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Energy Division

U.S. HEAT PUMP RESEARCH AND DEVELOPMENT PROJECTS 1976–1986

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ABSTRACT

This document, which is an updated version of *U.S. Heat Pump Research and Development Projects*, published in August 1982 by the U.S. Department of Energy, is a compilation of one-page summaries and publication and patent information for 233 individual research and development projects on heat pumps covering the years 1976 through 1986. The majority of the projects refer to heat pumps in space-conditioning applications. The document is intended to include information on all projects in the United States for which results are publicly available. Ten different indexes are included to aid the reader in locating specific projects.

1. INTRODUCTION

The purpose of this document is to facilitate information exchange on heat pump research and development (R&D) projects in the United States. The document is oriented toward individual researchers, technical project monitors, and program administrators who need a greater awareness of the type of R&D work occurring on heat pump technologies.

The Office of Buildings and Community Systems of the U.S. Department of Energy (DOE) has been funding R&D in advanced heat pumps and appliances since 1976. Much of that research has been managed for DOE by the Oak Ridge National Laboratory (ORNL). This document was prepared through the efforts of the Building Equipment Research Program at ORNL.

This document is a compilation of summaries, publications, and patent information about individual heat pump R&D projects sponsored by DOE, the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and a few other organizations. The document is intended to include all U.S. projects for which results are publicly available.

This report includes information on projects started since 1982 along with updated information on completed and current projects that date from 1976 and appeared in a previous document entitled *U.S. Heat Pump Research and Development Projects*, published in August 1982 by DOE. For the present document, a special effort was made to include information on publications and patents related to the projects.

The project summaries are arranged in technology groups. The heat pumps referred to in the projects in all groups are for space-conditioning applications except for heat pumps in the industrial applications group. These is no duplication of project summaries; therefore, projects that address more than one major technical area are found in the section on Crosscutting Projects. Within each technology group, summaries are arranged by contract completion date in reverse chronological order, providing the reader easy access to the most recent projects.

2. OVERVIEW OF CONTENTS

A total of 233 projects are summarized in this document. The following table shows the breakdown of projects by technology groups.

106	**Electric Vapor Compression System Projects**	
	30	Air source
	34	Water source and ground coupled
	22	Solar assisted
	8	Refrigerant mixtures
	12	Energy storage
32	**Solar-Powered System Projects**	
	9	Dynamic vapor compression
	23	Chemical and absorption
49	**Fossil-Fuel-Fired System Projects**	
	22	Stirling engine driven
	7	Internal combustion engine driven
	6	Rankine, Brayton, and other engine driven
	14	Chemical and absorption
29	**Projects with Industrial Applications**	
	24	Electric and fossil-fuel fired
	5	Heat transformers
4	**Projects Using Novel Heat Pump Cycles**	
13	**Crosscutting Projects**	
233	**Total**	

3. ORGANIZATIONS SPONSORING HEAT PUMP RESEARCH AND DEVELOPMENT

Organizations sponsoring the majority of publicly available research on heat pumps in the United States are listed below.

U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585
(202) 252-9130

Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303
(415) 855-2398

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631
(312) 399-8311

Niagara Mohawk Power Corporation
300 Erie Boulevard West
Syracuse, NY 13202
(315) 474-1511

New York State Energy Research
and Development Authority
Two Rockefeller Plaza
Albany, NY 12223
(518) 465-6251

4. DESCRIPTION OF SUMMARY FORMAT

The format used in this document is a revision of a form used in an earlier document entitled, *U.S. Heat Pump Research and Development Projects*, report DOE/CE-0035 published by the U.S. Department of Energy in August 1982. The summary format includes project title; names of principal investigators; organization name, address, and telephone number; contract agency name, contract number, and contract period; funding amount and source; project objectives and description; citations of available publications; and information on issued patents. A brief description of each item follows.

The project title is short yet informative enough to enable the project to be categorized by technology group. The summary title is not necessarily the same as the actual contractual title.

The principal investigator is the person or persons responsible for carrying out the project. Also included is the principal investigator's organization, the address of the organization, and the telephone number. If a subcontractor was awarded some major part of the project, information on the subcontractor is included.

The contract agency can be either the agency awarding the contract or the agency having program management responsibility over the contract. In the latter case, the contract number given is the subcontract number between the contract agency and the principal investigator. The contract number can be useful in identifying published reports and other project information. The contract period shows the dates the project was started and completed. For many ongoing projects, the project completion date is given as "continuing."

Project funding information, provided when available, includes the amount, the source, and the level of funding. Some projects have more than one funding source. For some projects, such as those sponsored by the Electric Power Research Institute, the amount of funding is not included. The level of funding is given as a percentage of total funding.

A brief statement of the purpose of the project is given in the project objectives section. More detail is included in the description of the project. For completed projects, the description contains conclusions; for ongoing projects, the description includes project status, attained milestones, major activities to be pursued, and obstacles to be overcome.

The publications cited are related only to the project described and are listed in chronological order by publication date. Citations include author or corporate author, title, report number, publication source if different from the author's affiliation, and publication date. Most publications can be purchased from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

If the publication is not available from the National Technical Information Service, we suggest that the contract agency for the project be contacted.

Patent number, inventor, title, and date of issuance are included for inventions that resulted from the projects. Copies of patents can be purchased from

Patent Office
Commissioner of Patents
Washington, DC 20231

5. ELECTRIC VAPOR COMPRESSION SYSTEMS

5.1 Air-Source Systems

5.1.1 Seasonal Performance Modeling of Electrically Driven Air-Source Heat Pumps—IEA Annex XII

Principal Investigator: Steven K. Fischer
Organization: Oak Ridge National Laboratory
P.O. Box Y, Bldg. 9102-2
Oak Ridge, TN 37831
Telephone: (615) 574-2017

Contract Agency: International Energy Agency
Contract Number:
Contract Period: March 1986, continuing
Funding: $10,000
Source: DOE **Level:** 16%
Other countries 84%

Project Objectives:

To assess the adequacy of existing techniques for modeling the seasonal performance of air-source heat pumps, to define the needs for additional fundamental information and research activities.

Project Description:

This project is supported by a national team in each of the following participating countries: Austria, Belgium, Federal Republic of Germany, Japan, Switzerland, and the United States. The initial meeting was held during March 1986 in Karlsruhe, Federal Republic of Germany. Several tasks were agreed on at that meeting and are currently being performed:

- Each country is using its own field data to validate its models
- Switzerland is converting its air-to-water heat pump model so that it can be validated using data for an air-to-air heat pump
- The United States is modifying its model so that it can be validated using data for an air-to-water heat pump

Publications:

None provided.

5.1.2 Advanced Design Analysis, Tools, and Techniques for Heat Pumps and Air Conditioners

Principal Investigators: C. Keith Rice
Steven K. Fisher
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-2016

Contract Agency: Department of Energy
Contract Number: DE-AC05-840R21400
Contract Period: 1976, continuing
Funding: $2,250,000
Source: DOE **Level:** 100%

Project Objective:

To develop computer-based tools for heat pump analysis that are flexible enough to (1) provide research tools that can lead to an understanding of the steady-state and field performance characteristics of current and future advanced heat pump systems; (2) meet the Oak Ridge National Laboratory (ORNL) research needs for system optimization, modeling of capacity modulation, modeling of ground source systems, and modeling of systems using nonazeotropic refrigerant mixtures; and (3) provide industry with general, validated and documented design tools for improving system efficiency and reliability.

Project Description:

The development of a "Heat Pump Design Package" is an evolutionary project. Computer simulation of steady-state performance was developed and documented in 1976 and 1977. This evolved into a steady-state computer design model documented in 1981, which was devised concurrently with system optimization techniques for single-speed air-source heat pumps. During 1982, initial simulations of variable capacity heat pumps were developed so that potential improvements to single-speed heat pumps could be compared with benefits derived from continuous modulation. A model is currently being completed to calculate seasonal and annual performance factors from inputs of building characteristics, equipment steady-state performance specifications, and weather data. These models will be documented and validated. With supporting tools, such as contour and dynamic loss plotting and optimization-ready subroutines, these models will complete the design package. Selection of a recommended optimization code and workshops on uses of the package are planned in 1987/88. In a related effort, development of a program to analyze refrigerant charge inventory and better model variable speed heat pumps has been initiated.

A hands-on workshop demonstrating the heat pump model was held in late 1982. Thirty-four individuals from industry, universities, and other organizations attended. At the present time, more than 70 copies of ORNL heat pump models have been requested by and provided to organizations outside of ORNL. About a third of these requests were heat pump manufacturers.

Formal reports are being prepared on the Oak Ridge heat pump models: an annual performance factor/loads model for residential air-source heat pumps and design tools for heat pump development.

Publications:

C. K. Rice et al., *Design Optimization and the Limits of Steady-State Heating Efficiency for Conventional Single-Speed Air-Source Heat Pumps*, ORNL/CON-63, Oak Ridge National Laboratory, October 1981.

S. K. Fischer and C. K. Rice, *The Oak Ridge Heat Pump Models: I. A Steady-State Computer Design Model for Air-to-Air Heat Pumps*, ORNL/CON-80/R1, Oak Ridge National Laboratory, August 1983.

S. K. Fisher and C. K. Rice, "System Design Optimization and Validation for Single-Speed Heat Pumps," *ASHRAE Trans.* **91**(2), June 1985.

C. K. Rice and S. K. Fischer, "A Comparative Analysis of Single- and Continuously-Variable Capacity Heat Pump Concepts," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-842131, August 1985.

5.1.3 Advanced Central Heat Pump Development

Principal Investigator: Glendon A. Raymond
Organization: Carrier Corporation
P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 432-7462

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-1
Contract Period: Nov. 15, 1982, through May 4, 1987
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To develop and demonstrate a heat pump that offers significantly improved performance, favorable load characteristics to utilities, and economic and comfort benefits to consumers.

Project Description:

This project includes the development and prototype testing, under laboratory and field conditions, of a heat pump for application as a central unitary system in residential and light commercial buildings. The advanced central heat pump should:

- Offer 30% or better improvement in heating seasonal performance (a heating seasonal performance factor of 10.4 Btu/W·h or higher)
- Meet or exceed the cooling efficiency of current high-performance air conditioners (a seasonal energy efficiency ratio of 14.0 Btu/W·h or higher)
- Reduce peak demand by 2 kW or more for heating and offer demand-limiting control or demand reduction for cooling
- Reduce outdoor sound levels
- Improve the reliability and efficiency of defrost systems
- Incorporate control improvements for comfort, zoning, and thermostatic set back

These goals are subject to modification as the work progresses to ensure a balance among product efficiency, load characteristic improvements, and installed cost.

A management plan was developed and analysis was initiated to identify specific improvement options to be incorporated into the work. Simulation algorithms necessary for development and evaluation of component and integration options were prepared. Studies of such options and their costs were begun, with particular attention to water heating integration, compressor staging, and performance improvements in key components.

Subsequent work focused on a market analysis to assess the economic feasibility of the cited goals. Component development and testing progress was accomplished in the area of improved compressor performance. Engineering prototype development is under way.

Publications:

G. D. Hudelson, "Advanced Central Heat Pump Development," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3979, November 1984.

5.1.4 Variable-Speed Capacity-Modulation Research

Principal Investigators: C. Keith Rice
William A. Miller
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-2016

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: 1984–1987
Funding: $1,200,000
Source: DOE **Level:** 100%

Project Objectives:

To identify the most promising continuously modulating residential applications of heat pumps; to establish most probable operating requirements and configurations, including compressor type; to determine the performance potential for various heating/cooling load mixes; to work with industry partners for most efficient technology transfer and support.

Project Description:

The research consists of a coordinated analytical and experimental program in five currently planned areas:

- Modulating compressor characterization-reciprocating, rotary scroll
- System steady-state and dynamic tests and refrigerant control analysis
- Modulating system assessments including compressor screening analysis and application and operation strategies (including domestic hot water and/or zoning)
- Modulating analysis methods
- Proof-of-concept development and technology transfer

The work will deal exclusively with air-to-air heat pumps for residential application. Output from the work will be a set of modulating system design tools, case studies in the use of the models, and a broadly based assessment of the design requirements of modulating systems for best performance.

Publications:

C. K. Rice and S. K. Fisher, "A Comparative Analysis of Single- and Continuously-Variable Capacity Heat Pump Concepts," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.1.5 Step-Modulating Heat Pump Field Test

Principal Investigator: Stephen E. Veyo
Organization: Westinghouse Electric Corp.
R&D Center
1310 Beulah Road
Pittsburgh, PA
Telephone: (412) 256-1000

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24712C
Contract Period: Sept. 1, 1982, through Sept. 30, 1986
Funding: $809,230
Source: DOE **Level:** 100%

Project Objectives:

To perform a field evaluation of an advanced electric heat pump developed by Westinghouse under contract to Oak Ridge National Laboratory.

Project Description:

The advanced heat pump demonstrated a high level of reliability throughout the test period. Hardware failures were limited to an indoor blower bearing and coupling, an off-the-shelf motor start relay, and a conventional motor start capacitor. Functional software deficiencies in the microprocessor-based control system were corrected, but a problem with intermittent anomalous system fault indications was never fully resolved.

During the first full year of operation, a heating seasonal performance factor (HSPF) of 8.13 Btu/W·h and a cooling season energy efficiency ratio (SEER) of 8.35 Btu/W·h were observed. This is in good agreement with performance predictions of 8.22 and 8.56, respectively, based on the actual weather profile, building load characteristics, and operating strategy. The heat pump capacity proved to be significantly greater than optimum for the residence.

When resistance heat was required during the first heating season, it was locked on until the thermostat was satisfied, resulting in undesirable on/off cycling of the compressor and reduced efficiency. During the second heating season the system was modified to permit modulation of the resistance heat, which resulted in a significant increase in low-temperature energy efficiency. The HSPF for the second heating season improved to 8.51 Btu/W·h.

A formal report on the engineering field evaluation of the Westinghouse/DOE advanced electric heat pump is being prepared.

Publications:

S. E. Veyo and T. J. Fagan, *Advanced Electric Heat Pump Dual-Stroke Compressor and System Development: Final Report*, ORNL/Sub/79-24712/3, December 1983.

S. E. Veyo, "Dual-Stroke Heat Pump Field Performance," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.1.6 Air-to-Air Heat Pump Dynamic Losses Field Tests

Principal Investigator: Van D. Baxter
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-2104

Contract Agency: Department of Energy
Contract Number: DE-AC05-840R21400
Contract Period: November 1981 through September 1986
Funding: $448,000
Source: DOE **Level:** 100%

Project Objectives:

To determine under field conditions the degradation of an air-source heat pump's performance caused by cycling, frosting, and defrosting; to provide accurate field data for these phenomena to be used in validating analytical models.

Project Description:

A data system interface was developed for a commercially installed air-to-air heat pump in a test house at the TECH site in Knoxville, Tennessee. This interface splits the energy used and the energy delivered into several categories. During the first 2 to 5 min of each duty cycle, data are stored in transient mode channels. During the remainder of the duty cycle, data are stored in steady-state mode channels. Upon initiation of a defrost cycle, data are stored in a third set of channels. After termination of a defrost cycle, data are stored for another 75 to 80 s in the defrost channels to ensure that penalties in operating efficiency are charged to the defrost cycle. The experiments on cycling losses have been completed. During the heating season, defrosting losses were responsible for 10.2% of the total energy consumption (excluding supplemental electric resistance heating), frosting losses for 3.7%, startup transient losses for 8.5%, and off-cycle parasitics for 3.3%. For the cooling mode, it was found that startup transient losses accounted for 2.8% of the total energy use and off-cycle parastics for 4.4%. The data have been used to validate the Oak Ridge National Laboratory annual performance factor (APF) model dynamic loss and APF predictions.

Concurrent with the experiment on cycling losses (on alternate months), the system was operated with a desuperheater water heater. Effects of the desuperheater on the heating and cooling seasonal efficiency of the heat pump were investigated. The desuperheater was found to yield no significant seasonal efficiency improvement in heating relative to a heat pump/electric resistance water heater system. This is because the desuperheater reduces the heat pump capacity for space heating, thus causing increased use of backup electric heat. Cooling seasonal efficiency was 30% better for the desuperheater system, and overall annual performance improvement was 14%. Overall heat pump dynamic loss levels were not significantly changed by the desuperheater in either heating or cooling mode.

A commercially available two-speed heat pump was installed in the test house (TECH house 3) in August 1984. It was operated in both single- and dual-speed mode (alternating on a weekly basis) to ascertain the benefits of the two-stage modulation. Test results indicate that heating seasonal performance was virtually identical for both modes. Two-speed mode cooling performance was about 7% better than that of the single-speed mode.

Publications:

V. D. Baxter, L. A. Abbatiello, and R. E. Minturn, "Comparisons of Field Performance to Steady-State Performance for Two Dealer-Installed Air-to-Air Heat Pumps," *ASHRAE Trans.* **88**(2), June 1982.

V. D. Baxter, "Comparison of Field Performance of a High Efficiency Heat Pump With and Without a Desuperheater Water Heater," *ASHRAE Trans.* **90**(1), January 1984.

V. D. Baxter and J. C. Moyers, *Air-Source Heat Pump: Field Measurement of Cycling, Frosting, and Defrosting Losses, 1981–1983*, ORNL/CON-150, November 1984.

V. D. Baxter and J. C. Moyers, "Field Measured Cycling, Frosting, and Defrosting Losses for a High Efficiency Air Source Heat Pump," *ASHRAE Trans.* **91**(2), June 1985.

V. D. Baxter, "ORNL Air-Source Heat Pump Field Experiments," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.1.7 Design Goals for Advanced Heat Pumps

Principal Investigator: Stephen R. Petersen
Organization: National Bureau of Standards
Operations Research Division
U.S. Department of Commerce
Washington, DC 20234
Telephone: (301) 921-3701

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-15
Contract Period: Sept. 15, 1982, through June 15, 1986
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To quantify the economic benefits of advanced heat pumps, to assess the potential impact of various utility incentives for advanced units, to determine the economically optimal design goals for residential heat pumps.

Project Description:

The project seeks to develop optimal design goals for advanced heat pumps based on benefits both to consumers and utilities. The work includes utility and manufacturer contacts as well as econometric, engineering, and impact analyses.

Advanced electric heat pumps that reduce both energy use (in kilowatt-hours) and peak demand (in kilowatts) were studied to measure economic benefits to utilities to help assess potential utility incentive programs for advanced heat pumps. Such incentives, coupled with direct consumer benefits (e.g., energy cost savings and improved reliability) were evaluated to determine economic applications for advanced electric heat pumps and whether their manufacture in production quantities was viable. Such analyses required attention to alternative design strategies; regional, climatic, and utility characteristics; and projected energy costs.

The economic benefits of performance and demand improvements were analyzed, and a cost model was developed. This model included an empirical heat pump performance model that allowed parametric evaluation of alternate design impacts. A number of tentative findings, based on regional analyses using projected energy prices, were identified:

- Integration of year-round domestic water heating into the heat pump is economically feasible in all climates
- Dual compressors used to improve low-temperature heat pump capacity are unlikely to be cost effective in most applications
- Adjustable-speed heat pumps are likely to be cost justified when water heating is integrated into the heat pump

Publications:

None provided.

5.1.8 Unitary Heat Pump Field Performance Data Survey

Principal Investigator: James C. Burke
Organization: Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140-2390
Telephone: (617) 864-5770

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-00219C
Contract Period: Sept. 24, 1984, through Dec. 31, 1985
Funding: $142,502
Source: DOE **Level:** 100%

Project Objectives:

To establish the status of existing data on heat pump field performance, to compare the data with user needs, to determine what type of additional work is warranted.

Project Description:

Over 100 individuals in over 90 organizations were contacted. Thirty-eight programs involving over 700 heat pumps, 90% of which were residential air-to-air units, were identified. The programs can be categorized in three levels, based on the type of measurements obtained: level 1—energy input only; level 2—input and output; and level 3—input, output, and dynamic losses.

The fifteen level 1 programs identified were characterized by simple "load research" instrumentation, typically wattmeters and magnetic tape recorders. The potential accuracy of this method is good ($\pm 1\%$ or less), and the frequency of readings (typically 15 min) is adequate. Except for startup problems, data reliability was normally good. In the twelve level 2 programs, output was typically obtained either by the "flip-flop" method (error 10–15%) or from calculation of building load (error >20%). Results were used to obtain approximate values of heating seasonal performance factor (HSPF). Comparison with analyses was very limited. Twelve level 3 programs of instrumentation involved 46 heat pumps. Heat pump output was normally measured by the duct enthalpy method for heating and sensible cooling (5–10% error). Three techniques were employed or considered for estimating latent cooling loads: assumed total/sensible ratio (about 15% error), measured condensate (about 5% error), and measured relative humidity (not used successfully to date). All level 3 programs present HSPF and some estimate of dynamic losses, frequently with comparison to predictions based on the ARI 240-81 rating method. The emphasis (and accuracy) has normally been less for cooling.

The key reasons cited for needing heat pump field test data were load management, consumer information, product design, and model validation. The major types of thermal performance data needs reported included energy consumption and savings [HSPF and seasonal energy efficiency ratio (SEER)], load profiles, and information on advanced designs.

The data base on heat pump field performance is large but uneven in terms of completeness and quality. Energy input data are abundant and frequently reliable, but the results are seldom either statistically valid or easily generalized. A considerable amount of HSPF (and much less SEER) data is also available. Certain comparisons of these experimental performance factors with ARI 240-81 predictions have indicated good apparent agreement (within $\pm 10\%$). However, questions remain both on the general applicability of ARI 240-81 and on the specific methods used in normalizing the test data. Relatively little detailed data on dynamic losses are available and even less on comparison with analysis. Unresolved experimental problems include optimization of flip-flop techniques, practical field measurement of cooling load, and means of detecting performance degradation. Also, very few programs presented error analyses.

Recommendations included a 2-year program of level 3 field testing at approximately six locations supplemented by laboratory testing and analysis. An initial step proposed was the careful comparison of ARI-240-81 with existing test data. Also recommended was additional level 1 testing to provide a statistical data base for development of utility demand profile models.

Publications:

J. C. Burke et al., "Summary and Evaluation of Field Performance Data on Unitary Heat Pumps," ORNL/Sub/85-00219/1, April 1986.

5.1.9 Research and Development Needs in Heat Pump Reliability

Principal Investigator: Nance C. Lovvorn
Organization: Alabama Power Company
600 North 18th Street
P.O. Box 2461
Birmingham, AL 35291
Telephone: (205) 250-4377

Contract Agency: Electric Power Research Institute
Contract Number: RP2417-1
Contract Period: Feb. 1, 1984, through Dec. 31, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To identify and prioritize areas of research related to heat pump reliability, to perform portions of said research where possible.

Project Description:

The Alabama Power Company's Heat Pump Assured Service Program has been the heat pump industry's source of much as-installed heat pump reliability and maintenance information. This project utilizes the experiences of the assured service program personnel to help direct the Electric Power Research Institute's research and development efforts in the heat pump reliability area.

The first recommended research area to arise from this project was the performance of a survey of actual heat pump replacement life. The Alabama Power contract was amended to perform this survey, and the survey has been completed. During the successful heat pump replacement life survey, almost 1700 heat pump owners in the Alabama Power Company's service area were contacted. The major findings include the following:

- Almost 80% of the original units installed between 1964 and 1974 are still in operation
- Between 96 and 98% of the respondents surveyed still had heat pumps
- The median age to replacement is approximately 20 years in Alabama
- Almost half of the units replaced were still fully operational at the time of replacement

Much additional information regarding reasons for replacement, summaries by manufacturer, and other factors has been obtained and is included in the final report.

Publications:

N. C. Lovvorn, "Update on Heat Pump Reliability," *Proc. Seminar on Heat Pump Research and Applications, February 23, 1984*, CONF-840266, EM-3797, November 1984.

Final Report, EM-4163, April 1985.

5.1.10 Monitoring of Central and Room Heat Pumps

Principal Investigator: Charles E. Bullock
Organization: Carrier Corporation
Research Division
P.O. Box 4808
Syracuse, NY 13221
Telephone: (315) 432-6204

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-9
Contract Period: Apr. 1, 1982, through Dec. 31, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To collect, analyze, and report field operating data and measure critical aspects of heat pump performance including heating and cooling energy delivered, energy consumed, operating times, and other key parameters on daily, monthly, and seasonal bases; to report peak power demand characteristics; to investigate relative effects of equipment sizing and local climate.

Project Description:

Field monitoring of unitary, air-source heat pumps in both the heating and cooling modes was the focus of this project. Nine residential central systems and five residential and commercial room heat pumps in a variety of climatic conditions were studied.

- Dual-split heat pump with electric supplemental heat (Dallas, Texas)
- Dual-split add-on (bivalent) with a gas furnace (Birmingham, Alabama)
- Dual-split hybrid with a gas furnace (Liverpool, New York)
- Dual-split add-on with an oil-fired furnace (Cazenovia, New York)
- Dual-split hydronic hybrid in series with an oil-fired boiler (Central Square, New York)
- Dual-split hydronic hybrid add-on in parallel with an oil-fired boiler (Long Island, New York)
- Triple-split heat pump with a desuperheater water heater (Kingsport, Tennessee)
- Triple-split with two single-speed compressors (Minneapolis, Minnesota)
- Triple-split with one dual-speed compressor (Batchtown, Illinois)
- Room heat pump (Liverpool, New York)
- Room heat pump (Boston, Massachusetts)
- Room heat pump (Baltimore, Maryland)
- Packaged terminal heat pump (Belleville, Illinois)
- Packaged terminal heat pump (Atlanta, Georgia)

A large volume of useful data was obtained and has been analyzed.

Publications:

W. R. Reedy and C. E. Bullock, *Northern-Climate Heat-Pump Field-Performance Evaluation, Final Report*, EPRI-EM-2319, July 1982.

C. E. Bullock and S. C. Pederson, "Recent Heat Pump Investigations for Northern Climate Applications," *Proc. 2nd International Energy Exposition and Conf., Energex '84, May 14, 1984*, CONF-840506, May 1984.

C. C. Hiller, "EPRI Heat Pump Field Performance Testing," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.11 Laboratory Tests on Dynamic Losses

Principal Investigator: William A. Miller
Organization: Oak Ridge National Laboratory
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Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: October 1980 through October 1985
Funding: $969,000
Source: DOE **Level:** 100%

Project Objectives:

To provide detailed system and component performance data, to quantify the dynamic losses, to seek and evaluate methods for reducing these losses.

Project Description:

Air-to-air split system residential heat pumps of nominal 3-ton capacity were instrumented and tested in the laboratory. The coefficient of performance (COP), capacity of the system, and component efficiencies were measured during cooling and heating mode steady-state and cycling conditions as well as frosting-defrosting conditions to gain a better understanding of the physical processes that affect the dynamic operation of a heat pump.

Cycling operation, including off-cycle parasitics, is roughly 10% of the total annual heat pump operating energy. This loss in efficiency occurs because of the loss of refrigerant in the condenser and evaporator when the unit is deenergized. A restrictor that inhibits the migration of refrigerant during the off-cycle would reduce annual operating heat pump energy to 5%. A continuously variable speed heat pump could also reduce cycling losses by 68% of losses for a nonmodulating system because of its load-following characteristics.

Frosting losses, caused by frosting of the outdoor coil, are less than 5% of the total annual heat pump energy usage, while defrosting can be 8 to 14%, depending on the type of defrost control. Heat pumps operating with demand defrost controls in predominantly heating load climates have roughly a $25/year energy cost reduction as compared with time-temperature defrost controls. The modulating heat pump system would reduce both frosting and defrost losses because at part-load operation little if any frost forms on the outdoor coil and therefore fewer defrost cycles are required for maintaining system efficiency and reliability.

Publications:

W. A. Miller, *Laboratory Evaluation of the Heating Capacity and Efficiency of a High-Efficiency Air-to-Air Heat Pump with Emphasis on Frosting/Defrosting Operation*, ORNL/CON-69, December 1982.

W. A. Miller, "Frosting Experiments for a Heat Pump Having a One-Row Spine Fin Outdoor Coil," *ASHRAE Trans.* **90**(1), January 1984.

W. A. Miller, "The Laboratory Evaluation of the Heating Mode Part-Load Operation of an Air-to-Air Heat Pump," *ASHRAE Trans.* **91**(2), June 1985.

W. A. Miller, "Laboratory Experiments of Heat Pump Dynamic Losses," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13,1984*, CONF-841231, August 1985.

5.1.12 Heat Pump Water Heater Field Tests

Principal Investigator: Doug Hegebarth
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Contract Agency: Electric Power Research Institute
Contract Number: RP2376-2
Contract Period: June 1, 1985, through Aug. 1, 1985
Funding:
Source: EPRI **Level:** 100%

Subcontractor: Pacific Northwest Laboratory

Project Objectives:

To quantify for improved heat pump water heaters hot water delivery characteristics, energy consumption characteristics, electrical demand characteristics, magnitude of "free" air conditioning/dehumidification benefits, and performance relative to electric resistance water heaters.

Project Description:

Dedicated heat pump water heaters offer significantly reduced operating costs with respect to electric resistance water heaters, as verified by numerous field tests done by utilities. The "free" air conditioning and dehumidifying provided by such devices have usually been identified as beneficial by the users, but few attempts have been made to quantify the resultant additional economic value.

This project will field test three improved residential dedicated heat pump water heaters to quantify performance of newer designs. This project is also intended to evaluate and refine an improved approach to organizing field tests, including improved data collection and analysis, hardware, software, and procedures. The improved field test data collection and analysis approach is being developed with consideration for eventual use by individual utilities and, if successful, will be commercialized by the Electric Power Research Institute for that purpose.

Publications:

None provided.

5.1.13 Dynamic Control of Heat Pumps

Principal Investigator: Floyd C. Hayes
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Telephone: (608) 787-3404

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-11
Contract Period: Oct. 7, 1982, through June 30, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To develop an economical, dynamic control system that will significantly reduce cyclic and defrost losses in heat pumps; to define the optimum control strategies for the dynamic control system; to design, build, and test a breadboard system; to analyze the efficiency and economic improvements attainable with the concept; to estimate the market potential of the concept.

Project Description:

This project includes analysis, proof-of-concept testing, and evaluation of a dynamic control system to reduce cycling and defrost losses in heat pumps. Such losses can reduce the heating seasonal performance factor (HSPF) as much as 14%. In addition, cycling losses decrease the seasonal energy efficiency ratio (SEER) of heat pumps by as much as 11% for the cooling mode of operation. For heating, about 75% of the dynamic losses during startup and defrost are due to the location of the charge.

Reduction of these cycling losses would significantly improve the seasonal performance of heat pumps and improve their ability to quickly respond to heating and cooling loads. Reliability would also be improved by reducing the potential for slugging the compressor with liquid refrigerant and by decreasing the strenuous operating conditions for the compressor during startup and defrost.

Breadboard testing and analysis were completed, resulting in identification of strategies for reduction of cyclic losses. These control strategies showed promise of yielding 3.6% improvements in SEER and 1.7% improvements in HSPF with a two-year payback in added costs.

Publications:

None provided.

5.1.14 Feasibility Study for Variable-Speed Drives for Heat Pumps

Principal Investigator: Ned Mohan
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Contract Agency: Electric Power Research Institute
Contract Number: RP2033-4
Contract Period: Oct. 27, 1981, through June 15, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To evaluate the feasibility of modulating heat pump capacity by compressor-motor speed variation.

Project Description:

Conventional heat pumps achieve capacity control by cycling on and off as necessary to match the load. At part-load conditions, cycling degrades efficiency and decreases comfort. By varying compressor speed in response to heating and cooling loads, the following benefits are expected: (1) improved performance and user comfort, (2) decreased equipment wear, (3) reduced starting currents, and (4) reduced operating costs.

Higher first costs for controls and motors may partially offset these benefits. Six advanced ac motor concepts were addressed for unitary reciprocating and rotary compressors for residential and light-commercial applications. The six concepts include:

- Square wave, voltage source inverters (VSIs)
- Square wave, current source inverters (CSIs)
- Pulse-width-modulated (PWM) VSIs
- Electronically commutated synchronous motors (ECM) with a permanent magnetic field
- Pole-amplitude-modulation (PAM) in induction motors
- High-frequency, high-speed motors (HFM) using low-loss magnetic materials

These concepts will be compared analytically against conventional and two-speed compressor motors, and requirements for further research and development will be identified if warranted.

Data on adjustable-speed drives were collected from available literature and other sources including manufacturers and utilities. Analyses of the speed modulation options focused on waveform distortion and conditions unique to hermetic compressors. A PWM transistorized inverter was built and tested to study output characteristics, including harmonics, under various speed and load conditions. This inverter was also tested while driven in a VSI mode. Five ECM concepts and a commercially available Japanese (Fuji) six-step inverter module were evaluated. Manufacturer contacts were established to obtain reliable data on manufacturing and cost implications on both motors and compressors. A draft report was prepared which concluded that:

- VSI and PWM inverter-driven induction motor drives appear to be most attractive for continuous speed adjustments in a six-to-one range. The cost of such drives is approximately $220 to $300 per ton of compressor capacity.
- Continuously adjustable heat pumps show a reasonable payback period (four to seven years in cooling-dominated locations with relatively high electricity costs compared with single speed heat pumps).
- Further research is needed to reduce current harmonics into the utility system to improve the power factor of the VSIs and PWM inverters.

Publications:

None provided.

5.1.15 Compressor Improvements for Heat Pumps

Principal Investigator: James H. Saunders
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Department of Energy and Environment
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Contract Agency: Electric Power Research Institute
Contract Number: RP2033-10
Contract Period: Oct. 18, 1982, through May 30, 1985
Funding:
Source: EPRI **Level:** 100%

Subcontractor: David N. Shaw

Project Objectives:

To demonstrate the capacity and coefficient of performance (COP) increases, particularly for high-lift (e.g., low-source temperature) conditions, that have been predicted for the scavenge cycle; to demonstrate the feasibility of capacity modulation using brushless dc motors to maintain high motor efficiency.

Project Description:

The project included development, equipment fabrications, testing, analysis, and evaluation of two vapor-compression heat pump modifications offering improved performance, reduced peak demand, and increased comfort control. These modifications to conventional hermetic compressors include use of (1) scavenge heat cycle, and (2) a variable-speed brushless dc motor.

The scavenge heat modification flashes a portion of the condensed (liquid) refrigerant and reintroduces this vapor into the cylinder(s) of a reciprocating compressor. A special expansion valve and heat exchanger remove the vapor at a pressure and temperature above those inside the evaporator. New cylinder ports, uncovered as the piston completes its suction stroke (i.e., bottom dead center position), are added to the compressor for vapor reintroduction. This process decreases power consumption by reducing recompression of the flash vapor.

The second modification substitutes a brushless dc motor for the conventional ac motor. Brushless dc motors with electronic commutation have the advantage of high efficiency and very long life (i.e., greater than 50,000 h). An additional advantage of the brushless dc motor is that speed modulation can be achieved over a wide power range with the same electronics that effect commutation.

Preliminary analyses of the modifications have been completed. Significant benefits are predicted, but further development and physical verification are required. A breadboard test system was developed, and engineering of the scavenge-cycle modification was completed. Design of the brushless dc motor was initiated.

Testing of the scavenge cycle at single-speed conditions resulted in substantial increases in heating capacity and COP. At −15°F (−26°C) evaporating and 110°F (43°C) condensing temperatures, the scavenge cycle had a heating capacity and heating COP improvement of 80% and 25%, respectively, when compared with the conventional compressor. System operation to date has been stable and reliable.

Publications:

D. N. Shaw, "Compressors for Heat Pumps," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.16 Evaluation of Multizone Versus Central Electric Space Heating and Cooling Systems

Principal Investigator: Harvey Bernstein
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Contract Agency: Electric Power Research Institute
Contract Number: RP2376-1
Contract Period: Jan. 3, 1984, through Mar. 31, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To identify which environmental, physical, and demographic conditions favor using zoned electric heating and cooling systems and which favor central electric heating and cooling systems; to quantify to the extent possible the magnitude of the impact of various factors on power demand, energy consumption, and overall cost-effectiveness of the various types of zone and central space conditioning systems.

Project Description:

The approach to achieving a greater understanding of the issues involved entails:

- Collecting and analyzing of existing data from utility studies, various governmental and institutional studies, and the open literature, comparing zoned and central systems
- Using the data collected from the work done by others to develop models and correlations for predicting power demand, energy consumption, and economic impacts of various configurations and operating strategies of multizoned and central systems
- Planning structured experiments for model verification and additional primary data collection

Performance of the structured experiments is not under the current contract.

Eighteen potentially useful utility data sets were identified. Difficulties with data tape readability or missing data made it possible to analyze only seven of the data sets. Preliminary examination of the findings indicate slightly lower energy consumption from zoned systems, but this result was not statistically significant because of unknowns regarding auxiliary heat use, primarily wood stoves and fireplaces.

Publications:

None provided.

5.1.17 Heat Exchanger Requirements for Potable-Water Protection

Principal Investigator: Thomas J. Marciniak
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Contract Agency: Electric Power Research Institute
Contract Number: RP2033-13
Contract Period: Oct. 1, 1982, through Feb. 15, 1985
Funding:
Source: EPRI **Level:** 100%

Subcontractor: National Conference of States on Building Codes and Standards, Inc. (NCSBCS)

Project Objectives:

To increase the efficiency and reduce costs of heat pumps by examining requirements necessitating double-wall heat exchangers.

Project Description:

Both the efficiency and cost of electric heat pumps using potable water as heat source/sink were adversely affected by requirements for double-wall heat exchangers. Heat pump water heaters and reclaim desuperheaters were similarly affected. The double-wall requirements were imposed by various building codes and environmental regulations based on concerns over contamination of potable water by heat pump refrigerants, lubricants, and motor-burnout products. The validity of such requirements was not clear in view of materials and fabrication techniques used. Such requirements impeded further application of efficient heat pump technologies. The project examined the issues involved by:

- Identifying specific requirements for double-wall heat exchangers in heat pumps
- Determining the basis for such requirements
- Assessing the performance and cost impacts of the requirements
- Evaluating the water-protection concerns associated with water-to-refrigerant and refrigerant-to-water heat exchangers in heat pumps
- Analyzing the adequacy of single-wall heat exchanger or refrigerant-dye use
- Developing recommended language for building codes and regulations for the subject heat exchangers

Review of the plumbing and mechanical provisions of the major building code models revealed that the subject equipment was not specifically addressed. Requirements governing water-cooled compressors and condensers for large air conditioning applications were applied. Data were obtained from manufacturers on double-wall heat exchangers. Initial equipment cost increases of 8 to 40% were incurred by double-wall code requirements.

Neither the toxicity nor other hazards of refrigerants, lubricants, burn-out products, and combinations of these appeared to justify the code requirements.

Publications:

T. J. Marciniak, "Heat Exchanger Requirements for Potable Water Protection," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.18 Heat Pump Zoning Benefits Evaluation

Principal Investigator: Edmund A. Nephew
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Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: April 1984 through October 1984
Funding: $62,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate by analytical methods the potential benefits of zoning with residential space-conditioning systems.

Project Description:

Seven different temperature control strategies were chosen that varied in the application of night setback, capacity modulation, and zoning. Building heating and cooling loads and energy consumptions were computed for each temperature control strategy. The potential energy savings estimated for each of these three departures from full-time, full-capacity strategy are as follows: night setback, 14–15%; capacity modulation, 7–30%; and zoning, 12–32%.

Publications:

E. A. Nephew and J. C. Moyers, "Scoping Evaluation of Potential Benefit of Zoning with Residential Space-Conditioning Systems," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.1.19 Heat Pump Water Heater Laboratory Tests and Computer Design Model

Principal Investigator: Kay H. Zimmerman
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Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: April 1982 through October 1984
Funding: $275,000
Source: DOE **Level:** 100%

Project Objectives:

To provide an analytical capability that can assist the industry in evaluating the effect of improved components or new design features on heat pump water system performance.

Project Description:

The heat pump water heaters on the market today are made up of components from existing technologies. In general they have not been specifically designed for the use intended. As a result, the efficiencies of these systems can likely be improved through system analysis and optimization.

A commercially available, separated type heat pump water heater was instrumented and installed with a 52-gal commercially available water storage tank in an insulated enclosure. The environment in the enclosure was controlled with respect to both temperature and humidity.

Steady-state tests were conducted for ambient temperatures from 50 to 100°F (10 to 37.8°C), relative humidity from 20 to 90%, and entering water temperature from 115 to 130°F (46.1 to 54.4°C). Data were collected, and a data base was developed. The analytical steady-state design model was created by modifying an existing heat pump model with newly developed subroutines. The experimental data were used to validate the design model. Early parametric studies illustrated the model's potential usefulness in design studies.

Publications:

K. H. Zimmerman, "Laboratory Test, Design Model Validations, and Parametric Study of a Heat Pump Water Heater," *Proc. 7th Heat Pump Technology Conference, Oklahoma State University, Oct. 15–16, 1984*, 1984.

K. H. Zimmerman, *Heat Pump Water Heater Laboratory Test and Design Model Validation*, ORNL/CON-173, March 1986.

5.1.20 Monitoring of Improved Air-Source Heat Pumps

Principal Investigator: Charles E. Bullock
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Contract Agency: Electric Power Research Institute
Contract Number: RP789-3
Contract Period: Dec. 17, 1979, through Sept. 15, 1984
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To collect, analyze, and report field operating data; to measure critical aspects of heat pump performance including heating and cooling energy delivered, energy consumed, operating times, and other key parameters on daily, monthly, and seasonal bases; to report peak power demand characteristics; to investigate the relative effects of equipment sizing and local climate.

Project Descriptions:

Field monitoring of unitary, residential, air-source heat pumps in both the heating and cooling modes was the focus of this project. Seven split-system installations representing a variety of climatic conditions were studied.

- Dual-split heat pump with an electric auxiliary heater (Dallas, Texas)
- Dual-split add-on (bivalent) with a gas furnace (Liverpool, New York)
- Dual-split hydronic add-on in series with an oil-fired boiler (Central Square, New York)
- Triple-split heat pump with a desuperheater water heater (Kingsport, Tennessee)
- Triple-split heat pump with two single-speed compressors (Manlius, New York)
- Triple-split heat pump with two single-speed compressors (Minneapolis, Minnesota)
- Triple-split heat pump with one dual-speed compressor (Batchtown, Illinois)

This work continues the field monitoring efforts of a prior project (RP789-1) by the same contractor in conjunction with the Niagra Mohawk Power Company. The earlier project focused on equipment designed in the mid-1960s installed in northern climates. This project extends the work into other climates and addresses improved equipment. Data collection was completed in December 1981. Performance simulations for typical weather years have been modeled, based on the collected data, and compared with expected performances. A draft report concludes that:

- Measured heating seasonal performance factors ranged from 5.6 to 7.4 and cooling season energy efficiency ratios ranged from 7.2 to 9.6
- Power demand of these systems was 1.8 to 8.5 kW less than that of central electric furnaces, with the greatest reductions found with the add-on heat pumps
- Monitored performance agreed very well with performance ratings based on industry standards (ARI 240-81)

Publications:

W. R. Reedy and C. E. Bullock, *Northern-Climate Heat Pump Field Performance Evaluation, Final Report*, EPRI-EM-2319, July 1982.

C. E. Bullock and S. C. Pederson, "Recent Heat Pump Investigations for Northern Climate Applications," *Proc. 2nd International Energy Exposition and Conf., Energex '84, May 14, 1984*, CONF-840506, May 1984.

C. C. Hiller, "EPRI Heat Pump Field Performance Testing," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.21 Heat Pump Research and Development Review

Principal Investigator: Robert V. Steele
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Contract Agency: Electric Power Research Institute
Contract Number: RP2033-17
Contract Period: May 10, 1983, through July 31, 1984
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To review the state of the art for residential and commercial heat pumps, to examine the impacts of expanded use of heat pumps on utility systems, to determine the key research and development (R&D) issues affecting the attractiveness of heat pumps to both utilities and their customers, to identify new R&D initiatives for consideration by the Electric Power Research Institute in pursuing its objectives in residential and commercial end-use technologies.

Project Description:

Two workshops, one each on commercial and residential heat pumps, were conducted to bring together experts in the field to review R&D of electric heat pumps. Participants were invited from utilities, manufacturers, other research organizations, and architectural/engineering firms. Groups were kept small (20 to 25) to promote free discussion. A two-day seminar on residential heat pump R&D and findings was also included.

Publications:

R. V. Steele, *Proc. Seminar on Heat Pump Research and Applications,* CONF-840266, EPRI-EM-3979, November 1984.

5.1.22 Advanced Electric Residential Heat Pump

Principal Investigator: Stephen E. Veyo
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Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24712C
Contract Period: Oct. 1, 1979, through June 30, 1984
Funding: $4,534,000
Source: DOE **Level:** 77%
Westinghouse 23%

Project Objectives:

To develop a preproduction prototype, commercially and economically viable advanced heat pump that could provide satisfying performance with an annual energy efficiency at least 20% better than the most efficient units available in the market place in early 1979.

Project Description:

The heat pump concept developed by Westinghouse used the well-known vapor compression refrigeration cycle with R-22 as the working fluid. To achieve the target efficiency, Westinghouse developed an improved reciprocating compressor with two-step capacity modulation along with the higher efficiency air movers, a breadboard microprocessor-based control system, and higher effectiveness heat exchangers. The relative proportions of the compressor, blower, fan, and heat exchangers were specified through system optimization to minimize annual ownership cost and were constrained to provide comfort. A market analysis was also conducted which projected the 1990 market to be greater than 680,000 units. The dual-stroke compressor used an eccentric cam between crank pin and connecting rod to change the stroke of the piston upon a reversal in the direction of crankshaft rotation. The ratio of minimum to maximum capacity could be selected as a parameter of optimization. The incremental cost of this compressor was estimated to be one-third that of the compressor with two-speed drive motor. An indoor blower, 50% more efficient, and an outdoor fan, twice as efficient, were designed, built, and tested. A breadboard system and a preprototype system were laboratory tested to verify analytical performance estimates and to develop the control software. Field evaluation testing of the preprototype unit was conducted for one year by Westinghouse in a residence in the Pittsburgh area. The testing showed a heating seasonal performance factor (HSPF) of 2.5, excellent performance in a northern climate, and a respectable cooling seasonal energy efficiency ratio of 8.5 Btu/h·W. The unit was optimized for northern climate application to provide its best performance in the heating mode. Although the original performance objective was achieved and reasonable agreement was obtained (measured HSPF 7% that predicted), a second year of field testing with a debugged system is being considered to add to the credibility of the performance results and to correct a deficiency with the supplemental resistance heat controls.

Publications:

J. C. Kastovich et al., *Advanced Electric Heat Pump Market and Business Analysis—Final Report*, ORNL/Sub/79-24712/1, April 1982.

S. E. Veyo, *Advanced Electric Heat Pump Component Development and Evaluation—Interim Report*, ORNL/Sub/79-24712/2, September 1982.

D. Ariewitz et al., "A High-Efficiency Indoor Air Mover," *ASHRAE Trans.* **89**(2B), June 1983.

T. Wright et al., "A High-Efficiency Heat Pump Fan," *ASHRAE Trans.* **89**(2B), June 1983.

S. E. Veyo and T. J. Fagan, *Advanced Electric Heat Pump Dual-Stroke Compressor and System Development—Final Report*, ORNL/Sub/79-24712/3. December 1983.

R. R. Young et al., "High-Efficiency Dual Stroke Compressor for Heat Pumps," *ASHRAE Trans.* **90**(I), January 1984.

Patents:

U.S. 4,236,874: F. J. Sisk, Dual Capacity Compressor with Reversible Motor and Controls Arrangement Therefor, Dec. 2, 1980.

U.S. 4,449,376: R. Draper et al., Design of an Indoor Unit for an Advanced Electric Pump, May 22, 1984.

U.S. 4,449,377: R. Draper, Application of Thermosyphon Evaporator to an Optimal Residential Heat Pump Outdoor Unit, May 22, 1984.

U.S. 4,463,302: H. S. Kirschbaum, A Two-Capacity Compressor with a Two-Strength Motor that Uses Interchange of Main and Auxiliary Windings, July 31, 1984.

U.S. 4,463,303: H. S. Kirschbaum, Six Pole/Eight Pole, Pole Changing Single-Phase Motor, July 31, 1984.

U.S. 4,465,962: H. S. Kirschbaum, APSC Single-Phase Motor System Capable of Balanced Operation at More Than One Land Point Employing Both an Autotransformer and a Capacitor Network, Aug. 14, 1984.

U.S. 4,470,271: R. Draper et al., Outdoor Unit Design for an Advanced Electric Heat Pump, Sept. 11, 1984.

U.S. 4,473,788: H. S. Kirschbaum, Single Phase Pole Changing Motor for Hermetic Compressor, Sept. 25, 1984.

U.S. 4,476,422: H. S. Kirschbaum, Pole Changing Single-Phase Motor, Oct. 9, 1984.

U.S. 4,479,419: R. W. Wolfe, Dual Capacity Reciprocating Compressor, Oct. 30, 1984.

U.S. 4,494,447: F. J. Sisk, Self-Latching Eccentric Cam for Dual Stroke Compression, July 22, 1984.

U.S. 4,516,916: W. A. English and R. R. Young, Oil-Cooled Compressors, May 14, 1985.

5.1.23 Performance Analysis of Air-to-Air Heat Pumps

Principal Investigator: Heinz Jaster
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Corporate Research and Development
P.O. Box 43, Bldg. 37
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Contract Agency: Electric Power Research Institute
Contract Number: RP1495-1
Contract Period: Oct. 29, 1980, through Apr. 30, 1984
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To provide both quantitative data on and algorithms for accurate prediction of performance of conventional heat pumps.

Project Description:

The purpose of this project was to develop and validate algorithms for determination of seasonal heating efficiencies for conventional heat pumps. The work combined both experimental and analytical investigations including:

- Field monitoring of nine heat pumps in occupied homes
- Laboratory tests of cycling transients and defrost effects
- Development of a detailed simulation model and a simplified algorithm for performance prediction

Nine single-family residences in three differing climates were equipped with 2.5-ton, single-speed, air-to-air heat pumps with auxiliary electric-resistance heat. These systems were instrumented to measure capacity, performance, power (demand), and energy consumption of major components and the total systems. Seasonal and representative performance were analyzed including accounting for cycling and defrost effects. The results were compared against Department of Energy (DOE) and industry testing and rating procedures.

A literature survey on seasonal performance measurement and algorithms was completed. A detailed simulation model and an improved simplified model based on separate day and night load lines were developed.

Comparison of field data with predictions indicated that cycling rates in the test homes were substantially lower than commonly supposed and that the resulting efficiency penalities were negligible. The time spent defrosting was found to be the single most important, and sensitive, factor governing field performance. This time was predicted by the new algorithms within 6% for all but one residence. The DOE standard rating algorithm, applied to the actual weather and load, also predicted the performance factor very well, although this was accomplished by overestimating the cycling effects and underestimating the frost/defrost effects.

Publications:

R. S. Miller and H. Jaster, *Performance of Air-Source Heat Pumps, Final Report*, EPRI-EM-4226, November 1985.

5.1.24 Heat Pump Water Heaters

Principal Investigator: Morton H. Blatt
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Energy Systems and
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Contract Agency: Electric Power Research Institute
Contract Number: RP2033-5
Contract Period: Sept. 11, 1981, through Mar. 31, 1984
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To evaluate the experience of electric utilities with heat pump water heaters; to develop a guide on heat pump water heaters for utility use which will address the technology, its application and economics, and experimental techniques for further tests.

Project Description:

This work included an analysis of heat pump water heater technology, a review of utility field test experience and experimental designs, and an assessment of utility impacts of heat pump water heater use. Further research requirements were identified. The technologies addressed include:

- Integral models (combined heat pump and tank in a single package) with both immersion and external condensers
- Remote units (separate heat pump and tank units connected by water piping)
- Heat pumps equipped with desuperheater water heaters

Forty-six utility experiments were identified by a literature search and manufacturer survey. Twenty of these experiments (including 85 units) were documented in a prior study sponsored by the U.S. Department of Energy. Data from 11 manufacturers and utility experiments on 278 units were analyzed. A draft report of the analysis summarizes the following:

- Commercially available heat pump water heater characteristics
- Comparative economics of heat pump water heaters
- Findings of the 46 utility experiments
- Experimental design and instrumentation considerations
- Research requirements

The report concludes that:

- Heat pump water heaters are viable in many applications with peak electricity demand reductions of 0.03–0.46 kW in winter and 0.08–0.29 kW in summer
- Heat pump water heaters use approximately 50% less energy than resistance water heaters
- Further research is needed to improve performance and to determine both utility and space-conditioning load impacts of heat pump water heaters

Publications:

J. E. Dobyns and M. H. Blatt, *Heat Pump Water Heaters, Final Report*, EPRI-EM-3582, May 1984.

J. M. Calm, "Heat Pump Water Heaters," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.25 Monitoring of Air-to-Air Multizone Heat Pump Systems

Principal Investigator: J. Patrick Quinn
Organization: International Energy Systems Corp.
1754 Technology Drive, Suite 116
San Jose, CA 95110
Telephone: (408) 280-6002

Contract Agency: Electric Power Research Institute
Contract Number: RP1201-15
Contract Period: Nov. 12, 1980, through Mar. 31, 1984
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To acquire performance data on residential multizone heat pumps, to monitor occupant use of zonal control, to examine the impacts of zonal demand diversity on electrical power demand, to compare energy use of multizone heat pumps to that of zoned resistance heating and other alternative systems.

Project Description:

Two multizone heat pumps located in Reno, Nevada, were monitored. Each system used a single outdoor compressor and heat exchanger unit serving five separate indoor heat exchangers. The indoor units were individually controlled, thereby enabling heating and cooling on a room-by-room or zone-by-zone basis. Each indoor unit included a supplemental resistance heater for use during defrost of the outdoor unit and when additional capacity was needed. A customized data acquisition system was assembled by Micrologic, Inc., and installed in October 1981. Integrating energy meters recorded energy use during installation of the data acquisition system and served as a backup data system.

Some data were lost during data system failures. A consultant, retained to reanalyze the performance data, concluded that only short-term performance comparisons of the baseboard heating and the multizone heat pumps were possible. The coefficients of performance of the multizone heat pumps, on a few selected days in December, were approximately 1.2 to 1.5. The project demonstrated that multizone heat pumps can operate successfully as zone control space conditioning systems and can lower peak power demand.

Publications:

C. C. Hiller, "EPRI Heat Pump Field Performance Testing," *Proc. Seminar On Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

5.1.26 Survey of Heat Pump Field Performance Data

Principal Investigator: Richard E. Crane
Organization: Synergic Resources Corporation
Three Bala Plaza East, Suite 555
P.O. Box 1506
Bala Cynwyd, PA 19004-3406
Telephone: (215) 667-2160

Contract Agency: Electric Power Research Institute
Contract Number: RP1940-5
Contract Period: Jan. 3, 1983, through Dec. 31, 1983
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To identify and document electric utility experience in field monitoring of air-to-air heat pumps used in space heating and cooling systems.

Project Description:

Telephone surveys and site visits were conducted with electric utilties to identify and document valid field performance data on air-to-air heat pumps used in residential space heating and cooling systems. A technical literature review of laboratory and field performance data on residential heat pumps was performed to supplement the survey efforts.

Results presented in the draft final report centered on describing and documenting the heating seasonal performance obtained in ten field test projects covering a cumulative total of 13 utilities and 151 heat pump installations. Climate conditions represented ranged from 2799 heating degree-days in Alabama to more than 7500 heating degree-days in Ontario, Canada. Average heating seasonal perfomance (SPF) ranged from a high of 2.74 in Alabama to a low of 1.53 in Utah. Methodology used to determine SPF included "flip-flop" tests, calculation of heating load, comparison with similar residences using electric resistance heat, and historical data (sequential years).

Publications:

Informal report available on request.

5.1.27 Heat Pump and Air-Conditioner Test Procedures

Principal Investigator: David A. Didion
Organization: National Bureau of Standards
Building 226, Room B-126
Gaithersburg, MD 20899
Telephone: (301) 921-2994

Contract Agency: Department of Energy
Contract Number: 7452507
Contract Period: 1981–1983
Funding:
Source: DOE **Level:** 100%

Project Objective:

To provide industry an equitable testing and rating procedure for determining the seasonal energy performance of central residential heat pumps and air conditioners.

Project Description:

This project included laboratory experiments and analysis using the National Bureau of Standards (NBS) heat pump simulation model. Results of the project expanded or enhanced the current Department of Energy (DOE)/NBS evaluation procedure to cover a wider range of new products. A procedure was drafted for rating mix-matched systems (split air conditioner units that have an evaporator coil other than the one tested with the condenser). The existing DOE/NBS rating procedure is based on a single cyclic test to characterize unit performance. This test assumes that the anticipator thermostat controls the cycle rate as a parabolic function of load. Newly developed control devices may be inserted in a heat pump's control circuitry. Extensive review and analysis of laboratory and field data were conducted to determine if systems with these new controls were receiving the proper rating value. Development of ASHRAE Standard 116P was supported by committee participation and revision of the document. This effort included technical support of DOE during the rule-making phase to amend the current test procedure to reflect modifications advocated by Standard 116P.

Publications:

D. A. Didion, "The Effect of a Time-Delayed Stack Damper on Off-Cycle Heat Losses for Residential Heating Equipment," ASHRAE Technical Paper, May 1983.

D. A. Didion, *Low-Voltage Room Thermostat Performance*, NBS BSS 150, May 1983.

D. A. Didion, *A Laboratory Investigation of Refrigerant Migration in a Split Unit Air Conditioner*, NBSIR 83-2756, May 1983.

5.1.28 Technical Support in Evaluation of Central Air Conditioning and Heat Pump Performance

Principal Investigator: Morton H. Blatt
Organization: Science Applications, Inc.
P.O. Box 2351
Lajolla, CA 92038
Telephone: (714) 454-3811

Contract Agency: Department of Energy
Contract Number: AC01-79CS10757
Contract Period: March 1979 through June 1982
Funding: $400,000
Source: DOE **Level:** 100%

Project Objectives:

To provide technical support in seasonal performance modeling of central air conditioners and heat pumps.

Project Description:

The contractor completed an evaluation of heat pump defrost performance and seasonal performance and component balance modeling of central air conditioners and heat pumps.

Publications:

Science Applications, Inc. *User's Manual for Heat Pump Seasonal Performance Model (SPM) with Selected Parametric Examples*, SAI-444-82-141-LJ, June 1982.

5.1.29 Research and Development Opportunities for Large Heat Pump Systems

Principal Investigator: David Goldenberg
Organization: TRW
800 Oak Ridge Turnpike
Building B
Oak Ridge, TN 37830
Telephone: (615) 482-9054

Contract Agency: Oak Ridge National Laboratory
Contract Number: 62B-13817C
Contract Period: September 1980 through July 1981
Funding: $110,000
Source: DOE **Level:** 100%

Project Objectives:

To establish existing populations of air-conditioning equipment and commercial buildings; to describe air-conditioning equipment market sizes; to compare the relative energy use of systems; to assess the effects of nontechnical factors on the development and increased use of energy efficient air-conditioning equipment and systems; to assess the opportunities for research, design, and development (RD&D) work leading to improvements or increased use of energy efficient equipment or systems; to formulate recommendations for RD&D activities in these areas.

Project Description:

A relatively successful RD&D effort by government and industry for residential heat pump equipment was under way. This study provided descriptions and assessments of air-conditioning equipment and systems in the commercial milieu to be used for initial planning of RD&D activities pertaining to the commercial sector.

Use of currently available equipment and systems that are energy efficient is limited by the economic situation of building owners. Increasing energy prices do not show much potential for changing this situation. Case histories of energy efficient buildings (in available literature) highlight the potential of existing equipment and systems, but most of the systems (and equipment) being installed in commercial buildings do not measure up to this potential. A program of market development is needed before development of the next generation of air-conditioning equipment and systems will hold much promise.

The high priority recommendations of this study dealt with development of the market for energy efficient heating, ventilating, and air-conditioning systems and equipment by reversing existing market forces that promote energy consumption. Second priority recommendations dealt with technical research and educational programs covering research of systems application and operation, increasing the number of technical people who are competent in the area of energy system efficiency improvement, and other areas.

Publications:

D. Goldenberg, "RD&D Opportunities for Large Heat Pump Systems," *Proc. DOE Heat Pump Contractors' Program Integration Meeting*, CONF-810672, March 1982.

M. MacDonald, D. Goldenberg, and E. Hudgins, *RD&D Opportunities for Large Air Conditioning and Heat Pump Systems*, ORNL/Sub/80-13817/1&2, June 1982.

5.1.30 Demonstration of a Heat Pump Water Heater

Principal Investigator: Robert P. Blevins
Organization: Energy Utilization Systems, Inc.
365 Plum Industrial Court
Pittsburgh, PA 15239
Telephone: (412) 325-2820

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-07321C
Contract Period: August 1978 through June 1981
Funding: $984,000
Source: DOE **Level:** 75%
EUS and various electric utilities 25%

Project Objectives:

To demonstrate the reliability and operating efficiency of a residential heat pump water heater by installing 85 units in climatically dispersed single-family homes and monitoring these installations for a period of one year.

Project Description:

The project was a continuation of an R&D effort carried out by Energy Utilization Systems (EUS) under the sponsorship of the U.S. Department of Energy. It involved the field demonstration of an air-to-water heat pump water heater designed for residential applications. Eighty-five units were installed in single-family homes located in the service territories of 20 climatically dispersed electric utilities. Utility personnel collected operating data and forwarded the data to EUS on a monthly basis. These data were then analyzed, and a monthly coefficient of performance (COP) was calculated for each unit.

The monitoring phase of the project was concluded in December 1980. Results indicated an average COP of 1.93, confirming that the units saved about half the energy that would have been used by resistance-type water heaters for many locations.

Publications:

R. L. Dunning et al., *Research and Development of a Heat Pump Water Heater, Vol. 1, Final Summary Report*, ORNL/Sub-7321/1, August 1978.

R. L. Dunning et al., *Research and Development of a Heat Pump Water Heater, Vol. 2, R&D Tasks Reports*, ORNL/Sub-7321/2, August 1978.

B. D. Sloane et al., *Demonstration of a Heat Pump Water Heater, Vol. 3, Design Report*, ORNL/Sub-7321/3, December 1979.

R. P. Blevins, et al., *Demonstration of a Heat Pump Water Heater, Vol. 4, Final Report*, ORNL/Sub-7321/4, June 1981.

5.2 Water-Source and Ground-Coupled Systems

5.2.1 Water-Loop Heat Pump Field Evaluation

Principal Investigator: To be determined
Organization:
Telephone:

Contract Agency: Electric Power Research Institute
Contract Number: RP2480-1
Contract Period: Jan. 1, 1984, through Dec. 31, 1988 (est.)
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To obtain and analyze field performance data for water-loop heat pumps (WLHPs), to use these data to develop WLHP performance algorithms, to develop improved WLHP control and operational strategies.

Project Description:

The project includes a field test of current generation WLHPs in a medium-size, occupied commercial building for one calendar year in order to quantify performance, to identify areas needing improvement, and to develop algorithms characterizing WLHP performance. The field test data will be used to develop control and operational strategies that will improve the field performance of the system. These strategies will be incorporated into the current generation WLHP system, and the system will be field tested for a second calendar year to quantify performance, to provide data for identifying promising research areas, and to develop algorithms characterizing WLHP performance with the improved control and operational strategies.

Publications:

N/A.

5.2.2 Advanced In-Ground Heat Source and Storage Technology—IEA Annex VIII

Principal Investigator: Vince C. Mei
Organization: Oak Ridge National Laboratory
P.O. Box Y, Bldg. 9102-1
Oak Ridge, TN 37831
Telephone: (615) 574-2017

Contract Agency: International Energy Agency
Contract Number:
Contract Period: February 1986–February 1987
Funding: $750,000
Source: All participating countries
Level: Task shared

Project Objectives:

To exchange information about the development of ground source heat pump and thermal storage technology among participating countries.

Project Description:

The International Energy Agency Annex VIII is supported by a team in each of the following participating countries: Canada, the Federal Republic of Germany, Switzerland, and the United States. Each team has the functions of performing a certain type of work related to the subject. Oak Ridge National Laboratory is to perform advanced ground coil modeling work for heat pump winter operation, to validate the models, and to conduct parametric studies. Switzerland is to monitor pilot facilities and current designs of vertical heat exchangers. Canada is to perform field experiments to generate data for model validation and full-scale experiments to determine the best operational strategy, and to assess different types of ground heat exchangers. The Federal Republic of Germany is to monitor several existing ground source heat pump projects. The United States has completed all of its tasks except simplification of the models.

Publications:

None provided.

5.2.3 Optimized Ground-Coupled Heat Pump Mechanical Package and Field Experiment

Principal Investigators: Van D. Baxter (ORNL)
Mark Catan (Brookhaven National Laboratory)
R. O'Neil (Niagara Mohawk Power Corporation)
Organization: Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37831
Telephone: (615) 574-2104

Contract Agency: Department of Energy
Contract Numbers: DE-AC05-840R21400
19X-69748V
86X-22035C
Contract Period: October 1982 through January 1987
Funding: $894,000
Source: DOE **Level:** 84%
Niagara Mohawk 16%

Subcontractor: H. M. Hughes, Friedrich–Climate Master Division

Project Objective:

To develop and test an optimized proof-of-concept ground-coupled heat pump so that the technology is readily available for development and commercialization by the private sector.

Project Description:

This project included four phases and thirteen different tasks. The first phase involved the development of analytical design tools for ground-coupled systems. A model for liquid-refrigerant heat exchangers was developed and integrated into the ORNL heat pump optimization program. Parametric correlations for the ground coil under various operating conditions were developed.

The second phase involved ground-coupled heat pump system life-cycle cost optimization. Sensitivity studies, cost performance tradeoffs, and model validation with laboratory data were conducted.

Phase III involved the fabrication and laboratory testing of two production prototypes. Phase IV will require the design of two complete systems (mechanical package and ground coil) and the field testing of those designs. On the basis of these tests, the ground-coupled concept will be evaluated for economic viability.

Publications:

J. W. Andrews, P. D. Metz, and J. H. Saunders, *A Refined Computer Program for the Transient Simulation of Ground-Coupled Heat Pump Systems*, BNL-34818, April 1984.

V. D. Baxter and M. A. Catan, "Optimization of a Ground-Coupled Heat Pump," *Proc. 7th Heat Pump Technology Conference, Tulsa, Oklahoma*, October 1984.

M. A. Catan and V. D. Baxter, "An Optimized Ground-Coupled Heat Pump System Design for Northern Climate Application," *ASHRAE Trans.* **91**(2), June 1985.

H. M. Hughes, "A Parametricized Cost Model for Unitary, Water-Source Heat Pumps," *ASHRAE Trans.* **91**(2B), June 1985.

M. A. Catan, "Optimized Ground-Coupled Heat Pump Mechanical Package," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

M. A. Catan et al., *Optimized Ground-Coupled Heat Pump Design, Phase I, Final Report*, BNL-51957, October 1985.

5.2.4 NYSERDA Commercial Ground Water Heat Pump Demonstration Project

Principal Investigator:
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: New York State Energy Research and Development Authority
Contract Number:
Contract Period: November 1984 through December 1986
Funding:
Source: NYSERDA **Level:** 100%

Project Objectives:

To collect and analyze accurate site specific data from three ground water heat pump (GWHP) systems and one earth-coupled heat pump (ECHP) system in buildings of the small commercial sector, to document the experience in a form useful to building owners and designer/builders.

Project Description:

The project includes monitoring and evaluation of three GWHP demonstration sites and one ECHP site. The four sites, three buildings used for light manufacturing and a school building, and their systems follow:

- Moira, New York, National Safety Wear—six 6-zone GWHPs
- Poughkeepsie, New York, Fargo Manufacturing Company—two 2-zone ECHPs
- Syracuse, New York, Frank McCarthy School—five 3-zone GWHPs
- Waterford, New York, Alltek Energy Systems—three 3-zone GWHPs

All sites shall be monitored for one complete heating season and one cooling season.

Publications:

None provided.

5.2.5 Detroit Edison Commercial Earth-Coupled Heat Pump Demonstration Project

Principal Investigator: Brad Hesse
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Detroit Edison
Contract Number:
Contract Period: June 1985 through September 1986
Funding:
Source: Detroit Edison **Level:** 100%

Project Objectives:

To provide Detroit Edison with required monitoring and analytical systems to characterize the seasonal performance of the earth-coupled heat pump systems and to characterize pertinent building electrical uses.

Project Description:

The site consists of two water source heat pumps using an earth loop for heating and cooling a commercial office building. The contributions of two electric space heaters and two tankless demand hot water heaters were also monitored.

Publications:

None provided.

5.2.6 Horizontal Ground Coil Heat Pump Field Performance Evaluation

Principal Investigator: W. S. Johnson
(Previous investigator: Robert L. Reid)
Organization: Energy, Environment, and Resources Center
Mechanical and Aerospace Eng. Dept.
University of Tennessee
327 South Stadium Hall
Knoxville, TN 37996
Telephone: (615) 974-5307

Contract Agency: Oak Ridge National Laboratory
Contract Number: 92X-7685C
Contract Period: Sept. 15, 1981, through June 30, 1986
Funding: $397,000
Source: DOE **Level:** 87%
Univ. of Tennessee 13%

Project Objectives:

To design and perform a set of field experiments that will (1) verify the horizontal coil design methodology developed by Battelle under a previous subcontract, (2) determine the effectiveness of the horizontal coil during cooling operation, and (3) determine annual and seasonal performance factors for horizontal coil ground-coupled systems.

Project Description:

A horizontal serpentine ground coil was installed at the Tennessee Energy Conservation in Housing (TECH) test site in Knoxville, which is operated jointly by the University of Tennessee (UT), Tennessee Valley Authority, and Oak Ridge National Laboratory (ORNL). The coil was designed for the heating mode, using an existing design procedure, developed by another ORNL subcontractor (Battelle-Columbus Laboratories). The coil provided a heat source/sink for an existing water-to-water heat pump previously operated by UT as a solar-augmented system. Data collection began in November 1982. The ground coil had adequate heat transfer capacity to supply the heating needs of TECH house 1 during the 1982–83 winter season. Heating loads were met without auxiliary electrical resistance heat, and the seasonal performance factor (SPF) for heating was 2.6.

The ground coil did not have adequate heat transfer capacity to supply the total cooling load during the 1983 summer. Although the sensible cooling load was met as long as ambient temperature remained below 98°F (36.7°C), the latent load was met only during the first two to three weeks of summer, prior to soil drying. The SPF for cooling was 1.1. This mediocre performance was traced to large air gaps between the ground coil and the soil. The ground coil was reinstalled with sand backfill around the pipe. Cooling performance during 1984 was only marginally improved, however. Heating performance during the 1983–84 winter was nearly identical to that during 1982–83.

In November 1984, a ground-coupled heat pump system designed by an industry group (GEOSystems and Charles Machine Works of Oklahoma) was installed in TECH house 5. This system consists of a water-to-air heat pump and a 1200-ft ground coil. The performance of this system will be determined during the 1984–85 test year.

Publications:

W. S. Johnson et al., *TECH House I Horizontal-Coil Ground-Coupled Heat Pump: Heating Season Performance*, ORNL/Sub/81-7685/1&92, September 1983.

W. S. Johnson et al., *TECH House I Horizontal-Coil Ground-Coupled Heat Pump: 1983 Cooling Season Performance*, ORNL/Sub/81-7685/2&92, May 1984.

W. S. Johnson et al., *TECH House I Horizontal-Coil Ground-Coupled Heat Pump: 1983–84 Annual Performance*, ORNL/Sub/81-7685/3&92, August 1985.

W. S. Johnson et al., "Ground-Coupled Heat Pump Research at the University of Tennessee," *Proc. DOE/ORNL Heat Pump Conf.*, CONF-841231, August 1985.

5.2.7 Residential Earth-Coupled Heat Pump Technology Transfer

Principal Investigator: Patrick J. Hughes
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: March 1985 through June 1986
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To transfer heat pump technologies evaluated and/or developed by Niagara Mohawk Power Corporation (NMPC) Research and Development (R&D) to other appropriate NMPC departments and to the rate-paying public, to validate previously developed bin analysis algorithms for earth-coupled heat pump system design and performance prediction.

Project Description:

A total of nine earth-coupled heat pump systems will be installed during the project. Five of the sites will be equipped with manual performance monitoring devices. Weekly performance data will be collected from the sites for a one year time period.

Publications:

None provided.

5.2.8 Ground Coil Modeling

Principal Investigator: Vince C. Mei
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-4945

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: 1981–1986
Funding: $238,000
Source: DOE **Level:** 100%

Project Objectives:

To derive ground coil design models that are better than present methods, which are either mathematically unsound or over simplified and do not provide proper ground coil designs.

Project Description:

The modeling effort was divided into four phases:

- Phase 1, ground coil operation involving heat transfer only, such as deep well vertical tube in tube arrangements
- Phase 2, ground coil operation involving soil phase change and soil seasonal temperature variation at depth, such as horizontal ground coil water operation
- Phase 3, ground coil operation involving both heat transfer and mass transfer, such as horizontal ground coil summer operation
- Phase 4, ground coil operation involving thermal interference from adjacent coil legs

Phase 1 has been completed. The model derived was validated by laboratory experimental data. Phase 2 has been completed for single coil operation. Efforts are under way to model multicoil arrangement. Phase 3 is temporarily on hold. A model including moisture migration will be more complicated than other ground coil models, but it can be readily formed without any major difficulties. However, it is generally recognized that the ground coil heat pump (GCHP) is more efficient for winter operation where moisture migration toward the coil is a plus. Summer soil dry out is a big concern for GCHP. Unless there are test data to prove the competitiveness of GCHP with high-efficiency air-source heat pumps, modeling the GCHP with moisture migration becomes pointless.

Phase 4 is completed. The mathematical model was developed and then validated with field experimental data collected by The University of Tennessee at the Tennessee Energy Conservation in Housing site. It was found that the effect of thermal interference did exist and could be seen from the soil temperature profile around the coils. A 28-day simulation of the field data indicated that the two-coil trench arrangement could absorb 50 to 60% more heat from the ground than a single-coil trench.

Publications:

V. C. Mei and S. K. Fischer, "Vertical Concentric Tube Ground-Coupled Heat Exchanger," *ASHRAE Trans.* **89**(2B), June 1983.

V. C. Mei and S. K. Fischer, *A Theoretical and Experimental Analysis of Vertical, Concentric Tube Ground-Coupled Heat Exchangers*, ORNL/CON-153, October 1984.

V. C. Mei and C. J. Emerson, "New Approach for Analysis of Ground Coil Design for Applied Heat Pump Systems," *ASHRAE Trans.* **91**(2), June 1985.

V. C. Mei, "Theoretical Heat Pump Ground Coil Analysis with Variable Ground Farfield Boundary Conditions," *AIChE Heat Transfer Symposium Series 245,* **81**, August 1985.

5.2.9 Hydronic Heat Pumps

Principal Investigator: Robert Fischer
Organization: Battelle Columbus Laboratories
505 King Road
Columbus, OH 43201
Telephone: (614) 424-6424

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-6
Contract Period: May 31, 1982, through Dec. 31, 1985
Funding:
Source: EPRI **Level:** 100%

Subcontractors: Battelle, Frankfurt
Honeywell, Inc.

Project Objectives:

To investigate the technical and economic potential of hydronic heat pumps, to perform a preliminary market identification survey, to determine future research requirements in this technology.

Project Description:

Potential benefits of hydronic heat pumps include:

- Reduced heating costs to users of hydronic systems
- A utility load-leveling option when coupled with thermal storage
- Conservation of oil and reduction in foreign oil dependence

This project is a feasibility analysis of heat pumps for retrofit, add-on, and new construction with hydronic heating systems in residential and light commercial applications. The study includes:

- A survey of the relevant literature and available equipment
- Development and analysis of concepts
- Simulation of hydronic heat pump system performance
- Evaluation of economics and market potential
- Preparation of a plan for further research and development

Approximately 17% of existing homes are heated with hydronic heating systems, and many of these systems are oil fired. Almost none of these systems use heat pumps, although a market has been developing for heat-only hydronic heat pumps in Europe. Over 50,000 such systems were installed in Europe, mostly in West Germany, by the end of 1980, typically as add-on (bivalent) systems with oil-fired boilers. A literature search identified data on both domestic and European hydronic heat pumps and heating systems. System modeling of candidate systems provided performance data that permits both technical and economic evaluations of hydronic heat pump concepts.

Economic evaluations of various hydronic heat pump configurations should be completed by the fourth quarter 1985, with the final report completed in early 1986.

Publications:

None provided.

5.2.10 Crawl Space Earth-Coupled Heat Pump Experiments

Principal Investigator: James F. Martin
Organization: Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-3977

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-14
Contract Period: Oct. 31, 1979, through Dec. 31, 1985
Funding:
Source: EPRI **Level:** 50%
DOE 50%

Project Objectives:

To determine through experimental and analytical studies the extent to which the performance of an air-to-air heat pump could be improved by making use of the thermal energy that is stored naturally in the earth of the crawl space of a house to preheat (or precool) the source air of the heat pump.

Project Description:

Oak Ridge National Laboratory has been investigating a novel form of ground-coupled heat pump as part of the Thermal Energy Storage Program for the Energy Storage Division of the Department of Energy (DOE). The concept was that of preheating the heat pump inlet air by drawing it through the crawl space. Tests have confirmed that the heat obtained is drawn primarily from the ground beneath the crawl space. The testing was continued to obtain a statistically significant amount of performance data and to ensure a wide range in outside weather conditions.

The technical approach included comparison of heat pump performance between one conventional and two modified crawl space earth-coupled heat pump installations, measurement of the various factors contributing to differences in heat pump/house energy use among the three test houses, and comparison of measured house loads and energy usage with calculations obtained through use of the DOE-2 computer simulation.

Involvement by the Electric Power Research Institute in this project is new. Prior progress under DOE funding included tests involving two occupied houses during the 1979 winter and tests drawing air through a tunnel insulated from the crawl space but open to the earth. These tests confirmed that heat is drawn from the ground. Tests on the three unoccupied test houses during the 1981/82 and 1982/83 heating seasons were not complete nor totally conclusive because of experimental difficulties, which have since been resolved.

Testing was completed in April 1984 as planned. Analysis of test results revealed that the crawl space earth-coupled houses had approximately the same seasonal energy consumption as the control house. This was partly due to loose insulation on ducting located in the crawl space. However, peak 15-min average demand was reduced by 0.9 kW (8%) for the open loop crawl space earth-coupled house and by 2.6 kW (23%) for the closed loop crawl space earth-coupled house, compared with the control house. Number and duration of defrost cycles were also significantly reduced for the crawl space earth-coupled houses compared with the control house. Computer analysis showed that crawl space earth-coupled heat pump seasonal energy consumption should be slightly better (6–11%) than the control house if insulation integrity is maintained. Further computer analysis is planned to identify optimum operating strategies.

Publications:

M. Ternes, "Earth Thermal Storage for Enhanced Performance of Air-to-Air Heat Pumps," presented at 17th IECEC Conference, August 1982.

J. J. Carbajo et al., "Energy Savings Resulting from a Ground-Coupled Air-to-Air Heat Pump." *Proc. IECEC, Aug. 19, 1984*, CONF-840804, August 1984.

5.2.11 Residential Market Support Software for Waterfurnace International, Inc.

Principal Investigator: Patrick Hughes
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Waterfurnace International, Inc.
Contract Number: N/A
Contract Period: June 1985 through December 1985
Funding: N/A
Source: Waterfurnace **Level:** 100%

Project Objectives:

To develop bin method analysis routines to predict earth-coupled heat pump system performance, to develop algorithms to optimally size heat pumps and earth heat exchanger loops, to develop algorithms to predict competing systems performance, to develop cost models for both earth-coupled heat pumps and competing systems, to develop economic analysis routines for system comparison, to integrate the above routines into a market support software package linking remote sites to central computer.

Project Description:

This project provides a manufacturer of earth-coupled heat pumps with market support software. Dealers and distributors can access routines residing on a central computer via modem; these routines provide sizing guidelines, performance prediction, and cost estimates for site-specific input. Performance and economic analysis is also provided for a variety of competing systems. This software package is intended to be used as both a design tool and a marketing tool. The algorithms included on this package result from previous monitoring and modeling projects.

Publications:

None provided.

5.2.12 Modeling of Earth-Coupled Heat Pump Systems

Principal Investigator: Joseph E. Rizzuto
Organization: NYSERDA
Two Rockefeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number: 748-CON-BCS-85
Contract Period: October 1984 through December 1985
Funding: $228,400

Source:	**Level:**
NYSERDA	41%
Niagara Mohawk	41%
Rochester Gas and Electric	18%

Subcontractors: Niagara Mohawk Power Corporation
W. S. Fleming and Associates

Project Objectives:

To provide a mechanism for sizing and optimizing earth-coil configurations through (1) development of a simplified earth-coupled heat pump model, (2) verification and/or correlation of the model utilizing field data from past demonstration programs, and (3) development and publication of earth-coupled heat pump information.

Project Description:

This program will develop a mechanism for sizing and optimizing earth-coil configurations and predicting the performance of earth-coupled heat pump systems. As part of this effort, one additional year of data will be collected on two existing sites that employ multiple coils and depths and have extensive field temperature sensors. The model development includes three steps: (1) utilization of field data collected in the Niagara Mohawk/New York State Energy Research and Development Authority/Rochester Gas and Electric program to examine and verify the suitability of existing complex earth heat transfer models; (2) utilization of the verified, detailed model as a standard comparison with test parametric ranges of validity of existing simpler models; and (3) use of the verified, simple model to generate the market support and commercialization materials for the key user groups. A manual of acceptable practices for earth-coupled heat pump systems will also be developed.

The primary product from this program is the predictive methodology for performance and optimization of earth-coupled heat pump systems. This methodology will be provided to potential users and shall consist of model documentation, predictive procedures, and acceptable practices. The products of this project will provide a mechanism for the design and optimization of earth-coupled heat pump systems and will enhance their entry and acceptance into the marketplace.

Additional performance data have been collected on the two well-instrumented earth-coupled heat pump (ECHP) systems; the ECHP model has been developed and is now being validated.

Publications:

None provided.

5.2.13 Performance Monitoring and Evaluation of Open and Closed Loop Water Source Heat Pump System at Stewart's Ice Cream Headquarters— Saratoga, New York

Principal Investigator: Judson Brown
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: June 1984 through December 1985
Funding:
Source: Niagara Mohawk Power Corporation **Level:** 100%

Project Objective:

To analyze the energy and economic performance of a water-source heat pump and plate heat exchanger used as the central heating and cooling plant for an office space conditioning system (composed of circulating water loop and zone heat pumps).

Project Description:

The central water source heat pump and plate heat exchanger are being monitored and evaluated. The performance of analogous system components in a more conventional system (such as a boiler and cooling tower) are being modeled. Energy and economic performance of the central components will be compared with conventional components.

Publications:

None provided.

5.2.14 Residential Earth-Coupled Heat Pump—Long-Term Monitoring

Principal Investigator: Patrick Hughes
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: October 1984 through October 1985
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To establish a procedure for evaluating the long-term performance of the residential earth-coupled heat pump (ECHP) field trial sites; to establish a procedure for tracking the maintenance record of the ECHP systems at each site; to evaluate performance and document maintenance requirements for eight sites for the period Oct. 1, 1984, to Oct. 1, 1985; to utilize the existing backup performance monitoring equipment to the greatest extent possible.

Project Description:

An eight-site field test of state-of-the-art residential ECHP systems in New York is under way to determine if performance of such systems can be expected to continue at the high first year level throughout the system life. No long-term data are currently available on ECHP systems operating under New York climate and soil conditions. Previous experiences in Sweden indicate that under certain circumstances, performance degradation can occur. Long-term monitoring is desirable to establish whether performance degradation occurs at the field test sites.

Publications:

None provided.

5.2.15 Testing of Earth-Coupled Heat Exchangers Under Extreme Load Conditions

Principal Investigator: Patrick Hughes
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: January 1985 through September 1985
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To operate earth-coupled heat exchanger (ECHX) systems under extreme load conditions and gather performance data; to provide for a reduced pipe length ECHX system to increase flow rates and fluid temperature differentials; to perform testing over the peak heating months; to perform analysis of ECHX performance test data to characterize heating transfer rate, heating capacity limits, and further detail ECHX profiles such as degradation patterns, etc.; to provide for normalization of performance data to establish comparative cost-effectiveness evaluations; to provide further data toward the support of ECHX sizing methods.

Project Description:

In an earlier project entitled "Commercial Earth-Coupled Heat Pump Demonstrations," an annual performance and economic analysis of eight different ECHX designs showed significant variances across these designs. Throughout this year-long monitoring effort, all ECHXs were operated simultaneously in parallel. Consequently, the minimum fluid temperatures experienced by the ECHXs were in the range of 40°F. In other words, the ECHXs were unable to reach peak or maximum conditions of heat transfer, yet indications of ECHX design performance differences were found.

During the current project, the ECHX systems were operated under more extreme load conditions. This was accomplished by shutting off portions of the ECHX system alternately over the peak heating months. This provided both increased flow and reduced fluid temperature to specific ECHX designs. Effectively, this created higher heat exchange rates than those experienced with the total ECHX system operations.

The above operations strategy is anticipated to provide more detailed, accurate, and extreme performance data such that heating capacity, heat exchange rates, and corresponding cost-effectiveness evaluations can be characterized for each ECHX design type. It is intended, then, that the analysis of the obtained test data will thus allow for a well-supported and detailed definition of the optimum ECHX designs for small commercial buildings.

Publications:

None provided.

5.2.16 Ground-Coupled Heat Pump Program

Principal Investigator: Joseph E. Rizzuto
Organization: New York State Energy Research and Development Authority
Two Rockefeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number: 510-CON-BSC-83
Contract Period: September 1982 through January 1985
Funding: $820,000

Source:	**Level:**
NYSERDA	44%
Niagara Mohawk	44%
Rochester Gas and Electric	12%

Project Objectives:

To assess the technical and economic feasibility of ground-coupled heat pumps so as to encourage the use of space heating systems that provide both reduced energy consumption and favorable utility load characteristics, to evaluate horizontal freeze-based and non-freeze-based systems, to determine the performance and cost effectiveness of vertical heat exchangers, to evaluate the use of the earth-coupled heat pump for the production of domestic hot water.

Project Description:

Under this program, nine ground-coupled heat pump systems will be installed in residential applications in upstate New York. Heat pumps from three different manufacturers will be used. Also, ground coil configurations will include freeze-based and non-freeze-based horizontal systems as well as vertical heat exchangers. The systems will be evaluated with and without the production of domestic hot water. The utilization of multiple pipes within a single trench and the performance of shorter, more heavily loaded ground coils will be evaluated.

Seven ground-coupled heat pumps were installed in the Syracuse, Rochester, and Albany areas in September 1982 with system monitoring commencing in December 1982. Modifications to the seven systems for the production of domestic hot water and the installation of two additional systems to evaluate multiple pipe configurations and the use of smaller collectors were initiated in October 1983.

Publications:

W. S. Fleming and Associates, *Residential Earth-Coupled Heat Pump Demonstration.*

5.2.17 Ground-Source Heat Pump Technology Transfer

Principal Investigator: Gary D. Allhusen
Organization: New York State Energy Research and Development Authority
Two Rockefeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number:
Contract Period: 1984–1985
Funding: $40,000

Source:	**Level:**
NYSERDA	50%
Empire State Electric Energy Research Cooperation	50%

Subcontractors: W. S. Fleming and Associates, Inc.
Westinghouse Electric Corporation

Project Objectives:

To disseminate information gained from recent ground water and earth-coupled heat pump projects so that industry and consumers are aware of ground source heat pump benefits.

Project Description:

The project is aimed at the New York State heating, ventilating, and air conditioning industry, well drillers, excavators, design engineers, architects, and the general public.

Ground source heat pump information will be presented in a technical booklet of approximately 20 pages, at a seminar held in different locations throughout the state, and in a leaflet providing a general description. The contractors of the ground water and earth-coupled heat pump projects will prepare a package of information describing characteristics, installation, and maintenance of ground source heat pumps. The package will be sent to a marketing firm to be rewritten and published as an interesting, attractive technical booklet. The package will also be used in a utility-sponsored seminar to introduce the technology, demonstrate installation and maintenance procedures, make comparisons with conventional means of heating and cooling, and discuss economic benefits of ground source heat pumps. The marketing firm will publish along with the technical booklet a leaflet describing the characteristics of ground source heat pumps. The leaflet will be less technical than the booklet and more appropriate for the general public.

Ground source heat pumps require less energy and have lower demand requirements particularly during the coldest days than electric resistance heating and air-to-air heat pumps. As a result of increased use, arising from our technology transfer efforts, peak demand load requirements of the electric utilities will be reduced. Energy consumed in the production of electricity for heating and cooling will be reduced.

Publications:

A Technical Guide to Ground-Source Heat Pumps, New York State Energy Research and Development Authority.

5.2.18 Multiple Shallow Vertical-Coil Heat Pump Experiment

Principal Investigators: Van D. Baxter
Vince C. Mei
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-4945

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: 1983–1985
Funding: $75,000
Source: DOE **Level:** 100%

Project Objectives:

To study the performance of shallow well systems, to analyze from the field test data the economic viability by comparing the performance with other types of ground coil heat pump systems.

Project Description:

Six shallow wells with depths ranging from 60 to 100 ft (18.3 to 30.5 m) were drilled at the Tennessee Energy Conservation in Housing site. Polyethylene U-tubes of 1.5 in. OD (3.81 cm OD), schedule 40 were installed in the well. Five wells were back filled with cement and one with sand. The six wells could be operated in any combination. However, in the tests performed so far, the wells operated in series connection only. Total depth of the wells was 460 ft (140.2 m). The fluid used in the system was a 20% methanol–water mixture. The ground coil was connected to a 2.5-ton water-to-water heat pump. For the past heating and cooling seasons, a heating coefficient of performance (COP) of 2.9 and a cooling COP of 1.8 were obtained.

Publications:

V. C. Mei and V. D. Baxter, "Performance of a Ground-Coupled Heat Pump with Multiple Dissimilar U-Tube Coils in Series," *ASHRAE Trans.* **93**, July 1986.

5.2.19 Analytical and Experimental Investigation of Soil Freezing

Principal Investigator: Vince C. Mei
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-4945

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: 1981–1985
Funding: $156,000
Source: DOE **Level:** 100%

Subcontractor: In cooperation with Canadian National Research Council at Ottawa

Project Objectives:

To analyze the effect on ground coil heat pump system performance of soil freezing around the coil due to temperature gradient around the coil.

Project Description:

A mathematical model for ground coil operations coupled with soil freezing has been developed and solved numerically. The field experimental data by Brookhaven National Laboratory were used for validation. The calculated daily energy absorption from the ground matched excellently with the test results. It was also found from parametric study that unless the ground coil inlet fluid temperature is much lower than the soil moisture freezing point, the amount of heat released by soil freezing will likely be very small.

Publications:

V. C. Mei, "New Approach for Analysis of Ground-Coil Design for Applied Heat Pump Systems," *ASHRAE Trans.* **91**(2), 1985.

V. C. Mei, "ORNL Ground Coil Analytical and Experimental Studies," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.2.20 Field Trials of Residential Earth-Coupled Heat Pumps

Principal Investigator: Patrick J. Hughes
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: July 1982 through October 1984
Funding:

Source:	**Level:**
Niagara Mohawk Power Corp.	42%
NYSERDA	42%
Rochester Gas and Electric	16%

Project Objectives:

To evaluate the cost and performance that the earth-coupled heat pump industry can currently offer in the residential market in New York; to evaluate from the utility and homeowner viewpoints; to monitor and report heating/cooling performance over one year for seven sites; to monitor and report heating/cooling performance over one year for nine sites; to monitor and report the relative values of one, two, and four pipes in horizontal trenches.

Project Description:

A nine-site field test of state-of-the-art residential earth-coupled heat pump systems in New York is under way. Three heat pump manufacturers participated in 1982/83 and four in 1983/84. Vertical and horizontal earth-coupled heat exchangers were tested. One-, two-, and four-pipe-per-trench horizontal loops were monitored under identical inlet temperature, flow, and cyclic conditions. The systems addressed three end uses: heating, cooling, and water heating. This project represents the first major evaluation of this technology under the harsh climate and soil conditions of Central New York.

Publications:

P. J. Hughes and R. J. Hackner, *The New York State (USA) Demonstration of Residential Earth-Coupled Heat Pumps: Synopsis of Monitored Performance*, presented at the Second International Energy Agency Commission of the European Communities Workshop on Solar-Assisted Heat Pump Systems, Vienna, Austria, May 8–10, 1985.

P. J. Hughes et. al., *Results of the Residential Earth-Coupled Heat Pump Deomonstration in Upstate New York*, presented at the 1985 ASHRAE Summer Meeting in Hawaii, June 1985.

5.2.21 Demonstration of Earth-Coupled Heat Pump Systems for Commercial Buildings

Principal Investigator: Thomas M. Griffin
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number: Project SS149
Contract Period: January 1983 through September 1984
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To demonstrate earth-coupled heat pump technology in a "typical" small commercial building; to install, monitor, and evaluate several types of vertical earth heat exchangers; to develop cost-effectiveness criteria for heat exchangers; to develop vertical heat exchanger heat pump design and sizing information.

Project Description:

A seven-zone small commercial office building is being monitored and its energy performance evaluated. The system includes eight vertical earth coil heat exchanger types. A monitoring period of 12 months was to be completed in the summer of 1984. Results of vertical heat exchanger and heat pump performances and system economics were expected in the fall of 1984. The earth-coupled heat pump system has successfully satisfied all building load conditions to date.

Publications:

None provided.

5.2.22 Ground Water Heat Pump Evaluation

Principal Investigator: Joseph E. Rizzuto
Organization: New York State Energy Research and Development Authority
Two Rockfeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number: 398-EU-RCU-81
Contract Period: September 1981 through September 1984
Funding: $944,235

Source:	**Level:**
NYSERDA	31%
ESEERCO	63%
New York Power Authority	6%

Subcontractors: Empire State Electric Energy Research Cooperation
1271 Avenue of Americas
New York, NY 10020

Westinghouse Electric Corporation
77 Penn Center Boulevard
Pittsburgh, PA 15235

Project Objective:

To measure accurately the actual heating efficiency (or seasonal performance factor) of commercially available ground water heat pumps installed in New York State single-family residences.

Project Description:

This project evaluated the field service performance of ground water source heat pumps. Preliminary indications were that these devices could be applied in as much as half of New York State. Because they used thermal energy stored in the ground, ground water heat pumps appeared to be the most energy-efficient electrical heating option in the state (using as little as one-third the electricity of an electric furnace).

The contractor instrumented suitable ground water source heat pumps, acting in coordination with the local electric utility. Data were transmitted to a central computer, which was used to analyze the results. Information about heat pump malfunctions, well water service requirements, water quality, and homeowners' attitudes were recorded. The energy efficiency of 15 installations in several different locations in the state were calculated and reported. All seven state electric utilities plus the New York Power Authority were involved in the project through the Empire State Electric Energy Research Cooperation.

Publications:

Empire State Electric Energy Research Cooperation, Final Report, EP81-5, April 1985.

5.2.23 Vertical Earth Heat Pump System—IEA Annex II

Principal Investigator: Bernt Baeckstroem
Organization: Chalmers University of Technology
S-41296 Gothenburg
Sweden

Telephone: 46-31-810-100

Contract Agency: International Energy Agency
Contract Number:
Contract Period: January 1981 through July 1984
Funding: 900,000 SK ($177,000)
Source: DOE **Level:** 36%
Other four countries 64%

Project Objectives:

To investigate state-of-the-art techniques in the participating countries; to assess climate and geological conditions, energy, and power demand of normal residential buildings in the participating countries as an input for sizing calculations.

Project Description:

This project is supported by a national team in each participating country (Austria, Canada, Denmark, Sweden, and the United States). The work was all analytical in nature. Using existing design methods, 37 different example systems were analyzed. Variables included four different building loads, seven soil types, two brine temperature levels, three climate zones, three coil configurations, and two methods of summer soil recharging. Components such as ground heat exchanger elements (pipes), drilling methods, solar collectors, and ambient air heat exchangers were described, and actual market prices were collected.

The technical potential of the vertical earth heat pump (VEHP) technique is assumed to be rather good, and no serious barriers have been noticed. The economic considerations show that the VEHP systems are not competitive today due to the relatively high investment costs for installation of the heat exchanger in the ground.

The technical behavior as well as the economy of the VEHPs depend on the size of the plant and on the mean temperature level of the storage. Calculations show that ground temperatures below the freezing point are desirable but not useful in all soil types because of geotechnical problems.

Publications:

Bernt Baeckstroem, *International Energy Agency Advanced Heat Pumps Annex II—Vertical Earth Heat Pump Systems, Final Report*, Swedish Council for Building Research, 1983.

5.2.24 Laboratory Test of a Residential Low-Temperature Water Source Heat Pump

Principal Investigator: Vince C. Mei
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-4945

Contract Agency: Department of Energy
Contract Number: W-7405-eng-26
Contract Period: 1981–1984
Funding: $205,000
Source: DOE **Level:** 100%

Project Objectives:

To characterize the water source heat pump performance at different inlet water temperatures and flow rates.

Project Description:

A low-temperature water source heat pump, designed for ground water application, was tested in the laboratory at water inlet temperatures ranging from 45 to 70°F (7.2 to 21.1°C) and water flow rates of 5 to 13 gpm (1.14 to 2.95 m^3/h). It was found that the steady-state heating coefficient of performance (COP) ranged from 3.0 at 45°F to 3.45 at 70°F at a 9-gpm water flow rate. Cooling COP was from 3.75 at 45°F to 2.85 at 70°F at 9 gpm. The heat pump capacity was linear with the inlet water temperature. The cycling loss was also a linear function of water inlet temperature, but not a function of water flow rate. When water pumping power was not included, the higher the water flow rate, the higher the COPs. However, when a 150-ft (46-m) head was assumed on water pumping power calculations, it was found that the higher the flow rate, the lower the COPs. It was concluded that for ground water heat pump systems, pumping power is an important factor in determining the system COP.

Publications:

V. C. Mei, "Laboratory Test of a Residential Low-Temperature Water Source Heat Pump," *ASHRAE Trans.* **89**(2B), 782–794 (June 1983).

V. C. Mei, *Laboratory Test of a Residential Low-Temperature Water Source Heat Pump,* ORNL/CON-100, April 1984.

5.2.25 Monitoring of Residential Water-Source Heat Pumps

Principal Investigator: Gilbert M. Freedman
Organization: Allegheny Electric Cooperative
212 Locust Street
P.O. Box 1266
Harrisburg, PA 17108
Telephone: (717) 233-5704

Contract Agency: Electric Power Research Institute
Contract Number: RP1201-14
Contract Period: Sept. 22, 1980, through Nov. 31, 1983
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To measure the technical performance of residential water-source heat pumps in retrofit applications for rural residences; to compare the performance and cost data obtained with other types of heating systems (air-to-air heat pumps; oil, gas, and electric furnaces; and active solar systems).

Project Description:

This project examined groundwater heat pumps including:

- Field monitoring of two water-to-air heat pumps
- Performance comparison with alternative systems
- Comparison of costs
- Evaluation of utility impacts

The two heat pumps were installed as retrofits to oil- and coal-fired furnaces in rural Pennsylvania locations. One site used water reinjection into a second well and the other used surface disposal. The University of Pennsylvania analyzed the data and modeled both the heat pumps and alternative systems under a separate contract with Oak Ridge National Laboratory (ORNL).

Energy consumption of these heat pumps for part of the 1980/81 heating season was monitored with kilowatt-hour meters. The primary microprocessor-based data acquisition systems were installed in July 1981, and monitoring began in October 1981. Performance data for the 1981/82 season (an extremely cold winter for the sites) indicated monthly coefficients of performance ranging from 2.2 to 3.0.

Publications:

G. M. Freedman and D. L. Mohre, "Monitoring of Residential Groundwater Heat Pumps," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984*, CONF-840266, EPRI-EM-3797, November 1984.

G. M. Freedman et al., "Maintaining Residential Groundwater Source Heat Pumps in the Northeast" (to be published).

5.2.26 Thermal Performance and Economics of Ground-Coupled Heat Pumps

Principal Investigator: Robert D. Fischer
Organization: Battelle Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone: (614) 424-6424

Contract Agency: Oak Ridge National Laboratory
Contract Number: 7800-X06
Contract Period: Sept. 2, 1980, through Sept. 30, 1983
Funding: $289,000
Source: DOE **Level:** 100%

Project Objectives:

To determine the potential energy use benefits and economic viability of earth heat source/heat sink equipment, to establish preferred design configurations for various soil/weather conditions across the United States.

Project Description:

Under this project, information on the design and performance of past and present ground-coupled heat pump systems in the United States, Canada, and Europe was reviewed. Models for computing simultaneous heat and moisture transfer in soils were evaluated.

This project uncovered a substantial volume of historic and current research on ground-coil heat pump technology. Approximately 27 individual ground-coil heat pump design and simulation methodologies have been studied. In addition, numerous visits and phone contacts were made throughout Europe and North America to obtain information on the status of various ground-coil activities. A news release describing this study, issued in December 1980, resulted in a significant number of individuals and local installers responding with information on their experience and activities in ground-coil heat pump systems.

The technical and economic feasibility of three types of ground-coupled systems, single deep well, multiple shallow well, and horizontal coil, was assessed for nine U.S. cities. Also included was a parametric assessment of coil installation costs, a sensitivity analysis of the effect of soil moisture migration on horizontal coil systems, and the evaluation of heating-only ground-coupled systems, with cooling in northern areas supplied directly from the ground coils without heat pump assistance.

Life-cycle costs with a 2% discount rate were lower for all ground-coupled systems in five cities than for a standard air-source heat pump (ASHP). Simple paybacks ranged from a low of 3 years to over 30 years relative to the ASHP. Ground-coupled systems were found to be most economically competitive in cities with high heating and low cooling loads. Simple deep-well and horizontal systems appeared to be about equally attractive in terms of simple payback relative to the ASHP. Direct cooling with the deep-well systems was found to be inadequate to handle the cooling load even in northern cities.

Publications:

R. D. Fischer, *Models of Simultaneous Heat and Moisture Transfer in Soils*, ORNL/Sub/80-7800/1&06, October 1983.

D. A. Ball et al., *State-of-the-Art Survey of Existing Knowledge for the Design of Ground-Source Heat Pumps*, ORNL/Sub/80-7800/2&06, November 1983.

R. D. Fischer, and G. H. Stickford, *Technical and Economic Feasibility of Horizontal, Multiple Shallow-Well, and Deep-Well Ground Coupling for Residential Heat Pump Applications*, ORNL/Sub/80-7800/3&06, November 1983.

R. D. Fischer et al., "An Assessment of Ground-Coil Heat Pump Technology," *Proc. 7th Oklahoma State Heat Pump Technology Conference*, October 1984.

5.2.27 Well-Water-Source Heat Pump Field Performance Study

Principal Investigator: Richard S. Dougall
Organization: University of Pittsburgh
Mechanical Engineering Dept.
648 Benedum Hall
Pittsburgh, PA 15261
Telephone: (412) 624-5335

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7985
Contract Period: October 1980 through September 1983
Funding: $111,000
Source: DOE **Level:** 100%

Project Objectives:

To analyze data pertaining to the field performance characteristics of two well-water-source heat pumps (WWSHP) so that seasonal performance factors and energy consumption characteristics of the WWSHP could be evaluated; to develop a mathematical model that simulated the actual performance satisfactorily and then to use this model to compare WWSHP with other heating and cooling systems.

Project Description:

This project was the data analysis and modeling phase related to a companion project involving data gathering that was performed by Allegheny Electric Cooperative, Inc., Harrisburg, Pennsylvania, and funded by Electric Power Research Institute.

The WWSHP has an important advantage over air-to-air heat pumps in that the heat source (i.e., well-water or other groundwater) remains at a relatively uniform temperature throughout the year. Because of this, the coefficient of performance (COP) remains reasonably high, even when outdoor air temperature becomes very low. WWSHPs have the potential of being economical for heating rural residences in northern climates when these residences have an easily available supply of groundwater.

Two existing, single-family residences, one at Bedford, Pennsylvania, and the other at East Freedom, Pennsylvania, were selected by Allegheny Electric and retrofitted with commercially available water-source heat pumps. One heat pump was reversible and supplied heating and cooling; the other was a nonreversible, heating-only unit. The heat pumps were instrumented so that perfomance data could be obtained. An automated data acquisition system was installed at both sites. Valid data acquisition from the sites was started in October 1981 for the Bedford site and in February 1982 for the East Freedom site. Data were stored on cassette tape and transferred on a weekly schedule to the University of Pittsburg for reduction and analysis.

Over the 2-year test period, the nonreversible unit operated at a heating seasonal performance factor (HSPF) of nearly 3.0, including an allowance for water-pumping energy; the HSPF for the reversible unit was only 1.8. The low heating performance of the reversible unit suggests that it was optimized for a cooling application, with the heating mode an added feature.

Neither system required significant supplemental resistance heat, which indicates that groundwater-source heat pumps are more likely to have a positive influence on winter peak demand and utility load profile than are air-source heat pumps. The nonreversible unit had a payback period of about 4 years, a savings of approximately $680/year over oil systems at 1984 prices. Payback for the reversible unit was over 40 years relative to oil systems because of its low SPF. Well-drilling or water-disposition costs would affect overall feasibility of such systems.

Publications:

R. S. Dougall et al., *Monitoring of Residential Groundwater Source Heat Pumps in the Northeast*, ORNL/Sub/80-7985/1, March 1986.

5.2.28 An Investigation of Ground Source Heat Pumps Using Direct Expansion

Principal Investigator: Andy Blackshaw
Organization: E-Tech, Inc.
3570 American Drive
Atlanta, GA 30341
Telephone: (404) 458-6643

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-61612C
Contract Period: September 1980 through August 1982
Funding: $138,246
Source: DOE **Level:** 100%

Project Objectives:

To perform an experimental investigation and feasibility assessment of direct expansion of refrigerant in an earth heat exchanger as a means for utilizing the ground as a heat source/sink for heat pumps.

Project Description:

The project was divided into two tasks. First a small-scale, well-instrumented, variable-capacity, ground-coupled heat pump system was developed and built. Pressures and temperatures were measurable at various locations around the heat pump circuit. Refrigerant flow rate was measurable to determine system heating and cooling capacity. Three types of earth heat exchangers were tested under heating conditions (ground cooling) with this experimental apparatus. The system was reversible, and the same earth heat exchangers were tested under cooling conditions (ground heating). Various refrigerant flow control and compressor protection devices were tested for applicability to the direct expansion system.

The best earth heat exchanger configuration determined in task 1 was used as a model for development of a full-scale system in task 2. A 2.5-ton prototype system was designed and constructed. The refrigerant flow control and compressor protection devices determined to be most applicable in task 1 were used in the full-scale systems developed in task 2.

An open-type compressor was used initially on the subscale system of task 1. However, there was a problem with minor amounts of liquid floodback causing bearing damage, even with the use of a suction accumulator. A hermetic compressor was installed in its place because it is more compatible with such operation.

Problems with cooling-mode operation prevented successful development of this concept. During cooling operation, all of the charge stayed in the condenser (ground coil), thus starving the evaporator and causing the low-pressure switch to shut off the compressor.

Publications:

None provided.

5.2.29 Ground-Coupled Heat Pump Demonstration

Principal Investigator: Joseph E. Rizzuto
Organization: New York State Energy Research and Development Authority
Two Rockfeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number: 422-EU-RCU-82
Contract Period: July 1981 through April 1982
Source: NYSERDA **Level:** 11%
Opemhimer 89%

Subcontractor: Spencertown Geo-Solar Associates
P.O. Box 38
Spencer, NY 12165

Project Objectives:

To study several field configurations relative to their heat transfer characteristics with both dry and moist ground conditions present, to develop a methodology for specification of ground-loop design in relation to heat pump performance, to develop a methodology for specification of system economics of ground-coupled heat pumps in relation to air-to-air and well water heat pumps.

Project Description:

Ground-coupled heat pumps offer the potential for achieving significantly higher coefficients of performance than air-to-air heat pumps. Although the coefficients of performance may be less than well water heat pumps, the cost of installation would be lower in many instances and the risk of contamination of either the heat pump or the ground water would be avoided.

A field experiment was conducted in Spencertown, New York, during which various ground-loop designs and operating strategies were evaluated. The ground-coupled system consisted of ~2000 ft of polyethylene pipe subdivided into eight ground-coupled loops. A means was provided for introducing water in the vicinity of the buried pipe. The fields were instrumented with temperature and moisture sensors. Data were collected to assess field and heat pump performance.

A substantial amount of heat can be drawn from the ground while ground temperatures are maintained substantially above the freezing point.

Publications:

Spencertown Geo-Solar Associates, *Ground-Coupled Heat Pump Demonstration,* Report 83-20.

5.2.30 Ground Energy Coupling

Principal Investigator: Philip D. Metz
Organization: Brookhaven National Laboratory
Building 701
Upton, NY 11973
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Contract Agency: Department of Energy
Contract Number: DE-AC02-76CH00016
Contract Period: October 1980 through September 1981
Funding: $190,000
Source: DOE **Level:** 100%

Project Objectives:

To determine the feasibility of ground coupling for various heat pump systems; if feasibility is confirmed, to create comprehensive and reliable design guidelines for optimal ground-coupled heat pump systems.

Project Description:

The possibility of using the ground as an energy source or storage element has been studied often because it represents an available and inexpensive resource applicable to many systems. This project studied its application and potential impact on heat pump systems. Analysis and field results indicated that the ground is a satisfactory moderate temperature heat source/sink. As a result, ground-coupled heat pump systems have great potential for economy and energy efficiency. Resistive heating is never used, which reduces energy consumption and utility generating capacity requirements while increasing load factors. At the same time, the defrost cycle—and its related stress to the heat pump—is eliminated.

This project started from a literature search and assembled ground energy coupling computational methods. From these methods energy transfer and recovery characteristics were estimated and checked by field experiment. These characteristics were fed into heat pump system analysis routines already existing at Brookhaven National Laboratory (BNL). System impact was evaluated. The control field experiments consisted of tanks and pipes installed in the ground using configurations developed early in the project. These field tests were conducted as a scientific experiment, with some of the installed equipment operated as a control.

A digital computer program called GROCS was written to model three-dimensional underground heat flow in order to simulate the behavior of ground-coupling devices accurately. Both soil thermal property experiments and 12 ground-coupling-device experiments were conducted at BNL, including 4 buried tanks, 7 earth coils in various configurations and lengths, and a group of 6 sealed vertical wells. One earth coil was used to heat a house on the BNL site with no use of resistance heating. Computer model predictions were compared with experimental design procedures.

Publications:

P. D. Metz, "The Use of Ground-Coupled Tanks in Solar-Assisted Heat-Pump Systems," *J. Solar Energy Eng.* **104**: 366–372 (November 1982).

P. D. Metz, "A Simple Computer Program to Model Three-Dimensional Underground Heat Flow with Realistic Boundary Condition," *J. Solar Energy Eng.* **105**: 42–49 (February 1983).

P. D. Metz, "The Use of Serpentine Earth Coils in Ground-Coupled Heat Pump Systems," *J. Solar Energy Eng.* **106**: 438–446 (November 1984).

Patents:

U.S. 4,361,135: P. Metz, Cooperative Heat Transfer and Ground-Coupled Storage System, Nov. 30, 1982.

5.2.31 Groundwater Heat Pumps: An Examination of Hydrogeologic, Environmental, Legal, and Economic Factors Affecting Their Use

Principal Investigators: D. J. Bacon
T. E. Gass
Organization: National Water Well Association
500 West Wilson Bridge Road
Worthington, OH 43085
Telephone: (614) 846-9355

Contract Agency: Department of Energy
Contract Number: AC01-78CS20060
Contract Period: Sept. 28, 1978, through Mar. 28, 1980
Funding: $124,293
Source: DOE **Level:** 100%

Project Objectives:

To assess the feasibility of expanded use of groundwater as a heat source for heat pumps.

Project Description:

This project comprised three principal tasks, as follows:

Task 1. Collection of Hydrologic and Climatologic Data. This task involved assessing the availability and characteristics of groundwater supplies throughout the United States for use with groundwater heat pumps. This assessment was made on a state-by-state basis and included evaluation maps for each state. Water quality was considered because it affects the performance and life expectancy of the water-to-refrigerant heat exchanger and, in extreme cases, the technical viability of the groundwater heat pump option.

Task 2. Economic and Energy Analysis of Groundwater Heat Pumps. Using information and data collected in task 1, together with manufacturers' performance data on water-source heat pump performance, a comparative analysis of the energy consumption and owning and operating cost of groundwater heat pumps was undertaken. The analysis was based on an hour-by-hour computer simulation of the performance of the groundwater heat pump and more conventional heating/cooling systems in a typical single-family residence in nine cities representative of the various geographic and climatic regions.

Task 3. Environmental and Legal Consequences of Using Groundwater as an Energy Source. This task involved (1) evaluating the environmental problems that can potentially result from expanded use of groundwater heat pumps and (2) conducting a survey of federal, state, and local regulations that might affect the potential use of groundwater heat pumps. It was concluded that groundwater heat pumps can effect significant energy savings, compared with air-source heat pumps. The economics are very favorable so long as the cost of the well is not chargeable to the heat pump system. If one or more wells must be charged to the system, the economics may or may not be favorable.

Publications:

D. M. Armitage, *Groundwater Heat Pumps: An Examination of Hydrogeologic, Environmental, Legal, and Economic Factors Affecting Their Use, Vol. I, Executive Summary*, DOE/CS/20060–5120, November 1980.

5.2.32 Assessment of HP-ICES Concept Recovering Heat from Waste Water with Cascaded Heat Pumps

Principal Investigator: D. W. Wade
Organization: Georgia Institute of Technology
Georgia Tech Research Inst.
Atlanta, GA 30332
Telephone: (404) 894-2000

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4551
Contract Period: June 20, 1978, through Dec. 31, 1979
Funding: $58,167
Source: DOE **Level:** 100%

Subcontractors: McCurry and Associates

Project Objectives:

To develop the concept of a heat-pump-centered integrated community energy system (HP-ICES) that reclaims low-grade thermal energy from a community's waste-water effluent, to evaluate its potential performance and economics, to examine its potential application.

Project Description:

Cascaded electrically driven heat pumps were used with the extracted heat delivered by a moderate-temperature water piping system. Heat was removed from the piped water by each subscriber for space heating.

A thermodynamic performance analysis projected an overall coefficient of performance from 2.181 to 1.164 for waste-water temperatures from 50 to 80°F (from 10 to 27°C) for this particular HP-ICES. Site-specific designs for this HP-ICES were presented for application in Conyers and Cornelia, Georgia. Economic analysis on the basis of a life-cycle cost comparison showed that application in Conyers would be more costly than conventional systems because of the current low energy costs for natural gas heating. On the other hand, similar analysis for application in Cornelia showed that this particular HP-ICES as designed specifically for this site was cost competitive in the immediate market with conventional residential and light commercial heating, ventilating, and air-conditioning systems. The primary environmental concern of this HP-ICES is its impact on sewage treatment: high rates of heat recovery from waste-water effluent may reduce biodigestion rates, and high rates of heat rejection to the effluent may be so severe that bacteria essential for biodigestion would be killed.

Publications:

D. W. Wade et al., *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report*, ANL/ICES-TM-28, February 1979.

D. W. Wade et al., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report*, ANL/CNSV-TM-23, December 1979.

5.2.33 System Development Study of HP-ICES Based on Ice-Making Heat Pump Using Surface Water as a Source and Sink and a Distributed System

Principal Investigators: Paul A. Anderson
Donald M. Carlson
Organization: Honeywell, Inc.
Energy Resources Center
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Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4845
Contract Period: Sept. 28, 1978, through Nov. 30, 1979
Funding: $55,166
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the feasibility of developing a heat-pump-centered integrated community energy system (HP-ICES) based on the use of privately owned ice-making heat pumps within each building for domestic hot water, space heating, and cooling.

Project Description:

A closed-loop water distribution system within the community was the heat source and sink. In the heating mode, users drew off water and returned an ice slurry; in the cooling mode, the procedure was just the opposite. The energy interchange or balance among the various users was essential to this HP-ICES. A surplus of ice during the heating season was accumulated for summer cooling (this was later shown to be economically unfeasible). If either the ice surplus was not used during the summer or the ambient temperature rose above 35°F (1.7°C), the closed loop slurry system was inactivated and the heat pumps operated in the conventional air-source mode.

The concept of this particular HP-ICES was applied to a planned unit development around a shopping mall in Bloomingdale, Illinois. This concept suffered from the need for further technological development, impact on land use, and low initial revenues that were inadequate to defray the up-front costs of the community portion of the system on a current basis. Finance charges to support early use of this HP-ICES in a growing community and additional costs of the on-site heat pump system present economic barriers that can be overcome by escalation of energy and power rates.

Publications:

Honeywell, Inc., *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report,* ANL/ICES-TM-31, March 1979.

Honeywell, Inc., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report,* ANL/CNSV-TM-18, November 1979.

5.2.34 System Development Study of HP-ICES Using a Distributed System and Groundwater as Source and Sink

Principal Investigators: Walter J. Schaetzle
C. Everette Brett
Marvin S. Seppanen
Organization: Bureau of Engineering Research and Natural Resources Center
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Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4550
Contract Period: June 20, 1978, through Nov. 30, 1979
Funding: $64,378
Source: DOE **Level:** 100%

Project Objectives:

To analyze the feasibility of applying a heat-pump-centered integrated community energy system (HP-ICES) using water from aquifers as the source, sink, and distribution medium to provide space heating and cooling.

Project Description:

The aquifer (accessed by at least two wells) was also used for annual storage of thermal energy without consumptive use and requiring only low-temperature lift. This particular HP-ICES system was analyzed for demonstration projects for a portion of downtown Louisville, Kentucky (major buildings), and a section of Fort Rucker, Alabama (dispersed subdivision of homes).

Economically, this particular HP-ICES system demonstrated improvement in both energy usage and capital costs. The system saved over 60% of the energy required for resistance heating, saved over 30% of the energy required for most air-source heat pumps, and saved over 60% percent of the energy required for gas, coal, or oil heating when compared with energy input required at the power plant for heat pump consumption. Capital costs for this particular HP-ICES were lower than a standard air-source heat pump system or gas, oil, or coal heating system plus air conditioner. In general, for a small residence or small commercial system, capital cost for an air-source heat pump is approximately 100% more than an equivalent water-source heat pump with the same Air Conditioning and Refrigeration Institute listed capacity; however, this can be offset by the cost of wells and the water distribution system.

In the demonstration projects, the Louisville HP-ICES showed a payback of 3 years while the Fort Rucker system showed 30 years. The primary difference was that at the latter, the cost of new heat pumps was charged to the system, while at the former either new construction requiring heating and cooling systems or existing chillers were used with no cost charged to the system.

Publications:

W. J. Schaetzle and C. E. Brett, *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report*, ANL/ICES-TM-30, March 1979.

W. J. Schaetzle et al., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report*, ANL/CNSV-TM-25, December 1979.

5.3 Solar-Assisted Systems

5.3.1 Ground-Coupled Solar-Assisted Heat Pump Project

Principal Investigator: Jerald D. Parker, Oklahoma State Univ.
Organization: Oklahoma Gas and Electric
321 Harvey
P.O. Box 321
Oklahoma City, OK 73101
Telephone: (405) 624-5900

Contract Agency: Electric Power Research Institute
Contract Number: RP1191-6
Contract Period: Sept. 18, 1979, through Dec. 31, 1982
Funding:
Source: EPRI **Level:**
OG&E

Subcontractors: Oklahoma State University, Stillwater, OK 74078

Project Objectives:

To compare the performance of a solar- and ground-assisted heat pump system, a ground-assisted heat pump system, and a conventional air-to-air heat pump system; to measure performance in terms of (1) overall life cycle costs, (2) peak demand on the electrical system, (3) reliability and maintenance factors, and (4) kilowatt-hour consumption to consumer.

Project Description:

Three identical houses located on adjacent lots in Perkins, Oklahoma, were equipped with different heating and cooling systems: air-to-air heat pump, ground-assisted heat pump, and solar-ground-assisted heat pump. The three houses were occupied by owner-families. Each house was instrumented, and a weather station was located in the yard of one house. All instrumentation was connected to a data collection system located in a building attached to the center house.

Data acquisition began in June 1980. Data for OG&E's peak demand days showed peak demand from the two ground-coupled heat pumps to be half that of the air-to-air system. Data for the winter season (1980–1981) indicated a significant difference in energy consumption between the air-to-air and ground-coupled systems. On the peak demand day for December, the air-to-air system required a maximum of 3.8 kW while the ground-coupled system required only 1.5 kW.

The solar-ground-assisted system did not perform as well as the other ground-assisted system. A major leak was found in the ground heat exchanger of the solar-ground-assisted system which resulted in its poorer performance. Data collection was terminated in March 1983.

Publications:

J. D. Parker and B. Frierson, *Performance Maintaining of Ground-Coupled Solar-Assisted Heat Pump Systems,* EPRI-EM-1697, February 1981.

J. D. Parker et al., *Performance Comparison of Air- and Ground-Coupled Heat Pump Systems, Final Report,* EPRI-EM-3408, January 1984.

J. W. White and J. D. Parker, "Ground-Coupled Heat Pump Tests," *Proc. Seminar on Heat Pump Research and Applications, Feb. 23, 1984,* CONF-840266, November 1984.

5.3.2 Technical Support—Solar-Assisted Heat Pump Systems

Principal Investigator: John W. Andrews
Organization: Brookhaven National Laboratory
Building 701
Upton, New York 11973
Telephone: (516) 282-7726

Contract Agency: Department of Energy
Contract Number: DE-AC02-76CH00016
Contract Period: October 1980 through September 1982
Funding: $300,000
Source: DOE **Level:** 100%

Project Objectives:

To provide technical and program planning assistance to the Active Solar Heating and Cooling Division of the U.S. Department of Energy in connection with the development of energy-conserving and cost-effective solar-assisted heat pump systems.

Project Description:

To provide a system that met the technical and economic constraints, this project required the following elements: (1) high-efficiency heat pump hardware with performance characteristics tuned to the solar application, (2) low-cost storage and an available alternate heat source/sink to supplement the solar energy source, and (3) low-cost means for collecting the solar energy in a form best suited to the system configuration. A reservoir of technical expertise was required to define and attain program goals in each of these areas. These activities fell into three categories, which progressed to increasingly active roles in the overall program. These categories were contract monitoring, technical support, and program planning.

In addition, selected systems analysis tasks were carried out, the outcomes of which significantly affected the direction of the program. Promising system configurations were identified in each of two general categories—those using the ground as heat source/sink but not as storage for actively collected solar energy, and those using the ground as an active storage element.

Publications:

J. W. Andrews, "Ground-Coupled Solar Heat Pumps: Analysis of Four Options," *Proc. 3rd Annual Systems Simulation, Economic Analysis/Solar Heating and Cooling Operational Results Conf., Apr. 27, 1981*, CONF-810405, BNL-29007, 1981.

J. W. Andrews, "Technical Support: Solar-Assisted Heat Pump Systems," *Proc. DOE Heat Pump Contractors Program Integration Meeting, June 2, 1981*, CONF-810672-23, BNL-29681, 1981.

J. W. Andrews, "Solar Energy and Heat Pumps: Can This Marriage Be Saved," *Proc. IECEC Conf., Aug. 9, 1981*, CONF-810812-26, BNL-29627, 1981.

J. W. Andrews, "DOE Solar-Assisted Heat Pump Program: Its Evaluation and Its Potential," *Proc. Active Contractors Review Meeting, September 1981*, CONF-810912-10, BNL-29677, 1981.

J. W. Andrews and P. D. Metz, "Worldwide Applications of Ground-Coupled Heat Pumps, Conventional and Solar Assisted," *Proc. 3rd AAPG Circum-Pacific Energy and Materials Conf., Aug. 22, 1982*, CONF-820834-6, BNL-32828, 1982.

J. W. Andrews, M. A. Catan, and P. LeDoux, *Solar Energy and Heat Pumps: Evaluation of Combined Systems for Heating and Cooling of Buildings*, BNL 51603, September 1982.

J. W. Andrews, "Selection of Optimal Ground-Coupled Solar Heat Pump Systems," *Proc. Workshop on Solar-Assisted Heat Pumps with Ground-Coupled Storage, Sept. 14, 1982*, CONF-8209265, September 1982.

J. W. Andrews and M. A. Catan, "Comparative Evaluation of Ground-Coupled Heat Pumps that Use Solar Energy," *Proc. 2nd Workshop on Solar Assisted Heat Pumps with Ground-Coupled Storage, May 8, 1985*, CONF-850513201, BNL-36191, March 1985.

Patents:

U.S. 4,390,008: J. W. Andrews, Hot Water Tank for Use with a Combination of Solar Energy and Heat Pump Desuperheating, June 28, 1983.

5.3.3 Multiple Slide Screw Compressor

Principal Investigator: Joseph A. L. N. Gagnon
Organization: Dunham-Bush, Inc.
179 South Street
West Hartford, CT 06110
Telephone: (203) 249-8671

Contract Agency: Brookhaven National Laboratory
Contract Number: DE-AC03-79CS30035
Contract Period: September 1979 through February 1982
Funding: $627,151
Source: DOE **Level:** 100%

Project Objectives:

To develop the best possible compressor for use in series solar heat pump systems.

Project Description:

The compressor had to be able to operate at extremely high efficiency levels from a compression ratio as low as 1.5 up to a compression as high as 6.5. It also had to have the capability to adjust to the widely varying inlet flow requirements efficiently as dictated by the operating conditions of the series solar heat pump system.

The project included three distinct phases. Phase 1 consisted of the continued development testing of a research machine to optimize the mechanical design of the overall concepts involved. This also involved the development of estimated performance maps for the final machine. The design of the final machine was based on what was learned in phase 1.

Phase 2 involved the design of a 25-ton (heating) helical screw type compressor that accomplished the requirements for operation stated above. The compressor had variable inlet flow capability, variable compression ratio capability, and intermediate level vapor injection capability.

Phase 3 would have encompassed the building, testing, and performance mapping of the 25-ton compressor that was designed during phase 2. However, the project was terminated before phase 3 because a market study indicated very low production potential for a 25-ton solar-assisted heat pump.

Publications:

D. N. Shaw, "Multiple Slide Screw Compressor," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Meeting, March 26, 1980*, CONF-800340, 1980.

D. N. Shaw, "Multiple Slide Screw Compressor," *Proc. DOE Heat Pump Contractors Program Integration Meeting, June 2, 1981*, CONF-810672, March 1982.

D. N. Shaw, *Multiple Slide Screw Compressor for Use in Solar-Assisted Heat Pumps, Final Report*, DOE/CS30035-T2, 1982.

5.3.4 Solar Heat Pump Simulator

Principal Investigator: Mark A. Catan
Organization: Brookhaven National Laboratory
Building 701
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Telephone: (516) 282-2504

Contract Agency: Department of Energy
Contract Number: DE-AC02-76CH00016
Contract Period: October 1980 through September 1981
Funding: $175,000
Source: DOE **Level:** 100%

Project Objectives:

To demonstrate the feasibility of constructing heat pumps capable of achieving high coefficients of performance (COPs) at high evaporating temperatures, to explore the practical means to realize and enhance this performance potential; to test prototype solar heat pumps produced by contractors under the solar-assisted heat pump (SAHP) program; to identify solar heat pump systems that best exploit the realizable potential.

Project Description:

A heat pump hardware simulator capable of testing water-to-water heat pumps operating in steady state and unsteady state modes was constructed. A water-to-water heat pump was built using "off the shelf" components and tested at high and low source temperatures. Results of these tests demonstrated the feasibility of achieving continuously rising COPs; these results were used to establish goals for the SAHP program.

The simulator was used to test, under steady state and unsteady state conditions, the first of two prototype SAHPs developed under DOE contract. Results of these tests demonstrated that the nominal goal of a COP of 6 at a water source temperature of 90°F (32.2°C) was achieved.

The simulator was modified to accommodate the second prototype SAHP. A heat pump component test facility, to be used for component optimization studies, was constructed. A cooperative experimental effort was formed between several heat exchanger manufacturers and Brookhaven National Laboratory to identify optimal refrigerant heat exchangers for marketable SAHPs.

Publications:

M. A. Catan, "Solar-Heat-Pump Simulator," *Proc. DOE Heat Pump Contractors' Program Integration Meeting*, CONF-810672, BNL-29679, June 1981.

M. A. Catan and E. A. Kush, "Test Results of Prototype Solar-Assisted Heat Pumps," *Proc. IECEC Meeting*, BNL-29626, CONF-810812, August 1981.

M. A. Catan, "Solar Heat Pump Simulator," *Proc. Active Contractors' Review Meeting*, BNL-29678, CONF-810912, September 1981.

M. A. Catan, *Dynamic Performance of a Prototype Solar-Assisted Heat Pump*, BNL-51503, December 1981.

M. A. Catan, *Steady-State Testing of an Advanced Solar-Assisted Heat Pump*, BNL-51564, June 1982.

M. A. Catan, *The Brooklyn Solar Heat Pump Simulator: Technical Description and Experimental Results*, BNL-51627, July 1982.

5.3.5 A Second-Generation Solar-Assisted Heat Pump System

Principal Investigator: G. W. "Dusty" Rhodes
Organization: Fafco, Inc.
235 Constitution Avenue
Menlo Park, CA 94025
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Contract Agency: Department of Energy
Contract Number: DE-AC03-80CS30224
Contract Period: July 1980 through September 1981
Funding: $131,000
Source: DOE **Level:** 100%

Project Objectives:

To determine the performance analysis, definition, and design criteria of plastic collectors for use with heat pumps; to collect data and performance analysis of ground-coupled heat exchanger configurations; to conduct commericalization and marketing analysis.

Project Description:

Work on this project included

- Analysis using computer models of thermal performance of the proposed solar collector configuration options
- Development of design criteria for the solar collector and system components, based on operating requirements and conditions determined by the system performance analysis
- Collection of ground temperature data and heat flow data (pertinent data from other researchers were utilized)
- Reduction and analysis of ground-coupling data
- Development of useful equipment and system sizing criteria
- Development of criteria and a plan for widespread commercial system acceptance

Publications:

G. W. Rhodes et al., *Second-Generation Ground-Coupled Solar-Assisted Heat Pump Systems*, DOE/CS/30224, January 1981.

5.3.6 Ground Coupling and Heat Pump Compatible Solar Collectors

Principal Investigator: Jerry Alcone
Organization: Science Applications, Inc.
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Albuquerque, NM 87102
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Contract Agency: Department of Energy
Contract Number: DE-AC03-80CS30219
Contract Period: June 1980 through June 1981
Funding: $30,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate existing ground coupling models and analyses, to identify and evaluate existing collector systems that are compatible with solar heat pump systems.

Project Description:

A survey was conducted of existing models and analyses of the storage and/or extraction of thermal energy (heat or cool) from the ground to identify and evaluate for each model or analysis the assumptions used, their validation status, their range of applicability, and new research efforts. The survey results identified and ranked by system type and geographic region the most promising existing collectors for use in solar heat pump systems. Data from these collectors were analyzed to determine the cost performance characteristics of heat pump compatible solar collectors.

Publications:

None provided.

5.3.7 The Phoenix House, City of Colorado Springs Solar-Assisted Heat Pumps

Principal Investigator: Douglas M. Jardine
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Contract Agency: Department of Energy
Contract Number: DE-AC03-79CS30207
Contract Period: June 1979 through June 1981
Funding: $466,000
Source: DOE **Level:** 100%

Project Objectives:

To stimulate the development of a preferred ground-coupled solar-assisted heat pump system; to improve the system's performance and design data base; to conduct engineering field tests for the system on different types of building applications in different climatic regions of the United States—Colorado (residential), Ohio (industrial), and New Mexico (commercial).

Project Description:

This project was characterized as engineering field testing of preferred solar-assisted heat pump (SAHP) systems in different climates. The performance of technological improvements in the form of new products designed specifically to operate optimally within SAHP fluid heat sink and heat source requirements were evaluated under controlled conditions. Technical and economic information on the performance of SAHP systems operating with ground-coupled storage subsystems (GCSS) in various climates were evaluated. Data were gathered, and the thermal performance of GCSS was evaluated based on empirical data on soil temperatures, densities, thermal conductivity, and moisture contents. The result of this work was the selection of the best marketable components and products for the SAHP and the knowledge of—and experience with—the operation of the preferred SAHP for space heating and cooling.

Publications:

D. M. Jardine and D. W. Jones, *Phoenix: City of Colorado Springs Solar-Assisted Heat Pump Project, Technical Report*, COO-4351-6, June 1978.

D. M. Jardine, "Phase II: Phoenix/City of Colorado Springs Solar-Assisted Heat Pump Project," *Proc. 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, March 1979.*

D. M. Jardine, "Phoenix/City of Colorado Springs Solar-Assisted Heat Pump Project: Phase III," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 1980.*

5.3.8 Development of Marketable Solar-Assisted Heat Pumps

Principal Investigator: Roger Hundt
Organization: Lennox Industries, Inc.
1600 Metro Drive
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Carrollton, TX 75006
Telephone: (214) 245-2525

Contract Agency: Department of Energy
Contract Number: DE-AC03-78CS31720
Contract Period: February 1978 through May 1981
Funding: $1,049,000
Source: DOE **Level:** 100%

Project Objectives:

To analyze, design, fabricate, and test heat pumps that effectively utilize solar input in the 40 to 110°F range to be used in optimized residential-sized solar-assisted heat pump (SAHP) systems.

Project Description:

This project was divided into three phases.

- Phase 1 — Conceptual Design and Commercialization and Marketing Plan
- Phase 2 — Detailed Design and Performance Prediction
- Phase 3 — Choice of System, Testing, and Prototype Delivery

During Phase 1, a study was conducted to identify a conceptual design and solar heat pump arrangement that would be marketable in quantity. This was accomplished by simulating various arrangements in various areas of the country. An in-line approach, adding solar energy directly to the evaporator of the heat pump, was identified for further study during phase 2 because of its near-term potential for reaching the marketplace. Phase 2 included the detailed design of two system configurations of the in-line approach (with a reversing value and without a reversing value), accompanied by additional simulations and performance mappings. The most cost-effective in-line systems were chosen for fabrication, testing and prototype delivery to the Department of Energy during phase 3.

Publications:

R. Hundt, "Development of Marketable Solar-Assisted Heat Pumps," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting*, CONF-800340, March 1980.

General Electric Company, *Open-Cycle Heat Pumps for Industrial Waste Heat Utilization. Project Technical Report: Phase I—Feasibility Study for the Period May 12, 1980 through Oct. 10, 1980*, ORNL/Sub/80-24717/7, NYSERDA/81-28, October 1981.

R. Hundt and S. Heard, *Development of Marketable Solar-Assisted Heat Pumps, Phase II—Summary Report. Technical Results*, DOE/CS/31720, February 1981.

5.3.9 Design and Field Testing of Solar-Assisted Earth Coils

Principal Investigator: James E. Bose
Organization: Oklahoma State University
101 Industrial Building
Stillwater, OK 74074
Telephone: (405) 624-5638

Contract Agency: Department of Energy
Contract Number: DE-AS03-79CS30210
Contract Period: August 1978 through January 1981
Funding: $160,000
Source: DOE **Level:** 100%

Project Objectives:

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.

Project Description:

A field demonstration laboratory using unprepared earth as a heat sink/source device was developed at Oklahoma State University. The demonstration laboratory consists of a 1000-ft (304.8-m) horizontal earth coil and two vertical heat exchangers. The horizontal heat exchanger is a 4-in. (10.2-cm) polyvinylchloride (PVC) pipe buried in a serpentine pattern at a depth of 4 ft (1.22 m). Undisturbed temperatures of this depth are cyclic and depend on latitude, moisture content, and soil type.

Two types of earth coils were designed, constructed, and are operational on the Oklahoma State University campus. The 1000-ft (304.8-m), 4-in. (10.2-cm) PVC coil was the heat source/sink for two commercial heat pump systems.

Integral to the earth coil is a 1000-gal (4546-L) uninsulated storage tank in which solar energy from 200 ft^2 (18.6 m^2) of solar collectors can be added directly to the heat pump or circulated through the 1000-ft (304.8-m) earth coil system.

Publications:

J. E. Bose, "Design and Field Testing of Solar-Assisted Earth Coils," *Proc. 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, March 1979.

J. E. Bose et al., "Earth Coils and Geo-Thermal Wells Used as a Solar Energy Storage Device," *Proc. Solar Energy Storage Options Workshop, Mar. 18, 1979*, CONF-790328-P1, March 1979.

J. E. Bose et al., "Experimental Results of a Low-Cost Solar-Assisted Heat Pump System Using Earth Coil and Geo-Thermal Well Storage," *Proc. 4th Annual Heat Pump Technology Conference, Apr. 9, 1979*, CONF-790446, April 1979.

J. E. Bose et al., "Earth Coils and Geo-Thermal Wells Used as Solar Energy Storage Devices," *Proc. International Solar Energy Society Meeting, May 28, 1979*, CONF-790541 (Vol. I), May 1979.

J. E. Bose, "Design and Field Testing of Solar-Assisted Earth Coils," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, March 1980.

J. E. Bose et al., "Earth-Coupled and Solar-Assisted Heat Pump Systems," *Proc. 5th Annual Heat Pump Technology Conference, Apr. 14, 1980*, CONF-800451, April 1980.

J. E. Bose, *Design and Field Testing of Solar-Assisted Earth Coils. Final Report, Aug. 1, 1978–Jan. 31, 1981*, DOE/CS/30210-T1, 1981.

5.3.10 Instrumentation and Monitoring of the Twin Crown Realty Buildings in Denver, Colorado

Principal Investigator: David K. Hays
Organization: Solar Environmental Engineering Co.
2524 East Vine Drive
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Telephone: (303) 221-5166

Contract Agency: Department of Energy
Contract Number: DE-AC03-79CS30115
Contract Period: June 1979 through December 1980
Funding: $79,000
Source: DOE **Level:** 100%

Project Objectives:

To monitor and evaluate the performance of the two solar-augmented heat pump systems of the Twin Crown Realty buildings in Denver, Colorado.

Project Description:

Two 3500-ft^2 (325-m^2) commercial office buildings were environmentally conditioned by a system of seven solar-augmented heat pumps that were identical in mechanical design with the exception of the solar collection loop. In one building the collection loop was an air system; in the other the collection loop was a hydronic system. Thus, a direct comparison could be made between an air collection system and a hydronic collection system.

The two systems were instrumented to provide all necessary data for complete system and subsystem performance analyses. The performance of the two systems was determined by performing standard energy balances on the gathered data. Comparisons of the two systems were made on the basis of collector efficiency, energy stored, energy utilized, and other performance factors associated with the two systems.

The specific tasks were

- To locate, select, purchase and install all sensors required for monitoring and analyzing the performance of the twin Crown Realty buildings
- To filter, reduce, and analyze the gathered data to determine monthly load fractions
- To analyze system performance by simulating real-time data reduction and analysis on the gathered data

Publications:

D. K. Hays, "Instrumentation and Monitoring of the Twin Crown Realty Buildings in Denver, Colorado," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting*, CONF-800340, March 1980.

5.3.11 Solar Hybrid Energy Project

Principal Investigator: E. C. Kern
Organization: Massachusetts Institute of Technology
Lincoln Laboratory
P.O. Box 73
Lexington, MA 02173
Telephone: (617) 862-5500

Contract Agency: Department of Energy
Contract Number: EG-77-S-02-4577
Contract Period: September 1977 through December 1980
Funding: $1,037,000
Source: DOE **Level:** 100%

Project Objectives:

To design, install, and experimentally evaluate residential solar heating and cooling systems that utilize a heat pump and either photovoltaic/thermal (PV/T) or exclusively photovoltaic (PV) collectors.

Project Description:

PV/T collectors are solar collectors in which PV cells and flat-plate thermal collectors share a common aperture. PV power was provided by a utility-interactive PV power system. In this power system a PV or PV/T array and an inverter operate in parallel with, and supply power to, a utility line. The inverter converted dc power obtained from the PV array to ac power which could be supplied either to the residence or the utility. Based on life-cycle cost considerations, recommendations were made concerning the most favorable heat pump and PV/T or PV collector system configurations for northern and southern climates. Based on these recommendations, residential and laboratory experiments were carried out (1) to identify factors affecting system operation which were not included in the design phase analyses and to reevaluate the results of these analyses, (2) to evaluate the effects of modifying commercially available heat pumps, (3) to evaluate the compatibility of a two-speed air-source heat pump and utility-interactive PV power system, and (4) to establish the reliability of a prototype system.

During the design phase of the project, a preferred residential heat pump and collector configuration were identified for both northern and southern climate locations. The preferred collectors (PV or PV/T) were identified for each location. Experimental data were used to quantify a temperature "defect" that may exist in previous simulations involving air-source heat pumps. Laboratory data were obtained which show that the steady-state operations of an air-source heat pump and a utility-interactive PV power system are compatible. Substantial data from a residential prototype system were obtained. These data established the reliability and effectiveness of the combined heat pump and PV power system. It was demonstrated that the secondary heat pump functions of "boosting" and domestic hot water heating are difficult to perform effectively at low compressor speed.

Publications:

E. C. Kern and M. C. Russell, *Hybrid Photovoltaic/Thermal Energy System,* COO-4577-1, March 1978.

E. C. Kern, "Photovoltaic/Thermal Collectors and Heat Pumps," *Proc. American Section of the International Solar Energy Society, Aug. 28, 1978*, CONF-780808, COO-4577-2, 1978.

E. C. Kern, *Phase-One Experiment Test Plan Solar Photovoltaic/Thermal Residential Experiment,* COO-4577-6, March 1979.

M. C. Russell and E. C. Kern, "Optimization of Photovoltaic/Thermal Collector Heat Pump Systems," *Proc. International Solar Energy Society Meeting, May 28, 1979*, CONF-79541-20, COO-4577-7, 1979.

S. D. Hendrie, "Evaluation of Combined Photovoltaic/Thermal Collectors," *Proc. International Solar Energy Society Meeting, May 28, 1979*, CONF-790541-54, COO-4577-8, 1979.

M. C. Russell, *Solar Photovoltaic/Thermal Residential Systems,* COO-4577-9, December 1979.

M. C. Russell, "Solar Hybrid Energy Product," *Proc. DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340-5, COO-4577-10, 1980.

5.3.12 Evaluation of Demonstration Program for Useful Solar Heat Pump Performance

Principal Investigator: Jerry Alcone
Organization: Science Applications, Inc.
200 Lomas North West, Suite 600
Albuquerque, NM 87102
Telephone: (505) 247-0381

Contract Agency: Department of Energy
Contract Number: SERI-XP-0-9208-1
Contract Period: April 1980 through October 1980
Funding: $66,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate heat pump experiment and demonstration sites to assess thermal, economic, and reliability behavior of the systems; to analyze existing solar-assisted heat pump (SAHP) systems to generate experimental data that could be used to substantiate systems analyses performed in FY 1979 and FY 1980; to identify areas for future development emphasis in the heat pump program.

Project Description:

Potential sites were identified for data collection and analysis. After site analysis criteria were defined, several operating systems were selected and their performance data reviewed. Existing analyses were reviewed, and standards were defined for comparing systems. The selected systems were analyzed according to these standards, and a position paper was developed for the U.S. Department of Energy summarizing the status of SAHP systems and recommending future efforts.

Publications:

None provided.

5.3.13 Ground-Coupled Solar-Assisted Heat Pump Field Performance

Principal Investigator: Sam V. Shelton
Organization: E-Tech, Inc.
3570 American Drive
Atlanta, GA 30341
Telephone: (404) 458-6653

Contract Agency: Department of Energy
Contract Number: DE-AC03-79SF10549
Contract Period: July 1979 through September 1980
Funding: $178,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate six ground-coupled solar-assisted heat pump systems in four geographical areas—two in Atlanta, Georgia; two in Baltimore, Maryland; and one each in Charleston, South Carolina, and Tallahassee, Florida.

Project Description:

The six systems studied utilized a water source heat pump, low-temperature collector array, and a ground coil buried 4 ft (1.22 m) beneath the surface. This ground coil consisted of approximately 1000 ft (304.8 m) of 1.5-in. (3.81-cm) polyethylene plastic pipe. Two system control concepts were used. In the first concept, the solar heat was put into the ground and the heat pump always used the ground as its heat source. In the second concept, the solar heat was added to a storage tank, and the heat pump alternately used either the storage tank or the ground as its heat source. All systems were comprehensively instrumented to gather operational performance data. These data were collected and analyzed to determine each system's performance. All systems were in service from February 1980 to Sepetember 1980. The systems showed good performance, with heating coefficients of performance in excess of 2.0. The coils in Florida failed during summer operation, however, due to ground coil temperatures in excess of 120°F. In comparing the two system types, data scatter was too large to reach a conclusion.

Publications:

E-Tech, Inc., *Solar-Assisted Heat Pump Field Performance Evaluations, Technical Status Report, 1 April 1979–31 July 1979*, DOE/SF/10549-T6, August 1979.

E-Tech, Inc., *Solar-Assisted Heat Pump Field Performance Evaluation, Final Report*, DOE/SF/10549-T1, November 1980.

S. V. Shelton, "Ground-Coupled Solar-Assisted Heat Pump Performance," *Proc. Annual DOE Active Solar Heating and Cooling Contractor's Review Meeting*, CONF-800340, March 1980.

5.3.14 Solar Rock-Bed-Augmented Heat Pump

Principal Investigator: Edward F. Sowell
Organization: California State University
Fullerton, CA 92634
Telephone: (714) 870-3876

Contract Agency: Department of Energy
Contract Number: DE-AS02-78CS34697
Contract Period: February 1978 through September 1980
Funding:
Source: DOE **Level:** 100%

Project Objectives:

To define the performance advantages and disadvantages of a thermal storage/heat pump subsystem when used in the series-parallel configuration.

Project Description:

This project evaluated the feasibility and cost effectiveness of an arrangement of an air-type solar-collector rock-bed and an electrically driven refrigeration machine for building heating and cooling. In this study, the condenser and evaporator were located at opposite ends of the rock bed of an otherwise normal air-type solar heating system. The bed served as a time delay for heating and cooling effects of the condenser and evaporator and thus stored heat, augmenting the heat pump at night and serving as cold-side storage during the cooling season. Optimum utilization of load management modes required prediction of the next day's demand and solar availability. Efforts were made to develop a complete strategy for mode selection and the implementation of this strategy as a TRNSYS subroutine.

Tasks completed included:

- Development of TRNSYS-compatible computer simulation subroutines to model the rock bed and heat pump
- Performance of a sensitivity analysis of the anticipated operating conditions to determine the relationship between the various parameters
- Performance of life-cycle cost analysis
- Preparation of conceptual designs to predict performance and costs for the system

Publications:

E. F. Sowell and P. W. Othmer, *Series-Parallel Solar-Augmented Rock-Bed Heat Pump. Technical Progress Report, 2/1–7/31, 1978*, DOE/CS/34697-T2, COO-4697-1, July 1978.

E. F. Sowell, "Series-Parallel Solar-Augmented Rock-Bed Heat Pump," *Proc. 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, March 1979.

E. F. Sowell, "Control for Residential Land Management Using Rock-Bed Heat Pump and Solar Collectors," *Proc. Solar Energy Storage Options Workshop, Mar. 18, 1979*, CONF-790328, March 1979.

E. F. Sowell et al., *Series-Parallel Solar-Augmented Rock-Bed Heat Pump. Convolution Model of Rock Bed*, DOE/CS/34097-T1, COO-4697-3, December 1979.

E. F. Sowell and P. W. Othmer, *Series-Parallel Solar-Augmented Rock-Bed Heat Pump. Final Report*, DOE/CS/34697-T3, COO-4697-2, December 1979.

5.3.15 Solar Energy Earth Storage System Mini-Prototype Testing Program

Principal Investigator: S. W. Yuan
Organization: Rise, Inc.
6701 Montour Drive
Falls Church, VA 22043
Telephone: (703) 534-6177

Contract Agency: Department of Energy
Contract Number: DE-AP03-80SF11121
Contract Period: February 1980 through August 1980
Funding: $10,000
Source: DOE **Level:** 100%

Project Objectives:

To complete the investigation of a one-tenth-scale experiment of a solar energy earth storage system.

Project Description:

The system under investigation consists of a volume of earth isolated from its surroundings by an impermeable membrane. Predicted moisture migration away from the membrane will generate a zone of low moisture content, and thus low thermal conductivity, impeding heat loss from the storage volume.

The performance of the one-tenth-scale model of an earth-coupled heat transfer system was evaluated. Hourly temperature data were recorded, and monthly and annual heat losses from storage were determined.

Theoretical calculations of the expected changes in earth temperature during the winter were made based on heat loss and heat use.

Publications:

S. W. Yuan, *Solar-Energy Earth-Storage System (SEESS) Mini-Prototype Testing Program. Final Report, Feb. 15–Aug. 15, 1980*, DOE/SF/11121-T1, 1980.

S. W. Yuan and M. M. Majdi, "Mini-Prototype Solar Energy Earth Storage System," *Energy* **6**(7), July 1981.

5.3.16 Low-Cost Heating and Cooling Using a Direct-Expansion Solar Collector and Heat Pump

Principal Investigator: Elric W. Saaski
Organization: Sigma Research, Inc.
2950 George Washington Way
Richland, WA 99356
Telephone: (509) 735-0663

Contract Agency: Department of Energy
Contract Number: DE-AC03-79SF10542
Contract Period: June 1979 through August 1980
Funding: $96,000
Source: DOE **Level:** 100%

Project Objective:

To investigate the design and economics of a direct-expansion solar collector and heat pump system.

Project Description:

In this new design, solar energy absorbed by exposed panels directly vaporized a refrigerant fluid. The resulting low-temperature vapor was 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 operated at or below ambient temperature, resulting in a significant reduction in heat loss and eliminating the need for glass covers and insulation.

The new collector was found to be 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 provides significant thermal input to the collector under the proper meteorological conditions.

The use of a microprocessor to control the heat pump improved the average coefficient of performance (COP). The microprocessor examined temperature throughout the system and controlled the compressor speed and the expansion valve to ensure optimum performance.

The solar-assisted heat pump provided efficient utilization of available solar energy with a collector of minimal cost. In addition, the system provided 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.

Publications:

E. W. Saaski, "Low-Cost Heating and Cooling Using a Direct-Expansion Solar Collector and Heat Pump," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Meeting*, CONF-800340, March 1980.

5.3.17 Evaluation of Solar Collectors for Heat Pump Applications

Principal Investigator: C. Gary Skartvedt
Organization: American Heliothermal Corporation
2625 South Sante Fe
Denver, CO 80223
Telephone: (303) 778-0650

Contract Agency: Department of Energy
Contract Number: DE-AC04-78CS35351
Contract Period: September 1978 through June 1980
Funding: $98,000
Source: DOE **Level:** 100%

Project Objectives:

To 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; to conduct an experimental determination of effective night sky temperatures and convective heat transfer coefficients for surfaces with dimensions representative of flat-plate solar collectors.

Project Description:

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 included 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 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 were fabricated.

Publications:

C. G. Skartvedt, "Evaluation of Solar Collectors for Heat Pump Applications," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting*, CONF-800340, March 1980.

5.3.18 Development of a Solar-Assisted Heat Pump for the Heating and Cooling of Buildings

Principal Investigator: Amir L. Ecker
Organization: Northrup, Inc.
302 Nichols Drive
Hutchins, TX 75141
Telephone: (214) 225-7351

Contract Agency: Department of Energy
Contract Number: DE-AC03-78CS31718
Contract Period: February 1978 through April 1980
Funding: $1,072,000
Source: DOE **Level:** 100%

Project Objectives:

To carry out the conceptual and detailed design, analysis, fabrication, and testing of heat pumps that efficiently utilize solar input in the 40 to 100°F (4.4 to 37.8°C) range for heating and also provide effective cooling for residential applications (1 to 5 tons); to conduct studies of system configuration including commercialization potential.

Project Description:

The goal of this project was to develop the hardware for solar-assisted heat pump (SAHP) systems that offer increased performance with minimum monetary trade-off. In addition to the engineering development work associated with the analysis, design, fabrication, and testing of advanced high-performance heat pumps and related system hardware, a marketing analysis and plan were developed for producing and marketing these systems.

The scope of the design effort included the formulation of SAHP system designs for residential systems sized from 1 through 4 tons. The hardware development of optimized high-efficiency vapor compression cycle heat pumps for use in conjunction with SAHP systems was the primary focus of the development work. Compressor capacity control and optimized heat exchangers were emphasized.

Publications:

A. L. Ecker, "Development of a Solar-Assisted Heat Pump for the Heating and Cooling of Buildings," *Proc. 3rd Annual Solar Heating and Cooling R&D Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, March 1979.

A. L. Ecker, "Development of a Solar-Assisted Heat Pump for the Heating and Cooling of Buildings," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, March 1980.

5.3.19 Solar-Assisted Heat Pump-2: Analytical Selection of Marketable SAHP Systems

Principal Investigator: William Kahan
Organization: Singer Company
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Fairfield, NJ 07006
Telephone: (201) 256-4000

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS31467
Contract Period: September 1977 through April 1980
Funding: $336,000
Source: DOE **Level:** 100%

Project Objectives:

To identify the configurations of solar-assisted heat pump (SAHP) systems and associated components that have the best market potential for the various climatic regions of the United States.

Project Description:

To achieve the program objective, an efficient analytical model was used to compare the thermal and economic performance of the following competing 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; and (5) a parallel SAHP system. Thus, optimized systems were compared and ranked according to their marketability. This comparison was performed in a number of U.S. climates to assess the dependence of system rank on climate.

The life-cycle costs of the competing systems were calculated for five U.S. locations. For each location, calculations and comparisons were made for a large range of fuel costs at the time the system was installed. Furthermore, for each value of CF (the cost of energy at the time of installation), 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 with each other.

The reported 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.

Publications:

R. C. Estes and W. Kahan, "Analytical Selection of Marketable SAHP Systems," *Proc. Solar Energy and Conservation Symposium Workshop, Dec. 11, 1978*, CONF-781235, December 1978.

R. C. Estes and W. Kahan, "Optimization and Comparison Strategies for Solar Energy Systems," *Proc. Solar Energy and Conservation Symposium Workshop, Dec. 11, 1978*, CONF-781235, December 1978.

W. Kahan, "SAHP-2: Analytical Selection of Marketable SAHP Systems," *Proc. 3rd Annual Solar Heating and Cooling Research Development Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, March 1979.

W. Kahan, *Analytical Selection of Marketable SAHP Systems. Final Report, Sept. 30, 1977–Dec. 31, 1979*, DOE/CS/31467-R2, SAN-1467-1, January 1980.

W. Kahan, "SAHP-2: Analytical Selection of Marketable SAHP Systems," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, March 1980.

5.3.20 Systems Analysis of Solar-Assisted Heat Pump Ground-Coupled Storage and Dual Source Strategies

Principal Investigator: Jeffrey H. Morehouse
Organization: Science Applications, Inc.
1710 Goodridge Drive
McLean, VA 22102
Telephone: (703) 827-4915

Contract Agency: Department of Energy
Contract Number: SERI-XP-9-8288-1
Contract Period: October 1979 through March 1980
Funding: $109,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the performance and economic advantages to solar-assisted heat pumps (SAHP) of ground-coupled storage and dual-source strategies.

Project Description:

This study extended the Solar-Assisted Heat Pump Comparative Analysis done by Science Applications in FY 1979 by using the same baseline residential systems and adding ground-coupled storage. Thermal and economic performance of the systems with ground coupling was compared with that of systems without ground coupling. A short study to bracket the performance/economics improvement that could be obtained using a dual-source strategy was included. The previous studies of series and parallel SAHP systems were extended by performing sensitivity analysis on engineering and economic parameters to determine what could be done to make these systems more cost effective.

Publications:

M. K. Choi and J. H. Morehouse, "Thermal and Economic Assessment Storage for Residential Solar Heat Pump Systems," *ASME*, 80-WA/SOL, November 1980.

N. M. White and J. H. Morehouse, *Parametric Sensitivity Study for Solar-Assisted Heat-Pump Systems, Final Report*, SERI/TR-98288-1, July 1981.

M. K. Choi et al., *Comparison of Ground-Coupled Solar Heat Pump Systems to Conventional Systems for Residential Heating, Cooling and Water Heating, Final Report*, SERI/TR-98288-2, July 1981.

5.3.21 Investigation of Heat Pump Impact on Solar Collector Design and Cost

Principal Investigators: John W. Andrews
William G. Wilhelm
Organization: Brookhaven National Laboratory
Solar Technology Group
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Contract Agency: Department of Energy
Contract Number: EY-76-C-02-0016
Contract Period: June 1978 through September 1979
Funding: $210,000
Source: DOE **Level:** 100%

Project Objectives:

To assess the impact of advanced electric-powered heat pumps on the solar collector component of solar-assisted heat pump systems; to investigate, by means of computer simulation, collector performance and cost specifications; to identify low-cost collector concepts consistent with cost/performance goals determined as above.

Project Description:

Advanced electric-powered heat pumps, designed to match the requirements of solar-assisted heat pump systems, have been developed by the U.S. Department of Energy. These new heat pumps have had far-reaching impacts on the performance requirements of other components of the system. This project assessed this impact on the solar collector component. Collector performance specifications set by system requirements were determined. Using existing design procedures, collector concepts were generated and evaluated. Cost reduction was the principal criterion for the evaluation. Test panels of selected designs were fabricated to provide point calibrations.

This project activity was divided into the following tasks: task 1—system analysis to determine collector performance requirements; task 2—search for collector concepts meeting the requirements identified in task 1; task 3—cost vs yield analysis; and task 4—identification of cost factors and an analysis of the means for cost reduction.

In a follow-on project, thin-film collectors were developed for direct heating and cooling as well as for heat pump applications.

Publications:

J. W. Andrews, "Heat Pump Impact upon Solar Collector Design and Cost," *Proc. 1979 ISES Congress, Atlanta, Georgia, May 1979.*

J. W. Andrews, "Solar-Assisted Heat Pump Program Overview and Summary of Work at Brookhaven National Laboratory," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 6, 1980*, CONF-800340, BNL-27662, 1980.

J. W. Andrews, "Solar-Assisted Heat Pump Research and Development Program in the United States," *Proc. ISES Workshop on Performance of Heat Pump Systems, May 8, 1980*, CONF-8005150-1, BNL-27722, 1980.

J. W. Andrews, *Solar Performance Goals for Solar and Ground-Coupled Heat Pump Systems*, BNL-51259, September 1980.

J. W. Andrews et al., *Development of Low-Cost Polymer Solar Collectors, Annual Report*, BNL-51693, September 1983.

5.3.22 Rock-Bed Storage With Heat Pump

Principal Investigator: Harry E. Remmers
Organization: Zia Associates, Inc.
5590 Arapahoe Road
P.O. Box 1466
Boulder, CO 80306
Telephone: (303) 449-9170

Contract Agency: Department of Energy
Contract Number: DE-AC02-78CS34704
Contract Period: April 1978 through June 1979
Funding: $107,000
Source: DOE **Level:** 100%

Project Objectives:

To establish the technical feasibility, for most retrofit applications, of mating a heat pump to a rock-bed storage unit for optimal performance at the lowest cost.

Project Description:

This study analyzed the physical restraints involved in coupling a heat pump to a conventional rock-bed-storage-type air system with flat-plate collectors. Only components currently available were used so that accurate pricing and performance data could be incorporated into the study. The main result of the feasibility study was a control strategy that optimized the performance of cost-effective heat pump/solar systems. These systems were modeled and subsequently analyzed using the TRNSYS computer program and a life-cycle cost analysis (LCCA) program. A detailed load model of a baseline house was formulated as a part of the TRNSYS analysis.

The analysis also resulted in the development of a technique to confine the range of heat pump/rock-bed storage systems to those systems that are feasible for a specific location and set of economic conditions.

Several modifications and additions were made to the TRNSYS and LCCA computer programs during the course of the study.

Publications:

H. E. Remmers, "Rock-Bed Storage with Heat Pump," *Proc. 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting*, CONF-78093, March 1979.

G. L. Mills and H. E. Remmers, "Heat Pump/Rock-Bed Storage Systems," *Proc. Solar Energy Storage Options*, CONF-790328, March 1979.

H. E. Remmers and G. L. Mills, *Rock-Bed Storage with Heat Pump*, COO-4704-3, Zia Associates, Inc., May 1979.

5.4 Systems Using Refrigerant Mixtures

5.4.1 Refrigerant Mixture Measurements in Two-Phase Flow

Principal Investigator: David A. Didion
Organization: National Bureau of Standards
Room B128, Building 226
Washington, DC 20234
Telephone: (301) 921-2994

Contract Agency: National Bureau of Standards
Contract Numbers: 745-1111, 745-1278
Contract Period: October 1981, continuing
Funding: $150,000 (FY-1982)
Source: NBS **Level:** 100%

Project Objectives:

To design and construct a facility with which the heat transfer coefficient in two-phase flow of fluid mixtures may be measured, to provide a data base and develop a method for predicting forced-convection evaporative and condensing heat transfer coefficients of mixtures based on the transport and thermodynamic properties of their components.

Project Description:

The convective heat transfer coefficient is the single most important property for the design of heat exchangers. For those heat exchangers that have internal boiling or condensation coupled with forced convection (e.g., refrigerant systems, steam power systems, etc.), the complexity of flow conditions are such that the coefficient values are normally completely empirically based. Because this study focuses on binary mixtures that are nonazeotropic (different boiling and condensation points), the problem is complicated even further. In single-component fluids, it is typical to establish an empirically based functional relationship between the convective heat transfer coefficient and the other transport properties (e.g., conductivity, viscosity, etc.) for a given range of flow patterns and thermodynamic conditions. Once these relationships are established for categories of fluids, it is possible to predict the heat transfer coefficient based on the measures of other transport properties that are significantly easier to make. In the area of nonazeotropic mixtures, virtually no such relationships among the transport properties exist.

The specific group of fluids being studied is that of fluorocarbons that are used or intended to be used as refrigerants. The apparent advantages of using non-azeotropic mixtures in refrigerant systems are (1) improvement in efficiency, (2) less environmental (ozone) impact, (3) multilevel evaporators, and (4) self-lubricating working fluids. The evaluation of any of these possible advantages entails an overall performance evaluation of the refrigerant system, which in turn requires knowledge of the transport properties of the refrigerant.

Publications:

None provided.

5.4.2 Experimental Evaluation of Modified Heat Pump Cycles and Systems Hardware Using Nonazeotropic Refrigerant Mixtures

Principal Investigator: David A. Didion
Organization: National Bureau of Standards
Center for Building Technology
Division 745
Gaithersburg, MD 20899
Telephone: (301) 921-2994

Contract Agency: Oak Ridge National Laboratory
Contract Number: DE-AI05-OR21589
Contract Period: May 1985 through September 1988
Funding: $425,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the thermodynamic and operational behavior of conventional and modified vapor-compression heat pump cycles and systems hardware using nonazeotropic refrigerant mixtures (NARMs).

Project Description:

In FY-1985 and FY-1986, a laboratory breadboard test loop featuring a variable-speed compressor and counterflow water-to-refrigerant heat exchangers was designed and fabricated. The operation of the loop was characterized with one NARM refrigerant mixture.

In FY-1987 and FY-1988, four tasks will be conducted:

- Task 1—Conduct experiments with the existing breadboard loop to demonstrate achievement of the operational advantages of the use of NARMs as compared with conventional single-component refrigerants
- Task 2—Determine analytically and experimentally the heat-exchanger characteristics that are most favorable for use with NARMs
- Task 3—Conduct analytical studies to investigate the potential performance of novel refrigeration cycles for use with NARMS
- Task 4—Conduct experiments to investigate the performance of one or more novel NARM cycles

Publications:

None provided.

5.4.3 Measurement of the Specific Heat of the Liquid and Vapor Phases of Nonazeotropic Refrigerant Mixtures

Principal Investigator: Reinhard Radermacher
Organization: National Bureau of Standards
Center for Building Technology
Division 745
Gaithersburg, MD 20899
Telephone: (301) 921-3579

Contract Agency: Oak Ridge National Laboratory
Contract Number: DE-AI05-OR21589
Contract Period: October 1986 through September 1987
Funding: $100,000
Source: DOE **Level:** 100%

Subcontractor: University of Maryland

Project Objectives:

To obtain specific heat data for selected nonazeotropic refrigerant mixtures (NARMs) over a wide temperature range [calculation of specific heat from an equation of state (EOS) is susceptible to substantial error because it involves the second derivative of the EOS; these measurements will both provide useful specific heat data and permit adjustment of the EOS parameters].

Project Description:

The specific heat of four refrigerant mixtures will be measured with a heat-conduction calorimeter over the entire temperature range from room temperature to the critical temperature of the mixture (but not exceeding 200°F) for five compositions and pure components in the liquid and vapor phases. The measurements in the vapor phase will be performed on superheated vapor under constant volume conditions. The specific heat will be obtained by a straightforward calculation based on thermodynamic relations. All data will be used to fit the parameters of the EOS so that it reproduces the vapor pressure data and also provides accurate values for the specific heat.

Publications:

None provided.

5.4.4 Evaluation of Advanced Vapor-Compression Using Nonazeotropic Refrigerant Mixtures

Principal Investigator: Richard L. Merriam
Organization: Arthur D. Little, Inc.
32 Acorn Park
Cambridge, MA 02140
Telephone: (617) 864-5770

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-22000C
Contract Period: Jan. 1, 1985, through Apr. 1, 1987
Funding: $220,131
Source: DOE **Level:** 100%

Subcontractor: W. Cooper (Consultant)

Project Objectives:

To identify candidate nonazeotropic mixtures and advanced heat-pump-cycle concepts with emphasis on their potential for single-speed capacity modulation with active mixture composition control, to evaluate the cycles analytically and recommend the most promising cycles and mixtures for further development.

Project Description:

This work covers the conceptual study of advanced cycles that will take advantage of nonazeotropic refrigerant mixture characteristics. Nonazeotropic refrigerant mixtures have the potential to attain, with single-speed compressor operation, capacity-modulation benefits as well as enhanced low-ambient-outside-temperature heating-mode capacity when compared with R-22, the refrigerant most commonly used in air-to-air heat pumps.

The results of the study to date show that modest gains (~5%) in coefficient of performance and capacity may be made by using mixtures in a heat pump. An approximate 10% increase in performance is possible in a cooling-only machine. The final report is being prepared.

Publications:

None provided.

5.4.5 Energy and Heat-Transfer Characteristics of Refrigerant Mixture Systems

Principal Investigator: Wilbert F. Stoecker
Organization: University of Illinois
144 Mechanical Engineering Building
1206 West Green Street
Urbana, IL 61801
Telephone: (217) 333-0916

Contract Agency: Oak Ridge National Laboratory
Contract Number: 7762-X01
Contract Period: September 1979 through December 1986
Funding: $281,000
Source: DOE **Level:** 100%

Project Objectives:

To assess the performance benefits that could result from the use of nonazeotropic refrigerant mixtures as the working fluid in domestic refrigerator-freezers; recently, to conduct basic heat transfer studies as well as computer modeling of refrigeration systems using mixtures as working fluids.

Project Description:

An analytical and experimental investigation was conducted of an R-12/R-114 mixture as a working fluid. In phase I, cycle calculations were made based on assumed state points. A dual-evaporator, dual-condenser laboratory test apparatus was constructed. In phase II, a computer model using ideal mixing rules was developed and used to conduct optimization studies of a two-evaporator refrigerator-freezer. The laboratory apparatus was operated to confirm the general predicted system behavior and to measure heat transfer coefficients. In the current phase, the computer model is being upgraded to incorporate nonideal mixing behavior and improved component models. A new test apparatus has been constructed to study condensing heat transfer. This apparatus includes provision for heat exchanger flow visualization as well as measurement of heat transfer coefficients.

Publications:

W. F. Stoecker and P. F. Launay, "An Evaluation of Using a Refrigerant Mixture in a Heat Pump for Water Heating," *Proc. Conference on Waste Heat Recovery for Energy Conservation*, CONF-800966, September 1980.

P. F. Launay, *Improving the Efficiency of Refrigerators and Heat Pumps Using a Nonazeotropic Mixture of Refrigerants*, ORNL/Sub-81/7762/1, October 1981.

W. F. Stoecker, *Energy Characteristics of a Two-Evaporator Refrigerator Using a Refrigerant Mixture*, ORNL/Sub/81-7762/2&01, March 1982.

W. F. Stoecker and C. I. McCarthy, *The Simulation and Performance of a System Using an R-12/R-114 Refrigerant Mixture*, ORNL/Sub/81-7762/3&01, May 1984.

W. F. Stoecker, "Internal Performance of a Refrigerant Mixture in a Two-Evaporator Refrigerator," *ASHRAE Trans.* **91**(1B), 1985.

W. F. Stoecker, "Condensing Coefficients When Using Refrigerant Mixtures," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.4.6 Examination of Nonazeotropic Mixture Refrigerants for Heat Pumps

Principal Investigator: David A. Didion
Organization: National Bureau of Standards
U.S. Department of Commerce
Gaithersburg, MD
Telephone: (301) 921-2994

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-8
Contract Period: Jan. 1, 1982, through Sept. 30, 1986
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To develop a simulation model of a vapor compression cycle operating with binary nonazeotropic refrigerant mixtures, to perform a parametric evaluation of performance advantages of nonazeotropic mixtures.

Project Description:

Three tasks to develop the methods and perform an examination of nonazeotropic mixture refrigerants for heat pumps are included:

- Thermodynamic modeling of refrigerant mixtures
- Heat transfer modeling of mixtures in heat pump cycles
- Examination of heat pumps using nonazeotropic mixtures

The modeling efforts will take advantage of coordinated experimental programs sponsored by the National Bureau of Standards (NBS) involving physical measurements of mixtures. Algorithms developed will be incorporated into the existing NBS physical heat pump model. Candidate binary mixtures will be evaluated on seasonal performance and demand bases.

Conventional vapor-compression heat pumps employ single-component refrigerants or azeotropic mixtures of refrigerants as their working fluids. Azeotropic mixtures function essentially as single-component refrigerants because their vapor- and liquid-phase compositions are the same at a given pressure. In nonazeotropic mixtures, the concentrations of individual components vary by state of the fluid in the working range. At condenser and evaporator conditions, the vapor is richer than the liquid in the more volatile component. The resultant effect is that nonazeotropic mixtures provide a performance advantage over single-component refrigerants or azeotropes. Data on mixtures are very limited, and none of the recognized public-domain, physical-principle models of heat pumps presently accommodate nonazeotropic mixtures.

A literature search and contacts with manufacturers were initiated; the manufacturers contacted indicated considerable interest. Property measurements were completed on the R13B1/152a mixture. The improvements centered on an accumulator algorithm and suction-gas state determination. The thermodynamic modeling effort progressed with development of algorithms for dew and bubble surfaces that predict liquid densities to $\pm 0.1\%$.

An equation-of-state model was formulated and verified against data on both single-component and mixture refrigerants. The evaporator algorithms of the heat pump model were refined, and data on R22 were collected using an evaporative heat transfer coefficient apparatus developed for this effort. Laboratory tests of various R13B1/R152a mixtures were made in a heat pump. The equation-of-state model was incorporated into a physical-principles heat pump model for further concept analysis. Screening of refrigerant mixtures was initiated.

Publications:

None provided.

5.4.7 Performance of Nonazeotropic Binary Refrigerant Mixture in a Residential Heat Pump

Principal Investigator: David A. Didion
Organization: National Bureau of Standards
Bldg. 226, Room B128
Gaithersburg, MD 20899
Telephone: (301) 921-2994

Contract Agency: Oak Ridge National Laboratory
Contract Number: DE-AI-83OR21335
Contract Period: March 1983 through May 1986
Funding: $100,000
Source: DOE **Level:** 100%

Project Objectives:

To quantify the performance of the typical residential heat pump operating with a nonazeotropic binary refrigerant mixture as a working fluid.

Project Description:

This project involved laboratory performance measurements of a relatively unmodified, commercially available air-to-air heat pump designed for R22 when charged with a nonazeotropic binary mixture of refrigerants R13B1 and R152a. Tests were conducted with both the stock capillary tube and modified short-orifice expansion devices. For the mixture tests, refrigerant charge for optimum performance was determined.

The effect of gliding temperature within the two-phase region of the condenser and evaporator was found to be small. The experiments confirmed that some capacity improvement at low air-source temperature was obtained by storage of the low-capacity refrigerant component in the suction-line accumulator. The measured performance was approximately 11% lower in both efficiency and capacity compared with R22 in the cooling mode. The high-temperature heating capacity was 8% lower and efficiency was 3% lower than R22. The low-temperature heating capacity was 14% higher and efficiency was 2% higher than R22. These results show an improvement in heating performance at the expense of reduced cooling-mode performance.

Publications:

D. A. Didion and W. J. Mulroy, "The Performance of a Residential Heat Pump Operating with a Non-Azeotropic Binary Refrigerant Mixture—An Interim Report," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

5.4.8 High-Temperature Working Fluids and Nonazeotropic Mixtures in Compressor Driven Heat Pumps—IEA Annex VI

Principal Investigators:
T. Berntsson, Chalmer Technical University
H. Schnitzer, Graz Technical University
W. F. Stoecker, University of Illinois
Telephone:

Contract Agency: International Energy Agency
Contract Number:
Contract Period: June 1982 through January 1985
Funding: $200,000
Source: DOE **Level:** 20%
Other participating IEA countries 80%

Project Objectives:

To gather theoretical and experimental information for heat pump systems operating with new working fluids or mixtures with emphasis on nonazeotropic mixtures, to evaluate their potential in comparison with other heat pump systems.

Project Description:

This project is supported by a national team in each of the following participating countries: Austria, Denmark, Finland, West Germany, Sweden, and the United States.

The project shows that heat pump performance can be improved in several ways by the use of nonazeotropic mixtures. The coefficient of performance as well as the heating capacity can be improved considerably if the temperature gradients of the heat sink and heat source are sufficiently high, at least above 5°C. Also, other parameters, such as condensing pressure and temperature, the compressor discharge temperature, and variation of the heating capacity with the load, can be influenced in a positive way. These possible improvements apply equally to space heating and industrial applications.

To gain the various advantages with mixtures, one must design the system and the components properly. It was shown that the design of all components in a heat pump are influenced when a mixture is used. The choice of a mixture and its composition is essential to performance. This choice is dependent on the temperature level and the temperature gradient of both the heat sink and the heat source. In the search for the appropriate types of mixtures, knowledge of the state and transport properties is important. There are several methods for estimating mixture properties when the corresponding data for the pure components are known. To use the methods for mixtures of refrigerants, one must carry out a great number of measurements of state and transport properties with both pure compounds and with mixtures.

Publications:

T. Berntsson et al., *High Temperature Working Fluids and Nonazeotropic Mixtures in Compressor Driven Heat Pumps—State-of-the-Art Report*, January 1984.

5.5 Energy Storage Systems

5.5.1 Steady-State Performance Characteristics of Latent Heat TES/Heat Pump Systems

Principal Investigators: R. A. Whisnant
T. W. Sigmon
Organization: Research Triangle Institute
P.O. Box 12194
Research Triangle, NC 27709
Telephone: (919) 541-5878

Contract Agency: Office of Advanced Conservation Technologies, Department of Energy
Contract Number: DE-AC01-79ET26707
Contract Period: July 1979 through July 1981
Funding: $325,000
Source: DOE **Level:** 100%

Project Objectives:

To determine the relative viability of various coupled latent heat thermal energy storage (TES) heat pump systems for residential space heating and cooling applications; to describe the sensitivity of their relative viability to selected geographic, economic, and system performance parameters.

Project Descriptions:

Two current projects were completed that wholly or in part addressed various technical issues involved in the implementation of heat pump systems combined with TES.

The first of these involved the determination of steady-state performance characteristics for six generic TES/heat pump configurations and the comparison of the operational performance of these systems with other space heating and cooling technologies. Of these latter systems, four were commercial or near commercial air conditioner or heat-pump-coupled TES systems. Steady state performance was established for all systems. Operational performance and system life cycle costs were determined for the six generic designs for a limited set of application conditions. Operational performance was established through use of a computer simulation that utilized a control algorithm to identify appropriate modes of operation under a time-of-day electric utility rate structure. This software package was used to compute operational performance for the other systems considered.

The second project established a reliable method of estimating seasonal energy use by TES/heat pump systems and used this methodology to evaluate a large number of possible system designs and to identify a smaller number of systems that merit more detailed analysis. The approach to evaluate performance was a modification of the bin analysis approach. This was completed and applied to a number of system designs.

Publications:

Research Triangle Institute, *Dispersed Energy-Storage Analysis, Vol. 1, Investigation of Technical and Economic Issues Related to Energy-Storage Systems*, RTI-1855-01-01F, May 1982.

5.5.2 Development of Concepts for Low-Cost Energy Storage Assemblies for Annual Cycle Energy System Applications

Principal Investigator: D. L. Cooper
Organization: Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
Telephone: (614) 424-7411

Contract Agency: Oak Ridge National Laboratory
Contract Number: 7800-X07
Contract Period: Sept. 12, 1980, through May 31, 1981
Funding: $59,147
Source: DOE **Level:** 100%

Project Objectives:

To devise and evaluate diverse storage concepts, to develop detailed designs for those that promise minimum cost while still meeting the functional requirements of Annual Cycle Energy Systems.

Project Description:

Battelle evaluated a large number of ice storage tank/heat exchanger coil configurations and designs and detailed the design of three of the most promising of these. Because of the requirements for high insulation and mechanical integrity for long periods (20 years or more), none of the designs led to substantial reductions in cost.

Publications:

G. H. Alexander et al., *Development of Concepts for Low-Cost Energy Storage Assemblies for Annual Cycle Energy System Applications*, ORNL/Sub-7800/1, October 1981.

5.5.3 Development of the Concept of a Split Ice-Maker, Air-Evaporator Heat Pump for Use in an Annual Cycle Energy System

Principal Investigator: Mason H. Sommerville
Organization: University of North Dakota
Engineering Experiment Station
Box 8164, University Station
Grand Forks, ND 58202
Telephone: (701) 777-3132

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7434
Contract Period: Dec. 1, 1977, through Jan. 31, 1981
Funding: $232,043
Source: DOE **Level:** 100%

Project Objectives:

To develop a split air–water evaporator for residential Annual Cycle Energy Systems (ACES); to instrument and monitor two ACES demonstration houses in the Grand Forks, North Dakota, area.

Project Description:

Three types of multiple-source heat pumps were designed and tested: (1) the parallel evaporator, (2) the series evaporator, and (3) the parallel evaporator with active subcooling. The series evaporator and the parallel evaporator were tested in a house in Larimore, North Dakota. The parallel evaporator with active subcooling was, by far, the most promising and in addition to its applicability to ACES, offers a potential solution to the problem of defrosting of air evaporators. A system with the parallel evaporator with active subcooling was tested in a home in Crookston, Minnesota.

Publications:

C. P. Kipp, *Annual Cycle Energy System (ACES) Impact upon a Utility's Load Duration Curve,* 80-EES-12-01, December 1980.

D. V. Mathsen, *A Summary of Monitoring Efforts and Results from the ACES-Equipped Larimore, North Dakota, and Crookston, Minnesota, Houses,* 80-EES-12-03, December 1980.

M. H. Sommerville and S. G. Penoncello, *The Design and Development of a Split Evaporator Heat Pump System,* ORNL/Sub-7434/1, December 1981.

5.5.4 Annual Cycle Energy System Design, Setup, Testing, Analysis, and Implementation

Principal Investigators: Robert Minturn, Van D. Baxter, et al.
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-5213

Contract Agency: Department of Energy
Contract Number: W-7405-eng-26
Contract Period: 1976 through 1981
Funding: $5,181,000
Source: DOE **Level:** 100%

Project Objectives:

To incorporate in a practical system the outstanding energy conservation potential that exists when a unidirectional heat pump and the interseasonal storage of energy are combined to provide heating, cooling, and domestic hot water to buildings; to develop and test this system; to determine its applicability to different geographic areas; to make available to the private sector the methodology for designing such systems.

Project Description:

Field testing of the Annual Cycle Energy System (ACES) and other heat pump systems was carried out at the University of Tennessee TECH site near Knoxville, Tennessee. Two identical houses at the site provided the location for carefully controlled, well-instrumented experiments on residential heating, ventilating, and air-conditioning (HVAC) systems. For four years, performance data were gathered and analyzed on the ACES, an all-electric system, and two commercially available heat pump systems. A weather station on site allowed performance data to be correlated with actual weather conditions. In the laboratory, ice-maker heat pumps were developed for ACES applications, and low-temperature solar panels were evaluated as alternate energy sources for the ACES. Computer programs were developed to accurately simulate the performance of a number of ACES configurations under field conditions. These programs were used to compare the performance and economics of a number of HVAC systems throughout the United States. This project proved that the ACES is reliable and durable and is among the most energy efficient systems available. Savings of 50% of the energy used by state-of-the-art high-efficiency heat pumps were achieved. However, because of the relatively high cost of the system (two to four times the cost of conventional residential HVAC systems), ACES was not a viable consumer product.

Publications:

H. C. Fischer et al., *Summary of Annual Cycle Energy System Workshop I Held October 29–30, 1975, at Oak Ridge, Tennessee*, ORNL/TM-5243, July 1976.

J. C. Moyers et al., *Design Report for the ACES Demonstration House*, ORNL/CON-1, October 1976.

E. A. Nephew et al., *The Annual Cycle Energy System: Initial Investigations*, ORNL/TM-5525, October 1976.

E. C. Hise, *Performance for the ACES Demonstration House, August 1976 through August 1977*, ORNL/CON-19, March 1978.

A. S. Holman and V. R. Brantley, *ACES Demonstration Construction, Startup, and Performance Report*, ORNL/CON-26, October 1978.

A. S. Holman et al., *Annual Cycle Energy System (ACES) Performance Report, November 1977 through September 1978*, ORNL/CON-42, May 1980.

E. A. Nephew et al., *Theory and Design of an Annual Cycle Energy System (ACES) for Residences*, ORNL/CON-43, May 1980.

R. E. Minturn and L. A. Abbatiello, *ACES 1979 Capabilities and Potential*, ORNL/CON-48, June 1980.

M. L. Ballou et al., *MAD: A Computer Program for ACES Design Using Monthly Thermal Loads*, ORNL/CON-51, March 1981.

L. A. Abbatiello et al., *Performance and Economics of the ACES and Alternative Residential Heating and Air Conditioning Systems in 115 U.S. Cities*, ORNL/CON-52, March 1981.

V. D. Baxter, *ACES: Final Performance Report Dec. 1, 1978, Through Sept. 15, 1980*, ORNL/CON-64, April 1981.

J. L. Bledsoe et al., *Data Collection and Processing for the ACES*, ORNL/CON-59, August 1981.

E. A. Nephew and L. A. Abbatiello, *Performance and Economics of Eight Alternative Systems for Residential Heating, Cooling, and Water Heating in 115 U.S. Cities*, ORNL/CON-89, November 1982.

V. D. Baxter, *ACES Tests at the TECH Site: 1981*, ORNL/CON-96, August 1983.

M. A. Kuliasha and W. P. Poore, *Assessment of the Load Management Potential of the Annual Cycle Energy System*, ORNL/CON-140, March 1984.

Patents:

U. S. 4,057,074: H. C. Fischer, Bidirectional Piston Valve, Nov. 8, 1977.

5.5.5 ACES Control Package

Principal Investigator: A. G. Baitz
Organization: Robertshaw Controls Company
1701 Byrd Avenue
Richmond, VA 23261
Telephone: (804) 282-9561

Contract Agency: Oak Ridge National Laboratory
Contract Number: 19X-14290V
Contract Period: Aug. 10, 1977, through Feb. 21, 1980
Funding: $9590
Source: DOE **Level:** 100%

Project Objectives:

To design and build an Annual Cycle Energy System (ACES) control package for a single-family residence to serve as a prototype unit for possible commercial production.

Project Description:

The subcontractor designed, constructed, and delivered a prototype unit for the year-round control of a minimum ACES in a single-family residence. The package consisted of control closure input sensors, a central clock and logic box, and contact closure electromechanical relays for operation of output devices. Also delivered was a manual control box for checking the logic box and ACES operation.

A manual describing the system, specifications, installation, operation, checkout, sensor literature, instructions, drawings, and a parts list was supplied.

Publications:

Robertshaw Controls Company, *ACES Control System,* March 1980.

5.5.6 Plate-Type Ice Maker Heat Pump Development and Testing

Principal Investigator: Van D. Baxter
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-2104

Contract Agency: Department of Energy
Contract Number: W-7405-eng-26
Contract Period: 1977–1980
Funding:
Source: DOE **Level:** 100%

Subcontractors: University of North Dakota

Project Objectives:

To develop and evaluate plate-type ice maker heat pumps (IMHP) for the annual cycle energy system (ACES) program.

Project Description:

The plate-type IMHP was investigated as an alternative to the brine-chiller-type mechanical package for ACES. For the IMHP, ice was produced on evaporator plates above the storage tank and periodically harvested. The brine-chiller concept produced ice on a secondary heat exchanger submerged in the storage tank.

Three harvesting schemes were tested: hot gas; stored refrigerant; and dual fluid, off cycle. The hot-gas scheme tended to penalize excessively the heating output of the system. Stored-refrigerant schemes eliminated that problem but caused compressor failures from floodback and oil dilution. The dual-fluid schemes exhibited no such problems and demonstrated an ability to harvest during compressor off cycles. Therefore, it was concluded that dual-fluid, off-cycle schemes are the best for use with IMHPs.

Performance test results indicated that the IMHP had only slightly better performance than the brine-chiller systems. Further, the storage ice packing density for the IMHP was about half that of the brine-chiller. This would mean that the IMHP would need about twice the storage volume for the same energy storage. IMHPs were concluded to be an uneconomical alternative for the ACES systems. They may, however, be the better choice for short-term (diurnal) storage air-conditioning systems.

Publications:

H. C. Fischer, *Development and Testing of a Single-Plate and a Two-Plate Ice-Maker Heat Pump,* ORNL/CON-21, April 1978.

V. D. Baxter, *Intermediate Report on the Performance of Plate-Type Ice-Maker Heat Pumps,* ORNL/CON-23, October 1978.

V. D. Baxter, *Ice-Maker Heat Pump Development: Final Report,* ORNL/CON-50, September 1980.

M. H. Somerville and S. G. Penoncello, *The Design and Development of a Split Evaporator Heat Pump System,* ORNL/Sub-7434/1, December 1981.

5.5.7 Assessment of HP-ICES Based on a Centralized System and Annual-Cycle Energy Storage

Principal Investigator: Fred S. Dubin
Organization: Dubin Bloome Associates
42 West 39th Street
New York City, NY 10018
Telephone: (212) 840-6780

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4549
Contract Period: June 20, 1978, through Nov. 30, 1979
Funding: $66,850
Source: DOE **Level:** 100%

Project Objectives:

To assess the feasibility of a heat-pump-centered integrated community energy system (HP-ICES) based on a community scale, annual-cycle energy storage approach using both latent and sensible thermal energy storage with water as the medium.

Project Description:

This centralized system used an ice-making heat pump driven by an electric motor or an engine. Space heating and cooling as well as service-water heating were provided. Detailed case studies of applying this HP-ICES concept were made on the market square project in Washington, D.C., and Park Plaza in Boston, Massachusetts.

The ice-generating HP-ICES used the heat of fusion of water as a heat source, converting water into ice. The annual overall coefficient of performance was expected to reach a value of 4.85 and related to source energy, a value of $4.85 \times 0.31 = 1.5$. This was greater than 0.713, the value for which the HP-ICES would perform equally well with a conventional system having the same cooling and heating output.

In the Washington, D.C., case study, the annual source energy input was found to be about 60% and the life-cycle annual average cost was 40% of the corresponding quantities for a conventional central system with equal heating and cooling capacity. The annual average operating and administration cost for this HP-ICES was less than 70% of the corresponding costs for the conventional system, while the initial cost of the HP-ICES was 70% larger than that of a conventional system.

In the Boston case study, the annual source energy input for this HP-ICES was found to be 35% and energy cost was about 30% of the corresponding quantities for the conventional system. The annual average operating and administration cost for this HP-ICES was 41% of the conventional system cost, while the initial cost for this HP-ICES was 4.5 times as great as that for the conventional system.

Publications:

F. S. Dubin et al., *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report,* ANL/ICES-TM-29, February 1979.

F. S. Dubin et al., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report,* ANL/CMSV-TM-8, August 1979.

5.5.8 Economic Evaluation of the Annual Cycle Energy System

Principal Investigator: J. W. MacArthur
Organization: Honeywell, Inc.
Energy Resources Center
2600 Ridgeway Parkway
Minneapolis, MN 55413
Telephone: (612) 378-4673

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7470
Contract Period: May 22, 1978, through Oct. 31, 1979
Funding: $212,299
Source: DOE **Level:** 100%

Project Objectives:

To assess the economic viability of the Annual Cycle Energy System (ACES), to determine its economic competitiveness with other more conventional heating and cooling systems, to compare the seasonal coefficients of performance of ACES with conventional systems.

Project Description:

Computer codes were developed to simulate ACES and conventional system performance and to calculate economics of operation; these codes were applied to single-family and multifamily residential and small commercial buildings in Atlanta, Philadelphia, and Minneapolis.

In brief, the full ACES was found to be the most energy efficient system evaluated for single-family and multifamily dwellings, but at a cost unacceptable for systems installed at 1978's prototype prices. However, under a reduced equipment price scenario (projected 1982), the economic picture was more favorable.

In commercial applications, the ACES was again found to deliver significant energy savings and was economically superior to oil, gas, and electric systems at 1978 equipment and fuel prices in all locations.

Publications:

J. W. MacArthur, *Economic Analysis of Annual Cycle Energy Systems,* ORNL/Sub-7470/1-V1-3, May 1980.

5.5.9 Aid in the Development of an ACES Design Handbook for Large Buildings

Principal Investigator: Robert G. Werden
Organization: Robert G. Werden & Ass., Inc.
Jenkintown, PA 19046
Telephone: (215) 885-2500

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7225
Contract Period: Nov. 15, 1976, through Oct. 31, 1979
Funding: $237,464
Source: DOE **Level:** 100%

Project Objectives:

To assist Oak Ridge National Laboratory in the development of an Annual Cycle Energy System (ACES) design handbook for large buildings, to provide consultation to DOE and the ACES program on heating, ventilating, and air-conditioning (HVAC) systems in large buildings.

Project Description:

The project was terminated in October 1979 following a DOE decision not to pursue ACES applications in larger buildings at that time. At the time of termination, considerable information on hardware had been gathered and designed methodologies were being developed. This information is currently being retained should interest in this concept be revived. In addition to handbook development, the subcontractor acted as technical liaison with the Southern States Energy Board and the State of Maryland in a project, later dropped, to put an ACES in a state office building. This involved, among other things, an analysis of the performance and economics of three ACES configurations in three candidate office buildings. The subcontractor also provided consultation on numerous occasions to ORNL and to DOE headquarters on questions pertaining to HVAC systems in larger buildings.

Publications:

None provided.

5.5.10 ACES Feasibility and Commercialization

Principal Investigator: D. W. Talbott
Organization: The National Association of Homebuilders Research Foundation
P.O. Box 1627
Rockville, MD 20850
Telephone: (202) 762-4200

Contract Agency: Department of Energy
Contract Number: EC-77-C-05-2130
Contract Period: Sept. 1, 1976, through Feb. 28, 1979
Funding: $88,157
Source: DOE **Level:** 100%

Project Objectives:

To evaluate Annual Cycle Energy System (ACES) applicability by climate and house type, to compare energy costs for ACES and conventional systems.

Project Description:

The National Association of Homebuilders Research Foundation concluded that significant energy savings using ACES can be shown for all house types in all of the 16 climatic zones. They calculated that ACES energy savings at 1978 rates would justify first costs of ACES installations ranging from $5800 to $7500 and that if first costs could be brought within this range, the market potential for ACES might approach 0.5 million units per year.

Five potential barriers to implementation were recognized: (1) financing the higher capital cost; (2) lack of product reliability experience; (3) experienced suppliers and installers; (4) nonavailability of turnkey systems; and (5) local acceptance of innovation.

Publications:

National Association of Homebuilders Research Foundation, Inc., *Research Program on the Economic Feasibility and Commercialization Potential of ACES, Final Report,* ORO/2130/1, February 1979.

5.5.11 Investigation of Alternate Types of Water Storage Components To Be Utilized in Conjunction with the ACES

Principal Investigator: Irwin G. Cantor
Organization: The Office of Irwin G. Cantor
919 Third Avenue
New York, NY 10022
Telephone: (212) 486-9450

Contract Agency: Oak Ridge National Laboratory
Contract Number: 19X-14233V
Contract Period: Feb. 24, 1977, through Jan. 1, 1978
Funding: $12,169
Source: DOE **Level:** 100%

Project Objectives:

To determine the cost and availability of water storage tanks suitable for Annual Cycle Energy System (ACES) installation.

Project Description:

The subcontractor conducted research on the cost and availability of water storage tanks suitable for ACES installations and found that most commonly used tanks such as wood-stave welded steel are the least economical construction materials for such use. Field-erected construction procedures, using locally available materials and field experience, were found to be the most economical answer to tank requirements. The subcontractor concluded that integration of the ACES tank with the total house design was essential for economical development of ACES and that the use of the tank as a portion of the foundation walls indicated as much as 50% could be saved in total tank cost.

Publications:

I. G. Cantor Company, *Investigation of Alternate Types of Water-Storage Components to be Utilized in Conjunction with the ACES,* ORNL/Sub-78/14233/1, December 1977.

5.5.12 Performance Evaluation: Energy Efficiency at Volney Town Hall

Principal Investigator: Judson Brown
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period:
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To monitor and evaluate the performance and cost effectiveness of the Volney Town Hall's unique building systems such as (1) heat pump coupled to building storage mass, (2) solar domestic hot water system, (3) super insulated envelope, and (4) solar air collectors.

Project Description:

A heat pump coupled to sand mass heat storage is one of the elements in this unique public building design. This system, together with other building systems designed to provide low energy use, has been monitored for one year. The overall energy performance of the Town Hall is excellent in comparison with other assembly buildings; however, the mass-coupled heat pump system has not made a major contribution to the overall energy performance because it does not function as an auxiliary heat source to the building, but merely as a means of moving heat in and out of storage within the building.

Publications:

None provided.

6. SOLAR-POWERED SYSTEMS

6.1 Dynamic Vapor Compression Systems

6.1.1 Design and Fabrication of an Advanced Prototype Solar-Powered Turbocompressor Heat Pump

Principal Investigators: Frank R. Biancardi
James W. Sitler
G. Melikian
Organization: United Technologies Research Center
Silver Lane
East Hartford, CT 06108
Telephone: (203) 727-7234

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS34510
Contract Period: September 1977 through October 1983
Funding: $1,920,000
Source: DOE **Level:** 100%

Project Objectives:

To design, fabricate and assemble a MOD-2 heat pump which incorporated design improvements and features identified in the laboratory and field testing of the MOD-1 unit. Design objectives: to achieve higher system performance, reliability, and lower manufacturing cost.

Project Description:

This project was a continuation of a research and development effort started in 1974 under the National Science Foundation/Energy Research Development Association; later Department of Energy (DOE) sponsorship (Solar Active Buildings Systems Office) expanded in 1977 to include the design, development, and test of Rankine-cycle heat pumps powered by solar energy for use in multifamily residential and light commercial buildings.

Under a recently completed program phase, the MOD-1 prototype solar-powered turbocompressor heat pump was successfully subjected to 250 h of extensive laboratory testing to demonstrate its component and overall performance, reliability, and endurance characteristics. As part of the solar cooling engineering field test effort, the MOD-1 was modified and used in a complete United Technologies Research Center (UTRC) solar cooling system in a Hamilton Test Systems, Inc., office building located in Phoenix, Arizona.

The UTRC heat pump (HP) system incorporated a Rankine cycle power loop in which a centrifugal turbine was used to drive a centrifugal compressor in a vapor compression refrigeration loop. The thermal energy to the power loop was provided at temperatures up to 300°F (149°C) by a medium-concentration solar collector array. Auxiliary energy for cooling was provided by a fossil-fuel-fired furnace. Heating was 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 was rated at 18 tons for cooling and ~500,000 Btu/h (147 kW) for heating. It utilizes low-maintenance air-cooled condensers for heat rejection and conventional heating, ventilating, and air conditioning design heat exchangers and controls. Refrigerant 11 was used as the working fluid in both the power and cooling loops.

The measured coefficient of performance (COP) in the heat pump mode ranged from 1.4 to 2.5 at output capabilities from 200,000 to 550,000 Btu/h (59 to 161 kW). A cooling COP of 0.5 to 0.75 at up to 20 tons of output was demonstrated in laboratory and field tests. During laboratory testing, MOD-2 system hardware and control modifications demonstrated improved operational characteristics relative to the MOD-1 unit and a cooling COP of 0.75 to 0.90 at more than 20 tons of output. The MOD-2 unit was then shipped to Phoenix, Arizona, field test site. The MOD-2 unit was in operation at the field test site through the 1985 season and demonstrated heating as well as cooling system capacity.

Publications:

F. R. Biancardi and P. Young, "Design, Development and Testing of a Prototype Multi-Family Residential Sized Solar-Powered Turbocompressor Heat Pump System," *Proc. 3rd Annual Solar Heating and Cooling R&D Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, March 1979.

G. Melikian, B. W. Rhodes, and T. N. Obee, "Results of Systems Simulation and Economic Analysis of a Solar-Powered Turbocompressor Heat Pump," *Proc. 2nd Annual Systems Simulation and Economics Analysis Conf., San Diego, Calig., Jan. 25, 1980.*

F. R. Biancardi, G. Melikian, and J. W. Sitler, "Development of a Solar-Powered 18-Ton Rankine Cycle Heat Pump," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26, 1980*, CONF-800340, March 1980.

G. Melikian, F. R. Biancardi, and M. D. Meader, "Test Evaluation of a Prototype 18-Ton Solar Powered Heating and Cooling System," *Proc. 15th Intersociety Energy Conversion Engineering Conf., Seattle, Wash., Aug. 21, 1980*, CONF-800806.

F. R. Biancardi, J. W. Sitler, and G. Melikian, "Development and Test of Solar Rankine Cycle Heating and Cooling Systems," *ASHRAE Trans.* **88**, January 1982.

Design, Development and Testing of a Solar-Powered Multi-Family Residential Prototype Turbocompressor Heat Pump, Extended Test Program Interim Report, R82-953050-1.

Design, Development and Testing of a Solar-Powered Multi-Family Residential Prototype Turbocompressor Heat Pump, R82-953050-2, February 1984.

P. Melikian et al.,"Development, Test, and Evaluation of an Improved Solar Rankine Cycle Heat Pump," *Proc. 18th Intersociety Energy Conversion Engineering Conf., Orlando, Fla., August 21–26, 1985.*

Patents:

U.S. 4,464,908: A. Landerman et al., Solar-Powered Turbocompressor Heat Pump System, Aug. 14, 1984.

6.1.2 Assessment of Solar-Powered Cooling of Buildings, Including Analysis of Thermal Energy Storage Parameters for Solar-Driven Chillers

Principal Investigator: Henry M. Curran
Organization: Hittman Associates, Inc.
9190 Red Branch Road
Columbia, MD 21045
Telephone: (301) 730-7800

Contract Agency: Department of Energy
Contract Number: DE-AC03-79CS30202
(Old Contract Number: DE-AC03-78SF10508)
Contract Period: April 1979 through January 1982
Funding: $427,000
Source: DOE **Level:** 100%

Project Objective:

To provide technical assistance on the development of active solar cooling technology in three areas: Rankine, absorption, and thermal energy storage.

Project Description:

The Rankine work included a survey of the organic working fluids used in Rankine engines in the United States and other countries, the preparation of a procedure for dynamic stability testing of organic working fluids, and development of a performance test plan for Rankine cooling equipment. Additional activities included site visits, review of contractor reports, and an evaluation of proposals. The absorption work included providing technical input to the solar cooling commercialization readiness assessment, providing reviews of contractor reports, and evaluating proposals. The storage work included definition of the operating characteristics of Department of Energy–funded solar cooling equipment; development of solar collectors suitable for space cooling applications and thermal storage subsystems; identification of the thermal storage needs and basic design requirements; and identification of needed research and development of solar cooling thermal energy storage.

Publications:

H. M. Curran and S. Heibein, "Thermal Storage for Solar Rankine and Absorption Cooling System," *Proc. Solar Energy Storage Options Workshop, Mar. 18, 1979*, CONF-790328-P1, 1979.

H. M. Curran, "Solar Cooling Systems Evaluation," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, 1980.

H. M. Curran, "Solar Cooling Thermal Energy Storage Study," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, 1980.

H. M. Curran, *Experimental Testing of Control Strategies for Solar Cooling Systems*, H-C-1007/010-81-999, February 1981.

H. M. Curran, *High-Temperature Solar Cooling Systems*, H-C-1007/010-81-1013, March 1981.

H. M. Curran, *Evaluation of Hybrid Solar/Fossil Rankine Cooling Concept*, H-C-1007/010-80-990/R, March 1981.

H. M. Curran, *On-Site Solar Thermal Electric Power Generation*, H-C-1007/010-81-1027, May 1981.

H. M. Curran and J. Devries, *Options for Thermal Energy Storage in Solar Cooling Systems, Final Report*, DOE/CS/30202-T2, H-C-1007/060-80-976, May 1981.

H. M. Curran, *Hybrid Refrigerant/Sorption Solar Cooling Systems*, H-C-1007/010-81-1044, August 1981.

6.1.3 Solar Heating and Cooling Systems: Development Preproduction Design and Power Generation

Principal Investigators: R. L. Buchholz
G. Marshall
S. Scarbrough
Organization: Honeywell, Inc.
1700 West Highway 36
Roseville, MN 55113
Telephone: (612) 378-4134

Contract Agency: National Aeronautics and Space Administration
Contract Number: NAS8-32093
Contract Period: July 6, 1976, through Sept. 30, 1981
Funding: $7,200,000
Source: DOE **Level:** 100%

Project Objectives:

To design, develop, install, and operationally test solar heating and cooling systems with high performance, low cost, modular application, and marketability.

Project Description:

As the prime contractor responsible for the solar system design, Honeywell teamed with Barber Nichols of Denver, Colorado, and Lennox Industries of Dallas, Texas, to provide the full range of system and subsystem design, fabrication, installation, maintenance, and evaluation. Solar energy systems delivered were residential heating (two), residential heating and Rankine cycle air conditioner (RCAC), cooling (four), multifamily light heating and RCAC cooling (two), and commercial RCAC cooling (two). Additionally, a 16-kVA RC power generation module and a high-efficiency, high-temperature RCAC power generation module were delivered. Other major accomplishments included: full qualification of the Lennox collector to the interim performance criteria, development of a low-cost collector support structure and headers, definition and testing of several RCAC improvements, and analysis of RC power generation.

The program was completed. All systems performed well, amassing more than 20 years of total operational time. The preliminary evaluation results of the operational history and data indicated that (1) space-heating systems were technically state of the art; (2) RCAC cooling systems performed as designed but appeared unattractive from an energy-cost standpoint; and (3) advanced development in RCAC systems (hardware, configuration, and controls) was essential.

Publications:

R. L. Buchholz and G. Marschall, "Solar Heating and Cooling Systems," *Proc. DOE Heat Pump Contractors Program Integration Meeting*, CONF-810672, March 1982.

6.1.4 Development of a High-Temperature Solar-Powered Water Chiller for Use in a Solar Heating and Cooling System

Principal Investigator: Richard A. English
Organization: Energy Systems Division
Carrier Corporation
Carrier Tower, P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 424-4623

Contract Agency: Department of Energy, San Francisco Operations Office
Contract Number: DE-AC03-77CS31590
Contract Period: October 1977 through September 1981
Funding: $1,676,996
Source: DOE **Level:** 100%

Subcontractor: Mechanical Technology, Inc.
20 Plains Road
Ballston Spa, NY 12020
Mr. Ewan Choroszylow
(518) 785-2334

Project Objectives:

To design, construct, test, and analyze a solar-powered, Rankine cycle, 25-ton air-cooled water chiller.

Project Description:

The design concept developed was a dual loop, Rankine power cycle driving a Rankine vapor compression cycle. A single working fluid, R-113, was used. Both loops were connected to a common air-cooled condenser. The prime mover was a 24,000-rpm turbine directly driving a centrifugal compressor. Under design conditions of 45°F (7.2°C) leaving water, 95°F (35°C) entering condenser air, and 290°F (143°C) entering solar hot water, the unit was designed to produce 25 tons. The cycle employed a regenerator and a suction gas heat exchanger that act synergistically to increase cycle efficiency. The heat exchange components, working fluid, and turbocompressor configuration were optimized to produce a high overall coefficient of performance, which is predicted to be above 0.70. The auxiliary energy source was a variable-speed induction motor, which could drive the compressor when solar energy was not available. The turbomachine shaft was supported on hydrodynamic gas bearings to eliminate conventional lubricants from the cycle.

The turbomachine was built by the subcontractor and tested successfully on air. The chiller was rebuilt in a water-cooled configuration to facilitate initial turbomachine testing. The turbomachine was installed and the complete test facility instrumented. Spin tests evaluated the rotor dynamics and bearing performance in the R-113 environment.

Publications:

R. A. English, *Development of a High-Temperature Solar-Powered Water Chiller. Phase I. Technical Progress Report, Sept. 26, 1977–June 1, 1978,* Vols. 1 through 4, SAN-1590-1/1 through 1/4, June 1978.

R. A. English, "Development of a High-Temperature Solar-Powered Water Chiller," *Proc. 3rd Annual Solar Heating and Cooling R&D Branch Contractors' Meeting, Sept. 24, 1978,* CONF-780983, March 1979.

R. A. English, *Development of a High-Temperature Solar-Powered Water Chiller. Vol. I. Phase II: Technical Progress Report, June 1, 1978–March 31, 1979,* DOE/CS/3159073, March 1979.

R. A. English, *Development of a High-Temperature Solar-Powered Water Chiller. Vol. I. Phase II: Technical Progress Report, Apr. 1, 1979–Sept. 30, 1979,* DOE/CS/31590-T2, November 1979.

R. A. English, "Development of a High-Temperature Solar-Powered Water Chiller," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26, 1980,* CONF-800340, March 1980.

R. A. English, *Development of a High-Temperature Solar-Powered Water Chiller. Phase III. Technical Progress Report, Oct. 1, 1979–July 31, 1981,* DOE/CS/31590, February 1982.

R. A. English, "Development of a High-Temperature Solar-Powered Water Chiller," *Proc. DOE Heat Pump Contractors Program Integration Meeting, June 2, 1981,* CONF-810672, March 1982.

6.1.5 Demonstration of Solar System Turbine Engine for Heating and Cooling

Principal Investigator: J. Martin
Organization: Energy Technology, Inc.
4914 East 154 Street
Cleveland, OH 44128
Telephone: (216) 587-0555

Contract Agency: Department of Energy, San Francisco
Contract Numbers: (phase 1) DE-AC03-77CS34543
(phase 2) DE-AC03-80CS30214
Contract Period: Sept. 1, 1977, through Nov. 31, 1980
Funding: $91,000
Source: DOE **Level:** 100%

Project Objectives:

To design, fabricate, and test actual heat source solar Rankine turbine engine for application to commercial air conditioning systems: phase 1—to perform the basic engineering design and analysis studies; phase 2—to demonstrate system performance (additional phase programs were planned but canceled due to lack of funds).

Project Description:

The solar cooling system consisted of three major subsystems: heat source, Rankine engine, and a conventional vapor compression loop. The Rankine engine was designed to supplement the low temperature solar input with a high-temperature source from a concentrating collector and a combustion heater. This permitted a large reduction in solar collector size, therefore reducing capital cost. The working fluid for the Rankine engine was steam.

The test turbine was designed to produce 31 hp at a design speed of 75,000 rpm to drive a solar cooling system to a nominal 30-ton capacity. A solar collector requirement of 55 ft^2 (5.1 m^2) per ton of cooling was projected, if 20% of the annual energy supplied was at 1000°F (538°C). The initial turbine design point efficiency estimate was 78%.

Tests were conducted at the Energy Technology, Inc., Steam Turbine Test Facility. A natural-gas-fired steam generator was used to simulate the solar collector thermal output, and the refrigerant compressor load on the turbine was simulated with a direct-driven water pump.

The turbine was tested up to 60,000 rpm at a power output of 24 hp. An efficiency of 68% was measured at this condition. Because of limitations in contract funding, the testing was discontinued with the rotating unit in good condition. Extrapolation of the measured data to the design conditions indicated that, at the design speed of 75,000 rpm, a power output of 35 hp and an efficiency of at least 75% would have been reached.

Publications:

Energy Technology, Inc., *Design and Demonstration Tests of a Steam Turbine For Solar Cooling. Final Report, Sept. 19, 1977–Nov. 31, 1980,* DOE/CS/30214-T1, 1980.

6.1.6 Chiller Driven by a Solar-Steam-Powered Rankine Engine

Principal Investigators: N. Lior
H. Yeh
Organization: Dept. of Mechanical Engineering
University of Pennsylvania
111 Towne, Building D3
Philadelphia, PA 19104
Telephone: (215) 243-4803

Contract Agency: Department of Energy, San Francisco
Contract Number: DE-AC03-78ET20110
Contract Period: November 1977 through October 1980
Funding: $678,000
Source: DOE **Level:** 100%

Project Objectives:

To design and develop a 20-ton superheated steam Rankine chiller.

Project Description:

System features include a solar collection loop to heat to 260°F (127°C); a gas-fired boiler to further superheat to 1100°F (593°C); and a five-stage, 15,000-rpm radial outflow steam turbine and rotary expander design. The stored water was flashed to steam.

Design of the turbine unit and test loop and fabrication of the two units was completed. Performance maps of the turbine were measured using the steam power loop.

Publications:

R. P. Kroon et al., *Design of a 30-hp Solar Steam-Powered Turbine, Topical Report,* DOE/ET/20110-3, May 1980.

N. Lior and H. Yeh, *Chiller Driven By a Solar-Steam-Powered Rankine Engine (CSSPRE), Technical Status Report, Oct. 1, 1980–Feb. 28, 1981,* DOE/ET/20110-T1, 1981.

N. Lior et al., "Energy Analysis of Solar Rankine Power Cycle Used For Cooling," *Proc. American Solar Energy Society Meeting, June 1, 1983,* CONF-830622, SAN-20110-9, 1983.

S. Subbiah, *Test Facility for the Solar-Powered/Fuel-Assisted Hybrid Rankine Cycle (SSPRE), Phase III Report,* DOE/ET/20110-11, May 1983.

N. Lior et al., *Analysis of the Solar Powered/Fuel-Assisted Rankine Cycle Cooling System, Phase I, Revision,* DOE/ET/20110-5-REV, April 1985.

6.1.7 Development of Advanced Rankine/Rankine Solar Heating and Cooling Systems

Principal Investigator: R. Nelson
Organization: AiResearch Manufacturing Company of California
2525 West 190 Street
Torrance, CA 90509
Telephone: (213) 321-4372

Contract Agency: National Aeronautics and Space Administration
Contract Number: NAS8-32091
Contract Period: 1975 through 1980
Funding: $5,000,000
Source: DOE **Level:** 100%

Project Objectives:

To develop and demonstrate three sizes of integrated solar heating and cooling systems that would be commercially attractive to the residential/commercial market.

Project Description:

Three different capacity systems were built and tested in the laboratory. System sizes (based on maximum cooling capacity) were 3 tons, 25 tons and 75 tons. The systems were designed to operate either with a flat plate solar collector or with 60-H power driving an electric motor hermetically sealed within the system. The refrigerant, R11, was used in both loops of the system.

The project was terminated in 1980 before field testing was done because of lack of funding.

Publications:

AiResearch Manufacturing Company, *Prototype Solar Heating and Cooling Systems—Progress Report, July 1976–December 1977,* NASA-CR-150570, March 1978.

AiResearch Manufacturing Company, *Prototype Solar Heating and Cooling Systems, Monthly Progress Reports, 1 Jan. 1978–31 Mar. 1978,* NASA-CR-32091, April 1978.

AiResearch Manufacturing Company, *Preliminary Design Package For Solar Heating and Cooling Systems,* NASA-CR-150674, AiResearch-76-13448, May 1978.

AiResearch Manufacturing Company, *Preliminary Design Activities for Solar Heating and Cooling Systems, Status Report, 12 July–1 Sept. 1976,* NASA-CR-150673, AiResearch-76-12994, May 1978.

AiResearch Manufacturing Company, *Prototype Solar Heating and Cooling Systems, Monthly Progress Reports, 1 April–30 June 1978,* NASA-CR-150829, July 1978.

AiResearch Manufacturing Company, *Prototype Solar Heating and Cooling Systems, Monthly Progress Reports,* NASA-CR-150830, October 1978.

AiResearch Manufacturing Company, *Prototype Solar Heating and Cooling Systems, Monthly Progress Reports, 1 Nov. 1978–28 Feb. 1979,* NASA-CR-161204, April 1979.

6.1.8 Testing of Residential Solar Chillers

Principal Investigator: Paul Auh
Organization: Brookhaven National Laboratory
Building 701
Upton, NY 11973
Telephone: (516) 282-7726

Contract Agency: Department of Energy
Contract Number: DE-AC02-76CH00016
Contract Period: October 1978 through September 1979
Funding: $50,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the performance of advanced cooling devices under various realistic operating conditions through the use of hardware simulators.

Project Description:

Hardware simulators were developed for tests of solar cooling and heating subsystems and systems. The simulator was capable of performing tests at steady state, transient, dynamic, and part or full load conditions.

Publications:

P. Auh, *Development of Hardware Simulators for Tests of Solar Cooling/Heating Subsystems and Systems: Phase I. Residential Subsystem Hardware Simulator and Steady State Simulation*, BNL 51120, September 1979.

P. Auh, *Development of Hardware Simulators for Tests of Solar Cooling/Heating Subsystems and Systems: Phase II. Unsteady State Hardware Simulation of Residential Absorption Chiller*, BNL 51121, September 1979.

6.1.9 Development of Rankine Cycle Solar Driven Heat Pump Systems

Principal Investigator: J. C. Graf
Organization: General Electric Company
P.O. Box 8661
Philadelphia, PA 19101
Telephone: (215) 962-5565

Contract Agency: National Aeronautics and Space Administration, Huntsville
Contract Number: NAS8-32092
Contract Period: May 1, 1976, through July 31, 1979
Funding: $8,591,800
Source: DOE **Level:** 85%
GE 15%

Project Objectives:

To design and construct solar heating and cooling systems for the residential/commercial markets; to install, monitor, and deliver prototype systems.

Project Description:

This design concept was configured with two separate hermetically sealed loops: a Rankine driven loop and a conventional heat pump loop. The working fluid for the solar-driven Rankine cooling loop was FC88, which was circulated via a feed pump through a vapor generator into the expander. The vapor from the expander was condensed in an air-side condenser. Energy for the vapor generator was supplied by a solar-supplied thermal storage loop. This loop featured GETC-100 evacuated tubular collectors that operated at temperatures up to 320°F (160°C). The primary solar collector loop used a 35% mixture of ethylene glycol and water circulated by a pump through a heat exchanger that transferred the energy to a thermal storage loop.

A residential (3-ton) unit and two commercial (10-ton) units were fabricated and tested. Test results for the 3-ton unit indicated cooling performance to be below those goals, with typical values of 31,000-Btu/h (9.1-kW) cooling capacity and a seasonal operating coefficient of performance (COP) of 0.59 due primarily to lower than design goal expander efficiency. Tests with the 10-ton units, which were slightly different in design and featured an improved expander design, agreed favorably with and in some instances were better than design goals.

Based on operating experience and additional studies, General Electric believes that significant improvements in operating COP are possible with projected values of 0.9 as compared with test values of about 0.7 for the 10-ton units. Market studies indicated that moderate penetration is possible in the late 1980s.

Publications:

General Electric Company, *Solar Heating and Cooling Systems Design And Development. Status Summary through December 1977,* N-78-28613, April 1978.

6.2 Chemical and Absorption Systems

6.2.1 Development of Solar-Driven Absorption Air Conditioners

Principal Investigators: Michael A. Wahlig
Joseph Rasson
Organization: Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
Telephone: (415) 486-5787

Contract Agency: Department of Energy
Contract Number: DE-AC03-76SF00098
Contract Period: October 1976 through September 1985
Funding: Part of $17,720,000
Source: DOE **Level:** 100%

Project Objectives:

To develop solar-driven absorption-cycle refrigeration systems that achieve significantly higher seasonal conversion efficiencies than is possible using other cooling approaches.

Project Description:

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

Initially, a conventional gas-fired ammonia–water absorption chiller was partially reconstructed for solar-powered operation. It demonstrated the capability to predict the performance of single-effect absorption chillers accurately under operating conditions appropriate for solar-powered operation. Following this, a single-effect ammonia–water absorption chiller was designed, fabricated, and tested successfully. It incorporated tube-in-tube heat exchangers, an internally powered solution pump for reduced parasitic power use, and a rectification path for the hot generated vapor that increased the chiller coefficient of performance (COP). This chiller technology served as the basis for subsequent advanced-cycle designs.

Preliminary designs were conceived for a series of advanced-cycle chillers based on the regenerative absorption cycle concept. The first of these, a double-effect regenerative cycle (2R) chiller has been designed, fabricated, and tested successfully. By addition of a unique second stage to a conventional single-effect chiller, the 2R chiller efficiency increases continuously as a function of the inlet temperature from the solar collectors, reaching a COP of about 1.2 (in cooling mode) at 140°C inlet temperature.

The next advanced-cycle chiller, a single-effect regenerative absorption cycle (1R) chiller, is in the design phase. The 1R chiller will have fewer heat exchangers and less heat-exchanger area than the 2R chiller, yet it should achieve higher efficiency, namely, a COP of 1.5 at 140°C inlet temperature.

Publications:

K. Dao, M. Simmons, R. Wolgast, and M. A. Wahlig, *Performance of an Experimental Solar-Driven Absorption Air Conditioner*, LBL 5911, January 1977.

K. Dao, *A New Absorption Cycle: The Single-Effect Regenerative Absorption Refrigeration Cycle*, LBL 6879, February 1978.

K. Dao, *Conceptual Design of an Advanced Absorption Cycle: The Double-Effect Regenerative Absorption Refrigeration Cycle*, LBL 8405, September 1978.

K. Dao, M. A. Wahlig, and J. Rasson, "Development of Solar-Driven Absorption Air Conditioners," *Proc. DOE Active Systems Contractors' Review Meeting, Sept. 9–12, 1981, Washington, D.C.*, LBL-12839, July 1981.

M. L. Warren and M. A. Wahlig, "Cost and Performance Goals for Commercial Active Solar Absorption Cooling Systems," *Proc. ASME Solar Energy Conference, Apr. 26, 1982*, CONF-820410-6, LBL-13050, December 1981.

K. Dao, J. Rasson, and M. A. Wahlig, *Testing Results of an Ammonia–Water Absorption Air-Conditioner Designed for Solar Cooling Applications*, LBL-16929 (Draft), November 1983.

6.2.2 Chemical/Hydrogen Energy Storage System: Chemical Heat Pump Program

Principal Investigator: Allessio Mezzina
Organization: Brookhaven National Laboratory
Upton
Long Island, NY 11973
Telephone: (516) 282-3920

Contract Agency: Department of Energy
Contract Number: DE-AC02-76CH0016
Contract Period: 1979–1985
Funding: $1,200,000
Source: DOE **Level:** 100%

Subcontractors: EIC Laboratories, Inc., Newton, Massachusetts
TRW, Inc., McLean, Virginia
Rocket Research Corporation, Redmond, Washington
Southern California Gas Company, Los Angeles, California
Solar Turbines, Inc., San Diego, California

Project Objectives:

To provide technical management and support to the Department of Energy (DOE) Chemical Heat Pump Program.

Project Description:

A brief overview of the Chemical Heat Pump Program is presented as a forerunner to more detailed project and systems descriptions that will follow. Program background, rationale, technology description, and research and development needs are addressed. Chemical heat pumps (CHPs) comprise reversible reactions that can be driven by low-grade heat. Thermal energy is absorbed in one direction and liberated in the reverse direction, thus serving as a basis for system designs applicable to space conditioning or process heat management and offering the capability for high-density energy storage as an integral part of the system.

This program provides technical management and support to the DOE Chemical Heat Pump Program. Projects included: (1) design and fabrication of a 150,000 Btu/h sulfuric acid–water CHP at Rocket Research Corporation; (2) design and fabrication at EIC Laboratories, Inc., of a 10,000 Btu/h calcium chloride–methanol CHP engineering development unit; and (3) paired metal hydrides at Southern California Gas Company/Solar Turbines, Inc., emphasizing fabrication and test of heat–mass flow enhancement designs of metal hydride components. Sulfuric acid–water CHP technology advanced to the point of technology transfer via licensing arrangement with Mitsubishi, Japan. Markets were identified for temperature amplification systems.

Publications:

EIC Laboratories, Inc., *Methanol-Based Heat Pump for Solar Heating, Cooling, and Storage*, BNL 515000, March 1981.

TRW, Inc. *Chemical Heat Pump Cost Effectiveness Evaluation—Final Report*, BNL 51484, May 1981.

Rocket Research Corporation, *Sulfuric Acid Chemical Heat Pump Program, March 1982 through November 1982—Final Report*, BNL 51763, March 1984.

Southern California Gas Company and Solar Turbines, Inc. *Heat/Mass Flow Enhancement Design for a Metal Hydride Assembly—Final Report*, BNL 51864, February 1985.

Patents:

Rocket Research Corporation has been granted patent rights to the sulfuric acid–water CHP developments.

Southern California Gas/Solar Turbines, Inc., were granted background patent waivers relevant to metal hydride selection for paired hydride systems.

6.2.3 Technical Support for Rankine and Absorption Solar Cooling Systems Program

Principal Investigator: Michael A. Wahlig
Organization: Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
Telephone: (415) 486-5787

Contract Agency: Department of Energy
Contract Number: DE-AC03-76SF00098
Contract Period: October 1976 through September 1984
Funding: $1,372,000
Source: DOE **Level:** 100%

Project Objectives:

To provide technical support to the Department of Energy (DOE) Headquarters and DOE San Francisco Active Solar Cooling Development Program.

Project Description:

Lawrence Berkeley Laboratory performed technical support activities for DOE Headquarters and DOE San Francisco in the areas of solar absorption and Rankine cooling, including technical monitoring of contracts, proposal reviews, program planning, and coordination with other organizations.

Publications:

M. A. Wahlig, A. Heitz, and B. Boyce, "Overview—Absorption/Rankine Solar Cooling Program," *Proc. DOE Active Solar Heating and Cooling Contractors' Review Meeting, Incline Village, Nevada, March 26–28, 1980*; LBL-10770, March 1980.

M. A. Wahlig, M. Warren, and R. Glas, "Technical Support of the Active Solar Rankine and Absorption Cooling Program," *Proc. DOE Active Systems Contractors' Review Meeting, September 9–12, 1981, Washington, D.C.*, LBL-12914, June 1981.

M. L. Warren and M. A. Wahlig, *Cost and Performance Goal Methodology for Active Solar Cooling Systems*, LBL-12753, February 1982.

M. A. Wahlig, A. Heitz et al., "Overview of Active Solar Absorption/Rankine Cooling Program," *Proc. DOE Active Systems Contractors' Review Meeting, June 2, 1981*, CONF-810672, LBL-13054-R, March 1982.

M. A. Wahlig et al., "Active Solar Cooling," *Energy and Environment Division, Annual Report, FY 1981*, LBL-13500, September 1982.

E. J. Cairns and M. A. Wahlig, *Solar Energy Program, FY 1982 Annual Report*, LBL-15296, March 1983.

J. Goldsmith et al., *Overview Paper for the Topical Review Meeting of Solar Cooling Technologies*, DOE/CS/30204-T2, July 1983.

6.2.4 Solar Cooling Studies and Systems Analysis

Principal Investigators: Dave K. Anand
Redfield W. Allen
Organization: University of Maryland
College Park, MD 20742
Telephone: (301) 454-4994

Contract Agency: Department of Energy
Contract Number: DE-AC03-79CS-30204
Contract Period: July 1979 through September 1983
Funding: $219,000
Source: DOE **Level:** 100%

Project Objectives:

To develop simulation models and computer programs that optimize studies and parametric analyses of cooling machines, cooling system performance, and stochastic weather data; to provide technical support to DOE; to conduct specialized research in active solar cooling development.

Project Description:

The past and current work in component modeling and simulation was integrated for both Rankine and absorption solar technology areas. A simplified cooling design technique was developed. A methodology was formulated to make fair comparative measurements of current projects that develop solar absorption chillers and systems.

Assistance was provided in reviewing proposals and reports. An overall systems analysis and testing plan was developed for the System Development Branch, Active Buildings Division research and development activities. System simulation studies were provided in the photovoltaic-thermal area.

Publications:

D. K. Anand, "Stochastic Predictions of Solar Cooling System Performance," *J. Solar Energy Eng.* **102**(1), February 1980.

D. K. Anand and R. W. Allen, "Solar Cooling Studies and Systems Analysis," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26, 1980*, CONF-800340, 1980.

S. R. Venkateswaran and D. K. Anand, "Design Procedure for Combined Photovoltaic/Thermal Solar Collector—Heat Pump Systems," *Proc. Annual Meeting of the American Section of the International Solar Energy Society, June 2, 1980*, CONF-800604-P2, 1980.

D. K. Anand et al., "Transient Simulation of Absorption Machines," *Proc. 3rd Annual Systems Simulation, Economic Analysis/Solar Heating and Cooling Operational Results Conference, Apr. 27, 1981*, CONF-810405, 1981.

D. K. Anand, "Simplified Cooling Design Charts," *Proc. Annual Meeting of the American Section of the International Solar Energy Society, May 26, 1981*, CONF-810509, 1981.

J. Goldsmith et al., *Overview Papers for the Topical Review Meeting of Solar Cooling Technologies*, DOE/CS/30204-T2, July 1983.

E. O. Bazques and D. K. Anand, "Control Aspects of Photovoltaic/Thermal Energy Systems," *Proc. IECEC, Aug. 19, 1984*, CONF-840804, August 1984.

6.2.5 Test and Development of Air-Cooled Absorption Chillers for Solar-Cooling Applications

Principal Investigator: Wendell J. Biermann
Organization: Carrier Corporation, ESD
Carrier Tower
P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 424-4626

Contract Agency: Solar Energy Research Institute
Contract Number: DE-FC02-80ET20643
Contract Period: October 1979 through November 1982
Funding: $530,000
Source: DOE **Level:** 100%

Project Objectives:

To design and operate air-cooled chillers from single-family residential sizes up to the commercial rooftop size range.

Project Description:

A rooftop solar package was installed at the Siegler-Fagen distribution center in Phoenix, Arizona, in the fall of 1981. Field measurements of performance were obtained.

Publications:

W. J. Biermann, *53-kW Water-Cooled Solar Cooling Package for BDP Distribution Center, Phoenix, Arizona, Final Report*, DOE/ET/20643-T2, December 1982.

W. J. Biermann, *35-kW Water-Cooled Solar Cooling Package for Siegler-Fagen Parts and Supply Building Computer Room, Phoenix, Arizona, Final Report*, DOE/ET/20643-T1, December 1982.

6.2.6 Air-Cooled Absorption Chillers for Solar Cooling Applications

Principal Investigator: Wendell J. Biermann
Organization: Carrier Corporation, ESD
Carrier Tower
P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 424-4626

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS31587
Contract Period: September 1977 through October 1982
Funding: $1,232,880
Source: DOE **Level:** 100%

Project Objectives:

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

Project Description:

A 3-ton (10-kW) unit was developed using chemical composition for an air-cooled absorption chiller. This unit, designated as prototype I, had a coefficient of performance of 0.76.

Possible absorbent-refrigerant combinations were surveyed, and the most promising candidate system was selected. Numerical measurements were made of vapor pressures, relative enthalpies, specific heat capacities, viscosities, thermal conductivities, and heat transfer coefficients. A 3-ton (10-kW) air-cooled absorption chiller was designed and constructed. Prototype II used a shell and tube evaporator, had a provision for "winterizing," and reduced fan power. Two prototype II chillers were supplied to Arizona State University and Colorado State University for field testing. A 20-ton (70-kW) air-cooled absorption chiller based on prototype II technology was designed and constructed. A breadboard unit was constructed and operated under test conditions. It produced 2.3 tons (8 kW) of cooling at the design point of 230°F (110°C) hot water entering the generator, 95°F (35°C) ambient air, and 45°F (7.2°C) chilled water to the load. This unit proved the basic design concepts and refined some of the heat transfer coefficient data.

Publications:

W. J. Biermann, *Candidate Chemical Systems for an Air-Cooled Solar-Powered Absorption Air Conditioner Design*, Parts 1–3, DOE/CS/31587-T1, June 1978.

W. J. Biermann, "Development of a Single-Family Absorption Chiller for Use in a Solar Heating and Cooling System," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, 1980.

W. J. Biermann, *Properties of the Carrol Systems and a Machine Design for Solar-Powered, Air-Cooled, Absorption Space Cooling, Phase I and Phase II, Final Report*, DOE/CS/31587-T2, May 1981.

W. J. Biermann, and R. C. Reimann, "Air-Cooled Absorption Chillers for Solar Cooling Applications," *Proc. DOE Heat Pump Contractors' Program Integration Meeting, June 2, 1981*, CONF-810672, March 1982.

R. C. Reimann and W. J. Biermann, *Development of a Single-Family Absorption Chiller for Use in a Solar Heating and Cooling System*, Phase III, DOE/CS.31587-T3, Vol. 2, October 1984.

Patents:

U.S. 4,405,340: R. C. Reimann, Dillusion Cycle Control for an Absorption Refrigeration System.

U.S. 4,467,623: R. C. Reimann, Counterflow Absorber for an Absorption Refrigeration System, Aug. 28, 1984.

U.S. 4,484,456: R. C. Reimann, Triple Loop Heat Exchanger for an Absorption Refrigeration System, Nov. 27, 1984.

U.S. 4,485,638: R. C. Reimann, Heat Exchanger Bypass System for an Absorption Refrigeration System, Dec. 4, 1984.

6.2.7 Analysis of Active Solar Absorption and Rankine Cooling System for Residential and Commercial Buildings

Principal Investigator: Jeffrey H. Morehouse
Organization: Science Applicatons, Inc.
1710 Goodridge Drive
McLean, VA 22102
Telephone: (703) 827-4915

Contract Agency: Department of Energy, San Francisco
Contract Number: DE-AC03-81SF11573
(Old Contract Number: XB-0-9145-1)
Contract Period: September 1980 through September 1982
Funding: $242,000
Source: DOE **Level:** 100%

Project Objectives:

To analyze the performance and economics of state-of-the art absorption and Rankine systems on a comparative basis with conventional systems; to modify computer programs to model the system operation of absorption and Rankine solar cooling systems effectively, using state-of-the-art chillers, storage, collectors, and control strategies.

Project Description:

Science Applications, Inc., had performed a preliminary analysis comparing absorption and Rankine systems previously. This study was an extension that analyzed residential and commercial sizes of both technologies on a performance and cost basis against competing conventional systems to assess their status and help formulate program goals. As part of this task, updated cooling system simulation models were developed and baseline thermodynamic studies were performed.

A TRNSYS compatable computer model was developed to simulate seasonal operation of active solar cooling systems. Specific component performance data were used to input the program. Results of this study were used in the active program research requirement task.

Publications:

P. J. Hughes and J. H. Morehouse, "Improved Heat Pump Model for TRNSYS," *Proc. International Solar Energy Society Meeting, May 28, 1979*, CONF-790541, 1978.

N. M. White et al., "Thermal and Economic Comparisons for Sensible and Latent Storage in Residential Systems," *Proc. Annual Meeting of the American Section of the International Solar Energy Society, May 26, 1981*, CONF-810509, 1981.

J. H. Morehouse and W. B. Scholten, "Alternate Applications for Solar Cooling Machines," *Proc. Intersociety Energy Conversion Engineering Conference, Aug. 9, 1981*, CONF-810812, 1981.

M. K. Choi et al., "Status of Several Solar Cooling Systems with Respect to Cost/Performance Goals," *Proc. Annual Meeting of the American Section of the International Solar Energy Society, June 1, 1982*, Vol. 5, Pt. 1, CONF-820629, 1982.

W. B. Scholten and J. H. Morehouse, *Active Program Research Requirements (APRR), Final Report, Volume 1*, DOE/SF/11573-T1, October 1983.

6.2.8 Determination Properties of Fluids for Solar Cooling Applications

Principal Investigator: R. Thomas Podoll
Organization: SRI International
33 Ravenwood Avenue
Menlo Park, CA 94025
Telephone: (415) 859-5834

Contract Agency: Department of Energy
Contract Number: DE-AC03-80CS30221
Contract Period: September 1980 through January 1982
Funding: $121,857
Source: DOE **Level:** 100%

Project Objectives:

To determine pressure-volume-temperature (PVT) data and calorimetric data for organic refrigerant and absorbent fluids and their binary mixtures that would be accurate enough to be used for the design of solar-powered cooling engines.

Project Description:

Calorimetric and PVT data were determined for a number of organic refrigerant and absorbent fluids and their binary mixtures. The fluids tested included:

- Refrigerants—ammonia, methylamine, ethylamine, dichlorofluoromethane, difluorochloramethane,
- Absorbents—ethylene glycol, 1,4-butanediol, diethylene glycol, dimethyl ether, n,n-dimethylacetamide, n,n-dimethyldecanamide

Publications:

R. T. Podoll, *Determination of Properties of Fluids for Solar-Cooling Applications, Literature Survey*, SRI-PYU-2221, February 1981.

R. T. Podoll et al., *Determination of Properties of Fluids for Solar-Cooling Applications, Final Report*, DOE/CS/30221-T2, August 1982.

6.2.9 Water-Cooled Absorption Chillers for Solar Cooling Applications

Principal Investigator: Harry Hale
(Previous Investigator: W. J. Biermann)
Organization: Energy Systems Division
Carrier Corporation
Carrier Tower
P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 432-6655

Contract Agencies: Bonneville Power Administration; National Aeronautics and Space Administration
Contract Numbers: BPA: 14-03-6280N/DE-AC79-79BP10467
NASA: DEN 8-000007/DEN 8-000015
Contract Period: 1977 through 1982
Funding: $1,718,177
Source: BPA **Level:** 71%
NASA 29%

Project Objectives:

To develop a broad line of absorption chillers designed to operate with hot fluids at as low a temperature as practical while rejecting heat to a stream of water; to develop a packaging concept for solar application in which controls, pumps, valves, and other system components could be factory assembled into a unitary solar module.

Project Description:

A design point was selected on the basis of what might reasonably be expected from a system using good-quality flat-plate solar collectors. The following conditions were chosen.

Rating conditions:
Hot water 180°F (82°C) (3.33 gpm/ton)
Cooling water 85°F (29°C) (7.00 gpm/ton)
Chilled water 45°F (7.2°C) (2.40 gpm/ton)
Size range:
15–150 tons (50–500 kW); smaller units were contained in preassembled solar packages

A low-temperature absorption chiller was designed, laboratory tested, and field tested. It was suitable for solar, geothermal, or energy-recovery applications. The manufacturability of the low-temperature chiller was demonstrated on a commercial production line. The low-temperature chiller design included 15 tons, 75 tons, and 130 tons. Packaging of the 15-ton chiller into a simple unitary solar package was completed. The 15-ton chiller was installed and monitored for one year at Ross Control House, Vancouver, Washington, with a steam auxiliary at Tyler, Texas; with an electric-driven heat pump as auxiliary at Big Eddy control house, Dalles, Oregon; and with improvements and tracking concentration through collectors at the BDP Distribution Center, Phoenix, Arizona. The 130-ton chiller, a scale-up of the 15-ton chiller, was installed in the Frenchman's Reef Holiday Inn, American Virgin Islands. Two 75-ton chillers based on the same design as the 130-ton chiller were designed, constructed, and tested at Houston, Texas, and Las Vegas, Nevada.

Publications:

None provided.

6.2.10 Unitary Solar Heating/Cooling System Package Development

Principal Investigator: Richard H. Merrick
Organization: Preway
P.O. Box 534
Evansville, IN 47704
Telephone: (812) 424-3331

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS34593
Contract Period: June 1977 through December 1981
Funding: $1,304,488
Source: DOE **Level:** 100%

Project Objectives:

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

Project Description:

Commercialization of a 3-ton solar package was achieved. Operation led to system improvements and cost reduction of this product.

A 25-ton unitized package was developed and successfully tested. An evaporatively cooled absorption chiller was developed, and its reliability and manufacturability was established. Elimination of the separate cooling tower reduces first cost, installation cost, and parasitic power.

The gas-fired auxiliary mode of operation was added to the evaporatively cooled chiller to create a double effect, dual solar/gas unit.

Publications:

R. H. Merrick, *Unitary Solar Heating/Cooling System Package Development. Progress Report, June 1, 1977—Jan. 31, 1978,* COO/4593-1, 1978.

R. H. Merrick, "Development of Unitary Solar Heating/Cooling Packages," *Proc. 3rd Workshop on the Use of Solar Energy for the Cooling of Buildings, Feb. 15, 1978,* CONF-780299, October 1978.

R. H. Merrick, "Engineering Design Construction and Testing of a Salt-Water Absorption Unit Optimized for Use with A Solar Collector Heat Source," *Proc. 3rd Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24, 1978,* CONF-780983, March 1979.

R. H. Merrick, "Unitary Solar Heating/Cooling System Package Development," *Proc. 3rd Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24, 1978,* CONF-780983, March 1979.

R. H. Merrick, "Unitary Solar Heating/Cooling System Package Development," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Meeting, Mar. 26, 1980,* CONF-800340, 1980.

R. H. Merrick, "A Direct, Evaporatively Cooled, Three-Ton Lithium Bromide–Water Absorption Chiller For Solar Application," *ASHRAE Trans.* **88**, January 1982.

R. H. Merrick, *Evaporatively Cooled Chiller for Solar Air Conditioning Systems Design and Field Test,* DOE/CS/34593-T15, June 1984.

6.2.11 Open-Cycle Chemical Heat Pump and Energy Storage Systems

Principal Investigator: Harry I. Robison
Organization: Coastal Carolina College (CCC)
Univ. of South Carolina (USC)
Energy Laboratory
Conway, SC 29526
Telephone: (803) 347-3161

Contract Agency: Department of Energy
Contract Number: EG-77-C-01-4042
Contract Period: July 1980 through September 1981
Funding: $98,488
Source: DOE **Level:** 100%

Project Objectives:

To speed the development of a marketable solar-powered chemical heat pump that was a technically viable, environmentally acceptable, and economically competitive alternative to conventional space heating and cooling methods.

Project Description:

Two types of solar regeneration equipment were tested: trickle collector and plastic solar collectors with off-the-shelf regenerator. The system used water as refrigerant and had no mechanical compressor, no vacuum or pressure system, no condenser, no gas-fired generator, and no large insulated storage. It could be powered by solar heat, waste heat, or off-peak electricity. Testing was completed on the trickle-collector and the plastic collectors. The contractor built a 2800 ft^2 (260-m^2) house to test system operation. With a solar fraction of 1.0, the 24-h coefficient of performance was 0.6 (refrigeration effect divided by the total incident solar energy). The system energy efficiency ratio was 9.8.

The CCC/USC system was designed to test components, compare various operating modes, compare different desiccants and combinations of desiccants, compare rooftop and packed-column concentrators, obtain operating experience with a desiccant heat pump (DHP), and verify the authenticity of the Collier and Gandhidasan desiccant-reconcentration models. Successful operation of the machine did show that a heating cycle using the heat of sorption of a desiccant solution could be added to a desiccant cooling system, thus creating an open-cycle liquid desiccant heat pump.

A second-generation liquid desiccant energy storage/cooling system was constructed. The new hybrid system, constructed by Coastal Energy Laboratory in cooperation with Midland-Ross Corporation, discharged heat to the outside air. Waste heat from a 5-ton vapor compressor was used to concentrate the salt brine during off-peak hours. The unique energy storage capability of the liquid desiccant allowed the energy recovered to be stored in a small tank in the form of chemical energy for later use. During the period of peak electrical use in the afternoon, the DHP assumed the dehumidification/cooling load, and the vapor compressor was shut down.

The development by Midland-Ross Corporation of an all-plastic cross-flow heat exchanger that acts as an absorber, heat exchanger, and regenerative evaportive cooler made it possible to design and build the new unit.

Publications:

H. I. Robison, "Liquid Sorbent Solar Air Conditioner," *Proc. Alternative Energy Sources Symposium. Dec. 5, 1977*, CONF-771203, 1977.

H. I. Robison and S. H. Houston, "Passive Solar Heat Pump," *Proc. 4th National Passive Solar Conference, Kansas City, Mo., 1979.*

H. I. Robison and S. H. Houston, "Thermochemical Energy Storage for Heating and Cooling," *Proc. Solar Energy Storage Options, Mar. 18, 1979*, CONF-790328-P2, 1979.

H. I. Robison and S. H. Houston, "Solar-Powered Saline Sorbent-Solution Heat Pump/Storage System," *Proc. Alternative Energy Sources II, Dec. 10, 1979*, CONF-791204.

P. Gandhidasan et al., "Analysis and Simulation of Forced-Flow Solar Collector/Regenerator," *Proc. American Section of International Solar Energy Society*, 1981.

H. I. Robison, *Open-Cycle Chemical Heat Pump and Energy Storage System*, Subcontract ZE-O-9185-1, CCC/USC Energy Laboratory, Conway, S.C., 1982.

H. I. Robison and H. Harris, "Year Round Operational Test Results of a Chemical Heat Pump Powered by Waste Heat, Off-Peak Electricity, or Solar Energy," *Energex '82—Aug. 23, 1982*, CONF-8208151, Vol. 1, 1982.

H. I. Robison, "Operational Experience with a Liquid Desiccant Heating and Cooling System," *Proc. 18th IECEC, Aug. 21, 1983*, CONF-830812, August 1983.

H. I. Robison, *Open-Cycle Chemical Heat Pump and Energy Storage System, Final Report*, CCC/USC Energy Laboratory, Conway, S.C., 1983.

H. I. Robison, W. Griffiths, and O. Arnas, "Liquid Desiccant/Vapor Compressor Hybrid Air Conditioner and Energy Storage System for Load Management," *Solar Energy in the Southeast*, North Carolina Solar Energy Association, Raleigh, N.C., 1984.

Patents:

U.S. 4,164,125: W. Griffiths, Solar Energy Assisted Air-Conditioning Apparatus and Method, Aug. 14, 1979.

U.S. 4,287,721: H. I. Robison, Chemical Heat Pump and Method, Sept. 8, 1981.

6.2.12 Open-Cycle Lithium Chloride Solar Cooling

Principal Investigators: George O. G. Lof
Terry Lenz
Organization: Solar Energy Applications Lab
Solar House I
Colorado State University
Fort Collins, CO 80522
Telephone: (303) 491-8632

Contract Agency: Department of Energy
Contract Number: DE-AC03-79CS30206
Contract Period: September 1979 through May 1981
Funding: $31,993
Source: DOE **Level:** 100%

Project Objectives:

To determine evaporation rates and the coefficients of heat transfer and mass transfer experimentally in a packed column designed for use in an open-cycle lithium chloride absorption cooling system operated by solar-heated air.

Project Description:

The project involved investigation of evaporation rates and coefficients of heat transfer and mass transfer in a packed column through which lithium chloride solution trickles and is reconcentrated by solar-heated air. Data that were acquired confirmed predictions of performance.

Further work on this cooling system was initiated in September 1981, as Task 6 under a multitask contract DE-AC03-81-CS30569. A budget of $50,000 was allocated to an investigation of vacuum pumping methods and requirements in the lithium chloride–water absorption cooling unit and the design of a complete solar cooling system. This work was completed in February 1982.

Publications:

G. O. G. Lof et al., *Open Cycle Lithium Chloride (Solar) Cooling, Final Report*, DOE/CS/30206-T1, December 1981.

T. Lenz et al., "Residential Cooling with Solar Heated Air and Open-Cycle Lithium Chloride Absorption Chiller," *Proc. Solar World Congress, Aug. 15, 1983*, CONF-830839, 1983.

6.2.13 Multiple-Effect Absorption Cycle Solar Cooling

Principal Investigator: Gary C. Vliet
Organization: The University of Texas at Austin
Center for Energy Studies
Department of Mechanical Engineering
Austin, TX 78712
Telephone: (512) 471-7571

Contract Agency: Department of Energy, San Francisco
Contract Number: DE-AC03-79SF10540
Contract Period: Sept. 1, 1979, through Nov. 30, 1980
Funding: $51,032
Source: DOE **Level:** 100%

Project Objectives:

To develop a dynamic computer model of the water–lithium bromide double-effect absorption cooling cycle, to use the code to assess the effect on performance of variations in the cycle's several design and operating parameters, to assess the cost of double-effect absorption cooling per unit of capacity for varying capacity.

Project Description:

The absorption cycle is one of the alternatives for solar cooling, and the double-effect absorption cycle is a competitor to proposed Rankine cycle solar cooling systems. Although the Rankine cycle has the specific advantage of mechanical/electrical output, the double-effect cycle has been available for several years; however, there has not been significant interest in it for application to solar cooling systems.

This project included the development of a dynamic computer model to simulate the performance of a water–lithium bromide double-effect absorption cooling system. The code was used to investigate the effect on cycle performance of the several design and operational variables for the cycle. Some project cost data on intermediate capacity units were also made.

The method of refrigerant flow control was important in maintaining high performance over a wide range of source temperatures. This capability is particularly important for a solar-driven system, where the source temperatures will vary considerably. The solution pump characteristic was important, particularly at high source temperatures, with one approaching constant displacement preferred. The relative allocation of heat exchanger area to the cycle's seven heat exchangers was very important to cycle performance and cost, since a large portion of the cost of absorption systems was in heat exchange surface.

A secondary objective of the study was to assess the cost of absorption cycle cooling per unit of design capacity. It would appear that there is merit in considering intermediate capacity double-effect systems in the range of 20 to 100 tons. Since the increased capital costs of the double-effect units (over single) are probably considerably less than the incremental collector cost for solar systems or life-cycle fuel costs for conventional systems, it would appear that the double-effect cycle is a viable choice.

Publications:

G. C. Vliet, "Multiple Effect Absorption Cycle Analysis," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, 1980.

M. Nazer et al., "Double Effect Absorption Cooling," *Proc. 1st SOLERAS Workshop, Apr. 1, 1980*, CONF-8004244, MRI/SO2-0601, 1980.

G. C. Vliet, *Water–Lithium Bromide Double-Effect Absorption Cooling Analysis—Final Report*, DOE/SF/10540-T2, December 1980.

M. B. Lawson, "Water–Lithium Bromide Double-Effect Absorption Cooling Cycle Analysis," *ASHRAE Trans.*, Vol. 88, CONF-820112, January 1982.

G. C. Vliet, "Multiple-Effect Absorption Cycle Solar Cooling," *Proc. DOE Heat Pump Contractors Program Integration Meeting, June 2, 1981*, CONF-810672, March 1982.

6.2.14 Analysis of Liquid-Phase Heat Pump System

Principal Investigator: Kirk Collier
Organization: Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Telephone: (303) 231-1761

Contract Agency: Department of Energy
Contract Number: DE-AC02-77CH00178
Contract Period: October 1979 through September 1980
Funding: $25,000
Source: DOE **Level:** 100%

Project Objectives:

To investigate the use of liquid desiccants in heat pump applications.

Project Description:

Overall prospects for the use of open-cycle desiccant and absorption systems appear promising. However, there are unanswered questions pertaining to year-round use of the systems. These involve unknown performance-climate relations and the potential of using the systems for both heating and cooling. The Solar Energy Research Institute explored 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 (where the salt-solution working fluid flows over the collector in direct contact with the atmosphere) was analyzed. If the salt solutions (LiCl and $CaCl_2$) do not freeze or lose water in the winter, the same collectors that 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 were adapted to winter conditions for candidate cities. Results of the simulation determined which operating modes were possible, i.e., as direct heat in absorption heating or as a heat source for a conventional heat pump. In addition, potential problems with freezing and crystallization were assessed.

Publications:

R. Barlow and K. Collier, "Optimizing the Performance of Desiccant Beds for Solar-Regenerated Cooling," *Proc. Annual Conf. of the International Solar Energy Society, May 26, 1981*, CONF-810509-28, SERI/TP-631-1157, March 1981.

6.2.15 Operation and Maintenance of Solar Energy Cooling System

Principal Investigator: J. Frissora
Organization: Sunmaster Corporation
12 Spruce Street
Corning, NY 14830
Telephone: (607) 937-5441

Contract Agency: National Aeronautics and Space Administration
Contract Number: DEN8-000005
Contract Period: January 1979 through September 1980
Funding: $958,000
Source: DOE **Level:** 100%

Project Objectives:

To manage the operational test phase of the large industrial-scale solar energy cooling system installed at the Holiday Inn on Frenchman's Reef, a large resort hotel in the Caribbean.

Project Description:

Sunmaster operated and maintained the solar energy collection system which provided heated water to the 200-ton absorption chiller.

Publications:

None provided.

6.2.16 Thermal Storage for Solar Cooling Using Paired Ammoniated Salt Reactions

Principal Investigators: F. A. Jaeger
E. Fox
Organization: Martin Marietta Aerospace Division
P.O. Box 179
Denver, CO 80201
Telephone: (303) 973-4804

Contract Agency: Department of Energy
Contract Number: DE-AC02-78CS34700
Contract Period: July 1978 through September 1980
Funding: $428,000
Source: DOE **Level:** 100%

Project Objectives:

To design, construct, and test a reversible thermochemical heat and storage system.

Project Description:

The experimental system was similar in operation to an absorption refrigerator except that this unit contained sufficient absorber to be used for thermal storage and operated in the batch mode rather than continuously. The unit consisted of two high-temperature reactors, an ammonia condensor, an ammonia storage tank, an expansion valve, an evaporator, and heat exchangers. Specific tasks of this project were to:

- 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

Publications:

W. R. Haas et al., "Thermochemical Energy Storage and Heat Pump System Using Ammoniated Salts," *Proc. Solar Energy Storage Options Workshop, Mar. 18, 1979*, CONF-790328, March 1979.

F. A. Jaeger and C. A. Hall, "Ammoniated Salt Heat Pump/Thermal Storage System," *Proc. International Seminar on Thermochemical Energy Storage, Stockholm, Jan. 7–9, 1980*, CONF-800133, 1980.

F. A. Jaeger, "Thermal Storage For Solar Cooling Using Paired Ammoniated Salt Reactions," *Proc. Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, Mar. 26, 1980*, CONF-800340, March 1980.

W. R. Haas et al., "Ammoniated Salt Heat Pump," *Proc. Miami International Conf. on Alternative Energy Sources, Dec. 10, 1979*, CONF-791204, 1981.

Final Report, MCR-81-581, September 1981.

6.2.17 Calcium Chloride–Methanol Chemical Heat Pump for Solar Heating and Cooling

Principal Investigator: Peter O. Offenhartz
Organization: EIC Corporation
55 Chapel Street
Newton, MA 02158
Telephone: (617) 965-2710

Contract Agency: Brookhaven National Laboratory
Contract Number: 490105-S
Contract Period: April 1977 through September 1980
Funding: $618,300
Source: DOE **Level:** 100%

Project Objectives:

To design, construct, and field test a solar-activated chemical heat pump for residential heating, cooling, and domestic hot water, incorporating adequate (chemical) storage for overnight heating and late afternoon/early evening cooling.

Project Description:

The research segment of this project focused on determining the thermodynamic and kinetic behavior of the $CaCl_2$-CH_2OH reaction, as well as the extent of corrosion and side reaction. It was determined that practical heat pumping is feasible at an absorber-evaporator temperature difference above 100°F (38°C), making the cycle exceptionally well suited to space heating in central and northern climates and cooling with dry-air heat rejection. A detailed thermodynamic analysis indicates coefficients of performance (COPs) of 0.6 for cooling and 1.6 for heating. The reaction components were strictly noncorossive toward copper and aluminum, and no side reactions occurred. The size of $CaCl_2$ pellets was optimized, and it was determined that the pellets would cycle without chemical or physical degradation.

The hardware development effort focused on the $CaCl_2$ heat exchanger, which was the key element in the design. A one-third scale unit was constructed and tested; the experimental cooling COP is 0.52 (excellent agreement with the theoretical analysis). The original heat exchanger design showed some distortion due to salt expansion and contraction, but this problem was overcome by stiffening the salt-bed container. The conceptual design for a full-scale system was completed, specifications were prepared for all components, and a control system was developed. The next stage of work was the detailed design, construction, and field testing of a solar-activated unit.

Publications:

P. O. Offenhartz, "Method-Based Single Substrate Heat Pump for Solar Thermal Storage," *Proc. Second Annual Thermal Energy Storage Contractors' Information Exchange Meeting, Sept. 29, 1977*, CONF-770955, 1977.

P. O. Offenhartz, "Methanol–Calcium Chloride Chemical Heat Pump for Solar Air Conditioning, Heating, and Storage," *Proc. Solar Energy Storage Options Workshop, Mar. 18, 1979*, CONF-790328, 1979.

P. O. Offenhartz et al., *Methanol-Based Heat Pump for Solar Heating, Cooling, and Storage, Phase II, Final Report*, SAND-78-8182, January 1980.

P. O. Offenhartz et al., "Engineering Prototype Studies on the $CaCl_2$-CH_3OH Chemical Heat Pump for Solar Air Conditioning, Heating, and Storage," *Proc. 15th IECEC, Aug. 18, 1980*, CONF-800806, 1980.

P. O. Offenhartz, "Chemical Heat Pump Based on the Reaction of Calcium Chloride and Methanol for Solar Heating, Cooling, and Storage," *Proc. 5th Annual Thermal Storage Meeting, Oct. 10, 1980*, CONF-801055, March 1981.

6.2.18 Thermal Storage Studies for Solar Heating and Cooling Applications Using Salt Chemical Heat Pumps

Principal Investigator: Peter O. Offenhartz
Organization: EIC Corporation
55 Chapel Street
Newton, MA 02158
Telephone: (617) 965-2710

Contract Agency: Department of Energy
Contract Number: DE-AC02-79CS30248
Contract Period: September 1979 through April 1980
Funding: $26,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the simulated performance of liquid-phase chemical heat pumps in solar heating and cooling applications.

Project Description:

Chemical heat pumps are absorption-cycle thermally activated heat pumps with the inherent capability of chemical storage of thermal energy. Under sponsorship of the U.S. Department of Energy, work was performed on three different cycles: H_2SO_4/H_2O; NH_4NO_3/NH_3; and $CaCl_2/CH_3OH$. The first two were based on liquid–gas reactions, and the last on a solid–gas reaction. This difference required the development of two separate simulation packages. All three chemical heat pumps had to be capable of operating under fairly extreme conditions. Absorber-evaporator temperature differences as great as 130°F (55°C) had to be achievable. This is technically and economically important because it permits (1) forced-air (dry) heat rejection even in desert climates; (2) domestic hot water preheat from the absorber, providing "free" domestic hot water in summer; and (3) 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.

Publications:

P. O. Offenhartz, "TRNSYS Simulation of Chemical Heat Pumps For Solar Heating, Cooling, and Storage," *Proc. Systems Simulation and Economics Analysis Workshop, Jan. 23, 1980*, CONF-800101.

P. O. Offenhartz, *Thermal Storage Studies for Solar Heating and Cooling: Applications Using Chemical Heat Pumps, Final Report*, DOE/CS/30298-T1, April 1981.

6.2.19 Development of New Fluids for Solar Absorption Cooling Applications

Principal Investigator: Robert A. Macriss
Organization: Institute of Gas Technology
4201 West 36th Street
Chicago, IL 60632
Telephone: (312) 890-6444

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS31439
(Old Contract Number: EG-77-C-03-1439)
Contract Period: September 1977 through October 1978
Funding: $97,000
Source: DOE **Level:** 100%

Project Objectives:

To develop new fluids for solar absorption cooling systems.

Project Description:

This was an experimental and analytical project. The three major tasks were to

- Identify, screen, and make preliminary selection of potential candidate fluid systems
- Develop data to evaluate the most promising candidates
- Use the data to project the coefficients of performance of solar absorption cooling cycles employing the new fluids

Over 100 potential refrigerants and over 100 potential absorbents were screened. Among these, 6 groups of refrigerants were selected for further consideration, resulting in about 100 potential refrigerant-absorbent combinations.

Publications:

R. A. Macriss et al., *Analysis of Advanced Conceptual Designs for Single-Family-Size Absorption Chillers*, SAN-1439-8, September 1978.

R. A. Macriss et al., *Analysis of Advanced Conceptual Designs for Single-Family-Size Absorption Chillers—Final Report*, SAN-1439-2, February 1979.

6.2.20 Design of a Solar Air Conditioner Using a Solid-Phase Absorbent

Principal Investigator: Peter O. Offenhartz
Organization: EIC Corporation
55 Chapel Street
Newton, MA 02158
Telephone: (617) 965-2710

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS34537
Contract Period: September 1977 through September 1978
Funding: $160,000
Source: DOE **Level:** 100%

Project Objectives:

To design, construct, and test a solar air conditioner based on solid-phase absorbent.

Project Description:

Solid-phase absorption air conditioning offers two important potential advantages over conventional lithium bromide systems: built-in storage so that an auxiliary thermal storage tank is not required and higher heat rejection temperatures so that dry air heat exchange can replace the cooling tower. To develop a practical air conditioner based on solid-phase absorption, it was first necessary to find a suitable chemical reaction and then to design an appropriate heat exchange system. The absorber was to be a low-cost inorganic salt that provided air conditioning by reacting with water vapor. The thermodynamics and kinetics of the reaction were chosen such that dry-air heat rejection could be accomplished while relatively low solar collector temperatures and a coefficient of performance (COP) above 0.60 were maintained. Sufficient thermal storage was provided in the dehydrated absorber to permit essentially 100% solar operation, without utility backup. The reaction of calcium chloride monohydrate ($CaCl_2/H_2O$) to produce calcium chloride dihydrate was selected for development. No side reactions were found, and the reaction appeared completely reversible. EIC developed a preliminary heat exchanger design that was compact, low in cost, and relatively easy to construct. The reaction of $CaCl_2/H_2O$ appeared to meet design objectives. The projected COP of the air conditioner was 0.70 and could be increased significantly if the heat exchanger weight and thermal capacitance were reduced.

Publications:

P. O. Offenhartz, "Development of Solid-Phase Absorption Air Conditioner with Built-In Storage," *Proc. 3rd Workshop on the Use of Solar Energy for the Cooling of Buildings, Feb. 15, 1978*, CONF-780249, October 1978.

P. O. Offenhartz et al., "Design of a Novel Solar Air Conditioner Using a Solid-Phase Absorber," *Proc. 3rd Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24, 1978*, CONF-780983, DOE/CS/34537-T1, March 1979.

6.2.21 Analysis of Advanced Conceptual Designs for Single-Family-Sized Absorption Chillers

Principal Investigator: Robert Lacey
Organization: Southern Research Institute
2000 Ninth Avenue South
Birmingham, AL 35205
Telephone: (205) 323-6592

Contract Agency: Department of Energy
Contract Number: DE-AC03-77CS31586
Contract Period: September 1977 through August 1978
Funding: $114,000
Source: DOE **Level:** 100%

Project Objectives:

To find means of improving the performance or reducing the cost of a solar-powered absorption chiller in the size range of 3 tons.

Project Description:

An investigation was conducted of new refrigerant/absorbent (R/A) pairs, additives to currently used R/A pairs, and modifications to the cycle. The tasks included:

- Literature search
- Definition of criteria
- Analysis of conceptual designs
- Comparison and selection of promising systems
- Recommendations

Publications:

None provided.

6.2.22 The Operational Envelope of Solar-Powered Absorption Heat Pumps

Principal Investigator: Noam Lior
Organization: University of Pennsylvania
III TB-03
Philadelphia, PA
Telephone: (215) 243-4803

Contract Agency: National Science Foundation (Research Applied to National Needs)
Contract Number: GI 29779
Contract Period: 1972 through 1975
Funding:
Source: Univ. of Penn. **Level:**
NSF-RANN

Project Objectives:

To determine limits of operation, both ideal and realistic, using first- and second-law analysis of absorption heat pumps; to conduct fundamental studies in multistage flash evaporation for possible application with multieffect absorption heat pumps.

Project Description:

Thermodynamic analyses were performed to determine the absorption heat pump–solar collector combination characteristics that result in a saving of collector area by using such a heat pump in lieu of a direct solar heating system. Energy analysis of absorption heat pumps was conducted.

Analysis and experiments in flash evaporation were conducted which showed relevance to multieffect absorption heat pumps.

Publications:

N. Lior et al., "Operational Envelope of Solar-Powered Absorption Heat Pumps," *Proc. Annual Meeting of American Section of the International Solar Energy Society*, CONF-810509, May 1981.

6.2.23 Gas- or Solar-Fired Residential Heat Pump Using a Variable Effect Process

Principal Investigator: Ken Kauffman
Organization: Absorption Process Technology
4920 City Line Avenue, A207
Philadelphia, PA 19131
Telephone: (215) 473-7905

Contract Agency: Absorption Process Technology (APT)
Contract Number:
Contract Period:
Funding:
Source: APT (self-funded) **Level:** 100%

Subcontractors: Franklin Research Center
David Aronson Associates
Johnson Engineering Company

Project Objectives:

To build and test a 3-ton (cooling) engineering prototype, to refine the design and construct prototypes, to field test the prototypes and demonstrate for manufacturer licensing.

Project Description:

A new process and machine concept for absorption heat pumping are being developed. The variable effect machine attains the performance of single-effect, multi-effect, or anywhere in between. Triple-effect is attained with mild winter conditions. The process matches the application: heat exchange with air streams occurs over a range of temperature, and the outdoor temperature varies widely over time. The machine uses a slowly rotating thin film heat exchanger for efficiency, compactness, and low cost.

The design of a 3-ton (cooling) engineering prototype has been completed. Funding is being sought for building and testing the prototype, and for its commercial development.

Publications:

K. Kauffman, "Solar Applications of a Variable Effect Absorption Process," *Proc. Annual Meeting of the American Section of the International Solar Energy Society, May 26, 1981*, CONF-810509, 1981.

7. FOSSIL-FUEL-FIRED SYSTEMS

7.1 Stirling Engine-Driven Systems

7.1.1 Integration of Analysis and Experiments for Stirling Cycle Processes

Principal Investigator: Joseph L. Smith
Organization: Massachusetts Institute of Technology
77 Massachusetts Ave.
Cambridge, MA 02139
Telephone: (615) 253-2296

Contract Agency: Oak Ridge National Laboratory
Contract Number: 19X-55915C
Contract Period: Jan. 1, 1986, through Dec. 31, 1988
Funding: $178,694
Source: DOE **Level:** 100%

Project Objectives:

To investigate heat transfer during compression and expansion in a number of geometries similar to those used in Stirling machinery, to integrate experimental and analytical approaches on the component level so that verified model input for larger-scale analyses can be obtained.

Project Description:

The project consists of the following three phases:

- Phase 1—a survey of existing analytical and experimental techniques that will determine an optimum variable set for both modeling and verification
- Phase 2—An experimental and analytical investigation of heat transfer in a closed single-space system with various heat transfer surfaces; development and testing of new instrumentation techniques for heat transfer during compression and expansion
- Phase 3—An experimental and analytical investigation of heat transfer in a two-space system with measurement of mass and energy flows between the spaces

Publications:

None provided.

7.1.2 Stirling Engine Technology for Application in Buildings

Principal Investigator: F. C. Chen
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-0712

Contract Agency: International Energy Agency
Contract Number: N/A (IEA Annex XI)
Contract Period: May 1986 through May 1988
Funding: $150,000 (U.S. share—$60,000)
Source: DOE **Level:** 100%

Subcontractor: Arthur D. Little, Inc.
Cambridge, Massachusetts

Project Objectives:

To gain through international cooperation a more complete strategic assessment of the technology of Stirling engine-driven heat pumps than can be obtained through present individual programs, to identify topics for further international cooperative research efforts.

Project Description:

This project is being conducted on a task-sharing basis whereby each participating country contributes the services of a national team at its own expense. The operating agent, Oak Ridge National Laboratory, contributes additional tasks, which are described below. The participating countries are Denmark, Japan, Sweden, and the United States.

Each participant prepares a summary of relevant nonproprietary information on current basic research and system development activities in the respective country. The operating agent organizes and coordinates the activities of the annex. Using the information contributed, the operating agent will conduct a strategic technical and economic assessment of the technology for Stirling engines and Stirling engine-driven heat pumps, focusing on a comparative evaluation of the kinematic-drive and free-piston approaches. The operating agent will prepare a final report documenting work done, conclusions, and recommendations for future cooperative activities.

Three project workshop meetings and study tours are planned, one each in Japan, Europe, and the United States.

Publications:

International Energy Agency Implementing Agreement for a Programme of Research and Development on Advanced Heat Pump Systems, Annex XI: Stirling Engine Technology for Application in Buildings, draft report.

7.1.3 Assessment of Free-Piston Stirling Engine Driven Heat Pump Technology

Principal Investigator: W. Peter Teagan
Organization: Arthur D. Little, Inc.
32 Acorn Park
Cambridge, MA 02140
Telephone: (617) 864-5770

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-00205C
Contract Period: May 22, 1984, through Dec. 31, 1987
Funding: $152,294
Source: DOE **Level:** 100%

Project Objectives:

To assess the technical status of free-piston Stirling engine (FPSE) driven heat pump technology, to identify programmatic approaches for resolving remaining technical and economic issues that represent barriers to their commercial development.

Project Description:

The assessment is complete. The program reviewed the recent experience with FPSE driven heat pump systems and identified key technical and cost issues that should be the focus of future program efforts. The effort emphasized experience with the programs undertaken by General Electric Company (inertial compressor concept) and Mechanical Technology, Inc. (hydraulically coupled system) because they have received the major funding by the Department of Energy and others since the late 1970s.

Issues addressed by the study include the status and prospects of FPSEs as heat pump drives, design and operational characteristics that might limit reliability and life, unique factors such as gas spring losses which influence the efficiency of FPSE, and the cost constraints on the system to be economically competitive with conventional equipment and other heat-actuated heat pump options. Special attention was given to the impacts of unlubricated seal and bearing options on system life, reliability, and cost.

Based on the above, a comprehensive program was outlined consisting of supporting analyses, supporting research and development, and system development which, if fully funded, would lead to field testing of a commercial prototype FPSE heat pump system in about 5 years.

Publications:

W. P. Teagan, "Assessment of Free-Piston Stirling Engines as Heat Pump Drives," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

Arthur D. Little, Inc., *Status of Free Piston Stirling Engine Driven Heat Pumps—Development, Issues, and Options. Final Report*, ORNL/Sub/84-00205/1, April 1986.

7.1.4 Free-Piston Stirling Engine Diaphragm-Coupled Heat-Actuated Heat Pump Component Technology Program

Principal Investigator: Robert A. Ackermann
Organization: Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, NY 12110
Telephone: (518) 785-2211

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-47985V
Contract Period: Nov. 15, 1983, through Feb. 28, 1987
Funding: $927,485
Source: DOE **Level:** 100%

Project Objectives:

To improve the performance of a hydraulic transmission/compressor that was designed and fabricated during a previous phase of the project, to couple the improved hardware with an existing free-piston Stirling engine, to test the performance of the heat pump system over a range of ambient temperatures and compressor strokes.

Project Description:

Mechanical Technology, Inc. began development in 1980 of a hydraulically driven compressor coupled to a free-piston Stirling engine by a metal diaphragm. The compressor is double-acting and oriented in a transverse position relative to the engine. The original hardware included a counterweight inside the hydraulic transmission to eliminate transverse vibrations. Experiments with the original transmission/compressor indicated that hydraulic and compressor losses were significantly larger than design predictions.

In this phase of the project, a series of analytical and experimental investigations identified hardware modifications to improve the performance of the transmission/compressor. Improved components were designed and fabricated whenever procurement times and costs were reasonable. The largest performance improvement occurred when the counterweight inside the transmission was removed and replaced with spring-mounted balancers located externally on the transmission housing. Other improvements included replacing the compressor piston rings, streamlining the oil passages, and using low-viscosity oils.

Performance testing of the improved hardware was completed in January 1986. The results indicate that the efficiency of the transmission is about 85% and the isentropic efficiency of the compressor is about 75%. The experiments also demonstrated the feasibility of the external balancers and the ability of the Stirling engine displacer motor to control the system over the range of ambient temperatures from 0 to 95°F. Future goals are to improve the performance of the free-piston Stirling engine so that the heat pump cooling capacity can be increased from the current value of about 2.5 tons to 3.0 tons.

Publications:

T. M. Moynihan and R. A. Ackermann, "Test Results for a Stirling-Engine-Driven Heat-Actuated Heat Pump Breadboard System," *Proc. 19th IECEC*, August 1984.

Mechanical Technology, Inc., *Free-Piston Stirling Engine Diaphragm-Coupled Heat-Actuated Heat Pump Component Technology Program—Phase I/IA Final Report*, ORNL/Sub/80-61618/1, June 1985.

T. J. Marusak, "Breadboard Development of a Hydraulically Coupled Free-Piston Stirling Engine Heat Pump Compressor," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

7.1.5 Analysis of General Electric Stirling/Rankine Inertial Compressor System

Principal Investigator: Fang C. Chen
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37381
Telephone: (615) 574-0712

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: Apr. 1, 1985, through Dec. 31, 1986
Funding: $233,000
Source: DOE **Level:** 100%

Project Objectives:

To confirm the pressure-regulated gas spring control system concept employed in the General Electric Proto 2 Unit, to predict the eventual level of performance attainable by an improved thermally activated heat pump comprising of a free-piston Stirling engine and an inertially coupled refrigerant compressor.

Project Description:

A modified dynamic model coupled to an existing Stirling engine thermodynamic model will be validated using Proto 2 data. The resulting model will be exercised to estimate the potential of suggested Proto 2 design changes for improved thermal performance and to assess the pressure-regulated gas spring control concept. Compressor power requirements at four rating points will be developed and matched to engine output over the range of refrigerant gas spring control pressures. Thermal performance of an improved Proto 2 unit will be estimated to show the performance potential of the free-piston Stirling engine/inertial compressor concept.

Publications:

None provided.

7.1.6 Stirling Engine Technology

Principal Investigator: James E. Dudenhoefer
Organization: NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Telephone: (216) 433-4000

Contract Agency: Oak Ridge National Laboratory
Contract Number: DE-AI05-82OR21005
Contract Period: Sept. 23, 1982, through Dec. 31, 1986
Funding: $550,000
Source: DOE **Level:** 100%

Subcontractors: Sunpower, Inc.
Foster Miller Associates
Mechanical Technology, Inc.

Project Objectives:

To develop free-piston Stirling engine (FPSE) technology applicable to heat-activated heat pumps.

Project Description:

The National Aeronautics and Space Administration (NASA) has tested and characterized an existing 1-kW FPSE with a dashpot load. Test data collected throughout a test matrix have been used to update and validate a NASA-developed FPSE performance computer code. The test matrix exercised the engine over a wide range of conditions to find parameters to which the engine has sensitivity. The matrix not only varied the engine operating conditions, but it also varied the configuration of engine hardware.

A hydraulic load output device was designed, fabricated, and coupled to the FPSE. Presently, the engine/hydraulic output system characterization test is under way for the investigation of dynamic interaction. A hydraulic output simulation code has been written and successfully coupled to the FPSE performance computer code for complete simulation. The testing of the hydraulic output device is intended to demonstrate feasibility, efficiency, and potential practicality of a hydraulic power system driven by an FPSE.

Publications:

Detail Design and Stability Verification of Hydraulic Output Stirling Engine, NASA Contractor Report CR-167976, January 1983.

Testing and Performance Characteristics of a 1-kW Free-Piston Stirling Engine, NASA TM-2999, April 1983.

Test Results and Description of a 1-kW Free-Piston Stirling Engine with a Dashpot Load, NASA TM-83407, August 1983.

J. Schreiber, "Test Results and Description of a 1-kW Free-Piston Stirling Engine with a Dashpot Load, *Proc. 18th IECEC, Orlando, Florida*, 1983.

"Development of Free-Piston Stirling Engine Performance and Optimization Codes Based on Martini Simulation Technique," prepared for NASA under contract NAS3-22256, May 1984.

Comparison of Free-Piston Stirling Engine Model Predictions with RE-1000 Engine Test Data, NASA TM-83650, August 1984.

J. G. Slaby, "Overview of NASA Lewis Research Center Free-Piston Stirling Engine Activities," *Proc. 19th IECEC*, DOE/NASA-1005/2, August 1984.

R. Tew, "Comparison of Free-Piston Stirling Engine Model Predictions with RE-1000 Engine Test Data," *Proc. 19th IECEC*, DOE/NASA-1005-3, ISBN 0-89448-115-0, August 1984.

J. Schreiber, "Initial Results of Sensitivity Tests Performed on the RE-1000 Free-Piston Stirling Engine," *Proc. 19th IECEC*, August 1984.

Free-Piston Stirling Engine/Linear Alternator 1000-Hour Endurance Test, NASA Contractor Report CR-174771, March 1985.

J. G. Schreiber, "Initial Results of Sensitivity Tests Performed on the RE-1000 Free-Piston Stirling Engine," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

7.1.7 Stirling Engine Driven Heat Pump Systems Analysis

Principal Investigator: Fang C. Chen
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-0712

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: Oct. 1, 1984, through Sept. 30, 1986
Funding: $160,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate existing and newly proposed Stirling engine driven heat pump (SEHP) systems for the purpose of guiding decisions about their further development.

Project Description:

Oak Ridge National Laboratory (ORNL) manages a SEHP development program for the U.S. Department of Energy. The development work is performed both in-house at ORNL and under subcontract at other research organizations. This project provided independent evaluations of SEHP systems that were needed for effective management of the development program. It is expected that improved and/or new SEHP system concepts will evolve from this project.

Publications:

None provided.

7.1.8 Natural-Gas-Fired Kinematic Stirling/Rankine Commercial Heat Pump Development

Principal Investigator: L. Johannson
Organization: Stirling Power Systems
7101 Jackson Road
Ann Arbor, MI 48103
Telephone: (313) 665-6767

Contract Agency: Gas Research Institute
Contract Number: 5083-242-0845
Contract Period: Sept. 1, 1983, through Apr. 30, 1986
Funding: $5,860,585
Source: GRI **Level:** 100%

Subcontractors: Institute of Gas Technology
Borg-Warner Research Center

Project Objectives:

To develop an economically competitive gas heat pump for light commercial applications (10-ton cooling capacity) based on kinematic Stirling engine technology.

Project Description:

The kinematic Stirling/Rankine gas heat pump concept is based on a Stirling cycle engine that has been under development for over a decade. The V160 Stirling engine has been converted to natural gas and is well characterized with thousands of hours of operating experience. In this phase, a heating, ventilating, and air-conditioning systems manufacturer (Borg-Warner) is collaborating with Stirling Power Systems (SPS) to develop an engine-driven heat pump system. Borg-Warner's role involves the design, assembly, and test of a laboratory prototype heat pump breadboard, with SPS focusing on the V160 Stirling engine development to meet the system endurance, reliability, performance, and cost requirements. A piston-type open shaft freon compressor has been selected as the best match for the V160 engine. Both the engine and compressor have been tested and fully characterized by performance maps. The experimental heat pump system was evaluated by Borg-Warner. The control system for automatic cycling of the V160 endurance engine to simulate heat pump duty is operational. Engine performance data obtained with the improved engine heater at the maximum design pressure of 15 MPa and a heater temperature of 700°C indicates that the engine should be capable of producing the power and torque needed to provide 10 tons of cooling.

Publications:

Gas Research Institute, *Phase IB Development of Kinematic Stirling/Rankine Commercial Gas-Fired Heat Pump System, GRI Annual Report (September 1983–December 1984)*, GRI-85/0126.

L. Johannson et al., "Kinematic Stirling/Rankine Commercial Gas-Fired Heat Pump System," presented at the 1984 International Gas Research Conference.

7.1.9 Free Piston Stirling Engine Development

Principal Investigator: Robert A. Ackermann
Organization: Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, NY 12110
Telephone: (518) 785-2211

Contract Agency: Gas Research Institute
Contract Number: 5082-242-0721
Contract Period: Dec. 1, 1982, through Mar. 31, 1986
Funding: $4,889,490
Source: GRI **Level:** 100%

Subcontractor: Lennox Industries

Project Objectives:

To develop the technology to utilize a free-piston Stirling engine (FPSE) as a gas-fueled prime mover for a heat pump in the residential market (3-ton cooling capacity); to design, fabricate, and ship a breadboard heat pump unit to a heat pump manufacturer for independent testing.

Project Description:

This long-term development program is not scheduled for commercialization until the early 1990s. In the present phase of engine technology development, the effort has focused on engine component improvement for the design and fabrication of an advanced FPSE (called the Mark 1) for driving a hydraulically coupled refrigerant compressor in a breadboard heat pump system. The compressor development is being funded by the Department of Energy in a parallel and coordinated program to the Gas Research Institute engine development.

Several technical goals have been achieved so far. Specifically, the external combustor system has operated successfully on residential pressure gas at a thermal efficiency of 80 to 82% [higher heating values (HHV)]. In addition, an indicated efficiency of 28% (HHV) has been measured with the engine. An engine gas bearing design has also been established for pumping bearing supply gas from the displacer gas spring for self-sustaining engine operation. Successful operation of the redesigned compressor with the external balancers has enabled the engine/compressor to operate stably and achieve the minimum performance goals (2.5 tons of refrigeration) for heat pump operation. In the endurance engine development work, the ceramic combustor liner test has logged 3900 h without failures, and the endurance engine has accumulated 6000 h of the initial 10,000-h goal without forced shutdowns.

Publications:

T. J. Marusak and Ted Gilles, *Free-Piston Stirling Engine Development Annual Report (Dec. 1, 1982–Dec. 31, 1983)*, GRI-84/0074, April 1984.

T. J. Marusak and R. A. Ackermann, *Free-Piston Stirling Engine Development Annual Report (Dec. 1, 1983–Dec. 31, 1984)*, GRI-85/0117, July 1985.

7.1.10 Reversing Flow Tests of Stirling Engine Components

Principal Investigator: Paul D. Roach
Organization: Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Telephone: (312) 972-8146

Contract Agency: Oak Ridge National Laboratory
Contract Number: 10X-43106V
Contract Period: Sept. 1, 1982, through Mar. 31, 1986
Funding: $198,000
Source: DOE **Level:** 100%

Project Objective:

To provide performance data on Stirling engine regenerator materials under conditions of reversing flow.

Project Description:

A reversing flow test facility was assembled. Preliminary and fundamental experiments were performed. Regenerator performance tests, which were to be conducted using the facility to span representative operating conditions encountered during earlier testing of a free-piston Stirling engine coupled to a linear inertia compressor (General Electric prototype 2), were not achieved.

Publications:

None provided.

7.1.11 Free-Piston Stirling Engine/Rankine Analysis and Data Evaluation

Principal Investigator: Frederick P. Griffin
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 576-4684

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: Jan. 1, 1982, through Sept. 30, 1985
Funding: $671,000
Source: DOE **Level:** 100%

Project Objectives:

To assess existing Stirling engine analytical capabilities; to develop an efficient, but mathematically accurate, method for predicting the performance of free-piston Stirling engines (FPSEs).

Project Description:

The concept of using an FPSE to drive a Rankine cycle heat pump was studied. This task was directed toward understanding the discrepancy between the actual performance of experimental hardware and the predictions made by their designers prior to testing. The measured losses in hardware were much larger than predicted values. Accordingly, an efficient solution method (linear harmonic analysis) was developed to examine how the important loss mechanisms affect the thermodynamic and dynamic performance of these free-piston systems.

Sensitivity studies using the linear harmonic solution method showed that the thermodynamic loss assumptions used in an analysis do have a significant impact on the predicted dynamic behavior (frequency, strokes, displacer phase angle) of an FPSE. Two losses that are particularly important are heat transfer in the cylinders and pressure drop in the regenerator and heat exchangers.

Publications:

N. C. J. Chen and F. P. Griffin, *A Review of Stirling Engine Mathematical Models,* ORNL/CON-135, August 1983.

N. C. J. Chen and F. P. Griffin, "Effects of Pressure-Drop Correlations on Stirling Engine Predicted Performance," pp. 708–713 in *Proc. 18th IECEC*, Paper No. 839114, 1983.

B. K. Newman, *Stirling Engine Patents: International Patent Inventory*, ORNL/CON-119, September 1983.

R. D. Banduric and N. C. J. Chen, *Nonlinear Analysis of Stirling Engine Thermodynamics,* ORNL/CON-154, June 1984.

N. C. J. Chen, F. P. Griffin, and C. D. West, *Linear Harmonic Analysis of Stirling Engine Thermodynamics,* ORNL/CON-155, August 1984.

N. C. J. Chen, F. P. Griffin, and C. D. West, "Linear Harmonic Analysis for Stirling Machines and Second-Law Analysis of Four Important Losses," pp. 1973–1981 in *Proc. 19th IECEC*, Paper No. 849141, 1984.

N. C. J. Chen, F. P. Griffin, and C. D. West, *Simplified Analysis of Stirling Engines and Heat Pumps,* ORNL/TM-9498, March 1985.

N. C. J. Chen, F. P. Griffin, and C. D. West, "Simplified Analysis of Stirling Engines and Heat Pumps," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

N. C. J. Chen and F. P. Griffin, *Linear Harmonic Analysis of Free-Piston Stirling Engines,* ORNL/CON-172, June 1986.

7.1.12 Development of a Diaphragm-Activated Hydraulically Coupled Refrigerant Compressor

Principal Investigator: Ralph Hise
Organization: Consolidated Natural Gas Research Company
11001 Cedar Avenue
Cleveland, OH 44106
Telephone:

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-61618C
Contract Period: June 1, 1980, through Sept. 30, 1985
Funding: $2,975,800
Source: DOE **Level:** 79%
CNG 21%

Subcontractor: Mechanical Technology Inc.
968 Albany-Shaker Road
Latham, NY 12110
R. A. Ackermann

Project Objectives:

To design, develop, and demonstrate a proof of principal diaphragm-actuated, hydraulically coupled compressor for use with a free-piston Stirling engine in a residential gas-fired heat pump system.

Project Description:

Between 1978 and 1980, Consolidated Natural Gas Research Company (CNG), together with Mechanical Technology Inc. (MTI), developed a Stirling engine driven residential heat-actuated heat pump under the gas conservation (GASCON) program. In June 1980, the Department of Energy/Oak Ridge National Laboratory became a third partner in this program, with the primary objective of developing a demonstrator engine/compressor power module based on some newly conceived and promising GASCON concepts. The key element in this new concept was the use of a hydraulic transmission that hermetically seals the engine working fluid from the compressor working fluid by a flexible metal diaphragm.

A compressor/engine matching analysis and a stability analysis showed that the power module, which was represented by a two-degree-of-freedom resonant system, would operate stably over the full range of heat pump conditions. A compressor design evolved, and predictions indicated that it would meet the criteria for performance and cost. Tests employing a hydraulic simulator test rig revealed that properly designed and fabricated diaphragms can attain long life. Preliminary experiments with the entire engine/compressor system indicated that hydraulic and compressor losses were significantly larger than design predictions.

Publications:

R. A. Ackermann, J. D. English, and T. M. Moynihan, "Stirling Engine Heat-Actuated Heat Pumps," *Proc. 18th IECEC*, August 1983.

Mechanical Technology Inc., *Free-Piston Stirling Engine Diaphragm-Coupled Heat-Actuated Heat Pump Component Technology Program, Phase I/IA Final Report*, ORNL/Sub/80-61618/1, June 1985.

Patents:

U.S. 4,434,617: M. M. Walsh, Startup and Control Method and Apparatus for Resonant Free-Piston Stirling Engine, July 27, 1982.

U.S. 4,432,204: M. M. Walsh, Linear Hydraulic Drive System for a Stirling Engine, Feb. 21, 1984.

U.S. 4,450,685: J. C. Corey, Balanced Single-Bore Oil-Driven Compressor, May 29, 1984.

7.1.13 Preliminary Design of Linear Alternator Dynamometer for Free Piston Stirling Engine

Principal Investigator: Kang Pil Lee
Organization: Aspen Systems, Inc.
100 Puritan Lane
Sudbury, MA 01776
Telephone: (617) 443-7647

Contract Agency: Oak Ridge National Laboratory
Contract Number: 62X-05907V
Contract Period: July 27, 1984, through Oct. 31, 1984
Funding: $32,886
Source: DOE **Level:** 100%

Project Objectives:

To prepare a preliminary design of a dynamometer for free-piston Stirling engines (FPSEs) capable of detailed simulation of a double-acting inertia piston compressor and other loads (dynamometer design is to be compatible with Sunpower's RE-1000 FPSE).

Project Description:

A preliminary design of a linear-alternator-type dynamometer is complete. The dynamometer was designed to be used as a versatile load device for FPSEs with power capacities up to 3 kW, strokes up to 5 cm, and frequencies up to 60 Hz.

The dynamometer has two major components: the electromechanical transducer and the control system. The electromechanical transducer is of the moving armature coil/permanent magnet field type. The microprocessor-based control system modulates the current in the armature coil according to desired load characteristics.

A detailed digital simulation of the dynamometer load/FPSE system predicts that the dynamometer load simulation will be accurate and will converge quickly. The dynamometer design has the following features:

- Low moving mass
- Low inductance
- Almost constant, uniform magnetic field
- Almost linear current-force relationship
- Fast convergent and stable control system

Publications:

K. P. Lee and W. M. Toscano, *Preliminary Design of Linear Alternator Dynamometer for Free Piston Stirling Engines*, ORNL/Sub/84-05907/1, June 1985.

7.1.14 Isothermalization Study of Stirling Cycle Heat Pumps

Principal Investigators: R. J. Kramer
C. T. Hsu
Organization: University of Tennessee
Knoxville, TN 37996-0100
Telephone: (615) 974-5115

Contract Agency: Oak Ridge National Laboratory
Contract Number: 378-07685C
Contract Period: May 1, 1984, through Oct. 31, 1984
Funding: $20,197
Source: DOE **Level:** 100%

Project Objectives:

To develop and apply a near-isothermalized, second-order computer code that will allow for the Stirling-cycle heat pump process of compression and expansion to follow any arbitrarily defined condition between the two limiting cases of isothermal and adiabatic.

Project Description:

It was proposed that Urieli's simulation method for Stirling-cycle analysis be adopted in the computer code development, which accounts for both heat transfer and frictional losses.

The technical approach included:

- Literature survey of available isothermalization concepts in Stirling cycle
- Model selection for the expansion and compression processes
- Near-isothermalized code development to simulate the processes between the two limiting cases of isothermal and adiabatic
- Computer code development against the results of isothermal process
- Applications in isothermalized Stirling machine utilizing the existing expansion and compression volume equations
- Documentation and description of computer codes developed in performing the previous five steps

The project had the following results:

- A second-order computer model based on an ideal adiabatic model was modified to simulate the effects of cylinder isothermalization on Stirling heat pump performance
- Parametric analyses were conducted by varying the heat transfer coefficient of the working spaces from zero (adiabatic) to very high values to approach isothermal conditions
- Making the adiabatic cylinders more isothermal actually reduced performance, at least until near perfect isothermality was approached
- In between the extreme of adiabatic and isothermal conditions, a performance minimum was indicated
- High transient heat transfer losses contributed to the poor performance for the minimum case
- No code validation was made because no Stirling heat pump test data were available

Publications:

None provided.

7.1.15 Development and Demonstration of a Stirling/Rankine Heat-Activated Heat Pump—Phase III

Principal Investigator: Richard C. Meier
Organization: General Electric Company
Advanced Energy Programs Dept.
P.O. Box 527
King of Prussia, PA 19406
Telephone: (215) 962-2000

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-17485C
Contract Period: July 1982 through September 1983
Funding: $446,847
Source: DOE **Level:** 100%

Project Objectives:

To conduct engine/compressor technology development activities according to the phase 2 recommendations, which included engine/compressor performance validation, matching, and heat exchanger losses.

Project Description:

The phase 3 test program included (1) compressor performance verification, (2) engine/compressor matching, (3) engine performance, and (4) engine heat exchangers loss analysis. In phase 3, the compressor performance was verified by adding a linear velocity differential transducer to the compressor assembly to directly measure the motion of the compressor free piston. The measured piston motion was lower than expected. The engine/compressor unit's operation was significantly affected by the matching of the engine and the compressor operating characteristics. The measured maximum indicated that engine performance was 25%, compared with 27% in phase 2. The phase 3 test results of heat exchangers indicated where improvements in heat exchangers can be made to improve performance.

Publications:

W. Chin et al., "Parametric Testing and Evaluation of a Free-Piston Stirling Engine/Linear Compressor System," *Proc. 18th IECEC*, CONF-830817-53, August 1983.

General Electric Company, *Development and Demonstration of a Stirling/Rankine Heat-Activated Heat Pump. Final Report, Phase IIIB—Engine Technology Development Testing,* ORNL/Sub/82-17485/1, November 1984.

7.1.16 Stirling Heat Pump Project with Martini Engineering

Principal Investigator: W. R. Martini
Organization: Martini Engineering
2303 Harris
Richland, WA 99352
Telephone: (509) 375-0115

Contract Agency: Oak Ridge National Laboratory
Contract Number: 62X-43168V
Contract Period: December 1982 through April 1983
Funding: $4000
Source: DOE **Level:** 100%

Project Objectives:

To develop a user-oriented, validated, computer code capable of simulating Stirling cycle heat pumps of different mechanical arrangements.

Project Description:

An improved second-order computer model for simulation of Stirling-cycle machines has been developed. It takes into account the effects of adiabatic compressions and expansion spaces and the operation of the Stirling machine, both as a heat engine and as a heat pump. Once the machine dimensions and operating conditions are specified, the model calculates basic power (without losses) and heat rates from the Schmidt equations for an isothermal cycle and nonsinusoidal volume change. A correction for adiabatic working spaces is then made on the basic power and heat rate terms. Losses are calculated individually and are coupled from each other and from the cycle. These losses are then subtracted from the basic power and heat terms to determine actual performance.

A validation program was prepared and used to compare some of the published predicted data for the General Motors 4L23 Stirling engine with those calculated by the second-order model. The code predicted the power output within 10% and the efficiency to within 5%.

The model has not been verified with measured Stirling data to determine its accuracy.

Publications:

W. R. Martini, *IS082, A Fast Design Program for Stirling Cycle Heat Engines and Heat Pumps,* Final Report, April 1983.

W. R. Martini, "A Revised Isothermal Analysis Program for Stirling Engines," *Proc. 18th IECEC,* CONF-830812-51, August 1983.

7.1.17 Duplex Stirling Gas-Fired Heating-Only Heat Pump—Phases 1 and 2

Principal Investigator: William T. Beale
Organization: Sunpower, Inc.
6 Byard Street
Athens, OH 45701
Telephone: (614) 594-2221

Contract Agency: Gas Research Institute
Contract Number: 5081-341-0464
Contract Period: May 1, 1981, through Nov. 30, 1982
Funding: $633,449
Source: GRI **Level:** 100%

Project Objectives:

To construct a laboratory demonstration duplex Stirling heating-only heat pump with a 10-kW heating capacity at −8°C source temperature, to measure its performance over a range of source temperatures, to make an analytical assessment of the penalty incurred by optimization for heating and cooling in comparison to an optimization for heating only, to refine the cost and payback time estimates made in the first analytical study; phase 2—to demonstrate the hardware proof-of-concept.

Project Description:

This project was a continuation into hardware test of an initial study that resulted in a projected heating coefficient of performance of over 1.5 for a duplex Stirling heating-only heat pump.

The duplex Stirling machine built was a breadboard version of a 10-kW heat pump comprising a gas burner, free-piston Stirling engine, free-piston Stirling heat pump in the same helium pressure enclosure, and the associated heat exchanges, controls, and accessories that make up the complete system. The novel features of this heat pump were its great simplicity, with only three moving parts within the pressure enclosure, the absence of any flexing or sliding isolation seals, high thermodynamic performance, and complete power-load matching over the entire range of sink temperature without recourse to complex control processes.

The full-scale model in phase 2 was assembled, tested, and gas fired. This phase of the development was expected to verify the full-scale performance of the heating-only heat pump and provide a data base with which to approach selected manufacturers for support before going to the next phase of development.

The heat pump fell short of the desired goals. Investigation of the application as a heat pump was discontinued.

Publications:

W. T. Beale et al., *Duplex Stirling Heating-Only Gas-Fired Heat Pump, Final Report,* PB-81-181323, January 1981.

D. Gedeon et al., *Duplex Stirling Gas-Fired Heat Pump, Phase 2, Breadboard Demonstration, Final Report,* PB-85-170421/XAB, November 1982.

W. T. Beale et al., "Duplex Stirling Heat Pump Development," *Proc. 1983 International Gas Research Conf., June 13, 1983,* CONF-830664, 1983.

Patents:

U.S. 4,458,495: W. T. Beale, Pressure Modulation System for Load Matching and Stroke Limitation of Stirling Cycle Apparatus, July 10, 1984.

7.1.18 Stirling Cycle Application Study

Principal Investigator: Ken Hansen
Organization: General Electric
P.O. Box 8661
Philadelphia, PA 19101
Telephone: (215) 962-2000

Contract Agency: Gas Research Institute
Contract Number: 5081-345-0534
Contract Period: January 1982 through September 1982
Funding:
Source: GRI **Level:** 100%

Project Objectives:

To assess the application of Stirling cycle technology to the spectrum of thermodynamic machines (engines, coolers, heat pumps, etc.) that can be activated by the external combustion of natural gas, especially in ways that utilize energy more efficiently and exhibit improved performance characteristics over present methodologies.

Project Description:

The majority of product-oriented Stirling engine developments in the United States focused on three major areas; auto engines, electric power generation, and space conditioning. No effort had been made to determine if these applications were the most suitable to the types of Stirling engines available. Specifically, there could be a range of other potential Stirling engine applications that might prove to be more economical, receive wider acceptance, and experience earlier commercialization than those under investigation.

General Electric performed a survey of the state of the art in Stirling engine technology and established a classification system for grouping the engines according to specific type and power. Following this, a study of possible applications was made from some of the data compiled over previous years. Key application parameters such as hours of operation per year, emissions noise, and environment were used to evaluate the suitability of engine types. Power requirements for applications in apartments, shopping centers, and commercial buildings were identified. Certain characteristic applications were studied in depth to achieve a proper understanding of the requirements involved. Performance, projected costs, and operating characteristics were optimized by adapting a conceptualized design to these particular applications.

Good energy price scenarios were made in the past for use in analyzing the gas-fired heat pump market. These were updated and revised to arrive at a consensus projection for the cost of various energy forms over the next decade. This projection was used to evaluate the market potential of the Stirling engines used in the characteristic applications mentioned above.

Publications:

None provided.

7.1.19 Analytical Study of Liquid-Piston Heat Pump Technology

Principal Investigator: Joseph Gerstmann
Organization: Advanced Mechanical Technology, Inc.
141 California Street
Newton, MA 02158
Telephone: (617) 964-2042

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-6506
Contract Period: Aug. 15, 1981, through Aug. 31, 1982
Funding: $41,000
Source: DOE **Level:** 100%

Project Objectives:

To demonstrate the feasibility of a liquid-piston heat pump operating on a Stirling cycle.

Project Description:

This project included development of second-order computer models for a Stirling cycle having either adiabatic or isothermal cylinders. The results predicted by the second-order models were corrected to account for nonideal situations such as "shuttle" heat transfer, piston friction, regenerator reheat loss, and heat exchanger ineffectiveness to determine optimal design parameters. The analysis indicated that economically attractive performance could be achieved by a liquid-piston heat pump having isothermal cylinders, whereas the performance of a machine having adiabatic cylinders would be marginal.

Another product of the project was a computer program for the analysis of a Stirling cycle with two adiabatic cylinders and constant wall temperature heat exchangers with dead volume in the regenerator and heat exchangers. This second-order model used the Rios formulation of the regenerator temperature profile that exists in the periodic steady state. The utility of this formulation is that the temperature distribution of a high-effectiveness regenerator can be predicted without requiring a very large number of iterations.

Publications:

J. Gerstmann and K. Hules, *Analytical Study of Liquid-Piston Heat Pump Technology—Interim Report,* ANL/CT-85-2, December 1985.

7.1.20 Free-Piston Stirling Engine Technology Development

Principal Investigator: George R. Dochat
Organization: Mechanical Technology Inc.
968 Albany Shaker Road
Latham, NY 12110
Telephone: (518) 785-2242

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-6420
Contract Period: July 1, 1981, through Dec. 31, 1981
Funding: $188,000
Source: DOE **Level:** 100%

Project Objectives:

To gain an improved understanding of free-piston and Stirling engine technology by providing both analytical and experimental evaluation of specific loss mechanisms within the engine during operation.

Project Description:

The 1-kW free-piston Stirling technology demonstrator engine was built and operated. Past efforts focused on getting the engine to the point of development where meaningful tests could be conducted. Free-piston Stirling engine driven heat pumps are candidate viable options with engine sizes in the 1 to 10 kW range.

This project used the technology demonstrator engine (TDE) system, a 1-kW free-piston Stirling engine/linear alternator, as a test bed to evaluate specific loss mechanisms within the engine. The specific loss mechanisms to be evaluated included compression space hysteresis, different regenerator matrices, displacer clearance seal, and displacer gap. The evaluation included the current analytical procedures for calculating the specific losses, performance of a series of tests to isolate each loss, comparisons of actual performance with predicted performance, and determination of adequacy of present analytical methods. An improved understanding of basic engine processes led to increased performance capability and, therefore, directly benefited the development of heat-activated heat pumps, fluid pumps, and engine-generator sets.

Publications:

R. Berggren and T. Moynihan, *Free-Piston Stirling Engine Experimental Program: Part 1—Baseline Test Summary,* ANL-CT-83-7 Part 1, June 1983.

T. Moynihan et al., *Free-Piston Stirling Engine Experimental Program: Part 2—An Evaluation of Loss Mechanisms,* ANL-CT-83-7 Part 2, June 1983.

7.1.21 Development of 1-kW Kinematic Stirling Engine

Principal Investigator: James Bledsoe
Organization: General Electric Company
P.O. Box 8661
Philadelphia, PA 19101
Telephone: (215) 962-1492

Contract Agency: Department of Energy
Contract Number: DE-AC01-76ET32002
Contract Period: May 1976 through November 1981
Funding: $6,400,00
Source: DOE **Level:** 100%

Project Objectives:

To develop a 1-kW kinematic Stirling engine with candidate application to be integrated into an engine driven heat pump system.

Project Description:

This project was a continuation of a research and development effort initiated by the Department of Energy (DOE)/Nuclear to drive a Stirling engine with an isotope power heat source. The isotope power heat source was removed, but development of the engine has continued.

This engine was built and operated successfully. The bulk integrated into the engine design because of the initial isotope power heat source made the engine very expensive. It was concluded that kinematic Stirling engine driven heat pumps are candidate viable options with engine sizes greater than 10 kW.

Publications:

General Electric Company, *Stirling Isotope Power System Program, Final Report, January 1978–December 1980,* DOE/ET/32002-T1, December 1980.

7.1.22 Development and Demonstration of a Stirling/Rankine Heat-Activated Heat Pump—Phase 2

Principal Investigator: Richard C. Meier
Organization: General Electric Company
P.O. Box 8661
Philadelphia, PA 19101
Telephone: (215) 962-3868

Contract Agency: Department of Energy, Chicago Operations
Contract Number: DE-AC02-77CS20043
Contract Period: December 1976 through June 1981
Funding: $7,573,500

Source:	**Level:**
DOE	50%
Gas Research Institute	50%
General Electric (for program support and extra scope)	+30%

Project Objectives:

To demonstrate that the performance predictions established in the phase I program can be achieved, to assess whether the product cost goals are attainable.

Project Description:

The Stirling engine driven heat pump under development in this project utilized a natural gas combustor/Stirling engine/linear inertia compressor assembly in place of the conventional motor-compressor unit employed in electric heat pumps. Heat input from the gas combustor provided thermal energy to the Stirling engine working fluid, helium. The engine power piston was directly connected to the compressor housing with the refrigerant being compressed by a free piston reciprocating within the housing.

Publications:

General Electric Company, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump, January–June 1977*, COO/2911-1.

General Electric Company, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump, July–December 1977*, DOE/CS/20043-2.

General Electric Company, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump, July–December 1978*, DOE/CS/20043-4.

General Electric Company, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump, January–June 1979*, COO/2911-5.

General Electric Company, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump, July–December 1979*, DOE/CS/20043-T1.

W. S. Chin and W. B. Carlson, "Performance of a Free-Piston Stirling Engine for a Heat Pump Application," *Proc. 14th IECEC*, August 1979.

R. C. Meier, *Development and Demonstration of a Stirling/Rankine Gas-Activated Heat Pump*, PB 80-205388, October 1979.

R. C. Meier, "Development of the General Electric Stirling Engine Gas Heat Pump," *IGT Conference on Future Alternatives in Residential/Commercial Space Conditioning*, CONF-800429, June 1980.

General Electric Space Division, *Development and Demonstration of a Stirling/Rankine Heat-Activated Heat Pump Semiannual Report, January–June 1980*, COO/2911-7.

General Electric Space Division, *Development and Demonstration of a Stirling/Rankine Heat-Activated Heat Pump Semiannual Report, July–December 1980*, DOE/CS/20043-T4.

Patents:

U.S. 4,307,997: W. D. Richards et al., Free-Piston Inertia Compressor, Dec. 29, 1981.

7.2 Internal Combustion Engine-Driven Systems

7.2.1 Commercial Rotary Internal Combustion Engine Heat Pump Development

Principal Investigator: A. McEachern, Jr.
Organization: Teledyne Continental Motors
P.O. Box 90
Mobile, AL 36601
Telephone: (205) 438-3411

Contract Agency: Gas Research Institute
Contract Number: 5083-242-0930
Contract Period: Nov. 1, 1984, through Feb. 28, 1989
Funding: $4,565,642
Source: GRI **Level:** 100%

Project Objectives:

To develop an economically competitive gas heat pump (GHP) for light commercial applications (10-ton cooling capacity) based on rotary engine technology.

Project Description:

This concept represents one of the two commercial GHP concepts presently under development by the Gas Research Institute (GRI). The rotary internal combustion (IC) engine has the potential for longer life and lower cost than a reciprocating IC engine and is a prime candidate for mid-term entry into the light commercial heat pump market. The present effort focuses on (1) performance evaluation of the baseline (existing) rotary engine hardware as obtained from a European vendor, (2) optimization of the engine design to meet GRI's targets for heat pump applications, and (3) preliminary heat pump system design. Changes in the rotary engine design to include apex and rotor end seals and a heavy duty rotor bearing as well as cast-iron water-cooled engine housings are being implemented. Initial engine performance results indicate that the engine thermal efficiency is ~27% (HHV) for optimum fuel economy conditions. Over 1000 h of tests on one engine have been accumulated without failures or noticeable wear. The redesign of the engine bearings is complete. A life of 100,000 h is predicted for the main bearing.

Publications:

None provided.

7.2.2 Evaluation of the Braun Engine/Compressor Assembly in Natural Gas Heat Pump Units—Phase 1 Laboratory Evaluation

Principal Investigator: Wai Chan
Organization: Minnegasco, A Company of Diversified Energies, Inc.
201 South 7th Street
Minneapolis, MN 55402
Telephone: (612) 372-4944

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-22022C
Contract Period: November 1985 through December 1986
Funding: $300,000 (phase 1)

Source:	**Level:**
DOE	50%
Minnegasco	25%
Northern Gas	25%

Subcontractors: Tectonics Research, Inc.
Mammoth (Division of Lear Siegler)

Project Objectives:

To design, fabricate, and laboratory test a heat pump unit that utilizes the Braun engine/compressor.

Project Description:

This project is a continuation of the research and development effort on the gas-fired, spark-ignition, Braun linear engine/compressor as designed for use in light commercial heat pump applications. Phase 1 will be a laboratory test of an air-to-air heat pump unit at standard conditions established by the Air Conditioning and Refrigerant Institute to determine correctness of operation and to demonstrate performance.

Continuation into the following phase (field testing) is subject to achieving satisfactory results from this laboratory unit test and in the durability testing that is on-going at Tectonics Research, Inc.

Publications:

None provided.

7.2.3 Free-Piston Linear Engine Development

Principal Investigator: A. T. Braun (Tectonics Research, Inc.)
Organization: Honeywell, Inc.
Technology Strategy Center
1700 West Highway 36
Roseville, MN 55113
Telephone: (612) 378-4162

Contract Agency: Oak Ridge National Laboratory
Contract Numbers: Seals, 86X-61613C
Part I, 86X-61619C
Part II, 86X-47972V
Contract Period: March 1980 through December 1986
Funding: $3,096,812 with Honeywell
$1,025,947 with TRI
Source: DOE **Level:** 100%

Subcontractors: Tectonics Research, Inc.
9556 West Bloomington
Freeway, Minneapolis, MN 55431

Project Objectives:

To develop and demonstrate proof of principle of a gas-fired, spark-ignited, free-piston, integral linear engine compressor for light commercial heat pump applications.

Project Description:

Honeywell, Inc., was prime contractor for the initial phase of work through January 1983, with Tectonics Research, Inc. (TRI), as subcontractor. Honeywell was phased out on completion of proof-of-concept effort so that costs could be reduced and the project could be better managed. The prime contractor for the second part of the work is TRI. In the first contract, a novel refrigerant seal was developed which performed adequately in limited durability tests. An experimental unit was designed and fabricated that consisted of a carbureted short-stroke version of the existing engine, the novel seal, and a compressor section designed for this application. In laboratory testing, stable operation was achieved over a limited range of simulated environmental conditions, but engine efficiency was low. The seal was proven, and the concept demonstrated. In part II, a revised compressor section was fitted to the original fuel-injected, long-stroke engine, and the operating characteristics of the system are to be determined in laboratory tests. Included in part II are five phases: analysis and design, full load performance testing, natural gas verification and partial load testing, hermetic bellows design and testing, and durability testing. As of September 1985, phases 1 through 4 had been funded.

Publications:

Honeywell, Inc., *Development of a Braun Linear Engine Driven, Heat-Actuated Heat Pump*, ORNL/Sub/80-61619/1, July 1984.

Tectronics Research, Inc., *Hermetic Bellows Seal for Braun Linear Engine—Design, Test, and Demonstration*, ORNL/Sub/80-61613/1, June 1985.

A. T. Braun, "Status of the Braun Free-Piston Engine-Driven Heat Pump," *Proc. DOE/ORNL Heat Pump Conference Dec. 11–13, 1984*, CONF-841231, August 1985.

Patents:

U.S. 4,424,008: A. Braun, Hermetic Seal for Compressors or the Like, Jan. 3, 1984.
U.S. 4,556,369: A. Braun, Bellows Seal, Dec. 3, 1985.

7.2.4 Evaluation of Rotary IC Engine Reliability and Durability for Gas Heat Pump Application

Principal Investigator: R. Syson
Organization: Wedtech
595 Gerard Avenue
Bronx, NY 10451
Telephone: (212) 993-0500

Contract Agency: Gas Research Institute
Contract Number: 5084-242-1128
Contract Period: May 1, 1985, through June 30, 1986
Funding: $1,609,000
Source: GRI **Level:** 100%

Project Objectives:

To construct and evaluate the performance of a low-cost 4 to 5 hp gas-fired rotary engine, to establish the basis for an optimized engine configuration for application to a 3-ton residential heat pump.

Project Description:

Rotary engine technology has several key "potential" advantages compared with classical reciprocating engine approaches for residential applications: high specific power output, less complexity, low cost, low noise/vibration, smooth torque output, and ease of scale to different sizes. The first three features address the most critical issues facing the Gas Research Institute (GRI) in its goal of achieving a near-to-mid-term engine driven heat pump product.

Phase 1 consists of four principal efforts:

- Development of laboratory engine design that meets GRI's specifications for a 3-ton heat pump
- Fabrication of three engines
- Engine evaluation tests
- Prototype engine design

Publications:

None provided.

7.2.5 Residential Reciprocating Internal Combustion Engine Heat Pump Phase I

Principal Investigator: J. Swain
Organization: Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
Telephone: (614) 424-7403

Contract Agency: Gas Research Institute
Contract Number: 5084-242-0974
Contract Period: July 1, 1984, through June 30, 1986
Funding: $1,250,000
Source: GRI **Level:** 100%

Project Objectives:

To develop a reciprocating engine driven heat pump with a 3-ton cooling capacity, to establish an engine/compressor configuration, to fabricate two engines, to obtain efficiency and durability characteristics.

Project Description:

This project utilized state-of-the-art engine technology in conjunction with well-established manufacturing techniques and provided a relatively low-risk approach to a near-to-mid-term engine driven heat pump.

This two-year phase 1 program consisted of five elements:

- An engine design was developed, including engine cycle, combustion system, and fuel control
- Engine/compressor matching was evaluated, focusing on torque/speed relationships
- Engine performance maps were generated for torque, fuel consumption, emissions, and noise (full load and part load)
- Two optimized engines were endurance tested for 2500 h each
- Cost of preliminary engine original equipment manufacturing and installed heat pump system was estimated

Publications:

None provided.

7.2.6 Natural Gas Heat Pump Field Demonstration

Principal Investigator: Sam V. Shelton
Organization: Georgia Institute of Technology
Administration Building
Atlanta, GA 30332
Telephone: (404) 894-3289

Contract Agency: Gas Research Institute
Contract Number: 5081-341-0503
Contract Period: June 1981 through December 1982
Funding: $75,000
Source: GRI **Level:**
AGLC

Project Objectives:

To demonstrate the feasibility and cost effectiveness of operating an internal combustion (IC) gas-fired heat pump in a residential application.

Project Description:

The heat pump used in this project was a 1.6-L, European Ford, four-cylinder engine coupled to a West German compressor. Engine optimization for stationary heat pump operation was the primary thrust of the packaged space conditioning unit. Near term commercialization (1982) and high-efficiency performance [cooling coefficient of performance (COP) of 0.85 to 1.0; heating COP of 1.5 to 1.8] were the major anticipated advantages of this equipment. Emphasis was placed on determining the actual performance, maintenance costs, operating costs, noise level, and overall economic viability of this new heat pump. This project represented the first full-scale field test of this type of heat pump in the United States and included the practical evaluation of a very near term engine heat pump in an American residence. Atlanta Gas and Light Company (AGLC) funded the initial evaluation and shared the cost of the field test. Site design, site modification, equipment purchase, equipment installation, and instrument setup were completed. The engine ran for 2.5 years without maintenance or failure. Field-measured COPs (energy delivered to house air divided by energy delivered by the fuel) were 1.49 for heating and 0.57 for cooling. The engine was oversized. It was estimated that a 1.1-L engine would produce COPs of 1.8 and 0.88 for heating and cooling, respectively.

Publications:

S. V. Shelton, *Natural Gas Internal Combustion Engine Driven Heat Pump*, presented at 6th Heat Pump Technology Conference, Oklahoma State University, Tulsa, Oklahoma, November 1982.

S. V. Shelton, *Natural Gas Internal Combustion Engine Driven Heat Pump Study*, GRI-81/0193, April 1983.

7.2.7 Assessment of Internal Combustion Engines as Drivers for Heat-Actuated Heat Pumps

Principal Investigators: James C. Burke
W. P. Teagan
P. G. Gott
Organization: Arthur D. Little, Inc.
32 Acorn Park
Cambridge, MA 02140
Telephone: (617) 864-5770

Contract Agency: Oak Ridge National Laboratory
Contract Number: 62B-13836C
Contract Period: May 1980 through December 1980
Funding: $49,222
Source: DOE **Level:** 100%

Project Objectives:

To assess the present suitability and future potential of gas-fired and oil-fired internal combustion (IC) engines for use in heat-actuated heat pumps for space conditioning applications.

Project Description:

Results of this study were used as a resource in future program planning and included the definition of research and development tasks that could be undertaken to improve the suitability of IC engine heat pump applications. The study focused on drives for residential and light commercial machines up to 100-kW output—or ~50-hp-engine input.

This program to assess the potential of IC engine heat pumps consisted of four tasks:

- *Task 1*—Review prior experience with piston engine drives for small, long-term stationary applications similar to heat pumps to understand prior success and problems and the approach for minimizing such problems in future applications
- *Task 2*—Establish characteristics of current engines in terms of cost, performance, maintenance, and operational features for various engine types of interest for heat pump applications
- *Task 3*—Prepare and evaluate conceptual designs of IC engine heat pump systems on the basis of cost, performance, economics, and operational and institutional factors to obtain a preliminary assessment of the potential of IC engine-driven heat pump systems
- *Task 4*—Identify program options for IC engine heat pump development

The work on this program, which has been completed, indicated that IC engine heat pump systems appear sufficiently promising to warrant further development, particularly in the larger sizes applicable to multifamily and light commercial applications. Recommended development options include system demonstration, annual performance simulation, production cost projections, and market analysis.

Publications:

A. D. Little, Inc., *Assessment of Internal Combustion Engines as Drivers for Heat Pumps, Final Report,* ORNL/Sub/80-1383C/1&02, January 1984.

7.3 Rankine, Brayton, and Other Engine-Driven Systems

7.3.1 Light Commercial Brayton/Rankine Space Conditioning System

Principal Investigators: David Friedman
Kenneth Tester
Wiley Cowell
Organization: AiResearch Manufacturing Company
2525 West 190 Street
Torrence, CA 90509
Telephone: (213) 323-9500

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24706C
Contract Period: March 1979 through December 1983
Funding: $7,000,000

Source:	**Level:**
DOE	39.3%
Gas Research Institute	39.3%
AiResearch	21.4%

Project Objectives:

To develop a (10-ton) Brayton/Rankine gas-fired space conditioning system and components, to analyze the market and business potential for the product, to test prototype systems and subsystems under simulated field conditions in the laboratory.

Project Description:

This program was a continuation of a research and development effort carried out initially under the sponsorship of the American Gas Association and more recently by the Gas Research Institute and the Department of Energy.

The system consisted of a natural-gas-fueled, Brayton cycle turbine engine driving the centrifugal vapor compressor of a Rankine cycle heat pump through a magnetic coupling. The system offered a high performance potential by utilizing the most advantageous working fluid for each cycle. An air/gas mixture was used in the heat engine, where high turbine inlet temperatures provided high thermal efficiency; and refrigerant-12 was used in the heat pump, because of its desirable thermodynamic characteristics. Waste heat energy from the Brayton cycle engine was transferred to the building in the heating mode.

Extensive breadboard system testing and system analysis were performed. The predicted overall efficiency of the Brayton cycle engine was 27% at the cooling design point, and the predicted overall coefficient of performance at the energy source was 1.0 and 1.2 for cooling and heating, respectively, including parasitics.

Two prototypes were tested and were unable to achieve the milestone turbine-compressor efficiency of 27%. The program was terminated in December 1983.

Publications:

AiResearch Manufacturing Company, *Phase II Brayton/Rankine 10-Ton Gas-Fired Space Conditioning System, First Annual Technical Report,* ORNL/Sub-80/24706/1, July 1982.

Gas Research Institute, *Phase II Brayton/Rankine 10-Ton Gas-Fired Space Conditioning System, Final Report, March 1979–December 1983,* 84/0129.

7.3.2 Determination of Thermal Stability of Organic Working Fluids for Rankine Cycle Systems

Principal Investigator: Dean Morgan
Organization: Thermo Electron Corporation
101 First Avenue
Waltham, MA 02154
Telephone: (617) 890-8700

Contract Agency: Department of Energy, San Francisco
Contract Number: DE-AC03-80CS30220
Contract Period: Sept. 30, 1980, through Sept. 30, 1982
Funding: $418,244
Source: DOE **Level:** 100%

Project Objectives:

To determine the rate of decomposition of organic working fluids due to either pyrolytic or chemical reactions as functions of temperature and the materials in contact with the fluid, under operating conditions comparable with those occurring in Rankine engine solar applications.

Project Description:

This program involved the long-term testing of organic fluids used and/or proposed for solar Rankine cooling systems under conditions that approximated or exceeded those expected in actual operating systems.

Five identical loops were constructed to perform the fluid testing. These loops included all of the components in an actual Rankine engine with the exception of the expander, which was to be replaced with a variable orifice pressure letdown valve to reduce the boiler pressure to the condenser pressure. Design considerations allowed for operations at temperatures that approached thermal stability temperatures of organic fluids with the capability to operate at boiler conditions up to 398.9°C and 1150 psia. Working fluids tested in the loops included:

- Loop 1, R-11 without lubricant
- Loop 2, R-11 with lubricant
- Loop 3, R-113 without lubricant
- Loop 4, R-113 with lubricant
- Loop 5, R-114 without lubricant

Fluid degradation was tested at multiple boiler outlet temperatures. Harvard University provided the chemical analyses for measurement of fluid degradation.

Publications:

D. Morgan, *Determination of the Thermal Stability of Organic Working Fluids Used in Rankine Cycle Systems. Final Test Plan*, TE-4293-168-81, January 1981.

D. Morgan, K. Mills, and Z. Zakak, *Determination of the Thermal Stability of Organic Working Fluids Used in Rankine-Cycle Power Systems for Solar Cooling*, TE170-464-82, DOE/CS/30220-T1, Oct. 1, 1983.

7.3.3 Rankine/Rankine Heat Pump

Principal Investigator: Robert Moriarty
Organization: Mechanical Technology, Inc.
968 Albany Shaker Road
Latham, NY 12110
Telephone: (518) 785-2595

Contract Agency: Gas Research Institute
Contract Number: 5011-341-0149
Contract Period: March 1979 through March 1982
Funding: $3,000,000
Source: GRI **Level:** 10%
NYSERDA 90%

Project Objectives:

To design, develop, and test a residential application gas-fired heat pump (GHP).

Project Description:

The heat pump was targeted for a capacity of 10.8 kW cooling or 11.2 kW heating. The compact, hermetic system was made up of two rotating assemblies: a high-speed (48,000 rpm) turbomachine core and a low-speed (1200 rpm) assembly that consists of a vapor generator, two condensers, and an evaporator.

The GHP differed from conventional heat pumps in several ways. The heat pump was fired by a gas-fired atmospheric combustor. Rotating heat exchangers were used to circulate the conditioned air, and there was no pump in the power cycle or reversing valve in the refrigeration cycle. The GHP was a single-package system in a compact housing and changed air flow circuits to convert from a cooling to a heating mode. Also, the GHP used waste heat recovery to improve its performance in the heating mode.

The GHP used both a Rankine power cycle and a Rankine refrigeration cycle. The components of these cycles were configured into three basic modules: a power module that drove the system, a condenser module that served both the power and refrigeration cycles, and an evaporator module that cooled and conditioned the house air or absorbed heat from the outside air. The condensers and the evaporator never changed their respective functions. The change from cooling to heating mode was done via rerouting of the air flow circuits. The path of the power and refrigerant cycle fluids inside the heat pump never changed, and no reversing valve was required. Air entered the heat pump through air ducts, was pumped by and through the rotating heat exchangers, and exited via discharge ducts.

In phase 1 of this program, the design, procurement, fabrication, and component testing along with analysis studies for system performance, cost, and market applications were completed. In phase 2, system performance maps were completed for the laboratory model. A proposed phase 3 effort involved the engineering development of a prototype unit with participation by commercial heating, ventilation, and air conditioning vendors.

Publications:

E. Enbar and R. Moriarty, *Rankine/Rankine Cycle Gas-Fired Heat Pump, Final Report, March 1979–March 1982*, PB82-254640, MTI-82TR-3, GRI-82/0014, June 1982.

7.3.4 Advanced Heat-Exchanger Technology Development

Principal Investigator: A. Fejer
Organization: Institute of Gas Technology
3424 South State Street
Chicago, IL 60616
Telephone: (312) 567-5734

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-6551
Contract Period: August 1981 through December 1981
Funding: $28,000
Source: DOE **Level:** 100%

Project Objectives:

To examine the technological issues of closed-cycle gas turbine systems, principally related to heat exchangers and combustors; to investigate further the concept of a total energy system that uses turbomachinery to provide varying heating, cooling, and electrical loads.

Project Description:

An analytical study program was conducted by the Institute of Gas Technology to investigate improvements in gas-to-gas heat-exchanger technology for use in external-combustion heat engines. This study was expected to produce a preliminary design for an advanced oil- or gas-fired heat exchanger for use in a compound heat pump gas turbine (CHPGT) using cogeneration techniques. The work included the following tasks:

1. Identification of the state-of-the-art technology in gas-to-gas heat-exchangers
2. Identification of typical CHPGT application and determination of the design requirements for the application identified
3. Determination of the necessary technological advancements to state-of-the-art designs to meet requirements of task 2
4. Conceptual design of radiant/convective and fluidized-bed heat exchangers for the application of task 2
5. Analysis of the conceptual heat-exchanger design and selection of a configuration for a design study
6. Design study of the selected externally fired heat-exchanger
7. Outline and discussion of studies required for final heat-exchanger design.

A report was issued which provided an assessment of current improvements to CHPGT heat-exchanger technology and the analysis of a representative non-site-specific CHPGT applicator.

Publications:

None provided.

7.3.5 A High Seasonal Performance Factor Gas Heat Pump for the North Central United States

Principal Investigator: Paul F. Swenson
Organization: Consolidated Natural Gas Service Company
11001 Cedar Avenue
Cleveland, OH 44106
Telephone: (216) 421-6144/6314

Contract Agency: Department of Energy, Consumer Product Division
Contract Number: DE-AC02-76CS20041
(Old Contract Number: EY-76-C-02-2883)
Contract Period: February 1976 through December 1979
Funding: $2,475,004
Source: DOE **Level:** 50%
CNGSC 50%

Subcontractors:

Advanced Mechanical Technology, Inc.
Masco Corporation
Mechanical Technology, Inc. (principal subcontractor)
Phillips Engineering
Scientific Energy Systems Corporation
William E. Hill and Company

Project Objectives:

To demonstrate the technical feasibility of a steam-turbine-driven heat-actuated heat pump for small and/or large commercial applications, to identify those market areas where a steam turbine-driven heat-actuated heat pump could represent an attractive and competitive product, to identify the parameters under which a business venture could succeed based on manufacturing and marketing steam-turbine-driven heat-actuated heat pumps.

Project Description:

The program consisted of four principal elements: (1) technical effort, (2) market potential study, (3) comparative cost of ownership study, and (4) system cost analysis. The technical effort, initiated ahead of the other program elements, included system specifications, component and system design, component and subsystem bench test, and a full 7.5-ton breadboard system demonstration test.

The market potential study, conducted by William E. Hill and Company, indicated that the estimated first-cost premium would result in an unacceptably small market at either the 7.5-ton or 100-ton size levels. In spite of the large first-cost premiums, the 7.5-ton high seasonal performance factor (HSPF) system appeared to offer payback periods of 10 to 15 years and the 100-ton system payback periods of 6 to 12 years, depending particularly on local utility rates and also on application.

Following a review of the above results, the Consolidated Natural Gas, Department of Energy, and Mechanical Technology, Inc., project management team determined that all technical effort should be terminated. The basis for this determination was the very low potential indicated for the HSPF gas heat pump to become a profitable product line. Despite the severe cost obstacles posed by the high-performance steam turbine prime mover, it provided an acceptable operating efficiency. The steam prime mover also demonstrated the ability to provide these desirable characteristics: (1) quiet operation, (2) long service life with infrequent scheduled maintenance, and (3) low emissions when fired with natural gas or light oils.

Publications:

Consolidated Natural Gas Company and Mechanical Technology Inc., *A High Performance Factor Gas Heat Pump for the North Central United States: Final Report,* DOE/TIC-11248, MTI 79TR68, January 1980.

Patents:

U.S. 4,055,964: P. F. Swenson and P. B. Moore, Heat Pump System, Nov. 1, 1977 (reissued June 21, 1983).
U.S. 4,178,772: P. F. Swenson and P. B. Moore, Heat Pump System, Dec. 18, 1979.
U.S. 4,312,188: P. F. Swenson and P. B. Moore, Heat Pump System, Jan. 26, 1982.

7.3.6 Consolidated Natural Gas Service Company Heat-Pump Integrated Community Energy Systems Assessment

Principal Investigator: Paul F. Swenson
Organization: Consolidated Natural Gas Research Center
Mechanical Technology Inc.
11001 Cedar Avenue
Cleveland, OH 44106
Telephone: (216) 421-6314

Contract Agency: Department of Energy
Contract Number: 31-109-38-4980
Contract Period: Sept. 1, 1977, through Oct. 1, 1979
Funding: $180,000
Source: DOE **Level:** 99%
CNG 1%

Subcontractor: Institute of Gas Technology

Project Objectives:

To perform economic and performance analyses of the heat-actuated heat-pump-centered integrated community energy system (HAHP-ICES) concept to both general and site-specific communities consisting of a mix of residential and commercial buildings located in close proximity to a central utility plant.

Project Description:

The analyses were used to assess energy savings, reduction in environmental emissions, factors affecting economic and commercial viability, and expected market impacts as compared with conventional heating, ventilating, and air conditioning (HVAC) systems.

The HAHP-ICES concept consisted of a central plant thermal utility that satisfied the heating, cooling, and domestic hot water needs for a community of buildings located in close proximity to the central plant. A distribution system of insulated piping physically connected the central plant to the community. The major component of the central plant was a gas-fired steam generator/turbine-driven heat pump.

Two communities were used to provide thermal loads for the central plant. The first, a hypothetical community located in a climate similar to that of Chicago, was used as a base case for utility plant design and showed that the HAHP-ICES could reduce energy consumption up to 30%, with emissions for various pollutants being reduced between 39 and 77%. Economics were favorable provided that the ratio of heating to cooling requirements was greater than 3:1, the region climate featured a high number of heating days (this factor can be offset by thermal load selection), and energy costs and utility rate structures were reasonable.

The site-specific community consisted of 42 townhouses, five 120-unit low-rise apartment buildings, five 104-unit high-rise apartment buildings, one 124,000-ft^2 (11,520-m^2) office building, and a single 135,000-ft^2 (12,542-m^2) retail building located in Monroeville, Pennsylvania. The analysis for this community indicated energy savings of 15 to 22% and pollutant reductions of 20 to 81%. Economic studies showed a favorable rate of return on utility plant investment as compared with conventional HVAC systems (24–32%) but slightly lower return than conventional district heating (about 34%). Both energy savings and economics were strongly affected by the number of steam turbines employed in the central plant. Market studies indicate that moderate impact is possible in the 1980–1990 time frame.

Publications:

P. F. Swenson et al., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report,* ANL/CNSU-TM-29, January 1980.

P. F. Swenson et al., *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report,* ANL/CNSV-TM-7.

7.4 Chemical and Absorption Systems

7.4.1 Evaluation of Absorption Fluid System Research Needs

Principal Investigator: Robert A. Macriss
Organization: Institute of Gas Technology
4201 West 36th Street
Chicago, IL 60632
Telephone: (312) 890-6444

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-47989C
Contract Period: January 1984 through January 1987
Funding: $309,975
Source: DOE **Level:** 100%

Project Objectives:

To collect, catalog, and coarsely screen available U.S. and foreign data on known absorption fluid systems; to identify research areas (temperature, pressure, enthalpy, etc.) where existing data are missing, incomplete, or inaccurate.

Project Description:

In the first year of this project, 150 U.S. publications containing data that relate to properties of absorption fluids were identified; from these, 67 were selected as primary sources of relevant data. Coarse screening and evaluations were performed. Data gaps for key fluids were summarized, and unresolved conflicts in the data were noted. With few exceptions, all candidate fluids for development activities dealing with advanced absorption heat pump concepts were found to have data gaps that need to be addressed in the near future.

In the second year, 300 foreign publications principally from western Europe and Japan were identified, 127 of which were selected as sources of relevant data. The conclusion after processing the foreign data was the same, that significant data gaps exist relative to current needs in support of absorption heat pump development activities.

In the third and current year, additional foreign data will be sought, principally from Russia, and all relevant data collected will be subjected to a fine screening and will be formatted for electronic data processing storage and retrieval.

Publications:

R. A. Macriss and T. S. Zawacki, *Absorption Fluids Data Survey, Final Report on USA Data*, ORNL/Sub/84-47989/1, Institute of Gas Technology, December 1985 (draft).

R. A. Macriss, J. M. Gutraj, and T. S. Zawacki, *Absorption Fluids Data Survey, Final Report on Foreign Data*, ORNL/Sub/84-47989/2, Institute of Gas Technology, April 1986 (draft).

7.4.2 Development and Proof Testing of Advanced Absorption Refrigeration Cycle Concepts

Principal Investigator: Floyd Hayes
Organization: Trane Company
3600 Pammel Creek Road
LaCrosse, WI 54601
Telephone: (608) 783-1925

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-17498C
Contract Period: February 1983, continuing
Funding: $1,050,000
Source: DOE **Level:** 57%
Trane 43%

Project Objectives:

To screen and evaluate advanced absorption cycle concepts in combination with known state-of-the-art absorption fluids, to develop advanced cycle components and optimize system design, to fabricate and proof test the selected advanced absorption cycle in a laboratory breadboard system configuration, to fabricate and proof test the selected advanced absorption cycle in a proof-of-concept prototype unit.

Project Description:

Target performance goals at the beginning of the project were steady-state coefficients of performance of 1.2 at −8.3°C and 1.6 at 8.3°C in the heating mode and 0.7 at 35°C in the cooling mode. Analysis and evaluation have been completed, and an advanced cycle exceeding the target performance goals was selected. The primary phase 1 results of this program are as follows:

- The gas-fired absorption heat pump can be an attractive heating/cooling alternative in the commercial market. The economics look best in areas that have high heating loads.
- The economics of the commercial gas-fired absorption heat pump will improve as the cost of gas increases, at least up to the point where an all-electric system shows lower operating costs in northern climates.
- Compared with the conventional electric chiller/gas boiler system used as the reference system in this study, the gas-fired absorption heat pump accomplishes the Department of Energy's goal of conserving energy and provides much more balanced loads for both electric and gas utilities.
- The preferred absorption cycle for commercial gas-fired heat pumps contains the following efficiency enhancement features:
  - Absorber heat exchange and generator heat exchange
  - Absorber/generator heat exchange
  - Regeneration
  - A resorption/desorption circuit to replace the conventional condenser/evaporator circuit
- The preferred fluid at this point appears to be the ternary mixture $NH_3/H_2O/LiBr$, with $CH_3,NH_2H_2O/LiBr$ a possible alternative. The preferred binary mixture is NH_3/H_2O.

The next phase of work will be conducted to determine if the performance that has been predicted can be achieved in a practical system. Development of components, system design, fabrication, and proof testing of the selected cycles are proceeding.

Publications:

F. C. Hayes and R. J. Modahl, "Evaluation of Advanced Design Concepts for Absorption Heat Pumps," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11– 13, 1984*, CONF-841231, August 1985.

7.4.3 Absorption Heat Pump Simulation and Studies

Principal Investigator: Gershon Grossman
Organization: Technion–Israel Institute of Technology
Haifa 32 000
Israel
Telephone: (04) 292074

Contract Agency: Oak Ridge National Laboratory
Contract Number: 19X-43337V
Contract Period: January 1983, continuing
Funding: $100,000
Source: DOE **Level:** 100%

Project Objectives:

To develop a computer simulation code for absorption heat pumps to be used in the analysis of advanced absorption cycles and fluids.

Project Description:

A modular computer simulation program has been developed which can simulate absorption systems in varying cycle configurations and with different working fluids. Most of the objectives of the project have been met. The program has been applied to simulate a variety of single-stage, double-stage, and dual loop heat pumps and heat transformers with five different fluid combinations. The code is generally quite robust, but some problems are still encountered with fluids with a volatile absorbent such as NH_3/H_2O. The program is user friendly and has been tried by several ORNL research staff members and subcontractors.

Some final improvements in the program are presently being added. A final report including a user's manual should be available by December 1986.

Publications:

G. Grossman, *Multi-Stage Absorption Heat Pumps for Industrial Applications—Final Report*, ORNL/Sub/83-43337/1, October 1984.

G. Grossman and E. Michelson, *Absorption Heat Pump Simulation and Studies: A Modular Computer Simulation of Absorption Systems—Final Report*, ORNL/Sub/83-43337/2, April 1986.

7.4.4 Development and Proof Testing of Advanced Absorption Refrigeration Cycle Concepts

Principal Investigator: Robert C. Reimann
Organization: Carrier Corporation
Carrier Tower
P.O. Box 4800
Syracuse, NY 13221
Telephone: (315) 432-7462

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-17499C
Contract Period: November 1982, continuing
Funding: $1,600,000
Source: DOE **Level:** 100%

Project Objectives:

To screen and evaluate advanced absorption cycle concepts in combination with known state-of-the-art absorption fluids, to develop advanced cycle components and optimize system design, to fabricate and proof test the selected advanced absorption cycle in a laboratory breadboard system configuration, to fabricate and proof test the selected advanced absorption cycle in a proof-of-concept prototype unit.

Project Description:

Target performance goals at the beginning of the project were steady-state coefficients of performance of 1.2 at 17°F (−8.3°C) and 1.6 at 47°F (8.3°C) in the heating mode and 0.7 at 95°F (35°C) in the cooling mode.

The final result of the selection process resulted in the choice of a somewhat novel "dual loop" cycle that double-couples two independent single-stage machines to produce two-stage efficiencies. The cycle is characterized by the coupling of both the high-side condenser and absorber to the low-side generator, and producing heat to the load as the sum of the low-side condenser and absorber minus that required by the high-side evaporator. Because the two loops are isolated from each other with respect to any mass transfer, different absorbent-refrigerant pairs can be used in each loop, thus permitting considerable freedom in selection of suitable pressures, in ability to utilize pairs of limited thermal stability, isolation of flammable refrigerants or absorbents from the direct-fired generator and independent selection of pairs for optimum efficiency of the cycle.

Lithium bromide–water will be used in the upper temperature loop because of the demonstrated chemical stability in excess of 300°F (150°C), high latent heat refrigerant, and proven experience. Methylamine will be the lower-temperature-loop refrigerant, dissolved in a 60% lithium bromide–water solution absorbent. This choice was made on the basis of anticipated chemical stability and an acceptable set of pressures.

Anticipated activities in phase 2 include the following.

1. Testing and evaluation of fluids with respect to chemical stability and transport properties as well as testing of potential "backup" candidates.

2. Construction and testing of a single-stage machine as an intermediate step to reduce the risks and unknowns of the assembly of too many unproven technologies simultaneously. This direct-fired machine would employ a 1:1 mole ratio of zinc bromide–lithium bromide as the absorbent and methanol as the refreigerant and would establish the direct-fired generator design, test the flue gas recuperator, and serve as a test bed for data collection. Preliminary cycle calculations indicate that this system's performance, though marginal in comparison with the dual-loop system, has potential in meeting the project goals, as well as use in other applications.

3. Design, construction, and testing of the advanced dual-loop machine employing data from items 1 and 2 above.

A possible third phase is anticipated in which a packaged, proof-of-concept prototype would be constructed from the results of phase 2.

Publications:

R. C. Reimann, "Advanced Absorption Heat Pump Cycles," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984*, CONF-841231, August 1985.

Patents:

U.S. 4,542,628: W. J. Biermann et al., Coupled Dual Loop Absorption Heat Pump, Sept. 24, 1985.

U.S. 4,542,629: W. J. Biermann, Variable Effect Desorber-Resorber Absorption Cycle, Sept. 24, 1985.

U.S. 4,546,620: W. J. Biermann, Absorption Machine with Desorber-Resorber, Oct. 15, 1985.

U.S. 4,548,048: R. C. Reimann and R. A. Root, Direct-Fired Absorption Machine Flue Gas Recuperator, Oct. 22, 1985.

U.S. 4,570,456: R. C. Reimann and R. A. Root, Submerged Bundle Counterflow Generator for Use in Gas-Fired Absorption Machines, Feb. 18, 1986.

7.4.5 Development and Proof Testing of Advanced Absorption Refrigeration Cycle Concepts

Principal Investigator: Benjamin A. Phillips
Organization: Phillips Engineering
721 Pleasant Street
St. Joseph, MI 49085
Telephone: (616) 983-3935

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-17497C
Contract Period: November 1982, continuing
Funding: $2,069,000
Source: DOE **Level:** 100%

Project Objectives:

To screen and evaluate advanced absorption cycle concepts in combination with known state-of-the-art absorption fluids, to develop advanced cycle components and optimize system design, to fabricate and proof test the selected advanced absorption cycle in a laboratory breadboard system configuration, to fabricate and proof test the selected advanced absorption cycle in a proof-of-concept prototype unit.

Project Description:

Target performance goals at the beginning of the project were steady-state coefficients of performance of 1.2 at −8.3°C and 1.6 at 8.3°C in the heating mode and 0.7 at 35°C in the cooling mode. Analysis and evaluation have been completed, and an advanced cycle exceeding the target performance goals was selected.

The selection of the generator absorber heat exchanger (GAX) cycle for phase 2 development of a breadboard test unit using ammonia–water was accepted by the Department of Energy and Oak Ridge National Laboratory. It was also proposed that if the program was successful, it should be followed by trials of the ammonia/lithium bromide–water combination.

The phase 2 work was started by designing the breadboard test unit for operation with electric heat at three refrigeration tons of capacity. Fabrication and proof testing of the selected cycle in laboratory breadboard configuration have been completed. Measured performance of the laboratory breadboard exceeded the original performance goals. Development of components, system design, fabrication, and proof testing of a packaged proof-of-concept prototype unit are proceeding.

Publications:

B. A. Phillips, "Analyses of Advanced Residential Absorption Heat Pump Cycles," *Proc. DOE/ORNL Heat Pump Conference, December 11–13, 1984*, CONF-841231, August 1985.

7.4.6 Dual-Cycle Absorption Heat Pump Phases 1 and 2

Principal Investigator: David A. Ball
Organization: Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
Telephone: (614) 424-4901

Contract Agency: Gas Research Institute
Contract Number: 5083-242-0850
Contract Period: May 1985 through April 1987
Funding: $5,000,000
Source: GRI **Level:** 100%

Project Objectives:

To develop a residential-size gas heat pump.

Project Description:

A level 1 breadboard system was constructed and tested in phase 1 (all coefficient of performance and capacity goals were achieved). In phase 2, eight packaged prototypes will be evaluated under actual residential conditions in a field experiment. Data from this work will be used to achieve an optimized design for full-scale field tests in 1987.

Publications:

None provided.

7.4.7 Double-Effect Absorption Heat Pump Phases 1, 2, and 3

Principal Investigator: Edward A. Reid
Organization: Columbia Gas
1600 Dublin Road
Columbus, OH 43216
Telephone: (614) 481-1284

Contract Agency: Gas Research Institute
Contract Number: 5080-341-0344
Contract Period: Oct. 1, 1980, through March 1986
Funding: $4,500,000
Source: GRI **Level:** 60%
Columbia Gas 40%

Project Objectives:

To develop a residential-size gas heat pump.

Project Description:

Heating and cooling coefficients of performance of 1.6 and 0.8, respectively, were achieved in phase 1 with a breadboard system.

In phase 2, an advanced breadboard system using commercial-like components is under evaluation. Corrosion has been reduced to less than 1 mil/year, and one solution pump option has attained 5000 simulated operating hours.

In phase 3, a packaged prototype heat pump will be designed and constructed. Optimization will continue on key components such as the solution pump and control system.

Publications:

F. B. Cook et al., *Research, Development, and Demonstration of an Advanced Heat-Actuated Heat Pump, Annual Report, October 1980–September 1981*, PB-82-25490, April 1982.

F. B. Cook et al., *Research, Development, and Demonstration of an Advanced Heat-Actuated Heat Pump, Phase I, Final Report, October 1980–Aug. 31, 1982*, PB-83-249466, September 1982.

W. F. Morse et al., "Columbia's Gas Heat Pump, Progress Report," *Proc. 1983 International Gas Research Conference, June 13, 1983*, CONF-830664, 1983.

7.4.8 Heat and Mass Transfer in Absorption Fluids

Principal Investigator: Horacio Perez-Blanco
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-0419

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: May 1984 through August 1985
Funding: $100,000 (phase 1)
Source: DOE **Level:** 100%

Project Objectives:

To develop information on materials compatibility and on specialized instrumentation toward building a test facility to study heat and mass transfer in absorption fluids.

Project Description:

This test facility would be devoted to developing experimental correlations for heat and mass transfer in absorption fluids. As far as possible, the correlations will be based on existing theories or on dimensional analysis of experimental results.

Publications:

J. C. Guien, J. H. De Van, and H. Perez-Blanco, *Corrosion of Materials in Absorption Heating and Refrigeration*, ORNL/TM-9646, June 1985.

7.4.9 Development and Demonstration of an Ammonia–Water Absorption Heat Pump

Principal Investigator: Richard H. Merrick
Organization: Arkla Industries, Inc.
P.O. Box 534
Evansville, IN 47704
Telephone: (812) 424-3331

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-61603C
Contract Period: January 1980 through September 1984
Funding: $575,000
Source: DOE **Level:** 95%
Arkla 5%

Project Objectives:

To develop a residential air-source ammonia–water absorption heat pump designed to operate in the heating mode only and deliver its output as hot water.

Project Description:

This project extended absorption chiller technology to the design of heat pumps. At the time of project inception, Arkla Industries produced the only residential chiller in the United States. Technology used for the ammonia–water chiller produced by Arkla Industries was applied to development of the absorption heat pump.

Four laboratory breadboard versions of the heat pump were built to investigate the effect of various options for the thermodynamic cycle and the hardware. After thermal performance objectives were achieved, five copies of a packaged version were built and used in a variety of performance evaluation experiments including steady-state, cycling, frosting, and durability tests.

Publications:

D. Kuhlenschmidt and R. H. Merrick, "An Ammonia–Water Absorption Heat Pump Cycle," *ASHRAE Trans.* **89**(1), CONF-830102-4, January 1983.

7.4.10 Organic Absorption Gas-Fired Residential Heat Pump

Principal Investigator: Kevin P. Murphy
Organization: Allied Corporation
P.O. Box 1087R
Morristown, NJ 07960
Telephone: (201) 455-2064

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24610C
Contract Period: October 1979 through August 1984
Funding: $4,481,000
Source: DOE — **Level:** 60%
Gas Research Institute — 40%
Allied Corporation — 17% additional

Subcontractors:

Phillips Engineering Company
721 Pleasant Street
St. Joseph, MI 49085
Ben Phillips
(616) 983-3935

Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 01240
E. Shorey and D. Lee
(617) 864-5770

United Technologies Research Center
East Hartford, CT 06108
Gorken Melikian
(203) 727-7554

Project Objectives:

To develop an organic absorption gas-fired residential heat pump system to a production prototype level, to analyze the market and business potential for the absorption heat pump market, to evaluate the system first cost and actual annual performance and operation costs, to develop computer simulation of the absorption system to examine design variables more efficiently, to develop data for toxicity and product safety, to identify problems (by operating some test units in actual service).

Project Description:

This project was a continuation of a research and development effort carried out initially under the sponsorship of the American Gas Association and more recently by the Gas Research Institute and the U.S. Department of Energy.

The gas-fired absorption cycle heat pump under design and development in this project was based on a novel organic absorption fluid pair. The absorber fluid was ethyltetrahydrofurfurylether (ETFE), and the refrigerant was chlorotrifluorethane (R-133A). The system was characterized by higher capacity and coefficient of performance in the heating mode than in the cooling mode. Thus, a heat pump system using this fluid combination is more applicable to the northern climates. These organic fluids are compatible with aluminum, and offer a potential fabrication cost advantage over conventional ammonia–water absorption equipment.

ORNL/Sub/79-24610/3 is the third report of the series on development of absorption-type gas-fired heat pumps using organic working fluids. The residential heat pumps were to provide the full heating and cooling requirements of a house down to 0°F outdoor temperature. This volume addresses the design, construction, development, and testing of early units for an outdoor field trial for both residential use and continuous-run operation outdoors. Simultaneously, those components of the heat pump system that had not attained full performance levels, i.e., sealed absorption system and auxiliary components, were developed individually on breadboard test units to attain the design requirements for full performance. Six absorption heat pumps using R-133a and ETFE as the working fluids were designed, constructed, developed, and tested as part of the field trial. Five units were operated outdoors during most of two winters and two summers. Two of those were on residences, and three were applied to the laboratory building, two of which operated on continuous run and the third on a continuous on/off cycle. The sixth unit was used for development of cycling operation to high efficiencies. Problems of operation in a northern climate were investigated during the outdoor operation of the five units during a total of 34,263 h of operation.

ORNL/Sub/79-24610/4 is the fourth in a series of reports covering work on the development of a residential-sized absorption heat pump using organic-type working fluids. This report covers the development work on the R123a/ETFE pair and an economic analysis of the system. Extensive thermodynamic and physical properties of the R123a/ETFE system were developed. Theoretical analysis of the data was made

and showed very good performance. Subsequent testings on equipment not fully developed for R123a/ETFE confirmed this performance. The economic analysis showed that the system was competitive in most areas of the United States if improved performance goals (coefficient of performance of 1.5) could be met. The most important factors in determining competitiveness are heating-to-cooling ratios and the relative cost of gas and electricity.

Publications:

B. A. Phillips, "Development of a Residential Gas Absorption Heat Pump," *ASHRAE Trans.*, **89**(1), January 1983.

Allied Corporation Chemical Sector, *Development of a Residential Gas-Fired Absorption Heat Pump. Final Report: Component Development and Field Trial Program,* ORNL/Sub/79-24610/3, August 1985.

Allied Corporation Chemical Sector, *Development of a Residential Gas-Fired Absorption Heat Pump. Final Report: Physical and Thermodynamic Properties of R123A/ETFE; System Development and Testing; Economic Analysis,* ORNL/Sub/79-24610/4, August 1985.

7.4.11 Experimental Evaluation of Prototype Absorption Heat Pumps

Principal Investigators: David A Didion
Organization: National Bureau of Standards
Building 226, Room B-126
Gaithersburg, MD 20899
Telephone: (301) 921-2994

Contract Agency: Oak Ridge National Laboratory
Contract Number: NBS-IEA, DE-AI05-810R20890
Phillips, 86X-17497C
Contract Period: June 1982 through March 1984
Funding: $215,000
Source: DOE **Level:** 100%

Subcontractor: Phillips Engineering Company, 721 Pleasant Street, St. Joseph, MI 49085

Project Objectives:

To obtain comprehensive data in the laboratory on the component and system performance of two prototype absorption heat pumps in steady-state and cyclic modes of operation.

Project Description:

Two residential absorption heat pumps were developed previously with the Department of Energy/Oak Ridge National Laboratory and Gas Research Institute funding. One of these was a heat-only, ammonia–water system developed by Arkla Industries. The other, developed by Allied Corporation and Phillips Engineering Company, provided heating and cooling using a CFC refrigerant and Allied's proprietary ETFE absorbent. Both units met performance goals. Only steady-state system performance was measured. This project measured component and system performance under transient conditions. The National Bureau of Standards (NBS) and Phillips Engineering have modified their respective units (NBS, the Arkla unit, and Phillips, the Allied unit) for measurement of fluid concentrations and flow rates and additional pressures and temperatures. Laboratory experiments were run under startup, shutdown, and steady-state modes of operation.

An absorption water chiller and an absorption heat pump were extensively tested under steady-state and cyclic operating conditions. The tests were performed on two different units, one for a cooling only and one for a heating only application, and the results were reported in two separate parts. In addition to the "black box tests" of the units, the causes for the degradation during part-load operation were investigated in more detail using the absorption chiller. Migration of the fluids during the off periods was found to be a major contribution to the degradation. Furthermore, the influence of various heating water temperatures and flow rates and the sensitivity of the charge on steady-state performance were more closely investigated employing the absorption heat pump.

Testing and rating procedures were developed for gas-fired absorption devices operating in either the heating or cooling modes. These procedures were designed to include the effects of part-load and cyclic operation, variations in outdoor temperature, and frost formation during the heating mode. Both air-source and groundwater-source absorption heat pumps were considered, as well as air-cooled and groundwater-cooled air conditioners and water chillers. A calculation procedure was presented for estimating the heating and cooling seasonal performance and cost of operation of residential water chillers, air conditioners, and heat pump units.

Publications:

D. A. Didion and R. Radermacher, "Investigation of the Part-Load Performance of an Absorption Chiller," *ASHRAE Trans.* **89**(1), January 1983.

R. Radermacher et al., *Laboratory Evaluation of the Steady-State and Part Load Performance of Absorption Type Heating and Cooling Equipment*, NBSIR-84-2816, March 1984.

B. Weber et al., *Test Procedures for Rating Residential Heating and Cooling Absorption Equipment*, NBSIR-84-2867, April 1984.

R. Radermacher, "Laboratory Experiments on Absorption Heat Pumps," *Proc. DOE/ORNL Heat Pump Conference*, CONF-841231, August 1985.

7.4.12 Study of the Simultaneous Heat and Mass Transfer in Absorption/Desorption Processes

Principal Investigator: Gershon Grossman
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-1083

Contract Agency: Oak Ridge National Laboratory
Contract Number: W-7405-eng-26/AA-55-15-15-0
Contract Period: October 1980 through September 1982
Funding: $100,000
Source: DOE **Level:** 100%

Project Objectives:

To develop fundamental and quantitative information on the combined heat and mass transfer occurring in absorption and desorption.

Project Description:

Absorption and desorption processes occur in many chemical engineering operations. One application of particular interest where these processes take place is in absorption heat pumps and chillers. It was realized quite some time ago that basic information, including theoretical models and experimental data on the simultaneous heat and mass transfer in absorption/desorption, was lacking. The literature describes mass transfer under isothermal conditions or heat transfer at fixed concentrations. Little information was available on the combination of both. Empirical data on the combined process were gathered by manufacturers of absorption equipment for selected material combinations under limited operating conditions. These data were not generally available.

Two theoretical models were developed on the simultaneous heat and mass transfer process in absorption. The first model involved laminar flow and considered the variation in concentration and temperature in a falling film as the process takes place. Results included the heat and mass transfer coefficients and scaling laws of the process. The second model involved turbulent flow and considered the effect of varying eddy diffusivity, as governed by the Reynolds number, on the temperature and concentration distribution.

The models were used to design an adiabatic absorber for the Oak Ridge National Laboratory 45-kW prototype absorption heat pump. However, the kinetics of the absorption of water vapor in lithium bromide solution were more rapid than anticipated, such that no significant improvement in the absorption rate could be measured with this working fluid pair.

Publications:

G. Grossman, *Simultaneous Heat and Mass Transfer in Absorption of Gases in Laminar Liquid Films*, ORNL/TM-8366, September 1982.

G. Grossman, "Simultaneous Heat and Mass Transfer in Absorption/Desorption of Gases in Laminar Liquid Films," *Proc. AIChE Winter Annual Meeting*, 1982.

G. Grossman, "Simultaneous Heat and Mass Transfer in Film Absorption Under Laminar Flow," *Int. J. Heat Mass Trans.* **26**, 357–71, (1983).

G. Grossman and M. T. Heath, *Simultaneous Heat and Mass Transfer in Absorption of Gases in Turbulent Liquid Films*, ORNL/TM-8503, July 1983.

Patents:

U.S. 4,458,500: G. Grossman and H. Perez-Blanco, Adiabatic Absorber, 1982.

7.4.13 Space Conditioning Performance Analysis and Simulation Study

Principal Investigator: Ulrich Bonne
Organization: Honeywell, Inc.
10701 Lyndale Avenue South
Bloomington, MN 55420
Telephone: (612) 887-4477

Contract Agency: Gas Research Institute
Contract Number: 5014-341-0144
Contract Period: May 1, 1981, through March 31, 1982
Funding: $100,000
Source: GRI **Level:** 100%

Project Objective:

To prepare a comprehensive report that documents the performance characteristics and the various factors that influence system performance of advanced and conventional space conditioning systems.

Project Description:

Performance simulations using computer codes were used to project system performance and cost savings in terms of energy savings for advanced and conventional heating and cooling systems. The advanced systems were gas-fired engine driven heat pumps and gas-fired absorption heat pumps. The conventional system had an electric driven heat pump with supplemental gas heating for the heating mode. Gas heating supplemented absorption and engine driven systems.

Honeywell proprietary codes, FLAME and HFROST, were used to study conventional systems; HSORB was used to study the absorption systems. The analysis was performed to study the effects of component sizes and efficiencies, electric power and gas consumption, mode of operation, climate, refrigerant circuit features, unit cycling and controls, and unit losses on overall system performance and cost efficiency. Cost efficiency, which served as a ranking parameter for the various heat pump systems, was defined as the ratio of net space conditioning system output to the equivalent gas input (normalized to account for electric power consumption).

Additional factors analyzed included the benefits of integrating space heating and water heating functions and the effects of barriers or standards to efficient use of natural gas.

Publications:

A. Patani and U. Bonne, *Space Conditioning Performance Analysis and Simulation Study, Annual Report, February 1980–February 1981*, PB-82-199001, July 1981.

7.4.14 Dissociation Pressure Measurements on Salts Proposed for Thermochemical Energy Storage and Chemical Heat Pumps

Principal Investigator: Robert W. Carling
Organization: Sandia Laboratories
Exploratory Chemistry Division
Livermore CA 94550
Telephone:

Contract Agency: Department of Energy
Contract Number: DE-AC04-76DP00789
Contract Period: 1978 through July 1979
Funding: Not Available
Source: DOE **Level:** 100%

Project Objectives:

To measure data on the reaction energies and pressure/temperature relationships of the salts used in chemical heat pumps by assembling an apparatus with a sensitive cantilever balance used to prepare salt samples in situ so that stoichiometry of the salt hydrate, ammoniate, or methanolate is known prior to pressure measurements.

Project Description:

Pressure/temperature data were obtained over large temperature (293 to 523 K) and pressure (10^{-3} to 10^5 torr) ranges. The entire experiment was controlled and data were recorded using a desk-top calculator.

Dissociation pressure measurements were made on the $MgCl_2/H_2O$ and $CaCl_2/NH_3$ systems. For the first time on any hydrate system, complete second- and third-law analyses were done on $MgCl_2 \cdot 6H_2O$ and $MgCl_2 \cdot 4H_2O$. This was made possible by generating free energy functions from available heat capacity data for $MgCl_2 \cdot 6H_2O$, $MgCl_2 \cdot H_2O$, and $MgCl_2 \cdot 2H_2O$. Results for $MgCl_2 \cdot 6H_2O$ yielded enthalpies of dissociation at 298.15 K of 27.86 ± 0.11 and 28.00 ± 0.03 $kcal \cdot mol^{-1}$ H_2O for second- and third-law analyses, respectively. For $MgCl_2 \cdot 4H_2O$, the values determined were 31.7 ± 0.6 and 32.0 ± 0.2 $kcal \cdot mol^{-1}$ H_2O. These values show excellent internal consistencies (second- and third-law agreement) and external agreement with dissociation enthalpies 27.82 and 32.42 $kcal \cdot mol^{-1}$ H_2O for $MgCl_2 \cdot 6H_2O$ and $MgCl_2 \cdot 4H_2O$, respectively, obtained from solution calorimetry experiments.

Values for the enthalpies of dissociation of the calcium chloride ammoniates were also determined: 10.6 ± 0.07, 10.04 ± 0.08, 16.2 ± 0.2, and 18.7 ± 0.2 $kcal \cdot mol^{-1}$ NH_3 for $CaCl_2 \cdot 8NH_3$, $CaCl_2 \cdot 4NH_3$, $CaCl_2 \cdot 2NH_3$, and $CaCl_2 \cdot NH_3$, respectively. These data confirm those previously reported for $CaCl_2 \cdot 8NH_3$ and $CaCl_2 \cdot 4NH_3$ and established reliable values for $CaCl_2 \cdot 2NH_3$ and $CaCl_2 \cdot NH_2$.

Publications:

R. W. Mar and R. W. Carling, *Thermochemistry of Hydrated Salts*, SAND79-8503, March 1979.

R. W. Carling, *Dissociation Pressure Measurements on Salts Proposed for Thermochemical Energy Storage*, SAND79-8033, July 1979.

P. O. Offenhartz et al., *A Heat Pump and Thermal Storage System for Solar Heating and Cooling Based on the Reaction of Calcium Chloride and Methanol Vapor*, SAND79-8512, August 1979.

P. O. Offenhartz et al., "A Heat Pump and Thermal Storage System for Solar Heating and Cooling Based on the Reaction of Calcium Chloride and Methanol Vapor," *J. Solar Energy Eng.* **102**, 59 (1980).

R. W. Carling, A. T. Wondoloski, and D. C. Macmillan, *Heat of Formation of $CaCl_2 \cdot 2CH_3OH$ and $CaCl_2 \cdot 2C_2H_5OH$ by Solution Calorimetry,"* SAND80-8689, June 1980.

R. W. Mar and R. W. Carling, "The Calcium Chloride–Ethanol System," *Thermochimica Acta* **45**, 213 (1980).

R. W. Carling, "Dissociation Pressures and Enthalpies of Reaction in $MgCl_2 \cdot nH_2O$ and $CaCl_2 \cdot nNH_3$," *J. Chem. Thermo.* **13**(6), 503–512 (1981).

R. W. Carling, "Thermochemical Measurements of Gas–Solid Reactions Proposed for Chemical Heat Pumps," *Proc. Workshop on Techniques for Measurement of Thermodynamic Properties, Albany, Oregon, 1979*, USBM IC 8853, 1981 [Inf. Circ. U.S. Bur. Mines 1981, IC 8853, 323–33].

R. W. Carling, A. T. Wondolowski, and D. C. Macmillan, "Enthalpy of Formation of $CaCl_2 \cdot 2CH_3OH$ and $CaCl_2 \cdot 2C_2H_5OH$ by Solution Calorimetry," *J. Chem. Thermo.* **14**, 125 (1982).

8. INDUSTRIAL APPLICATIONS

8.1 Electric and Fossil-Fuel-Fired Systems

8.1.1 Advanced Open-Cycle Centrifugal Vapor Compression Heat Pump

Principal Investigator: T. L. Iles
Organization: Garrett Corporation
AiResearch Manufacturing Company
2525 West 190 Street
Torrance, CA 90509
Telephone: (213) 321-5000

Contract Agency: Gas Research Insitute
Contract Number:
Contract Period: March 1981, continuing
Funding:
Source: GRI **Level:** 100%

Subcontractors: Niro Atomizer, Inc.
APV Company

Project Objectives:

To develop a gas turbine-driven centrifugal vapor compressor system to be used with low temperature evaporators serving as preconcentrators in a drying facility.

Project Description:

The system uses as a heat source water vapor that is exhausted from an evaporator and mechanically compressed in the steam chest of the same evaporator. The system incorporates a single-stage centrifugal compressor used in a multieffect evaporator with high temperature differentials but at the lower cost of a single-stage compressor. The compressor can increase the vapor saturation temperature up to 45°F (7.2°C) at a design flow of 35,000 cfm. The gas turbine engine that drives the compressor is a Garrett model 1E831-800. Equipment design was completed in 1981. The installation design and equipment fabrication was completed in 1982. Field testing at a milk-drying facility is under way.

Publications:

T. L. Iles et al., *Open-Cycle Centrifugal Vapor-Compression Heat Pump, Annual Report, March 1983–February 1984,* PB-85-113405/XAB, April 1984.

8.1.2 Open-Cycle Rotary Screw Steam-Compression Heat Pump

Principal Investigators: R. Sakhuja
F. E. Becker
Organization: Thermo Electron Corporation
101 First Avenue
Waltham, MA 02154
Telephone: (617) 890-8700

Contract Agency: Gas Research Institute
Contract Number: 5011-342-0094
Contract Period: January 1979, continuing
Funding:
Source: GRI **Level:** 100%

Subcontractor: Beloit Power Systems

Project Objectives:

To develop and commercialize both the open-cycle and Rankine cycle heat pump systems, to develop and commercialize an open-cycle steam-compression heat pump that takes advantage of the rotary screw compressor's unique ability to recompress wet and contaminated waste steam while overcoming inherent size limitations.

Project Description:

The system utilizes excess low-pressure steam or that produced from an excess heat source with a waste-heat boiler and compresses this steam to the desired pressure level for process use. The compressor is driven by a gas-fired prime mover such as a gas turbine or gas engine. To enhance system performance, the prime mover exhaust and cooling jacket heat is recovered to generate additional process steam or hot water. The major fraction of the energy in the steam is already available to the compressor as latent heat. As a result, only a small fraction of additional energy is required to raise its pressure and temperature to a useful level. Although significant energy savings can be realized by use of the steam heat pump system, such a concept must also be justified economically. Economic analyses have shown favorable simple payback periods of one to three years depending on the nature of the excess heat or steam source, steam flow rate, pressure ratios, and fuel cost.

A proof-of-concept field test system, fabricated and tested at Thermo Electron, included all the major components and was of adequate size to demonstrate the performance and operating characteristics of a full-sized system. The system was based on a 2200-cfm (1.04-m^3/s) screw compressor with a built-in pressure ratio of 3:1. The compressor was driven by a 500-hp (373-kW), 1200-rpm industrial gas engine through a 1:7.7 ratio gearbox. The system was designed for a nominal steam flow rate of 10,000 lb/h (1.26 kg/s) at an inlet pressure of 30 psia (207 kPa) and an outlet pressure of 90 psia (621 kPa).

A test facility was built to investigate important operating parameters of the system's modified screw compressor. The compressor was tested over a wide range of operating conditions, with experimental results showing excellent agreement with predicted performance. The compressor's operation with wet steam and water injection was completely satisfactory, demonstrating its suitability for use in a steam heat pump.

A prototype system was installed at a batch chemical plant. Field data collection began in May 1983. The system has successfully completed 3650 h of operation.

Publications:

R. Sakhuja and F. E. Becker, *Open-Cycle Vapor Compression Heat Pump, Annual Report for 1979,* PB-80-205461, July 1980.

R. Sakhuja and F. E. Becker, *Open-Cycle Vapor Compression Heat Pump, Annual Report for 1980,* PB-82-110503, May 1981.

F. E. Becker and R. Sakhuja, "Development of an Open-Cycle Vapor Compression Heat Pump System," *Proc. 1981 International Gas Research Conference, Sept. 28, 1981*, CONF-810909, 1982.

8.1.3 Development of a Brayton-Cycle Solvent Recovery Industrial Heat Pump

Principal Investigator: G. E. Limburg
Organization: AiResearch Manufacturing Company
2525 West 190th Street
Torrance, CA 90509
Telephone: (213) 512-4553

Contract Agency: Department of Energy, Idaho Operations
Contract Number: DE-AC07-78CS40005
Contract Period: Sept. 28, 1978, continuing
Funding: $2,845,937
Source: DOE **Level:** 99%
AiResearch 1%

Project Objectives:

To develop a Brayton-cycle industrial heat pump for removing solvent and water vapor from the air-stream while returning the heat of vaporization to the process.

Project Description:

The heat pump system has been constructed and was tested at the AiResearch facilities in Torrance, California. Testing has been completed, with performance meeting design criteria. Solvent removal rates of over 500 lb/h of mixtures of methyl ethyl ketone, toluene, cyclohexane, and xylene and water removal of 70 lb/h were observed. The system will be installed in a 3M facility in Hutchinson, Minnesota, and will be operational in 1986.

The final report for developmental testing is being prepared and is expected to be available in 1986.

Publications:

AiResearch Manufacturing Company, *Technical Report: Cycle Selection of a High-Temperature Heat Pump,* 79-16174, July 12, 1979.

AiResearch Manufacturing Company, *Topical Report: Brayton-Cycle Solvent Recovery System (Phase I System Optimization),* 80-17028, June 16, 1980.

AiResearch Manufacturing Company, *Summary: Brayton-Cycle Solvent Recovery System,* 80-17394, Nov. 5, 1980.

AiResearch Manufacturing Company, *Brayton-Cycle Recovery System,* 81-17748, Feb. 23, 1981.

AiResearch Manufacturing Company, *Technical Description and Economic Analysis Brayton-Cycle Solvent/Heat Recovery System,* 81-18592, Dec. 21, 1981.

AiResearch Manufacturing Company, *Brayton-Cycle Solvent Recovery System (Phase II System Design),* 82-19051, June 16, 1982.

8.1.4 Heat Pump in Complex Heat and Power Systems

Principal Investigator: Eric Hindmarsh
Organization: ICI Americas
17300 Saturn Lane, Suite 113
Houston, TX 77058
Telephone: (713) 480-9495

Contract Agency: Electric Power Research Institute
Contract Number: RP2220-3
Contract Period: June 15, 1985, through June 30, 1986
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To develop a general methodology for the placement of heat pumps in an existing industrial processing arrangement; to consider the opportunities for, and implications of, increased thermal integration by other means, as well as by heat pumping; to examine the heat and power supply systems associated with industrial processing systems to assess conventional arrangements in particular, with respect to true marginal costs, and to assess the opportunities for and implications of heat pumping; to develop a procedure for rapid assessment of the economic potential for a heat pump installation in a total industrial processing system (in this context, a total system is one with the best practical integration between the process and the facilities that supply the process with heat and power).

Project Description:

There are at present a number of installed applications of heat pump technology within the process industries. Many of these applications have been evaluated without reference to the thermodynamic characteristics of the overall process; and they have not been properly assessed in terms of their impact on the overall site utility system. Correct assessment of heat pump opportunities necessitates a complete and full understanding of the thermodynamics of the processing unit, the site heat and power systems, and associated interactions.

The contractor has developed novel techniques for the optimal design and integration of process plants based on the underlying process thermodynamics. These techniques provide a framework to explore and understand the thermodynamics of heat pump placement in total systems and are capable of systematically examining:

- The thermodynamic implications of heat transfer into, within, and out of a process
- The thermodynamic implications on a process of different site utility systems that supply heat and electricity
- the alternative process modifications (e.g., pressure shifting of distillation columns) that could achieve effects similar to those produced by heat pumping

In this study, these techniques were used to develop a new procedure for identifying and assessing heat pump opportunities within selected sectors of the process industries.

Publications:

None provided.

8.1.5 High-Temperature Absorption Working Pair

Principal Investigator: Donald C. Erickson
Organization: Energy Concepts Company
627 Ridgely Avenue
Annapolis, MD 21401
Telephone: (301) 266-6521

Contract Agency: Oak Ridge National Laboratory
Contract Numbers: 86X-22013V and 86X-22014C
Contract Period: May 1981 through May 1986
Funding: $290,000
Source: Energy Concepts **Level:** 66%
DOE 34%

Subcontractor: University of Maryland (R. Radermacher)

Project Objectives:

To verify the technical and economic feasibility of an absorption heat pump capable of operating at temperatures up to 500°F (260°C) using a novel noncorrosive aqueous absorbent comprised of certain combinations of alkali nitrates and nitrites.

Project Description:

Boiling point elevation data were collected for a wide variety of compositions and vapor pressure. The solution composition has been optimized to provide operating temperature capability to 500°F (260°C), together with moderate cost and an acceptably low crystallization temperature threshold. A computer model was prepared. High-temperature cycles using this absorbent can achieve 126°F (70°C) lifts with forward and reverse cycle with substantially less deviation from Raoultian behavior than $LiBr/H_2O$.

Negotiations are under way for extending this work through a second phase, which will include construction of a laboratory-scale mockup (7-kW thermal output) and actual operation to validate the measured and calculated properties.

Publications:

D. C. Erickson, "Economic Options for Upgrading Waste Heat," *Proceedings 5th Industrial Energy Technology Conference, Houston, Tex.*, Vol. 2, pp. 582–588, 1983.

D. C. Erickson, *A High-Temperature Non-Corrosive Absorption Working Pair*, presented at Absorption Heat Pumps Congress, Paris, Mar. 20, 1985.

Patents:

U.S. 4,454,724: D. C. Erickson, Aqueous Absorbent for Absorption Cycle Heat Pump, June 19, 1984.

8.1.6 Heat Pumps in Evaporation

Principal Investigator: Don R. Vredeveld
Organization: Union Carbide Corporation
P.O. Box 8361
South Charleston, WV 25303
Telephone: (304) 747-4829

Contract Agency: Electric Power Research Institute
Contract Number: RP2220-2
Contract Period: May 15, 1985, through Dec. 31, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To review and characterize current evaporator technology and applications; to develop specific case study information on up to ten evaporator applications covering the range of fluids, operating conditions, and plant environments encountered in the process industries; to analyze the use of electric heat pumps in each of these representative processes; to generalize the results of these case study analyses into application guidelines for the appropriate use of heat pumps in evaporation.

Project Description:

The development and application of electrotechnologies for the process industries have often been conducted with insufficient attention to the practical implications of integrating these technologies into new or existing plants. This can result both in misapplication of existing technology and in misdirected technology development efforts.

In this study, the contractor applied advanced process integration techniques to the use of electric-driven heat pumps in conjunction with evaporation processes in the chemical, petroleum, textile, pulp and paper, dairy, food, and related industries that employ evaporation. Representative evaporation processes were identified and characterized. The use of heat pumps in a selected number of these processes was analyzed in detail using process integration methodologies. Generalized guidelines for the appropriate application of heat pumps to each of these processes was developed, and research and development needs were identified.

Publications:

None provided.

8.1.7 Development and Demonstration of a High COP Rankine Heat Pump for Generation of Process Steam, Combined Cycle, Steam Compression Industrial Heat Pump

Principal Investigator: William Koebbeman
Organization: Mechanical Technology, Inc.
968 Albany Shaker Road
Latham, NY 12110
Telephone: (518) 899-2976

Contract Agency: Department of Energy, Idaho Operations
Contract Number: DE-AC01-77CS40074
Contract Period: Oct. 14, 1977, through Dec. 31, 1985
Funding: $2,981,994
Source: DOE **Level:** 99%
Mechanical Technology 1%

Project Objectives:

To design, develop, install, and field demonstrate a combined cycle heat pump for generation of process steam in an industrial plant.

Project Description:

Heat pump compressors conventionally are electric motor driven. In this concept, the compressor ("pumping" low-pressure steam to process steam levels) is driven by the turbine output of a closed, organic Rankine cycle loop. The heat source both for the Rankine cycle and for generating low-pressure steam is industrial waste heat. Elimination of electrical power to drive the compressor provides the economic advantage of this heat pump system.

Major emphasis in the development of this system is the turbine. It must be designed optimally for efficiency and cost so that there is a short payback period during the time that waste energy is being recovered.

The heat pump system was constructed and tested at the Mechanical Technology Malta Test Facility. All design objectives were met or exceeded. Addition of a motor-generator set allows a user to generate electricity during periods of reduced steam requirements or to produce steam either by use of waste heat or electrically during periods of reduced waste steam availability.

Publications:

Mechanical Technology, Inc., *Materials Test Report, Technical Report 2,* 78TR120, July 1978.

Mechanical Technology, Inc., *Environment Effects Report, High COP Heat Pump System, Technical Report 5,* 79TR1, September 1978.

Mechanical Technology, Inc., *Application Survey and Market Assessment for High COP Heat Pump Project, Final Report, Contract Modification M005,* 81TR27, January 1981.

Mechanical Technology, Inc., *High COP Heat Pump System, Phase I Results Technical Report 1A,* 82TR14, November 1981.

Mechanical Technology, Inc., *High COP Heat Pump Bearing and Seal Testing,* 82TR22, December 1981.

Mechanical Technology, Inc., *Development and Test of a COP Rankine Heat Pump for Generation of Process Steam–Management Plan for Phase 2 Fabrication and Test,* 82TR49, June 1982.

Mechanical Technology, Inc., *Development and Test of a High COP Rankine Heat Pump for Generation of Process Steam, Final Report for Phase 2 Fabrication and Test,* 84TR14, October 1984.

8.1.8 Development of a Plastic Film Heat Exchanger for Industrial Heat Pumps

Principal Investigator: E. C. Guyer
Organization: Dynatech Research and Development Company
99 Erie Street
Cambridge, MA 02139
Telephone: (617) 868-8050

Contract Agency: Department of Energy, Idaho Operations
Contract Number: DE-AC07-84ID12550
Contract Period: September 1984 through November 1985
Funding: $181,126
Source: DOE **Level:** 100%
Dynatech 5%

Project Objectives:

To determine and demonstrate the technical feasibility and economic viability of the use of inexpensive heat exchangers, in a heat pump application, which use plastic films as the heat exchange media.

Project Description:

Dynatech examined the technical and economic feasibility of development of inexpensive heat exchangers that use plastic films as the heat transfer media. During phase 1 of the project, materials were evaluated for fabricability, cost, and thermal performance; conceptual designs were considered. During phase 2, a small laboratory scale model was fabricated, and several film materials were tested in a simulated heat pump environment.

Publications:

E. C. Guyer and D. L. Brownell, *Design of Heat Exchange Element for Plastic Film Heat Exchanger,* Dynatech Report 2324, December 1984.

8.1.9 Development and Demonstration of an Electric Heat Pump for Waste Heat Recovery in Industry

Principal Investigator: W. C. Moreland
Organization: Westinghouse Electric Corporation
Research and Development Center
1310 Beulah Road
Pittsburgh, PA 15235
Telephone: (412) 256-2002

Contract Agency: Department of Energy
Contract Number: DE-AC01-77CS40327
Contract Period: July 1977 through November 1985
Funding: $3,897,146
Source: DOE **Level:** 92%
Westinghouse 8%

Project Objectives:

To demonstrate the technical feasibility and economic viability of using a methanol working fluid in electrically driven heat pumps to reclaim low temperature waste heat from industrial processes.

Project Description:

The specific technical and economic goals were:

- Delivery temperatures in the range of 250 to 350°F (121 to 177°C)
- Source temperatures in the range of 180 to 250°F (82 to 121°C)
- Paybacks of four years or less

The Westinghouse Research and Development Center developed an electrically driven closed Rankine cycle high-temperature heat pump that uses methanol as the working medium. The heat pump extends the technology approximately 100°F (38°C) above that of available commercial units. Testing on the unit was completed at the Westinghouse Large Pennsylvania Test Facility. The system performed close to design predictions. At a waste steam pressure of 10 psig, the measured output capacity was 33,000 lb/h of 63-psig steam with 20°F superheat at a coefficient of performance of 4.6.

Publications:

P. H. Snyder and W. C. Moreland, *The Selection of Working Fluid Candidates for Use in High-Temperature Industrial Heat Pumps*, DOE/CS/40327T3, NTIS No. DE83003725, December 1978.

G. C. Gainer, R. M. Luck, and W. C. Moreland, *Thermal Stability and Materials Compatibility Tests of Five High-Temperature Working Fluid Candidates*, Westinghouse Research Report 79-9E98-SOTEM-M1.

W. C. Moreland, J. S. Eder, and R. W. Wolfe, *Preliminary Design Report—Development and Demonstration of an Electric Heat Pump for Waste Heat Recovery in Industry*, DOE/CS/40327-T1, March 1981.

W. C. Moreland and R. W. Wolfe, *Development and Demonstration of an Electric Heat Pump for Waste Heat Recovery in Industry*, Draft, Westinghouse Report 85-9D8-SOFTEM-R1, July 1985.

8.1.10 Twin Film-Falling Film Heat Exchanger

Principal Investigator: E. F. Doyle
Organization: Thermo Electron Corporation
45 First Avenue
P.O. Box 459
Waltham, MA 02254
Telephone: (617) 890-8700

Contract Agency: Department of Energy, Idaho Operations
Contract Number: DE-AC05-84ID12540
Contract Period: September 1984 through October 1985
Funding: $170,769
Source: DOE **Level:** 93%
Thermo Electron 7%

Project Objectives:

To develop a twin film-falling film heat exchanger for industrial heat pumps capable of recovering heat from contaminated waste steam at higher heat transfer rates than those presently available.

Project Description:

Thermo Electron is determining the economic and technical benefits of utilization of a heat exchanger in which a condensing waste steam film inside of verticle tubes is used to evaporate a clean water falling film on the outside of the tubes. During phase 1, a laboratory model was fabricated and tested in a clean condensing-steam environment. Heat transfer coefficients varying from 412 to 691 Btu/(h·ft·°F) were obtained. Phase 2 consisted of testing the laboratory model with simulated contaminated waste steam and making a detailed economic comparison with conventional shell and tube and falling film evaporators.

Publications:

E. F. Doyle and J. Balsavich, *Development of an Evaporator for Industrial Heat Pumps Capable of Recovering Heat from Contaminated Sources: Phase I Final Report,* DOE/ID/12548-1, August 1985.

8.1.11 Hybrid High COP Heat Pump Application Study

Principal Investigator: William R. Koebbeman
Organization: Mechanical Technology, Inc.
968 Albany Shaker Road
Latham, NY 12110
Telephone: (518) 899-2976

Contract Agency: Electric Power Research Institute
Contract Number: RP2220-1
Contract Period: Sept. 13, 1984, through Aug. 30, 1985
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To define the potential impact on utilities caused by new load and industrial customer load management options created by the hybrid heat pump; to identify potential demonstration sites for the unit; to formulate technical and economic screening tools that utilities and their industrial customers can use to identify and evaluate potential applications.

Project Description:

Under Department of Energy (DOE) funding, Mechanical Technology, Inc. (MTI), has designed, fabricated, and completed a 100-h laboratory test on a high coefficient of performance (COP) heat pump. Utilizing an organic Rankine cycle, the MTI unit recovers low-level waste heat to generate low-pressure steam and to power a Freon-driven axial compressor to boost the pressure of the steam to usable process levels. Though the development of the unit has been technically successful to date, its application appears to be quite limited because of the difficulties inherent in attempting to integrate it into complex plants that experience significant fluctuations in both waste heat availability and steam demands. However, the unit's applicability should be appreciably enhanced by the addition of a motor/generator to the machinery train. Such an addition would give the unit the flexibility of operating in a cogeneration mode or as a motor-driven steam compressor. It would thus be able to accommodate wide shifts in the plant's steam, electric, and waste heat loads.

Under DOE funding, the motor/generator addition will be designed, procured, and incorporated into the existing prototype machine. Concurrent with this activity, this study funded by the Electric Power Research Institute will be conducted to assess the potential technical and economic markets—and the resultant utility impacts—of the hybrid unit and to identify potential industrial demonstration sites. Such a demonstration may be pursued, with industrial cofunding, if the results of the study are positive.

All technical work, with the exception of the site identification effort and the writing of the final report, is now complete. In summary, it was estimated that the technical market for the hybrid high COP heat pump (HHP) would be about 500 units with the potential to recover 167×10^{12} Btu/year. An examination of the competition posed by other technologies was then used to estimate the economic market (about 220) for the HHP. The HHP competes with two basic groups of technologies: one group tends to improve process heat integration and thereby reduce both waste heat flows and steam demand; the other consists of alternative systems for generating steam and/or recovering waste heat. The HHP was compared with three competing systems: cogeneration using a back-pressure steam turbine, cogeneration using a gas turbine with waste heat boiler, and an electric driven heat pump. Because of the large number of site-specific factors, industrywide characterization is not practical; however, application guidelines and sensitivities will be provided in the final report to assist potential users.

Publications:

None provided.

8.1.12 Absorption Heat Pump Augmented Distillation Column Prototype

Principal Investigator: Donald C. Erickson
Organization: Energy Concepts Company
627 Ridgely Avenue
Annapolis, MD 21401
Telephone: (301) 266-6521

Contract Agency: Department of Energy, Office of Energy Related Inventions
Contract Number: DE-FG01-84CE15172
Contract Period: Apr. 9, 1984, through Oct. 8, 1984
Funding: $25,000
Source: DOE **Level:** 100%

Project Objectives:

To locate a retrofit site and bring about the first use in the United States of an absorption heat pump for directly recycling distillation reject heat.

Project Description:

This process uses overhead vapor condensing heat upgraded by an absorption heat pump which reboils the same or a nearby fractional distillation column.

The work of the program was divided into two phases. In phase 1, a suitable application for the absorption heat pump augmented distillation column prototype was identified. A preliminary design, cost estimate, and schedule were prepared. A letter of intent and cost sharing commitment were obtained from the industrial user of this invention.

In phase 2, a detailed engineering design was prepared based on data available from phase 1. A prototype was assembled, and its performance was monitored for six months.

Publications:

D. C. Erickson, "Absorption Cycle Fundamentals and Applications Guidelines for Distillation Energy Savings," *6th IECTC Proceedings, Houston, Tex.*, 1984.

Patents:

U.S. 4,402,795: D. C. Erickson, Reverse Absorption Heat Pump Augmented Distillation Process, Sept. 6, 1983.

8.1.13 Low-Temperature Waste Heat Utilization Chiller System

Principal Investigator: Scott J. Hynek
Organization: Foster-Miller Associates
350 Second Avenue
Waltham, MA 02154
Telephone: (617) 890-3200

Contract Agency: Oak Ridge National Laboratory
Contract Number: 41X-28906C
Contract Period: August 1979 through September 1983
Funding: $1,001,244
Source: DOE **Level:** 100%

Project Objectives:

To design, develop, and demonstrate an industrial refrigeration system to be powered primarily by the 140°F (60°C) waste hot water (available at certain industrial sites and government-owned gaseous diffusion plants), to investigate commercial applications of this system, to commercialize it by teaming with a manufacturer.

Project Description:

The waste-heat-driven chiller system consisted of a Rankine cycle driving a reverse-Rankine cycle. This integrated system shared a common working fluid (R-22), a common condenser, and a common crankcase that housed the expander and compressor. One bank of compressor cylinders was transformed into expander cylinders by replacing the head with a specially designed head containing rotary valves. A hermetically housed induction generator absorbed any surplus shaft power and provided speed control. The induction generator operates as a motor to make up the shaft power deficit on hot days. The preliminary system design was completed. Standard components (including condenser and compressor) were selected, and special components (such as rotary expander valve and boiler feed pump) were designed. During phase 2 of the project, system components were tested. A complete demonstration system was constructed during phase 3.

The power output from the expander exceeded design predictions by 5 to 7% at condensing temperatures of 75 to 85°F (24 to 29°C); however, parasitic losses were higher in the system than estimated from design calculations, so that overall performance was marginally lower than design predictions. The machine is capable of producing 0°F refrigeration when driven with 140°F heat; however, economic viability requires a continuous source of waste heat and continuous, year-round demand for refrigeration.

Publications:

S. J. Hynek et al., *Design and Component Testing of a Low Temperature Waste Heat Driven Refrigeration System, Phases I & II Progress Report*, ORNL/SUB/80-28906/1, March 1982.

S. J. Hynek and H. Borhanian, *Demonstration of a Low Temperature Waste Heat Driven Refrigeration System*, ORNL/SUB/80-28906/2, September 1983.

8.1.14 Heat Pumps in Distillation

Principal Investigator: G. E. Harris
Organization: Radian Corporation
P.O. Box 9948
Austin, TX 78766
Telephone: (512) 454-4797

Contract Agency: Electric Power Research Institute
Contract Number: RP1201-23
Contract Period: September 1981 through July 1982
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To determine the range of applicability of electrically driven heat pumps to distillation processes.

Project Description:

Technical, economic, and market-related constraints were considered in determining the potential applicability of heat pumps for both new and retrofit situations. The approach to determine the range of applicability of heat pumps to distillation included:

- A survey of heat pump system and component manufacturers
- Formulation of simplified external distillation models
- Formulation of open and closed cycle heat pump models
- Development of cost estimation routines for heat pumps
- Life cycle economic analysis of heat pump applications
- FORTRAN program to perform the above analyses
- A survey and evaluation of candidate distillation processes

Publications:

G. E. Harris, *Heat Pumps in Distillation Processes, Final Report*, EPRI-EM-3656, August 1984.

8.1.15 Impact of Electrically Driven High-Temperature Industrial Process Heat Pumps on Electrical Utilities

Principal Investigator: Neil N. Turner
Organization: General Electric Company
Bldg. 23, Room 352
1 River Road
Schenectady, NY 12345
Telephone: (518) 385-0819

Contract Agency: Electric Power Research Institute
Contract Number: RP1967-2
Contract Period: August 1981 through May 1982
Funding:
Source: EPRI **Level:** 100%

Project Objectives:

To define the effects on utilities of large-scale industrial heat pump utilization.

Project Description:

This project assessed load impact on utilities, assessed electrical noise effects caused by load fluctuations, performed case studies and potential applications, defined the current state of research, defined compressor performance maps and applications, and reported on institutional and regulatory considerations.

Publications:

None provided.

8.1.16 Industrial Process Heat Pump Service Study

Principal Investigator: Rudy Eggert
Organization: General Electric Company
Building 23, Room 116
1 River Road
Schenectady, NY 12345
Telephone:

Contract Agency: Department of Energy
Contract Number: DE-AC02-80CS40449
Contract Period: Aug. 18, 1980, through Apr. 30, 1982
Funding: $320,000
Source: DOE **Level:** 100%

Project Objectives:

To assess the potential energy savings of high-temperature heat pumps [230–400°F (110–204°C)] in different industries and at the national level, to estimate the economic market and fuel savings.

Project Description:

The 108 processes identified in the DOE industrial data base were matched to various heat pump cycles (open, partially open, and closed). System performance (coefficient of performance, fuel savings, horsepower) and capital costs (compressors, flash tanks, heat exchangers) were used to develop the economic attractiveness of each match. Results were tabulated by standard industrial classifications and net fuel savings (including increased utility fuel usage) and summarized.

Surveys were made of nine sites in the pulp and paper industry. One site in the pulp and paper industry and one site in the chemical industry were chosen for detailed preliminary design studies.

Publications:

None provided.

8.1.17 Compound Absorption Cooling from Low-Grade Heat Using Advanced Desorbers

Principal Investigators: Dr. William T. Hanna
William H. Wilkinson
Organization: Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
Telephone: (614) 424-4794

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7805
Contract Period: February 1980 through October 1981
Funding: $428,765
Source: DOE **Level:** 100%

Project Objectives:

To demonstrate the commercial feasibility of an advanced absorption cooling system known as the Compound Absorption Chiller (CAC), which was motivated by low-grade heat.

Project Description:

The project was organized into four phases: (1) feasibility determination, (2) concept and experiment design, (3) experimental studies, and (4) prototype construction and testing.

In phase 1 (feasibility) the major results were the development of a detailed computer performance model for the compound absorption cooling (CAC) system and the use of that model with absorption equipment cost data to predict the relative cost and benefits of using CAC systems. The results of phase 2 (engineering analysis) were the definition of three desorber designs and an experimental plan for ranking them and the design of a heat exchanger using the best of these designs for incorporation into the later test unit. In phase 3 (experimental), the desorber tests, planned in phase 2, were carried out for one pool type and two advanced desorbers; one of the advanced desorbers, a counterflow unit, gave improved heat transfer and improved costs as compared with a pool desorber. In phase 4 (test effort), the CAC demonstration unit was designed and built with a waste-heat-driven, 140°F input chiller with 25 to 50 tons of refrigeration. Postcontract activities included plans for commercialization via a licensed manufacturer and operation of the CAC demonstration unit in an industrial type application.

Publications:

None provided.

8.1.18 Open-Cycle Electric-Driven Industrial Heat Pump

Principal Investigators: H. M. Leibowitz
D. W. Chaudoir
Organization: Mechanical Technology Inc.
20 Plains Road
Ballston Spa, NY 12020
Telephone: (518) 785-2211

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24713C
Contract Period: September 1979 through September 1981
Funding: $407,924
Source: DOE **Level:** 100%

Subcontractors: Ford, Bacon and Davis Utah, Inc.
375 Chipeta Way
Salt Lake City, UT 84108

Project Objectives:

To develop a detailed design of a demonstration-size open-Rankine-cycle heat pump, which would demonstrate the system's technical concept.

Project Description:

To evaluate the potential uses of low-temperature heat sources at 130 to 200°F (54.4 to 93.3°C). Mechanical Technology Inc. (MTI) developed an open-Rankine-cycle heat pump that utilized this low-temperature energy. The open-type heat pump did not have an evaporator on the heat source side or a condenser on the process side.

The open-type heat pump utilized the heat source, clean waste water streams, as the system's working fluid and as the process fluid. The system accomplished the transition by directly flashing the waste water stream in a critically sized flash tank. The water vapor was then compressed to a useable temperature and pressure by a series of single-stage centrifugal compressors. The compression train featured a desuperheat station after each stage. The desuperheat station reduced the temperature of the stream to a reasonable level to permit the use of standard materials in the compressor, thereby yielding the extra benefit of reducing the required compression power. After the compression/desuperheat process, the fluid was directed to the process use.

The design of the heat pump system was accomplished by a joint effort of MTI and Ford, Bacon and Davis Utah, Inc., under subcontract to MTI. The design effort included development of system diagrams and specific component purchase specifications. The design consisted of four subsystems that included the flashing process, compression/desuperheat process, motor control center, and microprocessor-based control systems. The detailed design was completed in February 1981.

Initial analytical estimates of total performance improvements from continuous desuperheating were found to be erroneous. The revised estimate of a 3% total performance improvement was not significantly greater than the performance improvement obtainable with stage-wise desuperheating. This project was not continued beyond the design phase.

Publications:

The Economic Analysis and Design of Industrial Heat Pumps for Low-Temperature Waste Heat Utilization, Vol. I, ORNL/Sub/79-24713/2-VI, MTI-81 TR 30, February 1981.

The Economic Analysis and Design of Industrial Heat Pumps for Low-Temperature Waste Heat Utilization, Vol. II (Appendixes), ORNL/Sub/79-24713/2-VII, MTI-81 TR 30, February 1981.

8.1.19 EAST Facility Requirements Documentation

Principal Investigator: F. Joseph McCrosson
Organization: South Carolina Energy Research Inst.
1401 Main Street
Suite 670
Columbia, SC 29201
Telephone: (803) 256-6400

Contract Agency: Savannah River Operations Office
Contract Number: DE-AC09-77ET12866
Contract Period: Sept. 1, 1980, through July 31, 1981
Funding: $485,604
Source: DOE **Level:** 100%

Subcontractors: Mechanical Technology, Inc.
2731 Prosperity Avenue
Fairfax, VA 22031
Robert H. Badgley
(703) 698-9000

United Technologies Research Center
East Hartford, CT 06108
Frank R. Biancardi
(203) 727-7234

Project Objectives:

To develop and document the initial design requirements for the proposed Energy Applied Systems Test (EAST) Facility at the Savannah River Plant, Aiken, South Carolina.

Project Description:

Development of the EAST Facility requirements was one element of the Department of Energy Residual Energy Application Program (REAP) to recover large quantities of residual energy at federal nuclear facilities and to stimulate waste heat recovery in the private sector. The proposed government-owned, contractor-operated east facility would provide development and confidence testing for industrial heat pumps, absorption chillers, and Rankine-cycle power generation systems. The core EAST Facility would simulate waste streams in the range of 100 to 1000°F (38 to 538°C) and would be capable of around-the-clock multisystem/subsystem testing of two 0.5 to 2.0 MW power generation systems and two 5 to 50 million Btu/h (1465 to 14,650 kW) heat pump systems (alternatively, one 2 to 6 MW power generation system and one 50 to 100 million Btu/h heat pump system).

Publications:

P. W. Yngve and F. H. Zander, *Residual-Energy-Applications Program: EAST Facility Requirements Document,* DOE/ET/12866-8-Vol. I and Vol. II, July 1981.

8.1.20 Ejector Heat Pump Applications (Low-Grade Heat Recovery Project)

Principal Investigators: Harry G. Arnold
Horacio Perez Blanco
William R. Huntley
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-5764

Contract Agency: Department of Energy
Contract Number: W-7405-eng-26,
AA-55-15-15-0
Contract Period: July 1980 through May 1981
Funding: $35,000
Source: DOE **Level:** 100%

Project Objectives:

To determine the technical feasibility and the economic potential of steam ejectors for low-grade waste heat recovery.

Project Description:

The Waste Heat Recovery Program administered by Oak Ridge National Laboratory has the objective of identifying and developing technology for recovering waste heat at temperatures below 194°F (90°C). Under this program, a variety of heat pump and refrigeration technologies are being developed by subcontractors. There was also an in-house effort whose overall objective was to identify, screen, and develop advanced, high-risk concepts that show adequate potential for waste heat recovery.

Even though steam ejectors have found widespread use in thermal-recompression applications, the range of operating conditions was different from the conditions found in low-grade heat recovery.

This project consisted of evaluating jet ejectors for heat pump applications. The compression ratios, temperature boosts, efficiencies, and costs were evaluated for specific industrial applications. It was found that even when recovering subatmospheric steam (about 2 psia), ejectors can in some special cases provide process heat cheaply. In these special cases, it was assumed that the boiler providing motive steam is paid for and that process steam pressure is reduced via the steam ejector.

Publications:

H. G. Arnold, W. R. Huntley, H. Perez-Blanco, "The Steam Ejector as an Industrial Heat Pump," *ASHRAE Trans.* **88**(2), 1982.

8.1.21 Technical Assessment of Residual Energy Applications and EAST Facilities Studies Conceptual Design of Large-Scale Heat Pump for Central Energy Management System

Principal Investigators: Frank R. Biancardi
R. W. Bass
A. M. Landermand
Organization: United Technologies Research Center
Silver Lane
East Hartford, CT 06108
Telephone: (203) 727-7234

Contract Agency: South Carolina Energy Research Institute (SCERI)
Contract Number: DE-AC09-77ET12866-SUB-15 (and SUB-20)
Contract Period: November 1979 through April 1981
Funding: $197,800
Source: SCERI **Level:** 100%

Project Objectives:

To select systems comprised of current and near-term equipment capable of economically recovering 110 to 150°F waste heat from federal facilities, utilities, and industries to produce electric power and thermal energy at useful temperatures.

Project Description:

At federal facilities and utilities where large amounts of waste heat are available, recovery and distribution of energy is handled by a central energy management system and utilized in an adjacent industrial park. For industrial waste heat recovery, recovered energy is used on site.

An analytical study was undertaken to identify specific power generation and heat pump requirements for low-temperature waste heat recovery from government, utility, and industrial sources, to develop techniques needed to evaluate the performance and cost characteristics of various power system and heat pump options, and to perform economic analyses on selected designs. Recently completed DOE-sponsored studies as well as other available literature were reviewed to define waste heat sources and industrial thermal end-uses. Distinct waste heat sources and industrial end-uses were selected as representative applications and used for heat pump design specifications. Two of these applications typify large sources of waste heat and colocated industrial park end-uses; the remaining four represent in-plant industrial sources and end-uses. Rankine-cycle heat pump configurations and working fluid options were assessed, and four configurations were selected for further study on the basis of cost and performance. Five different prime movers were examined as potential compressor drivers; gas turbines and diesels were selected on the basis of high overall performance. A similar design assessment was performed for power recovery systems. A conceptual design of an economically attractive central energy management system for use at an industrial park located near the Portsmouth Gaseous Diffusion Plant was made.

This work was continued and extended to cover industrial parks under funding from the Electric Power Research Institute, research projects 1276-1 and 1275-26.

Publications:

R. W. Bass and A. M. Landerman, "Preliminary Evaluation of Large-Capacity High Lift Heat Pump Concepts," study performed by United Technologies Research Center for the U.S. Department of Energy.

R. W. Bass, A. M. Landerman, and F. R. Biancardi, "Conceptual Design of Large Scale Heat Pump for Central Energy Management System," study performed by United Technologies Research Center for the U.S. Department of Energy.

8.1.22 Open-Cycle Heat Pump for Industrial Waste Heat Utilization

Principal Investigator: C. R. Snyder
Organization: General Electric Company
Corporate Research and Development
P.O. Box 43
Schenectady, NY 12301
Telephone: (518) 385-0162

Contract Agency: Oak Ridge National Laboratory
Contract Number: 86X-24717C
Contract Period: May 12, 1980, through Oct. 12, 1980
Funding: $112,000
Source: DOE **Level:** 81%
NYSERDA 19%

Project Objectives:

To study the feasibility of the open-cycle industrial process heat pump at several sites for the purpose of demonstrating the concept.

Project Description:

The feasibility study was completed with evaluation of three sites and four process configurations. The site visits provided process information on flow rates, process temperatures, pressures, dynamics behavior, energy balances, control functions, and plant operating philosophy. Additional information on the plant utilities and possible equipment location was also obtained. Comparative evaluations were made considering energy savings, cost savings, value of operating experience, and potential for wide application. Energy cost and application potential information was gathered for New York State. Component costing was completed on two process configurations showing merit. The phase I report indicated that two applications were possible for either a full-scale or a smaller demonstration-size prototype.

Publications:

Open-Cycle Heat Pumps for Industrial Waste Heat Utilization Project, Technical Report: Phase I—Feasibility Study, ORNL/Sub/80-24717/7, NYSERDA/81-28, October 1980.

8.1.23 System Development Study of HP-ICES Using Air or Industrial-Waste Heat Source and a Cascaded or Distributed System

Principal Investigators: Harold G. Lorsch
Richard E. Crane
Organization: Franklin Research Center
20th and Race Streets
Philadelphia, PA 19103
Telephone: (215) 448-1000

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4547
Contract Period: June 20, 1978, through Nov. 30, 1979
Funding: $68,321
Source: DOE **Level:** 100%

Project Objectives:

To assess the potential applications, expected performance, economics, and implementation of a heat-pump-centered integrated community energy system (HP-ICES) predicated on a common piping loop from or to which users (buildings) extract or reject heat via their own water-source heat pump.

Project Description:

A central plant maintained the water temperature in the common piping loop within a desired range. The common piping loop could be supplemented with heat from a diesel-driven air source heat pump, boilers in a central plant, or waste heat from industrial sources. Cooling was accomplished by a cooling tower or pond. The HP-ICES was either cascaded or distributed depending on whether a central heat pump was included.

If little or no waste heat is available from nearby industrial installations, high community energy density rates (corresponding to urban conditions) are required for economic viability of this particular HP-ICES. If large amounts of waste heat are available and the HP-ICES is owned by the municipality, even relatively low-density communities look promising. For this particular HP-ICES, 16 to 32% less resource energy (than conventional systems) was used during the heating season; at peak heating, the savings was 37 to 51%. Although there was no resource energy savings for the cooling season, 19% was saved during the peak cooling period. Overall, the annual resource energy savings was 14 to 34%.

So that the applicability of this HP-ICES to particular sites could be demonstrated, designs were made for Phillipsburg, New Jersey, and Walden, Illinois. Analysis concluded that conversion (retrofit) of the Heckman Terrace Public Housing Development in Phillipsburg to this HP-ICES was economically feasible compared with the existing system and in light of the availability of nearby industrial waste heat and natural gas as a supplement. The mixed residential/commercial Walden, Illinois, community did not promise any savings when equipped with this HP-ICES primarily because of the low cost of natural gas in the area.

Publications:

R. E. Crane et al., *Heat-Pump-Centered Integrated Community Energy Systems—Interim Report,* ANL/ICES-TM-26, February 1979.

R. E. Crane et al., *Heat-Pump-Centered Integrated Community Energy Systems—Final Report,* ANL/CNSV-TM-24, December 1979.

8.1.24 Comparison of Centralized and Distributed HP-ICES That Uses Low-Temperature Industrial Waste Heat

Principal Investigator: Lincoln B. Katter
Organization: Rocket Research Company
11441 Willows Road
Redmond, WA 98052
Telephone: (206) 885-5000

Contract Agency: Argonne National Laboratory
Contract Number: 31-109-38-4546
Contract Period: June 20, 1978, through Nov. 30, 1979
Funding: $71,941
Source: DOE **Level:** 100%

Project Objectives:

To compare centralized and distributed heat-pump-centered integrated community energy systems (HP-ICES) that use low-temperature industrial waste heat.

Project Description:

Service options evaluated were space heating, cooling, water heating, and combinations thereof. Geographic location, overall system size, and heat source characteristics were the major factors addressed. The HP-ICES considered incorporated two-pipe systems using water as the thermal transport medium.

Case studies for application were made for Everett and Seattle, Washington, and San Antonio, Texas. In all cases, on-site use of oil was eliminated by HP-ICES. However, winter electricity use increased by 50% in Everett, which would not make this HP-ICES attractive there although life-cycle costs were favorable. For Seattle, winter electricity demand increased somewhat and that for summer decreased (without real escalation in oil prices beyond inflation). HP-ICES economics are very unattractive. For San Antonio, both summer and winter electricity demands increased by 50%. Payback could not be achieved within 15 years, and life-cycle costs of HP-ICES were unfavorable.

It was concluded that for the HP-ICES systems considered and sites applied, payback is never attractive enough to encourage investment. Life-cycle costs are marginally attractive and indicate that the most attractive sites have a high density of end-users that are located close to the waste heat source. However, these sites tend to be in established neighborhoods where large-scale construction necessary for pipeline installation and customer hook-ups would probably not be encouraged unless outstanding economics could be demonstrated.

Publications:

Rocket Research Company, *Heat-Pump-Centered Integrated Community Energy Systems: System Development—Interim Report*, ANL/ICES-TM-27, February 1979.

Rocket Research Company, *Heat-Pump-Centered Integrated Community Energy Systems—Final Report*, ANL/CNSV-TM-20, November 1979.

8.2 Heat Transformers

8.2.1 Advanced Heat Transformer

Principal Investigators: H. Perez-Blanco
M. R. Patterson
Organization: Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37831
Telephone: (615) 574-5442

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: January 1984 through July 1985
Funding: $90,000
Source: DOE **Level:** 100%

Project Objective:

To develop a numerical model of an advanced heat transformer that can reach high delivery temperatures and/or larger temperature boosts than a conventional single-stage machine.

Project Description:

A computer model is now operational and has been coupled to a numerical optimizer to specify the distribution of heat exchangers in order to achieve minimum payback periods.

Publications:

M. R. Patterson and H. Perez-Blanco, "Sensitivity of Absorption Cycle Calculations of Fluid Property Errors Calculated Stochastically," *Proc. 19th IECEC*, CONF-840804-10, August 1984.

M. R. Patterson and H. Perez-Blanco, "Design of an Advanced Absorption Heat Pump for Minimum Payback Period," presented at ASME Winter Annual Meeting, November 1985.

H. Perez-Blanco and M. R. Patterson, *Conceptual Design and Optimization of a Versatile Absorption Heat Transformer*, ORNL/TM-9841, March 1986.

8.2.2 Low-Grade Heat-Actuated Absorption Heat Pump for Temperature Boosting

Principal Investigators: Gershon Grossman
Horacio Perez-Blanco
W. R. Huntley
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-0419

Contract Agency: Oak Ridge National Laboratory
Contract Number: W-7405-eng-26/AA-55-15-15-0
Contract Period: October 1979 through September 1984
Funding: $948,000
Source: DOE **Level:** 100%

Subcontractor: Arkla Industries, Inc.

Project Objectives:

To develop a conceptual design of an industrial-type absorption heat pump for upgrading waste heat.

Project Description:

The heat pump was specifically designed to boost the temperature of low-grade heat, typically from about 140°F (60°C) to about 250°F (120°C). The conceptual design formed the first step toward the construction of a prototype working system.

An analysis resulted in a conceptual design of the heat pump system providing the information needed for detailed design and construction of a laboratory working system. Multistaging of the heat pump was investigated for increased temperature boosting, and a preferred two-stage configuration was identified. Open-cycle evaporation and desorption were considered for cases of low-temperature differential between the heat source and sink. Suitable working materials were considered, and component performance was analyzed with a computer model that was developed to analyze the behavior of the entire conceptual system under a variety of postulated operating conditions.

The computer model, which is available for investigation of different configurations and operating conditions, was used in the detailed design of the laboratory system.

The 45-kW single-stage prototype system was built and successfully operated. It demonstrated close agreement with the predictions of the computer model.

Publications:

W. R. Huntley, "Performance Test Results of an Absorption Heat Pump That Uses Low-Temperature [60°C (140°F)] Industrial Waste Heat," *Proc. 18th IECEC*, Vol. 4, pp. 1921–1926, August 1983.

W. R. Huntley, *Performance Test Results of a Lithium Bromide–Water Absorption Heat Pump That Uses Low-Temperature [60°C (140°F)] Waste Heat*, ORNL/TM-9072, June 1984.

Patents:

U.S. 4,458,499: G. Grossman, Absorption Heat Pump System, July 10, 1984.

U.S. 4,458,500: G. Grossman and H. Perez-Blanco, Absorption Heat Pump System, July 10, 1984.

8.2.3 Sulfuric Acid/Water Chemical Heat Pump

Principal Investigator: E. C. Clark
Organization: Rocket Research Company
York Center
Redmond, WA 98052
Att: William F. Thorn
Telephone: (206) 885-5000, ext. 293
Telex: 152364

Contract Agency: Brookhaven National Laboratory
Contract Numbers: 494588-S, 568761-S
Contract Period: October 1979 through September 1981
Funding: $699,740
Source: DOE **Level:** 100%

Project Objectives:

To verify the capability of the sulfuric acid/water system; to design, construct, and test sulfuric acid chemical heat pump/chemical energy storage verification test unit (VTU), which will incorporate as many commercial, mass-producible design features as necessary to demonstrate system economic and technical feasibility.

Project Description:

The VTU was designed to function both as a storage heating, ventilating, and air-conditioning unit and a temperature-enhancement industrial chemical heat pump (ICHP). For purposes of gaining scaling criteria, the nominal storage design capacity was 106 Btu (1016 ergs), with a nominal delivered heat rate of 150,000 Btu/h (44 kW). Rocket Research Company, under contract to Brookhaven National Laboratory, conducted a four-phase program. Phases 1, 2, and 3 consisted of a requirement analysis, detailed design, and fabrication of the VTU. Generic applications were identified that included industrial waste heat pumping, space conditioning, air or gas moisture removal, steam accumulation, cogeneration, and energy storage. The VTU design incorporated two of the above designs: waste heat pumping and space conditioning. It also incorporated combined generator-condenser and absorber-evaporator reaction components made of steel shells coated with acid-resistant porcelain. Teflon-lined acid plumbing and valves were used, and the acid storage tank was fabricated from steel lined with porcelain and capable of vacuum operation. Phase 4 consisted of testing the VTU including performance and design point mapping and accumulation of 100 h operating time at constant output, all in the ICHP mode. This system is currently in the early stages of commercialization development by Mitsubishi Corporation under an agreement with Rocket Research Company concerning licensing of the technology.

Publications:

Final Report, BNL Contract 494588-S, RRC-82-R-813, Jan. 15, 1985.
Final Report, BNL Contract 568761-S, RRC-82-R-868 [no date provided].

Patents:

U.S. 4,532,778: E. C. Clark and D. D. Huxtable, Chemical Heat Pump and Chemical Energy Storage System, Aug. 6, 1985.

8.2.4 Chemical Heat Pump Cost-Effectiveness Evaluation

Principal Investigator: Warren R. Standley
Organization: TRW Energy Engineering Division
8301 Greensboro Drive
McLean, VA 22102
Telephone: (703) 734-6534

Contract Agency: Brookhaven National Laboratory
Contract Number: 51903-S
Contract Period: June 1980 through March 1981
Funding: $98,346
Source: DOE **Level:** 100%

Project Objectives:

To compare the cost effectiveness and energy effectiveness of existing chemical heat pump (CHP) concepts with a baseline of conventional energy technologies and a group of near-term emerging energy technologies with which CHPs are expected to compete.

Project Description:

The analysis was structured to evaluate these systems functioning as the primary space conditioning unit of both a "standard" single-family detached home and a "representative" commercial building. Each heating, ventilating, and air conditioning system and application was analyzed in each of two locations in the United States, the southwest (Albuquerque, New Mexico) and the northeast (Boston, Massachusetts). In addition, the CHPs were evaluated in two representative industrial waste heating upgrading applications and compared to potentially competitive technologies for industrial heat pumping.

The Energy Engineering Division of TRW conducted a comparative economic and energy consumption evaluation of CHPs in support of the Chemical/Hydrogen Energy Storage Systems Program at Brookhaven National Laboratory (BNL). CHPs extract thermal energy from a low-temperature source and reject it to a higher-temperature sink. Unlike vapor-compression heat pumps, CHPs make use of reversible chemical reactions between a working fluid (or vapor) and one or more stationary phases (solid or liquid). CHPs are being developed by Department of Energy and BNL because they offer the promise of lower overall cost and greater efficiency than separate units for heating, cooling, and (in solar operations) storage. They are also being considered for industrial process heat upgrading applications. In these roles, CHPs must compete successfully on economic levels with present-day baseline systems and with near-term emerging technologies. This study addressed both aspects of the comparison, that is, the cost effectiveness and energy resource effectiveness of CHPs.

Under contract to BNL, TRW conducted a cost-effectiveness and energy resource evaluation of two CHP concepts: a sulfuric acid–water CHP and a methanol–calcium chloride CHP. The CHPs were compared to baseline and emerging competitive technologies for providing space conditioning services to residential and commercial buildings and for upgrading industrial process heat, using levelized annual cost as the measure of cost effectiveness. The study concluded that CHPs could be cost effective and conserve energy resources in applications for industrial process heat up-grading and, in specific applications, for residential heating and cooling. CHPs for commercial office building space conditioning are neither resource effective nor cost effective.

Publications:

R. Gorman et al., *Chemical Heat Pump Cost Effectiveness Evaluation—Final Report,* BNL 51484, May 1981.

8.2.5 Heat Pump Concepts for Industrial Use of Waste Heat

Principal Investigator: Horacio Perez-Blanco
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-0419

Contract Agency: Department of Energy
Contract Number: W-7405-eng-26/AA-55-15-15-0
Contract Period: January 1980 through June 1980
Funding: $28,000
Source: DOE **Level:** 100%

Project Objectives:

To identify appropriate research subjects.

Project Description:

The availability of low-grade waste heat throughout the industrial sector and the pattern of process heat demand had to be established. Along with this information, a variety of heat pump technologies geared to recovering the waste heat available and providing process heat had to be analyzed. Two technologies were chosen for further research.

The waste heat rejected by the industrial sectors was determined from information available in the open literature. The data are available only at the two-digit level of the Standard Industrial Classification. The profile of process heat vs temperature demand at the same level of aggregation was also determined from data available in the open literature. It was determined that industrial heat pumps able to provide process heat at about 212°F (100°C) from waste heat at 140°F (60°C) (or higher) should find applications in the industrial sector.

Industrial heat pumps may be implemented in any of the following ways: electrically driven, heat driven, and waste heat driven. From the standpoint of energy conservation, the heat-driven and the waste-heat-driven types offer the greatest potential. Electrically driven heat pumps are available in the commercial market and are of limited research interest. Therefore, one heat-actuated and two waste-heat-actuated heat pump concepts were analyzed.

From this analysis, it was concluded that steam ejector heat pumps offered a low-cost, dependable (albeit inefficient) technology for temperature boosting. Absorption heat pumps, as examples of waste-heat-fired concepts, either in a closed or open configuration, were determined to be worthy of further research. It was also established that two-stage absorption heat pumps may be necessary to meet the desired temperature boosts.

Publications:

H. Perez-Blanco, *Heat Pump Concepts for Industrial Use of Waste Heat,* ORNL/TM-7655, 1981.

H. Perez-Blanco and G. Grossman, *Cycle and Performance Analysis of Absorption Heat Pumps for Waste Heat Utilization,* ORNL/TM-7852, 1981.

H. Perez-Blanco and F. C. Chen, "Some Heat Pump Concepts for Residual Heat Utilization," *Alternate Energy Sources III*, Vol. 2, 1983, pp. 293–308.

9. NOVEL HEAT PUMP CYCLES

9.1.1 Stirling Cycle Heat Pump Research—Evaluation of Concept

Principal Investigator: Norberto Domingo
Organization: Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831
Telephone: (615) 574-1083

Contract Agency: Department of Energy
Contract Number: DE-AC05-84OR21400
Contract Period: July 1982, continuing
Funding:
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the Stirling-cycle heat pump concept with characteristics that are suited for residential space-conditioning applications.

Project Description:

Analytical efforts to date include (1) conducting heat pump simulations and (2) comparing performance and loss terms by two methods.

The technical approach followed in conducting heat pump simulations included mapping performance trends and trade-off relationships of a Stirling cycle heat pump and determining the effects of working gas, pressure, drive speed, source temperature, and dead volume on heating coefficient of performance (COP) and capacity. The following results were noted:

- Source temperature had low effect on heating COP and no effect on capacity
- Capacity may be modulated by pressure and speed
- Heating COP increased by using hydrogen as the working gas instead of helium
- Capacity decreased with hydrogen as the working gas
- Heating COP and capacity increased as drive speed increased

The technical approach followed in the comparative analysis with two methods of computation included (1) calculating performance and loss terms using the National Aeronautics and Space Administration–Lewis Research Center third-order code and the Martini second-order code and (2) determining the level of coherence between results predicted by two different types of analysis. The following results were noted:

- Poor agreement was found between pressure drop, mechanical friction, and conduction losses
- Fair agreement was obtained between the overall performance estimated despite the use of possibly incorrect loss predictions
- Levels of uncertainty between the two computer models were dependent on drive speed and gas pressure

Publications:

N. Domingo, W. L. Jackson, and F. C. Chen, *A Theoretical Analysis of a Kinetic Stirling-Cycle Heat Pump for Space Conditioning Applications,* ORNL/CON-149, March 1984.

N. Domingo, W. L. Jackson, and F. C. Chen, "A Numerical Analysis of a Kinetic Stirling-Cycle Heat Pump for Space Conditioning Applications," *Proc. 19th IECEC,* August 1984.

N. Domingo, *Comparative Analysis of a Stirling Heat Pump with Second and Third-Order Computer Models,* ORNL/CON-162, June 1985.

N. Domingo, "Stirling Cycle Heat Pump Studies," *Proc. DOE/ORNL Heat Pump Conference, Dec. 11–13, 1984,* CONF-841231, August 1985.

9.1.2 Analysis of Non-Vapor-Compression Heat Pump Cycles

Principal Investigator: Roger L. Demler
Organization: Foster-Miller Associates, Inc.
350 Second Avenue
Waltham, MA 02154
Telephone: (617) 890-3200

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-3
Contract Period: Feb. 24, 1982, through May 30, 1985
Funding:
Source: EPRI **Level:** 100%

Subcontractors: Martini Engineering
Oak Ridge Foster Miller Associates

Project Objectives:

To identify heat pump concepts warranting further research and development efforts to improve performance (particularly for operation at low source temperatures); to improve load characteristics to utilities; to offer alternatives to chlorofluorocarbon refrigerant, vapor-compression cycles.

Project Description:

The feasibility of electrically driven, non-vapor-compression cycle (modified Rankine) heat pump concepts were evaluated. Reverse Brayton and Stirling cycles as well as other concepts were studied. A literature search, screening of concepts, feasibility analysis, and economic analyses were included. Commercially available heat pumps generally utilize the vapor-compression refrigeration cycle as the means of transferring heat from a low-temperature source to a high-temperature sink. Chlorofluorocarbon working fluids are used almost exclusively in these heat pumps for space conditioning and water heating applications. An extensive amount of literature exists on prime movers using Brayton, Stirling, and other cycles, but little is known about their potential as electrically driven heat pumps. Recent investigations have suggested that alternative cycles may offer advantages at low-source temperatures.

Based on the data acquired in a literature search, discussions with experts on the subject, and preliminary analyses, screening of non-vapor-compression concepts for projected performance, costs, and other pertinent criteria was conducted. Three concepts were subjected to further technical feasibility and economic analyses:

- A moderate-pressure, adiabatic Stirling cycle based on a kinematic drive
- A highly pressurized, isothermalized free-piston Stirling cycle
- An open regenerated Brayton cycle

Magnetic (both low-field and superconducting electromagnetic) and thermoelectric concepts have been eliminated from further consideration. A contract amendment was negotiated to allow more detailed evaluation of the isothermalized Stirling cycle.

The life-cycle costs of non-vapor-compression heat pumps were analyzed and found to be noncompetitive with conventional heating and cooling alternatives. The analyses found that an isothermalized Stirling heat pump would be marginally competitive, subject to further development in northern climates in heating-only applications. The isothermalized Stirling heat pump offers lower electrical energy consumption than existing vapor compression cycles in cold weather and would be competitive, in this respect, with advanced vapor-compression cycles.

Publications:

None provided.

9.1.3 Evaluation of Ejector Heat Pump

Principal Investigator: C. T. Hsu
Organization: University of Tennessee
Knoxville, TN 37939
Telephone:

Contract Agency: Oak Ridge National Laboratory
Contract Number: 7685-526
Contract Period: January 1983 through November 1983
Funding: $15,000
Source: DOE **Level:** 100%

Project Objectives:

To assess the feasibility and potential performance characteristics of ejector heat pumps analytically, to identify possible research and development opportunities.

Project Description:

Elrod's theory of ejector design and one-dimensional gas dynamics were used to optimize ejector area and mass-flow ratios and to compute cycle performance for a range of operating conditions, boiler temperatures, and assumed nozzle and diffuser efficiencies. The off-design performance of fixed-geometry ejectors was evaluated. The effects of cycle variations and fluids on efficiency and performance were investigated. The analysis indicated that the expected coefficients of performance are achievable and the off-design performance is insensitive to evaporator temperature variations. The ejector heat pump is more attractive in the heating mode because it should offer better performance than direct furnace heating or electrical resistance heating.

Publications:

C. T. Hsu, *Investigation of an Ejector Heat Pump by Analytical Methods*, ORNL/CON-144, July 1984.

F. C. Chen and C. T. Hsu, "Performance of Ejector Heat Pumps," to be published in *Int. J. Energy Res.* **11** (1987).

9.1.4 Research and Development of an Air-Cycle Heat Pump Water Heater

Principal Investigator: William M. Toscano
Organization: Foster Miller Associates, Inc.
350 Second Avenue
Waltham, MA 02154
Telephone: (617) 890-3200

Contract Agency: Oak Ridge National Laboratory
Contract Number: Sub-7226
Contract Period: May 1977 through December 1979
Funding: $381,000
Source: DOE **Level:** 100%

Project Objectives:

To develop an air-cycle (reverse-Brayton) heat pump water heater, to analyze the market and business potential, to evaluate the system first cost and actual annual performance and operating costs, to field-demonstrate a system to obtain performance/cost data and to identify problems in actual service.

Project Description:

A reverse-Brayton air cycle heat pump water heater was designed for residential application. The system consisted of a compressor/expander, an air-water heat exchanger, an electric motor, a water circulation pump, a thermostat, and fluid management controls.

The advantage of a reverse-Brayton air-cycle heat pump for water heating is that the system is independent of an outdoor heat exchange installation with fan, refrigeration lines, and defrosting mechanism. The electric motor and compressor/expander need not be hermetically sealed or thermally coupled, which allows each component to be optimally designed and independently maintained. The working fluid is air. The thermal load, which is the sensible heat of the water, is easily matched with the sensible heat of the air in the air-water counterflow heat exchanger. The coefficient of performance (COP) and heat pump capacity do not vary significantly with the ambient temperature; therefore, if the system proves to be effective at standard ambient conditions, it can be considered for operation in any climate. The design goal was a COP of 1.7.

In the development program, a prototype heat pump system with a COP of 1.26 was built and tested. The difference between experimental and design thermodynamic performance was attributed to mass transfer losses and heat transfer losses. As part of the design effort, a thermodynamic parametric analysis of the water heater system was performed. It was determined that to obtain a COP of 1.7, the isentropic efficiency of both the compressor and expander must be at least 85%. This program was terminated because of the low COP achieved and the development cost to achieve the target COP of 1.7.

Publications:

J. T. Dieckmann et al., *Research and Development of an Air-Cycle Heat Pump Water Heater,* ORNL/Sub-7226/1, Oct. 1, 1979.

10. CROSSCUTTING PROJECTS

10.1.1 Advanced Positive Displacement Rotary Vapor Compressor

Principal Investigator: Ralph Hoffman
Organization: Trochoid Power Corporation
14789 Martin Drive
Eden Prairie, MN 55344
Telephone: (612) 937-9163

Contract Agency: Gas Research Institute
Contract Number: N/A
Contract Period: January 1981, continuing
Funding:

Source:	**Level:**
GRI	81%
Trochoid	19%

Project Objectives:

To develop an advanced positive displacement rotary vapor compressor with economy and ease of manufacture, high volumetric and compression efficiencies, economy of power consumption over a range of compression ratios, high-speed operation, and high durability.

Project Description:

A single rotor unit of ~300-lb/h capacity was designed. A mathematical model was developed covering the cycle analysis and critical operating characteristics. Extensive tests were conducted on wear rates and coefficients of friction.

The test unit was ~14 × 14 × 7 in., designed to run at 3450 rpm. Contrary to piston compressors of the same capacity, it was smaller than the 20-hp motor driving it. The unit had a waterjacket for instrumentation of heat transfer.

Studies relating to the maximum capacity for a given unit were concluded. Upper limits in size were limited by sonic velocities of the steam being compressed, and maximum machining facilities offering capabilities for machining the trochoidally shaped rotor and outer-envelope housing. A further constraint was the maximum allowable rubbing velocities of the chosen seal material.

Fluid tests of the unit were canceled, and laboratory tests have been scheduled instead.

Publications:

R. H. Roche and P. B. Stielstra, *Positive Displacement Rotary Compressor for Vapor Compression, Annual Report, January 1981 through January 1982*, PB-82-227620, February 1982.

10.1.2 Heat Pump Center—IEA Annex IV

Principal Investigator: Karl Holzapfel
Organization: Fachinformationszentrum
Energie-Physik-Mathematik
GmbH Karlsruhe
D-7514 Eggenstein-Leopoldshafen
Federal Republic of Germany
Telephone: 49-7297-824541

Contract Agency: International Energy Agency
Contract Number:
Contract Period: December 1982 through December 1988
Funding: 5,718,000 DM ($2,377,000)
Source: DOE **Level:** 18%
Other participating IEA countries 82%

Subcontractors: Forschungszentrum Graz
Kopernikusgasse 24
A-8010 Graz, Austria
P. V. Gilli

Project Objectives:

To expedite commercialization of heat pumps by eliminating noneconomic barriers; to promote regular contacts and information exchange among researchers, engineers, and government officials in the field of heat pumps; to encourage international exchange of technologies; to improve the quality, reliability, and accessibility of information concerning heat pumps.

Project Description:

The Heat Pump Center (HPC) is supported by a national team in each participating country. Each team has the functions of providing certain types of information to the HPC and serving as a point of contact for the services of the HPC. In the United States, the national team effort is provided by Oak Ridge National Laboratory. The activities of the Center are directed by a steering committee on which each participating country is represented. This is a subcommittee of the Executive Committee of the International Energy Agency Working Party on Advanced Heat Pumps. To date, the main activities of the Center have been the following:

- A quarterly newsletter
- Research, development, and demonstration project summaries
- A product information data base
- A survey of heat pump standards
- A bibliography on nonazeotropic mixed refrigerants
- A workshop on heat pumps for retrofit in the residential sector
- A survey of weather data sources

Publications:

IEA Heat Pump Center Newsletter, **1**(1), June 1983; **1**(2), December 1983; **2**(1/2), May 1984; **2**(3), October 1984; **2**(4), December 1984; **3**(1/2), July 1985; **3**(3), October 1985; **3**(4), December 1985.

"Non-Azeotropic Refrigerant Mixtures as Working Fluids in Compression Heat Pumps," *IEA Heat Pump Center Bibliography*, HDC-B1, October 1984.

Basic Research in Heat Pump Technology, RD&D Projects, HDC-R1-1, December 1984.

Heat Pump Applications in Residential and Commercial Buildings, RD&D Projects, HPC-R1-2, December 1984.

Application of Heat Pumps in Industry, District Heating, and in Integrated Community Energy Systems, RD&D Projects, HPC-R1-3, December 1984.

Indexes, Heat Pump RD&D Projects, HPC-R1-4, December 1984.

10.1.3 Field Test of Current and Diversified Add-On Heat Pumps and Gas Heating Systems

Principal Investigator: Patrick J. Hughes
Organization: W. S. Fleming and Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: June 1984 through April 1986
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objective:

To analyze the technical performance and cost effectiveness of current add-on heat pumps in conjunction with efficient and standard gas heating technologies.

Project Description:

Three heat pump and gas furnace heating system combinations installed in field situations were monitored and evaluated. System component performance were isolated through data analysis. Data analysis will lead to development of equipment-specific computer modeling. Results of this project are expected to define optimum combinations of add-on heat pumps and gas furnace technologies for northern climates.

Publications:

None provided.

10.1.4 Obtain HEICA Approval for Updated Heat Pump Algorithms

Principal Investigator: Patrick Hughes
Organization: W. S. Fleming & Associates, Inc.
5802 Court Street Road
Syracuse, NY 13206
Telephone: (315) 437-1780

Contract Agency: Niagara Mohawk Power Corporation
Contract Number:
Contract Period: January 1985 through December 1985
Funding:
Source: Niagara Mohawk **Level:** 100%

Project Objectives:

To develop bin analysis residential load algorithms, to develop bin analysis algorithms for conventional heating and cooling systems, to develop bin analysis routines for air source heat pumps, to develop bin analysis routines for water source heat pumps including the earth-coupled type, to implement the previous routines into a computer program to be used as a marketing tool, to obtain Public Service Commission approval of system algorithms.

Project Description:

In its efforts to increase the use of heat pumps, a local power utility desired models that accurately and quickly predict the performance of heat pump systems in residential applications. Bin method models predicting the performance of heat pump and conventional systems were developed. The routines are to be implemented into a marketing tool targeted at the different levels of customer, homeowner, dealer, builder, and engineer.

Publications:

None provided.

10.1.5 Heat Pump Manual

Principal Investigator: Jeffrey M. Seisler
Organization: Analytech Management Consulting
215 North West Street
Alexandria, VA 22314
Telephone: (703) 836-7692

Contract Agency: Electric Power Research Institute
Contract Number: RP2033-7
Contract Period: Jan. 19, 1982, through Aug. 31, 1985
Funding:
Source: EPRI **Level:**
National Rural Electric
Cooperative Association

Subcontractors: Ronald H. Howell and Harry J. Sauer, Jr., University of Missouri
Victor W. Goldschmidt, Purdue University
Mason Somerville, University of Arkansas

Project Objectives:

To prepare a manual on heat pumps that provides understandable answers to common questions on heat pumps and a guide to their application.

Project Description:

A reference manual for use by utility customer-service representatives and application engineers was prepared which addresses air-, water-, and ground-source systems and hybrid and solar-assisted heat pumps and provides a source of information on the following:

- What a heat pump is
- What it does
- What equipment is available
- Which types are best suited for representative residential applications
- How to size heat pump systems
- How to estimate energy consumption
- How to compare costs of heat pumps to alternative systems
- Operational tips to maximize energy conservation (e.g., insulation and night setback)
- Operation in tandem with other heating systems
- Considerations in selecting equipment for specific application
- Sources of further information

A brochure was also prepared for utility distribution to homeowners to provide summary information on heat pumps in a simple form.

Publications:

Heat Pump Manual, EPRI EM-4110-/SR, August 1985.

10.1.6 Technology Assessment of Unitary Heat Pumps

Principal Investigator: Morton H. Blatt
Organization: Science Applications, Inc.
Energy Systems & Conservation Division
476 Prospect Street
P.O. Box 2351
La Jolla, CA 92038
Telephone: (619) 456-6490

Contract Agency: Electric Power Research Institute
Contract Number: RP1495-2
Contract Period: Jan. 25, 1981, through Aug. 31, 1984
Funding: $102,423
Source: EPRI **Level:** 100%

Project Objectives:

To assess the technology status of electric heat pumps, to survey regulatory issues affecting heat pumps, to summarize the market status of heat pumps, to identify future research and development needs.

Project Description:

This project involved a survey of technical literature, contacts with heat pump manufacturers and trade associations for information about new heat pump concepts and technology trends, and compilation and analysis of market data. The status and effect of federal building energy efficiency, consumer product efficiency, chlorofluorocarbon production, and other regulations were reviewed. Special technical issues, such as modulation, defrost mechanisms, and controls were investigated, and recommendations regarding future research and development needs were made.

The literature search, contacts with experts in the field, and assessment were completed. A draft report was submitted, and required revisions were identified.

The major results of the study centered on the formulation of unitary heat pump research and development needs. Projects funded by the Electric Power Research Institute (EPRI) were recommended for those areas not currently being investigated by EPRI or others. Specific program elements were described in the following nine application areas:

- Increased retrofit applicability
- Improved low-temperature performance
- Improved part-load performance
- Improved water-source heat pumps
- Integrated space heating/water heating
- Precooling/evaporative cooling
- Improved solar-assisted and ground-coupled heat pumps
- Improved defrost
- Improved controls

Publications:

None provided.

10.1.7 Gas-Fired Heat Pump Research and Development—Review and Assessment

Principal Investigators: J. A. Kinast
J. Wurm
Organization: Institute of Gas Technology
3424 South State Street
Chicago, IL 60616
Telephone: (312) 567-3839

Contract Agency: Gas Research Institute
Contract Number: 5081-242-0541
Contract Period: September 1981 through February 1983
Funding: N/A
Source: GRI **Level:** 100%

Project Objectives:

To compile and analyze, from public and private sources, information on research investigations or proposed investigations on gas-fired air conditioning and gas-fired heat pumps; to provide research sponsors, research investigators, and the gas industry with this information in a ready source for assessing the potential of current and future research and developmental efforts on gas-fired air conditioning and gas-fired heat pumps.

Project Description:

One of the greatest hindrances to the rapid development of gas-fired heat pumps has been the lack of a compendium of knowledge of what had already been done or tried over the years. This bibliography would greatly accelerate development of prime mover systems, selection of refrigerants, and improvement of reliability and performance by putting years of related experience at the developer's fingertips. Knowledge of the information and techniques used by the electric heat pump industry to solve reliability problems will make it possible for the gas heat pump industry to avoid the same pitfalls and gain the respect of the consumer sooner.

The Gas Research Institute heat pump project advisors made known the need of a documented record of heat pump knowledge. This information was compiled into an annotated bibliography in a format designed to facilitate ease of information retrieval. Selected entries were provided with a short assessment or explanatory note and were indexed and cross-referenced.

Publications:

J. A. Kinast and J. Wurm, *Gas-Fired Heat Pump Research and Development: Review and Assessment, Final Report, September 1981–February 1983*, PB-84-153907, December 1983.

10.1.8 Heat-Pump-Centered Integrated Community Energy Systems (HP-ICES) (District Heating and Cooling with Heat Pumps)

Principal Investigator: James M. Calm
Organization: Argonne National Laboratory
Energy & Environmental Systems Div.
9700 South Cass Avenue, Bldg. 11
Argonne, IL 60439
Telephone: (312) 972-3730

Contract Agency: Department of Energy
Contract Number: W-31-109-eng-38
Contract Period: October 1978 through March 1981
Funding: $720,000
Source: DOE **Level:** 100%

Major Subcontractors (all subcontractors totaled 35):

University of Alabama
Consolidated Natural Gas Service Company
Dubin-Bloome Associated
Franklin Research Center
Georgia Institute of Technology
Honeywell Energy Resources Center
Rocket Research Company

Project Objectives:

To develop heat pump systems for district heating and cooling through concept innovation, system development, application feasibility studies, and system assessment (actual development of heat pumps was not included in this project).

Project Description:

District heating and cooling concepts using centralized, distributed, and cascaded heat pump systems were developed. In 15 application feasibility studies, using diverse sources and sinks, the systems examined showed promise for

- Substantially reducing on-site energy use for space heating and cooling and for water heating
- Substituting nonscarce resources for premium fuels
- Significantly reducing resultant source-energy use
- Offering load-management advantages to both electric and gas utilities
- Reducing adverse environmental impacts
- Resulting in favorable life-cycle costs and, for some systems, payback periods shorter than five years

Because the sources and sinks used are both varied and abundant, broad application potential is believed to exist for these systems.

The results of the project have been reported in 39 publications including a summary and an assessment of the systems developed. Subsequent project phases leading to physical demonstration and commercialization of successful concepts were initially anticipated but are not presently planned.

Publications:

J. M. Calm et al., *Heat-Pump-Centered Integrated Community Energy Systems: System Development Assessment,* ANL/CNSV-18, March 1981.

10.1.9 Engineering Field Test Planning

Principal Investigator: Myron Myers
Organization: National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, AL 35812
Telephone: (205) 453-2051

Contract Agency: Department of Energy
Contract Number: EX-76-A-29-1024
Contract Period: October 1979 through September 1980
Funding: $560,000
Source: DOE **Level:** 100%

Project Objectives:

To develop an engineering field test plan for four of the technologies researched and developed in the System Development Branch of the Department of Energy Active Solar Buildings Division.

Project Description:

National Aeronautics and Space Administration/Marshall Space Flight Center analyzed the readiness of Rankine, absorption, desiccant, and solar-assisted heat pump technologies and developed a plan to move toward marketable solar systems through an engineering field test program.

Publications:

None provided.

10.1.10 Common Study on Advanced Heat Pump Systems—IEA Annex I

Principal Investigator: Peter Kueppers
Organization: Kernforschungsanlage Juelich GmbH
Postfach 1913
D-5170
Juelich, West Germany
Telephone: 49-2461-614623

Contract Agency: International Energy Agency
Contract Number:
Contract Period: October 1978 through July 1980
Funding: 1,507,000 DM ($824,920)
Source: DOE **Level:** 27%
12 countries via IEA 73%

Subcontractors: Battelle-Institut E.V.
AM Romerhof 35
D-6000 Frankfurt AM Main 90
West Germany
David L. Hodgett

Resource Planning Associates
50 Church Street
Cambridge, MA 02138
Ann Quinn

Project Objectives:

To collect and evaluate data on advanced heat pump systems (i.e., heat-activated systems) currently under development; to assess their market potential; to derive relevant proposals for desirable developments and a future International Energy Agency research and development program.

Project Description:

General conclusions of the study show that electric heat pumps (for both heating and cooling) predominate in the United States as replacement for boilers and furnaces and in West Germany a similar situation exists with bivalent-alternative heating-only heat pumps. The first priority in most countries is to find a substitute for oil and second, to conserve energy. Present electric heat pumps meet the first priority but rarely contribute to the second, unless they are compared with direct electric heating. Advanced heat pumps, the best of which are internal combustion engine driven, are capable of conserving 30 to 50% prime energy. However, in terms of oil substitution, the superior systems are gas-fired: Brayton, Otto, and Stirling engine driven; the Rankine-Rankine; and the sorption systems. External combustion systems have a total flexibility of fuel use and are thus particularly attractive, especially in large unit sizes.

Most advanced heat pumps are not due for commercialization until 1985. Thus, the possibility of achieving worthwhile energy savings before 1990 appears low. Accelerated development of the systems with greatest potential for each application is desirable even if their use is not justifiable on economic grounds in the short term. The economic potential for all advanced heat pump systems is limited by strong competition from conventional systems.

The overall conclusion was relatively clear: so that the market share for advanced heat pumps as a group will expand, efforts should focus on advanced heat pumps most likely to generate market potential by the year 2000—absorption, Rankine-Rankine, and diesel-Rankine systems. Diesel-Rankine is suited to large installations; absorption and Rankine-Rankine show greatest potential for small heating-only applications. Electric heat pumps will predominate for combined heating and air-conditioning applications.

Publications:

D. L. Hodgett et al., *International Energy Agency Programme of Research and Development on Advanced Heat Pump System, Annex I, Common Study on Advanced Heat Pump Systems, Final Report. Vol. I: Results and Conclusions,* ISBN 3-88585-029-X, Battelle-Institut e.V. Frankfurt and RPA (Paris) for Kernforschungsanlage Juelich GmbH, July 1980 (available through Verlag TUV Rheinland GmbH, Koeln, Federal Republic of Germany).

D. L. Hodgett and G. Oelert, *International Energy Agency Programme on Research and Development on Advanced Heat Pump Systems, Annex I, Common Study of Advanced Heat Pump Systems, Final Report. Vol. II: Technology Survey,* BF-R-63.896-1, Battelle-Institut e.V. Frankfurt and RPA (Paris), July 1980 (available through ORNL).

M. Grapin et al., *International Energy Agency Programme of Research and Development on Advanced Heat Pump Systems, Annex I: Common Study on Advanced Heat Pump Systems, Final Report. Vol. III: Market Study,* RPA (Paris), July 1980 (available through ORNL).

10.1.11 Evaluation of New and Add-On Heat Pump Technology

Principal Investigator: Arvo Lannus
Organization: Gordian Associates, Inc.
711 Third Avenue
New York, NY 10017
Telephone: (212) 697-9023

Contract Agency: Department of Energy
Contract Number: EX-76-C-01-2121, EC-77-C-03-1699
Contract Period: Aug. 19, 1976, through Dec. 31, 1978
Funding: $94,000
Source: DOE **Level:** 100%

Project Objectives:

To evaluate the performance, cost, and market prospects of heat pumps, both conventional and advanced; to assess research and development needs and make recommendations concerning federal governnment policies and support for this type of space conditioning technology.

Project Description:

The study covered electric as well as experimental gas and other types of heat pumps and examined equipment for residential and commercial applications. Unitary equipment of the type applicable to light commercial, institutional, or industrial construction was investigated in preference to large built-up systems.

On-site energy consumption, energy and life-cycle cost, market prospects, institutional factors, and primary or resource energy efficiency of heat pumps for residential and commercial applications were evaluated. Only unitary equipment was considered. The investigation covered conventional electric heat pumps, experimental gas thermal engines, and absorption cycle machines under development. Other heat pumps were also considered as were combinations with solar energy systems.

Calculations of the on-site and primary energy effectiveness and cost of conventional and advanced heat pumps compared with electric and combustion furnaces and baseboard heat (all with appropriate cooling systems) were made by means of two hour-by-hour computer simulation programs, one for a residential building and one for a commercial building. As test buildings, a two-story frame single-family residence [1850 ft^2 (172 m^2)] and a two-story masonry office building [5580 ft^2 (518 m^2)] were selected. These buildings were hypothetically moved about to nine different cities selected as representative of the various climatic regions of the continental United States.

Energy costs, installed costs, and life-cycle owning and operating costs were determined for the residential and commercial heating, ventilating, and air-conditioning systems. Energy costs were based on locally obtained utility rates, accounting for base load usage and demand charges where appropriate. Installation costs were based on an estimate including labor, materials, shipping, handling, and taxes. Life-cycle costs were calculated assuming an 8% annual inflation in energy costs and a lower rate of inflation in maintenance costs.

Models of the residential and nonresidential building market were used to project market penetrations of heat pumps. The models account for replacements and conversions as well as new construction. Market projections were combined with primary energy consumption results to estimate potential energy savings from advanced electric and gas heat pumps. The study also considered institutional factors such as consumer attitudes, building codes, gas availability, and others.

Publications:

Gordian Associates, Inc., *Heat Pump Technology—A Survey of Technical Development, Market Prospects and Research Needs,* HCP/M2121-01, June 1978.

10.1.12 Analysis of Advanced Thermal Energy Storage Subsystems for Solar Heating and Cooling

Principal Investigator: Peter O. Offenhartz
Organization: EIC Corporation
55 Chapel Street
Newton, MA 02158
Telephone: (617) 965-2710

Contract Agency: Department of Energy
Contract Number: EG-77-C-02-4483
Contract Period: September 1977 through August 1978
Funding: $77,000
Source: DOE **Level:** 100%

Project Objectives:

To simulate the performance characteristics of advanced thermal energy storage subsystems for solar heating and cooling.

Project Description:

Four energy conditioning and storage subprograms were constructed and later integrated into a single system program that handled external variables such as solar input, environmental conditions, and heating/cooling load. This project provided two types of results: (1) a set of programs capable of simulating the performance of a wide variety of thermal storage and conditioning units under realistic assumptions as to collector, heat exchanger, storage media, and conditioning system performance; and (2) a set of full-year simulation runs for thermal energy storage/conditioning subsystems that were proposed in the literature. This project was divided into the following tasks:

- Design and construction of overall system model
- Construction of sensible, phase-change, and reversible chemical subsystem models (SPHW computer model)
- Electric heat pump energy conditioning with multiple storage possibilities (SAHP computer model)
- Absorption and rankine-cycle air conditioning with multiple heating options and storage possibilities (TACSH computer model)
- Simulation runs on published designs
- Additional simulation runs on the most promising designs

Publications:

P. O. Offenhartz et al., *Analysis of Advanced Thermal Storage Subsystems for Solar Heating and Cooling, Final Report, October 1, 1977–September 30, 1978,* COO-4483-F, November 1979.

10.1.13 Radisson Community Heating System

Principal Investigator: Joseph E. Rizzuto
Organization: New York State Energy Research and Development Authority
Two Rockefeller Plaza
Albany, NY 12223
Telephone: (518) 465-6251

Contract Agency: New York State Energy Research and Development Authority
Contract Number: 368-EU-TCE-81
Contract Period:
Funding: $53,000
Source: NYSERDA **Level:** 37%
NMPC 63%

Subcontractors: O'Brien and Gere Engineers, Inc.

Project Objectives:

To examine several alternate advanced heating and cooling systems using heat pumps, with hope that one or more systems would prove both cost effective and more efficient than available individual heating systems.

Project Description:

Three system options were developed to estimate detailed costs and energy consumption. The first option was a community water system distributing ground water to individual residence heat pumps. The second was a common water-source heat pump with hot or chilled water distribution to each house. The heat pump was driven by either a gas engine with waste heat recovery or by an electric motor. The third system option was a common air-source heat pump driven by a gas engine with waste heat recovery. The advanced heating systems were compared with modern gas furnaces and with standard and premium air-source heat pumps in each residence.

At present energy prices, an advanced system is not cost effective at this site, although all systems examined conserved energy compared with conventional heating equipment. Greater operating efficiency and moderately increased unit do not counterbalance the low capital cost of mass-produced individual heating systems.

Fluid distribution lines also add capital cost to the central systems. Large-sized developments (larger than 20 homes cluster at this site) are more likely to result in favorable economics. A more dense residential development would also reduce costs.

Publications:

W. A. Lester et al., *Radisson Community Heating Systems: Technical and Economic Comparison of Options, Final Report*, PB-83-178673, NYSERDA-81-30, December 1981.

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Sponsoring organizations are identified on the summary form under the entry "funding." Over 70% of the projects in this document are sponsored by the U.S. Department of Energy. Most of the remaining projects are funded by the other organizations mentioned in Chapter 3 of this document. Those sponsoring organizations and the corresponding project summary numbers are given in this index.

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