heat loss characteristics of evacuated collectors.

BACKGROUND

The principal investigator has previously been involved in the development of analytical methods for computing heat conduction in rarefied gases based on kinetic theory [1-4]. To insure that conduction through the partial vacuum present in an evacuated solar collector is well understood, application of these methods to study heat losses from evacuated solar collectors appeared advisable. Such a study would be expected to corroborate the results of experimental methods used in solar collector design.

Helium is present in atmospheric air at a partial pressure of 4×10^{-3} Torr and is known to penetrate most glasses, including those used in evacuated solar collectors. Since these collectors are evacuated to pressures of 10^{-5} Torr or less, equilibration of helium within the evacuated region would lead to pressures of the order of 10^{-3} Torr, and one would expect deterioration of collector performance. Application of rigorous theoretical methods to predict the effect of helium penetration on the heat losses from evacuated collectors should reveal the potential seriousness of this problem.

SUMMARY

Theoretical methods have been developed to describe heat conduction through the evacuated region of a solar collector in either flat plate or tubular geometry. These methods have been used to predict the minimum partial vacuum necessary to eliminate conduction losses, and the effect of helium penetration into the evacuated region. A model for helium penetration has been developed to predict helium penetration rates through glasses for which helium permeation data is available.

TECHNICAL ACCOMPLISHMENTS

- Theoretical methods developed under this program show that vacuum levels of 10^{-4} to 10^{-3} Torr will reduce conduction losses to 1-10% of the radiation loss at typical operating temperatures. Although current production methods yield evacuated tubes with pressures less than 10^{-5} Torr, such extreme evacuation is not justifiable on theoretical grounds.
- Based on currently available permeation data, helium would be expected to approach equilibrium pressure of 4×10^{-3} Torr in the evacuated region of an air heating collector within a year or two after being placed into service. The permeation rates are strongly dependent on the type of glass used and the temperature of the glass, as shown in Table 1. Better data on helium penetration is needed to substantiate these results.

Table 1. Time Constants for Helium Penetration of Evacuated Tubes

	Time Constant	
Temp.	#1 Borosilicate	#2 Soda-Lime
0°C	400 yr.	146,000 yr.
20	143	34,000
40	58	9,600
80	13	1,150
100	6.8	470
250	0.26	4.7

- Heat conduction rates through equilibrium helium depend strongly on the thermal accommodation coefficient of helium molecules on the collector and cover surfaces. Using currently available experimental data for accommodation coefficients, equilibrium helium would be expected to increase conduction losses to about 50% of the radiation loss of a typical evacuated tube collector. Again, reliable experimental data is needed for helium accommodation coefficients on materials used in evacuated solar collectors.

FUTURE ACTIVITIES

Experimental data on helium permeation rates and heat losses from evacuated tubes backfilled with helium is expected from the Owens-Illinois program. This experimental data will be compared to theoretical calculations to, hopefully, provide a clear understanding of the potential problem of helium penetration.

REFERENCES

1. J. R. Thomas, Jr., "Temperature Slip Problem with Arbitrary Accommodation at the Surface," Phys. Fluids 16, 1162-1164 (1973).

2. C. E. Siewert and J. R. Thomas, Jr., "Half-Space

Problems in the Kinetic Theory of Gases," Phys. Fluids 16, 1557-1559 (1973).

3. J. R. Thomas, Jr., T. S. Chang, and C. E. Siewert, "Heat Transfer between Parallel Plates with Arbitrary Surface Accommodation," Phys. Fluids 16, 2116-2120 (1973).

4. S. K. Loyalka, C. E. Siewert, and J. R. Thomas, Jr., "Temperature-jump Problem with Arbitrary Accommodation," Phys. Fluids 21, 854-855 (1978).

PUBLICATIONS FROM CONTRACT WORK

1. J. R. Thomas, Jr., "Heat Conduction in Partial Vacuum," Tech. Prog. Report for Period 7 Aug. 1978 to 31 Jan. 1979, D.O.E. Report ALO/5367-1, Feb. 1979.

2. J. R. Thomas, Jr., "Helium Penetration in Evacuated Solar Collectors: Theory and Effect on their Performance," ASME Paper 79-WAM/Sol-17, Dec. 1979.

3. D. C. Wideman and J. R. Thomas, Jr., "Heat Conduction in Rarefied Gases between Concentric Cylinders: Arbitrary Accommodation on Both Surfaces," Proc., 27th Heat Transfer and Fluid Mech. Inst. (in press).

COLLECTOR SEALANTS AND BREATHING

WESTINGHOUSE ELECTRIC CORPORATION

DE-AC04-78CS15362

M. A. MENDELSOHN

SEPTEMBER 25, 1978 - DECEMBER 31, 1979

OBJECTIVES AND BACKGROUND

The objectives of this program were: (1) to investigate the pertinent properties of a variety of possible sealants for solar collectors and identify the most promising candidates, and (2) to study the effect of breathing in flat-plate, thermal solar collector units. The study involved two types of sealants, Class PS which includes preformed seals or gaskets and Class SC which includes sealing compounds or caulks. It was the intent of the study to obtain data regarding initial properties of candidate elastomers from manufacturers and from the technical literature and to use those sources to provide data pertaining to endurance of these materials under environmental service conditions.

Where necessary, these data were augmented by experimental measurements. Environmental stresses evaluated by these measurements included elevated temperatures, moisture, ultraviolet light, ozone and oxygen, and fungus.

The second major area of the work involved a study of the effects of materials used and design on the durability of solar collectors. Factors such as design, fabrication, materials of construction, seals and sealing techniques and absorber plate coatings were observed on actual field units removed from service. Such phenomena as leakage, corrosion and formation of deposits on glazing and absorber plate were noted.

An evaluation of the properties of several desiccants was made in order to provide means to mitigate the deleterious effects of water on collector life. Adsorbents for organic degradation products of sealants were also investigated in order to protect the glazing and absorber plate from deposited coatings. Since adsorbents and desiccants in general tend to take up both water and organic decomposition products, relative affinities of a number of these agents for water and for organic compounds were determined.

SUMMARY AND TECHNICAL ACCOMPLISHMENTS

An extensive literature survey followed by laboratory screening tests were used to select candidate Class PS (preformed rubber seals) and Class SC (sealing compounds or caulks) elastomers for more comprehensive laboratory testing to assess their performance capabilities under the harsh environment of a thermal solar collector cell. Tests employed included thermal aging in air, hydrolytic stability, weathering resistance, corrosion of metallic substrates, ozone resistance and fungal susceptibility. Since the most hostile factor in the solar collector cell environment is long-term exposure to elevated temperatures in air, the thermal stability testing was extended to the monitoring of change in several physical properties during thermal aging in air. These included compression set, tensile characteristics, hardness and weight loss.

Although none of the elastomers tested were found to be entirely satisfactory, fluorocarbons displayed the best durability and thermal stability overall. The silicones were second best. Unfortunately the fluorocarbons tend to exhibit excessive low temperature compression set, a characteristic which could be a serious problem in geographic zones having relatively cold winters. The silicones show very poor resistance to compression set on thermal aging and, while the fluorocarbon is considerably superior in this respect, it nevertheless displays undesirably high values.

Due to the relatively short service life predictions in terms of resistance to compression set at elevated service temperatures obtained for all categories of elastomers, it is recommended that solar collector units be designed to provide continuous pressure by some type of spring loading against gaskets intended to seal the unit from water in the surrounding environment.

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 the three materials just mentioned.

Corrosion of substrates, hydrolytic stability, resistance to weathering, resistance to fungal organisms and to ozone were not, in general, found to be major problems. Corrosion problems become largely nonexistent if either anodized aluminum or mill finish aluminum is used for frame material rather than galvanized iron. It is suggested that fungicides be incorporated into fluorocarbon or butyl rubber formulations, but other elastomers in general possess adequate resistance to fungal organisms. Only the butyl rubber was found to have inadequate resistance to ozone and only the Class SC acrylic caulk appeared to be affected appreciably by the accelerated weathering exposure used.

The Class SC organic caulks, mono (acrylic), Hypalon (chlorosulfonated polyethylene) and butyl were found to evolve unacceptably high quantities of condensables and, in consequence, should not be used in locations where they have direct communication with the interior of the solar collector cell. This consideration also applies to some Class PS rubbers,

primarily in the butyl and several EPDM categories. A similar problem exists with the Class SC silicone caulks which evolve relatively large quantities of low molecular weight cyclic polysiloxanes which condense upon the glazing and are ultimately converted into an opaque white deposit of silica.

Because organic caulks such as acrylic or butyl lose their elastomeric properties rapidly on exposure to even rather mildly elevated temperatures in air, their use in solar collectors is not recommended. The Class SC silicones retain elongation very well, but are mechanically weaker than the Class PS silicones. They may be used in external applications where they are not subject to mechanical stress.

If adsorbents are to be used to limit deposition of condensables inside solar collector units, it is recommended that a duo-adsorbent, incorporating both silica gel and activated carbon, be chosen. The former adsorbent preferentially adsorbs water and the latter organic condensables. Since effective circulation of the solar collector atmosphere through the adsorbent to remove condensables before they deposit on the glazing or adsorber plate is a significant problem, it is still vital to select elastomers which evolve minimum amounts of condensables.

Five collectors, which had been in service at three different locations, were examined with regard to their design and quality of fabrication. Two of the collectors were poorly sealed, and three were moderately to well sealed. Problems associated with the collectors 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.

The use of an externally attached bladder to compensate for breathing caused by pressure-temperature change is feasible as long as considerable space is available underneath the collector. This approach will not solve problems associated with organic vapors from the sealants.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

We recommend a program to develop improved elastomeric gasketing materials for use in thermal solar collectors. These sealants should be designed to provide superior long-term retention of physical properties in the hostile environment of the solar collector, without causing side effects deleterious to the efficacy of the collector unit.

Two tasks are outlined for accomplishment of this objective. The first involves identifying the types of polymers which provide the best overall performance when used in thermal environments of 400°F, 300°F and 200°F, respectively. The second task consists of developing optimum chemical formulations which incorporate the polymers identified in the first task.

The materials developed should provide high thermal stability and very good resistance to attack by oxygen, ozone, moisture and weathering. Effort should also be directed toward reducing the compression set which elastomers normally display upon thermal aging under compression, and the formation of volatile materials during aging, particularly those which are likely to condense on the glazing or absorber plate.

PUBLICATIONS

The first publication involves a presentation at an American Chemical Society Symposium on New Applications for Plastics, "Sealants for Solar Collectors" (Houston, March 24, 1980).

Future publications will include written articles in the scientific and technical literature and oral presentations at technical society meetings.

X SOLAR CONTROLS TECHNOLOGY GROUP

OVERVIEW OF THE SOLAR CONTROLS PROGRAM

Lyle Groome, SOLAR ENERGY RESEARCH INSTITUTE
Mashuri L. Warren, LAWRENCE BERKELEY LABORATORY

NTRODUCTIÓN

The Solar Controls Program is a support element of the Solar Heating and Cooling Program of the Office of Solar Applications. In the past, work in this area has included assessment of controls needs for active solar systems and the development of control algorithms and hardware.

During the past year, control problems have been identified as a major source of solar energy system malfunctions. These problems, if unresolved, will present a barrier to commercialization of active solar systems. The emphasis of the controls program has accordingly been shifted to focus on solving these near term problems related to controller reliability and system design and operation.

Effective system control is the key to getting the highest performance and maximum cost effectiveness from in a solar system. Accordingly, the analysis and testing of system control strategies has been and also will continue to be a major element of the controls program plan.

PROGRAM OBJECTIVES

The major objectives for the controls effort are fourfold:

- o to address immediate problems being experienced in the field to improve the reliability and performance of existing controls technology.
- o to provide coordination and focus for all controls related activities throughout the active and passive building systems programs.
- o to provide support to industry and marketplace in the areas of education, training, information dissemination, and standards and certification.
- o to continue analysis and research in the development of advanced controllers and control strategies.

A number of specific problem areas related to these objectives have been identified and are being addressed by the controls program.

Immediate Problems.

Problem: There have been an alarming number of system failures that can be attributed to control problems.

A project is planned to review field data and literature to establish failure modes and identify causes of system failure. From this work will be developed recommended system control designs that avoid failures. Problems with component failures will be identified and addressed. A new research activity is planned to develop control algorithms and control hardware that will monitor system performance and that has fault detection capabilities and improper mode alarms.

Problem: Control component failures cause unreliable operation.

An objective of the Controls Program is to support industry efforts to establish quality control, establish standards for sensor accuracy and calibration, and for stability of control electronics, and to develop a product certification program. These efforts should develop information on component reliability for actuators such as pumps, valves, and freeze protection devices.

Coordination.

Problem: Controls problems are systems problems and apply to a diverse range of technologies. Each technology tends to address its own control problems isolated from work in other areas.

Technical management responsibility for the controls program is being integrated with the systems analysis effort at SERI and coordinated with development activities in the DHW, direct heating, heat pump, and cooling areas. The technical coordination of controls work across the various program elements will be assigned to an individual at SERI.

Support to Industry.

Problem: There is a lack of knowledge among designers as to the proper control techniques to use with different solar systems. There is lack of clear understanding of proper system installation, checkout, and troubleshooting procedures.

Several activities in the Program are currently analyzing the control requirements for solar systems and developing recommendations for control strategies, set points, and sensor placement. This information will be communicated to the industry along with information on installation, checkout, and maintenance. A controls handbook for domestic hot water systems is nearing completion. A similar one for space heating is being planned. Target audiences include system designers, manufacturers, installers, and maintenance personnel.

Analysis and Research.

Problem: Performance of active solar systems is often far from ideal because of improper design or improper control.

Applied research in controls is being directed toward improving system performance of solar heating and cooling systems by: standardizing and simplifying system configurations; assessing relative performance of different configuration and control options; integrating control with back-up system; and developing algorithms for advanced controllers. The program will also address the integration of controls for passive and hybrid systems.

Problem: Inaccurate models of control performance can lead to inefficient systems and improper control.

There are ongoing activities to develop accurate simulation tools for the analysis of controls. These models will be validated with experimental data from test facilities and instrumented systems. The validated simulation models will then be used; to determine recommended set-points and control variables, to determine conditions that minimize collector pump cycling, and to optimize sensor locations.

Problem: Large solar systems, particularly those with cooling capabilities, become very complex to implement; this leads to design flaws and installation problems.

To address this problem, the program will include activities to develop standard system designs wherever possible. The application of microprocessor technology to direct digital control of complex installations will be explored. There is discussion of developing an advanced control algorithms test facility at the LASL study center, which has a complex heating and cooling system, that would allow evaluation and validation of advanced control algorithms on a real building.

BACKGROUND

The present controls effort was essentially launched in FY77 with the preparation of the Controls RFP, in response to specific controls program needs, as identified in the solar heating and cooling R & D program plan. Other activities that year included the LBL and LASL inhouse controls projects and three contracts issued by NASA/MSFC as part of the Development in Support of the Demonstration Program.

In FY78 a number of new projects were funded, mostly as a result of the Controls RFP. Most of these have now been completed, or are in the final report stage. Unsolicited proposals from Drexel University, Middlebury College, and Rho Sigma were also supported.

In FY79 only two projects were initiated: fundamental studies of collector loop dynamics at Drexel was funded with a new contract through SAN; and a DHW controls manual was funded at SEEC through SERI.

HIGHLIGHTS OF CONTROLS PROGRAM

Various sectors have contributed to the controls program.

- Controls Manufacturers:
  - Technology assessment to identify field problems and areas where applied research is needed.
  - Develop and commercialize new controllers to meet market needs.
  - Quality assurance and product improvement.
- Universities and Independent Research Organizations:
  - Study fundamental control problems.
  - Develop new control algorithms for integrated energy management.
  - Prepare handbooks and reports.
- National Laboratories (LASL, LBL, and SERI):
  - Technical monitoring and support.
  - Testing and evaluation of alternative control strategies.
  - Preparation of reports on advanced control techniques.

Past Activities. Past work undertaken on controls for active solar systems has resulted in a number of accomplishments, which are described below:

- Advanced Controller Hardware. NASA contracts were undertaken in FY 1977 for the development of advanced controller hardware by three established manufacturers. The contracts with Andover Controls Corporation and Rho Sigma resulted in the development of microprocessor based controllers. The contract with Solar Controls Corporation resulted in the development of a modular controller. These three controllers were delivered to the NASA/Marshal Space Flight Center for Evaluation and reports describing the controllers have been published.

Three hardware development contracts were also undertaken in FY 1978 to apply advanced electronics to the control of active solar systems.

- Honeywell developed a microcomputer based Solar Energy Management System capable of controlling up to 12 outputs, with 14 clearly defined modes of solar system operation with provision for defining both the relay output table, and the priority for each mode. The SEMS controller has been delivered to LBL and is under evaluation.
- Solar Controls Corporation has developed a novel controller that implements two stage collector loop flow control with a modular electronic controller. Work on this controller is nearing completion.
- Rho Sigma has developed a microprocessor based controller for use with a two stage heat pump. The original proposal was to develop a continuously variable motor speed controller; however no heat pumps are commercially available with this feature. The prototype device has been used to operate a commercial two speed heat pump. A final report of this work is in preparation.

- Technology Assessment. An assessment of the need for new controllers for active solar systems was undertaken with three different contracts.
  - Honeywell performed analysis of cost effectiveness of different control strategies using their proprietary simulation program, and made recommendations for the most effective strategies in different regions. Emphasis was placed on energy conserving strategies such as temperature reset, and temperature setback strategies and "economizer" cycles.
  - Rho Sigma surveyed architecture and engineering firms, solar manufacturers, and installers, and reviewed their inhouse engineering experience to determine near term needs for new controllers. They found that there is no further need for government support of hardware development for domestic hot water systems and for peak load reduction, however there is still a need for algorithm development. In other areas such as active cooling and solar/heat pump systems additional hardware development may be necessary because the solar industry is too small to attract development efforts in the private sector. As the result of their work a follow on contract was developed to produce a variable frequency variable amplitude power supply for electric motors.
  - Solar Controls performed an extensive survey of solar architects, engineers, manufacturers, installers, equipment distributors, consultants, and designers. They concluded that while the industry is satisfied with controllers for simple DHW

and heating configurations, there is a need for design guidelines and installation handbooks. There is a need to develop algorithms for more sophisticated controls, such as solar/heat pumps, active solar cooling, and building energy management, and to develop thermostats specifically for solar applications. They stressed the important possibilities for microprocessor-based controllers.

- o Utility Assessment. The impact of solar on utility peak loads, and the possibilities for reduction of peak loads by using the thermal storage capabilities of solar for off-peak storage of required auxiliary back up, were explored in two studies by Georgia Institute of Technology and the Franklin Research Institute. These studies have just concluded and are in the final reporting stage. These studies should form a solid basis for evaluating the impact of solar auxiliary energy requirements on utility load profiles.

PLANNED ACTIVITIES FOR FY80

The FY80 activities of the Solar Controls Program are being planned to preserve the continuity of work now being performed while also focusing on near-term problems.

In September, 1979, supplemental funding of $400,000 was approved for the Controls Program in FY80. Discussions on the plan for this funding were held by SERI, LBL, LASL, DOE/SAN and various contractors, and a review was made of current work in the light of the new directions from DOE.

The recommendations for FY80 activities fall into three categories: Current Projects, New Initiatives, and Coordination Activities.

Current Projects. The present work of the controls program consists of the following projects:

- o DHW Control Handbook. A handbook for designers and installers of controls for domestic hot water systems is being prepared by SEEC under contract with SERI. This manual will provide direct assistance to system designers and installers in insuring proper design, proper positioning of sensors and other components, as well as correct installation and checkout procedures.

- o Analysis of Control Problems in Active Solar Systems. This activity is a continuation of the work at Drexel University on the analysis of the effects of insolation, set-points, and sensor placement on solar collector loop control. Sensitivity studies should establish guidelines for proper set-points and sensor placement, as well as provide the analytical basis for evaluation of advanced collector loop control strategies.

- o Experimental Validation of Dynamic Collector Loop Models. This follow-on task for Middlebury College is for collecting data from their well-instrumented collector system to validate the simulation work at Drexel and LBL. The total expenditure to date ($10 K) on the Middlebury contract has been amply supplemented with student energy and college resources.

- o Implementation and testing of advanced controllers. The controls work at Colorado State University is integrated with the systems development work in the Solar Houses. It includes the development and testing of a Luenberger Observer controller for off-peak storage, integration of an optimal controller into an air based system, and development of a reliable automatic drain-down collector system.

- o Evaluation of Advanced Controls for Building Energy Conservation. This task represents a redirection of the original proposal from Los Alamos Scientific Laboratory. The work in FY80 will include finishing the analysis work on their Adaptive Optimal Control concept and planning for the use of the LASL study center as a field test site for advanced control concepts. The building is a useful resource for this as it contains a complex active solar heating and cooling system that is well instrumented and has a performance history.

  LASL has analyzed energy savings by application of adaptive optimal control to active solar systems. Significant reduction of auxiliary energy consumption and improvement in solar utilization have been predicted. The LASL project addresses the problem of integrated control and energy management of a commercial scale active heating and cooling systems. As solar systems become more complex, traditional approaches to control become unwieldy.

- o Experimental Evaluation and Analysis of Control Strategies. Experimental work at Lawrence Berkeley Laboratory to evaluate of the relative performance of different active solar system control strategies for a variety of input meteorological conditions and output load demands is continuing in FY80. The primary goal is the experimental evaluation of the cost effectiveness of controllers and control strategies. New efforts directed at the analysis of control problems that affect system performance and reliability including a review of previous system failures, and establishing generic system configurations and control strategies for combined domestic hot water systems in combination with heating systems, are planned to begin in late FY80.

  In FY 1979 the system instrumentation was refined and the necessary computer software to run the facility and perform data analysis was developed. Experiment modifications have been completed to permit variable-flow and proportional-flow control of the collector loop. Analytical work in support of the experimental effort includes the application of theoretical models to describe dynamic collector operation and building temperature response. Analysis of the energy collection performance of on/off and proportional flow control collector loop strategies has been completed.

New Initiatives. Two new initiatives have been recommended for FY80.

- o Controls Handbook for Space Heating. This projects follows the DHW system handbook now being completed. The space heating handbook will answer an immediate need for standardization of control configurations and strategies for space heating systems. It may well be that this will be a two year effort, as the problems of heating systems are complex. Plans for this task will be developed late in FY80.

- o Performance Monitor Controller. This activity is intended to develop a commercial controller capable of monitoring the performance of a solar system, detecting faults, and alerting the operator or

owner. The work must address types of system failures, how to detect them, and implementation of a cost effective concept. Planning for this task will be developed late in FY80.

Coordination Activities. Technical Coordination is a necessary part of the Controls Plan.

- Technical coordination by SERI. Technical coordination by SERI includes the development and updating of the Controls Program Plan, assessment of controls activities and needs in both the active and passive technology areas, and technical coordination of all controls related work. This activity is newly developed and funds for it have not been identified at this time.

- Technical Monitoring of Controls Contracts. LBL is continuing to perform program support tasks that include program planning, preparation and evaluation of solicitations, proposal reviews, and technical monitoring of DOE solar controls contracts.

FY81 ACTIVITIES

The development of plans for Control work in FY81 is now underway. The goal is to develop a strong program that will solve the controls problems faced by the solar industry today, as well as to lead to more effective controls in the future.

REFERENCES

DOE/NASA Technical Memorandum TM-78243. "Development and Testing of the Solar Control Corporation Modular Controller andSolarstat Subsystem--Final Report," Solar Energy Applications Projects, August 1979.

DOE/NASA Contractor Report CR-150771, "Solar Control Design Package," Solar Control Corporation, August 1978.

DOE/NASA Technical Memorandum TM-78244. "Development and Testing of the Sunkeeper Control Corporation Integrated Programmable Electronic Controller and Hydronics Package--Final Report," Solar Energy Applications Projects, 1979.

DOE/NASA Contractor Report CR 161151. "Design Package for Programmable Controller and Hydronic Subsystem," Sunkeeper Control Corporation, March 1979.

DOE/NASA Technical Memorandum-78246. "Development and Testing of the Rho Sigma Incorporated Microprocessor Control Subsystem--Final Report," Solar Energy Applications Projects, October 1979.

DOE/NASA Contractor Report CR-150535. "System Design and Installation for RS600 Programmable Control System for Solar Heating and Cooling," Rho Sigma Inc., January 1978.

Final Report. Contract EG-77-C-03-1598. "Solar Energy Management Systems Development Program," Honeywell, 1979.

Final Report. Contract EG-77-C-03-1592. "Cost Effective Control Systems for Solar Heating and Cooling Applications," Honeywell, September 1978.

Final Report. Contract EG-77-C-03-1597. "Assessment of the Need for New Solar Controllers," Rho Sigma Inc., June 1978.

Draft. Contract DE-AC03-77CS31596. "Assessment of Needs for New Controllers," Solar Control Corporation, December 1979.

Interim Report I-C4827. Contract EG-77-C-03-1594. "Novel Control Strategies for Solar Assisted Systems," Franklin Research Center, Franklin Institute, October 1978.

Final Report. Contract EG-77-C-03-1595. "Management of Electric Back-Up Demand for Solar Heating and Cooling Applications," Georgia Institute of Technology, 1979.

Draft Final Report. Contract E-8-77-5-02-4512. "Development of a Dynamic Model of a Collector Loop for Solar Heating and Cooling System Control," Drexel University, November 1979.

Status Report. Contract W-7405-ENG-36. "Adaptive Control for Energy Conservation," Los Alamos Scientific Laboratory, March 1977.

Monthly Report. "CSU-DOE Programmatic Grant for Research and Development in Solar Energy Applications," Solar Energy Applications Laboratory, Colorado State University, May 1979.

Draft Final Report. "Two-Stage Approach to Cost Effective Controllers Via Adaptive Optimization," Corporate R & D Laboratory, The Singer Company, September 1978.

Report LBL-10352. "Experimental Test Facility for Evaluation of Controls and Control Strategies," Lawrence Berkeley Laboratory, January 1980.

Report LBL-10315. "Comparison of Proportional and on/off Collector Loop Control Strategies Using a Dynamic Collector Model," Lawrence Berkeley Laboratory, December 1979.

"Reliability and Maintainability Evaluation of Solar Control Systems," Argonne National Laboratory, 1979.

OPTIMAL CONTROL OF SHAC SYSTEMS

COLORADO STATE UNIVERSITY

EG77-S-02-4519

C. Byron Winn

October 1978 to September 1979

OBJECTIVES

The objectives of this program are to investigate optimal control strategies for SHAC and off-peak storage systems and also to investigate the applicability of optimal estimation procedures to SHAC systems.

BACKGROUND

Control. An optimal controller of the second kind is one which maximizes the difference between the solar energy collected and the associated pumping costs. This is an important problem because, even in a well designed solar heating system for a typical residential application, the fan used for collection alone will use more than 100 kWh of electrical energy per month. An optimal controller operating a four speed fan with a wide range could reduce the electrical consumption by half. This optimal control problem was first approached by Kovarik and Lesse [1]. They solved the problem numerically, but their solution could not be implemented because it was not a function of measurable states of the system and required advance knowledge of weather data. Winn and Hull presented an approximate analytical solution to the problem which can be implemented [2]. They showed close agreement between their results and the results of Kovarik and Lesse. This paper presents an alternate approximate solution to the problem with results equivalent to those of Winn and Hull. The problem is further simplified so that it can actually be implemented in a practical controller. An optimal controller of the second kind has been built and is installed in Solar House II at Colorado State University. This controller provides an alternative to the bang-bang controller as well as the proportional controller for solar heating systems.

The problem is to maximize the difference between the solar energy collected and the parasitic pumping costs, both of which are functions of collector mass flow rate, $\dot{m}$. That is, maximize

$$I = \int_0^{t_f} [C_1 Q_u(\dot{m}) - P(\dot{m})]dt \qquad (1)$$

where C_1 is a weighting factor which takes into account the difference between cost of energy to run the fan and that to provide auxiliary heating. A sufficient condition for this expression to be a local maximum is that the term

$$dI/dt = J = C_1 Q_u(\dot{m}) - P(\dot{m}) \qquad (2)$$

be a maximum at all times.

The energy collected can be found from the Hottel-Whillier-Bliss equation [3]

$$Q_u(\dot{m}) = F_R A_c [H_T \tau\alpha - U_L(T_i - T_a)] \qquad (3)$$

where

$$F_R = (\dot{m}C_p/U_L A_c)[1-\exp(-FU_L A_c/\dot{m}C_p)] \qquad (4)$$

and

A_c = collector area
H_T = solar insolation on the collectors
τ = transmissivity of the collector glazings
α = absorptivity of the absorber plate
U_L = overall collector loss coefficient
T_i = collector inlet temperature
T_a = ambient temperature
C_p = specific heat of the collector fluid
F = collector efficiency factor

To simplify this relationship, the exponential is expressed as a Taylor series and truncated after second order terms. With this approximation, the energy collected is expressed as

$$Q_u(\dot{m}) = (F - F^2 U_L A_c/2\dot{m}C_p) A_c [H_T \tau\alpha - U_L(T_i - T_a)] \qquad (5)$$

Now define the available energy as

$$f = Q_u/F_R = A_c[H_T \tau\alpha - U_L(T_i - T_a)] \qquad (6)$$

Hence,

$$Q_u(\dot{m}) = fF - fF^2 U_L A_c/2\dot{m}C_p. \qquad (7)$$

The parasitic pumping costs must also be expressed as a function of mass flow rate. The fan laws state that the power required by a fan is proportional to the cube of the flow rate [4]. This theoretical relationship will be changed by factors such as fan efficiency and changing flow regimes, which will also vary with flow rate. For this analysis, however, the parasitic pumping costs will be expressed as

$$P(\dot{m}) = C_2 \dot{m}^x. \qquad (8)$$

The appropriate value for x will be discussed later.

The problem now is to maximize

$$J = C_1 fF - C_1 fF^2 U_L A_c/2\dot{m}C_p - C_2 \dot{m}^x \qquad (9)$$

The flow rate is the only term in this expression which can vary significantly in a short period of time. Therefore, by taking the derivative of J with respect to flow rate and setting it equal to zero, the optimal mass flow rate can be determined as

$$\dot{m}_{OPT} = (C_1 fF^2 U_L A_c/2xC_2 C_p)^{1/(x+1)} \qquad (10)$$

This reduces to the results obtained by Winn and Hull [2]. The available energy, f, is determined from either

$$f = \dot{m}C_p(T_{OUT} - T_i)/F_R \quad (11)$$

if the collector fan is on, or

$$f = U_L A_c(T_{OUT} - T_i) \quad (12)$$

if the fan is off [2]. Here, T_{OUT} is the collector outlet temperature. Thus, the optimal mass flow rate is determined from a knowledge of the system parameters, the flow rate during the last time interval, and the collector inlet and outlet temperatures.

Identification. Although heat transfer properties of most construction materials are available in tabulated form, the overall heat transfer properties of buildings are quite difficult to determine. Even buildings of simple design are sufficiently complex to make the analytic determination of system parameters subject to a large degree of error. Thus the need is apparent for methods of parameter estimation which do not depend on tabulated properties of materials or the complexities of system geometry. This study describes one method of evaluating system parameters from measured data using the method of least squares to determine the system coefficients of an assumed model.

Two applications of this method were tried. The first involved estimating the parameters of a simulated (and therefore known) system, while the second was used to estimate parameters of an actual building located at the Solar Village on the Colorado State University Campus. This work is a continuation of research that has been reported at several previous conferences (see references).

SUMMARY

Control. We have demonstrated by means of both computer simulations and physical experiment that significant performance improvements can be realized through the use of optimal controllers of the second kind. We have constructed an optimal controller and installed and tested it in CSU Solar House II. We have identified a definite need for improved motor-fan combinations in air heating systems.

Identification. We have shown, again by means of both computer simulation and actual testing that building parameters can be determined through the use of system identification techniques. This has obvious applications to improved controllers in SHAC systems.

TECHNICAL ACCOMPLISHMENTS

- Designed, built, and tested an optimal controller of the second kind. This device ("OPTICON") controls the solar collection system in CSU House II in a manner such that the difference between useful energy collected and parasitic losses incurred in collecting the energy is maximized.

System parameters for CSU House II are shown in Table 1; the search table used in implementing OPTICON is shown in Table 2. Performance results are shown in Tables 3 and 4. It is clear from these results that the use of OPTICON leads to a dramatic improvement in the solar coefficient of performance

Table 1. System Parameters

Collector Area, A_c	57.93 m^2
Collector Loss Coefficient, U_L	13.9 $kJ\text{-}h^{-1}\text{-}°C^{-1}\text{-}m^{-2}$
Collector Efficiency Factor, F	0.9
Specific Heat of Air, C_p	1.004 $kJ\text{-}kg^{-1}\text{-}°C^{-1}$
Transmissivity Absorptivity, $\tau\alpha$	0.77
Weighting Factor, C_1	1.
Pumping Cost Constant, C_2	0.000045 $kJ\text{-}h^{1.3}\text{-}kg^{-2.3}$
Pumping Cost Exponent, x	2.3
Stage 1 Mass Flow Rate, $\dot{m}_1$	2082 $kg\text{-}h^{-1}$
Stage 2 Mass Flow Rate, $\dot{m}_2$	2218 $kg\text{-}h^{-1}$
Stage 3 Mass Flow Rate, $\dot{m}_3$	2322 $kg\text{-}h^{-1}$
Stage 4 Mass Flow Rate, $\dot{m}_4$	2491 $kg\text{-}h^{-1}$

Table 2. Search Table

$(T_{OUT}-T_i)$ (°C)		Fan Stage for Last Time Interval				
		0	1	2	3	4
Fan Storage for Next Time Interval	0	-∞→0	-∞→0	-∞→0	-∞→0	-∞→0
	1	0→22	0→6.4	0→6.1	0→5.8	0→5.5
	2	22→25	6.4→7.2	6.1→6.8	5.8→6.6	5.5→6.2
	3	25→29	7.2→8.2	6.8→7.8	6.6→7.5	6.2→7.1
	4	29→∞	8.2→∞	7.8→∞	7.5→∞	7.1→∞

Table 3. Simulation Results for 20 Jan., A Sunny Day

	Bang-Bang Control, Present Fan	Optimal Control, Present Fan	Optimal Control, Improved Fan	Optimal Control Infinitely Variable Fan
Energy Collected, kJ	496147	494238	487756	489446
Fan Energy Required, kJ	21922	20705	13732	14641
Objective Function ΣQ_u-P, kJ	474225	473532	474024	474805
SCOP'	22.6	23.9	35.5	33.4

Table 4. Simulation Results for 19 Jan., A Cloudy Day

	Bang-Bang Control, Present Fan	Optimal Control, Present Fan	Optimal Control, Improved Fan	Optimal Control Infinitely Variable Fan
Energy Collected, kJ	191875	189920	184838	186089
Fan Energy Required, kJ	17432	14869	6531	6818
Objective Function ΣQ_u-P, kJ	174442	175052	178307	179271
SCOP'	11.0	12.8	28.3	27.3

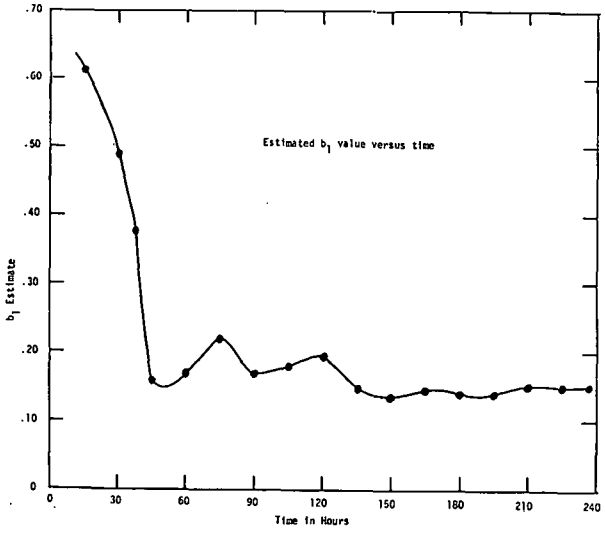
(SCOP[1]) relative to the more commonly used bang-bang controller.

- Developed procedure for rapid commercialization of OPTICON. Interfaced with an industrial organization (Solar Control Corporation) for commercialization of OPTICON.
- Developed an ambient temperature observer predictor (ATOP) for possible use with SHAC and/or storage systems.
- Developed an optimal control strategy for use with an off-peak storage system.
- Demonstrated that Kalman filters, Luenberger observers, and least squares filters may be very useful in control and identification of SHAC systems. For example, the results obtained from filtering actual data taken at a test facility at the CSU Solar Village are shown in Table 5.. The seven parameters that were being estimated are parameters in the differential equations that describe the thermal response of the system to exogenous inputs. The convergence of the process is illustrated by Figure 1, which shows a typical graph of a least squares parameter estimate as a function of time.

Table 5.

	True Value	Value by Least Squares	Percent Error In L.S. Value
ρ_1	.120	.115	-4.2
ρ_2	.730 E-11	.771 E-11	5.6
ρ_3	.117 E-3	.139 E-3	18.8
ρ_4	.146 E-3	.140 E-3	-4.1
ρ_5	.315	.295	-6.3
ρ_6	.308	.288	-6.5
ρ_7	.308 E-3	.289 E-3	-6.2

Figure 1.



FUTURE ACTIVITIES

Contract activities.

- Test OPTICON over a wider range of flow rates and in a smaller collector array than is presently being used. It is expected that very significant performance improvements will be realized when OPTICON is used in a system that is not over-sized.
- Examine applications of OPTICON to optimal controllers of the first and third kinds.
- Investigate the effects of biased and unbiased measurement noise on parameter value estimates and on convergence in estimation procedures.

Post-contract activities.

- Work with industrial organizations to commercialize OPTICON.
- Investigate the possibility of isolating certain parameters by applying the estimation techniques to selected data sets (e.g., nighttime data only).

PUBLICATIONS/REPORTS/REFERENCES

Publications

- Winn, C.B. and D.E. Hull, III, "Optimal Controllers of the Second Kind," J. of Solar Energy, Vol. 23, 1979.
- Winn, R.C. and C.B. Winn, "Implementation of an Optimal Controller of the Second Kind," DOE/SERI Conference on Systems Simulation and Economic Analysis, San Diego, CA., January, 1980.
- Winn, C.B. and K. Robinson, "Use of the ATOP System in the Control of an Off-Peak Storage Device," IEEE Conference on Decision and Control, Fort Lauderdale, FL., December, 1979.
- Hays, D.K., Parkinson, B.W. and C.B. Winn, "Real Time Identification of Parameters in Building Models," ISES Conference, Atlanta, Ga., May 1979.
- Hays, D.K., Parkinson, B.W. and C.B. Winn, "The Development of an Ambient Temperature Observer/Predictor (ATOP) for use with Solar Heating Systems," ISES Conference, Atlanta, Ga., May 1979.
- Kent, T.A. and C.B. Winn, "Performance of Controllers in Solar Heating and Cooling Systems," 2nd Annual Operational Results Conference, DOE/SERI, Colorado Springs, CO., November 1979.
- Pryor, D., Baer, C. and C. B. Winn, "Optimal Identification of Parameters in Passive Solar Buildings," DOE/SERI Conference on Systems Simulation and Economic Analysis, San Diego, CA., January 1980.
- Baer, C., Pryor, D., and C.B. Winn, "Enhancement of Performance of Active Solar Systems by Optimal Control and System Identification Techniques," DOE/SERI Conference on Systems Simulation and Economic Analysis, San Diego, CA., January 1980.

References

[1] Kovarik, M. and Lesse, "Optimal Control of Flow in Low Temperature Solar Heat Collectors," Solar Energy, Vol. 18, No. 6 (1976).

[2] Winn, C.B. and D.E. Hull, III, "Optimal Controllers of the Second Kind," J. of Solar Energy, Vol. 23, 1979

[3] Duffie, J.A. and W.A. Beckman, Solar Energy Thermal Processes, John Wiley & Sons, New York, 1974.

[4] Olsen, R.M., Essentials of Engineering Fluid Mechanics, International Textbook Co., Scranton, PA (1974).

A STUDY OF CONTROL INSTABILITIES IN SOLAR HEATING AND COOLING SYSTEMS

DREXEL UNIVERSITY

Contract# AS02-77CS34512

PETER HERCZFELD and ROBERT FISCHL

Contract Period - Begin: Jan. 1, 1979 - End: June 30, 1980

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.

BACKGROUND

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 uncertaintities may include stochastic climatic conditions, sensor tolerances, time delays and other phenomena. To understand the effect of these non-ideal conditions on the controller it is imperative to develop accurate control models which "track" controller action during potential malfunctions.

The control modeling was limited to a collector loop consisting of a collector, transport (i.e., piping), a mixed storage system, and to an on-off controller.

SUMMARY

A closed form analytic solution was found for the collector loop based on a distributed parameter, dynamic collector model. This solution, which accurately tracks the collector dynamics under various conditions was used for control studies. A parametric sensitivity analysis of the controller was carried out leading to selection criteria for the control set points of on/off controllers. The effect of various sensor locations on the controller performance was evaluated.

TECHNICAL ACCOMPLISHMENTS

Collector Model. 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. The solution is given below:

$$T_{fc}(\xi,t) = \gamma[F'(t)-e^{-\frac{\tau_{tc}}{\tau'_{fc}}\xi} F'(t-\tau_{tc}\xi)U(t-\tau_{tc}\xi) + e^{-t/\tau'_{fc}} A_1(\xi-t/\tau_{tc})U(\xi-t/\tau_{tc}) + e^{\frac{\tau_{tc}}{\tau'_{fc}}\xi} A_2(t-\tau_{tc}\xi)U(t-\tau_{tc}\xi)] + (1-\gamma)[f(t) + e^{-t/\tau_{fc}} A_1(\xi)] \quad (1)$$

where

$$F(t) = \frac{1}{\tau_{fc}} \int_0^t [\alpha_c f(\lambda) + T_a(\lambda)] e^{-(t-\lambda)/\tau_{fc}} d\lambda \quad (2)$$

In the above equation primed quantities refer to flow condition (γ=1) and unprimed quantities to stagnant condition (γ=0); $A_1(\xi,0)$ is the initial condition and $U(\cdot)$ is the unit step function.

The boundary condition, A_2, requires special attention. Under stagnant conditions (γ=0) a temperature difference exists between the various system components (i.e., collector, transport and storage) because of the differences in thermal constants and solar absorbance. If one assumes that each component is isothermal then one obtains step discontinuities. In reality, 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 phenomena, the temperature across the boundary region $\Delta\xi$ is modeled by a third order polynomial:

$$A_2 = \beta(T_1-T_0)\,\zeta^2(1-\zeta) + T_0 \quad (3)$$

with

$$\beta = 6.75, \quad T_0 = T_f(\zeta=0) \text{ and } T_1 = T_f(\zeta=2/3)$$

Here T_o and T_1 represent the stagnant temperatures at the boundary inlet and outlet, respectively

The solution given in Eq.(1) has been discussed elsewhere [2], it is sufficient to say that it properly reflects the collector dynamics as observed experimentally including pump cycling.

Computer Simulation. To evaluate the controller operation under various conditions a computer simulation program was developed [3]. The simulation algorithm is able to "track" the states of the system under transient conditions due to fast changes of the input data (climate) and due to discontinuities in system operation (e.g., pump switching). The program is able to give information on both the time and space distribution of the temperature profile around the collector loop in order to evaluate the effect of the sensor location on the control strategy. Fig. 1 illustrates the result of a typical computer run.

Parametric Sensitivity Studies. In order to establish the tradeoff between the energy collected, J_1, and pump cyling, 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 using Eq.(1) and the computer simulation 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 given in Table I. Typical results of the sensitivity analysis are shown in Fig. 2.

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 in 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 given by Eq.(1) was used to derive a condition for the selection of ΔT_{on} and ΔT_{off} [4]. The results for a clear sky condition are:

$$\Delta T_{off} = P(\mathring{m})/\mathring{m} \qquad (4)$$

where $P(\mathring{m})$, is the pumping power to maintain flow rate $\mathring{m}$, and

$$\Delta T_{on} = \left[\frac{1}{1+\omega^2\tau_{fc}^2}\right]\left[G - \omega\tau_{fc}(\alpha_c^2 - F^2)^{1/2}\right] \qquad (5)$$

where

$$G = \Delta T_{off}\,\tau_{fc}/\tau_{tc} + (T_s - T_a). \qquad (6)$$

Sensor 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, ξ=1, 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 as shown in Fig. 3. We have simulated the performance of the controller for a number of different sensor locations which are shown in Fig. 3. The results are summarized in Fig. 4 which shows the first turn-on time, t_{on}, and the total energy collected until 10:00 A.M. as a function of sensor location. These examples assume clear sky conditions and that the set points ΔT_{off} and ΔT_{on} are selected in accordance with the previous discussion. 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 upstream from the optimal position then the collector area will appear smaller than it actually is. This will cause cycling and a reduction in the energy collection.

FUTURE ACTIVITIES

A paper containing practical guidelines for control set point selections and optimal sensor locations is under preparation. These guidelines will aid the implementation of problem free controllers.

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. Orbach, 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 Flate Plate Collector Control System Sensitivity Analysis", Second Annual Systems Simulation and Economic Analysis Conf., San Diego, CA, Jan. 1980.

NOMENCLATURE

T_{fc}	Temperature of fluid in the collector
T_s	Temperature of mixed storage
T_a	Ambient temperature
$I(t)$	Solar flux on collector surface
I_o	Maximum solar flux on collector surface
$f(t) = I(t)/I_o$	Normalized solar flux
x	Distance along collector tubing
L	Length of tubing in collector
$\xi = x/L$	Normalized distance along collector tubing
C_c	Lumped capacitances of collector
A_c	Surface area of collector
U_L	Heat loss coefficient of collector
$\dot{m}_c$	Mass flow rate in collector
$(\tau\alpha)_c$	Transmittance-absorptance product of collector
c_p	Specific heat of fluid

$$a_c = \frac{I_o(\tau\alpha)_c}{U_{Lc}}$$

$$\tau_{fc} = \frac{C_c}{U_{Lc} F'} \qquad \tau_{tc} = \frac{C_c A_c}{\dot{m}_c c_p}$$

REFERENCES

1. S.A. Klein et al., "Transient Considerations of Flate-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", Workshop on Control of Solar Energy Systems for Heating and Cooling, Hyannis, Mass., May 23-25, 1978.

3. P.R. Herczfeld, R. Fischl, "Final Report DOE Contract E-8-77-5-02-4512", Submitted to Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U.S. Department of Energy.

4. 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.

Table I: Baseline system parameter values.

Nominal Values of Parameters			Climate	Set Points
$C_c = 10.22 \frac{kj}{C\text{-}m^2}$ $W = 1.0$ m $\dot{m}_c = 227.19 \frac{kg}{hr}$	$U_L = 18.65 \frac{kj}{m^2\text{-}C\text{-}hr}$ $(\tau\alpha) = .8281$ $C_p = 4.19 \frac{kj}{kg\text{-}C}$	$F' = .95$ $L = 2.0$ m $A_c = 2.0\ m^2$	$T_a(t) = 0$ C $I(t) = I_o \sin\omega(t-6)$ $I_o = 3000 \frac{kj}{m^2\text{-}hr}$	$\Delta T_{on} = 5$ C $\Delta T_{off} = 2$ C $\Delta T_h = 3$ C

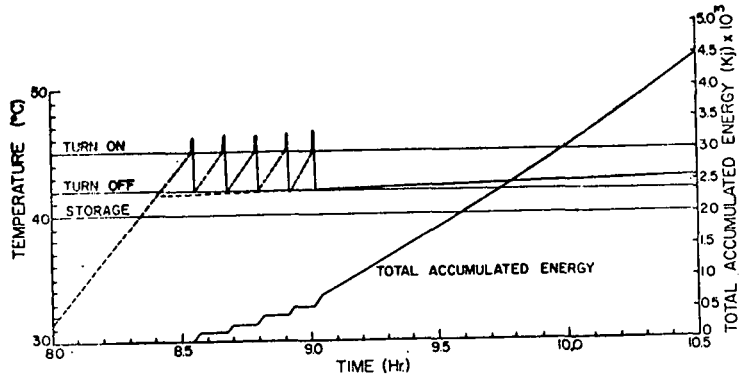
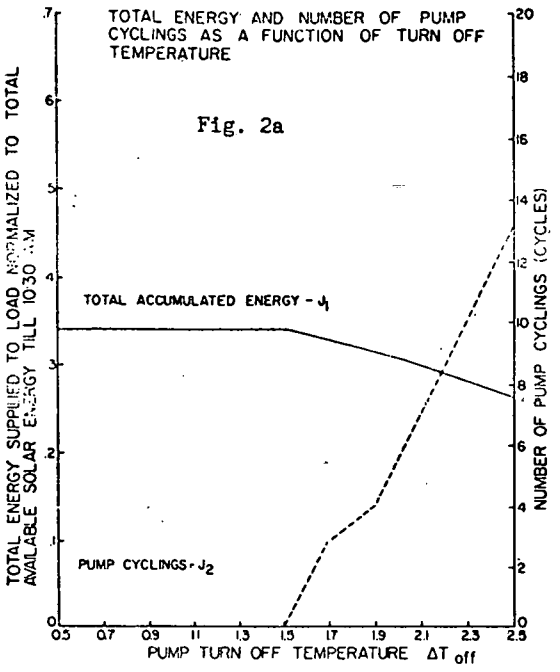


Fig. 1: In this figure the collector output temperature and accumulated energy are plotted as functions of time. The dotted portion of the collector output temperature corresponds to stagnant condition while the solid line corresponds to flow condition. This particular run shows cycling. It should be noted that there is energy collection during cycling however at a lower efficiency.



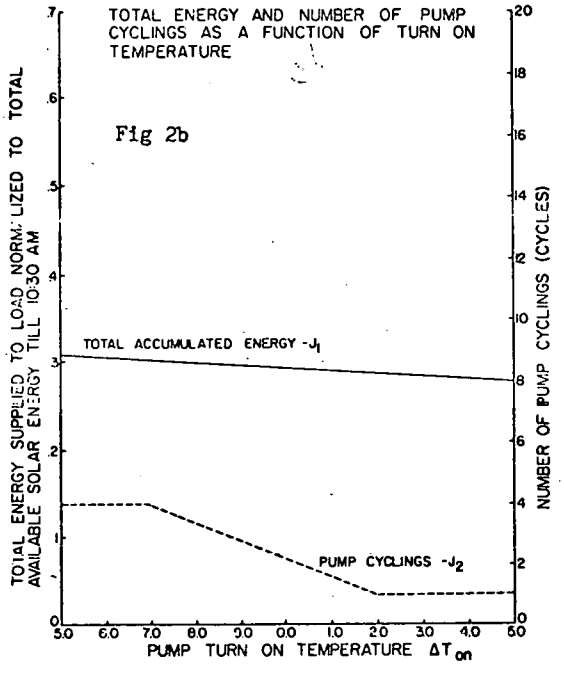


Fig. 2: The above figures (a,b) illustrate the results of the parametric sensitivity analysis of the controller performance in terms of energy collection (J_1) and pump cycling (J_2).

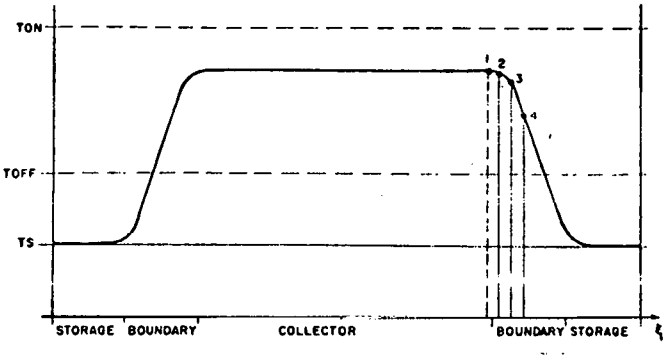


Fig. 3: Collector loop showing transport, boundary, and sensor locations.

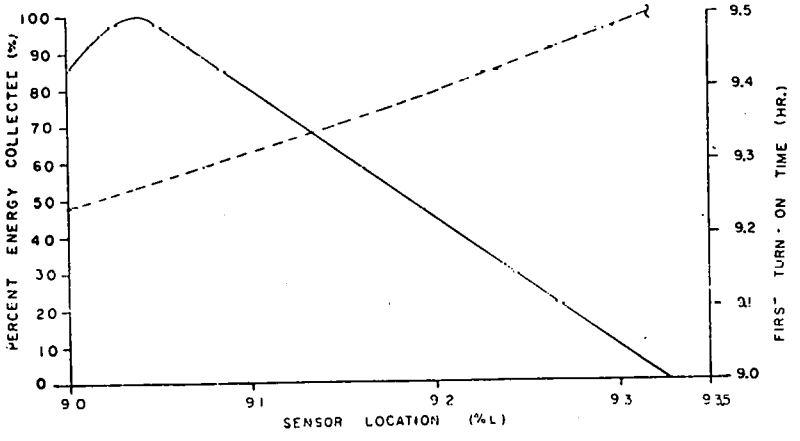


Fig. 4: Collected energy and first turn-on time vs. sensor location.

NOVEL CONTROL STRATEGIES FOR SOLAR SYSTEMS THAT REDUCE ELECTRIC UTILITY PEAK LOADS

FRANKLIN RESEARCH CENTER, PHILADELPHIA, PA 19103

CONTRACT NO. DE-AC0377-ET-20085 (FORMERLY EG-77-C-03-1594)

PRINCIPAL INVESTIGATOR: HAROLD G. LORSCH

PERIOD OF CONTRACT: BEGIN 9/19/77 END 12/31/79

OBJECTIVE

Reduce peak demands on electric utilities from solar heating/cooling backup systems by developing novel control strategies.

BACKGROUND

With the increasing shortage of fossil fuels, it can be expected that backup systems for solar heating and cooling systems will use electrical energy. This puts undesirable peak demands on the electric utilities supplying such solar heating/cooling customers. In the case of a Pennsylvania winter peaking utility, peak loads from solar heated homes at the time of the utility system peak averaged well over 95% of the loads from conventional electric resistance heated homes (Ref. 1). Other studies yielded lower peak loads for winter peaking utilities (Ref. 2). The evaluations of the coincidence between sunny days and cold days at different locations of the country (Refs. 3,4) constitute a limited approach to the problem; because, as a rule, winter peaking utilities experience their system peaks on cold days, but not necessarily on the coldest day of the year. Thus, such correlations may be indicative of the problem in a general way, but they do not predict how individual utilities will be affected by the addition of large numbers of solar heating customers to their systems.

Solar cooling installations, on the whole, are likely to be beneficial to electric utilities load patterns. In general, there exists a correlation between sunny weather and periods of summer peaking utility peaks which, of course, would be alleviated by solar cooling systems.

The above statements are valid for solar systems that are operated in the conventional way: the solar energy is first used to satisfy the building instantaneous demand, any excess solar energy is put in storage. When the building demand exceeds the solar system's instantaneous capacity, stored energy is used to satisfy it. Auxiliary energy is used only when neither the collector nor the storage systems can provide sufficient energy to satisfy the building demand. For a solar heating system this operating logic results in minimizing the total amount of auxiliary energy used during the year. Reference (5) showed that, for a solar cooling system, this operating strategy does not even result in minimum auxiliary energy use for a solar cooling system, and more sophisticated operating modes must be followed. In reality, (Refs. 1,2,&6) minimizing auxiliary energy consumption is not a condition of long-run cost minimization to the consumer because, over the long run, electric rates will be adjusted to reflect costs, and significant cost increases will be incurred by the electric utilities due to the reduced load factors caused by that method of operating backup heating systems (Refs. 1,2,&6). It would be to the advantage of both the homeowner and the utilities to operate solar heating systems in a mode that utilizes the inherent capability of their storage devices to reduce peak electrical loads from backup heating.

TECHNICAL ACCOMPLISHMENTS

- Detailed energy consumption analyses were performed using hourly meteorological data for three different locations in the country: northeast, south, west. The results of these calculations were checked against local utility historical experience and past energy consumption measurements. Where necessary, the results were modified to have the energy requirements of the conventionally heated/cooled home agree with measured results.

- From a large number of systems evaluated, twelve space heating and four space cooling systems were chosen for detailed analysis. They included conventionally electric powered and solar powered systems both with and without off-peak storage. The annual performance data for a Philadelphia, PA location of each of the heating systems are listed in Table 1. To show the effect of these systems on the utility peak load, the electrical demand of each system during the hour of the local utility's peak residential demand (class peak) is also shown.

- Installed costs were determined for all systems analyzed using manufacturer and contractor data escalated to 1980. 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 13.388%.

- The complete system of the Philadelphia Electric Company (PECo) was modeled under the conditions of "economic dispatch"; i.e., when an additional increment of power is required, the generator which can provide that power at the lowest increase in cost is called upon to furnish ("dispatch") that power. The PECo network was analyzed for each of the 8760 hours of the years 1985 and 1995 using economic dispatch for the generation units planned to be in service in those years. The system was modeled repeatedly under the assumption that, starting in the year 1980, all new single-family home customers of the utility would equip their homes with identical types of space heating/cooling systems. The eight types chosen were conventional or solar with or without off-peak storage. The total production costs of the utility were then calculated for each heating/cooling system penetration. The changes in production costs from the base system (electric resistance heating and electric air

Table 1. Annual Performance of Selected Space Heating Systems in Philadelphia, PA

SYSTEM	TOTAL ANNUAL ELECTRICAL ENERGY CONSUMPTION (GJ)	ELECTRICAL DEMAND AT UTILITY RESIDENTIAL LOAD PEAK (kW)	REDUCTION IN PEAK COMPARED TO RESISTANCE (%)	ENERGY PENALTY COMPARED TO NO OFF-PEAK STORAGE (%)
Resistance Heating	64	9.16	Base	Base
Resistance w/Off-Peak Storage	74	0.63	99	16
Conventional Solar	37	9.16	0	Base
Solar w/Off-Peak in Solar Storage Tank	77	0.63	99	108
Solar w/Separate Off-Peak Storage (2 Tanks)	47	0.63	99	27
Conventional Air to Air Heat Pump	27	7.19	23	Base
Heat Pump w/Off-Peak Storage	41	4.28	56	52
Solar Assisted Heat Pump	33	9.16	0	22
Solar Assisted Heat Pump w/Off-Peak in Solar Storage Tank	40	3.92	61	48
Solar Assisted Dual Source Heat Pump w/Direct Heating from Solar	20	7.19	23	Base
Solar Assisted Dual Source Heat Pump w/Direct Heating and Off-Peak in Solar Storage Tank	24	4.27	56	20
Solar Assisted Dual Source Heat Pump w/Direct Heating and Separate Off-Peak Tank (2 Tanks)	25	3.56	65	25

conditioning) were then divided by the number of homes equipped with these systems in the respective years: 34,400 for 1985 and 66,000 for 1995. The results are shown in Table 2. The last two columns are the "marginal production cost savings" to the utility for each of these homes. They do not include other savings, such as a capacity credit for lower generation capacity requirements.

- The energy cost for the base home was calculated to be $558 in 1985 and $847 in 1995. The marginal cost savings for many of the solar and storage systems is larger than these amounts. This means that the utility avoids marginal generation costs in excess of the cost of furnishing space heating/cooling energy to the base home. However, these savings cannot be passed on to the individual homeowner, since they are not true "savings" to the utility but merely a "cost avoidance." The benefits of this cost avoidance are passed on to all customers of that utility in the form of lower fuel charges. This can provide a rationale for the introduction of special tariffs to solar homeowners which are sometimes called "subsidies" (Ref. 1). These cost avoidances benefit all utility customers and therefore, virtually society as a whole. Therefore they should be used in considering national policy. The cost savings that can be passed on to the solar homeowner, on the other hand, must be determined on the basis of average costs and not marginal costs; see below.

- The costs to serve residential customers having different conventional or solar heating/cooling systems with or without off-peak storage were determined. These costs were determined on a cost allocation basis used by this utility to justify its rates to the State Public Utility Commission. Demand related costs are made up of three components:
Costs related to class peak. Class peak is the diversified peak demand of all residential customers of that utility during the winter season. (Due to diversity of demand, the class peak is lower than the product of an individual customer's maximum demand and the number of customers on the net.) These costs primarily represent costs of the local distribution net.
Costs related to individual customer maximum demand. These costs pertain to the costs of installing a line to the individual home.
Costs related to contribution to system peak. These costs essentially represent the capital costs of installing generation and transmission capacity. Although these facilities may be used only infrequently, they must be amortized over a fixed life-time.

- Customer related costs represent the costs of metering, billing, processing payments, etc. Since these costs are incurred for all customers of an electric utility, even for those who may require lights only, they have not been included in the heating/cooling cost analysis shown here.

Table 2. Annual Electric Production Cost Comparison for Home Heating Systems
Philadelphia Electric Company

Heating/Cooling System	Customer Annual Energy Consumption (kWh)	Annual Energy Savings per Customer (kWh)	Utility Cost Avoidance Per Customer ($)	
			1985	1995
Resistance Heating	19428	Base	Base	Base
Conventional Solar Heating	12308	7120	510	480
Solar Heating with Separate Off-Peak Storage (2 Tanks)	14508	4920	450	410
Conventional Air-to-Air Heat Pump	9158	10270	750	860
Solar Assisted Dual Source Heat Pump w/Direct Heating from Solar	7238	12190	900	1050
Conventional Solar Heating, Solar Air Conditioning	12824	6604	470	430
Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Cold Storage (2 tanks)	15524	3904	420	370
Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Hot Storage (2 tanks)	15502	3926	420	370

Notes:
Unless otherwise specified, all systems contain conventional electric air conditioning (A/C). Solar air conditioning units are absorption systems. All energy data are for space heating and cooling only.

• Energy related costs are essentially fuel costs. While this utility uses a constant fuel cost estimated to be 3.21¢/kWh on the average for 1985, it was felt that the lower cost of generating off-peak energy from nuclear and coal plants compared to the on-peak energy which includes oil-steam and gas turbine plants should be considered. A differential of 0.5 ¢/kWh has therefore been used between off-peak and on-peak energy costs. This is conservative and close to the value used for internal studies of energy storage previously undertaken by that utility. For many, if not most, utilities in the country, this differential is considerably larger. Assuming that 25% of the utility's energy is generated during the 8 off-peak hours 11 pm to 7 am, the off-peak and on-peak energy related costs were determined to be 2.835 and 3.335 ¢/kWh, respectively. The heating system without off-peak storage was assumed to use 60% of their electrical heating energy during off-peak hours.

• The annual heating/cooling costs incurred by a homeowner are made up of the costs the utility charges to serve him and the costs of ownership of the heating/cooling equipment in the home. These costs are shown for Philadelphia, PA for conventional and solar assisted resistance heating systems and for conventional and solar assisted heat pumps in Table 3, and for conventional and solar assisted air conditioning systems in Table 4. All the homes are equipped with central air conditioning which is consistent with the current construction practice in that area of the country. The effect of off-peak energy storage is clearly apparent in the tables.

FUTURE ACTIVITIES

Contract Activities. Similar calculations have been performed or are being performed for other utilities in different regions of the country. The final report is in preparation.

Post-contract activities. Other utilities throughout the United States will be contacted in order to familiarize them with the results of this analysis. Assistance will be offered to them to perform these analyses for their own networks using the methodology developed under this contract.

REFERENCES

1. Lorsch, H.G. et al., "Implications of the Residential Solar Space Conditioning on Electric Utilities," Report No. F-C4209, Franklin Institute Research Laboratories, 1976.
2. Feldman, S.L. and Anderson, B., "Utility Pricing and Solar Energy Design," NSF/RANN Grant No. APR-75-18006, Clark University, 1976.
3. Mellon, W.C., "Insolation and Temperature Statistics and Their Influence on the Design of Solar Heating Systems and the Electric Utility Interface," AS of ISES Conference, Winnipeg, Canada, 1976.
4. Asbury, J.F., Maslowski, C., and Mueller, R.O., "Solar Availability for Winter Space Heating: An Analysis of the Calendar Period 1953-1975. Argonne National Laboratory Report No. ANL/SPG-14.
5. Karaki, S. and Wilbur, P.J., "Solar Cooling," Franklin Institute Press, 1977.
6. Asbury, J.G., and Mueller, R.O., "Solar Energy and Electric Utilities: Should They be Interfaced?" Science, Vol. 195, February 4, 1977.

PUBLICATIONS RESULTING FROM THIS CONTRACT

Lorsch, H.G., "Combined Solar Heating and Cooling Systems," Commission of the European Communities, Joint Research Center, Ispra, Italy, October 1977.

Lorsch, H.G., "Novel Control Strategies for Solar Assisted Heating and Cooling Systems," Workshop on the Use of Solar Energy for the Cooling of Buildings, San Francisco, CA, February 1978.

Table 3. Annual Costs for Solar Heating and Heat Pump Systems (1985)

Consumption, Demand and Cost Data	Resistance Heating (Base System)	Conventional Solar	Solar With Separate Off-Peak Storage (2 Tanks)	Conventional Air-to-Air Heat Pump	Solar Assisted Dual Source Heat Pump w/Direct Heatin from Solar
Annual Consumption, kWh	19,428	12,308	14,508	9,158	7238
Demand at Winter Class Peak, kW	9.16	9.16	0.63	7.19	7.19
Individual Customer Max. Demand,kW	10.50	10.50	36.00	10.50	10.50
Contribution to System Peak, kW	1.61	1.61	1.61	1.61	1.61
1980, Installed Cost, $	1,930	17,237	21,406	2,422	20,818
Demand Related Costs:					
Demand at Class Peak, $32.37/kW	296.51	296.51	20.39	232.74	232.74
Individual Cust.Max. Dmd.,$1.48/kW	15.54	15.54	53.28	15.54	15.54
Contrib. to Sys. Peak, $170.55/kW	274.59	274.59	274.59	274.59	274.59
Energy Related Costs:					
On-Peak Consumption, 3.335 ¢/kWh	259.17	164.19	41.95	122.17	96.55
Off-Peak Consumption,2.835 ¢/kWh	330.47	209.36	375.64	155.78	123.12
Subtotal Cost-to-Serve, $	1176.28	960.19	765.85	800.82	742.54
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	258.39	2,307.00	2,855.00	324.25	2,787
TOTAL ANNUAL COST, $	1435.	3,267.	3,621.	1125.	3529.

Table 4. Annual Costs for Solar Air Conditioning

Consumption, Demand and 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)
Annual Consumption, kWh	19,428	12,824	15,524	15,502
Demand at Winter Class Peak, kW	9.16	0.63	0.63	0.63
Individual Customer Max. Demand, kW	10.50	36.00	36.00	36.00
Contribution to System Peak, kW	1.61	4.93	0.71	0.71
	1,930	27,980	35,200	31,908
Demand Related Costs:				
Demand at Class Peak, $32.37/kW	296.51	20.39	20.39	20.39
Individual Cust. Max. Dmd., $1.48/kW	15.54	53.28	53.28	53.28
Contrib. to Sys. Peak, $170.55/kW	274.59	840.81	121.09	121.09
Energy Related Costs:				
On-Peak Consumption, 3.335 ¢/kWh	259.17	171.09	44.69	44.69
Off-Peak Consumption,2.835 ¢/kWh	330.47	218.12	402.12	401.49
Subtotal Cost-to-Serve, $	1176.28	1303.69	641.57	640.94
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	258.39	3745.00	4712.00	4271.00
TOTAL ANNUAL COST, $	1435.	5049.	5354.	4912.

PUBLICATIONS RESULTING FROM THIS CONTRACT (Cont'd)

Lorsch, H.G., Oswald, R.L. and Crane, R.E., "Control Strategies for Electrical Peak Saving," Workshop on the Control of Solar Energy Systems for Heating and Cooling, Hyannis, MA, May 1978.

Lorsch, H.G., Oswald, R.L. and Crane, R.E., "Control Strategies for Solar Heating/Cooling Systems that Reduce Electric Utility Peak Loads," Conference AS of ISES, Denver, CO, 1978.

Lorsch, H.G., et al., "Novel Control Strategies for Solar Assisted Systems," Annual Progress Report I-C4827, Contract No. EG-77-C-03-1594, October 1978.

Crane, R.E., Lorsch, H.G., and Oswald, R.L., "Thermal Storage of Off-Peak Electrical Energy in Solar Heating and Cooling Systems," IEEE Meeting on Decision and Control, San Diego, CA, 1979.

Lorsch, H.G., "Active Solar Heating and Cooling Systems," Commission of the European Communities, Joint Research Center, Ispra, Italy, July 1979.

Crane, R.E., Lorsch, H.G., and Oswald, R.L., "Electric Utility Peak Load Reduction Through Solar Heating Systems Controls," to be presented at AS of ISES Conference, Phoenix, AZ, 1980.

CONTROLS FOR SOLAR HEATING AND COOLING*

LAWRENCE BERKELEY LABORATORY

W-7405-ENG-48

MASHURI L. WARREN, STEVEN R. SCHILLER, AND MICHAEL WAHLIG

PERIOD OF CONTRACT: Begin 7/74 End Open

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. The project will compare proportional as well as on/off collector loop control strategies. Experimental evaluation of the cost effectiveness of controllers and control strategies is expected to be the primary output of this task.

To analyse problems in the control of active solar systems that effect system performance and reliability: review literature to determine causes of controller failures and make recommendations for corrective measures; evaluate the potential for the use of microprocessors and advanced controllers and control strategies for the control of active solar systems; carry out theoretical studies of collector and load loop performance in support of the experimental work.

To perform technical support activities as part of the Systems Analysis and Controls program element of the 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 Department of Energy (DOE) solar controls contracts.

BACKGROUND

An experimental test facility for solar heating and cooling has been constructed to evaluate the operation and performance of an LBL-developed solar controller that has promising commercial potential. The LBL controller was designed to be intermediate in performance between a simple differential thermostat and an on-line microprocessor. The PROM-based controller operates the solar system according to a preprogrammed algorithm that translates operating state conditions (fluid temperatures, switch positions, comparator outputs) into a set of operating instructions (open or close valves, turn pumps on or off). The operating algorithm can be changed by reprogramming or exchanging the plug-in integrated circuit component, or by changing the sensors selected for comparison. The experimental solar heating system can be operated using different control algorithms, input meteorological conditions, and output load demands.

SUMMARY

In FY 1979 the test facility became operational and initial testing began. Emphasis has been on refinement of system instrumentation and the development of necessary computer software to run the facility and perform data analysis. Preliminary energy balance experiments with the load and collector loops under microcomputer control were successfully completed in November 1979. Experiment modifications have been completed to permit variable-flow and proportional-flow control of the collector loop. A series of experimental comparisons of proportional and on/off collector loop strategies are planned using typical meteorological year data. The evaluation of configurations for combined domestic hot water and heating systems has begun to determine necessary experiment modifications to test one and two tank domestic hot water systems in combination with hydronic space heating systems.

Other work has included the application of theoretical models to describe dynamic collector operation and building temperature response. Theoretical analysis of the energy collection performance of on/off and proportional flow control collector loop strategies has been completed. Papers have been presented at the Second System Simulation and Economics Conference held in January 1980 in San Diego. Technical program support activities, in cooperation with SERI and SAN, are continuing.

TECHNICAL ACCOMPLISHMENTS

Energy Balance Tests.

Collector Loop Energy Balance. Preliminary energy balance experiments were run with simulated solar heat input from the pseudo-collector, with the apparent collector temperature determined by the hp-9825A, and with the operation of the collector and load loop determined by the LBL electronic controller.

Energy balances are performed during the experiment by: 1) Determining the energy delivered by the pseudo-collector; 2) Determining the energy stored at the beginning and end of a period, and deducting estimated losses from storage; 3) Determining the amount of energy delivered to the load; and 4) Estimating piping heat loss.

Energy supplied by the pseudo-collector was calculated at 60 second intervals and the amount of energy in the storage tank was calculated at 30 minute intervals as the apparent solar insolation was increased from zero to a maximum of 950 W/m^2 and then back to zero. Over a long experimental run of 22 hours, the energy balance is quite acceptable.

Load Loop Energy Balance. Preliminary energy balance experiments were run with heat delivered from the storage tank to the heating coil located in the air duct. Power discharged in the heating coil was calculated every thirty seconds using a differential thermocouple measurement and the load loop flow measurement. Power delivered to the load was typically 12 kW. The load loop experiment was run for a period of 18 hours, with the building load calculated for a constant outdoor temperature of 0 ^{o}C and a building loss coefficient of 500 $W/^{o}C$. The overall energy balance for the 18 hour run is quite acceptable.

Theoretical Studies to Support Experiments.

Development of Dynamic Collector Model. The dynamic response of a solar collector was simulated using a collector energy balance equation which

* This work has been supported by the Systems Analysis and Design Branch, Systems Development Division, Office of Solar Applications, U. S. Department of Energy.

accounts for collector thermal capacitance. The model is used to evaluate the performance of proportional and on/off collector loop control for various set points, flow rates, insolation levels and patterns (clear and cloudy days), and ambient temperature conditions. Evaluation of control strategies (for collector loop only) is based on: collection efficiency, percent of maximum steady state efficiency, pump running time (parasitic power demands), and cycling.

Results indicate that the turn-on set point is not usually a critical factor in the collection of energy. The energy stored in the collector as it warms up is transferred to the storage tank once the fluid begins to circulate. Proportional flow controllers provide improved energy collection only during periods of interrupted or very low insolation when the maximum possible energy collection is relatively low.

Modeling of Building Load Dynamics. Work has also begun on development of a residential building temperature response model to simulate the effects of heat input on room air dynamics. This model gives the short time constant response appropriate for the heating of air within the structure and the long time constant response associated with the building structure. The model may be used in the test facility for evaluating advanced control strategies and controllers.

Technical Support Activities. Technical support activities have centered around the development of a solar controls program plan that integrates the ongoing and planned controls projects into a coherent program. Contact with individual controls projects has included review of progress reports, telephone discussions, visits to contractor sites, and contractor project reviews at LBL. LBL has had major input to the controls program planning process in meetings with SERI and SAN in developing and implementing an overall Systems Analysis Program Plan that includes a well defined controls element and that addresses both current field problems and longer range research questions.

FUTURE ACTIVITIES

Contract Activities. Plans for FY 1980 include a series of experimental tests of on/off and proportional flow control strategies for hydronic space heating systems for a variety of input meteorological and solar conditions. An economic analysis of the present value of future energy savings and the initial cost of implementing various control strategies will be done to determine if the control improvement is cost effective.

Experimental modifications are planned to allow the testing of control strategies for one and two tank domestic hot water systems used in combination with space heating systems.

A review of field control problems for active solar systems will be done to determine specific causes of control failures. Existing system configurations and control designs will be reviewed in the light of control problems to make recommendations as to what corrective measures should be taken by manufacturers, designers, and installers.

A comparative evaluation of control algorithms and currently available microprocessor based controllers for the control of active solar systems will be undertaken and the results published.

Technical support activities in coordination with SERI and SAN will continue.

Post-contract activities. Following the successful completion of the experimental testing of control strategies for active heating and domestic hot water systems, and the economic analysis of the benefits of improved performance, recommendations of system configurations and control strategies will be prepared and published. This will give guidelines to manufacturers, designers, and installers for cost effective control configurations and strategies.

REPORTS AND PUBLICATIONS

Steven R. Schiller, Mashuri L. Warren and David M. Auslander, "Comparison of Proportional and On/off Solar collector Loop Control Strategies Using a Dynamic Collector Model," Submitted to the ASME Journal of Solar Energy Engineering. Report LBL-10315, January 1980.

Mashuri L. Warren, et.al., "Experimental and Theoretical Evaluation of Control Strategies for Active Solar Energy Systems," LBL Annual Report for FY 1979.

Mashuri L. Warren, Steven R. Schiller, and Michael Wahlig, "Experimental Test Facility for Evaluation of Controls and Control Strategies," Second Annual Systems Simulation and Economic Analysis Conference, 23-25 January, 1980, San Diego, California. Report LBL-10352, January 1980.

Steven R. Schiller, Mashuri L. Warren, and David M. Auslander, "Comparison of Proportional and On/Off Solar Collector Loop Control Strategies using a Dynamic Collector Model," Second Annual Systems Simulation and Economics Analysis Conference January 23-25, 1980, San Diego, California. Report LBL-10347, January 1980.

Mashuri L. Warren, Ammar F. Sakkal, and Steven R. Schiller, "Predicting the Time Response of a Building Under Heat Input Conditions for Active Solar Heating Systems," Second Annual Systems Simulation and Economic Analysis Conference, 23-25 January, 1980, San Diego, California. Report LBL-10360, January 1980.

Mashuri L. Warren, Steven R. Schiller, and Michael Wahlig, "Evaluation of Proportional and On/Off Control for Solar Collector Loops," Paper 162 (EM-2-3). To be presented at the AS/ISES Annual Meeting, 2-6 June 1980, Phoenix, Arizona.

ADAPTIVE CONTROL FOR ENERGY CONSERVATION

LOS ALAMOS SCIENTIFIC LABORATORY

CONTRACT NUMBER W-7405-ENG-36-D504

PRINCIPAL INVESTIGATOR DONALD R. FARRIS

PERIOD OF CONTRACT: Begin 1976 End Continuing

OBJECTIVE

The objective of this project is to investigate the use of adaptive control concepts in buildings with solar-assisted heating, ventilating, and air-conditioning (HVAC) systems to maintain occupant comfort conditions while minimizing auxiliary energy use. Accomplishing this objective requires an energy management system capable of making sound tradeoffs. Optimal control theory is used along with a system identification technique to provide an adaptable strategy. The resulting overall approach is known as adaptive optimal control (AOC).

CONCEPT

The AOC concept can be explained with the system block diagram of Fig. 1. The building (plant) represents the nonlinear dynamics of the building and entire HVAC system. As control and exogenous disturbances (e.g., outside temperature) are applied in time, the dynamic building responds and the state of the building results. The applied control, the exogenous inputs, and the building state are measured as functions of time. These measured values are then used by the model identification block to estimate the parameters for a linearized system. This linearized system is valid only in a region about the operating point, so a subsequent estimation of the parameters will be needed when the operating point changes significantly.

The linearized system parameters are then used by the optimal control computation block to determine the control parameters. The optimal control computation is performed so as to minimize a performance index. This performance index is an integral quadratic form and its terms include deviations of room temperature from a set point and use of auxiliary energy. Because some of the tradeoff parameters in the performance index may change with successive optimization computations (e.g., the performance penalty for room temperature deviations might be relaxed at night), optimization data are

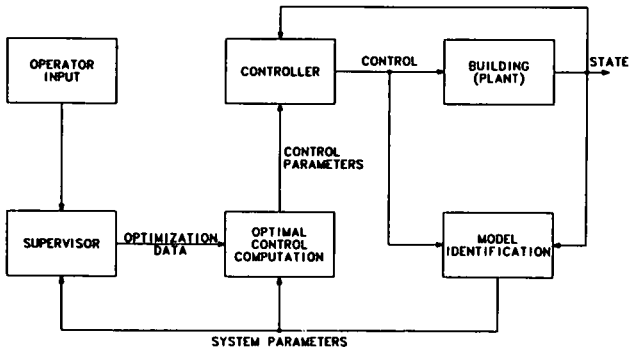


Figure 1. System block diagram.

plied by the supervisor block. The supervisor also provides a channel for the human building operator to communicate data to the system.

The optimal control computation produces the control parameters (gains, offsets) that are used by the controller to implement the closed-loop control. The building then operates with this optimal control for a period of time that would probably not exceed 15 minutes, and the process of model identification, optimal control computation, and controller implementation repeats itself. The AOC system is thus updated or adapted to remain optimal as the system undergoes changes of various forms.

SUMMARY

This investigation of the use of adaptive control concepts began with the definition of an HVAC system model to be used for simulation studies. Building operation was simulated under control of a conventional controller that embodies current strategies and under control of an AOC controller. System performances were compared for both heating and cooling. The heating results are more comprehensive and this report will focus on them. Both controllers maintained the room temperature quite well. The AOC controller; however, did so with significantly less auxiliary energy. Depending on simulation conditions the AOC auxiliary energy savings over the conventional controller were as high as 51% for a two-day simulation and 95% for a month-long simulation.

It must be remembered that these are savings in auxiliary, or back-up, energy that is used when the solar energy system cannot meet the heating or air-conditioning demands alone. When comparing controllers as we have, a claim of 100% savings in auxiliary energy means that the claiming controller is able to operate the solar energy system to meet the heating or air-conditioning demand without any back-up.

Still, the question of how the AOC controller is able to achieve these savings in auxiliary energy remains. The answer is that the AOC controller provides better management of the available sources of energy. In the two-day simulation that saved 51% of the auxiliary energy, the weather was sunny and very cold; and the AOC controller operated the storage tank at a lower temperature to improve collection and utilization of solar energy. In the month-long simulation, the weather varied, but was generally milder. One aspect of the AOC controller's management of the building is that the air-handling system is controlled to exhaust much less heated air to the outside. To illustrate, the AOC controller exhausts about 2,500,000 fewer Btu than the conventional controller. The reduction in auxiliary energy use is about 1,250,000 Btu and the reduction in solar energy use is about 1,270,000 Btu.

The complexity of large solar HVAC systems generates many sets of conditions for the controller to handle. The best operating strategies are not completely understood and, perhaps more important, they vary from one set of conditions to another as the above simulations indicate. The AOC technique has the power to examine those conditions on a regular basis (several times each hour), determine the best strategy at the moment, and implement the control automatically.

Plans have been made for a project to implement and test the AOC controller in the highly-instrumented National Security and Resources Study Center (NSRSC) at the Los Alamos Scientific Laboratory (LASL).

Significant industrial interaction has taken place to effect technology transfer. Industrial visits, seminars at universities, and paper presentations at conferences have been received with interest, and in several instances, further interaction has resulted.

TECHNICAL ACCOMPLISHMENTS

Some of the recent technical accomplishments are discussed below. For further information, the reader is referred to the publications listed and described at the end of this report.

- Set-Point Computation. To operate a building HVAC system with an AOC system, set points are needed. These set points are desirable values of system and control variables that the controller tries to attain. Two set-point computation methods have been tested, both of which resulted in improved system performance. One approach is based on the assumption that the set points define a system equilibrium. This approach leads to somewhat erratic solution behavior. A second approach under test at this time establishes schedules for set points based on time of day and/or various system variables. This second approach appears to work quite well.

- Riccati Equation Solution. In the optimal control computation, the present technique of integrating the differential equation to the steady state ($dP/dt \approx 0$) is time comsuming if allowed to converge without help, and attempts to speed convergence sometimes lead to convergence problems. A potentially faster and more practical solution method has been identified and applied to the AOC. The method is related to an eigenvector approach, but uses Schur vectors. Code debugging and simulation testing have yet to be carried out.

- Long-Term Simulation. The heating simulation codes have been modified to permit lengthy simulation periods (on the order of months). Preliminary AOC results have encountered problems with the numerical solution of the matrix Riccati equation. Even though these problems exist, the results have been very encouraging; and they can only improve as the Riccati solution is improved.

- Gain-Scheduling Study. A study has been done at the University of Notre Dame to investigate the use of precomputed and stored sets of controller parameters to be switched in and out in response to various system conditions. Based on the simple model used, preliminary results indicate this could prove a successful approach. This approach eliminates the need for much of the on-line computation in the AOC approach. If it proves successful, it would simplify AOC implementation.

FUTURE ACTIVITIES

Contract Activities. Plans have been made for a joint project with Johnson Controls, Inc. to implement and test the AOC concept in the NSRSC. Successful completion of this project will demonstrate that the AOC approach is practical and implementable. Implementation will permit a thorough comparative evaluation of the AOC, and the hardware that is installed in the NSRSC will be adequately flexible to permit study of other advanced control techniques. Recent DOE controls program developments have led to uncertainty about this project and it is not clear, as of this writing, whether the project will be completed.

Post-Contract Activities. If the above project is completed, a great deal of information will be available to aid industry in the development of advanced, energy-conserving, building controllers. If the project is terminated, the reports will still contain substantial information to aid industry, but the practical developmental experience will not exist.

PUBLICATIONS/REPORTS/REFERENCES

1. Farris, D.R. and T.E. McDonald, "Adaptive Optimal Control--An Algorithm for Direct Digital Control," ASHRAE Transactions 1980, Vol. 86, Part 1, February 1980.

2. Farris, D.R. and J. L. Melsa, "A Study on the Use of Adaptive Control for Energy Conservation in Large Solar Heated and Cooled Buildings," to appear in Proceedings, The 19th IEEE Conference on Decision and Control, December 1980.

3. Laird, M. A., System Identification and Adaptive Control Studies for a Solar Heated and Cooled Building, Master's Thesis, Department of Electrical Engineering, University of Notre Dame, Notre Dame, Ind., May 1978.

4. Somasundaram, M., Optimal Control Studies of a Solar Heating and Cooling System, Master's Thesis, Dept. of Electrical Engineering, University of Notre Dame, Notre, Dame, Ind., May 1979.

5. Schultz, D. G. and J. L. Melsa, State Functions and Linear Control Systems, McGraw-Hill Book Company, New York, 1967.

6. Sage, A. P. and C. C. White III, Optimum Systems Control, 2nd Ed., Prentice-Hall, Inc., Englewood Cliffs, N. J., 1977.

7. Sage, A. P., and J. L. Melsa, System Identification, Academic Press, Inc., New York, 1971.

8. Graupe, D., Identification of Systems, Robert E. Krieger Publishing Co., Huntington, N.Y., 1976.

Space does not permit a complete listing of publications, but the remaining publications on this project may be found in Ref. 1.

VARIABLE CAPACITY COMPRESSOR CONTROLLER

RHO SIGMA, INC.

M-78-C-01-5224

EDWARD S. PELTZMAN

BEGINNING - SEPT. 1978
ENDING - JUNE 1980

OBJECTIVE

Improve heat pump co-efficient of performance, COP, by matching its compressor speed to the heat pump load.

BACKGROUND

The COP of a heat pump is improved if the temperature difference between the evaporator and condenser coils is minimized to match the load requirements. This can be accomplished in several ways. This contract investigates one of the ways, controlling the compressor speed based upon heat pump load.

SUMMARY

The contract was divided into four phases:

1. Selection of a commercial heat pump which can have its compressor speed varied.
2. Selection of a motor speed control technique and generation of motor speed/heat pump load algorithum.
3. Design and Fabrication of a motor speed controller.
4. Controller testing and evaluation with a heat pump.

TECHNICAL ACCOMPLISHMENTS

Heat Pump Selection Criteria - An analysis was made of operating characteristics of heat pumps with respect to possible speed control techniques. The optimum speed controllable heat pump would require a three-phase compressor motor with an external pump lubricating system. The compressor's response and efficiency must be known over a wide range of operating speeds.

Design Microprocessor Variable Compressor Control - The design was completed for a three-phase motor speed controller which was to be operated from a microprocessor. The motor speed controller used a pulse width modulation technique which could have a conversion efficiency of 90%. The microprocessor optimizes the motor speed by solving a controller algorithum and sampling the environment.

Heat Pump Selection - 2 Speed. Since no commercially available heat pump could be continuously speed controlled without extensive modification, a compromise was made. The Lennox 2-speed heat pump would be used to demonstrate the variable capacity controller.

Speed Control Algorithum - Using the manufacturer's COP test data, a new algorithum was generated which would have the heat pump operate at the most efficient speed to maintain a structures temperature.

Microprocessor Controller - The two-speed heat pump was operated by an AIM 65 microprocessor solving the control algorithum, Figure 1.

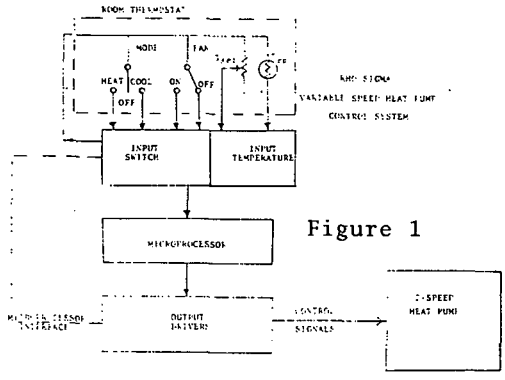


Figure 1

Test Results -The test results are being analyzed and will be covered in the final report.

Contract Activity - Complete final report.

Past Contract Activity - Rho Sigma plans to work with the heat pump manufacturer to develop a new line of controllers based upon this development.

XI SOLAR STORAGE TECHNOLOGY GROUP

SUMMARY OF THERMAL ENERGY STORAGE PROJECTS

ALLAN I. MICHAELS

ARGONNE NATIONAL LABORATORY
9700 SOUTH CASS AVENUE
ARGONNE, ILLINOIS 60439

ABSTRACT

The current status of contracts, the significant technical accomplishment to date and the planned future activities of contractors for thermal energy storage projects funded by The Office of Solar Applications for Buildings are summarized.

BACKGROUND

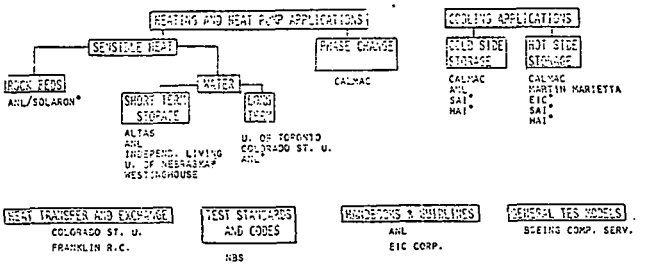
The general objectives of the thermal energy storage program of The Office of Solar Applications for Buildings are to develop, and promote the commercialization of thermal energy storage subsystems which have lower initial and life cycle costs per BTU stored and delivered, improved durability, higher volumetric storage density and greater retrofit capability.

The main thrusts of the program have been to assess and disseminate reliable and useful information on available thermal energy storage methods, to support innovative and engineering design improvements in conventional thermal energy storage devices aimed at lowering costs, and increasing performance, durability and retrofitability, and to support research and development and engineering projects for developing higher density thermal energy storage devices utilizing phase change materials and chemical reactions, with the objective of bringing these technologies to commercial readiness.

In recent years a new emphasis in the program has been to more closely focus the thermal energy storage development efforts on meeting the design and schedule requirements of specific solar applications. These include solar cooling systems utilizing Rankine, absorption and desiccant chillers, direct space heating and hot water systems, and solar assisted heat pump systems. In line with this new emphasis the Technical Accomplishments and Planned Activities summarized below are grouped with respect to the categories of Heating, Cooling and SAHP. It must be recognized, of course, that many thermal energy storage projects may be utilized in more than one solar application. Consequently, the results of these projects will appear under more than one category below.

A chart listing all projects which were in effect in FY 80, grouped in terms of solar system application and type of storage method (with a few additional categories) is given below. In FY 80, a total of 21 contracts were in effect. Of these, 18 are still active, but many of these will be completed by the end of FY 80. A number of new projects are presently being developed, but since they are still under negotiation, they will not be discussed in this summary.

EXISTING PROJECTS IN THERMAL ENERGY STORAGE AND HEAT EXCHANGE FOR SOLAR HEATING AND COOLING APPLICATIONS



* NEW PROJECTS.

\# TWO DIFFERENT PROJECTS.

NOTE: THE 3 CALMAC PROJECTS INDICATED ABOVE ARE FUNDED UNDER A SINGLE CONTRACT.

THERMAL ENERGY STORAGE FOR SPACE HEATING

SUMMARY

Water Tanks: For the gas-fired, solar DHW back-up heater, Altas has completed component tests and the design of the full-scale engineering prototype. Construction of this unit is nearly complete and tests will commence shortly. ANL has completed and published the documentation for the COMMIX-SA-1 3-Dimensional Water Tank Model and this code is available for distribution. A rectangular coordinate version of the code is being prepared. Vertical tank baffle designs have been analyzed. Horizontal tank baffle design analysis is beginning. ANL has procured equipment and tanks, and is constructing a test loop facility for testing a variety of baffle and inlet diffuser designs to promote temperature stratification in water tanks of various sizes and configurations. Independent Living, Inc. has completed material selection and tank design for the "Two-Hat" Modular, Sandwich Wall, Fiberglass Tank. A mold has been built and construction of the prototype tank will begin shortly. High temperature creep and creep rupture tests on the selected resin-glass system, to project lifetime, are proceeding. The University of Nebraska's Membrane Lined Water Tank, Phase I Study was completed. A draft Final Report was prepared. Many recommended designs were developed and tested, and cost analyses prepared. A follow-on project to complete development and field test "base-line" membrane lined tank designs for on-site construction is under negotiation. These on-site constructed tanks have projected installed costs of 1/3 to 1/2 that of conventional tanks. System modifications and instrumentation are underway at the 32,000 gallon underground University of Nebraska tank. This tank is being fully instrumented for obtaining detailed 3-dimensional temperature profiles in a wide variety

of operational modes to provide validation data for COMMIX-SA-1. Westinghouse has completed testing of two 500 gallon prefabricated foamed concrete prototype tanks. It has been concluded that only on-site pouring of foamed concrete tanks will be cost effective, but this is believed to be cost-competitive with, and to offer many advantages over conventional insulation and construction materials. A final report is being prepared. Boeing Computer Services has completed preparation, validation and documentation of two improved TRNSYS compatible one-dimensional water tank models.

Annual Storage: An Annual Storage Solar Energy Program "ASTEP" has been developed by the University of Toronto. This code has been validated against data from two actual annual storage solar systems and a Users' Manual has been drafted. Simulations have been run to determine optimum configurations for various climates, building types, and cost assumptions. Experiments and analyses are under way at Colorado State University to determine the performance and heat loss characteristics of a below-ground wet earth heat storage reservoir, separated by a plastic barrier from surrounding dry soil. Laboratory tests of soil thermal characteristics and modeling of heat and moisture transport in soils are also being conducted. ANL has initiated the development of a multi-dimensional salt gradient pond model, COMMIX-SA-SP. A 1/4 acre experimental pond will be constructed on-site in the near future. ANL is leading U.S. participation in an International Energy Agency Program for the evaluation of large, annual storage, solar heating plants.

Rock Beds: ANL is currently developing a 3-dimensional model for rock beds, COMMIX-SA-RB. A subcontract has been negotiated with Solaron Corporation for experimental studies, coordinated with this ANL modeling activity. Solaron will conduct tests on both horizontal and vertical flow rock beds to provide required thermo-physical parameters and data for the validation of the ANL model. Designs will be developed with the guidance of simulation studies performed with the model. Solaron will construct and test the improved design uniform flow, horizontal and vertical rock beds. BCS has developed an improved 1-dimensional rock bed model and is presently testing it against experimental data.

Phase Change Materials: A prototype (100,000 BTU) PCM-TES unit with sodium thiosulfate pentahydrate (115°F) has been built and successfully tested by Calmac Corp. On-site filling procedures were successfully tested. EIC completed its system analysis of advanced TES subsystems for a variety of space conditioning--TES combinations and climate conditions.

Heat Transfer and Exchange and Miscellaneous: The final report on The Franklin Research Center studies of self-driven heat circulation systems was published. Several technically promising systems were recommended for further development. The tests of the Direct Contact Liquid-Liquid Heat Exchanger have been completed at Colorado State University. Comparisons between the DCLLHEX and a conventional heat exchange system were inconclusive, but the DCLLHEX appeared to provide a significantly higher winter season performance. A simulation study, using a TRNSYS code validated against the experimental data is commencing. ANL published a revised and expanded second edition of its Thermal Energy Storage Design and Installation Manual. The NBS study of the interface-conflict between existing model building codes and TES devices is near completion and a report will be issued soon.

TECHNICAL ACCOMPLISHMENTS

Water Tanks:

- Altas Corp. completed tests and optimum design of components for their gas-fired auxiliary heater, fully integrated with a solar heated DHW tank.

- A full-scale engineering prototype was designed, and construction is nearing completion. This is an 80 gallon solar preheat tank, topped by a 25 gallon , 50,000 BTU/hr. gas back-up heater.

- Development of cost optimized production prototype hardware and designs for commercialization of this device is under way with funding from the Gas Research Institute.

- ANL has completed development, validation and documentation of its COMMIX-SA-1 Water Tank Model in cylindrical coordinates. Copies of the code with documentation have been supplied on request to users.

- Analyses were performed for seven cylindrical, vertical orientation tanks with different baffle configurations, to determine heat discharge efficiency and provide design guidelines for the experimental stratification program. Analysis of baffle configurations for horizontal tanks is underway.

- Preparation of a rectangular coordinate version of the code is under way.

- ANL has procured instrumentation, equipment and tanks, and is constructing a facility for testing a variety of baffle and inlet diffuser designs for promoting temperature stratification in vertical and horizontal orientation tanks of various sizes and shapes. Tests are scheduled to start soon on an 80 gallon DHW Tank, utilizing three different baffle configurations, based on COMMIX-SA-1 simulations.

- Boeing Computer Services completed development, validation and documentation of two improved TRNSYS compatible, 1-dimensional water tank models, one based on the Duffie-Beckman Model and the other on the Sharpe-Loehrke Model.

- Streamlined versions of these two codes, incorporating some simplifications to reduce computation time, were developed.

- Independent Living Incorp. has completed design of the wall structure, and selection of the materials for their fiberglass, sandwich wall, modular ("2-hat") water tank. The inner wall will be a hand laid-up, 3-layer, Derkane 470 Resin-glass fiber (increasing in concentration away from the water side) material. A 3-to-4-inch layer of urethane foam, with a sprayed-on outer fiberglass shell will complete the wall structure. This material is believed capable of a 20 to 30 year life with 180-200°F hot water storage.

- Tensile creep and creep rupture tests on the selected fiberglass material, at 200°F in water,

under way at higher than expected stresses, for experimental confirmation of the projected lifetimes.

- The tank design has been completed. A forming mold has been fabricated and the prototype fiberglass tank construction will begin shortly.

- The University of Nebraska Membrane Lined Water Tank Study was completed and a draft Final Report was written.

- Membrane lined tank projects and available membrane liner materials were surveyed and analyzed. EDPM, PVC and Laminated High Density Polyethylene were selected as the best available candidate liner materials.

- Alternate support structures, for various storage locations and sizes in residences were studied. On-site constructed rectangular and on-site-assembled-kit cylindrical tank designs were found to be most cost effective and installable. Costs and cost optimized dimensions were calculated for 500 to 10,000 gallon sizes. Membrane lined tanks were projected to have installed costs as low as 1/3 the cost of conventional tanks.

- Tank designs for direct air heating from storage (eliminating an external load side heat exchanger loop) were analysed and tested. Cost savings of 40% over conventional systems were projected.

- Free-convection DHW preheater coils located in the storage tank were analyzed and tested, and the optimum cost effective preheater type and length was selected. This is a commercially available prefinned copper tubing. Analyses and tests were conducted on auxiliary heating of storage, outlet-inlet designs and stratification baffle designs, and recommendations were made as to preferred methods.

- A follow-on project to complete development and field test "base-line" membrane lined rectangular tank designs for on-site construction is under negotiation.

- The University of Nebraska is nearing completion of system modifications and instrumentation of their 32,000 gallon underground tank, to obtain 3-dimensional temperature measurements in the tank in a wide variety of operational modes. This data will be used for validation of ANL's rectangular coordinate version of COMMIX-SA-1.

- Westinghouse has completed construction, thermal testing and analysis of two 500 gallon prefabricated, prototype, multi-layer foamed concrete tanks. A third, modular slab tank was prefabricated, but was not assembled and tested. Experiences with the prefabricated prototype tanks indicates that foamed concrete tanks will only be cost effective for on-site construction.

- A cost comparison, per unit R-value, of foamed concrete with other insulating materials indicated that the foamed concrete material falls midway in cost. However, the advantages of rapid on-site application and greater strength, moisture resistance and durability is believed to make it competitive with conventional insulating materials.

Annual Storage:

- The University of Toronto has completed development of an Annual Storage Solar Energy Simulation Program "ASTEP". This code has been validated against performance data from the Provident House and the Aylmer 30-unit annual storage solar projects. A draft users' manual has been prepared. A generalized, non-computer, storage-collector sizing method for annual storage solar systems is under development.

- Simulations of annual storage solar systems have been performed which indicate that for buildings of over 10,000 ft^2, in northern state climates, 100% solar annual storage systems are more cost effective than diurnal (optimized at 60% solar) systems. Small district heating systems are the most cost effective approach for smaller structures in northern climates.

- Colorado State University has constructed and is testing a moist earth heat reservoir. This reservoir is heated by hot water in plastic tube spirals, and is separated from the surrounding dry soil by a double-wall cylindrical plastic container. The reservoir, which is 19 feet in diameter and 8 feet deep and 7 feet below ground level, is instrumented with temperature, heat flux, moisture and flow measuring devices. A 90 day heat charging period has been completed, with a total heat storage of 5 million BTU's (2,204 BTU/ft^3). Steady state heat loss is currently 80,000 BTU/day or 1.6% of the full charge/ day.

- Laboratory measurements of the thermal conductivity and moisture migration of a variety of soils are nearing completion. Data obtained is consistent with the field experiment observations.

- Development of an improved heat and moisture flow model, based on corrections to the DeVries model, is nearly complete. This model is being validated against the laboratory and field experimental data.

- ANL is developing a multi-dimensional double diffusion salt gradient pond model, COMMIX-SA-SP.

- A 1/4 acre experimental salt pond has been designed and will be constructed on site, with ANL internal funding, in the near future.

- ANL has been designated the Lead U.S. Technical Representative for an International Energy Agency Project for the Design and Feasibility Analysis of Central Solar Heating Plants Utilizing Annual Heat Storage. ANL participated actively in formulating the IEA agreement for this project, to which the U.S. is a signatory.

- Support for this project has been obtained from LASL, ORNL, SERI and Battelle PNL. Personnel from ANL and these laboratories participated in an initial meeting in Ottawa, Canada at which detailed work plans for the project were prepared. The International Trade Committee of the SEIA has been contacted and is considering participating in the program.

Rock Beds:

- ANL is developing a 3-dimensional model for rock beds, COMMIX-SA-RB. Simulation runs, for idealized beds, have been made to evaluate the preliminary code structure. Results are considered satisfactory.

• A subcontract has been negotiated with Solaron Corp. for the performance of experimental studies, coordinated with the ANL modeling effort. Solaron will conduct tests on both horizontal and vertical flow rock beds to provide required thermophysical parameters for, and data for the validation of the ANL code. Improved design rock beds developed with the aid of ANL simulation analyses will be constructed and tested by Solaron.

• Boeing Computer Services has developed an improved, 1-dimensional, TRNSYS compatible rock bed code based on the Schumann Model. Experimental data is being used to validate the model. Some problems are being encountered due to the persistence of some channeling in the experimental system, which is not accounted for in any 1-dimensional model.

Phase Change Materials:

• Calmac Corp. has successfully tested, by calorimetric measurements and extensive cycling, a 100,000 BTU Prototype PCM-TES device utilizing sodium thiosulfate pentahydrate (115°F fusion temperature). This is a bulk system consisting of a plastic cylindrical tank with a liquid flow, internal heat exchanger, and a small internal circulation pump.

• A full-scale (360,000 BTU) tank was built and used in a successful test of on-site filling of an installed tank (necessary to reduce shipping costs and handling and installation problems).

• Two full-scale units were built and sold to customers who will be using them in system tests.

• EIC completed its system analysis of advanced TES subsystems for a variety of space conditioning-TES combinations and climate conditions. Advanced systems in general had lower performance than conventional water tank systems. However, PCM-TES subsystems showed some advantage in a SAHP system. The final report for this work has been published.

Heat Transfer and Exchange and Miscellaneous:

• Franklin Research Center completed its work and published the Final Report on its analysis of the technical feasibility of methods for downward circulation, self-driven, solar energy systems.

• Technically workable external and internal power cycle, and non-power cycle systems were identified. Three non-power cycle systems were recommended for further development, namely: vapor bubble pumping; vapor stream condensate entrainment; and injector pumping.

• Colorado State University has completed its testing of the Direct Contact Liquid-Liquid Heat Exchanger. Comparisons between the DCLLHEX and a conventional heat exchanger system were inconclusive since the two systems were not otherwise identical. However, the data indicates that the DCLLHEX collected approximately 17% more energy than the conventional system during the winter heating test period. No benefits were observed during the summer cooling tests. Further comparisons will be based on TRNSYS simulations.

• ANL published and distributed a revised and expanded second edition of its Thermal Energy Storage Design and Installation Manual. A much wider circulation of this manual is recommended, and some efforts are being made to promote its use in the solar industry.

• NBS is nearing completion of its study of the interface between existing model building codes and TES devices presently available or under development.

• A classification scheme compatible with the building code framework was devised, a literature survey of TES devices was performed, and existing and new PCM-TES devices were described and categorized. Code provisions in conflict with the use of PCM-TES devices are presently being identified.

FUTURE ACTIVITIES

Water Tanks:

• Altas will complete assembly and checkout tests of the back-up heater engineering prototype and write a final report.

• A study of stratification aspects and other design parameters, using COMMIX-SA-1, and more detailed testing of the engineering prototype is under consideration.

• ANL will complete development, validation and documentation of the rectangular coordinate version of COMMIX-SA-1.

• Simulation studies will be conducted on stratification designs for horizontal, rectangular, large-scale and annual storage tanks.

• ANL will complete tests of vertical and horizontal, cylindrical and rectangular tank stratification baffle and diffuser inlet configurations. Data will be used for validation of COMMIX-SA-1 and for the preparation of guidelines for the design of stratified tanks.

• Independent Living will complete fabrication and testing of the prototype fiberglass tank, and prepare cost estimates, and production and marketing studies (ILI plans to market this tank).

• Creep and creep rupture tests will be completed and the projected lifetime of the selected resin system calculated.

• University of Nebraska will complete development, field testing and technology transfer for rectangular on-site built, membrane lined tanks.

• The development and testing of direct air heating tanks, and of complete packaged TES kit systems, including DHW preheaters, stratification, auxiliary heating and controls is under consideration

• University of Nebraska will complete stratification experiments and deliver data to ANL.

• Westinghouse will complete analysis of experimental data, prepare cost estimates for on-site pouring of foamed concrete tanks, and a final report.

Annual Storage:

• The University of Toronto will complete and deliver the ASTEP code and documentation.

- Performance data and simulation results on the existing Canadian storage installations will be delivered in a Final Report.

- Preparation of a design guide for annual storage solar systems is under consideration.

- CSU will monitor heat loss at zero heat input, and will test the discharge characteristics of its moist soil heat reservoir. Soil drying behavior and the effectiveness of the plastic vapor barrier will be evaluated.

- The heat and moisture transport model will be validated with experimental data, and used to analyze a wide variety of soils, and alternate earth storage configurations and strategies.

- A laboratory experiment will be conducted to measure the heat flux around pipes in soil.

- ANL will complete the development, validation and documentation of the COMMIX-SA-SP Salt Gradient Pond Model, and utilize it to study the behavior and improved design of salt gradient ponds.

- The experimental 1/4 acre pond will be built and utilized to validate COMMIX-SA-SP and to investigate various salt pond phenomena.

- ANL and other laboratories will participate in the IEA annual storage, solar heating project.

Rock Beds:

- ANL will complete development, validation and documentation of the COMMIX-SA-RB Rock Bed Model and utilize it for the analysis and design of uniform flow horizontal and vertical rock beds.

- Solaron, under ANL guidance, will build and test uniform flow horizontal and vertical rock beds.

- BCS will complete validation of, and prepare documentation for the improved rock bed model.

Phase Change Materials:

- Calmac will complete engineering details and testing of the 115°F PCM-TES prototype, and evaluation of on-site filling procedures, and will document all results. A cost analysis and cost competitiveness study will be prepared. Calmac is expected to market this device.

Heat Transfer and Exchange and Miscellaneous:

- Franklin Research Center. The development and demonstration of the most promising self-driven heat circulation concepts is under consideration.

- CSU will complete validation of TRNSYS for the DCLLHEX with the experimental data, and will run simulations for five U.S. locations, for systems which are identical except for utilization of the DCLLHEX or a conventional heat exchanger subsystem. Cost analyses will also be prepared.

- A field test of the DCLLHEX, and preparation of a design, installation and operational manual is under consideration.

- NBS will complete Model Building Code analyses and prepare guidelines for PCM-TES devices. Similar analyses and recommendations for thermo-chemical TES devices will also be prepared.

THERMAL ENERGY STORAGE FOR SPACE COOLING

SUMMARY

Most of the projects discussed under the space heating category can also be utilized for cold side storage in cooling systems (exceptions are the Altas-DHW Back-up Heater, the Annual Storage Projects, the Calmac 115°F PCM unit and some of the Heat Exchange and Transfer and Miscellaneous Projects). Some projects also have a potential application in hot side storage for cooling systems. These include the ANL modeling and stratification test projets, the BCS modeling projects, and the water tank projects of Independent Living, the University of Nebraska and Westinghouse (since all of these have the potential for storing water up to 210°F). However, none of these projects will be discussed further under the cooling category.

In addition, there are a number of projects specifically aimed at space cooling applications, and these will be discussed under this category.

Calmac Corporation, utilizing essentially the same container and internal heat exchange system as in its 115°F unit, is developing PCM-TES units utilizing magnesium chloride hexahydrate (240°F transition temperature) and a Glauber salt based eutectic system (45°F transition temperature). Since the magnesium cloride hexahydrate melts congruently, no internal circulation pump is required. A 75,000 BTU prototype unit was built and extensively cycled with no performance deterioration. Some difficulty in durability of the plastic container was experienced, and a sturdier container is now under test. The Glauber salt eutectic was developed under subcontract, at the American Technological University by Dr. Maria Telkes. This mixture contains a thickening agent and no internal circulation is utilized inside the TES device. The mixture has a sharp transition at 45°F with a heat of fusion of 50 BTU/lb. It was cycled several hundred times with no deterioration in a laboratory scale unit, and is presently undergoing tests in a larger prototype unit. Results so far have been very satisfactory.

Martin-Marietta has been developing a thermo-chemical heat pump based on ammoniation/deammoniation of inorganic salts. The initial study utilized solid bed ammoniated salts. However, the limited heat transfer properties of these solid beds resulted in a shift to liquid state ammoniated salts. Sub-scale tests were completed and a full-scale prototype unit is presently under construction. These units are designed to produce both heating and cooling and a significant storage of thermal energy. At the present time the cost effectiveness of these systems has not been determined.

A number of system studies are under way to evaluate the use of thermal energy storage and thermo-chemical heat pumps in solar cooling applications. EIC has completed a study of advanced TES systems for a variety of solar applications. This was discussed briefly under the heating category. The EIC analysis of solid state thermo-chemical heat pumps indicated their performance to be below that of conventional water tank systems. An assessment of the use of TES in cooling systems indicated that it

was essentially beneficial. EIC is currently conducting a system analysis of two liquid phase thermo-chemical heat pumps, the H_2SO_4/H_2O and the liquid phase ammoniates systems. SAI has recently been assigned the task of performing system analyses to evaluate trade-offs for the use of TES in solar cooling systems, e.g., cold versus hot side , sensible versus PCM, single versus multiple stage, etc. Work has not yet begun on this project. HAI (Hittman Assoc.) recently received a contract to determine the engineering design parameters for TES units to be utilized for solar driven chillers currently under development with DOE funding. Work on this contract has begun but no results have yet been reported.

TECHNICAL ACCOMPLISHMENTS

- Calmac has designed, built and is testing prototype units with Magnesium Chloride Hexahydrate (240°F) and a Glauber Salt Eutectic (45°F). The 240°F unit has been extensively cycled with no performance deterioration. The plastic container, however, failed after a long test period. A sturdier plastic container is being tested. Cycling tests of the Glauber Salt Eutectic in a prototype device has recently begun. Results so far are satisfactory.

- Martin Marietta has conducted extensive laboratory and sub-scale tests on solid state and liquid state ammoniates of inorganic salts, and has defined the operating characteristics and parameters of thermo-chemical heat pumps based on paired salt combinations, including pairing with liquid ammonia. A selection was made of the two best candidate systems, namely liquid ammonia paired with liquid state ammoniates of either ammonium nitrate or ammonium thiocyanate.

- Corrosion tests have been conducted,on candidate ammoniates with A-36 carbon steel, 304L stainless steel and 5052 Al. The carbon steel, which is the most economical candidate, was attacked by the ammonium nitrate. Corrosion tests were then performed, and are continuing on a silicon fluid coated carbon steel. Results so far are satisfactory.

- Preliminary conceptual designs and cost estimates (approximately $4,000) were prepared for a 500,000 BTU, 100,000 BTU/hr. heating, 250,000 BTU, 80,000 BTU/hr. cooling unit, utilizing the liquid ammonia-ammoniated ammonium nitrate system. Based on this, an engineering prototype was designed and is bring constructed.

- EIC developed TRNSYS compatible models for advanced TES subsystems for a variety of space conditioning-TES combinations, and carried out simulations for the use of TES subsystems for space and DHW heating, SAHP, absorption and Rankine cooling, and thermally activated chemical heat pumps. A Final Report has been published.

- The performance of solid-gas (CHP) heat pumps appeared to be below that of conventional water tank systems, but relative performance was very strongly dependent on collector performance. For a CHP in the COP > 1 mode, with low loss evacuated tube collectors a significantly improved performance is indicated.

- TES for absorption cooling is very climate sensitive. An adequate capacity of TES, however, is critical for the performance of both absorption and Rankine chillers, since any use of back up is highly inefficient compared to electric air cooling.

- Under the new contract, new TRNSYS compatible codes have been developed for the H_2SO_4/H_2O and the liquid phase ammoniated salt chemical heat pumps. Preliminary simulations have been run for both heating and cooling in the COP $\leq$ 1 and COP > 1 operational modes. Early indications are that performance of both, and probably all, liquid phase systems will be about the same, provided the absorber is not volatile at the operating temperature.

FUTURE ACTIVITIES

- Calmac will complete development and testing of the 240°F and 45°F PCM-TES units, and of on-site filling procedures and equipment, and document the results.

- Martin Marietta will complete construction and testing of the engineering prototype unit, and prepare a performance evaluation and more realistic cost estimate.

- Development of an alternate design for the liquid ammoniates CHP which will permit continuous, rather than batch, operation is under consideration.

- Development of a CHP system for cooling only, which uses an ammoniated salt slurry and operates with a 150°F input is under consideration.

- EIC will complete comparison of the H_2SO_4/H_2O and liquid ammoniated salt systems with each other and with other systems analyzed in the previous contract.

- Performance comparisons for heating in the COP > 1 mode for the liquid CHP system will be made for a "passive" heating mode.

- SAI will conduct the system analyses of TES trade-offs in solar driven cooling systems.

- HAI will complete the specification of TES engineering design parameters for solar driven absorption, Rankine and desiccant chillers, and will identify TES R&D needs.

THERMAL ENERGY STORAGE FOR SOLAR ASSISTED HEAT PUMPS

The only current project which bears directly on this application is the CSU study of soil heat and water transport properties. Essentially all of the results of that study, which are described under the Space Heating Category, apply equally well to SAHP's operating in a ground coupled mode.

In addition, since the economics of an SAHP require a very low cost, and thus probably a low efficiency collector, it is important that any storage system coupled to the collector be highly stratified in order to maximize the collector efficiency. Thus, the ANL modeling and experimental work on developing stratified water tanks may improve performance in SAHP systems. Finally, the development of lower cost storage units, as in the University of Nebraska's membrane lined storage tank project, and of large, low cost storage methods, as in the annual storage projects, can contribute to the overall cost effectiveness of SAHP systems.

MODELING AND DEVELOPMENT OF THERMOCLINE AND HALOTHERMOCLINE STORAGE SYSTEMS

ARGONNE NATIONAL LABORATORY

ANL NO. 49572

W. T. SHA, E. I. H. LIN, K. V. LIU, J. G. BARTZIS AND Y. S. CHA

OCTOBER 1, 1978 TO SEPTEMBER 30, 1979

OBJECTIVE

(1)Develop and validate three-dimensional stratification model (COMMIX-SA-1), porous-media model (COMMIX-SA-RD), and double-diffusive-convection model (COMMIX-SA-SP), within the framework for the investigation of heat, mass and momentum transport phenomena in thermocline and halothermocline storage systems; (2) utilize the models developed to perform parametric studies on water tanks, rock beds, and salt-gradient solar ponds so as to optimize design and improve performance of these solar-energy components; (3) design, construct and test out improved vertical and horizontal rock beds; and, (4) investigate stability characteristics of salt-gradient solar pond.

BACKGROUND

Thermocline and halothermocline storage systems utilize temperature and salinity-temperature gradient zones, respectively, to enhance and to achieve their solar thermal energy storage functions. Stratified water tanks and rock beds, in which thermoclines separate the hot and cold regions, are suitable short- or long-term storage units for building heating and cooling; whereas solar ponds, which rely on halothermoclines for heat retention, are appropriate for numerous agricultural and industrial process heat applications and space conditioning. The three-dimensional thermohydrodynamic computer code COMMIX-SA, which was developed in FY 1978, has proven to be a very versatile and useful analytical tool, capable of elucidating fluid flow and heat transfer processes in stratified water tanks. Furthermore, it has proven to be valuable for identifying and evaluating improved tank designs and has thus brought about expansion of the work scope to include modeling of rock beds and salt-gradient solar ponds.

SUMMARY

COMMIX-SA-1 was validated and utilized to simulate the heat discharge and charge responses of stratified water tanks of various designs. Effects of tank geometry, flow rate, jetting, baffles and flow distributors on tank performance were determined. Design features enhancing stratification and performance were identified. COMMIX-SA-1 was documented and released.

Development of three-dimensional, time-dependent COMMIX-SA-RB computer code for rock bed analysis using porous medium formulation has been initiated, and very preliminary results on rock bed performance are obtained.

Development of the COMMIX-SA-SP code for solar pond applications has been initiated, and very preliminary results on 3-D heat loss modeling with an option of 2-D from the solar pond to ground are obtained.

TECHNICAL ACCOMPLISHMENTS

- Validation of COMMIX-SA-1 with available experimental results has yielded satisfactory agreement.

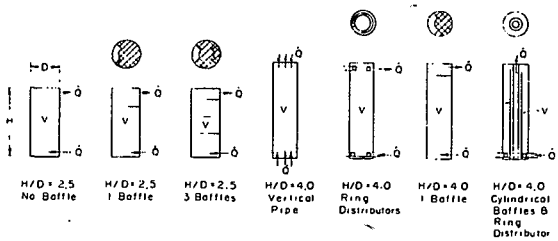
- Extensive parametric studies conducted with COMMIX-SA-1 have determined the effects of geometry, flow rate, jetting, baffles and flow distributors on the performance of heat storage tanks. Some of the design configurations investigated and the correpbnding simulated heat-discharge responses are shown in Fig. 1. Design features enhancing stratification and performance have been identified. They are: (i) large height-to-diameter (H/D) ratio (3, 4, or as large as practical); (ii) ring, pipe or disk distributors; (iii) non-conducting or low-conducting materials for baffles; (iv) low flow velocity; (v) cold ports near bottom and hot ports near top of tank; (vi) baffles (vertical baffles better than horizontal ones). A cylindrical tank with H/D = 4.0, equipped with VCCB's (i.e., vertical concentric cylindrical baffles) and an inlet ring distributor, has been shown to substantially upgrade discharge and charge efficiencies; details of this tank design and the associated heat-discharge temperature profile are illustrated in Fig. 2.

- Several color movies were produced based on COMMIX-SA-1 simulations which display stratification and internal wave phenomena that take place in the storage tanks. These movies aid viewers, particularly analyists and designers, in gaining insight of the pertinent physical processes.

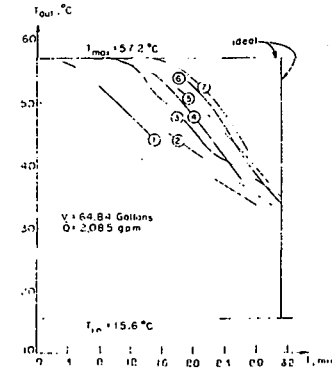
- Definitions of storage charge and discharge efficiencies and of thermal energy storage efficiency were developed.

- COMMIX-SA-1 was documented and released (ANL-80-8, December 1979).

- Development of three-dimensional, time-dependent, COMMIX-SA-RB computer code for rock bed analysis using porous medium formulation has been initiated at the beginning of this fiscal year. A preliminary literature survey on heat transfer coefficient and pressure drop correlations are completed. The very preliminary results on rock bed performance are obtained. The physical



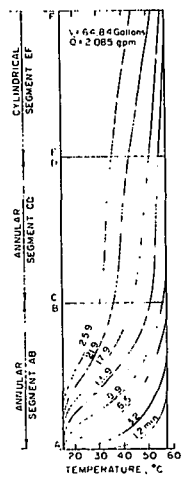
(a)



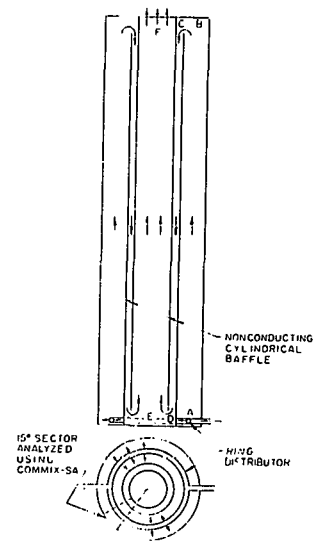
(b)

1. H/D = 2.5, No Baffle
2. H/D = 2.5, 1 Horizontal Baffle
3. H/D = 4.0, Vertical Pipe
4. H/D = 4.0, 1 Horizontal Baffle
5. H/D = 4.0, Inlet and Outlet Ring Distributor
6. H/D = 4.0, Conducting Cylindrical Baffles
7. H/D = 4.0, Nonconducting Cylindrical Baffles

Fig. 1. (a) Storage tank designs; and (b) corresponding heat-discharge responses determined from COMMIX-SA simulations.



(a)



(b)

Fig. 2. (a) Temperature profile during heat discharge from (b) storage tank with vertical concentric cylindrical baffles and ring distributor; Q = 2.035 gpm.

dimensions and arrangement of a typical rock bed, and the corresponding computational mesh used in the COMMIX-SA-RB code are shown in Fig. 3. Some of the typical velocity and temperature distributions across plane J =4 are shown in Fig. 4.

- A study was made on the basic principles, current designs, and economic advantages of salt-gradient solar ponds which resulted in the following assessments: (i) salt-gradient solar ponds are technically and economically feasible; (ii) continuing R&D effort should be focused on the reliability and efficiency aspects in order to improve the state of pond technology; and (iii) efforts on large-scale demonstrations of solar ponds in space heating, agricultural and industrial process heat and other low-temperature applications should be stepped up.

- Development of COMMIX-SA-SP code for solar pond applications has been initiated at the beginning of this fiscal year. Three-dimensional, time-dependent heat loss modeling with an option of 2-D from the solar pond to ground are completed and preliminary results are obtained. Based on the heat loss results, 2D calculations underestimates heat loss as compared with corresponding 3-D calculations.

FUTURE ACTIVITIES

Contract activities. Develop and validate a porous-media model for rock beds (COMMIX-SA-RB) and a double-diffusive-convection model for salt-gradient solar ponds (COMMIX-SA-SP).

Utilize the COMMIX-SA-RB for rock bed to study the flow-channeling problem, to determine effects of plenum geometry, internal partition and other design variables, and to optimize vertical and horizontal rock-bed designs. These analytical efforts will be interfaced with an experimental program (subcontracted to SOLARON Corp., Colorado) under which improved rock beds (particularly horizontal ones) are to be designed, constructed and tested.

Utilize the COMMIX-SA-SP for solar pond to study heat loss and stability characteristics of salt-gradient ponds, with the aim to determine methods of ensuring pond reliability and improving pond efficiency.

Further validate COMMIX-SA-1 as more experimental data become available. Perform further design studies with cylindrical, rectangular and irregular-shaped water tanks, annual storage units, and address fundamental questions such as scaling, stability of thermoclines, and promotion of stratification.

Post-contract activities. COMMIX-SA-1 will be maintained as required, and users of the code will be provided with needed assistance.

PUBLICATIONS

W. T. Sha and E. I. H. Lin, "Three-Dimensional Mathematical Model of Flow Stratification in Thermocline Storage Tanks," Application of Solar Energy 1978, Ed. S. T. Wu et al., pp. 185-202, UAH Press (1978).

E. I. H. Lin, W.T. Sha and A. I. Michaels, "On Thermal Energy Storage Efficiency and the use of COMMIX-SA for Its Evaluation and Enhancement," Proc. Solar Energy Storage Options Workshops, San Antonio, Texas, pp. 501-513 (March 1979).

E. I. H. Lin and W. T. Sha, "Effects of Baffles on Thermal Stratification in Thermocline Storage Tanks," Proc. Int. Solar Energy Society Meeting, Atlanta,Georgia (June 1979).

E. I. H. Lin, W. T. Sha and S. L. Soo, "Stability Considerations and a Double-Diffusive Convection Model for Solar Ponds," ANL-CT-79-34 (April 1979).

W. T. Sha, E. I. H. Lin, R. C. Schmitt, K. V. Liu, J. J. Oras, Jr., and H. M. Domanus, "COMMIX-SA-1: A Three-Dimensional Thermohydrodynamic Computer Program for Solar Applications," ANL-80-8 DRAFT (Dec 1979).

E. I. H. Lin, K. V. Liu and W. T. Sha, "COMMIX-SA: Validation, Application and Extension of a Solar Design Tool," Proc. 2nd Annual Systems Simulation and Economics Analysis Conference, San Diego, California (Jan 1980).

E. I. H. Lin, W. T. Sha and S. L. Soo, "Technical and Economic Feasibility of Solar Ponds in Large-Scale Agricultural Applications," Proc. 2nd Annual Systems Simulation and Economics Analysis Conference, San Diego, California (Jan 1980).

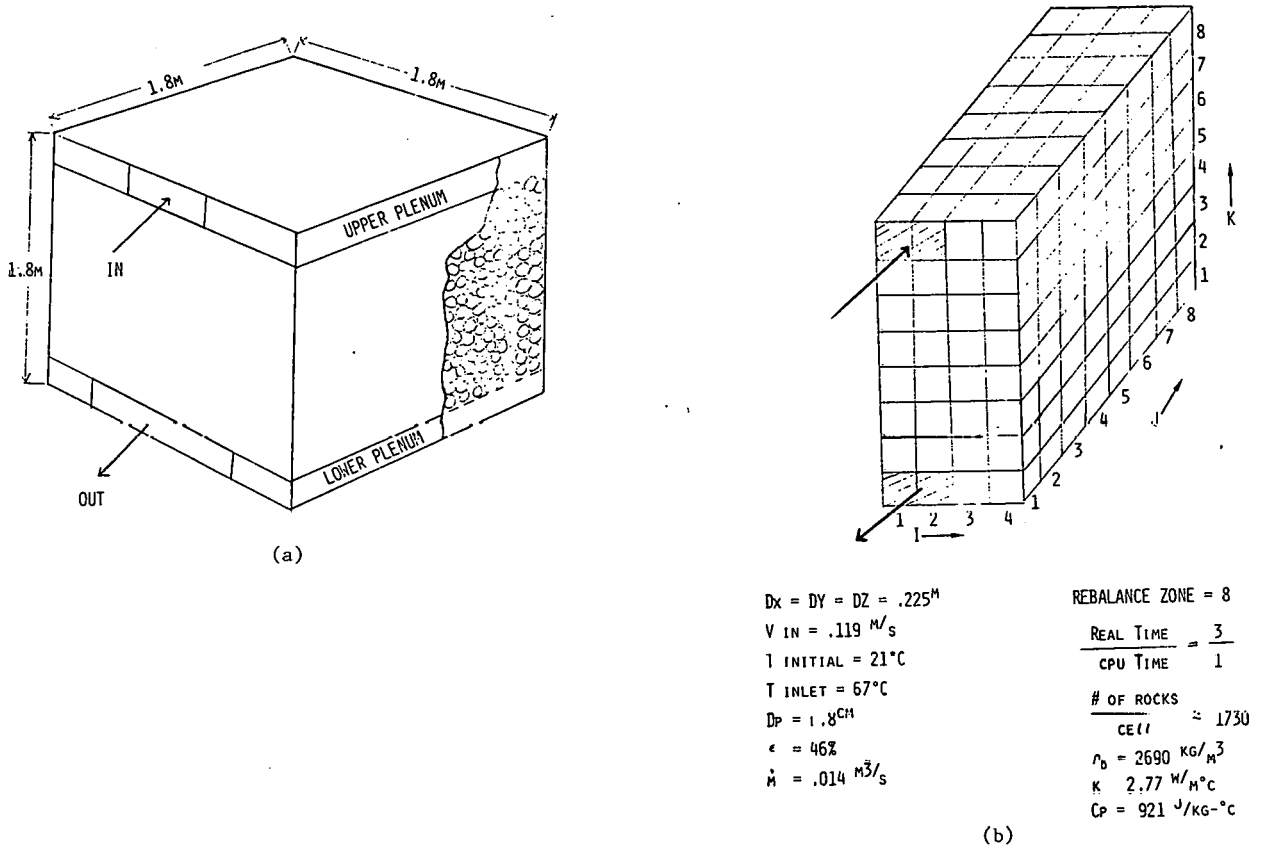


Fig. 3. (a) Physical dimensions and arrangement of a typical rock bed; and (b) computational mesh used in the COMMIX-SA-RB Simulation

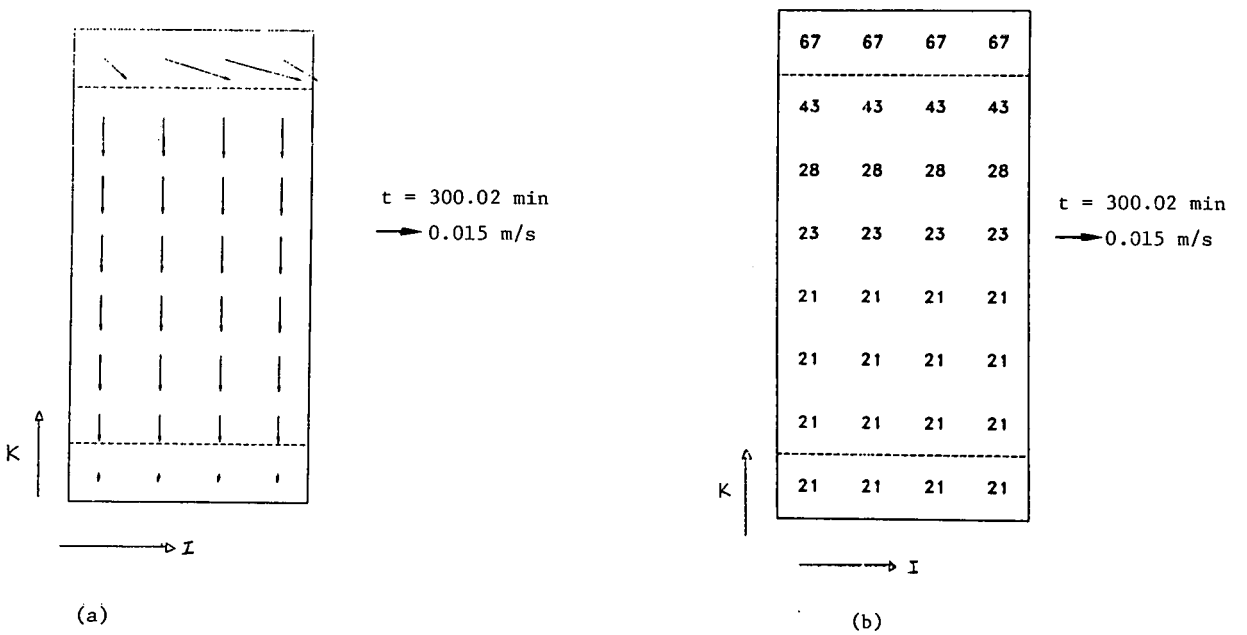


Fig. 4. (a) Velocity distribution at plane J = 4; and (b) Temperature distribution at plane J = 4.

STRATIFIED STORAGE MEASUREMENT AND ANALYSIS

ARGONNE NATIONAL LABORATORY

CONTRACT NUMBER 49589

PRINCIPAL INVESTIGATOR: ROGER L. COLE

PERIOD OF CONTRACT: Begin 10/79 End 9/80

OBJECTIVE

The objective of this task is to provide experimental verification of the efficacy of several tank shapes and baffle and diffuser configurations for promoting thermal stratification. Comparison of experimental results with analytical predictions will be used to validate the COMMIX-SA computer code. Guidelines based on the experimental results will be written for designers of thermal energy storage tanks.

BACKGROUND

The development of the COMMIX-SA computer code by ANL for 3-dimensional, transient analysis of stratification in storage tanks has led to several suggested baffle and diffuser configurations as well as suggested tank shapes [1,2].

SUMMARY

Major items have been procured and instrument setup and calibration has begun. Baffle configurations have been selected for the first series of tests using a tank similar in size and shape to a domestic hot water heater. Two 800-gallon tanks have been procured for testing stratification in tanks used for solar space heating.

Preliminary analysis shows that without any change of collection strategy, a thermally stratified system can collect about 4 percent more energy than an otherwise identical thermally mixed system. With a change of collection strategy, the thermally stratified system can perform substantially better than a thermally mixed system.

TECHNICAL ACCOMPLISHMENTS

- Major items have been procured. These include a data logger, a thermocouple array, a 65-gallon cylindrical tank, an 800-gallon cylindrical tank, and an 800-gallon rectangular tank. The equipment is being set up for testing the 65-gallon tank as shown in Figure 1. The storage tank shown in Figure 1 contains up to 800 gallons of heated water for the tests. The loop can be operated in either of two modes, flowing through the 65-gallon tank for testing or bypassing the 65-gallon tank. The bypass mode is used to heat the water in the storage tank up to operating temperature. In either mode the water can be returned to the storage tank, directed to the calibration tank, or drained. This is a versatile system in which the storage tank will become the test tank for the second series of tests.

- Three baffle configurations have been selected for the first series of tests in the 65-gallon tank. The first is a dip tube arrangement shown in Figure 2a to simulate conventional domestic hot water heaters. The second baffle configuration will be a single horizontal baffle shown in Figure 2b with horizontal inlet and outlet at the top and bottom. The third configuration shown in Figure 2c will have cylindrical baffles with a ring distributor at the bottom. Both the second and third configurations have been modeled extensively by Lin and Sha using the COMMIX-SA computer code [3].

- A preliminary analysis of thermally-stratified versus thermally-mixed domestic hot water systems was performed. Conditions were for a clear day at 40° latitude with a 60° collector tilt on February 21. Ambient temperature was assumed to be -2°C, the collector's $\tau\alpha$ product was 0.802, and the collector's loss coefficient was 5.21 $W/m^2 \cdot °C$. Water main temperature was assumed to be 10°C and the auxiliary heat turns on whenever the storage temperature drops below 35°C. A tempering valve limits maximum delivery temperature to 60°C.

Using the same collection strategy for both systems the stratified system can collect about 4 percent more energy than the mixed system. That the collection strategy used for a mixed system is inappropriate for a stratified system is readily apparent. The high flowrate (about 5 turnovers of storage per day) for mixed storage is too high for stratified storage which should be limited to 1 turnover per day. In addition, stratified system efficiency can be improved by varying the collector flowrate so that the outlet temperature remains constant. The constant outlet temperature--40°C was used for the analysis--need be only a few degrees above the auxiliary turn-on temperature. With the change of strategy, the stratified system requires only half as much auxiliary energy as the mixed system requires for the same size of collector.

The results, although preliminary, show that a change of collection strategy is essential if the full benefits of stratification are to be realized. The theoretical benefits may be somewhat greater than the 10-20 percent performance improvement predicted by the NBS [4] or the 20-percent performance improvement predicted by Connor and Mueller [5]. Neither NBS nor Connor and Mueller used a collection strategy that takes full advantage of stratification. In actual systems, the benefits of stratification will be less than those of theroretical predictions because perfect stratification is practically unattainable in a single tank, and existing systems usually achieve some degree of partial stratification.

FUTURE ACTIVITIES

Contract activities. In FY 1980, several different baffle and diffuser configurations will be tested in three storage tanks. Results will be compared with computer predictions, and the COMMIX-SA computer code will be validated. Experimental results will be published as guidelines for tank designers.

In FY 1981, the experiments will be extended to horizontal cylindrical tanks. The effect of scaling up the tank size will be measured. Tank design guidelines resulting from this work will be particularly valuable to designers of large one-of-a-kind tanks.

In FY 1982, the techniques and equipment developed for this project will be used to measure the performance of a direct contact boiler/ storage tank.

Post-contract activities. None.

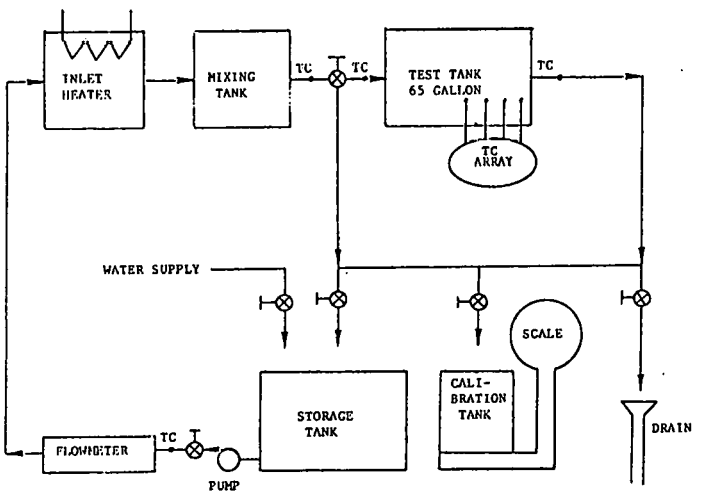
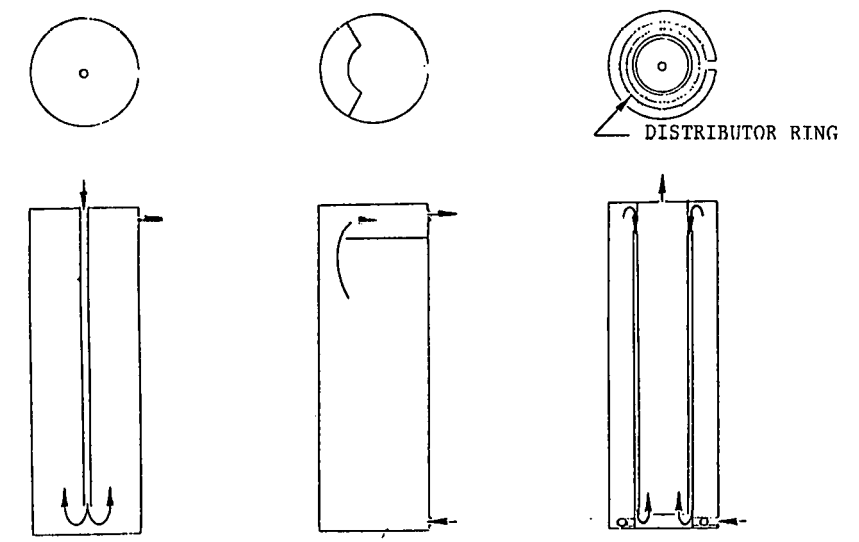


Figure 1. Schematic Diagram of Test Loop



A. DIP TUBE B. HORIZONTAL BAFFLE C. CYLINDRICAL BAFFLES WITH DISTRIBUTOR RING

Figure 2. Baffle Configurations

REFERENCES

1. W. T. Sha and E. I. H. Lin, "Three Dimensional Mathematical Model of Flow Stratification in Thermocline Storage Tanks", Proceedings of the 3rd Southeastern Conference on Solar Energy, ed. S. T. Wu, et. al., pp 158-202, Huntsville, Alabama (1978).

2. E. I. H. Lin and W. T. Sha, "Effects of Baffles on Thermal Stratification in Thermocline Storage Tanks", Proceedings of the 1979 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Atlanta, Georgia, (May 28-June 1, 1979).

3. E. I. H. Lin, W. T. Sha, and A. I. Michaels, "On Thermal Energy Storage Efficiency and the Use of COMMIX-SA for its Evaluation and Enhancement," Proceedings of Solar Energy Storage Options Workshop, CONF-790328-P2, pp 501-513, San Antonio, Texas, (March 19-20, 1979).

4. M. McCabe, J. Holton, and E. Streed, Intermediate Standards for Solar Domestic Hot Water Systems/HUD Initiative, Appendix A, National Bureau of Standards Report NBSR 77-1282 (July 1977).

5. D. W. Connor and R. O. Mueller, Elementary General Theory of Stratified Solar Thermal Systems, Argonne National Laboratory Report ANL/SPG-5 (to be published).

DEVELOPING AND UPGRADING OF SOLAR SYSTEM THERMAL ENERGY STORAGE SIMULATION MODELS

BOEING COMPUTER SERVICES COMPANY

EG-77-C-02-4482

JOHN K. KUHN

SEPTEMBER 1, 1977 - FEBRUARY 22, 1980

OBJECTIVE

"Developing and Upgrading of Solar Systems Thermal Energy Storage (TES) Simulation Models" is a program designed to develop high quality TES computer simulation models from the state of the art information and test data and make these models usable and available. Specifically:

- o Collect, standardize, and upgrade existing TES models from the literature and other contractors.
- o Correlate TES models with TES component test data.
- o Develop streamlined versions of validated TES component models.
- o Provide DOE and industry with a competent solar TES simulation tool.

BACKGROUND

Confidence in the currently available TES models was lacking due to insufficient detailed validation efforts. Regimes of reasonable applicability had not been adequately delineated. Consequently, there was a need to upgrade the accuracy and completeness of available thermal energy storage subsystem models to provide for more realistic simulation of system performance.

SUMMARY

After an extensive literature review, computer simulation models for the rock bed and water tank components were selected and upgraded. The rock bed model has as its basis the Schumann model (1) and the water tank model has as its basis the Duffie-Beckman model (2) and the Sharpe and Loehrke model (3).

Correlation of rock bed and water tank models with test data has proceeded using available data and tests performed specifically to validate the computer simulation models. To date, channeling in the rock bed has caused the rock bed model validation to be less accurate than desired but with the implication that the simulation model would be excellent for higher pressure drop systems. For the tests analyzed water tank model validation has proceeded with excellent correlation for water tanks with diffusers.

Streamlined versions of both rock bed and water tank models have been developed. These components, however, are designed to give more information than typical system simulation models and are therefore more complex than typical system component models.

The rock bed model and the water tank models have been designed to be incorporated into system simulation programs. At this time both water tank models have been incorporated into TRNSYS as component options. A TRNSYS Manual modification and the codes themselves are available. The rock bed incorporation, manual modification, and code will be available later this year.

TECHNICAL ACCOMPLISHMENTS

- o The TES component models selected are all based on one-dimensional models. There are two fundamental reasons for making this rather sweeping assumption. The first reason is that a properly designed rock bed operated in a cost-effective manner will exhibit "plug" flow and will follow the model closely. Our single largest difficulty in validating the model is a result of what we now believe to be channeling (non-plug flow). Our experience to date with water tank tests has indicated that the one-dimensional model is satisfactory from this point of view. The second reason for selecting one-dimensional models is the extreme complexity and cost involved in calculating the results using a three-dimensional model. These models are appropriate for research activities but inappropriate to install in typical codes used by practicing solar analysts.

- o The TES rock bed component simulation models selected all have as their basis the Schumann equations (1). These Schumann equations may be solved using various simplifying assumptions and different mathematical techniques. The technique selected is that used by Hughes (4) and a generalization of Mumma and Marvin (5). In summary, the equations are one-dimensional and assume forced fluid motion implying either charging (adding to storage) or discharging. The equations are coupled partial differential equations representing fluid and bed temperatures as a function of location and time. This method assumes that the rock temperature is fixed for a short time span, since it is only slowly changing compared with the air temperature. In a quasi-Galerkin approach, the bed temperature is represented by a polynomial of fixed degree (in this case linear). Given these polynomial representations for rock bed temperature, a closed form solution for the one-dimensional fluid equation can be obtained. This solution is then available for calculating the next set of rock bed temperatures using a more traditional finite difference representation for the rock bed equation. A complete development of the model method is shown in references (6), (7), and (8).

- o The TES water tank component simulation

models selected for investigation were the Duffie-Beckman model (2) and the Sharpe and Loehrke model (3). In addition to these models an algebraic model contained in SOLSYS (9) was explored. The Sharpe and Loehrke model had some advantages over the Duffie-Beckman model. It treats heat transfer via conduction in the liquid and offers the option of modeling two types of storage tanks, one with a fixed inlet position and one with a variable inlet position. The algorithm is well structured and computationally efficient. These codes are described in detail in reference (8).

o The correlation of TES models with component test data is essential for validation. In the case of the rock bed TES an additional validation was made prior to the test data comparisons. This validation was made by comparing the numerical solution of the differential equations to a known closed form solution with certain boundary conditions. For the cases considered the rock bed model was confirmed to within one degree centigrade. As a result of the various DOE demonstration programs a considerable body of data exist. However, the intention of most efforts has not been component model validation and instrumentation for this purpose has been inadequate. The exception has been the University of Wisconsin's Arlington House which is instrumented more carefully. Reasonably good model validation was obtained. Because of this reasonable correlation a special validation test series was conducted at this facility specifically for the purpose of validating the model. A preliminary look at these data indicates some channeling is still occurring. The details of these validation tests will be available in a few months. All validation information available at this date is reported in reference (8).

o Water tank model validation has proceeded with excellent correlation from several sites: Colorado State University, the National Bureau of Standards, and the Illinois Institute of Technology. In the case of Colorado State University, specific tests have been conducted to validate the model. It can be stated that in general the discrepancy between the experimental and model values are less than five percent. As in the case of rock bed "channeling", the results of the water tank simulation are dependent on having a good flow in the inlet. Simulation is poor without a diffuser. The results of these validations are reported in reference (8) and additional results will be available in a few months.

o In streamlining a code, the efficiency of the numerical algorithms, the sensitivity of parameters to the final result with the possibility of substituting average values or eliminating parameters, and perhaps a substitution of a transfer function which empirically describes the process are considered. Considerable attention has been given to the first of the above in the streamlining process. To date, there does not seem to be a possibility of eliminating or using average values since rather careful model evaluation was made initially and the parameters carefully selected. At this time there seems to be no immediate possibility of using a transfer function concept.

o Both the rock bed and water tank model are being incorporated into the TRNSYS simulation program. It is felt that DOE and industry are best served by having the components available for use in the most commonly used system simulation program. The water tank component has already been installe as an optional component in the TRNSYS library Documentation in the form of a modification to the TRNSYS manual, as well as the code are being prepared. The rock bed component will be installed and documentation prepared in a few months.

FUTURE ACTIVITIES

o Complete the validation of the rock bed model including limitations on its use.

o Incorporate the rock bed model into the TRNSYS Simulation program.

o Provide documentation and code to DOE and industry for the rock bed and water tank components incorporated into TRNSYS.

REFERENCES

(1) T. E. W. Schumann, "Heat Transfer: A Liquid Flowing through a Porous Prism", Journal of the Franklin Institute, Volume 208, p. 405, (1928).

(2) "TRNSYS - A Transient Simulation Program", Solar Energy Laboratory, University of Wisconsin, Rp. No. 38-9, (1978).

(3) M. K. Sharp and R. I. Loehrke, "Stratified Versus Well-Mixed Sensible Heat Storage in a Solar Space Heating System", ASME 78-HT-49.

(4) P. J. Hughes, "The Design and Predicted Performance of the Arlington House", M.S. Thesis, Mechanical Engineering Department, University of Wisconsin (1975).

(5) S. A. Mumma, W. C. Marvin, "A Method of Simulating the Performance of a Pebble Bed Thermal Energy Storage and Recovery System", ASME 76-HT-73, (1976).

(6) R. T. Haelsig, D. W. Halstead, R. M. Southall, G. F. vonFuchs, and A. W. Warren, "Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models", BCS COO-4482-1, (1978).

(7) J. K. Kuhn, G. F. vonFuchs, A. W. Warren, and A. P. Zob, "Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models", BCS-40235, (1978).

(8) J. K. Kuhn, G. F. vonFuchs, and A. P. Zob, "Developing and Upgrading of Solar System Thermal Energy Storage Models", BCS-40252, (1979).

(9) M. W. Edenburn, et.al., "SOLSYS - Energy System Simulation Computer Program", Sandia Laboratories (1965).

SALT HYDRATE THERMAL ENERGY STORAGE SYSTEM
FOR SPACE HEATING AND AIR CONDITIONING

CALMAC MANUFACTURING CORPORATION

EM-78-C-02-4698

CALVIN D. MacCRACKEN

December 1, 1977 to June 30, 1980

OBJECTIVE

The objective is to develop, test and make ready for the commercial market three different salt hydrate/heat exchanger modules with on-site filling techniques to cover storage of heat pump coolness (40°-50°F), solar or heat pump space heating (100 to 120 F), and solar energy for absorption air conditioning or Rankine engines (200 to 250 F).

CONCEPT

As reported at the DOE Solar Contractors Meeting in September 1978, the concept adopted for this work in thermal energy storage (TES) by phase change materials (PCMs) involves bulk storage rather than encapsulation or, in other words, internal heat exchange rather than external. Evenly spaced liquid carrying plastic tubes are coiled within a round open-top covered tank containing the PCM.

The chief advantage is much lower standby heat loss because the heat loss (or gain) path is different from the heat transfer path and because self-insulation results from build-up of solid material on the heat loss walls. Other important advantages are on-site filling, single nucleation, adaptability to stirring, accommodation to volume change, and compactness.

The 115°F PCM ($Na_2S_2O_3 \cdot 5H_2O$) uses a stirring pump to operate intermittently when the salt is in a liquid state to prevent stratification forming a dihydrate salt on the bottom of the tank. However, should the stirring pump fail the dihydrate dissolves by reheating to 150°F.

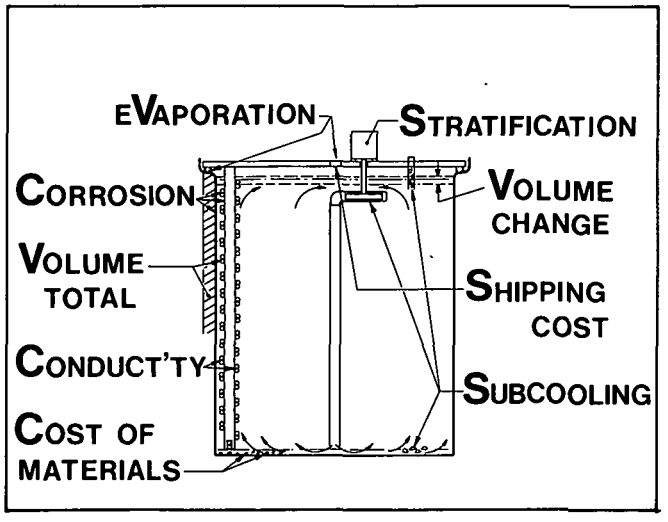
The 45°F and 240°F PCMs need no stirring but due to higher vapor pressures must have a layer of oil on top to prevent evaporation. The 45°F salt hydrate is a eutectic combination of seven different materials including a clay-type thickener to prevent stratification plus sodium sulphate, ammonium chloride and potassium chloride. Alternatively a calcium chloride mixture is under development.

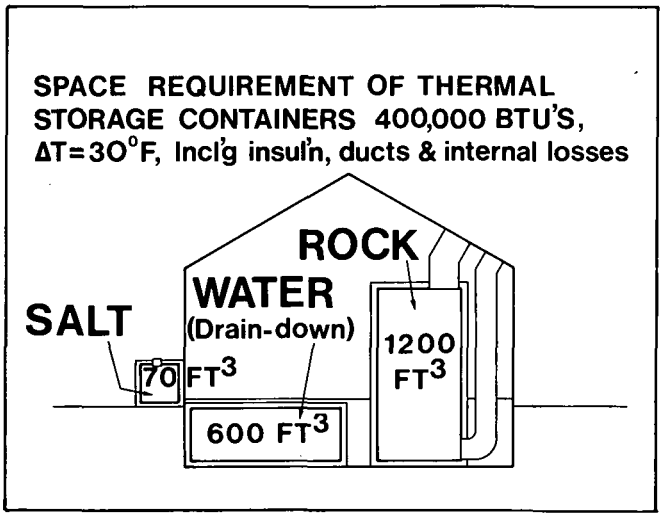
The 240°F PCM is magnesium chloride hexahydrate which needs no additives other than the oil cover. The concept of a lightweight plastic tank and tubing has been preserved at this higher temperature level also.

On-site filling of the 45° salt is by pumping a liquid from 55 gallon drums, in the 115° either by pumping from a heated tank truck or by melting crystal supplied in bags, and the 240° by again melting crystal. Crystal melting can either be in a separate contractor's heated tank or by a 3-step process of melting it in place in the tank/heat exchanger and refilling as it settles.

SUMMARY

As called for in our contract with DOE's Solar Applications Branch through Argonne National Laboratory, CALMAC has successfully developed PCM tank/heat exchangers for 45°, 115° and 240°F using liquid heat transfer fluids. These PCMs are all stable over repeated cycling. The storage efficiency is



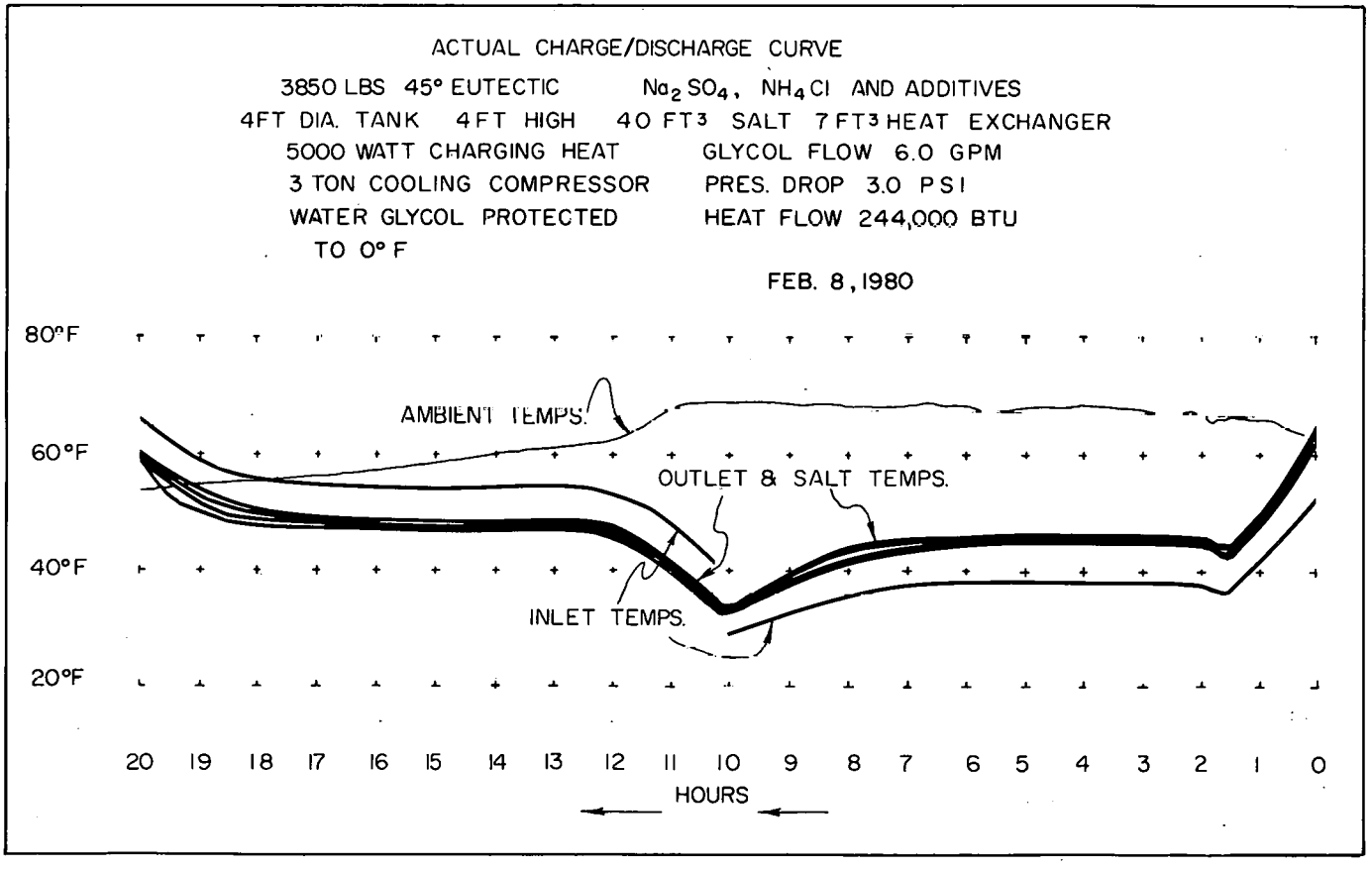


extremely high because of the bulk storage concept and high heat transfer area. The heat is charged and discharged at essentially constant temerature in 12-hour time cycles. Life expectancy appears good and required maintenance is low. Accessory pumping is compatible with standard solar circulators. Installations of the 115° salt have already been successfully made in the field. Shipping and field filling methods have been established.

The products are now essentially ready for marketing and CALMAC is accepting orders for prompt shipment for experimental use in solar, heat pump, and off-peak air conditioning applications, residential, commercial, or industrial. Commercial announcement and advertising of the product will, for a change, be delayed until documentation of field performance and marketing preparations are completed. As a by-product of the contract, work by others has provided practical PCMs adaptable to our tank/heat exchangers in virtually the entire range from -20°F to 250°F. With the use of duct coils and fan-coils, these storage units adapt equally well to air, hydronic or radiant distribution systems.

TECHNICAL ACCOMPLISHMENTS

- Limited commercial sales of the 45° and 115°F storage/heat exchanger units are now ready. Pricing literature and manuals are in preparation. The 240° modules will be marketed only when demand exists
- A successful outdoor field installation of the 115°F salt/heat exchanger, (HEATBANK-115®), has been made at a fully instrumented private home in a system involving solar heat and both off-peak resistance and condenser heat. This is jointly sponsored by General Public Utilities Company and Allied Chemical Company.
- A HEATBANK-115® has been installed at the Westinghouse Research Laboratory for use outside a test house with a solar-assisted water/water offpeak heatpump.
- Over 1000 cycles of the 45° salt and 10,000 cycles of the 115° salt in Allied Chemical Company laboratories have verified our experience that separation problems of salts are now under control.
- A new committee will be formed by ASHRAE to come up with a Test Standard to evaluate PCM storage units. The existing 94-77 Standard was shown to have shortcomings in this regard.
- The tank/heat exchanger for the salts is now in production for use with ice storage. Over 70 are providing 100% off-peak air conditioning in six different utility areas, many of them under a joint LILCO/Oak Ridge project.
- 45° salt may be pumped in to replace water/ice in ICEBANK-32® tanks thus achieving 1/3rd better C.O.P. and cooling capacity.
- Multiple modules can be conveniently connected in parallel to provide commercial sizing of both heating and cooling storage. A multiple cooling tank system is in operation in Alpine, New Jersey. Other multiple installations are planned.
- Many more salts have now been developed by Maria Telkes, Dow, Allied and Kay Labs which when used with the CALMAC tank/heat exchanger essentially cover the entire range from -20°F to 250°F. See table.



FUTURE ACTIVITIES

Contract. Work is proceeding on lowering costs in both materials and labor. A simpler stirring pump for the 115° salt, lower labor costs in mixing the 45° salt, lower tank costs in the 240° salt, are examples. Additives are being studied to perhaps eliminate a stirring pump.

Installation, service and operation manuals are to be written. Filling procedure manuals are also being prepared.

Cycling tests are continuing. Formal certification tests are being completed on 45° and 240° salts.

Tanks are being prepared for final delivery.

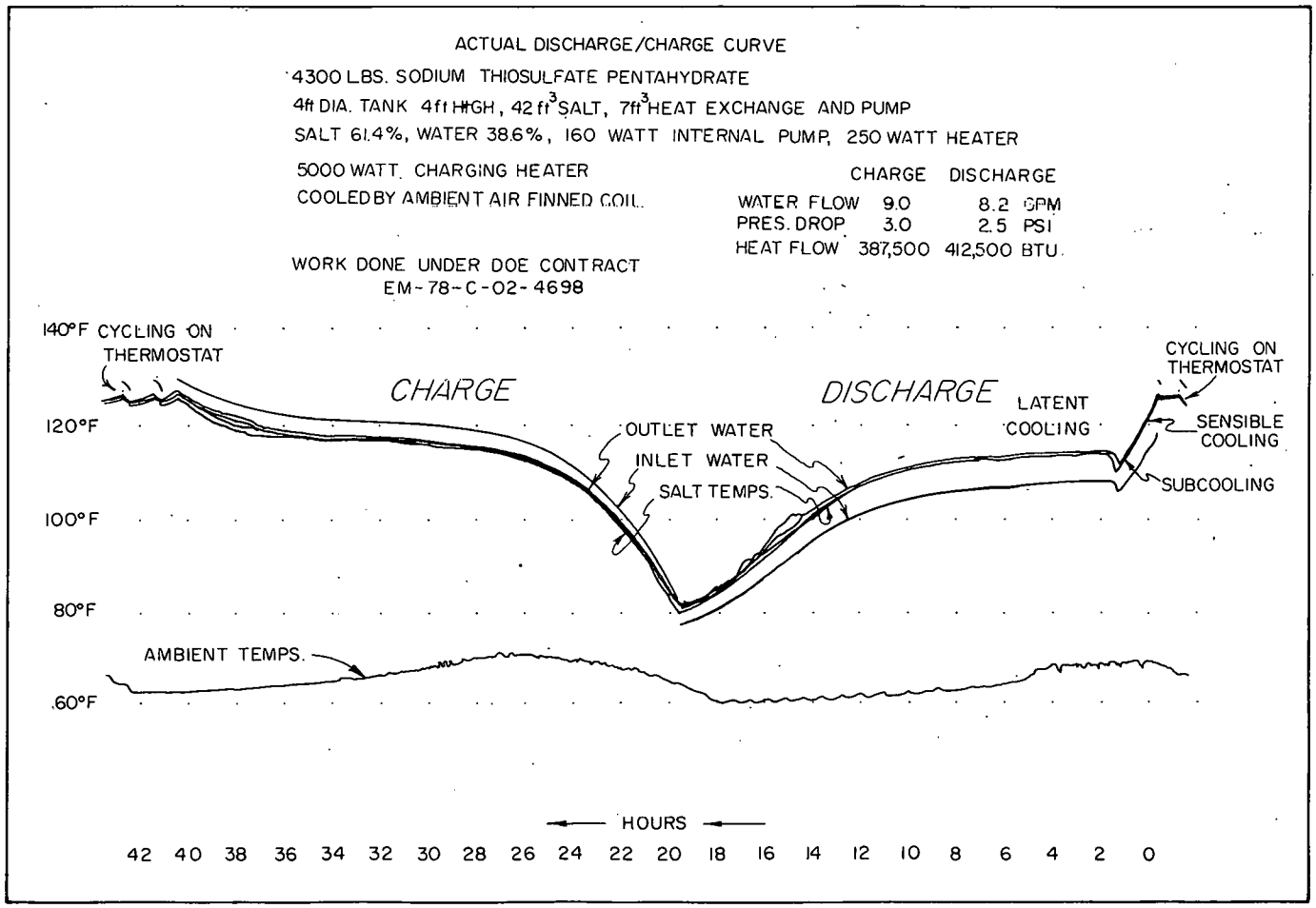
Post Contract. It is the considered opinion of our company based on many different indicators that thermal storage has the potential to burst into a vast industry. It depends greatly upon the quality of the system design technology, the equipment and the installation. Our ice storage residential jobs convince us that air conditioning contractors, properly trained, can do the field job well. The engineers who will do quality system design will require reliable, adaptable equipment. Thus quality in the equipment design is the key and this is far more important than getting to the market quickly. The market potential for TES in both solar and off-peak is huge. The interest in water-source heatpumps is growing rapidly. Solar and ground heat both have excellent low-cost adaptability to melting 32° or 45° PCMs.

We will, therefore, be involved in working to bring to market on our own certain parts of this whole picture and licensing others. We will concentrate on OEM sales to get broader coverage. We will be investigating what government support may be available in helping us get to a broad market.

We are convinced that the pieces to this intriguing puzzle are now ready to be put together.

PRACTICAL PCMs FOR BUILDING HEATING AND COOLING

Fusion Temp. °F	Material	Heat of Fusion Btu/lb.	Heat of Fusion Btu/ft^3	1980 Cost/ MM Btu	Stabilizer
32	Water	144	8250	$1.00	----
38	Na_2SO_4, KCl, additives	50	4600	600	Thickener
45	Na_2SO_4, NH_4Cl, KCl, Add's	50	4600	600	Thickener
52,55	Na_2SO_4	50	4600	600	Thickener
& 65	NH_4Cl, NaCl, additives	60	5500	500	Thickener
81	$CaCl_2 \cdot 6H_2O$	82	7800	700	Additive
89	Na_2SO_4, additives	100	9100	350	Crust
96	Disodium phospate $\cdot 12H_2O$	114	10800	1900	Pumping
113	Impure $Na_2S_2O_3 \cdot 5H_2O$(hypo)	75	7500	1000	Pumping
135	$MgNO_3 \cdot 6H_2O \cdot NH_4NO_3$	47	5000	2200	Additive
150	Trisodium phospate $\cdot 12H_2O$	100	10100	1400	Pumping
192	Magnesium nitrate $\cdot 6H_2O$	56	5700	2700	Additive
240	Magnesium chloride $\cdot 6H_2O$	73	7100	1000	Additive



TRNSYS SIMULATION OF CHEMICAL HEAT PUMPS FOR SOLAR HEATING, COOLING AND STORAGE: PART II: SIMULATIONS FOR WASHINGTON, D.C. AND FORT WORTH, TEXAS INCLUDING WINDOW EFFECTS

EIC CORPORATION, 55 CHAPEL STREET, NEWTON, MA 02158

DE-AC02-79CS30248

Peter O'D. Offenhartz

September 1, 1979 - April 15, 1980

ABSTRACT

TRNSYS-compatible subroutines for the simulation of chemical heat pumps have been written, and simulations (including heating, cooling, and domestic hot water) have been performed for Washington, D.C. and Ft. Worth, Texas. Direct weekly comparisons of the H_2SO_4/H_2O and $CaCl_2/CH_3OH$ cycles have been carried out, and an approximate comparison with a "conventional" hot water storage system has been made. In all cases simulated, the solar collector is a fixed evacuated tube system, which is necessary because chemical heat pumps operate at higher solar collector temperatures (>100°C) than "conventional" solar systems.

With standard residential loads, the chemical heat pumps performed surprisingly well. In the Ft. Worth climate, less than 45 m^2 of collectors were required to meet over 90% of the heating and cooling loads. In Washington, D.C., the area required to meet the cooling load was smaller (as little as 20 m^2, depending on window shading), but was sufficient to meet only 50-60% of the heating load. However, gas-fired backup via the heat pump was quite effective in reducing fossil fuel consumption: the thermal COPs in the heating mode were in the range 1.6-1.7. Since chemical heat pumps are designed to reject heat at relatively high temperatures, they were also effective in providing domestic hot water, supplying ca. 70% of the DHW in summer, ca. 50% in winter, and nearly 100% in spring and fall.

Direct solar gains through the windows were found to contribute the majority of the cooling load in Washington, and 25% of the cooling load in Ft. Worth. When direct solar gains, internal heat generation, and UAΔT (heat transfer) effects are taken into account, a simple model of the building heating and sensible cooling load can be constructed that agrees well with detailed simulations. This type of load modeling, coupled with the performance predictions generated here for chemical heat pumps, allows an inexpensive means of sizing the solar collectors and predicting year-round performance.

CHEMICAL HEAT PUMPS

Chemical heat pumps are absorption-cycle thermally activated heat pumps with the inherent capability of chemical storage of thermal energy. The concept dates back to Michael Faraday: the devices were once known as "Faraday refrigerators." Recent developments in the field have been reviewed by several authors (1-3).

Under DOE sponsorship, work is in progress on three different cycles: H_2SO_4/H_2O (4); NH_4NO_3/NH_3 (5); and $CaCl_2/CH_3OH$ (6). The first two are based on liquid-gas reactions, and the last on a solid-gas reaction. This difference has required the development of two separate simulation packages. Because thermodynamic data on the ammonia-based cycle are not of high accuracy, only limited simulations of this system have been carried out. However, preliminary runs have indicated that its performance is expected to be identical to the performance of the H_2SO_4/H_2O cycle, provided that the system is sized and operated in the region where salt precipitation does not occur.

All three chemical heat pumps should be capable of operating under fairly extreme conditions: absorber-evaporator temperature differences as great at 55°C (100°F) should be achievable. This is technically and economically important for three reasons: it permits forced air (dry) heat rejection even in desert climates, where the ambient temperature can exceed 40°C, thus, a cooling tower or swamp cooler is unnecessary; it permits domestic hot water preheat from the absorber, thus providing "free" DHW in summer; it permits system operation in the heating mode even on cold days, using either solar input or fossil (or wood!) heat. This helps reduce collector area (and expense), and conserves fuel even in the backup mode.

TRNSYS-COMPATIBLE LOAD MODEL

The load model used in these TRNSYS (7) simulations has the following characteristics: overall UA = 1200 kJ/°C-hr, capacitance = 40,000 kJ/°C, internal heat generation = 2300 kJ/hr, and air infiltration = 0.75 air changes per hour. The effective unshaded window areas for Washington were 4.2 m^2 (north and south) and 2.8 m^2 (east and west), for a total of 14 m^2. The window areas for Ft. Worth were smaller, 3.1 m^2 and 1.7 m^2 respectively. These areas are identical with those specified in the SERI (8) load package. Furthermore, as in the SERI package, the south windows have overhangs. The load model used here is, in effect, a simplified version of the SERI model, although internal humidity generation has been omitted (the SERI model incorrectly uses a fixed rate of vapor generation, regardless of driving forces), and some errors in the SERI window routine have been corrected.

It is possible to generate approximate heating (+) and sensible cooling loads (-) using the formula

$$LOAD = UA(T_{house} - \bar{T}_{amb}) \times \Delta t - WINDOW - GEN$$

where WINDOW is the direct solar gain and GEN the internal heat generation (appliances, lights, etc.) in the time interval Δt. The main inaccuracy arises from ignoring the time dependence of the outdoor ambient temperature T_{amb}. Load summaries are provided in Tables 1 and 2. The approximation for the heating load agrees quite well with the SERI model: the calculated annual heating load for Washington, 55.4 x 10^6 kJ, is only 9% below the value obtained in the detailed SERI simulation (60.7 x 10^6 kJ). There is a

TABLE 1. APPROXIMATE CALCULATIONS OF ANNUAL SENSIBLE COOLING LOADS FOR FT. WORTH AND WASHINGTON

Month	Fort Worth			Washington		
	Sensible Cooling Load (10^6 kJ)	Solar Radiation on Collector Surface (L+15°) (10^5 kJ/m^2)	Days Without Cooling Load	Sensible Cooling Load (10^6 kJ)	Solar Radiation on Collector Surface (L+15°) (10^5 kJ/m^2)	Days Without Cooling Load
May	1.6	5.5	13	0.7	5.0	24
June	5.1	5.8	0	1.5	5.1	12
July	8.3	6.2	0	3.8	4.8	1
August	6.9	6.3	0	3.1	5.3	2
September	2.7	6.0	9	1.1	4.7	15
Totals	24.6	29.7	22	10.2	24.9	54

TABLE 2. APPROXIMATE CALCULATIONS OF ANNUAL HEATING LOADS FOR FT WORTH AND WASHINGTON

Month	Fort Worth			Washington		
	Heating Load (10^6 kJ)	Solar Radiation on Collector Surface (L+15°) (10^5 kJ/m^2)	Days Without Heating Load	Heating Load (10^6 kJ)	Solar Radiation on Collector Surface (L+15°) (10^5 kJ/m^2)	Days Without Heating Load
January	7.9	4.1	3	14.2	3.5	0
February	4.7	4.4	8	11.6	3.4	0
March	3.6	5.8	9	7.8	4.6	3
April	0.3	5.0	24	2.7	4.8	13
October	0.2	5.7	26	1.4	4.4	12
November	2.7	4.8	10	6.2	3.4	2
December	6.8	4.3	0	11.4	2.7	0
Totals	26.2	34.1	80	55.3	26.8	30

greater discrepancy in the approximation for the cooling load: according to the SERI simulation, the annual sensible cooling load for Washington is only 6.9 x 10^6 kJ, compared to the 10.2 x 10^6 kJ found here. The difference may be traceable to errors found in the SERI window model; alternatively, a 1°C difference in indoor set point would produce a difference of this magnitude.

The detailed load model used in the simulations we have carried out differs from the approximation above in two major respects: (1) sensible capacitative effects are included, and (2) latent heat, including humidity capacitance, is accounted for. Table 3 provides a breakdown of the detailed cooling loads for a one week period in mid-July. The Washington and Ft. Worth loads are similar in most respects, but the average Washington ambient temperature is below 25°C, and hence heat transfer through the building actually removes a small amount of heat from the load. One implication of this breakdown is clear: over half the Washington load is due to direct solar gains through the windows, which could be sharply reduced by the judicious use of trees and awnings.

TABLE 3. COMPONENTS OF THE COOLING LOADS FOR FT. WORTH AND WASHINGTON, MID-JULY

	Washington	Ft. Worth
	(10^5 kJ/day)	
Heat transfer through walls and roof	-0.3	1.30
Direct solar gain through windows	0.89	0.75
Internal heat generation	0.55	0.55
Latent heat	0.47	0.42
Totals	1.56	3.03

SIMULATIONS IN THE COOLING MODE

One of the major cost items in any solar system is the solar collector itself. This is particularly true for chemical heat pumps, which require evacuated tube or other high performance collectors to achieve the required generator temperatures (ca. 130°C). For this reason, the study focused on the collector area needed to achieve >90% solar cooling. The storage capacity was set quite high -- ca. 250,000 kJ, roughly the thermal capacitance of a 1000 gallon hot water tank with a 20°C working range. This was clearly excessive, since the storage never became fully charged. However, storage capacity is not of great economic importance in chemical heat pumps -- the chemicals are cheap, and the cost of larger containers is a small portion of the total cost. Furthermore, at least in the case of solid-based heat pumps, there is no interaction between collector performance and storage size, unlike liquid systems, which operate at increasingly high temperatures as they are charged.

The requirement for a solar cooling fraction >90% may seem excessive. However, as we have argued elsewhere (9-11), a high solar fraction is essential to the success of solar cooling. Backup with natural gas is an inefficient use of fuel (it would be more efficient to burn gas at an electric utility, and use the electricity in a conventional air conditioner); backup with an electrical air-conditioner is an idea that would give nightmares to any utility executive.

Table 4 presents a summary of the main simulation results for Ft. Worth and Washington. For each

TABLE 4. SIMULATION RESULTS FOR SOLAR COOLING IN MID-JULY USING THE H_2SO_4/H_2O AND $CaCl_2/CH_3OH$ CHEMICAL HEAT PUMPS. PERFORMANCE OF THE NH_4NO_3/NH_3 CYCLE SHOULD BE NEARLY IDENTICAL TO H_2SO_4/H_2O. ALL ENERGIES BELOW ARE IN UNITS OF 10^5 kJ PER DAY.

	Washington					Fort Worth			
	H_2SO_4/H_2O			$CaCl_2/CH_3OH$		H_2SO_4/H_2O			$CaCl_2/CH_3OH$
Collector area	20 m^2	30 m^2	40 m^2	25 m^2	35 m^2	30 m^2	40 m^2	50 m^2	40 m^2
Cooling delivered	1.38	1.49	1.52	1.26	1.48	2.80	2.94	2.85	3.03
Latent portion of cooling	0.30	1.40	0.43	0.22	0.41	0.39	0.47	0.42	0.42
Solar energy collected	1.58	2.14	2.33	1.81	2.46	3.50	3.92	3.69	4.51
Collector efficiency (%)	51.5	46.5	37.9	47.1	45.7	51.6	43.4	32.7	49.5
DHW supplied by solar	0.48	0.55	0.56	0.35	0.48	0.46	0.48	0.47	0.47
Solar fraction, DHW	69%	83%	85%	53%	73%	69%	73%	72%	71%
Energy stored	-0.02	0.00	0.06	-0.11	-0.11	0.03	0.04	0.04	-0.11
Cooling COP	0.874	0.695	0.653	0.698	0.602	0.800	0.749	0.772	0.671

simulation, a one week period was selected (July 11-17 and July 15-22 respectively) that was representative of mid-summer conditions of temperature and insolation, including their variability. Possibly the most surprising result is that the collector area required for >90% solar cooling is not very different in Ft. Worth and Washington. This is due to the greater daily insolation in Ft. Worth. For example, during the period simulated, the H_2SO_4/H_2O system was able to meet 92% of the Ft. Worth cooling load with 30 m^2 of collector, and 96% of the Washington load with the same collector area. The $CaCl_2/CH_3OH$ system showed similar behavior, but the collector area required was 10-15% larger due to a smaller coefficient of performance.

The H_2SO_4/H_2O shows an interesting interaction between performance and collector size. When the collector area ia large, the generator temperature increases due to a high concentration of H_2SO_4. This reduces both collector efficiency and the cooling coefficient of performance. Under certain circumstances, performance can actually decrease with increasing collector size relative to the cooling load. However, this is probably not a major consequence, even at the ends of the cooling season, since the performance decrease is small.

Both systems supplied over 90% of the domestic hot water load (except when the collector was undersized). The percentage would have been higher, but the inlet temperature of the hot water preheater was restricted to maintain lower absorber and condenser temperatures. In retrospect, this restriction seems unnecessary.

As noted above, the coefficient of performance of the H_2SO_4/H_2O cycle depends on collector and storage size relative to the load. As shown in a previous paper (11), the COP can exceed 0.9 under optimum conditions. Furthermore, under the same conditions, the collector efficiency can exceed 50%. However, this only holds true when the storage volume is large relative to the input and output loads, so that the sulfuric acid concentration remains low, in the range 63-70% by weight. Under more normal circumstances, and in climates that require high heat rejection temperatures (and hence higher concentrations of H_2SO_4), the COP is generally in the range 0.7-0.8. The collector efficiency for the H_2SO_4/H_2O system in these simulations was generally around 45%.

The collector efficiency for the $CaCl_2/CH_3OH$ solid-phase cycle was also about 45%. However, the coefficient of performance was somewhat smaller, in the range 0.6-0.7. Neither the COP nor the collector efficiency depends strongly on sizing, a characteristic of solid-phase cycles. As noted previously (11), with the exception of size dependence, the two systems perform quite similarly despite major differences in design. As a general rule, the $CaCl_2/CH_3OH$ cycle has a coefficient of performance ca. 15% lower than the H_2SO_4/H_2O cycle, but operates at a slightly reduced solar collector temperature. For this reason, the $CaCl_2/CH_3OH$ cycle requires about 10% more collector area for the same level of performance.

SIMULATIONS IN THE HEATING MODE

As shown below, a collector sized to meet the full cooling load in Ft. Worth will be capable of meeting virtually the entire winter heating load when a chemical heat pump is used. For this reason, winter performance simulations in this climate are not particularly valuable. Of greater interest is the situation in which the collector is undersized with respect to the load, as is the case in Washington. Table 5 shows the results for the period January 19-24.

TABLE 5. SIMULATION COMPARISON OF THE MID-JANUARY WASHINGTON PERFORMANCE OF THE H_2SO_4/H_2O AND $CaCl_2/CH_3OH$ CHEMICAL HEAT PUMPS USING A 20 m^2 EVACUATED TUBE COLLECTOR. ALL ENERGIES BELOW ARE IN UNITS OF 10^5 kJ PER DAY

	H_2SO_4/H_2O	$CaCl_2/CH_3OH$
Space heat delivered	4.25	4.28
Auxiliary heat used	1.76	1.64
Solar energy collected	0.99	1.20
Collector efficiency (%)	39.7	47.9
DHW supplied by the chemical heat pump	0.31	0.37
Energy stored	0.03	-0.20
Heating COP	1.658	1.637

The collector area selected is only 20 m^2, which should be adequate for >90% solar cooling if proper window shading is employed. The two systems show major differences in the performance details but, once again, the "bottom line" - which in this case is fossil fuel usage -- is remarkably similar, with a difference of only 7% between the two systems. As is expected for a liquid-based cycle, the H_2SO_4/H_2O system operates at a higher coefficient of performance.

On the other hand, the $CaCl_2/CH_3OH$ cycle operates at a far higher collector efficiency. The difference in collector efficiency is traceable to the method of using both storage and backup. H_2SO_4/H_2O cycle must operate at high concentrations to provide heat pumping on cold days, and the use of backup in the generator also has the effect of increasing the generator temperature. Collector efficiency is hence reduced. In solid-phase systems, such as the $CaCl_2/CH_3OH$ cycle, this interaction is absent, and collector efficiency remains high.

It is notable that the two chemical heat pumps each reduce fossil fuel consumption by 60% in mid-January despite the small collector area used. Part of the savings arises from the highly efficient consumption of fossil fuel used in the heat pump backup. The other part arises from a similar amplification of the collector output. The $CaCl_2/CH_3OH$ cycle is particularly effective in amplifying the collector output; the product of the coefficient of performance and the collector efficiency is nearly 80%, far above the 65% maximum efficiency of the collector simulated (11).

EXTRAPOLATIONS AND COMPARISONS

Because of the interactions among storage size, collector area and load, it is somewhat difficult to generalize accurately the results of the simulations for the H_2SO_4/H_2O cycle. On the other hand, the $CaCl_2/CH_3OH$ cycle does not show such interactions, and it is possible to estimate performance over a full year by assuming constant coefficients of performance and constant collector efficiency. Results extrapolated in this way, using daily averages, are shown in Figs. 1 and 2. The performance of the H_2SO_4/H_2O cycle should be similar, with the collector area for a given level of performance, ca. 10% smaller.

Neither figure includes domestic hot water in the heating load. However, if the collector is sized to meet >90% of the cooling load, we estimate that at least 70% of the DHW load will also be supplied. With the high temperature capability of an evacuated tube collector, it is obviously possible to supply nearly 100% of the DHW load, using the chemical heat pump for additional thermal storage. However, it appears economically more attractive to maintain a lower DHW solar fraction, and use condenser and absorber waste heat in summer as the sole source of DHW preheat. Of course, in spring and fall, collector heat can be supplied directly to the DHW preheater to guarantee a high solar fraction. In winter, the need for DHW preheat competes with the need for space heat, hence it is most attractive to use the absorber and condenser for preheat, saving fuel even in the backup mode.

The effect of window shading (using trees or awnings) on the Washington cooling load is clearly shown in Fig. 1. The collector area required for >90% solar cooling drops from over 40 m^2 to under 25 m^2 when the effective window area is cut by a factor of two. Extra trees are probably cheaper than an additional 15 m^2 of evacuated tube collectors.

Figures 1 and 2 also show the value of a chemical heat pump in reducing fossil fuel consumption for heating. Even without a collector, fuel use is cut by nearly 40% because of the high COP of the heat pump (1.64). Fuel consumption for cooling is not shown, but can be estimated using the COP of the chemical heat pump (0.65 times the boiler efficiency, or roughly 0.5), the efficiency of a conventional air conditioner (ca. 2.5), and the efficiency of fossil fuel electrical generation (ca. 0.4). It is readily shown that below a solar fraction of 0.5, a chemical

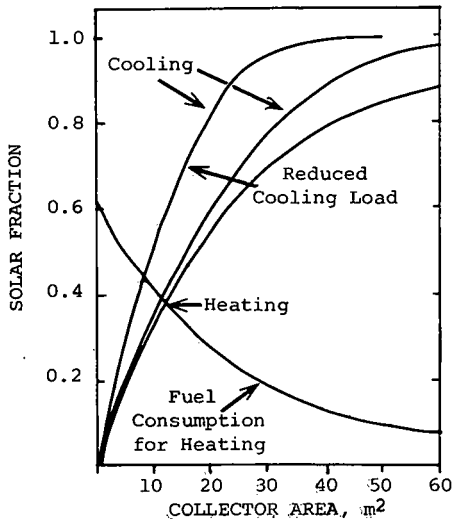


Fig. 1. Extrapolated annual performance of the $CaCl_2/CH_3OH$ chemical heat pump in Washington, D.C. The two cooling curves reflect the effect of extra window shading: the upper curve is for an annual cooling load of 9.6×10^6 kJ, while the annual load for the lower curve is 15.2×10^6 kJ. Fuel consumption is shown as a fraction of the annual use using a conventional boiler or furnace.

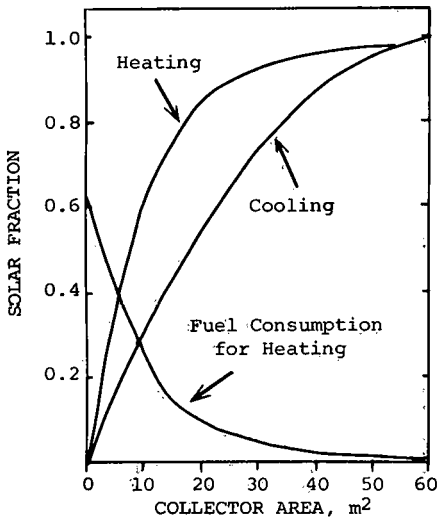


Fig. 2. Extrapolated annual performance of the $CaCl_2/CH_3OH$ chemical heat pump in Ft. Worth, Texas.

heat pump will consume more primary fuel for cooling than an electrical system. It is for this reason that we recommend sizing the collectors and storage so that a solar fraction >90% can be achieved: with 10% backup, primary fuel consumption would be reduced by 80%.

The high solar fractions achieved with relatively small collector areas are a unique feature of chemical heat pumps. Other systems can do as well in the cooling mode, but do not have the ability to pump heat in winter or provide DHW preheat from the absorber and condenser. For example, a $LiBr/H_2O$ chiller with 1000 gallons of insulated hot water storage has cooling performance curves quite similar to those shown in Figs. 1 and 2 for the $CaCl_2/CH_3OH$ system. (The collector area is 10-15% smaller due to higher collector efficiency and COP, although this assumes an

extremely well insulated storage tank operating in the 80-100°C range.) Figs. 3 and 4 illustrate the expected year-round performance of a LiBr/H_2O system with hot water storage. (Once again, domestic hot water is not included, but would be expected to be around 50% solar, depending on collector sizing.) In Washington, a 20-30 m^2 collector could be used to meet >90% of the cooling load. However, such a system would only cut about half the winter fuel consumption, compared to an 80% reduction using a chemical heat pump. In Ft. Worth, on the other hand, a 35 m^2 collector will allow >90% solar cooling and 85% solar heating. Thus, in climates where the cooling load predominates, the only technical advantages of chemical heat pumps may be their ability to supply "free" domestic hot water in summer, and their ability to reject waste heat without a cooling tower or other "wet" system. Ultimately, the comparison must be made on economic grounds, and must include a variety of cost-performance trade-offs, particularly the cost of the highly insulated hot water storage used for the LiBr/H_2O system (if storage is used at all), and the cost of evacuated tube collectors relative to high-performance flat-plate collectors that could be used with the LiBr/H_2O cycle, but not with chemical heat pumps.

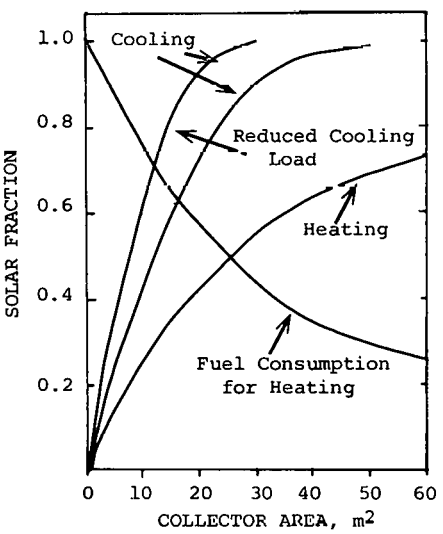


Fig. 3. Extrapolated annual performance of a solar system using a LiBr/H_2O chiller (COP = 0.75) and 1000 gallons of hot water storage for Washington, D.C.

CONCLUSIONS

TRNSYS simulations of chemical heat pumps indicate that this technology shows great promise for achieving high solar heating and cooling fractions, and in reducing fossil fuel consumption, using relatively small areas of high-performance collectors. Technical promise appears greatest in intermediate U.S. climates, where the annual heating load exceeds the annual cooling load, and in desert climates, where cooling tower water may be unavailable.

REFERENCES

1. P. O'D. Offenhartz, "Chemical Methods of Storing Solar Energy," Joint Conf. Am. Can. Sections of ISES, 8, 48, Winnipeg (1976).
2. W. M. Raldow and W. E. Wentworth, "Chemical Heat Pumps - A Basic Thermodynamic Analysis," Solar Energy, 23, 75 (1979).
3. W. E. Wentworth, D. W. Johnson and W. M. Raldow, "Chemical Heat Pumps Using a Slurry of Metal Salt Ammoniates in an Inert Solvent," Proc. ISES Conf., Vol. 1, p. 122, Atlanta, May, 1979.
4. C.C. Hiller and E. C. Clark, Sandia Laboratories Report No. SAND78-8824, July, 1979; C. C. Hiller and E. C. Clark, Development and Testing of the Sulfuric Acid-Water Chemical Heat Pump/Chemical Energy Storage System, Proc. 14th IECEC, Vol. 1, p. 510, Boston, Aug., 1979; C. C. Hiller and E. C. Clark, Development of the Sulfuric Acid-Water Chemical Heat Pump/Chemical Energy Storage System for Solar Heating and Cooling, Proc. ISES Conf., Vol. 1, p. 149, Atlanta, May, 1979.
5. F. A. Jaeger, Martin Marietta Corp., Denver, CO, private communication.
6. P. O'D. Offenhartz et al., J. Solar Energy Engrg. (ASME), in press; P. O'D. Offenhartz and F. C. Brown, Methanol Based Heat Pumps for Storage of Solar Energy, Proc. 14th IECEC, Vol. 1, p. 507, Boston, August, 1979.
7. S. A. Klein et al., "TRNSYS - A Transient Simulation Program," University of Wisconsin, Madison (Version 10.1).
8. C. LeBeouf, "Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses," Solar Energy Research Institute Draft Report, September 1979.
9. P. O'D. Offenhartz and J. M. Marston, "Analysis of Advanced Thermal Energy Storage Subsystems," Solar Heating and Cooling Research & Development Branch Contractor's Meeting, DOE, September, 1978 (CONF-780983), p. 196.
10. P. O'D. Offenhartz, J. M. Marston and J. I. Watts, "Analysis of Advanced Thermal Storage Subsystems for Solar Heating and Cooling," Final Report on Contract EG-77-C-02-4483.
11. P. O'D. Offenhartz, "TRNSYS Simulation of Chemical Heat Pump for Solar Heating, Cooling, and Storage," Proc. Second Symp. on Solar Simulation and Economic Analysis, San Diego, January, 1980.

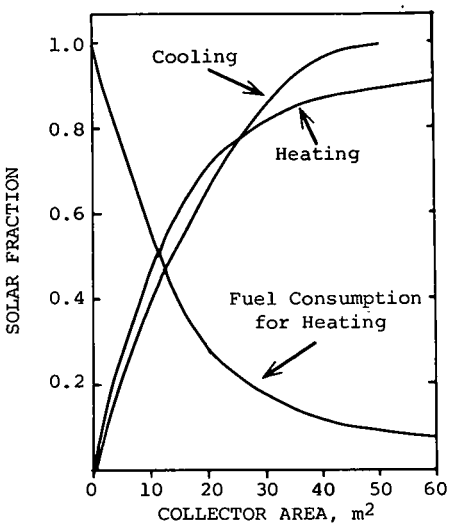


Fig. 4. Extrapolated annual performance of a LiBr/H_2O chiller with 1000 gallons of hot water storage for Ft. Worth, Texas.

SOLAR COOLING THERMAL ENERGY STORAGE STUDY

HITTMAN ASSOCIATES, INC.

DE-AC-03-79CS-30202

DR. H. M. CURRAN

1 FEBRUARY 1980 TO 31 JULY 1980

OBJECTIVE

The project objective is to identify the thermal storage requirements for solar cooling systems using absorption, Rankine and desiccant technologies, and to identify research and development needs.

BACKGROUND

This task is being performed for the Solar Thermal Storage Program at Argonne National Laboratory.

SUMMARY

The statement of work includes definition of the operating characteristics of DOE-funded solar cooling equipment, solar collectors suitable for space cooling applications, and thermal storage subsystems; identification of thermal storage needs and basic design requirements; and identification of needed research and development for solar cooling thermal energy storage.

TECHNICAL ACCOMPLISHMENTS

Work was started in February 1980 and preliminary results have been obtained. A related paper was prepared for presentation at the Seventh Energy Technology Conference.

FUTURE ACTIVITIES

Completion of this task is scheduled for July 1980.

PUBLICATIONS

John DeVries, "Thermal Energy Storage Design Criteria," Proceedings of Seventh Energy Technology Conference, Washington, DC, March 1980.

DEVELOPMENT OF AN IMPROVED WATER TANK FOR THERMAL STORAGE

INDEPENDENT LIVING, INC.

EM-78-C-02-4699

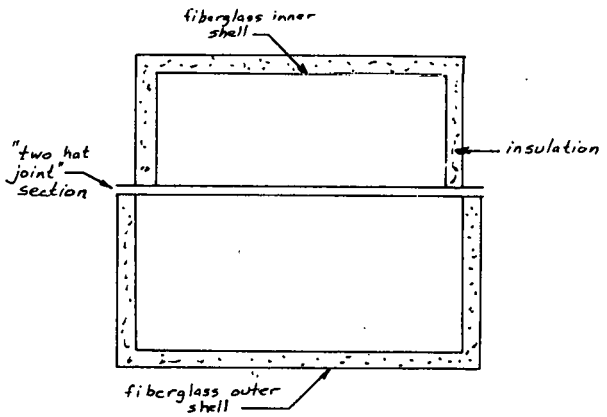
William T. Hudson and William M. Jones

JULY 15, 1978 - JULY, 1980

SUMMARY

Project efforts were concerned with demonstration of the basic concept and to determine above normal stress locations of the unique tank design. Material considerations were determined for all components of the tank's sandwich structure and a test program was developed to aid in selecting proper materials for the inner shell while also indicating performance expectations. A fiberglass tank mold has been fabricated according to design, with the prototype fiberglass tank to be fabricated in mid-March.

MODULAR THERMAL STORAGE TANK FIGURE 1



OBJECTIVE

To design and develop a modular, transportable, pre-insulated, efficient, easily installed, long life thermal storage tank which can be plant manufactured and shipped to distant locations. The objective is to identify, analyze, and implement materials which can be used for such a tank, to fabricate and test the tank and provide a volume product for the solar market.

CONCEPT

The concept is to use two fiberglass shells with foam insulation between them to create a sandwich effect. The tank is designed with an upper and lower hat, see Figure 1, so that one hat can be easily handled by two or three persons. The two hat concept will allow the total volume to be reduced by placing the top hat inside the bottom hat during shipping. Also, the two hat concept allows for any one hat to be retrofitted through the rough opening of a three foot entrance way. The idea is to develop a solar thermal storage tank which is capable of storing 180°F to 200°F water with an expected life of 20 to 30 years.

TECHNICAL ACCOMPLISHMENTS

Demonstration of the basic concept was achieved through the testing and analysis of a prototype steel tank, which as been at operational status since December, 1978. Analysis was completed on the type and design of the clamping devises to be used for sealing the "two hat joint" section of the fiberglass tank, see Figure 1. A spring loaded "C" shaped clamp was the result of this investigation. The concept was to obtain a clamping devise that distributes a constant force on the fiberglass flanges during expansion and contraction of the flanges during thermal cycles. The "two hat joint" section of the prototype steel tank was sealed with relative ease reinforcing an important aspect of the overall tank design. The "two hat joint" section seal was broken and resealed successfully. Mechanical and thermal tests and analyses were conducted on the prototype steel tank by means of a simulated solar energy system. These tests indicated above normal stress locations around the tank and in turn the need for additional fiberglass reinforcement at these locations.

The determination of the entire wall structure to be utilized for the fiberglass tank is completed. Extensive investigations determined that the inner shell of the tank should be hand lay up fiberglass, followed by three or four inches of urethane, and followed by an outer shell of sprayed-on fiberglass. Various independent studies were conducted concerning the type of insulation, the application of the urethane foam, the proper thickness alternatives for the insulation, and material considerations for the outer protective shell.

Of major importance was the determination of the proper materials to be utilized as the inner shell, see Figure 1, of the storage vessel. Numerous material considerations were investigated. The efforts in this area resulted in an inner shell wall specifically designed to withstand a continuous wet soak at elevated water temperatures of 180°F to 200°F through the utilization of an integrated fiberglass wall structure. The inner shell wall structure is composed of three layers of resin and glass, each with different resin to glass percentages while utilizing the same resin in each layer. The water side layer is resin rich to serve as a water barrier while the following layers have increasing glass percentages to serve as the structural member of the wall structure. The use of the same resin throughout the inner shell allows for polymer cross linking from layer to layer and results in a more stable wall structure. Mechanical design analyses are completed and the proper laminated wall structure is determined with a wall thickness of approximately .150".

The selection of the proper thermoset resin system to be utilized in the inner shell of the fiberglass tank is completed. The selection process included the project's testing program, case histories of material performance in similar environments, recommendations from various resin manufacturers and additional information supplied by tank fabricators. A group of twelve resin systems were tested for water absorption properties, permeation rates, and resin integrity when exposed to a 200°F water environment. These tests resulted in three resin systems believed to be suitable for the project's application. One of the three, Derakane 470, a epoxy novalac based vinyl ester resin, was deemed most suitable for maintaining resin integrity and for performing as the water barrier for the tank's inner shell as indicated by the test program and recommendations from experts.

The development of a test program to be utilized in the material selection process and also as an indication to a longevity of service for the fiberglass tank is developed and presently in operational status. The test for determination of water absorption characteristics, permeation rates, and resin integrity is completed, as described previously. Extensive investigations into the proper test to be utilized for indicating a longevity of service for the fiberglass tank resulted in the selection of a tensile creep and creep rupture test. A testing apparatus was fabricated and test coupons obtained from resin manufacturers. Presently tensile creep and creep rupture tests are being conducted with positive results. The objectives of the test program are as follows: 1) to indicate a longevity of service for the fiberglass tank by subjecting coupons to elevated tensile stresses at 200°F water during relatively short term periods and extrapolating this data to the expected operational stresses expected for the fiberglass tank for long periods of time, and 2) to determine whether a tensile creep stress equilibrium level occurs with the resin-glass system. If this does occur, a long term performance level can be estimated. The final results of the testing program will be found in the project's final report.

FUTURE ACTIVITIES

Contract activities. Future contract tasks include the immediate fabrication of the prototype fiberglass tank, the mechanical and physical testing of the tank while stationed in a simulated solar energy system environment, the continuation and completion of the test program, and an extensive study into marketing and production strategies for the solar thermal storage tank.

Post-contract activities. ILI, Inc. plans to offer the tank to the solar industry market following contract ending date.

REPORTS

Progress status reports have been written for contract activities for envery month since the project start. A final report is to be made available on the project ending date.

THERMAL STORAGE FOR SOLAR COOLING USING PAIRED AMMONIATED SALT REACTIONS

MARTIN MARIETTA CORPORATION

DE-AC02-78CS34700

F. A. JAEGER

JULY 1978 - SEPTEMBER 1980

OBJECTIVE

The objectives of this program are: Demonstrate concept feasibility using subscale system testing; measure compatibility of appropriate construction materials with candidate ammoniates; select the optimum combination of ammoniates for a residential heating and cooling system; investigate system practicality by conceptual design and cost estimates of a residential unit; demonstrate system performance by testing a full scale unit.

CONCEPT

The system (Figure 1) is similar in operation to an absorption refrigerator except this unit contains sufficient absorber to be used for thermal storage and operates in the batch mode rather than continuously. The unit consists of two high-temperature reactors, ammonia condenser, ammonia storage tank, expansion valve, evaporator, and heat exchangers.

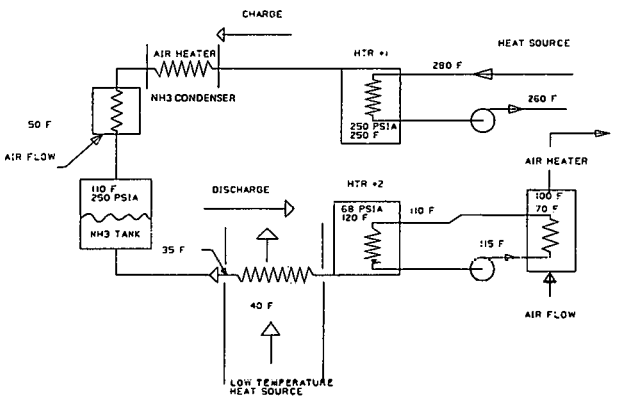


Figure 1 Flow Diagram $NH_3/NH_4NO_3 \cdot 3NH_3$ Heating Conditions

System operation is detailed in Figure 1. The upper half on the figure illustrates the charge mode; the lower shows the discharge mode. To charge the system in the heating mode, heat is supplied to both high temperature reactors simultaneously by a source at 280°F. The ammoniate dissociates endothermically giving off ammonia gas. The sensible heat and heat of condensation can be used to heat the building or can be discarded to the atmosphere depending on the demand. Maximum condenser temperature and pressure are as shown. In the discharge mode liquid ammonia flows through an expansion valve where it is vaporized and absorbs heat from a low temperature source at 40°F. It then flows to the high temperature reactor where it reacts giving off heat at 120°F. A fluid loop is then used to transfer the heat to a forced air heat exchanger and into the building.

In the cooling mode, heat is supplied to charge one reactor at a time so the other can be used to absorb ammonia that has been used for cooling. Ammonia is condensed using a condenser with a maximum air temperature of 100°F. To cool the building, liquid ammonia flows through an expansion valve to the evaporator and cools the air. It is absorbed in the other high temperature reactor at 80 psi and reacts to produce a maximum temperature of 130°F. The excess heat is rejected to the atmosphere.

SUMMARY

Subscale tests using solid ammoniates were conducted in a 5000-Btu-capacity system. These tests showed that the overall heat transfer coefficient was low (1 Btu/hr-ft^2-°F) and that forced ammonia circulation had little effect on the heat transfer rate. Similar tests using ammonium chloride, which is liquid when ammoniated, resulted in heat transfer coefficients of 50 Btu/hr-ft^2-°F. Physical property tests showed that the density of the liquid was three times that of the bulk density of the solid and that the reaction rate was about one order of magnitude greater for the liquid. Because of these properties, emphasis was shifted to the investigation of liquid ammoniates. Several compounds which liquify when ammoniated were identified. The most promising were tested to determine physical properties and performance in the subscale system. Compatibility tests were performed to determine the suitability of appropriate materials with the ammoniates.

A tradeoff study was made comparing the energy storage characteristics and the suitability for heating and cooling of several combinations of solid and liquid ammoniates. A liquid ammoniate coupled with pure ammonia was chosen as the most cost effective. An engineering test system with a storage capacity of 600,000 Btu was designed for this combination and preliminary layouts and cost estimates for a residential unit were made.

TECHNICAL ACCOMPLISHMENTS

- Subscale reactors with a 5000-Btu storage capacity and a 1000 Btu/hr heat transfer rate were used to test calcium chloride, manganese chloride, and ammonium chloride ammoniates. A total of 13 single reactor and three coupled reactor tests were performed and are described in detail in Ref. 1. Test results show that design heat transfer coefficients of 1 Btu/hr-ft^2-°F must be used with solid ammoniate systems and that coefficients of 50 Btu/hr-ft^2-°F can be used

for liquids. No significant improvement in solid system heat transfer was obtained when forced ammonia circulation was used.

- Several compounds that liquify when ammoniated at room temperature were identified including ammoniates of NH_4Cl, NH_4NO_3, $LiNO_3$, NH_4SCN, NH_4Br and NH_4I. Comparison of the cost of the chemical and the suitability of their equilibrium characteristics for space heating and cooling application resulted in the selection of NH_4Cl, NH_4NO_3 and NH_4SCN for further study. The equilibrium characteristics (pressure as a function of temperature and ammonia concentration) were measured for $NH_4Cl \cdot 3NH_3$, NH_4NO_3, $NH_4NO_3 \cdot 3NH_3$, $NH_4SCN \cdot 6NH_3$ (Reference 2 and 3).

- Other physical properties measured were density, freezing point, and viscosity. Heat of reaction and entropy changes were determined from equilibrium data. These properties are summarized in Table I.

Table I - Physical Properties

Ammoniate	Density, lb/ft^3	ΔH, Btu/lb NH_3	Freezing Point, °F	Viscosity, Centipoise
$NH_4Cl \cdot 3NH$	58.6	700	40	5 (Ref. 4)
$NH_4NO_3 \cdot 3NH_3$	62.4	689	-8	*
$NH_4SCN \cdot 2NH_3$	59.3	757	-40	*
$NH_4SCN \cdot 6NH_3$	54.6	629		*

* Not measured, viscosities appear to be the same as $NH_4Cl \cdot 3NH_3$

The ammoniates are clear, colorless liquids having the same appearance as water. Solubility of NH_4Cl in $NH_4Cl \cdot 3NH_3$ is small. That is, solid NH_4Cl is present through the full ammoniation range. NH_4SCN is completely soluble when one mole of ammonia per mole of NH_4SCN has been reacted, NH_4NO_3 is completely liquid when 1.2 mole of ammonia is absorbed.

- Corrosion tests of the ammoniates in contact with A-36 carbon steel, 304L stainless steel, and 5052 aluminum have been run. The results after 60 days exposure at the expected operating temperature are summarized in Table II.

Table II Corrosion Test Results

	304L Stainless Steel	Carbon Steel	Aluminum
$NH_4CL \cdot 3NH_3$	1	1	3
$NH_4SCN \cdot 2NH_3$	1	1	3
$NH_4NO_3 \cdot 3NH_3$	1	3	1

1-good, 3-poor

- Short-term corrosion tests (20 days) have been performed with A-36 carbon steel and $NH_4NO_3 \cdot 3NH_3$ in an attempt to develop an inhibitor or coating that allows the use of this low-cost material. Some success with a silicon fluid coating system has been realized. However, further long-term tests are necessary.

- Subscale system tests were performed on the ammonium nitrate and ammonium thiocyanate ammoniates (Ref. 2 and 5). Heat transfer coefficients were measured at 40 to 60 Btu/hr-ft^2-°F. Concentration limits for each of the ammoniates were determined.

- Various combinations of the liquid ammoniates were compared for use in a residential heating and cooling system having a heat storage capacity of 500,000 Btu and a maximum heating rate of 100,000 Btu/hr. The selected system uses a combination of $NH_4NO_3 \cdot 3NH_3$ and liquid ammonia. A conceptual design (Fig. 2) of the system was prepared and an equipment cost survey resulted in a total system cost estimate of about $4,000.

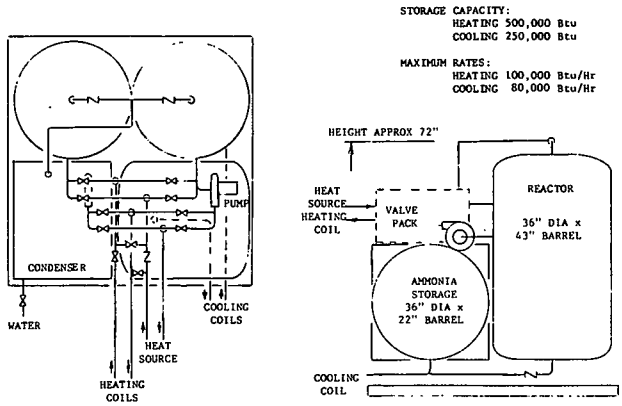


Figure 2 Residential System Layout

- Design of an engineering test unit capable of storing 600,000 Btu has been completed. Fabrication of the unit is in progress.

FUTURE EFFORT

Contractual Full-scale system test will be performed on the engineering test unit to verify system performance with ammonium nitrate ammoniate.

Postcontract Activities Further studies are proposed to investigate and develop alternate configurations of the ammonium nitrate system such as a system that would be capable of continuous operation rather than the present batch mode. Investigation and development of an absorption air conditioning system that would operate using a low temperature (150°F) heat source while maintaining a high C.O.P. (0.7) is also under consideration.

REFERENCES

1. Jaeger, F. A., W. R. Haas, S. Prince, Thermal Storage for Solar Cooling Using Paired Ammoniated Salts, Interim Report for the period July 1978-June 1979, July 1979, COO/4700-1.

2. W. R. Haas, F. A. Jaeger, T. J. Giordano, Ammoniated Salt Heat Pump, 2nd International Conference on Alternative Energy Sources, Miami, Florida.

3. Furrer, M. and Aegerter, A., Thermochemistry and Kinetics of the Reaction between Ammoniumchloride and Gaseous Ammonia October 1978, Swiss Institute for Reactor Research Wurenlinger, Switzerland, TM-HL-437.

4. Nissen, D. A., The Physical Properties of $NH_4Cl \cdot 3NH_3$, August 1979, Sandia Report 79-8049.

5. Jaeger, F. A. and Hall, C. A., Ammoniated Salt Heat Pump/Thermal Storage System, International Seminar on Thermochemical Energy Storage, Stockholm, Sweden, January 1980.

THERMAL ENERGY STORAGE CODE ANALYSIS

NATIONAL BUREAU OF STANDARDS

EA-77-A-01-6010

JOSEPH GREENBERG

JUNE 1979 - SEPTEMBER 1980

OBJECTIVES

This project is designed to categorize new and innovative thermal storage devices into a building code framework and to analyze these types of devices to identify potential code related problems that would prevent their commercialization, usage, or acceptance by local building code officials.

CONCEPT OR BACKGROUND

Thermal energy storage systems may possess characteristics which are inherently hazardous to health and safety unless proper precautions are exercised. Local building officials, charged with the responsibility for overseeing and enforcing the health and safety provisions of the various building, fire, electrical, plumbing and other codes, must be satisfied that solar components and systems proposed for installation comply with the accepted guidelines established for their jurisdictions. In order to assure a viable development of promising thermal energy storage systems, these health and safety considerations must be reviewed early in the hardware development phase to provide direction and guidance to equipment manufacturers regarding the ultimate acceptance of their equipment by code enforcing officials. It would seem imprudent to develop thermally efficient and cost effective hardware only to have the equipment untimately prohibited for installation because of local code restrictions or the unfavorable reaction by unknowledgeable code enforcement officials.

SUMMARY

Based on a literature search of phase change thermal storage concepts and systems, a classification scheme has been developed that orients these various systems into a hardware framework. This framework treats these thermal storage devices as elements of a building system to facilitate the code analysis that follows and places them in a contex that is understandable to building code officials. The classification scheme is tested by assigning the various phase change concepts under development to one of the generic classifications established. Under this framework, the recognized model codes are then reviewed and analyzed to identify restrictive code provisions that would preclude the acceptance of any of these devices. Where appropriate, system configurations and trade-offs will be identified, as well as recommended acceptance mechanisms that will allow integration of these thermal storage devices into the established building inspection process. Those thermo-chemical devices in a mature state of development will also be analyzed.

TECHNICAL ACCOMPLISHMENTS

o A classification scheme for analyzing phase change thermal storage devices in a framework compatable with building codes has been developed.

o Each classification has been defined in detail and a hardware schematic prepared. The breakdown in summarized as follows:

- o Air Systems
  - o Collector/Storage
    - o Free Standing/Building Integrated
    - o Individual "Window" Units
    - o Connected to Building Ductwork
  - o Storage Only
    - o Connected to Building Ductwork
- o Liquid Systems
  - o Storage Only
    - o Separated Elements
    - o Immiscible Fluid (Liquid to Liquid)
    - o Direct Contact Solid

o Existing and proposed phase change thermal storage devices have been fully described and categorized.

o Analysis is continuing to identify code provisions that would prevent the installation of existing and proposed devices.

FUTURE ACTIVITIES

o Complete code analysis and prepare definitive guidelines and recommendations.

o Develop classification for thermo-chemical storage devices and analyze code provisions.

o Continue development of final report.

PUBLICATIONS

An NBS report will be published describing approach, methodology, findings, and recommendations.

THE MONITORING OF THERMAL STRATIFICATION OF THE STORAGE TANK OF THE MABEL LEE HALL SOLAR HOT WATER SYSTEM

UNIVERSITY OF NEBRASKA

DE-AC02-79CS30247

EDWARD E. ANDERSON

Begin 9-15-79 End 9-30-80

OBJECTIVE

The principal objective of this project is to obtain an experimental data base for stratification in liquid storage tanks. This data base should be extensive enough to be used for verification of free convection stratified storage computer codes under a variety of operating modes. For verification purposes, the data base must include measurements of the inputs and outputs to the storage medium as well as measurements throughout the storage volume. All measurements need to be taken on a regular time cycle throughout a test. A wide variety of operating modes should also be included in order that the data base may be as extensive as possible.

CONCEPT AND BACKGROUND

The Mabel Lee Hall solar facility constructed under a grant from the State of Nebraska preheats the hot water required by the women's physical education building on the University of Nebraska-Lincoln campus. Originally this system was used to compare the performance of liquid and air collectors. Two collector systems, each having an effective collection area of 1750 square feet, are connected to a common liquid storage tank. The liquid collectors use "Rol-Bond" panels with black paint and two glazings of "Filon" and "Tedlar" film. "Sun-Temp" oil serves as the heat transfer medium. The air collectors also use the same glazing and absorbing paint. These collectors are based on the volume collector principle. The two systems may be operated singly or in parallel.

Storage consists of 32,000 gallons of water in a 32' by 16' buried storage tank which is 9' deep. This tank is sealed with a PVC thin film preseamed liner and insulated with expanded polystyrene. Internal heat exchangers are used to transfer heat from the liquid collectors to storage and from storage to the hot-water service. The latter heat exchanger serves to preheat the hot water. An external air-to-liquid heat exchanger located in the air collectors is used with the air system.

Storage instrumentation consists of flow and temperature change for the three storage streams and thirty temperatures throughout the storage medium. Additional thermocouples are being installed in the storage medium. All instruments are read and recorded by an Instrulab 2000 Dataloger at intervals of 2-1000 minutes. In addition, the flowrate-temperature change product may be integrated over a one-hour period and recorded.

Heating of the storage medium may be accomplished simultaneously or separately by two different means. The liquid collectors employ an internal heat exchanger while the air collectors circulate storage water through an external heat exchanger. It is then possible to operate this storage facility in several different modes. Under this program, complete data sets will be obtained for the fourteen different operating modes presented in Table I. Each data set will consist of two days of data for the three streams and thirty-five thermocouples. This will provide a variety of conditions for the verification of storage computer codes.

SUMMARY

Weather conditions have prevented the initiation of actual testing. At the present, system modifications required for the testing program have been designed and installed. Also, most of the instrumentation has been installed and calibrated. In-situ calibration has proved to be difficult and special techniques were developed.

FUTURE ACTIVITIES

When the possibility of freezing conditions has passed (hopefully by April 1), the storage tank will be drained so that the thermocouples may be installed and calibrated. The storage tank can then be refilled and the testing program started. Approximately three months will be required for testing. Complete data sets should then be available in August.

TABLE I TESTING SUMMARY

COOLANT MODE	NO COLLECTOR FLOW MODE	LIQUID COLLECTOR MODE		AIR COLLECTOR MODE	
		LOW FLOWRATE	HIGH FLOWRATE	LOW FLOWRATE	HIGH FLOWRATE
LOW FLOWRATE	X	X	X	X	X
HIGH FLOWRATE	X	X	X	X	X
NO FLOW		X	X	X	X

MEMBRANE-LINED FOUNDATIONS FOR LIQUID THERMAL STORAGE

UNIVERSITY OF NEBRASKA

CONTRACT #EM-78-S-02-4701

RICHARD C. BOURNE

MAY 1, 1978-DEC. 31, 1979

OBJECTIVE

The overall project goal was to evaluate the potential for using membrane-lined foundations as economical and durable thermal storage subsystems for solar heating installations. Specific objectives were:

1) to survey existing membrane-lined storage projects

2) to evaluate alternative membrane liner materials

3) to develop preferred designs for structural support of membrane storage liners

4) to develop and evaluate improved designs for heat transfer to and from membrane-lined storage containers, including:

   a) storage inlet/outlet designs
   b) domestic water preheating
   c) direct air heating from storage
   d) auxiliary heating of storage

5) to evaluate concepts for stratification enhancement in membrane-lined storage containers, including baffles, multiple tanks, and tank configurational variations.

BACKGROUND

Steel tanks are currently the most common storage containers for solar heated water. The membrane-lined storage alternative being investigated and further developed in this project has the following potential advantages compared to steel tanks:

Reduced Corrosion Problems Without a steel storage tank, no dis-similar metals need be used in liquid-based solar heating systems.

More Convenient Construction Scheduling The storage tank components easily fit through doorways, and may be installed at any time in the construction process, with excellent applicability to "retrofit" projects.

Improved Heat Transfer Configurations Easy access to the tank interior permits location of free-convection heat exchangers within the container, eliminating pumps, external heat exchangers, and some parasitic power consumption. Some membrane-lined designs facilitate forced air heating from the storage surface area.

Cost Reduction For residential solar space heating systems, membrane-lined storage containers may generally be completed for less than one-third the cost of steel tanks. The savings result partially from integration of the storage container into the building foundation. For example, the storage structure may be constructed in a basement corner, where only two new walls need be added.

A paper presented at the 1978 Solar R & D Contractors' Meeting (1) provided background on several existing membrane-lined storage installations, and discussed completed and future project activities as of fall, 1978. The project was designed to assess the current state of development of membrane-lined storage, develop optimized enclosure designs, and develop designs which improve storage heat transfer and temperature stratification. These objectives were pursued via the following three project activity lines:

Activity 1 included a survey of completed membrane-lined storage projects, a review of alternative membrane materials, and identification of the most cost-effective membrane enclosures for a range of building foundation types, for storage volumes of 250, 1500, and 5000 gallons.

Activity 2 involved development work aimed at improving heat transfer to and from storage, including:

2a) Techniques for direct heat transfer from the storage surface to forced air, with laboratory testing of several promising design concepts and cost-effectiveness studies based on test results.

2b) Techniques and details for water inlet to and outlet from membrane-lined storage containers.

2c) Comparison of alternative free-convection heat exchangers for preheating of domestic water, with laboratory testing of the preferred designs and cost-effectiveness studies based on the test results.

2d) Concepts for input of auxiliary heat to storage, for application where utilities offer rate incentives for off-peak energy consumption.

Activity 3 involved designs which promote storage temperature stratification to improve overall system performance, including multiple and baffled tank designs, development of cost models, and small-scale testing of promising designs.

Fig. 1 shows a typical membrane-lined storage container of rectangular configuration, which has served as a basis for comparison of improved designs developed in this project. The container is constructed in a basement corner by the addition of two mid-height masonry walls. Rigid foam boards insulate the container floor and walls. A 20 mil PVC liner provides water containment, and an 8 mil polyethylene top membrane is battened continuously to the liner around the top edge. Blanket insulation rests on the top membrane. A serpentine copper heat exchanger immersed near the top of the container serves as a preheater for domestic water. Inlet/outlet pipes serving collector and space heating circulation loops are not shown.

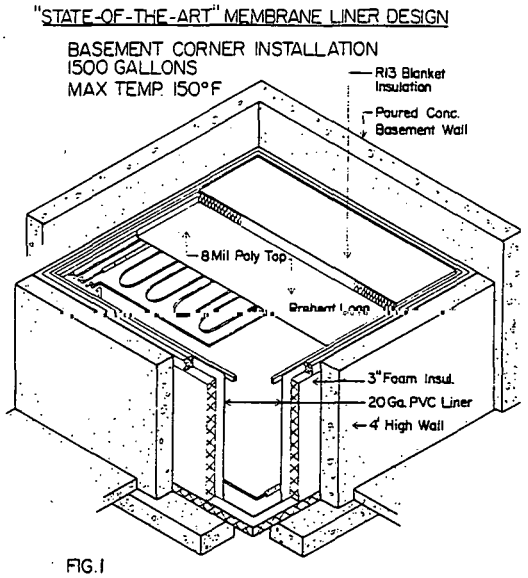


FIG.1
ISOMETRIC SECTION

Numerous membrane-lined solar storage installations were installed prior to 1978, but no systematic evaluation of these installations and potential design improvements had been made.

SUMMARY

Membrane-lined liquid thermal storage systems have been shown to have significant advantages over conventional tanks in terms of both cost and versatility. The following specific conclusions may be drawn from the project results:

1) A significant number of membrane solar storage systems are completed and operating successfully.

2) EPDM appears to be the longest life membrane material under expected temperature conditions, but PVC and cross-laminated PE are promising lower cost materials.

3) Site-built rectangular and kit-type cylindrical enclosures appear to provide the most cost-effective membrane support structures.

4) Both "jacketed cylinder" and floating "finned plate" direct air heating design concepts appear cost-effective after small-scale laboratory testing.

5) Domestic water preheating is most economically provided using a commercially available integrally-finned copper tube.

6) Auxiliary heating of storage appears to promise system simplification in addition to off-peak energy utilization.

7) Promising concepts exist for installation of low cost baffles in both rectangular and cylindrical membrane-lined tanks. Multiple tanks provide a slightly more expensive alternate "stratification-enhancing" concept; additional testing is required to identify the more cost-effective approach.

TECHNICAL ACCOMPLISHMENTS

- A survey of completed membrane-lined storage installations was conducted. Of the 61 projects identified by February 1979, 85% were residential, and 90% provided both space and domestic water heating. 35 of these projects use a cylindrical storage kit produced by Acorn Structures of Concord, Mass.. 77% of the projects used PVC as the lining material; Hypalon was the second most frequently used membrane. Problems were reported on 13% of the installations, about the same problem rate as reported nationally for conventional storage systems (2).

- Candidate membrane materials were identified and compared for a generated set of desirable performance characteristics. Three materials were selected for continued evaluation, including performance testing. EPDM rubber is expected to be the longest life membrane material under high temperature conditions, but PVC and laminated high density polyethylene are promising lower cost membrane materials.

- Alternate structural enclosure systems were compared for basement, crawl space, and slab-on-grade foundation types. Rectangular, cylindrical, hopper, and quadrant configurations were compared for each application. From the studies, site built rectangular and kit-type cylindrical enclosures were identified as the preferred membrane support structures. For the baseline 1500 gallon storage unit, project cost versus depth was plotted for each configuration and foundation type (Figs. 2 & 3). For the preferred enclosure types, cost versus volume was also graphed for storage sizes ranging from 500 to 10,000 gallons (Fig. 4).

FIG. 2 ENCLOSURE ALTERNATIVES - BASEMENT COST vs. DEPTH - 1500 GAL. CONTAINER.

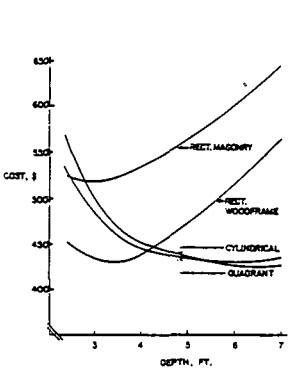


FIG. 3 ENCLOSURE ALTERNATIVES - SLAB ON GRADE COST vs. DEPTH - 1500 GAL. CONTAINER.

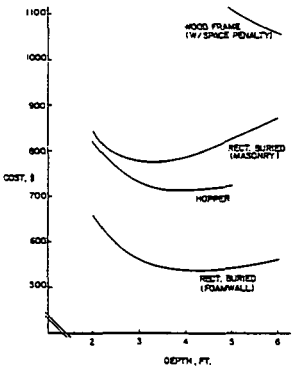
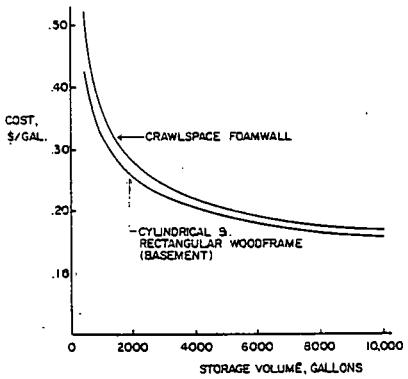


FIG. 4 ENCLOSURE COST vs. VOLUME



- Potential "direct air heating" techniques were evaluated for heat transfer from the storage surface to air forced through a surrounding "jacket". Preferred techniques were identified for both rectangular and cylindrical storage configurations (Figs. 5 & 6); performance models were developed and test installations were constructed for each of the two concepts. From the test results, the model was used to size systems for performance equal to the conventional fan-coil approach. Cost estimates were prepared for each, and direct air heating was found to promise 40% savings for each concept.

FIG. 5
SECTION VIEW - JACKETED CYLINDER CONCEPT

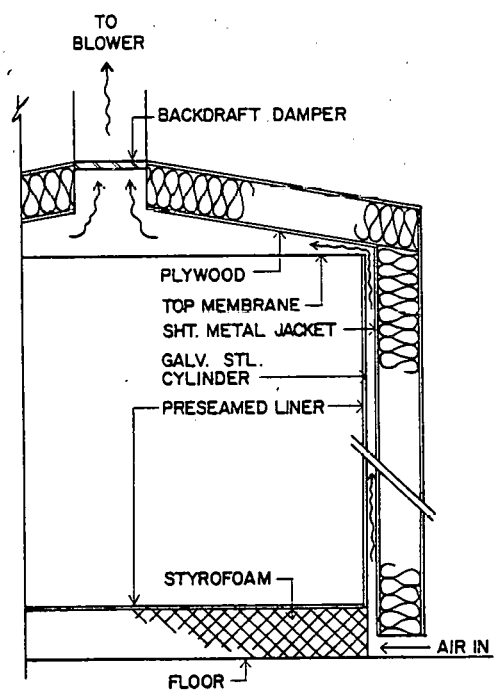
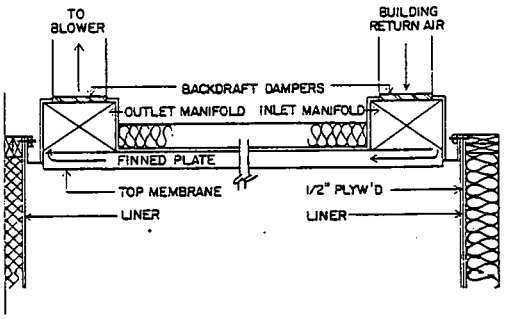
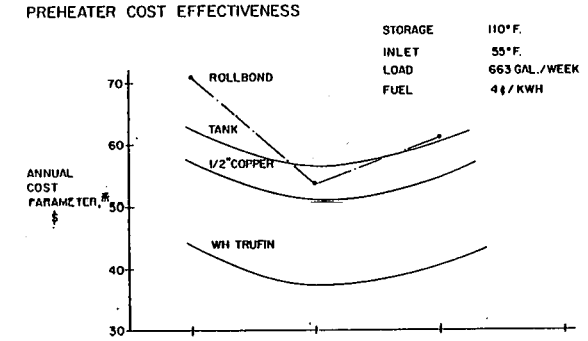


FIG. 6
FINNED PLATE CONCEPT



- Alternate domestic water preheater designs were compared and tested. Of 14 concepts identified for consideration, 3 tankless and one tank-type concept were selected for testing. From test results and cost estimates, optimum size was identified for each alternative (Fig. 7) based on a computerized domestic water demand projection. The demand model included a range of demand durations and time spacings. Of 4 designs tested, the finned copper tube had clearly superior cost-effectiveness.

FIG. 7
PREHEATER COST EFFECTIVENESS



1/2" COPPER, FT. >	100	150	200
ROLLBOND "/PANELS >	1	2	3
WH TRUFIN, FT. >	40	60	80
TANK, GALLONS >	30	50	70

* DOES NOT INCLUDE AMORTIZATION OF CONVENTIONAL WATER HEATER.

- Alternate storage inlet/outlet designs were identified and compared, and preferred designs selected for both the rectangular and cylindrical storage configurations.
- Alternate techniques were considered for auxiliary heating of storage. This technique has potential advantages of off-peak energy consumption and elimination of one auxiliary heating unit. Preferred designs were identified for both electric and combustion-type fuel sources.

- Alternate stratification-enhancing techniques for membrane-lined tanks were compared. Cost models were developed for varying tank configurations, baffled tanks, and multiple tanks. Small scale testing was conducted to evaluate technical feasibility and performance of alternate baffle concepts.

FUTURE ACTIVITIES

Contract Activities. Ongoing contract work is aimed at rapid delivery to the marketplace of the baseline membrane-lined storage designs. For these simple designs, only modest additional development appears necessary for market readiness. The baseline designs are most suited to onsite construction rather than pre-fabrication, and lead time for production systems development will not be necessary prior to widespread use.

The objectives of the continuing project are to complete development of the baseline systems and to begin technology transfer efforts. The baseline storage units are rectangular in shape and designed for integration into the building foundation. Domestic hot water preheaters are included, but baffles to promote thermal stratification are not. Designs for basement and slab-on-grade foundation types will be completed. The designs will not provide direct air heating from the storage surface.

Activity #1 will complete component development of membrane-liner materials and domestic water preheaters necessary for all baseline systems designs. High temperature, wet membrane tests will be completed for the three most promising membrane materials, and laboratory experiments will be conducted with various hot and cold patching techniques.

Activity #2 includes component development and engineering field testing of the foamwall storage unit structure, designed for slab-on-grade construction. In a cooperative venture with a California builder, a foamwall storage unit will be constructed and tested in an actual dwelling unit. The home will remain unoccupied during prototype testing, but will be occupied during the engineering field test phase.

Activity #3 will develop the woodframe basement corner storage unit through the engineering field test stage. System prototype and engineering field tests will again be accomplished with one installation, in a cooperative project with a Lincoln, Nebraska builder.

Activity #4 will identify a preferred market development path, and will begin familiarizing appropriate industry participants with baseline membrane storage designs. Installation manuals will be prepared, and workshops will be designed and conducted to begin training a workforce appropriate for installation and servicing of the baseline membrane-lined water storage units.

Post Contract Activities. In addition to activities designed to transfer the baseline designs to the marketplace, additional work is warranted to develop more advanced membrane-lined storage designs. The following future activities are contemplated to integrate more features into the storage container:

1) Continued development of direct air heating concepts including: a computerized performance model and optimization study; improvements in inlet/outlet manifolds; testing of liner thermal co-efficients; detailed development of blower, damper, and air filter components; and investigation of a double-contact finned plate for dual, stratified tank storage designs.

2) Continued development of stratification enhancing features for membrane-lined storage tanks, including: design development; full scale testing; and cost-effectiveness studies of two preferred alternatives.

3) Continued development of concepts for auxiliary heating of storage, including: sizing studies; design development; and full scale testing.

4) Detailed design of enclosure, internal components, and controls for storage containers which integrate direct air heating, stratification, and containers which integrate auxiliary heating of storage.

5) System testing of complete, full size integrated storage containers for 4 building foundation types, including slab on grade units with and without forced air heat, and 2 basement units with forced air heat.

PUBLICATIONS/REPORTS/REFERENCES

1. Bourne, Richard C., "Membrane-Lined Foundation Systems for Liquid Thermal Storage", Proceedings of 3rd Annual Solar Heating & Cooling Research and Development Branch Contractors' Meeting, Washington, D.C., Sept. 1978.

2. Sawyer, Stephen W., "The Cost, Performance, and Reliability Patterns of Solar Heating Systems: An Assessment of 177 Owners", presented at Solar Heating and Cooling Systems Operational Results Conference, Colorado Springs, November 1978.

3. Bourne, Richard C., "Direct Air Heating from Membrane-Lined Water Storage", Proceedings of Solar Energy Storage Options, San Antonio, March 1979, pp. 417-427.

4. Bourne, Richard C., "Membrane-Lined Thermal Storage Systems", presented at 2nd Miami International Conference on Alternative Energy Sources, Miami Beach, Dec., 1979.

COST EFFECTIVE IMPROVEMENT OF ROCK BEDS USED IN SOLAR AIR HEATING SYSTEMS

SOLARON CORPORATION

CONTRACT NUMBER: PENDING

DENNIS JONES

PERIOD OF CONTRACT: 18 MONTHS

OBJECTIVE

The overall objective of the project is the development of improved vertical and horizontal rock bed heat storage designs which will result in maximum cost effectiveness in solar air heating systems.

BACKGROUND

A variety of designs have been used in the application of rock beds to solar air heating systems. These designs have resulted in a wide range of system performances; from completely satisfactory to marginal. Those rock bed designs that have been very conservative in design and construction have produced wholly satisfactory system performance but have imposed several restraints on system installation. One of the major restraints has been the avoidance of horizontal rock boxes. There have been many otherwise good installation opportunities lost because the owner was unwilling to accept the space lost to a vertical rock bed of conventional design while crawl space areas potentially satisfactory for a horizontal rock bed went unused. These experiences have shown the need for a study of horizontal rock beds and a further need to refine the design and construction of vertical rock beds.

This project will consist of two major activities: an experimental phase will gather data on actual rock beds, both horizontal and vertical. An analytical phase will use these experimental data to develop and refine a three dimensional, finite difference rock bed model and associated computer code. Argonne National Laboratory (ANL) personnel will develop the model while Solaron will do the experimental work.

The experimental work will consist of construction of both present day and improved vertical and horizontal rock beds. These beds will be extensively instrumented and the resulting data will be forwarded to ANL where it will be used to develop and verify the 3D model.

The major outputs from this contract will be the 3D model and a rock bed design manual for both vertical and horizontal rock beds.

SUMMARY

This section is not applicable since work has not started on this contract.

TECHNICAL ACCOMPLISHMENTS

This section is not applicable since work has not started on this contract.

FUTURE ACTIVITIES

One vertical and one horizontal rock bed will be constructed using present day design methods. These beds will be operated and data gathered will be forwarded to ANL.

A rock testing apparatus will be built and operated to obtain rock flow and heat transfer data.

Data from the rock beds and the rock tester will be used by ANL personnel to develop a 3D model.

Proposed modifications to the vertical and horizontal rock beds will be evaluated by use of the ANL model. Several of the more promising modifications will be incorporated into the rock beds and further tests will be conducted. Results of these tests will be forwarded to ANL for further "tuning" of the 3D model.

As a result of these tests and further simulations by ANL personnel improved vertical and horizontal rock beds will be designed, built and tested.

A design manual for vertical and horizontal rock beds will be written and published.

LIGHTWEIGHT CONCRETE MATERIALS AND STRUCTURAL SYSTEMS
FOR WATER TANKS FOR THERMAL STORAGE
WESTINGHOUSE ELECTRIC CORPORATION
ADVANCED ENERGY SYSTEMS DIVISION

EM-78-C-02-4703

R. WILLIAM BUCKMAN, JR.

MARCH 1, 1978 - FEBRUARY 29, 1980

OBJECTIVE

The objective of this project is the development of a water storage system made with precast, or cast on-site, lightweight concrete structural and insulating elements possessing the necessary properties and capable of being easily assembled or fabricated, especially for retrofitting into and integration with existing residential and other structures. The thermal and structural property requirements for hot water storage tanks to achieve the requisite efficiency were determined in conjunction with the evolution of various conceptual tank designs.

SUMMARY

A state-of-the-art survey was made on the extent of lightweight concrete materials applicable to the construction of water tanks for thermal energy storage. Cellular concrete, produced using the protein process, was the selected material. Thermally efficient hot water storage tanks were fabricated from cellular concrete and thermal performance was evaluated using a static decay test since the test procedure specified in ASH/RAE 94-77 did not prove acceptable. Tanks were made from precast concrete elements which could be assembled offsite or onsite. Economic analysis indicates that cellular concrete provides a cost effective, durable insulating material. The total portability of the Celcore system plant makes this cellular concrete amenable to both onsite fabrication and retrofit application.

TECHNICAL ACCOMPLISHMENTS

• Foam or cellular concrete was the material selected to fabricate hot water storage tanks. Based on the results of the state-of-the-art survey (Ref. 1-23) on lightweight concrete materials and inquiries on availability of lightweight aggregate, it was concluded that cellular concrete offered the best combination of mechanical and thermal properties with low cost (see Table 1). A lack of general availability of lightweight aggregates precluded evaluation of this material. Comments from the Lightweight Aggregate Producers Association indicated retrenchment in this industry because of impact of environmental regulations and rising fuel costs. Foam or cellular concrete incorporates encapsulated air bubbles as the medium to control the density of the bulk concrete material. The encapsulated air bubbles in the wet concrete slurry upon solidification leave a matrix of a closed cell structure.

• Further optimization of the foamed concrete compositions was investigated to determine whether or not further enhancement in mechanical and/or thermal properties could be achieved. A polymer latex modifier Rhoplex ® MC-76, an acrylic emulsion, was reported to enhance the strength and abrasion resistance of concrete. Also, the alkaline-resistant glass fibers were added to enhance the crack-resisting properties. The volume fraction of fiberglass that could be added was limited by the ability of the concrete pumping system to deliver the concrete mix without clogging up. The data obtained on the experimental mixes is summarized in Table 2. The use of a polymer-latex addition to the mix appeared to have an adverse effect on mechanical properties while the use of glass fibers appeared to enhance the mechanical properties of the structural foamed concrete composites.

Table 1

Cost and Mechanical Property Data for Concretes

	Strength (psi)	Density (#/ft^3)	Quotation ($/cu yd)
Ready-mix concrete Burkhart, Monroeville, Pa.	3500 4000	150 150	41.60 42.10
Ready-mix concrete Haydite Aggregate Rochez, Pittsburgh, Pa.	3000	110	80.00
Ready-mix concrete F.O.B. job site (150-mile radius) Foam Concrete Celcore Systems, Inc. Ft. Lauderdale, Fl.	4000 200	100-110 18-20	60.00 55.00

• Thermal design analysis indicates that increasing the thickness of insulative concrete beyond about 12 inches provides a diminishing return (see Fig. 1).

• The first 500 gallon tank shown in Figure 2 had an average of approximately four inches of insulating cellular foam concrete. The second tank tested, shown in Figure 3, had approximately nine inches of insulating foam concrete. The difference in thermal performance is evident from the thermal decay history shown in Figure 4. Thermal performance testing following the procedures outlined in ASH/RAE 94-77 proved impractical experimentally since ΔT's on the order of less than 0.1°F must be measured.

• Economic analyses indicate that foamed concrete provides a cost-effective insulation material (see Table 2). Cellular concrete has the advantage of being composed of universally available materials; i.e., sand, cement, water, and air. The Celcore concrete plant is designed specifically for the manufacture of lightweight cellular concrete, both structural and insulating with the use of Celcore Prefoamed Foam. The plant is totally mobile, providing a flexibility for manufacturing not found in other tank-fabricating systems. Two men can operate

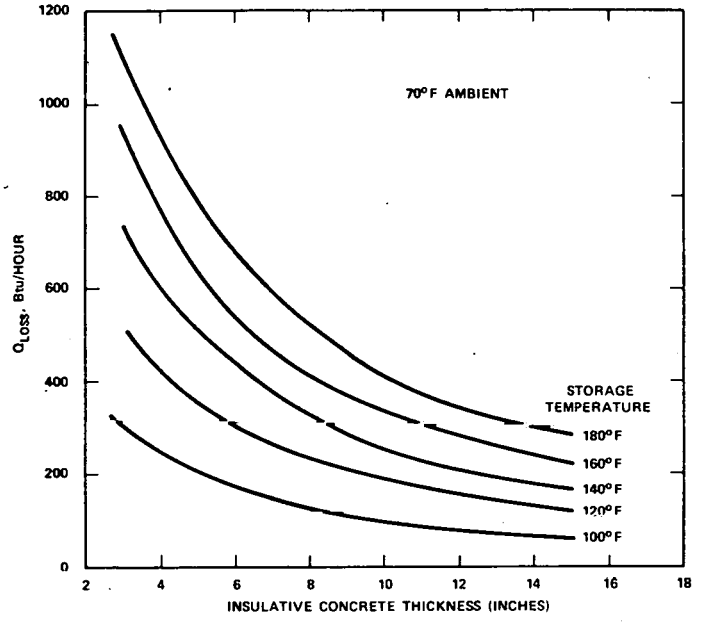


Figure 1. Steady state heat loss 500 gallon tank as a function of insulative concrete thickness (18 pcf)

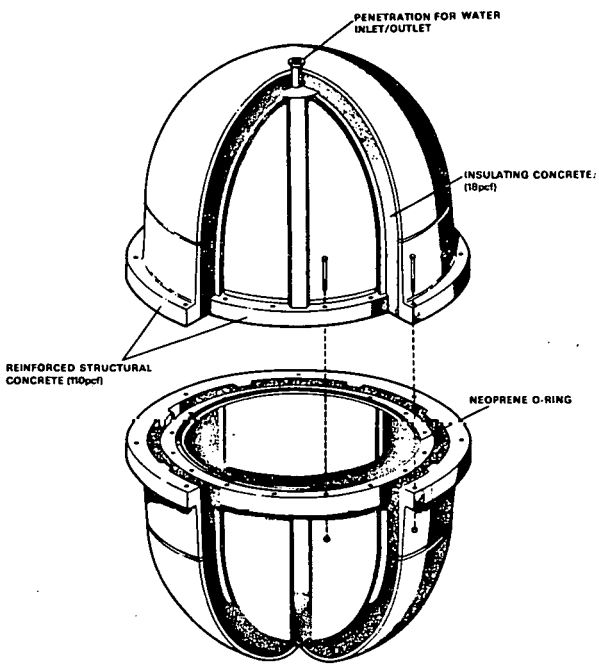


Figure 2. Lightweight concrete 500 gallon hot water storage tank - #1

Table 7

Thermal/Mechanical Properties of Cellular Concrete Compositions(e)

Batch	Density (#/ft^3) Wet	Dry	Additives	28-day Strength, psi Compressive	Modulus of Rupture	Splitting Tensile	Modulus of Elasticity (psi)	Thermal Conductivity BTU/in-ft^2-hr
A	118	106.7	none	3148^{+389}_{-248}	-	245^{+10}_{-15}	-	3.98
B	111	96.8	none	2202^{+132}_{-80}	-	210	-	2.94
C	118.6	108.5	none	3091^{+92}_{-84}	-	235 ± 10	-	4.78
D	122	108.2	none	4258^{+78}_{-84}	-	408^{+7}_{-8}	-	4.49
E	113.9	102.9	MC-76(a)	3673^{+41}_{-30}	390^{+45}_{-65}	298^{+58}_{-98}	2.63×10^6	3.1
F	124	113.5	MC-76 plus glass fiber(b)	3832^{+59}_{-82}	454^{+81}_{-154}	392^{+70}_{-60}	3.82×10^6	3.7
G	114.6	103.7	glass fiber(b)	3525^{+47}_{-59}	478^{+72}_{-63}	356^{+26}_{-33}	3.63×10^6	3.4
H	117.8	107.6	glass fiber(c)	3903^{+59}_{-83}	473^{+77}_{-48}	366^{+72}_{-78}	5.42×10^6	3.6
I	114.8	94.8	glass fiber(d)	2830	-	293	-	3.5
J	113.8	93.8	glass fiber(b)	3595	-	330	-	-
K	119.9	99.9	glass fiber(b)	4310	-	408	-	
L	31.3	23.2	none	133^{+11}_{-7}	-	18^{+2}_{-3}	-	0.49
M	35.5	26.3	none	168^{+16}_{-29}	-	-	-	0.58
N	23.7	16.5	MC-76(a)	93^{+36}_{-38}	11^{+4}_{-1}	-	6.46×10^4	0.33
O	22.6	15.1	MC-76(a)	60^{+8}_{-16}	10 ± 0	-	4.11×10^4	0.34
P	30.3	20.8	MC-76(a)	-	-	-	-	0.41
Q	34.2	25.3	No(a)	168^{+43}_{-77}	41^{+9}_{-6}	-	4.26×10^4	0.49

(a) MC-76, polymer latex addition.

(b) 7 lbs glass fiber per yard^3

(c) 14 lbs glass fiber per yard^3

(d) 3-1/2 lbs glass fiber per yard^3

(e) Mechanical properties average of 4 to 5 specimens. Thermal properties average of 3 specimens.

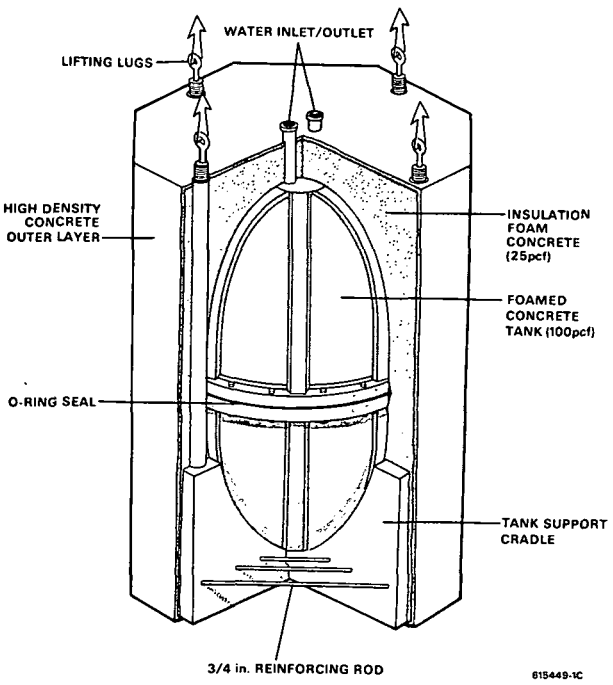


Figure 3. Lightweight concrete 500 gallon hot water storage tank - #2

a lightweight concrete plant and can place 10-12 cubic yards per hour of lightweight concrete at substantial distances from the pump, both vertically and horizontally. Although (as can be seen in Table 3) fiberglass is the least expensive material; when considering cost for placing, strength, durability, moisture resistance, foamed concrete would appear to have advantages in all these areas. Economic analysis information supplied by Celcore to allow tank fabrication completely onsite indicates that a tank can be fabricated and installed onsite at a cost of $1.84/gallon for a 500 gallon sized tank to approximately $0.59/gallon for a 2000 gallon sized tank. This assumes amortizing the cost of the concrete plant and forms in one year (an investment of approximately $130,000). Also, this assumes a production rate of 1300 tanks per year. Doubling the production rate would lower their cost estimates.

Table 3

Cost Comparison of Various Insulating Materials

	$/board ft	R	$/R
1. Foamed concrete (20#/ft^3)	0.07	2.9	0.024
2. Expanded polystyrene (2#/ft^3)	0.07	4.17	0.017
3. U-F foam (3#/ft^3)	0.25	4.3	0.058
4. fiberglass	0.333	3.16	0.01

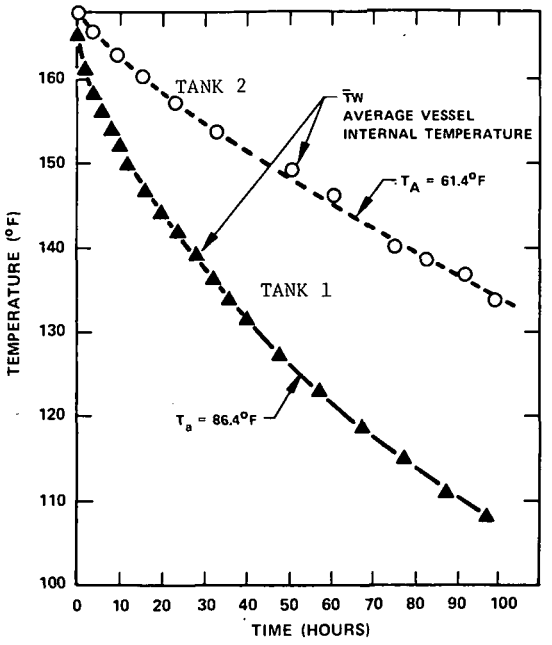


Figure 4. Storage temperature decay history

FUTURE ACTIVITY

The remaining task is preparation and submission of a final report detailing the results of the investigation. Three five-hundred gallon concrete tanks are available for use or further evaluation.

Results indicate that foamed concrete is a viable material for providing low-cost storage tanks for thermal energy storage.

Florida Celcore has indicated a willingness to produce the concrete tanks or concrete plants to produce tanks.

REFERENCES

1. J. K. Nesbit, Structural Lightweight-Aggregate Concrete, Concrete Publications Ltd., London, 1966.

2. H. G. Chan, W. A. Patterson, The Theoretical Prediction of Cracking Stres of Glass Fibre Reinforced Inorganic Cement, Journal of Material Science, 7 (1972) 856-860.

3. ACI Publication SP46, Proportioning Concrete Mixes
Cedric Wilson, Proportioning Normal Weight and Lightweight Structural Concrete Mixtures Using Shrinkage Compensating Cements, p. 1-10.
Donald J. Hall, Proportioning Concrete Mixtures Containing Chemical Admixtures, p. 97-108.
S. Popovics, Proportioning Concrete for a Specified Cement Content and/or for a Special Weight.

4. G. E. Troxell, H. E. Davis, J. W. Kelly, Composition and Properties of Concrete, McGraw Hill, New York, NY (1968) p. 261-284.

5. ACI Manual of Concrete Practice, Part I, 1968
Recommended Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 613A-59) p. 211-217.

6. A. B. Dunlap, Shrinkage of Lightweight Concrete, Research Memo 73-1D6-FIRCO-M1, Westinghouse Research and Development Center.

7. R. M. Zimmerman, P. A. Kozeliski, Properties of Normal and Lightweight Concrete Under Multiaxial Compressive Loadings, Technical Report No. 74, New Mexico State Univ., Engineering Experiment Station, Oct. 1971.

8. F. M. Lea, The Chemistry of Cement and Concrete, 3rd Ed. Chemical Publish Co., Inc. 1971, p. 557-591.

9. ACI Publication SP-44, Fiber Reinforced Concrete.
A. J. Majumdar and A. G. Tallentire, Glass Fiber Reinforced Cement Base Materials, p. 351-363, p. 1-36.

10. B. H. Gray, G. R. Williamson and G. B. Batson, Fibrous Concrete--Construc Material for the Seventies, May 1972. Construction Engineering Research Laboratory, Champaign, Ill.

11. V. Lack, V. P. Knazeva and A. P. Merking, Problems of the Microstructure of Aerated Concretes, Effect of Chemical Additives on the Microstructure of Aerated Concretes, Stavivo, 54 (1) 18-25 (1976) Chem. Abstr. 85 67323(

12. B. H. Gray, G. R. Williamson, and G. B. Batson, Fibrous Concrete - Construction Material for the Seventies, May 1972. Construction Engineering Research Laboratory, Champaign, IL.

13. V. Lack, V. P. Knazeva, and A. P. Merking, Problems of the Microstructure of Aerated Concretes. Effect of Chemical Additives on the Microstructure of Aerated Concretes, Stavivo, 54 (1) 18-25 (1976) Chem. Abstr. 85 67323 (1976).

14. B. P. Hughes and J. E. Guest, "Polymer Modified Fiber-Reinforced Cement Composites," Proc. I Int. Congr. Polymer Concretes, London, 1975, Construction Press, Lancaster, U.K. 1976, pp. 457.

15. V. M. Malhotra, Maturity Concept and Estimation of Concrete Strength: A Review - I, Indian Concrete Journal, April, 1974, pp. 122-138.

16. C. T. J. Dodson, The Failure of Bonds During the Fracture of a Random Fibrous Network Structure, Solid Mechanics and Engineering Design, The Proceedings of the Southampton 1969 Civil Engineering Materials Conf. Part I, Edited by M. Te'Eni.

17. J. H. Brown, Measuring the Fracture Toughness of Cement Paste and Mortar Magazine of Concrete Research: Vol. 24, No. 81, Dec. 1972.

18. T. W. Reichard, Creep and Drying Shrinkage of Lightweight and Normal Weight Concretes, National Bureau of Standards, Monograph 74, March 1964.

19. R. L. Blaine, H. T. Arni, and B. E. Foster, Interrelations Between Cement and Concrete Properties, Part I, Materials, Techniques, Water, Requirements and Trace Elements. Building Science Series 2, U.S. Dept. of Commerce. National Bureau of Standards, Building Research Division, Institute of Applied Technology, Aug. 1965.

20. R. L. Blaine, H. T. Arni, and B. E. Foster. Interrelations Between Cement and Concrete Properties. Part 4, Section 9. Shrinkage of Hardened Portland Cement Pastes.

21. W. S. Gray and G. P. Manning, Concrete Water Towers, Bunkers, Silos and Other Elevated Structures, Cement & Concrete Assn. London, U.K. 1973.

22. E. E. Pickering, Residential Hot Water Solar Energy Storage Subsystems Report No. NSF RA-N-75-095, National Science Foundation, Advance Energy Research and Technology, RANN Washington, D.C. Jan. 1976.

23. B. W. Shacklock, Concrete Constituents and Mix Proportions, Cement and Concrete Assn., London, SW1WOAQ 1974.

XII SOLAR ANALYSIS GROUP

SOLAR HEATING AND COOLING OF BUILDINGS - SYSTEMS RESEARCH, DEVELOPMENT AND TESTING

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
DE-AC02-79-CS-30122

S. KARAKI, D. S. WARD, W. S. DUFF, G. O. G. LOF, C. B. WINN

OCTOBER 1, 1978 to SEPTEMBER 30, 1979

OBJECTIVES

The objectives of this project are to:

- Develop and improve solar heating and cooling systems of both liquid and air types
- Analyze operational data obtained from long-term, continuous monitoring of systems
- Evaluate performance of systems
- Identify and correct operating problems
- Compare performance of different systems.

BACKGROUND

There are currently four solar heating and cooling systems under development and testing 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 a liquid system is in Solar House III. Over the past six years, more than a dozen different system configurations have been evaluated and compared. System components have consisted of two site-built collectors, four commercial factory-built flat-plate and evacuated tube collectors, two experimental evacuated tube collectors, five heat storage subsystems, three absorption cooling systems, a nocturnal evaporative cooling system, and five types of auxiliary heat supply units including an off-peak electric heat storage unit. Performance of the various systems developed and tested at CSU have been reported previously. Research being conducted with current systems are reported here, and for the convenience to the reader, the systems and results are described separately below.

LIQUID SYSTEMS IN SOLAR HOUSE I

DESCRIPTION

There are two liquid systems in CSU Solar House I. One system consists of Philips, Model IV, evacuated tube collectors, heat exchanger and 1000 gallons of water storage. A mixture of ethylene glycol and water is circulated through the collectors. The other system consists of single-glazed, selective surface, Miromit flat-plate collectors in a drain-back arrangement and a Bally storage unit containing water. Storage tanks for both systems are provided with a stratification device developed at CSU under previous joint U.S. Navy/DOE sponsorship.

The drain-back system supplies the required heat to the building space via a load heat exchanger and also to the domestic water preheater. Continuous measurements of heat delivery by the system is made by an on-line minicomputer. The second, (evacuated tube) system in Solar House I is "driven" by the mini-computer and controlled by a microprocessor to provide the same quantity of thermal energy to the load as the drain-back system. The solar heat from the second system, however, is rejected outdoors. Auxiliary heating for the building is provided by an off-peak electric heat storage unit with an Atmospheric Temperature Observer Predictor (ATOP) controller which minimizes electrical energy usage and maximizes solar thermal energy usage.

For the summer of 1980, the solar cooling system will consist of new experimental evacuated tube collectors and a "third-generation" lithium-bromide chiller made by Arkla.

SUMMARY

The use of electric auxiliary heat during the daytime has been completely avoided by an off-peak electric heat storage unit in parallel with the solar heat supply. A simple method of producing stratification in a solar heat storage tank has been implemented and is producing excellent results -- up to 25°F temperature difference from bottom to top. A modular highly insulated thermal storage tank was installed and is providing a reduction to about one-fourth of conventional loss rates. The potential of factory-built collectors over site-built collectors was demonstrated when the original site-built collectors were replaced and more than 50 percent collection efficiency improvement was recorded. Differences in the performance of different evacuated tubular collectors were found to be substantial, with the "best" evacuated tubular collectors outperforming good flat-plate collectors by a factor of two or better.

TECHNICAL ACCOMPLISHMENTS

- The use of electric auxiliary heat during the daytime (in periods of high utility system demand) has been completely avoided by use of a commercially available off-peak electric heat storage unit integrated with the solar heat supply system. The resulting savings in central station electric generating capacity, reflected in low consumer electric costs for off-peak power, have been demonstrated. A price difference of 2¢ per kilowatt-hour between day time and nighttime rates, where 25 percent of total annual heat requirements of 100 million Btu are typical, justifies the installation of the off-peak electric heat storage unit. Improvements in system control are now being made. Shown in Figure 1 is a plot of auxiliary furnace performance.
- Use of optimally designed perforated vertical baffles in a solar heat storage tank has resulted in sustained temperature stratification with a water temperature difference from bottom to top of the tank greater than 25°F. A seasonal increase in solar energy collection of 10 percent to 25 percent and a one-third reduction in auxiliary energy use should be achieved by this design. It is expected that solar cooling may be 50 percent greater through increased supply temperature to the chiller and decreased supply temperature to the collectors.

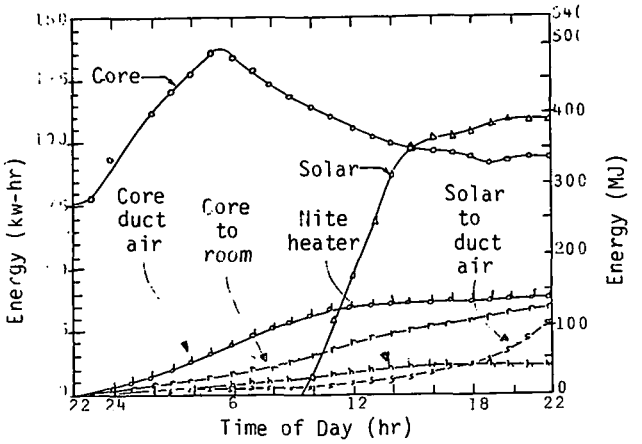


Figure 1. Off-Peak Auxiliary Furnace Performance, Typical Energy Distribution.

• Convenience and simplicity in heat storage tank construction has been demonstrated by use of the Bally modular sectional heat storage container with waterproof liner. Direct heat transfer from tank walls to rooms can be reduced to less than one-fourth of conventional rates. Durability of one type of waterproof lining was found to be inadequate, however, and more resistant materials such as butyl rubber or hypalon are recommended. Figure 2 is a schematic of the tank.

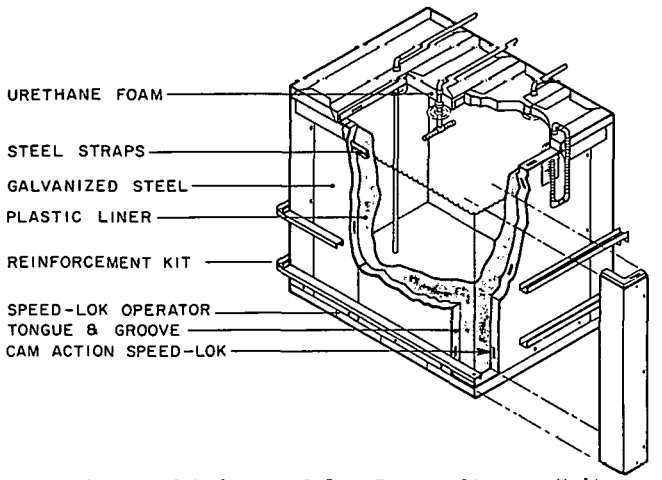


Figure 2. Prefabricated Solar Energy Storage Unit.

• Heat "losses" from storage tank walls (direct) heat transfer from tank surfaces to heated building space), prior to the new tank installation, provided 13.5 percent of the total space heating requirements of the building and 21 percent of the solar heat delivery to the building through the combination of forced circulation of heated fluid and the storage tank "losses". During the six months of the heating season on which measurements were based, 35,930 MJ of solar heat were supplied to the rooms of the house, of which 28,460 MJ were delivered to the rooms by the controls and fluid circulation system, 7470 MJ were delivered directly to the living space by transfer through the tank walls and accessories. In September and October, 3260 MJ were really lost by passive heating of the rooms from the storage tank surfaces at times when no heat was needed in the building. Only 5.8 percent of the annual collected solar heat was therefore wasted (by heat supply to the rooms when not needed in September and October).

• Among 11 solar heating systems in the path of a severe hailstorm, during which hailstones as large as 3.5 inch diameter impacted tempered glass covers on approximately 1000 solar collector panels, only 9 cover glasses were broken, none of which was in the five CSU solar heating installations. For the first time, it has therefore been amply demonstrated that even the largest hailstones cause insignificant damage to solar collectors provided with tempered glass covers.

• A large gain in solar heat collection was shown to be attainable by use of well-designed and built commercial collectors rather than collectors site-assembled from metal and glass components. Performance improvements as high as 50 percent were demonstrated. Average monthly efficiencies of the system in which site-built collectors were used were 16.5 percent, whereas efficiencies with factory-built collectors are in the vicinity of 25 percent.

• Comparison of two types of evacuated tube collectors, with each other and with good quality flat-plate collectors, demonstrated that solar energy delivery for space heating and hot water could be doubled, and for absorption cooling, tripled, by use of the most efficient evacuated tube collector. Differences in energy supply by a less efficient evacuated tube collector were considerably smaller, very little difference being observed between the output of a good 70C square foot flat-plate collector and the 500 square foct evacuated tube collector in space heating use.

Figures 3 and 4 are schematics of the two evacuated tubular collectors employed in the CSU Solar House I systems.

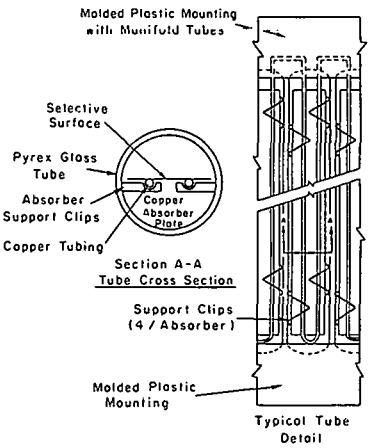


Figure 3. Cross-Section of the Corning Evacuated Tubular Collector.

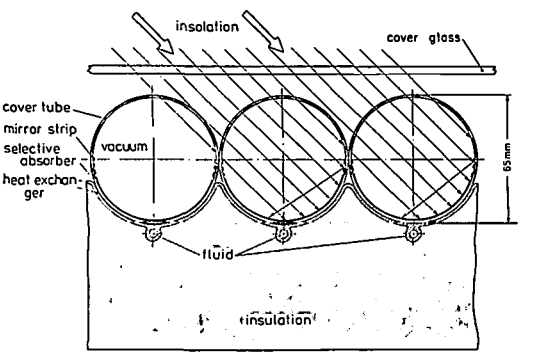


Figure 4. Cross-Section of the Philips Evacuated Tubular Collector.

FUTURE ACTIVITIES

Contract Activities. A drain-back system for the roof mounted flat-plate collector has been installed and is now supplying the building heating and hot water loads. An improved prediction algorithm for use in controlling the charge of the off-peak unit has been implemented. A third generation self-contained prototype Arkla LiBr absorption chiller will be installed in late May. CSU Solar House I will be operating with about 700 tubes of the new commercial prototype Philips heat pipe evacuated tubular collector by mid to late June.

Results of system operation with these components will be available shortly after the end of the present contract period in September 1980.

Post-Contract Activities. Results of system operation with the new components will be extended to other design variations and different geographic regions by the fast running simulation now under development and the TRNSYS code now being validated with current system operating data. A two-year plan for future activites and component system tests will be worked out with DOE and SERI in the next several months.

PUBLICATIONS

Löf, G. O. G., and W. S. Duff (1979) "Comparative Performance of Two Types of Evacuated Tubular Solar Collectors in a Residential Heating and Cooling System". Final Report, COO-2577-19, September.

Duff, W. S., C. E. Hancock and G. O. G. Löf (1979) "Operational Improvements in the CSU Solar House I System Supplied with Heat from Evacuated Collectors." Proceedings of the Second Annual Operational Results Conference, Colorado Springs, Colorado, November.

Conway, T, W. S. Duff, G. O. G. Löf, and R. G. Pratt (1979) "Comparative Performance of Two Evacuated Tube Solar Collectors in a Residential Heating and Cooling System - The Progress Report." Proceedings of the ISES Annual Meeting, Atlanta, May.

AIR SYSTEM IN SOLAR HOUSE II

DESCRIPTION

The air system in Solar House II consists of single-glazed, selective-surface flat-plate collectors, a pebble bed for thermal storage, and an air-to-air heat pump for auxiliary heating. The heat pump is used to cold charge the pebble bed during off-peak hours for summer cooling. An optional controller is provided for solar thermal energy collection and storage.

SUMMARY

- The air-heating solar system operated at 33 percent seasonal collection efficiency during the winter of 1978-79.
- Space cooling with off-peak cool storage of the pebble bed is economically advantageous to daytime direct costing with the heat pump if the cost ratio of peak to off-peak electrical energy rate is greater than 1.8.
- Optimal control can increase COP for solar energy collection.
- Two different air leakage rates into collector arrays showed that an array with 15 percent air leakage rate is more efficient than an array with an air leakage rate of 7 percent.

TECHNICAL ACCOMPLISHMENTS

- A system which consisted of commercial air-heating solar collectors (single-glazing and selective surface) had about the same collection efficiency as a system consisting of site-built double-glazed (glass) non-selective collectors (metal absorber).
- Performance of the space cooling system with cold-charge of the pebble bed during off-peak hours is given in Table 1 below.

Table 1. Monthly Average Daily Cooling Performance

Number	Item	Units	June	July	Aug	Sept	Season
1	Number of Days of Data		20	31	31	9	91
2	Heat Removed by Heat Pump during Cold Charge	MJ/day	156.28	200.52	143.95	205.26	171.99
3	Cold Charging of Pebble Bed	MJ/day	108.99	153.48	110.56	162.71	129.99
4	Room Cooling through Pebble Bed	MJ/day	110.78	146.61	101.64	155.41	124.28
5	Storage Efficiency	4/3	1.02	0.95	0.92	0.96	0.96
6	Cold Charge Efficiency	3/2	0.70	0.77	0.77	0.79	0.76
7	Direct Heat Pump Cooling	MJ/day	2.26	14.14	16.73	12.38	12.24
8	Total Room-Cooling including Cooling from Losses	MJ/day	138.69	189.40	137.51	190.70	160.71
9	Electrical Energy for Heat Pump during Cold Charge	MJ/day	64.96	84.22	61.46	84.53	72.27
10	Electrical Energy for Blower during Cold Charge	MJ/day	9.58	12.02	8.81	11.99	10.38
11	Electrical Energy for Heat Pump during Direct Cooling	MJ/day	0.81	5.72	6.80	4.68	4.91
12	Electrical Energy in Blower during Direct Cooling	MJ/day	0.12	0.74	0.88	0.63	0.64
13	Electrical Energy to Blower for Storage Discharge	MJ/day	6.33	10.01	6.17	9.90	7.38
14	Heat Pump COP for Cold Charge	2/9	2.41	2.38	2.34	2.43	2.38
15	Heat Pump COP for Direct Cooling	7/11	2.79	2.47	2.46	2.65	2.49
16	Cooling COP from Cold Charge	4/(9)+(10)+(11)	1.37	1.39	1.32	1.46	1.37
17	Average Daily COP for Cooling	8/(9)+(10)+(11)+(12)+(13)	1.70	1.68	1.63	1.71	1.67

- Measured and f-chart predicted performances of an air-type space heating system agree very closely.

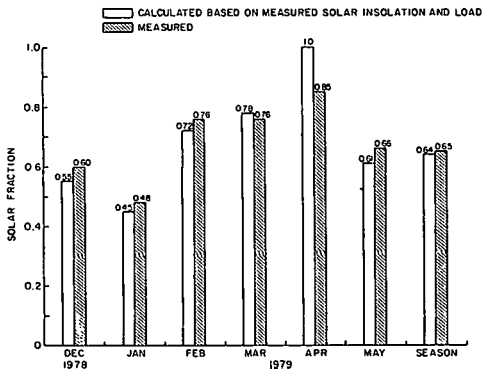


Figure 1. Comparisons of Measured and f-Chart Predicted Monthly and Seasonal Solar Fractions.

FUTURE ACTIVITIES

- Evaluate system performance with an optimal controller.
- Compare performances of systems optimally controlled and bang/bang controlled.
- Plan optimal control experiment for summer cooling with heat pump.
- Evaluate cooling system performance.

PUBLICATIONS/REPORTS/REFERENCES

Karaki, S., (1979) "Performance Evaluation of a Solar Air-Heating and Nocturnal Cooling System in CSU Solar House II." Final Report for the period June 1, 1977 to September 30, 1978. Prepared for the Solar Heating and Cooling Research and Development Branch Office of Conservation and Solar Applications, U. S. Department of Energy under Contract No. EY-76-S-02-2868, COO-2868-5, April.

Karaki, S., S. Waterbury and T. Lantz, (1979) "Thermal Performance of a Commercially Available State-of-the-Art Solar Air-Heating System." Prepared for the Operational Results Conference held in Colorado Springs, Colorado, November 27-30.

Karaki, S., T. E. Brisbane, S. Waterbury and T. Lantz, (1980) "Performance Evaluation of a State-of-the-Art Solar Air-Heating System with Auxiliary Heat Pump." Annual Report for the period 1 October 1978 through 30 September 1979. Prepared for the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U. S. Department of Energy, under grant DE-AC02-79-CS-30122, January.

LIQUID SYSTEMS IN SOLAR HOUSE III

DESCRIPTIONS

Two distinct systems have been employed in CSU Solar House III. Each system utilizes the Chamberlain state-of-the-art liquid-heating flat-plate collector (single cover with selective surface) and a lithium bromide absorption cooling unit. The first system configuration provided cooling and heating data from July 1978 through March 1979. A substantially modified system was incorporated into CSU Solar House III in April and May of 1979. Cooling and heating data have subsequently been acquired and analyzed and by April 1980 will provide insights into the effect of system design on the overall performance of the system.

The second system incorporates a heat pump as the heating and cooling auxiliary and constitutes a significant improvement in system design by reducing unwanted heat losses and electrical energy consumption for operating the solar system. The reduced heat losses were obtained by significantly reducing piping runs, increased quality and insulation value of the thermal storage unit, and relocation of the thermal storage unit in order to substantially reduce the interior heat losses which add to the cooling load. Electrical energy requirements to operate the solar system have been reduced to about one-third of the original value by careful reduction and relocation of the piping runs and by utilization of pumps with substantially improved efficiencies.

SUMMARY

- Two years of heating and cooling season data have been acquired and analyzed.
- Criteria for improved performance of solar heating and cooling systems have been developed and clearly delineated.
- Feasibility of solar cooling systems has been shown to be possible only when the thermal storage unit heat losses do not contribute to increasing the cooling load.
- The utilizability ($\overline{\phi}$) concept has been shown to provide reasonably accurate estimates of predicted solar collector performance.
- The results of performance evaluations have established the critical importance of detailed, careful, and intelligent design and proper installation of solar heating and cooling systems.

TECHNICAL ACCOMPLISHMENTS

- Data have been acquired and evaluated over a two-year performance period, including two heating and two cooling seasons. These data include the performance of two distinct heating and cooling system designs. Comparative analysis of the performance of these systems in succeeding years has provided a clear distinction of the effects of design alternatives on the overall system performance. Table 1 gives a brief summary of critical parameters which demonstrate the improved performance of the second system over the earlier design and has predictions based on the "utilizability" [1].

Table 1. Cooling Data and Analysis (August)

ITEM	$\overline{\phi}$	1978	1979
1. Solar radiation on collector (MJ/day)	1080	1079	1068
2. Useful solar collected (MJ/day)	366	316	358
3. Collector daily efficiency (percent)	34	29	34
4. Exterior heat losses (MJ/day)	----	34	54
5. Interior heat losses (MJ/day)	----	48	22
6. Solar cooling (heat removal)* (MJ/day)	220	90	144
7. Operating electrical energy (MJ/day)	----	59	18
8. Total energy savings** (MJ/day)	220	-16	112
9. System efficiency (percent)	20.4	-1.5	10.6

* Line 6 = [line 2 - line 4 - (line 5)(2.7)] COP of collector

** Line 8 = [line 6 - (line 7)(1.8)]

Comparison of the performance of these two systems provides a clear indication of the importance of system design and the limitations of the $\overline{\phi}$ design method.

- Table 1 also provides clear evidence that solar cooling systems with significant heat gains to the conditioned space (caused by thermal storage heat losses, etc.), are only marginally technically feasible and are not economically feasible.
- The effects on overall system performace by the electrical energy requirements of the solar system operations have been shown to be a critical factor. Minimizing electrical power requirements has been shown to be essential for both technical and economic feasibility of solar heating and cooling systems.
- A definitive design procedure for heating and cooling systems has been developed and a set of parameters has been clearly delineated for the purpose of design prediction and system performance evaluation. These parameters include average daily values (over a one-month period) of:
  1. Solar radiation on collector
  2. Useful solar energy collected
  3. Collection efficiency
  4. External solar system heat losses
  5. Internal solar system heat losses
  6. Usefulness/nonusefulness of heat losses
  7. Useful solar energy delivered to load
  8. Useful heating and/or cooling
  9. Solar operating electrical energy requirements
  10. Thermal equivalent of electrical energy usage
  11. Total energy savings of solar system
  12. Overall solar system efficiency.
- The concept of the usefulness or nonusefulness of interior heat losses from the solar system has been quantified. This factor will require further study.
- Reduced flow rates have been shown to result in temperature stratification in the thermal storage unit (cooling) season and have resulted in overall system improvements.

FUTURE ACTIVITIES

Future activities include the finalization of the evaluation of the 1979-80 heating season data, the

comparative performance of the three solar houses over the last two years, and the comparison of predicted and observed system performance.

PUBLICATIONS/REPORTS/REFERENCES

ard, D. S., H. S. Oberoi and J. M. Grebe (1979) "Improving Performance of Solar Cooling Systems." Proceedings of the Second Annual Solar Heating and Cooling Systems Operational Results Conference, Colorado Springs, November.

Ward, D. S., (1980) "Systems Analysis of the Thermal Performance of Operating Systems." Proceedings of the Solar Simulation and Economic Analysis Conference, San Diego, California, January.

Ward, D. S., J. C. Ward, H. S. Oberoi and M. Westhoff, (1980) "Improving Performance of Solar Heating and Cooling Systems." Submitted for presentation at the 1980 International Solar Energy Society Conference to be held in Phoenix, Arizona, June 1-5.

Ward, D. S., and J. C. Ward (1980) "Operating Performance Evaluation of Solar Heating and Cooling Systems." Submitted for presentation at the 1980 International Solar Energy Society Conference to be held in Phoenix, Arizona, June 1-5.

[1] Klein, S. A., (1978) "Calculations of Flat-Plate Collector Utilizability." Solar Energy, Volume 21, No. 5.

SOLAR COOLING STUDIES AND SYSTEMS ANALYSIS

UNIVERSITY OF MARYLAND

DE-AC03-79CS 30204

D. K. ANAND, R. W. ALLEN

JULY 1, 1979 - JUNE 30, 1980

OBJECTIVE

The objective of the research is to:

1. Integrate the past and current University of Maryland work in component modeling and system simulation with similar activities taking place in the mainstream of the national solar cooling program.
2. Continue the cooling systems analysis work, transient component modeling and develop a simplified cooling design technique.
3. Formulate a methodology for a fair comparative assessment of current projects developing solar absorption chillers and systems.
4. Prepare a state-of-the-art paper on absorption cycle fluids.
5. Provide technical assistance in reviewing proposals and reports, and in conducting site visits, in support of the national solar cooling program.
6. Conduct additional tasks as may be requested in support of the national solar cooling program. This is to include the development of an overall systems analysis and testing plan for the Systems Development Division R & D activities.
7. System simulation studies in the photovoltaic-thermal area.

BACKGROUND

A review of various studies, assessing solar heating and cooling technology, as well as barriers to commercialization, was made for the Solar Heating and Cooling R & D Branch, Office of Conservation and Solar Applications, Department of Energy.

In this review, interest was centered on solar cooling in two respects: 1) a purely economic and market penetration standpoint and 2) a purely technological approach stressing machine performance.

In addition to this review earlier research efforts have led to the following results:

- Completed a computer program for predicting the performance of Lithium bromide-water cooling machine.
- Completed a quick and general Solar Heating and Air-Conditioning Simulation Program (SHASP). Made Validation studies of SHASP, TRNSYS and f-CHART.
- Extended the use of the stochastic weather model to five cities.
- Obtained a simplified design approach for cooling system design. This work is based on correlation studies using SHASP.
- Completed a solar cooling system study for different control strategies.

SUMMARY

Accomplished significant technical support provided under this contract was in the form of reports covering project site visits, program review meetings, proposal reviews, state-of-the-art refrigerant/absorbent pairs review, and project attributes evaluation methodology. Technical research work was accomplished in the general area of solar cooling system computer model studies specifically dealing with stochastic predictions of systems performance, a simplified design method, closed-loop feedback control system predictions, and a simulation study of combined photovoltaic/thermal (PV/T) heat pump system for heating and cooling.

TECHNICAL ACCOMPLISHMENTS

- As part of technical support the University of Maryland team made a number of project site visits, participated in program review meetings, reviewed several proposals as well as reports. This has been documented in the form of internal reports to Lawrence Berkeley Laboratory.
- A study of the state-of-the-art review of refrigerant/absorbent pairs for solar powered absorption cooling applications was conducted. The objective of the study was to:
  - establish the current needs for continued research support in refrigerant/absorbent pairs and to ascertain the potential gains for continued and new work.
  - determine the bounds on the maximum possible improvements in cooling system performance.

  The present work reviews various contributions in general and specifically

reviews four DOE sponsored programs at IGT, Carrier Corp., SoRI, and EIC.

- A model of an absorption chiller that includes transient performance is being developed in this study. Specifically, the purpose is:
  - to develop a transient simulation model of the absorption chiller that will take into consideration the thermodynamic properties of the absorbent-refrigerant pairs as well as the heat transfer characteristics of each of the different components of the chiller.
  - to compare the time constants obtained from this study to available data.

- A stochastic predictions study of solar cooling system performance expands on previous efforts. The simulation program previously used modelled a very simple system. The new simulation models a more realistic system which includes collectors, hot side storage, auxiliary heat supply, pumps and valves, and features automatic controls and weather dependent loads.

  The results obtained using stochastic (probabilistic) weather and real weather were compared. The comparative study included total insolation, daily total collected energy, daily total cooling load, fraction of the load satisfied by solar means without auxiliary energy (percent solar), and average cycle COP. The results showed that the stochastic approach compared favorably with the real weather method.

- A simplified design method for cooling system design has been developed based on the solar cooling fraction. The approach similar to the f-CHART method is still under review for problems associated with regionality.

- A closed-loop feedback control system representation of a solar thermal system was derived for each of the various modes of solar operation. Analysis of the transfer functions resulted in identifying the various system parameters which must be optimized in order to obtain the maximum system response to a continuous input weather function. Using a stochastic weather model, which has been validated through the detailed simulation program SHASP, as input, the thermal response of the system was obtained in a closed-form. A methodology for using the closed-form solution to represent the response, and the joint probability density matrix to represent the probabilistic nature of the weather to obtain the long-term system performance was presented. The results compared well to the predictions of both the detailed simulation and the simplified design method.

- A document presenting attributes that are believed to be important considerations on the rating of new RFP's or follow on proposals of solar cooling projects was prepared. Specifically the attributes are grouped into five broad categories, viz: Thermal Performance, Hardward Performance, Commercialization, Economics, and Miscellaneous. The weighting factors assigned to each category and within each category have yet to be decided upon. Also guidelines for the weighting factors as well as the use of these attributes need to be formulated.

- A paper presenting a simulation study of combined photovoltaic/thermal (PV/T) solar collector-series heat pump systems for heating and cooling applications was completed. A computer program incorporating detailed performance models for the PV/T collector, electrical and thermal storage, heat pump and building load was developed to simulate the year-round operation of such a system. System simulations were made for three US locations to study the effect of important design parameters on the collector and overall system electrical and thermal performance.

  The long term performance was found to be relatively insensitive to electrical and thermal storage size over most of the range of values of practical interest. The collector area, orientation and performance parameters as well as the geographical location dependent weather and building loads have significant effect on the system performance that is critical from the point of view of design. Combined PV/T collector-heat pump systems are found to have the maximum potential for energy savings in cold regions with high thermal loads.

FUTURE ACTIVITIES

- Study additional sites for simplified design method.
- Continue system simulation and optimization of PV/T work.
- Complete transient analysis of component models.
- Continue technical support of the national cooling program including site visits and program review.

PUBLICATIONS

Reports

1) "Review of Absorbent/Refrigerant Cycle Fluid Studies"

Papers

1) "Dynamic Simulation of Solar Thermal Systems using Closed Form Solutions" 14th IECEC Conference, Boston, Mass., August 1979.

2) "Solar Cooling Performance Predictions Via Stochastic Weather Alorithms", The International Journal of Energy, Vol. 4, No. 4, Sept. 1979.

3) "Solar Thermal Systems Long-Term Performance Predictions Using Closed-Form Solutions", ISES Conference, Atlanta, Georgia, May 1979.

4) "A Simplified Solar Cooling Design Method for Closed-Loop Liquid Systems" ISES Con-

ference, Atlanta, Georgia, May 1979.

5) "Long-Term Solar Cooling Systems Performance Predictions Via a Simplified Design Method", SSEA Conference, San Diego, California, January 1980.

6) "Performance Studies of Combined Photovoltaic/Thermal Solar Heating and Cooling Systems", SSEA Conference, San Diego, California, January 1980.

7) "Stochastic Predictions of Solar Cooling System Performance", Transactions of ASME, Journal of Solar Energy, February 1980.

SOLAR HEATING AND COOLING SYSTEM ANALYSES

SCIENCE APPLICATIONS, INCORPORATED

SERI BOA BP-9-8150-1

P.I.: JEFFREY H. MOREHOUSE

PERIOD OF CONTRACT: BEGIN APRIL 15, 1979 END APRIL 17, 1981

OBJECTIVE

Science Applications, Incorporated (SAI) has contracted with the Solar Energy Research Institute (SERI) to perform solar heating and cooling system analyses under a basic ordering agreement. The general objective of this work is to analyze advanced solar heating and cooling (SHAC) system concepts for thermal and economic performance. The results of these analyses are to be used as inputs for programmatic planning of SHAC activities and efforts.

BACKGROUND

The present contract is an outgrowth of a previous DOE contract (EM-78-C-04-4261) entitled "Solar Heating and Cooling Systems Studies." The objectives of this previous contract were basically similar to the present contract, and many of the system models and methodologies previously developed have served as foundations for on-going system analyses.

Previous work under the DOE contract also included support of the National Energy Act Conservation Service (NEA) by providing candidate solar measures, simplified analysis tools, and other information related to satisfying the intent of the legislation. Additionally, SAI was involved in an effort to establish a validation methodology for SHAC simulation models. Reports related to this previous contract are listed in (1-6).

SUMMARY

Under this BOA contract, seven tasks have been assigned as of March 31, 1980. Each of the tasks is briefly described below and relevant reports are referenced.

Task 1: Technical Reporting. The work in this task was an extension of efforts which had been initiated under the DOE contract. Two work elements were addressed: 1) revision of "Heat Pump" and "Cooling" studies, and 2) informational support of the SERI Standard Assumptions Manual. The "Heat Pump" and "Cooling" studies have been submitted as reports (7,8), while the standard assumptions manual has been released as SERI draft document SERI/TR-351-402. The assumption manual was supported by SAI reports (9,10).

Task 2: SAHP-Sensitivities and Ground-Coupling. The solar-assisted heat pump parametric sensitivity study was initiated to determine possibilities for improvements to SAHP systems to get them to cost competitive levels (11). The ground-coupling study determined the thermal and economic performance characteristics of ground-coupled solar-assisted heat pumps compared to concentional systems and stand-alone ground-coupled systems (12).

Task 3: Building Energy Performance Standards (BEPS). Under this task, SAI provided support to the BEPS programs. Specific support has been given in determining the solar evaluation techniques (13), as well as supporting the planning of solar-related tasks. Presently, an alternate evaluation technique certification method and a manual of recommended practice are being worked on.

Task 4: NEA/RCS. The support of the Residential Conservation Service (RCS) has been funded under this task as a continuation of the previous contract's work.

Task 5: Ethanol from Biomass. This task represented a small SAI biomass project to identify all industrial-scale facilities (>1000 gallon/day) which could be used to make anhydrous ethanol.

Task 6: Industrial Process Heat Generic Systems. The objective of this task is to provide a complete analysis of a standardized solar thermal system configuration for low-temperature (212°F), liquid-based systems to provide hot water for industrial purposes. The analysis shall include trade-off studies for at least four selected sites. Work is to be completed in October 1980.

Task 7: International Solar Policy and Strategy Study. This task is being performed by TPI, Inc. under subcontract to SAI. The task is to provide technical assistance to DOE International Affairs in preparing a strategy document for DOE International Solar Energy Programs. The final report for this task is scheduled for completion on March 31, 1980.

TECHNICAL ACCOMPLISHMENTS

The major technical accomplishments include:

- A standardized thermal/economic framework was established for the direct comparison of residential heating, cooling and water heating technologies.

- Absorption and Rankine TRNSYS compatible performance models were developed for use in cooling program assessments.

- Residential solar assisted heat pump systems were analyzed versus conventional alternatives and found non-competitive. Further studies involving parametric sensitivities and ground-coupling indicated that no technical approach appears likely to make these systems competitive in the forseeable future. Ground-coupled stand-alone heat pumps appear most attractive among new technologies.

FUTURE ACTIVITIES

Two additional tasks are presently being formulated.

Task 8: Storage. This task is to be a comparative assessment of various storage means, both for residential and commercial systems. The previously developed simulation framework and models are to be utilized. Hot versus cold, sensible versus latent, multi-tank and off-peak charging are to be included in the thermal and economic assessments.

Task 9: Cooling. The previous cooling study will be extended to include various size cooling machines. The models will be refined and current cooling contractors performance data will be used to determine thermal performance.

REPORTS

1. P.L. Versteegen, et al.; "Survey of Currently Used Simulation Methods", Final Report, DOE Contract EM-78-C-04-4261; Science Applications, Inc.; SAI Report 79-846-WA; November 1978.

2. P.J. Hughes, et al.; "Survey of Component Modeling Activities", Final Report, DOE Contract EM-78-C-04-4261; Science Applications, Inc.; SAI Report 79-854-WA; December 1979.

3. J.H. Morehouse; "Direct Solar Heating Systems with High Performance Collectors: Thermal Performance and System Cost Estimates"; DOE Contract EM-78-C-04-4261; SAI Report 79-881-WA; January 1979.

4. W. Kennish; "Proposed IEA Reporting Format for Solar Energy Systems"; TPI, Inc. (SAI Subcontractor on DOE Contract No. DE-8C04-78CS-34261); Final Report; February 1979.

5. T.M. Knasel and Y. Mansoor; "Validation Status of Solar Heating Cooling Systems Models". DOE Contract EM-78-C-04-4261, Final Report; Science Applications, Inc.; SAI Report 79-855-WA; March 1979.

6. T.M. Knasel, et al.; "Validation Methodology for Solar Heating and Cooling Simulation Models"; DOE Contract EM-78-C-04-4261; Draft Final Report; Science Applications, Inc.; March 1979.

7. P.J. Hughes and J.H. Morehouse; "Comparison of Solar Heat Pump Systems to Conventional Methods For Residential Heating, Cooling and Water Heating"; Final Report SERI BOA BP-9-8150-1; Science Applications, Inc.; SAI Report 80-906-WA; April 1979.

8. J. H. Morehouse and P.L. Versteegen; "A Thermal and Economic Comparative Analysis of Absorption and Rankine Solar Cooling Systems for Commercial Buildings"; Draft Final Report, SERI BOA-9-8150-1; Science Applications, Inc.; SAI Report 80-909-WA; May 1979.

9. T.L. Freeman; "Evaluation of the 'Typical Meteorological Years' for Solar Heating and Cooling System Studies"; Final Report, SERI BOA BP-9-8150-1; Altas Corporation; SAI Report 80-969-WA; August 1979.

10. P.J. Hughes and J.H. Morehouse; "A TRNSYS-Compatible, Standardized Load Model for Residential System Studies"; Final Report, SERI BOA BP-9-8150-1; Science Applications, Inc.; SAI Report 80-915-WA; October 1979.

11. N.M. White and J.H. Morehouse; "Parametric Sensitivity Study for Solar-Assisted Heat Pump Systems"; Draft Final Report, SERI BOA BP-9-8150-1; Science Applications, Inc.; March 1980.

12. M.K. Choi, et al.; "Comparison of Ground-Coupled Solar Heat Pump Systems to Conventional Systems for Residential Heating, Cooling and Water Heating"; Draft Final Report, SERI BOA BP-9-8150-1; Science Applications, Inc.; February 1980.

13. "Building Energy Performance Standards: Evaluation Technique"; Technical Support Document; Final Draft; DOE Office of Conservation and Solar Applications, Division of Buildings and Community Systems; W.S. Fleming & Assoc. and Science Applications, Inc.; August 1979.

PAPERS

1. P.J. Hughes, "A Survey of Analysis Tools for Solar Heating and Cooling Systems Design", proceedings of AS-ISES Conference, V.2.1, Denver, Colorado (August 1978).

2. P.J. Hughes, et al.; "Survey of Simplified Design Methodologies for Solar Heating and Cooling Systems", proceedings of ISES Conference, V.2, p.1199, Atlanta, Georgia (June 1979).

3. P.J. Hughes, et al.; "Comparison of Combined Solar Heat Pump Systems to Conventional Alternatives", proceedings of ISES Conference, V.1, p.755, Atlanta, Georgia (June 1979).

4. P.J. Hughes, et al.; "Improved Heat Pump Model for TRNSYS", proceedings of ISES Conference, V.1, p.817, Atlanta, Georgia (June 1979).

5. J.H. Morehouse, et al.; "Residential Solar Heat Pump Systems: Thermal and Economic Performance", ASME 79-WA/Sol-25, New York City (December 1979).

SIMULATION AND DESIGN OF SOLAR THERMAL PROCESSES

Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin 53706

EY-76-S-02-2588.A003

J.A. Duffie, W.A. Beckman, S.A. Klein, and J.W. Mitchell

January 1, 1980 to December 31, 1980

OBJECTIVES

The objective of this project is to develop simulation and design methods for solar energy processes. The proposed work is in the following three areas:

(1) Development of TRNSYS components to further enhance the TRNSYS program in the areas of industrial process heat, controls, passive heating, photovoltaics, multizone buildings, chemical heat pumps, and thermosyphon systems.

(2) Development of design procedures for solar thermal processes. This includes further development of $\bar{\phi}$ and $\bar{\phi}$,f-chart approaches and development of components like FCHART.

(3) Providing services to TRNSYS and FCHART users on the operation of their programs.

SUMMARY

The current contract is pending. The work is an extension of that undertaken by the University of Wisconsin over the past six years. During previous years, the work has centered on development of the simulation program TRNSYS, of design methods such as f-chart, $\bar{\phi}$, $\bar{\phi}$,f-chart, and the computerized version FCHART. The work will extend the usefulness of these programs.

An indication of the scope of the program is provided by a list of the papers based on it that will be presented at the ISES meeting in June, 1980.

(1) The Effect of Air Flow Rate in Collector-Storage Walls.
(2) Prediction of Direct Gain Solar Heating System Performance
(3) Design Procedure for Solar-Assisted Series Heat Pump Systems
(4) Simplified Design Methods for Photovoltaic Systems
(5) Design of Space Heating Systems Employing Seasonal Sensible Storage
(6) Improvements in the Utilizability Relationships
(7) Comparisons of Chemical Heat Pump and Conventional Solar Heating Systems
(8) The Basis and Effects of Inaccuracies in Diffuse Radiation Correlation

TECHNICAL ACCOMPLISHMENTS

The following are technical accomplishments relevant to the current contract tasks:

- TRNSYS compatible models for continuous and batch chemical heat pump systems have been developed. Comparisons have been made between seasonal performance of conventional liquid-based solar heating and heating by a CHP. The CHP used is a "continuous" system using storage of refrigerant (NH_3) and absorbant ($NaSCN$-NH_3). The COP can be greater than one, leading to reduction in collector area required, but an increase in temperature of collection results.

- A general design method for direct gain passive heating systems has been developed. It is based on a combination of $\bar{\phi}$, the solar load ratio, and a storage-ventilation-ratio which includes effective thermal capacitance of the structure and the allowable room temperature swing. Agreement between TRNSYS simulations and the method is less than three percent on an annual basis.

- An economics subroutine for TRNSYS is complete and working, and a description of it is now being written. It will be included with the next version of TRNSYS to be distributed. The subroutine uses as inputs either the economic parameters P_1 and P_2, or a set of 26 economic parameters including those that make up P_1 and P_2 and also tax incentive structures, etc.

- A method for estimating monthly performance of photovoltaic systems has been developed which accounts for output in excess of loads being dumped, fed back to a utility, or stored in a battery. The photovoltaic component model used in TRNSYS was from ASU. The procedure is based on utilizability concepts. Annual system performance estimates compared to TRNSYS simulations are within a standard deviation of three percent for all system configurations examined.

- A method has been developed for designing building heating systems with storage capacity ranging from a few days (the upper limit of f-chart) to seasonal storage. The method is based on $\bar{\phi}$, the monthly average utilizability, and is used to assess effects of load heat exchanger, tank insulation, collector slope, etc. and the locations for which seasonal storage is most viable.

- TRNSYS compatible models of mass storage walls have been developed. One- and two-dimensional thermal network models of collector-storage walls with air flow through the gap have been compared. The one-dimensional model gives very nearly the same results as the more complex model. The one-dimensional model is used to assess effects of air flow rate and gap heat transfer coefficient on auxiliary energy requirement. It is found that auxiliary heat requirements are not significantly affected by air flow rate.

- A design procedure for series heat pump systems has been developed which accounts for energy delivered from heat pump only, solar only, and combined solar-heat pump modes, and allows for variable COP of the heat pump. The procedure is based on $\bar{\phi}$ and ϕ,f-chart methods. Results agree with TRNSYS within three percent on a seasonal basis.

- A preliminary version of FCHART 4.0 is now operable. The thermal analyses is a combination of the f-chart correlation used in Version 3 of the program, the newer $\bar{\phi}$,f-chart correlation and heat pump design methods. Economic analysis routines have been written. Sections implementing the f-chart correlation, a general optimization algorithm, and for producing output tables are nearly complete. The basic framework of the program is laid out, and most of the constituent subroutines are complete.

FUTURE ACTIVITIES

Contract Activities. The major activities are:

A. TRNSYS Development. The following are the major projects that will be undertaken.

1. Radiation processor—evaluate the various methods of separating total radiation into beam and diffuse components, and compare these methods to existing data.

2. Contoller—develop a controller component based on microprocessing concepts, and investigate the effects of non-optimum control strategies on performance.

3. Chemical heat pumps—develop component models for chemical heat pump.

4. Industrial process heat—develop and refine component model for 1 and 2 axis tracking concentrating collectors, and other associated industrial equipment.

5. Multizone building models—finalize the preliminary component model for multizone buildings.

B. Design Method Development

The major project will be the completion of Version 4.0 of FCHART. This will include systems such as series heat pumps, industrial process heating systems, long-term storage, passive systems, and improved methods for domestic hot water heating.

Post Contract Activities. The major deliverables of this contract are the TRNSYS and FCHART programs. These are widely used for the design and simulation of solar energy systems. The Solar Energy Laboratory will continue to make these programs available to users.

XIII SOLAR MATERIALS GROUP

DEVELOPMENT OF SELECTIVE SURFACES

THE BERRY GROUP

DE-AS04-78CS34293

JOHN L. COTSWORTH

PERIOD OF CONTRACT: Begin 9/25/78, End 12/30/80

OBJECTIVE

To investigate means of improving selective surfaces on copper, aluminum and stainless steel.

CONCEPT

Over a hundred samples of commercial and experimental selective surface coating candidates for solar absorbers for use in the 140°-170°F range have been collected, optically tested and most of them exposed in an accelerated thermal cycling solar test box designed under ASTM Committee standards to simulate extended periods of solar flat plate collector stagnation up to 450°F.

The purpose of the accelerated testing program is to predict time and conditions for deterioration of optical properties over expected 20-year life of a commercial collector as well as to study the mechanism of such deterioration utilizing within a year's time 150,000 Langleys and thermal cycling equivalent to 20 years use including expected stagnation intervals.

SUMMARY AND TECHNICAL ACCOMPLISHMENTS

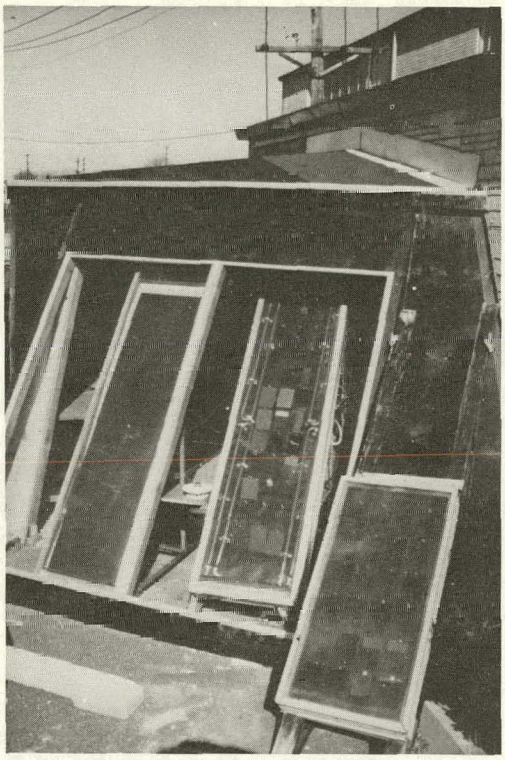
- All preliminary tests indicate electrodeposited black chrome on .1 to .2 mil nickel over copper exhibits durable optical properties. Absorptance has ranged from .93 to .96 and Emittance from .07 to .15 with acceptable commercial quality standards by several processes.

- The control of surface hue under "soot" usually formed on electroplated black chrome is deemed an important indicator of maintainable high Alpha readings. A dark hue rather than a light hue is essential.

- Continuous electrodeposition of black chrome on long copper strips in coil has aided in the successful development of automated production lines for modular fin-tube absorber assemblies, the fin and tubes being joined by (1) high speed welding, (2) roll forming and crimping and (3) roll forming and clipping.

FUTURE ACTIVITIES

By the end of 1980 tests of all commercially potential selective coatings including paints will have been completed for the 140°-170° range. Methods of coating application other than electroplating are also included, i.e. Vapor Deposition, CVD, Sputtering, etc.



Solar Coatings Test Facility

DEVELOPMENT OF SUPERIOR LIQUID COOLANTS CCF-1

DOW CORNING CORPORATION

DOE CONTRACT NUMBER EM-78-C-04-4296

JAMES A. MARINIK

SEPTEMBER 1, 1978 - DECEMBER 31, 1979

OBJECTIVE

The specific objective of this work was to establish the most cost effective solar heat transfer fluid through a comprehensive study of the four most common fluids being used. Criteria for making the assessment was the relative results of F.H.S.A. toxicological studies, fire hazards testing, thermal efficiency performances, corrosion studies, collector stagnation testing and physical property comparison data of various fluids.

CONCEPT

Dow Corning Corporation has conducted a 15 month study to determine the cost effectiveness of SylthermTM 444, a silicone heat transfer liquid, as compared to representative samples of three other commonly used fluids. The studies undertaken for this contract were broadly categorized as A) Data Collection and B) Analysis and Cost Effectiveness Determination. Contributing to cost effectiveness is the simplification of solar collector systems by the elimination of devices and premium metals used to protect against freezing, over-heating and corrosion. Cost effectiveness is evaluated from a variety of other data including stagnation performance in solar collectors.

SUMMARY

Criteria for making the assessment were relative results of fluid toxicity tests, fire hazards tests, collector stagnation tests and physical property comparison data of various fluids. The specific fluids evaluated were SylthermTM 444 silicone fluid by Dow Corning, PAO-LV polyalphaolefin hydrocarbon by Uniroyal, Prestone II® ethylene glycol/water solution by Union Carbide and Ambitrol NTC® propylene glycol/water solution by Dow Chemical. Although there is no essential difference in the installed cost when comparing solar systems based on each of these fluids, there is a very large cost difference between the systems when life cycle costing is performed on the systems. The system representing propylene glycol/water is by far the most costly system followed by the system representing ethylene glycol/water due to possible failures and maintenance schedules. The Uniroyal PAO-LV polyalphaolefin system is the third most expensive system. The SylthermTM 444 silicone system is the least expensive, offering little or no potential for catastrophic failure and not requiring any fluid maintenance.

TECHNICAL ACCOMPLISHMENTS

With regard to physical property data, the relatively high vapor pressure of the Ambitrol NTC® and Prestone II® water solutions presents a problem. Any system containing these fluids must be designed to accommodate high pressures. High pressure should not be a problem with either the PAO-LV or SylthermTM 444 fluids.

The results indicated that none of the fluids are toxic according to FHSA classifications for acute oral or dermal toxicity. Nor can any one of them be classified as an eye or skin irritant.

Low temperature viscosity data showed that the PAO-LV was much harder to pump at sub-freezing temperatures. A potential for non-circulation and premature pump failure was deemed to exist.

Corrosion analysis showed evidence of severe corrosion with the Ambitrol NTC®/water system in aluminum absorber plates.

The fluids were exposed to long-term conditions of stagnation in solar collectors to accelerate aging. Testing of these aged fluids indicated that the flash points for both the Ambitrol NTC® and Prestone II® solutions were dangerously low.

When the fluid properties, as determined by the test data, are taken into account in the system design, there is essentially no difference in the installed cost.

Economic analysis using the four different fluids indicates a major difference in maintenance costs over the life of the systems. Experience and testing has shown that SylthermTM 444 will exceed the 25 year life selected for analysis. No SylthermTM 444 maintenance is anticipated. Maintenance cost for the fluids are in decreasing order: Ambitrol NTC® > Prestone II® > PAO-LV > SylthermTM 444.

The potential for catastrophic failure was similarly evaluated for the life of each system. The projected cost of these fluid related failures is given in decreasing order: Ambitrol NTC® > Prestone II® > PAO-LV > SylthermTM 444.

Life cycle costs are a direct function of heat transfer fluid choice. Based on the economic analysis, fluid preference decreases in the order: SylthermTM 444 > PAO-LV > Prestone II® > Ambitrol NTC®.

FUTURE ACTIVITIES

Contract activities. The work for this contract has been completed.

Post-contract activities. Dow Corning is marketing SylthermTM 444 and SylthermTM 800, a higher temperature heat transfer liquid for industrial applications and concentrating collectors.

Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting
March 1980

PUBLICATIONS/REPORTS/REFERENCES

Development of Superior Liquid Coolants CCF-1, Final Technical Report, September 1, 1978 - December 31, 1979, by Robert M. Hodges, Contract EM-78-C-04-4296, December, 1979, 153p.

Copies available from:

Charles W. Leach
Government Marketing - C02318
Dow Corning Corporation
P.O. Box 1767
Midland, MI 48640

or

U.S. DOE - T.I.C.
P.O. Box 62
Oak Ridge, TN 37830

DEVELOPMENT OF IMPROVED INSULATION MATERIALS*

DOW CORNING CORPORATION

EM-78-C-04-4295

JAMES A. RABE

SEPTEMBER 1, 1978 - SEPTEMBER 30, 1979

OBJECTIVE

The objective of this project was to demonstrate a cost effective silicone foam insulation offering low thermal conductivity, resistance to outgassing and moisture retention, thermal stability, and flame resistance. The effort was to include formulation adjustments to obtain a low density (1-5 pcf) foam, performance testing to evaluate the foam's resistance to conditions within a stagnant solar collector, and a calculation of cost effectiveness.

BACKGROUND

The thermal stability, weatherability, and flame resistance properties desired of solar collector insulation are inherent in many silicone materials including at least one commercially available foam, Dow Corning® 3-6548. However, the high density (17-25 pcf) and thermal conductivity [0.542 BTU-in/(ft^2 hr°F)] of this product make it unattractive for such use. Similar formulations had been demonstrated with densities as low as 5 pcf and K-factors of 0.27 BTU-in/(ft^2 hr°F) and it appeared that further improvement was possible. These foams are prepared by reacting OH - functional materials with SiH - containing species in the presence of a catalyst. This liberates hydrogen, which acts as the blowing agent, and simultaneously produces crosslinks to cure the material. Two-part systems which will react when mixed at room temperature can be formulated.[1,2,3] Such products are designated Type IA foams below. One-part systems which are stable at room temperature but which react when heated can also be prepared.[4] These foams are designated Type IB below.

A silicone - "urethane" hybrid foam had also been investigated. It was prepared by reacting tolylene diisocyanate with a mercapto-functional silicone polymer and water to generate urethane-like crosslinks and CO_2 blowing agent.[5] The material was evaluated because it might offer the strength of urethane foam while retaining some of the stability of silicone foams. It is referred to below as Type II foam.

Any of the above foams could be installed as the only insulation in a solar collector. Alternatively, they could be part of a composite, in which the silicone foam is placed between the absorber plate and a layer of less expensive but thermally unstable insulation.

SUMMARY

The contract is complete and the final report has been written.[6] Formulation modifications have produced 2-3 pcf density versions of Type IA and Type II foams, while the lowest density acheived with Type IB was 6 pcf. The thermal stability of Type IA foam is superior to that of Type II foam, and both are better than polyurethane. Type IA foam is flame retardant and has excellent weatherability. When installed in a solar collector, it exhibits an insulating ability comparable to an equal thickness of fiberglass insulation. Type IA foam does not outgas or show any other sign of degradation during a 30 day stagnation test, and a collector containing Type IA foam by itself or as a composite with isocyanurate foam meets HUD Cycle 4 Thermal Performance Test requirements. The initial cost of silicone foam insulation would be greater than that of fiberglass or isocyanurate foam insulation. However, its superior thermal stability, flame resistance, excellent weatherability, and the freedom in collector design which those properties allow may make the silicone foam insulation more cost effective over the lifetime of a solar energy system.

TECHNICAL ACCOMPLISHMENTS

- Density reduction was accomplished for Type IA and IB foams by performing Plackett-Burman and Box-Behnken designed experiments on their formulations. While the lowest density obtainable in the Type IB work was 6 pcf, Type IA density could be reduced to about 1.5 pcf. However, the best overall Type IA propety profile (including density, friability, cell size, and K-factor) was acheived at 2.5-3 pcf. The density of Type II foam was reduced to 2 pcf without designed experiments. The thermal conductivities of low density Type IA and Type II foams were nearly identical to those of previous 5 pcf formulations. Apparently, the expected reduction in conductive heat transfer was offset by an increase in radiative heat transfer as density was reduced below 5 pcf. The K-factor of the final formulations [0.27 BTU-in/(ft^2 hr°F)] matches that of fiberglass insulation.

- The stability of low density silicone foams was evaluated by thermogravimetric analysis, aging at 200°C, weatherometer tests, flammability tests, and a 30 day stagnation test in a solar collector. Both Type IA and Type II foams possess greater thermal stability than urethane foam with Type IA being the most stable of the three. The thermal conductivity of Type IA foam remains unchanged after 30 days of aging in a 200°C oven, and its

compressive strength remains constant except for a slight increase during the first day. The foam also remains unchanged after 2000 hours of exposure to filtered UV radiation and water spray (ASTM-0822 condition E) in a weatherometer. After a 2 hr/200°C postcure or after standing for two days at room temperature, Type IA silicone foam passes the California Bulletin #117 burn test.

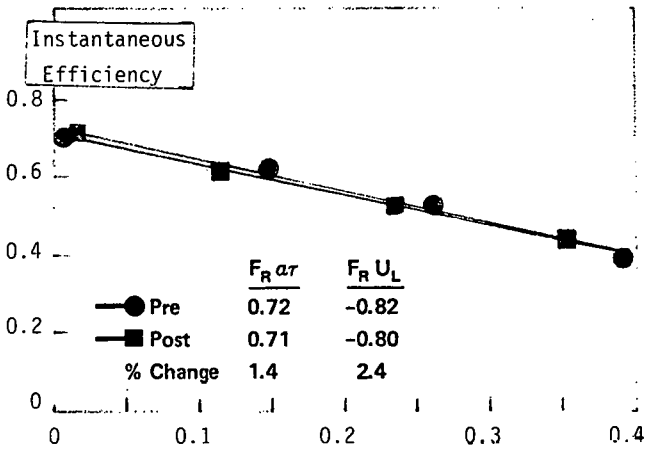
• The standard three inches of fiberglass insulation in two LOF SunPanel® Model 121 solar collectors was replaced, in one case by three inches of Type IA silicone foam and in the other by a composite of 1.5 inches of Type IA foam and 1.5 inches of Upjohn U-Thane® 210 isocyanurate foam. The collectors were tested by DSET Laboratories, Inc. as follows:

1. ASHRAE 93-77 Thermal Performance Test.
2. 30 day stagnation exposure test during which the collectors tracked the sun on an equatorial mount.
3. Repeat of full ASHRAE 93-77 test.

The initial performance of both collectors matched or exceeded that of the standard fiberglass-insulated collector. During stagnation, the changes in $F_R \alpha\tau$ and $F_R U_L$ parameters were less than 10% for both collectors. Thus, they met the HUD Cycle 4 Thermal Performance requirements. (Figure 1 shows the data for the collector containing composite insulation). In addition, there was no sign of outgassing or structural change in the insulation of either collector.

• A cost effectiveness comparison between Type IA silicone foam, Type IA foam - isocyanurate foam composite, isocyanurate foam, and fiberglass insulations a over 25 year period was generated with the aid of F-chart version 2, a computer program developed at the University of Wisconsin Solar Energy Laboratory. The initial cost of an 800 ft² collector system containing silicone foam insulation was estimated to be about 7.5% greater than a system containing isocyanurate or fiberglass, while a system containing silicone-isocyanurate composite insulation was intermediate. Because of this initial cost difference a system containing conventional insulation would be the most cost effective if its performance remained constant. However, its performance would be expected to drop as outgassing and other effects of thermal decomposition of the insulation reduce the collector's efficiency. Such changes should be minimal with silicone insulation. No quantitative comparison of long-term efficiency losses could be obtained, but it was shown that less than a 1% per year efficiency loss with conventional insulation would destroy its advantage. Thus, the superior stability of silicone foam may make it more cost effective than isocyanurate foam or fiberglass insulation over the lifetime of a solar energy system.

CHANGE DURING STAGNATION COMPOSITE INSULATION



FUTURE ACTIVITIES

This contract is complete. However, the silicone foams evaluated have been prepared on a laboratory scale only. A proposal has been submitted to D.O.E. for a contract continuation during which larger scale production of (a) 3 pcf Type IA foam insulation, and (b) silicone-isocyanurate composite foam would be demonstrated. The work would also include longer term performance testing to compare quantitatively efficiency losses of collectors containing silicone foam insulation vs. collectors insulated with conventional materials.

REFERENCES AND REPORTS

1. Smith, S. B., U.S. Patent No. 3,923,705 (1975).
2. Kittle, R. E., and Ronk, G. M., U.S. Patent 4,026,844 (1977).
3. Bruner, L. B., U.S. Patent 3,070,555 (1962).
4. Lee, C. L., and Ronk, G. M., U.S. Patent 4,026,835 (1977).
5. Homan, G. R., and Lee, C. L., U.S. Patent Pending.
6. Final Report, D.O.E. Contract No. EM-78-C-04-4295, Dow Corning Corporation, "Development of Improved Insulation Materials", September, 1979.

* This work was supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U.S. Department of Energy.

LOW-COST SOLAR ANTIREFLECTION COATINGS

HONEYWELL, INC.

DE-AC04-78CS35300

RAY J.H. LIN

24 JULY 1978 - 28 FEBRUARY 1980

OBJECTIVES

The objectives of this program were: a) to develop an accurate and rapid analytical method for monitoring the antireflection (AR) glass etching production process, b) to extend the developed large-scale AR etching process to new types of glass which are now most widely used as collector covers, and c) to improve the coating durability and demonstrate the large-scale production feasibility of organic AR coating on glass.

BACKGROUND

Etched AR coating on glass increases the solar transmission of glass by about 6%.[1] The use of two AR etched glass covers can increase the solar collector efficiency by ∿20-25%. The estimated manufactured cost including materials and fabrication is ∿10¢/ft^2.

The etching process had been scaled up to etch full-size glass panes at Honeywell, but chemical control of the etching solution had not been fully investigated and remained a problem. There was a lack of a fast and accurate testing method for monitoring the AR etching process. Analytical techniques were to be developed to solve this problem.

The scaled-up AR etching process was developed for the previously widely used ASG low iron glass which was discontinued. This program was also to extend the developed large-scale AR etching process to the new types of glass (e.g. ASG Solartex) which are now most widely used as solar collector covers.

Another AR coating on glass had been successfully made from Teflon FEP polymer[1,2]. Teflon FEP film had demonstrated 20-year exterior durability in Florida. The development was in its early stages but already showed promise of improving the transmittance of glass by ∿5 percent at less than 1¢/ft^2 for the material cost. There were some limitations in the coating and processing. The coating was applied by dipping. Thickness control had to be closely maintained to achieve low reflectance. The coating also had poor adhesion and abrasion resistance. The program was designed to address these problems and determine the feasibility of scaling up the process.

SUMMARY

The program was completed. All major objectives were achieved.

TECHNICAL ACCOMPLISHMENTS

- Developed analytic methods to monitor/control the process etchant solution
- Identified the role of the particulate/colloid nature of the etchant in determining the process equilibrium operating point
- Developed a phenomenological model for the process key reaction species incorporating the role of the etchant colloid phase
- Successfully extended the AR etching process to ASG Solartex glass in large-scale production
- Demonstrated scale-up feasibility for organic AR coating process for glass panels up to one foot by one foot with good batch sample to sample repeatability
- Significantly improved organic AR coating durability by a glass etch/silane coupling agent precoating processing step

FUTURE ACTIVITIES

Contract Activities. Deliver Final Report.

Post-Contract Activities. The AR etched glass has already been commercialized and is available to the public.

REPORTS

1. R.J.H. Lin, J.C. Lee, and P.B. Zimmer, "Low-Cost Solar Antireflection Coatings," Annual Report to DOE, October 1979.

REFERENCES

1. H.Y.B. Mar, R.J.H. Lin, P.B. Zimmer, R.E. Peterson, and J.S. Gross, "Optical Coatings for Flat Plate Solar Collectors," Final Report for ERDA under Contract No. NSF-C-957 (AER-74-09104), September 1975. Available from NTIS.

2. R.J.H. Lin and P.B. Zimmer, "Optimization of Coatings for Flat Plate Solar Collectors," Final Report for ERDA under Contract No. EY-76-C-02-2930, July 1977. Available from TIC, Oak Ridge, TN.

SELECTIVE PAINT AND BLACK CHROME COATINGS DEVELOPMENT

HONEYWELL INC.

DE-AC04-78CS14287

R.J.H. LIN AND P.B. ZIMMER

5 JUNE 1978 - 4 DECEMBER 1979

OBJECTIVE

The purpose of this program was to improve the performance of solar selective black chrome and paint coatings. Extensive study of the solution chemistry of the black chrome process and various undercoat/substrate combinations would lead to improved coating durability (especially thermal stability) and optical properties, improved control and reproducibility of the fabrication process, and reduced coating costs. Improving adhesion and abrasion resistance were the major concerns in the paint coating efforts, as was the development of techniques for large-scale application.

BACKGROUND

Many years of selective coatings research at Honeywell led to the selection of electroplated black chrome and selectively absorbing paints as the prime coatings candidates for solar absorbers. Recently, a program[1] was completed in which these coatings were optimized on the basis of their optical properties and durability.

Black chrome coatings produced during this program have very good optical properties (α = 0.95, ε = 0.09) and have been estimated to have a life of greater than 20 years, when a 1/2-mil nickel undercoat is used. A thinner undercoat (1/4-mil) has been shown to possibly provide sufficient protection for the steel substrate and results in a significant cost reduction. Undercoat/substrate combinations still needed to be investigated to achieve a low-cost coating system.

Selectively absorbing paint coatings made with iron-manganese-copper oxide were shown to have α = 0.92, ε = 0.13 when a silicone binder was used and α = 0.92, ε = 0.10 when an aliphatic urethane binder was used. These coatings were environmentally stable and low cost ($\sim$5¢/ft^2) but needed improvement in mechanical durability, adhesion and abrasion resistance. Large-scale fabrication techniques also needed to be developed.

SUMMARY

The program was completed.. Black chrome thermal stability and reproducibility were improved. Scale-up feasibility of selective paints has been demonstrated.

TECHNICAL ACCOMPLISHMENTS

Black Chrome

- Improved thermal stability of black chrome--from 250°C to 400°C
- Determined the effects of bath components and plating parameters on black chrome thermal stability and environmental durability
- Established optimal ranges of plating bath components and plating parameters for producing durable and optically efficient black chrome
- Improved control and reproducibility of the fabrication process
- Prepared a "Plater's Guide"
- Reduced coating costs for BLK-Cr on steel system
- Identified the most cost-effective BLK Cr on Aℓ Coating System--Aℓ/Zn/Ni(1/4-Mil)/BCr
- Demonstrated the feasibility of continuously coating BLK-Cr on Aℓ-foil

Selective Paint

- Thickness sensitive selective paint has been scaled up and fabricated on thirty-five hundred square feet of aluminum foil using a high-speed roll coater. The resulted optical properties were α = 0.92 and ε(100°C) = 0.14.
- Thickness-insensitive paint has been developed with α = 0.90 and ε = 0.30.
- Adhesion and abrasion resistance of thickness-sensitive selective paint has been significantly improved.

FUTURE ACTIVITIES

Contract Activities. The draft final reports of black chrome and selective paints were submitted and approved. The final reports are being published.

Post-Contract Activities. A follow-on proposal to develop large-scale technology for selective paints was submitted to DOE/LASL.

REPORTS

1. R.J.H. Lin and P.B. Zimmer, "Selective Paint and Black Chrome Coatings Development," Semi-Annual Report to DOE, December 1978.

2. W.D. McKelvey, P.B. Zimmer, and R.J.H. Lin, "Selective Paint Development," Technical Progress Report to DOE, August 1979.

REFERENCES

1. R.J.H. Lin and P.B. Zimmer, "Optimization of Coatings for Flat Plate Solar Collectors," Final Report for ERDA under Contract No. EY-76-C-02-2930, July 1977. Available from TIC, Oak Ridge, TN, or R.J.H. Lin, Honeywell Inc., Systems and Research Center, 2600 Ridgway Parkway, Minneapolis, MN 55413.

SELECTIVE IR REFLECTIVE COATINGS

HONEYWELL INC.

EM-78-C-04-4299

A.R. LEFKOW AND J.C. LEE

24 JULY 1978 - 23 OCTOBER 1979

OBJECTIVE

The objective of this program was the development of cost-effective methods for coating plastic solar collector glazings/windows with selective infrared (IR) reflective coatings. These greenhouse effect/heat mirror coatings enhance the performance and economic feasibility of solar collector systems, especially passive systems, and have application for reducing heat loss through building windows.

CONCEPT

Coatings with high infrared reflectance ($R_{10\mu} \sim 0.75 - 0.8$) have been fabricated on glass using sputtering and spray pyrolysis where a substrate temperature of higher than 450°C was used. The major technical limitation for coating plastic substrates is that a low temperature process has to be used.

Our approach to coating plastics (thick sheets and thin films) was to explore the possibility of adapting two low substrate temperature deposition processes, namely ion-plating and chemical vapor plasma deposition (CVPD) to apply metal oxide semiconducting thin films to plastic solar glazing materials. These semiconducting oxide thin films, with their plasma edges adjusted to 2.5 microns, have the solar spectral selectivity desired by virtue of their free-carrier metallic reflectivity at frequencies below their plasma frequency and transparency above the plasma frequency up to their intrinsic short wavelength absorption edge. Indium-tin oxide (In_2O_3/SnO_2), antimony doped tin oxide ($Sb:SnO_2$) and cadmium stannate (Cd_2SnO_4) were identified as candidate coating materials for this application, with only the first two explored during the course of this program. Coatings of indium-tin oxide, tin oxide and antimony doped tin oxide were deposited in two separately configured ion plating systems. Tin oxide and antimony doped tin oxide films were also deposited via an RF plasma reactor. Comparison of the electrical and optical properties of coatings deposited by both techniques clearly indicates that the CVPD technique is superior for this program.

TECHNICAL ACCOMPLISHMENTS

- Chemical vapor plasma deposition (CVPD) was identified as the most successful deposition approach investigated.

- Sb doped CVPD grown tin oxide films fabricated achieved 80-85% visible transmission with 35-40% (at 10 μm) and 50-55% (at 40 μm) IR reflectance.

- From the Hagen-Rubens relation, a factor of 6-fold increase in optically active doping concentration level is estimated to be required to shift the plasma edge to the solar spectrum optimum 2 microns and raise the IR reflectance to 80% state-of-the-art (for this materials system) performance. This was not further pursued because of the depletion of the program resources.

FUTURE ACTIVITIES

None.

REPORT

1. A.R. Lefkow and J.C. Lee, "Selective IR Reflective Coatings Development," Final Report to DOE, October 1979.

SUPERIOR HEAT TRANSFER FLUIDS FOR SOLAR HEATING AND COOLING APPLICATIONS

MONSANTO RESEARCH CORPORATION, DAYTON LABORATORY

CONTRACT DE-AC04-78CS45356

LEO PARTS, PRINCIPAL INVESTIGATOR

21 AUGUST 1978 - 31 DECEMBER 1979

OBJECTIVE

Evaluate commercially available, developmental, and candidate organic heat transfer fluids for solar heating and cooling applications. Provide information and guidelines for designers, manufacturers, and users of solar energy collection systems to allow them to select optimum fluids for their specific systems and applications.

BACKGROUND

Heat transfer by fluids is a mature engineering technology. The scientific and engineering aspects of the process have been described in numerous books [1-4] and other publications. Design equations have been developed that cover fluid flow and heat exchange conditions encountered in industrial and solar systems. Most of the knowledge gained in industrial fluids technology is directly applicable in solar design.

In the selection of heat transfer fluid, the collector designer, manufacturer, and user are limited to known, available fluids that must meet certain performance and handling properties requirements. The number of such fluids is not large. Prevailing technological and economic factors affect the availability of the chemically different types of fluids at any time.

The most recent compilation of information on heat transfer fluids was published by Geiringer as a handbook in 1962 [5]. A significant part of information compiled in this book has become obsolete because of the withdrawal of fluids from marketplace for environmental, health, and economic reasons.

SUMMARY

Information on limiting, design, and handling properties on fifty commercial and developmental heat transfer fluids was acquired, organized, and summarized in reports [6 and 7]. The final report [7] contains guidelines for the selection of superior fluids to meet specific collector operational and compatibility requirements. These guidelines include the use of heat transfer efficiency factors, that were calculated for the temperature ranges for which thermophysical data for the fluids were available.

TECHNICAL ACCOMPLISHMENTS

- The required design and handling properties of the fluids were determined through a survey in which 115 designers and manufacturers of solar collectors and collection systems participated and supplied information.
- A state-of-the-art survey of commercially available organic heat transfer fluids provided information on fifty fluids. These were grouped into nine classes. The final report contains an extensive compilation of tabularly organized information on limiting, design, and handling properties of these fluids. The limiting properties affix the use temperature ranges of the fluids. The design properties include the following thermophysical data: densities, vapor pressures, viscosities, specific heats, thermal conductivities, heats of vaporization and thermal conductivities. The handling properties include: compatibility and incompatibility with construction materials, chemical sensitivity, ignitability, physiological effects, and biodegradability characteristics.
- Ignitability tests were conducted with fluids for which autoignition and/or flash ignition data were not available from the manufacturers of the fluids.
- Mutagenicity tests were conducted with thirty fluids, using *Salmonella typhimurium* bacteria.
- Guidelines were developed for the selection of superior fluids to meet specific collector operational and compatibility requirements.
- Recommendations were made for future work pertaining to solar fluids.

FUTURE ACTIVITIES

Work under Contract DE-AC04-78CS45356 has been completed. A proposal for extension of this work has been submitted to DOE. The proposed program includes the preparation of a manual on fluids for solar heat transfer and storage applications. This manual would contain a tutorial section outlining pumping power and heat transfer efficiency calculations. To facilitate overview of information for comparative evaluation of fluids, most data would be presented in graphical form.

REFERENCES/REPORTS

1. D. Q. Kern, "Process Heat Transfer," McGraw-Hill Book Company, New York, 1950.

2. W. H. McAdams, "Heat Transmission," Third Edition, McGraw-Hill Book Company, New York, 1954.

3. R. C. Reid and T. K. Sherwood, "The Properties of Gases and Liquids; Their Estimation and Correlation," McGraw-Hill Book Company, New York, 1958.

4. C. O. Bennett and J. E. Moore, "Momentum, Heat, and Mass Transfer," McGraw-Hill Book Company, New York, 1963.

5. P. L. Geiringer, "Heat Transfer Media," Reinhold Publishing Corporation, New York, 1962.

6. L. Parts, D. R. Miller, and Q. E. Thompson, "Superior Heat Transfer Fluids for Solar Heating and Cooling Applications," ALO/45356-1, Semiannual Report under Contract DE-AC04-78CS45356, September 1978.

7. L. Parts, D. R. Miller, J. W. Leffingwell, and Q. E. Thompson, "Superior Heat Transfer Fluids for Solar Heating and Cooling Applications," ALO/45356-2, Final Report under Contract DE-AC04-78CS45356, March 1980.

NON-GLASS GLAZINGS

RESEARCH TRIANGLE INSTITUTE

DE-AC04-78CS30132

C. G. PITT

SEPTEMBER 1978 - SEPTEMBER 1980

OBJECTIVE

The objective of this program is to determine if silicones are useful competitive glazing materials for solar collectors. The evaluation includes a determination of the effect of various accelerated weathering tests applied to silicone elastomers, low temperature potting compounds and reinforced silicone rubber. The abrasion resistance and dirt retention of such materials are also being evaluated. An economic analysis of the use of silicones as an alternative to glass glazing in flat plate collectors is being performed.

BACKGROUND

Silicones are well known for their outstanding resistance to weathering. This in part relates to their basic structure $(SiO)_n$. In particular, silicones retain their properties over a wide temperature range, -50° ↔ 400°F, and are not adversely affected by moisture, are resistant to ultraviolet and thermal degradation, are biologically inert, chemically inert and flame resistant. They are therefore logical candidates for evaluation as glazing materials and modification to alleviate weaker aspects such as relatively poor abrasion resistance. The Polymer Research Laboratory at Research Triangle Institute has 19 years of experience in both basic and applied aspects of polymer study, including investigations of the radiolysis and photolysis of polydimethylsiloxane, the modification of this polymer and the synthesis of highly cross-linked siloxanes.

SUMMARY

Testing of selected silicone materials under exaggerated conditions, i.e., conditions more likely to provoke chemical changes than would be encountered in use, have been carried out to identify the types of changes to be expected in use. One finding is the fact that oxygen tends to promote cross-linking by ultra-violet radiation. Accelerated testing of selected samples has been carried out at DSET Laboratories, Phoenix, Arizona. The dust retention and decrease in transparency has been evaluated for samples exposed to 5 x 10^5 and 10^6 langleys. Chemical characterization and mechanical property determination of virgin and exposed samples is under way. The first phase of an economic analysis of the use of silicones as an alternative to glass glazing has been completed.

TECHNICAL ACCOMPLISHMENTS

- A number of silicone polymers and composites have been obtained or prepared. These are in the form of low molecular weight liquid samples, solid elastomer or rubber films and reinforced rubber films. The samples include variations in the proportion of pendant phenyl groups. For solid samples, varying amounts of silica fillers are represented. Reinforcement is in the form of glass and Teflon mesh.

- The effect of thermal exposure on weight loss and solar transmission has been determined for samples kept at 160°C in air and vacuum. Weight loss is greater in vacuum than in air and may be caused by the loss of oligomers. Small changes in solar transmission are noted, occurring for the most part in the first week of heating.

- Studies of the effect of ultraviolet radiation from a medium pressure mercury lamp on a series of liquid siloxanes with a varying proportion of phenyl pendant groups has revealed yellowing in those siloxanes containing pendant phenyl groups. Crosslinking was promoted by the presence of air; for dimethylpolysiloxanes the time to reach the gel point was reduced some 15-fold by the presence of air.

- The effect of ultra- violet radiation (medium pressure mercury lamp) on weight loss and solar transmittance has been determined. Although a significant proportion of the lamp's output is of lower wavelength than present in the solar spectrum at the earth's surface, the results are qualitative indicators of the types of changes to be expected. Very small changes in weight losses have been noted and no significant change in solar transmission has been found for most samples. All the samples become brittle.

- Selected silicone samples, an elastomer, reinforced silicone rubbers and low temperature curing potting compounds have been exposed to accelerated solar irradiation tests at DSET Laboratories. The solar transmittance before and after removal of dirt from samples exposed to 5 x 10^5 and 10^6 Langleys has been characterized.

Dirt retention is a significant problem with most but not all films. The dirt is adherent, with ultrasonication in soap solution required to remove most of it; brushing in soap solution to remove it all (see Figure 1). Characterization

of the surface using the attenuated total reflection technique and a fourier transform infrared spectrometer is in progress.

• The first phase of the economic analysis indicates that glass fiber reinforced silicone, but not unreinforced film, may be cost competitive with glass because of the reduction in material requirements.

FUTURE ACTIVITIES

1. Studies of abrasion effect on silicone films.
2. Comparative dirt retention studies (glass, PMMA, silicones)
3. Accelerated laboratory studies restricting irradiation to wavelengths present in solar spectrum at the earth's surface (< 290 nm)
4. Characterization of samples after exposure to 2 x 10^6 langleys of solar radiation.
5. Mechanical testing of samples.
6. Preliminary study of anti- abrasion coatings.

Several areas of interest for future programs exist. These include:

1. Evaluate laminates where silicones are used as abrasion and weather resistant coatings on cheaper polymers.
2. Evaluate plasma treated or plasma polymer coated organic polymers, to create a dust, photo and abrasion resistant coating.
3. Evaluate the deterioration of glass fiber reinforced silicones now believed to be associated with hydrolysis of the glass at the interface.
4. Develop quantitative data on dust accumulation and removal as a function of glazing material.

PUBLICATIONS

A. Schwartz, J. B. Weisbrook, D. T. Turner, "Promotion of Photocrosslinking of Polysiloxanes by Oxygen", submitted to Macromolecules.

REPORTS

Semiannual Reports
September 1978 - April 1979
April 1979 - September 1979

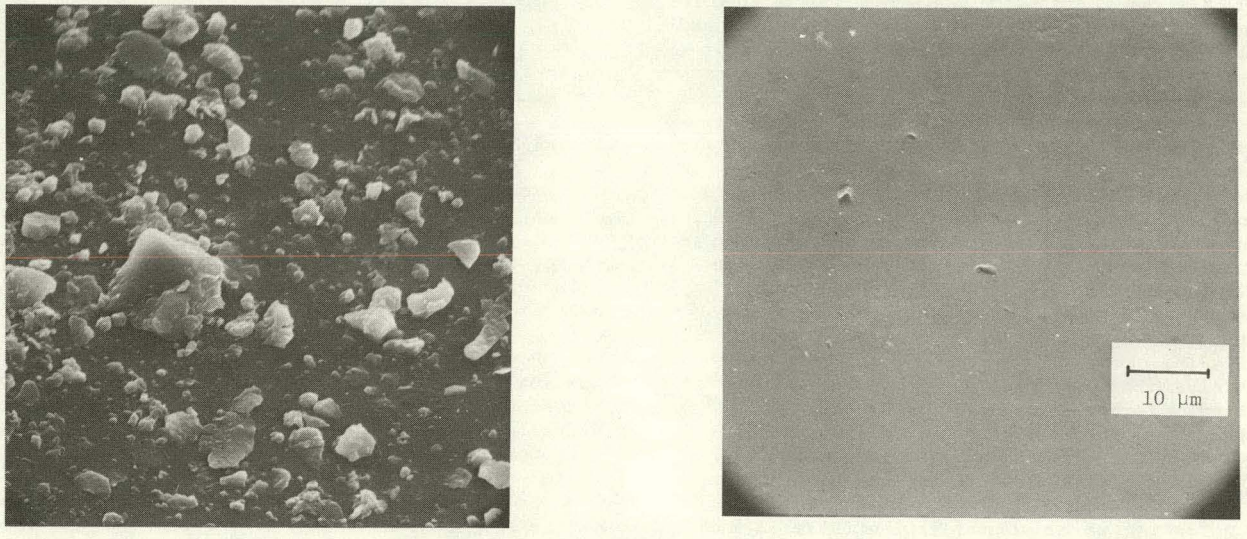


Figure 1. Scanning electron micrographs (equal magnification) of the surface of a silicone film exposed to 10^6 Langleys at DSET Laboratories and cleaned by ultrasonication in a 0.5% soap solution for 30 minutes (left) and by subsequent brushing in a 0.5% soap solution for 1 minute (right).

DEVELOPMENT OF POLYIMIDE MATERIALS FOR USE IN SOLAR ENERGY SYSTEMS

SOLAR TURBINES INTERNATIONAL

EM-C-04-5305

JOHN GAGLIANI

AUGUST 1978 - FEBRUARY 1980

OBJECTIVE

The major objective of this program is to optimize and characterize fire resistant, lightweight polyimide foams with improved insulation properties and a wide spectrum of rigidity and density for use in active and passive solar energy systems.

CONCEPT OR BACKGROUND

Foams have been available for many years and have become basic elements of conventional thermal insulation. Because of their large market, these foams have been modified to meet specific requirements including modifications to provide fire safety. These modifications have been carried out by the addition of fire retardant chemicals or by alteration of the polymer structure with reactive flame inhibiting groups. However, the many efforts to make these foams fire retardant have also increased the hazard of systems and personnel exposed to, or in the vicinity of the fire due to heavy emission of smoke and toxic by-products.

Solar Turbines International proposes to establish the most critical requirements for these materials through a new family of foams which are fire resistant, and no smoke emitting. These foams will play a vital role in providing lightweight systems for retaining solar generating heat and protecting sensitive equipment. These materials are based on polyimide technology.

SUMMARY

Two distinct products have been characterized and selected for use in insulation of solar energy systems. These products are derived from polyimide technology and include lightweight open cell flexible foams and rigid load bearing insulating foams. These materials do not burn when exposed to open flame and do not emit measurable quantities of smoke or toxic by-products. The materials possess good environmental and thermal insulating properties.

TECHNICAL ACCOMPLISHMENTS

The polyimide materials developed during the course of this program are open cell foams which are thermally resistant and possess the following major properties:

. The foams do not burn when exposed to open flames (LOI = 40).

. The smoke emission of these foams when exposed to open flames, measured with the NBS Smoke Chamber, is very low (DMS = 1).

. Both rigid and flexible foams have been totally resistant to environmental exposure for at least one year. These tests are still continuing.

. The polyimide foams possess no wicking properties when immersed in water for periods of up to six months.

. The thermal conductivity of the foam is 0.22 Btu/Hr/Ft^2/°F/In.

. The maximum continuous use temperature for these materials is 550°F.

. The flexible foams possess density characteristics in the range of 0.4 to 2.0 lbs/ft^3.

. The rigid foams can be fabricated for use as load bearing insulating foams.

. All these foams are produced from low cost microwave processing using commercially available raw materials.

FUTURE ACTIVITIES

Contract Activities. The program has resulted in optimization and selection of two distinct advanced polyimide insulating materials for use in solar energy systems. The major objectives have been accomplished and prototype samples for each of the candidates have been submitted.

Post-Contract Activities. The immediate effort must be directed toward coordination with other projects or programs to field test these polyimide products in solar energy systems. The data will then be used for commercialization of these products.

In addition to field testing activities, Solar Turbines International recommends a continuation of the program leading to polyimide structural foams possessing controlled thermal expansion characteristics. Solar Turbines International has developed methods for varying the coefficient of thermal expansion of polyimide materials. With this technique, the thermal expansion of any material used in the system can be matched. We propose to use this technology to fabricate prototype solar parabolic collectors which will be insulated by and constructed of polyimide materials.

PUBLICATIONS

Development of Polyimide Materials for Use In Solar Energy Systems, Final Report SR79-R-4650-14.

DEVELOPMENT OF SELECTIVE SURFACES

TELIC CORPORATION

DE-AC04-78CS35306

DR. JOHN A. THORNTON

SEPTEMBER 1978 - MARCH 1980

OBJECTIVE

The objective of the program is to develop methods for producing low cost selective absorber surfaces by dc reactive sputtering using magnetron type sources. Two representative absorber coatings were selected for development as vehicles for evaluating the sputtering technology. They were metal/metal-oxide cermets of the black chrome type and a multi-layer metal/oxide coating (Al_2O_3-Mo-Al_2O_3) which is known to have superior thermal stability. In two proof-of-concept phases a cermet coating was continuously deposited on aluminum foil, and hollow cathode magnetrons were used to deposit the Al_2O_3-Mo-Al_2O_3 coatings over short tubular sections.

CONCEPT OR BACKGROUND

Recent advances in sputtering technology using magnetically confined plasmas in so-called "magnetron configurations" permit coatings to be deposited over large areas with significantly increased deposition rates.[1] In the cylindrical magnetrons an intense and uniform sheet of plasma is magnetically confined over the outer surface of a post cathode as shown in Fig. 1 or over the inner surface of a hollow cathode as shown in Fig. 2. The plasma changes the post cathode into a line type source of sputtered coating material. Substrates may be placed around the circumference as shown in Fig. 1, or continuously passed by the source in an in-line coating mode. Cylindrical-post magnetrons over 2 m long have been fabricated for coating large areas.[2] Tubular substrates can be coated effectively by placing them surrounding a post or on the axis of a hollow cathode. In the planar magnetron shown in Fig. 3 a ring of sputter-producing plasma is magnetically confined over the cathode. These devices are particularly attractive for coating large plates which are transported perpendicular to the long dimension of the cathode. Large planar magnetron coating facilities capable of coating over 10 million ft^2 of surface annually are presently in operation.[3] Thus magnetron sputtering technology offers great promise for providing selective surfaces at low cost.

An effective selective surface consists of a low emittance substrate or base layer, a partially absorbing intermediate layer, and a nonabsorbing antireflective-type (AR) surface layer.[4] The layers may be discrete or graded. The partially absorbing layer may be a cermet, as is effectively the case in black chrome, or a two-layer combination consisting of a semi-transparent metal film over a dielectric layer, as is the

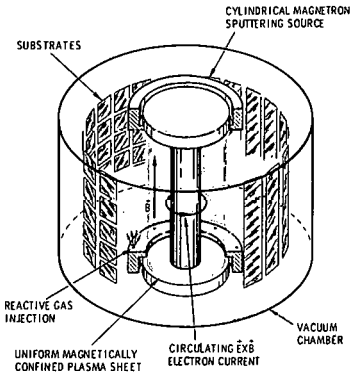


FIG. 1 Schematic illustration of cylindrical-post magnetron sputtering source.

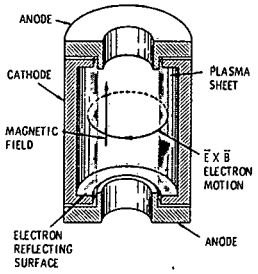


FIG. 2 Cylindrical-hollow magnetron sputtering source. Substrates not shown.

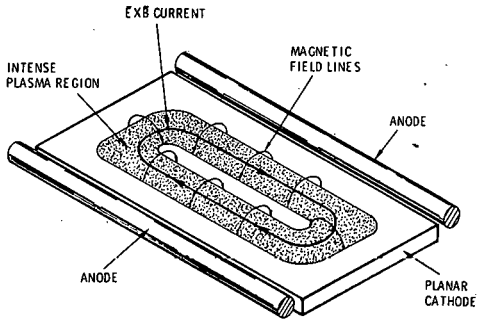


FIG. 3 Planar magnetron sputtering source.

case in the Al_2O_3-Mo-Al_2O_3 (AMA) coating. Our approach was to form cermet partially absorbing layers by dc reactive sputtering with pulsed gas injection and by co-sputtering from two sources. The AMA coatings were originally developed for a high temperature (860°C) space-borne application[5] and were selected for this work because of their superior thermal stability. We used glass, aluminum foil, stainless steel sheet and tubes, and copper sheet substrates in this investigation.

SUMMARY

All the objectives of the program have been achieved. Absorptances (α) of greater than 0.9 and room temperature emittances (ϵ) of less than 0.1 have been achieved with the following cylindrical magnetron sputtered coatings which are representative of the basic types described above: (1) reactively sputtered stainless steel - O_2 cermet with Al_2O_3 AR layer, (2) reactively sputtered stainless steel - CO cermet, (3) graded Cr/Al_2O_3 cermet formed by co-sputtering, and (4) Al_2O_3-Mo-Al_2O_3 (AMA) multilayer coating.

The sputtered AMA coatings show the greatest promise. These coatings exhibit $\alpha \sim 0.94$, $\epsilon \sim 0.07$, and stability in air to 450°C and in vacuum to at least 600°C. They are relatively easy to deposit and have been demonstrated on both tubular and flat substrates. Sputtering multilayer coatings presents little increase in difficulty over single layer coatings. The basic AMA materials (Mo, Al_2O_3 or Al) are in relative abundance and can serve to provide a diffusion barrier (Al_2O_3) and a low emittance underlayer (Mo) if these are required in addition to the absorber coating.

TECHNICAL ACCOMPLISHMENTS

● Coatings in which the partially absorbing layer is a 90 nm thick stainless steel (SS) cermet formed by reactive sputtering SS with pulsed O_2 injection, and the AR layer is 83 nm of reactively sputtered Al_2O_3, have yielded $\alpha = 0.90$ and $\epsilon = 0.07$. The coatings are stable in air at 150°C but lose α at 200°C.

● Coatings in which the partially absorbing layer is a 40 nm thick stainless steel (SS) cermet formed by reactive sputtering SS in Ar & CO, and the AR layer is 90 nm of the material which is formed by sputtering SS in pure CO, have yielded $\alpha = 0.89$ and $\epsilon = 0.08$. These coatings have the advantage of a relatively high deposition rate and were continuously deposited on 12-inch wide 2 mil thick aluminum foil in proof-of-concept experiments. The coatings are stable in air at 150°C but lose α at 200°C.

● Graded Cr/Al_2O_3 cermets have been formed by co-sputtering from Cr and Al_2O_3 (using rf) cylindrical magnetron targets. The coatings yielded $\alpha = 0.92$ and $\epsilon = 0.07$ and are expected to possess good thermal stability. Tests are underway.

● Al_2O_3-Mo-Al_2O_3 coatings, with both direct rf-sputtered and dc reactive sputtered Al_2O_3 layers, have been deposited on both flat plate and tubular substrates. Both cylindrical-post and hollow cathode magnetrons have been used. Optimum coatings typically exhibit $\alpha = 0.94$ and $\epsilon = 0.07$. See Fig. 4. The coatings with the rf-sputtered Al_2O_3 layers have thermal stabilities that are superior to those with the reactively sputtered Al_2O_3. The reactive sputtered coatings are stable to 300°C in air. In vacuum they are stable at 400°C but fail at 500°C. The rf sputtered coatings are stable at 450°C in air (100 hrs) and at least 600°C in vacuum. Higher temperature tests are still underway.

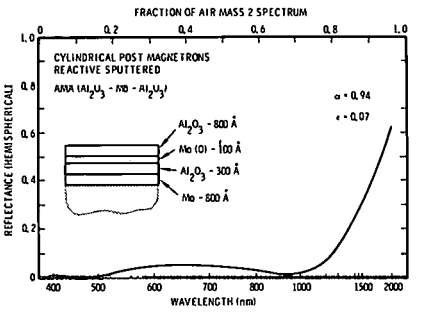


FIG. 4 Reflectance vs wavelength (distorted wavelength plot) for sputtered AMA coating.

FUTURE ACTIVITIES

Contract activities. The thermal testing of the sputter-deposited AMA coatings will be completed. Preliminary deposition experiments will be undertaken using planar magnetrons to deposit Al_2O_3 by reactive sputtering in a geometry compatible with the coating of large plates.

Post-contract activities. Sputter deposited AMA coatings will be sent to commercial vendors for testing. Discussions on the design of a laboratory scale pilot line for AMA strip coating will be undertaken with a commercial firm.

PUBLICATIONS/REPORTS/REFERENCES

1) J. A. Thornton and A. S. Penfold, in Thin Film Processes, ed. by J. L. Vossen and W. Kern, Academic Press, New York (1978), pp. 75-113.

2) A. S. Penfold, Metal Finishing, 77, 33 (1979).

3) J. A. Thornton, "Sputter Deposited Selective Absorber Coatings," Proceedings 2nd Amer. Electroplaters Soc. Inc. Coatings for Solar Collectors Symposium, St. Louis, Missouri (Oct. 1979). (Available from AES, Winter Park, Fl.)

4) G. Hass, H. H. Schroeder and A. F. Turner, J. Opt. Soc. Am. 46, 31 (1956).

5) R. E. Peterson and J. W. Ramsey, J. Vac. Sci. Technol. 12, 174 (1975).

6) J. A. Thornton, A. S. Penfold and J. L. Lamb, "Sputter Deposited Al_2O_3-Mo-Al_2O_3 Selective Absorber Coatings," paper to be presented at International Conf. on Metallurgical Coatings, April 21-25, 1980, San Diego, CA.

STUDIES FOR PREDICTABLY MODIFYING THE OPTICAL CONSTANTS OF DOPED INDIUM OXIDE FILMS

TUFTS UNIVERSITY, DEPARTMENT OF ELECTRICAL ENGINEERING, MEDFORD, MA 02155

DE-AC04-78CS35307

PROFESSOR RONALD B. GOLDNER

Begin 5 JUNE 1978 - End 31 MAY 1980

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) [Fig. 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 hydrolysis 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

To date, the studies have demonstrated that composition changes, and particularly cation doping, could be achieved. This has been accomplished for 8 dopants by a simple and economic spray hydrolysis process. The refractive index at 633 nm wavelength (n_{633}) can be modified by such doping - n_{633} changes $\lesssim$ 5% occur for dopant concentrations $\lesssim$ 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}, but only very small changes have been observed (< 1%), in contradistinction to that previously reported [3].

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, Zr) can be incorporated into indium oxide coatings by a simple and economic spray hydrolysis technique. Concentrations $\lesssim$ 25 mole percent have been readily achieved by this technique.

- n_{633} has been modified by cation doping by spray hydrolysis, with the largest changes occurring for bismuth doping (20% Bi → Δn_{633} = + 0.11), and for boron doping (16% B → $\Delta n_{633} \cong$ - 0.11).

TABLE 1

MODEL A PREDICTIONS AND COMPARISONS

DOPANT ION	STARTING DOPANT CONCENTRATION	DOPANT OXIDE	PUBLISHED n_{633} 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 (T DEPENDENT)
Al^{3+}	0.20	Al_2O_3	1.65	2.00	2.063-2.075
Sn^{4+}	0.1	$Sn\,O_2$	2.03	2.09	2.02
"	0.15	"	"	2.08	1.7
Zr^{4+}	0.03	$Zr\,O_2$	2.17	2.10	2.05
Cd^{2+}	0.20	$Cd\,O$	2.49	2.19	2.08 - 2.10
B^{3+}, Sn^{2+}	0.10,0.10	- - -	- -	2.02	2.0
" "	0.60,0.10	- - -	- -	1.68	1.88

- Anomalously low values of n_{633} have been observed for several sputtered Sn-doped In_2O_3 films (n_{633} as low as 1.7 has been observed for $\cong$ 13% Sn). This could lead to improved AR, highly conductive TIRR coatings.

- 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-Mesotti 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 8 cation dopants studies, and for estimating the relative local fields in the dopant cation oxides.

TABLE 2

MODEL B APPLIED TO DOPANT OXIDES

(USING MEASURED n_{DIO})

DOPANT	CONCENTRATION	MEASURED n_{DIO}(633 nm)	LATTICE CONST(Å)	DOPANT OXIDE	PUBLISHED n_{BULK} OXIDE	α_D(Å)^3	w_D	α_{DX}(Å)^3	w_{OX}
NO DOPANT	- - -	2.08 - 2.10	10.07-10.10	In_2O_3	2.10	α_{In}=6.5	0.56	1.5	3
B^{3+}	0.20	1.99	9.99-10.02	B_2O_3	1.46	α_B=1.6	0.56	1.5	2.14
"	"	"	"	"	"	"	"	1.07	3
Fe^{3+}	0.20	2.12-2.15	10.01-10.04	Fe_2O_3	2.88	α_{Fe}=9	0.44	1.5	3
"	"	"	"	"	"	α_{Fe}=7.8	0.55	"	"
Bi^{3+}	0.20	2.207-2.214	10.155-10.185	Bi_2O_3	2.57	α_{Bi}=11	0.87	1.5	3
Sb^{3+}	0.20	2.08-2.125 (T DEP.)	10.15-10.18	Sb_2O_3	2.087	α_{Sb}=7.2	1	1.5	3
Al^{3+}	0.20	2.063-2.075	10.06-10.09	Al_2O_3	1.65	α_{Al}=3.8	0.56	1.5	1.03
"	"	"	"	"	"	"	U	1.5	2.45
"	"	"	"	"	"	"	0	1.23	3
Sn^{4+}	0.10	2.02	10.09-10.12	SnO_2	2.03	α_{In}=1.55	1	1.5	2
"	0.15 (SATURATION)	1.70	10.14-10.17	"	"	- - -	- -	- - -	- - -
Zn^{2+}	0.03	2.05-2.06	10.08-10.11	ZnO_2	2.17	α_{Zn}=1.92	1	1.5	2
Cd^{2+}	0.20	2.08-2.10	10.10-10.13	CdO	2.49	α_{Cd}=4.59	0.86	1.5	3

POLARIZABILITY MODEL A

$$\left(\frac{n^2-1}{n^2+2}\right) = x\left(\frac{n_1^2-1}{n_1^2+2}\right) + (1-x)\left(\frac{n_2^2-1}{n_2^2+2}\right) \qquad \text{Equation 1}$$

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:

Equation 2

$$\left(\frac{n^2-1}{n^2+2}\right) = \left(\frac{9\overline{1}\overline{1}N}{3}\right)\alpha_{MOLECULE} = \left(\frac{9\overline{1}\overline{1}N}{3}\right)\left(w_C\alpha_C + w_A\alpha_A\right) \qquad (2a)$$

CATION DOPED CASE:

$$\left(\frac{n^2-1}{n^2+2}\right) = \frac{9\overline{1}\overline{1}N}{3}\cdot\left[w_C\left(x\alpha_D + (1-x)\alpha_C\right) + w_A\alpha_A\right] \qquad (2b)$$

n = REFRACTIVE INDEX

$1/N$ = VOLUME PER "MOLECULE".

$\alpha_{MOLECULE}$ = POLARIZABILITY OF MOLECULE (e.g., OF In_2O_3).

w_C = COMBINED STOICHIOMETRY AND LOCAL ELECTRIC FIELD WEIGHTING FACTOR AT CATION SITE.

α_C = POLARIZABILITY OF CATION.

w_A = COMBINED STOICHIOMETRY AND LOCAL ELECTRIC FIELD WEIGHTING FACTOR AT ANION SITE.

α_A = POLARIZABILITY OF ANION

α_D = POLARIZABILITY OF CATION DOPANT.

x = FRACTIONAL MOLE CONCENTRATION OF CATION DOPANT (= [DOPANT] / ([DOPANT] + [CATION]))

- n_{633} has been found to be insensitive to oxidation or reduction anneals, suggesting that doped indium oxide coatings could be used in either evacuated or nonevacuated collectors.

- A characteristic matrix program has been developed to predict reflection or transmission as a function of angle and wavelength, and is particularly useful for evaluating the effects of arbitrary graded optical constants profiles, especially for antireflection and heat mirror coatings.

FUTURE ACTIVITIES

1. The measurements of the wavelength dependence of the optical constants of the doped indium oxide (DIO) films need to be completed.

2. Attempts will be made to determine the optical constants profiles in the DIO films, using two techniques.

3. The low frequency conductivity and mobility measurements need to be completed

4. Attempts will be made to explain the anomalously low n_{633} found for sputtered Sn-doped indium oxide.

5. Attempts will be made to explain the deposition temperature dependence of n_{633} for Sb-doped films.

6. Attempts will be made to explain the small changes in n_{633} resulting from oxidation/reduction anneals.

POST CONTRACT ACTIVITIES

1. Attempts will be made to spray deposit thick, highly textured DIO films and determine the applicability of such films as selective absorbers.

2. Attempts will be made to fabricate different step-graded optical constants profiles by spray depositing a 3-layer film, each layer being a different dopant DIO film; and the resulting coatings will be evaluated for their AR/TIRR properties.

REFERENCES

1. R. B. Goldner and H. M. Haskal, Applied Optics 14, 2328 (1978).
2. R. B. Goldner, Applied Optics 16, 808 (1977).
3. W. W. Molzen, J. Vac. Sci. Tech. 12, 99 (1975).
4. K. Tanaka and Y. Ohtsuka, J. Appl. Phys. 49, 6132 (1978).
5. J. J. Brady and A. L. Lewis, Rev. Sci. Instr. 46, 48 (1975).

SURVEY AND EVALUATION OF AVAILABLE THERMAL INSULATION MATERIALS FOR USE ON SOLAR HEATING AND COOLING SYSTEMS

VERSAR, INC.

DE-AC04-78CS35363

BILL H. CHENG AND RALPH D. GIFT

September 18, 1979 - January 31, 1980

OBJECTIVE

The objective of this work was to survey and evaluate existing insulation materials for use in solar collectors and other solar heating and cooling system components.

BACKGROUND

The design of solar heating and cooling systems must minimize the amount of heat dissipated by thermal losses to the environment. Thermal insulation is applied to solar collectors, piping, ducting, and storage containers to reduce these losses. To insure maximum long-term performance, thermal insulation must withstand aging processes resulting from normal diurnal temperature - humidity cycles as well as elevated temperatures at stagnation. Other important factors include physical and chemical compatibility with other system components in direct contact with the thermal insulation itself.

Previous studies on thermal insulation have focused on building applications. Most of the available data have been based on measurements under controlled laboratory conditions near room temperatures. The environmental conditions under which thermal insulation are tested in the laboratory are those typically experienced in residential and commercial building applications. The emphasis of the present study is on the performance of thermal insulation under conditions experienced in flat plate collector operations. Data related to thermal cycling, outgassing, and corrosion were obtained under exposure conditions typically experienced in solar applications.

SUMMARY

A survey of insulation manufacturers was conducted. Data obtained from the survey and from the literature were tabulated and evaluated. Applications of thermal insulation were documented for both active and passive solar systems. Multifunction uses of insulation materials were investigated.

TECHNICAL ACCOMPLISHMENTS

- Survey of insulation manufacturers was conducted by mail and telephone interviews. Mailing lists were obtained from the following sources: periodicals (annual index of manufacturers), in-house technical periodicals, Thomas Register, manufacturing associations, Directory of Building Insulation Manufacturers (Department of Commerce), DOE/RECON system for literature search, and personal contacts. Useful responses were received from 62 sources.

- Material properties were compiled for the following types of thermal insulations:

  - Fiberglass
  - Rock wool
  - Polystyrene
  - Polyurethane/polyisocyanurate
  - Urea-formaldehyde
  - Foam rubber
  - Cellular glass
  - Calcium silicate
  - Perlite
  - Vermiculite
  - Cellulose

  Relevant material properties included:

  - Apparent thermal conductivity (k value)
  - Moisture absorption
  - Outgassing
  - Dimensional and thermal stability
  - Fire resistance
  - Ease of installation or application
  - Lifetime
  - Cost

- The application of thermal insulation in 97 different types of flat plate collectors was documented. Both liquid and air types were included. The designed thickness and material used for back and edge insulation were tabulated. Six observations emerged from an analysis of these data.

(1) It was found that most flat plate collectors used fiber glass as thermal insulation for the back and around the edges. The advantages of fiber glass are:

(a) good thermal resistance and light weight.
(b) non-combustible at collector operating temperatures.
(c) readily available in batt or blanket form.

However, fiberglass could lose dimensional stability because the breakdown of organic binders occurs around 400-500°F. The organic volatiles may condense on the underside of the glazing, leaving a whitish-blue coating which impairs the transmission of solar radiation. Therefore, fiberglass with high temperature binders or fiberglass with binders that can be preheated to expel volatiles prior to use are sometimes used. Several collector designs (e.g., Colt) use an improved product manufactured by Owens-Corning which is unbonded and unlubricated, and specifically developed for flat plate collector applications. This product, SI-100, designed to operate at temperatures up to 1000°F, is white and fluffy and is located on top of the more conventional fiberglass of yellow color.

(2) Polyurethane and isocyanurate thermal insulations constitutes the next largest group used in collectors. These cellular plastics have very high thermal resistance ("R" value per inch = 6-7 at a density of 2 pcf). This desirable property allows a shallower collector container for the same thermal resistance and requires less material for the collector container. In addition, it may cut down the edge losses by reducing the lateral area. A brand new collector using polyurethane foam may produce temperatures a few degrees hotter than those using fiberglass. However, polyurethane and isocyanurate have a tendency to outgas at ambient temperature, and outgassing is enhanced at elevated temperature (e.g., 200°F). After a period of from 6 to 12 months of collector operation, breakdown of cell structure occurs and air replaces the flurocarbon gas trapped inside closed cells. As a result, thermal resistance deteriorates. In addition, once outgassing happens and leakage through the edges occurs, whitish-blue frost or oil-like slick is formed on the underside of the glazing, cutting down the transmission of sunlight; therefore, the long term performance of collectors using polyurethane insulation decays with time.

Designers of solar collectors have coped with the out-gassing problem with three different approaches: (a) Use aluminum foil facing as a radiation, vapor, and outgassing barrier.
(b) Use a channel or trench design, where polyurethane/isocyanurate is embedded and is covered by aluminium foil.
(c) Use automatic temperature control for the collector to avoid runaway temperature during the no-flow condition. A good example is Daystar's "Temperature Limiter", where temperature is limited to 270°F regardless of ambient conditions.

Other problems reported in the literature include swelling of polyurethane insulation in collectors as a result of elevated temperature. The outcome was frame distortion and glass breakage.

(3) Normally, the insulation nearest the absorber plate is exposed to higher temperatures than the insulation far away from the absorber plate. It is possible to use one type of insulation adjacent to the absorber plate (e.g., fiberglass) and another type (polyurethane, isocyanurate, etc.) in areas which will not be exposed to extreme temperatures. The use of aluminum foil with fiberglass, polyurethane and isocyanurate, is gaining acceptance among collector designers.

(4) Another observation is a trend to use more thermal resistance for the back insulation, and less thermal resistance for the edge insulation.

(5) Some low temperature collectors, operating at temperatures a few degrees above the ambient temperature, are not insulated at all. Collectors for swimming pool heating fall into this category.

(6) In general, loose fill insulation materials are not recommended in collector design as they have a tendency to move and compact together during shipment from the factory to site and after the collector is erected in an upright, tilted position.

• The application of movable insulation in 20 passive solar systems was documented. The insulation used in these applications fell into four generic categories: (a) granular (b) rigid (c) flexible (d) optical.

The most important use for passive insulating systems is guarding south facing glass against heat loss during sunless periods. At present, technologies have not sufficiently evolved to offer highly transparent, cost effective window sections that are highly insulative as well. Until such windows are fully developed, intermediate solutions available to designers and builders will be mechanical in nature - movable shutters and blinds that fold, roll, or slide across the window area. Because these devices are not permanently fixed in place as transparent insulation would ideally be, conscientious user responsibility for deploying and retracting shades or shutters during the appropriate time is critical to the success of passive solar systems. It must be noted that a fixed permanent insulation with a lower thermal resistance will outperform a movable device having a higher resistance value but which is only deployed occasionally.

• Multi-functional uses of thermal insulation were documented for both building applications and solar applications. The major obstacles to commercialization in the solar application is the need for further investigations in the areas of materials research and mass production methods.

FUTURE ACTIVITIES

Contract Activities All tasks were completed before the project completion date.

Post-Contract Activities (1) The final report identified data gaps and recommended research for follow-on work. (2) Distribution of the final report to DOE, national laboratories, NBS, and insulation manufacturer associations is recommended.

PUBLICATIONS/REPORTS/REFERENCES

Publications

(1) Interim Technical Progress Report, May, 1979 (submitted).
(2) Final Report, March, 1980 (submitted).

References

(1) ASHRAE Handbook of Fundamentals, Chapter 19, 1977.
(2) ASHRAE Applications Handbook, Chapter 58, 1978.
(3) Duffie, J.A. and W.A. Beckman, "Solar Energy Thermal Processes," Wiley - Interscience Application. 1974.
(4) Tye, R.P. et al., "An Assessment of Insulation Materials and Systems for Building Applications", Dynatech R/D Company, 1978.
(5) Bourne, J.G. et al., "Building Insulation Materials Compilation," Dynatech R/D Company Report No. 1905, 1979.
(6) Skoda, L.F., and L.W. Masters, "Solar Energy Systems - Survey of Materials Performance," NBSIR 77-1314, 1977.
(7) Godette, M. et al., "Solar Energy Systems: Test Methods for Collector Insulations," NBSIR 79-1908, 1979.

XIV INDEX

INDEX

		PAGE
A	Acurex Corporation, Collectors	9-7
	AiResearch Manufacturing Company of California, Rankine	1-5
	AiResearch Manufacturing Company of California, Desiccant	3-5
	Altas Corporation, Hot Water	6-10
	Altas Corporation, Collectors	9-9
	American Heliothermal Corporation, Collectors	9-11
	Arizona State University, Special Project	7-3
	Arkla Industries, Incorporated, Absorption	2-5
	Argonne National Laboratory, Collectors	9-14
	Argonne National Laboratory, Overview of Storage	11-1
	Argonne National Laboratory, Storage	11-7
	Argonne National Laboratory, Storage	11-11
B	Battelle Columbus Laboratory, Collectors	9-16
	Berry Group, Materials	13-1
	Boeing Computer Services Company, Storage	11-13
	Brookhaven National Laboratory, Overview of Heat Pump Systems	4-1
	Brookhaven National Laboratory, Overview of Heat Pump Systems	4-5
	Brookhaven National Laboratory, Overview of Special Projects	7-1
	Brown University, Special Projects	7-6
C	California, University of, at Los Angeles, Collectors	9-20
	Calmac Manufacturing Corporation, Storage	11-15
	Carrier Corporation, Rankine	1-7
	Carrier Corporation, Absorption	2-9
	Carrier Corporation, Absorption	2-13
	Colorado State University, Desiccant	3-7
	Colorado State University, Special Projects	7-9
	Colorado State University, Special Projects	7-13
	Colorado State University, Controls	10-5
	Colorado State University, Analysis	12-1
D	Dow Corning Corporation, Materials	13-2
	Dow Corning Corporation, Materials	13-4
	Drexel University, Controls	10-9
	Dunham-Bush, Incorporated, Heat Pump	4-9
E	Energy Technology, Incorporated, Rankine	1-11
	EIC Corporation, Storage	11-18
	E-Tech, Incorporated, Heat Pump	4-13
F	Franklin Research Center, Special Projects	7-16
	Franklin Research Center, Controls	10-13
G	General Electric Company, Rankine	1-13
	Giner, Incorporated, Collectors	9-22
H	Hittman Associates, Incorporated, Admin/Management Support	8-9
	Hittman Associates, Incorporated, Storage	11-23
	Honeywell, Incorporated, Rankine	1-19
	Honeywell, Incorporated, Materials	13-6
	Honeywell, Incorporated, Materials	13-7
	Honeywell, Incorporated, Materials	13-9

I	Illinois Institute of Technology, Desiccant	3-9
	Independent Living, Incorporated, Storage	11-24
	Institute of Gas Technology, Desiccant	3-11
	Intertechnology/Solar Corporation, Collectors	9-24
K	Kaman Sciences Corporation, Heat Pump	4-15
L	Lawrence Berkeley Laboratory, Overview of Rankine Systems	1-1
	Lawrence Berkeley Laboratory, Overview of Absorption Systems	2-1
	Lawrence Berkeley Laboratory, Absorption	2-15
	Lawrence Berkeley Laboratory, Overview of Controls	10-1
	Lawrence Berkeley Laboratory, Controls	10-17
	Lennox Industries, Incorporated, Heat Pump	4-17
	Los Alamos Scientific Laboratory, Overview of Space Heating Systems	5-1
	Los Alamos Scientific Laboratory, Overview of Hot Water Systems	6-1
	Los Alamos Scientific Laboratory, Overview of Collectors	9-1
	Los Alamos Scientific Laboratory, Overview of Collectors	9-2
	Los Alamos Scientific Laboratory, Collectors	9-28
	Los Alamos Scientific Laboratory, Controls	10-19
M	Martin-Marietta Corporation, Storage	11-26
	Maryland, University of, Analysis	12-6
	Massachusetts Institute of Technology, Special Projects	7-18
	Monsanto Research Corporation, Special Projects	7-20
	Monsanto Research Corporation, Collectors	9-30
	Monsanto Research Corporation, Materials	13-10
N	NASA/Marshall Space Flight Center, Admin/Management Support	8-10
	NASA/Marshall Space Flight Center, Overview of Collectors	9-4
	National Bureau of Standards, Hot Water	6-13
	National Bureau of Standards, Collectors	9-32
	National Bureau of Standards, Storage	11-28
	Nebraska, University of, Storage	11-29
	Nebraska, University of, Storage	11-30
	New Mexico, University of, Special Projects	7-22
	Northrop Services, Incorporated, Collectors	9-35
	Northrup, Incorporated, Heat Pump	4-20
O	Ohio State University, Special Projects	7-24
	Oklahoma State University, Heat Pump	4-24
	OR/MS Dialogue, Incorporated, Special Projects	7-27
P	Pennsylvania, University of, Rankine	1-22
	Pennsylvania, University of, Collectors	9-37
	Pennsylvania, University of, Collectors	9-40
	Purdue University, Collectors	9-43
R	Rensselaer Polytechnic Institute, Collectors	9-48
	Research Triangle Institute, Materials	13-12
	Rho Sigma, Incorporated, Controls	10-21
S	Science Applications, Incorporated, Analysis	12-9
	Sigma Research, Incorporated, Heat Pump	4-28
	Singer Company, Heat Pump	4-30
	Solar Energy Research Institute, Overview of Desiccant Systems	3-1
	Solar Energy Research Institute, Special Projects	7-29
	Solar Energy Research Institute, Overview of Admin/Management Support	8-1
	Solar Energy Research Institute, Overview of Controls	10-1
	Solar Energy Technology, Incorporated, Collectors	9-51
	Solar Environmental Engineering Company, Inc., Heat Pump	4-34
	Solar Environmental Engineering Company, Inc., Hot Water	6-16
	Solar Environmental Engineering Company, Inc., Hot Water	6-17
	Solar Turbines International, Materials	13-14
	Solaron Corporation, Collectors	9-53
	Solaron Corporation, Storage	11-34
	Springborn Laboratories, Incorporated, Collectors	9-56

T	Telic Corporation, Materials	13-15
	Tennessee Technological University, Collectors	9-58
	Texas A&M University, Collectors	9-60
	Texas, University of, at Austin, Absorption	2-17
	Toronto, University of, Space Heating	5-10
	Total Environmental Action, Incorporated, Space Heating	5-12
	Trident Engineering Associates, Incorporated, Collectors	9-62
	Tufts University, Materials	13-17
U	United Technology Corporation, Rankine	1-26
V	Versar, Incorporated, Materials	13-19
	Virginia Polytechnic Institute, Collectors	9-66
W	Westinghouse Electric Corporation, Collectors	9-68
	Westinghouse Electric Corporation, Storage	11-35
	Wisconsin, University of, at Madison, Desiccant	3-14
	Wisconsin, University of, at Madison, Analysis	12-11
Z	Zeopower Company, Desiccant	3-17

*U.S. GOVERNMENT PRINTING OFFICE: 1980-640-258-2472