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Utility-Controlled Customer-Side Thermal Energy Storage Tests: Cool Storage

M. A. Kuliasha

POWER SYSTEMS TECHNOLOGY PROGRAM

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ACKNOWLEDGMENTS

This report is an account of a test of electric load management using residential cool storage that was conducted by five utilities under contract to Oak Ridge National Laboratory. The test is part of a comprehensive program for the research, development, and demonstration of load management on the electric power system sponsored by the Division of Electric Energy Systems of the U.S. Department of Energy. The assistance of David L. Mohre, Phillip Overholt, and J. Charles Smith of the Department of Energy is gratefully acknowledged.

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ABSTRACT

The adoption of energy storage for load management in the United States has been slow due to considerable uncertainty about the performance of energy storage equipment and the utility benefits of this load management option. To resolve some of the questions surrounding the use of energy storage for load management, the Division of Electric Energy Systems of the Department of Energy has cofunded with the participating utilities a nationwide concept test program for electric load management using utility-controlled customer-side thermal energy storage for residential space conditioning. Ten projects (five heat storage and five cool storage) were conducted by utilities under contract to Oak Ridge National Laboratory to (1) collect reliable load research data, (2) delineate and solve installation problems, (3) evaluate maintainability, (4) determine customer and utility acceptance, and (5) develop cost data.

This report describes the five cool storage projects and presents the utility and customer experience through the equipment installation, checkout, and operation phases of the program. The five heat storage projects are described in a separate report. Subsequent reports will describe and analyze the load research results obtained from the test and discuss the potential system impacts of this load management option.

Cool storage test projects were conducted by Arkansas Power and Light Company, Long Island Lighting Company, Pacific Gas and Electric Company, Virginia Electric and Power Company, and Wisconsin Electric Power Company. Data were collected during the 1980 cooling season. Two of the utilities, Arkansas Power and Light and Wisconsin Electric Power Company collected an additional season's data during 1981. The utilities tested cool storage systems manufactured by A. O. Smith Corporation, Carrier Corporation, Girton Manufacturing Company, and Calmac Manufacturing Corporation in both new and retrofit residential applications.

The results of the tests indicate that when properly designed and installed, cool storage equipment can provide adequate or even improved space conditioning over conventional air conditioning and shift a large portion of the electric load to off-peak periods. Thus, the concept of cool storage for residential space conditioning offers great promise as a load management tool.

However, the results of this test also indicate that residential cool storage is not ready for commercialization

in its present state of development. In this context, a system is considered to be capable of commercialization if it can be placed in the field and perform its intended function without excessive maintenance over an acceptable lifetime. Significant problems were experienced with all product designs tested. The problems experienced included inadequate compressor capacity, inadequate storage capacity, high energy usage, and poor equipment reliability, making the widespread implementation of current equipment of questionable benefit to either the utility or its residential customers. Improved equipment designs which solve the problems identified in these tests could make residential cool storage a viable load management option at some future date.

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1. INTRODUCTION

1.1 Load Management Issues

Historically electric utilities have designed their facilities to meet customer demands at minimum cost while providing a given level of service reliability. However, recent trends in capital costs and production expenses have caused many utilities to rethink their relationship with their customers. Rather than installing and operating facilities to meet any given load, consideration is being given to increasing efficiency by tailoring electric energy use to match electric energy supply.

Load management is the term used to refer to techniques that attempt to alter the electric energy consumption patterns of individual customers. The objectives most commonly cited for load management are to reduce the need for additional generation, transmission, and distribution investments; make more efficient use of existing facilities; shift fuel dependency from premium oil and gas to more abundant resources like coal and nuclear; and provide adequate electric service at a reasonable cost. Conceptually, load management involves extending the definition of the electric energy system to include the use of electric energy.

Many of the options available to utilities to shape the electricity consumption patterns of consumers involve either direct control of customer loads or voluntary control of loads through rate incentives. Frequently the loads targeted for control are either nonessential or possess energy storage characteristics to minimize customer inconvenience. Loads that involve storage are particularly attractive because they allow the consumer to use energy on demand yet allow the utility to supply electricity when it can be produced at the lowest possible cost.

More than 60% of the energy consumed by the residential sector is used for space conditioning while another 15% is used for water heating. In the commercial sector, 65% of all energy is used for space conditioning.[1] Essentially all residential and commercial cooling uses electrical devices, and the percentages of electric space and water heating are increasing. Electric water heating is an obvious load to manage because of its high energy usage and natural storage characteristics. However, control of the largest electric loads, space heating and space cooling, has been limited because the inherent storage characteristics of buildings do not allow extensive control without some decrease in customer comfort.

A number of electric space conditioning systems using thermal energy storage (TES) have been developed that offer the potential of meeting space conditioning needs while offering the utility considerable flexibility in the delivery of electric energy. The typical operation of these devices consists of accepting electric energy during some defined off-peak period (e.g., night, weekend, midday valley), storing the energy in the intended end-use form (e.g., heat or cool), and releasing the energy as required to provide space conditioning.

Ceramic brick electric heat storage systems have been extensively used in Europe.[2] Several other TES systems, including pressurized-water heat storage, chilled-water storage, and ice cool storage, have been developed to the point of being near-commercial. However, the adoption of any of these options for load management in the United States has been slow due to considerable uncertainty about the performance of the energy storage equipment and uncertainty about the utility benefits. A major question has been whether TES will result in a sufficiently large net reduction in utility costs, which can then be passed on to the consumer through rate incentives to justify the additional expense of the storage equipment.

To resolve some of the questions surrounding the use of TES for electric load management, the Division of Electric Energy Systems of the U.S. Department of Energy (DOE) has cofunded with the participating utilities a nationwide test program for electric load management using TES to evaluate the effectiveness of near-commercial heat and cool storage devices. The tests were contracted and managed by Oak Ridge National Laboratory (ORNL). The objectives of the DOE/ORNL tests were to (1) collect reliable load research data, (2) delineate and solve installation problems, (3) evaluate maintainability, (4) evaluate customer and utility acceptance, and (5) develop cost data. The results of the tests are expected to be useful to utilities in making local load management decisions and to DOE in establishing priorities for research and development efforts in load management.

1.2 Test Design

While customer-side TES has not been widely applied in the United States, a recent survey of utility load management activities has identified 86 utility-sponsored TES projects.[3] These projects generally consist of one or two installations in a given service area and, although valuable for determining the applicability of a particular TES concept to a given region, the information collected from such projects is inadequate for estimating what widespread implementation might mean to that utility. For example, one or two installations are inadequate to determine diversified demand profiles, maintainability, and installation costs, which can only be determined if sufficient data are collected to cover the range of applications and use characteristics in the region. However, neither manufacturers, utilities, nor customers have been willing to undertake such large-scale tests because of high costs and the uncertainty of the technology.

The DOE/ORNL tests were planned to consist of a number of projects covering a range of geographic, climatic, utility, and storage system characteristics. Each project was carried out by a utility under contract to ORNL. The utility was responsible (with ORNL approval) for the acquisition, installation, operation, and maintenance of all equipment used during the test. Each project consisted of a sufficient number of the same manufacturer's storage units installed in a given utility to collect load research data and provide reasonable estimates of equipment installation costs, reliability, and performance. The range of 30 to 50 storage installations per project was chosen as a compromise between established load research procedures and project funding limitations.

The projects were limited to near-commercial heat or cool storage (or both) for residential space conditioning with the optional addition of water heating. Hybrid systems involving nonelectric energy supply (e.g., solar with supplemental electric heating) were outside the scope of this test. The candidate storage systems were selected by the responding utilities on the basis of high potential for economic effectiveness and customer acceptance in their service area. The storage units were installed in new construction and in retrofit applications, depending on the market for storage heating or cooling in the utility's service area.

To provide a basis for comparison, a control group with conventional space conditioning systems was included in each project. Both the storage homes and control group were instrumented to collect the necessary load research data. In addition, several of the storage homes in each project were more fully instrumented to obtain detailed information on the storage unit characteristics. Because the objective of this test was to collect information to evaluate heat and cool storage for load management, the emphasis was on load research as opposed to equipment design-type data. (The Electric Power Research Institute has conducted a residential TES instrumentation and data verification program to analyze equipment performance.[4]) Data on utility operations and weather conditions were also collected to correlate with storage unit performance.

The data from all the projects were collected in a consistent manner so that the results from the various projects could be compared.

Remote utility control of the storage systems was required as a part of each project. This requirement arose because one of the desired results from the test was a measure of the effectiveness of various control strategies. Remote utility control allowed a number of implementation strategies, such as fixed time-of-day control or active utility control to minimize production costs, to be tried during the test. Active utility control also allowed the control strategy to be tailored to storage system performance under various weather conditions.

The projects were planned to cover two full conditioning seasons to increase the probability that a wide range of weather conditions would be experienced. However, as will be discussed later, delays in equipment installation and problems with storage system performance limited some of the projects to one season or less of operation.

1.3 Project Summaries

To identify utilities that might be interested in participating in the test program, some 200 utilities that had been previously identified as having a completed, ongoing, or planned project in customer-side TES or had indicated an interest in starting such a project were sent an outline in September 1977, describing the program and asking if they wished to receive a detailed Request for Proposal (RFP) to bid for participation. Sixty-four utilities requested the RFP, which was mailed in November 1977, and 17 proposals were submitted. From these proposals, eight utilities were selected to perform five heat storage and five cool storage projects (two of the utilities employed both heat and cool storage). The utilities included Arkansas Power and Light Company (AP&L), Long Island Lighting Company (LILCO), Pacific Gas and Electric Company (PG&E), Public Service Electric and Gas Company, Niagara Mohawk Power Corporation, United Power Association, Virginia Electric and Power Company (VEPCO), and Wisconsin Electric Power Company (WEPCO). The utilities were selected based on their qualifications, past experience, commitment to the project, and likelihood of success. The cool storage systems selected for testing by the chosen utilities were all static ice storage systems. The comments in the remainder of this report will therefore focus on this cool storage option.

This report describes the five cool storage projects. A companion report discusses the five heat storage projects.[5] The contracts for the cool storage projects were generally signed in the fall of 1978, and the installation of equipment was to begin in the spring of 1979 in preparation for the summer of 1979. However, as described in Sect. 4.1, delays in subcontracting for the installation of the equipment caused the utilities to miss the 1979 cooling season.

Data were collected during the summer of 1980 by all five utilities. In addition, two of the utilities, AP&L and WEPCO, collected a second season's data during 1981. This report summarizes the cool storage projects through the equipment installation, checkout, and operation phases of the projects. Subsequent reports will describe and analyze the load research results obtained from the tests and discuss the potential system impacts of this load management option.

The locations of the five cool storage projects are shown in Fig. 1. A summary description of each project is shown in Table 1 and is described in the following sections.

1.3.1 Arkansas Power and Light Company

The test group consisted of cool storage in 29 homes using A. O. Smith ice tanks retrofitted into existing 8.8- to 12.3-kW cooling capacity (2-1/2- to 3-1/2-ton) central air conditioning systems. The control group

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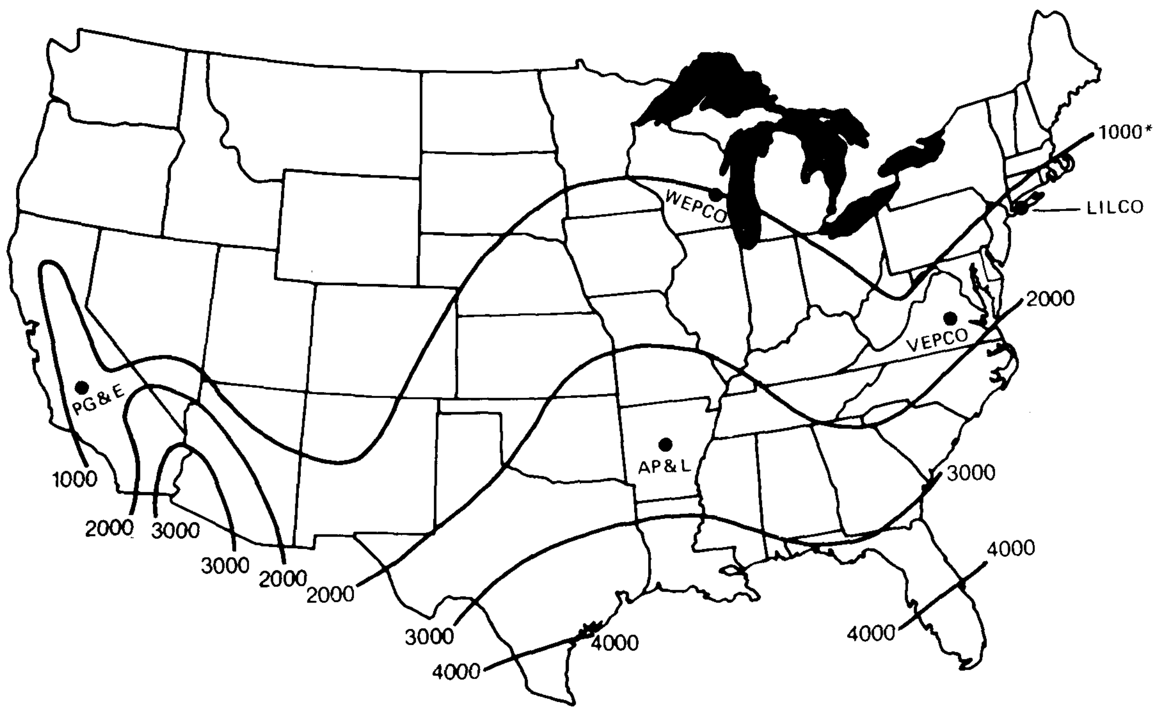

*LINES OF CONSTANT COOLING DEGREE DAYS [BASE 18.3°C (65°F)]

Fig. 1. Location of cool storage projects.

Table 1. Summary of cool storage projects

Utility	TES equipment	Number of test homes	Number of control homes	Home	Storage location	Condensing unit	Cooling degree days[a]	
							Average	1980
Arkansas Power and Light Co.	A. O. Smith	29	35	Existing	Equipment room	Retrofit	1925	2579
Long Island Lighting Co.	Calmac	50	35	Existing	Outside	Retrofit	1068	1435
Pacific Gas and Electric Co.	Girton	30	30	Existing	Outside	Retrofit	1671	2018
Virginia Electric and Power Co.	Carrier/Girton	29	40	New	Equipment room	New	1353	1729
Wisconsin Electric Power Co.	A. O. Smith	70[b]	25	Existing	Basement	New	450	484

[a] Base 18.3°C (65°F) — test location.

[b] Thirty-five full storage and 35 half storage.

consisted of 35 homes having conventional air conditioning. A. O. Smith storage water heaters were installed in 15 homes in place of existing electric water heaters. All data were collected using magnetic tape recorders. Storage control was exercised through an existing radio control system from the power system dispatch center.

1.3.2 Long Island Lighting Company

The test group consisted of cool storage in 50 homes using Calmac ice tanks retrofitted into existing air conditioning systems. The control group was 35 homes with conventional air conditioning systems. Data were collected using magnetic tape recorders. The storage systems were controlled by a radio communications system.

1.3.3 Pacific Gas and Electric Company

The test group consisted of cool storage in 30 homes using Girton ice tanks retrofitted to existing air conditioning systems. A control group of 30 homes had conventional air conditioning. Data were collected using magnetic tape recorders. Utility control of the storage systems was exercised using an existing radio control system.

1.3.4 Virginia Electric and Power Company

The test consisted of heat and cool storage in the same new homes. The cool storage portion of this project used Carrier and Girton cool storage tanks. The number of completed test locations ranged from 6 at the start of the 1980 cooling season to 29 by the end of the season. Heat for domestic hot water was reclaimed from the air conditioning system during the cooling season. Data were collected using magnetic tape recorders. Storage control was via leased telephone lines.

1.3.5 Wisconsin Electric Power Company

The two test groups consisted of cool storage retrofitted into 70 existing homes. Thirty-five homes used two or three A. O. Smith ice tanks with a full-size compressor for off-peak operation only. Another 35 homes used one ice tank with a compressor sized for nearly continuous operation.

The control group of 25 residences had conventional air conditioning. Storage control and data acquisition were through a two-way power line carrier communications system.

2. PROJECT DESCRIPTIONS

2.1 Utility Characteristics

The utilities selected to participate in the cool storage test program cover a range of climatic, demographic, and utility system characteristics. All three of these factors are important in determining the feasibility of customer-side cool storage for load management, and it was desirable to include a wide range of these conditions to increase the applicability of the test's final results.

Some important characteristics of the participating utilities are shown in Table 2.

Table 2. Participating utility system characteristics[a]

Utility	Installed capacity (MW)	Generation mix nuclear/coal/gas and oil/hydro/other (%)	Peak load (MW)		Annual load factor (%)
			Summer	Winter	
Arkansas Power and Light Co.	4,748	36/10/53/1/0	4,179	2,597	53.2
Long Island Lighting Co.	3,900	0/0/100/0/0	2,997	2,456	53.0
Pacific Gas and Electric Co.	11,400	0.4/0/50/16/33	13,440	10,640	59.3
Virginia Electric and Power Co.	10,100	32/30/31/3/4	8,484	7,445	57.5
Wisconsin Electric Power Co.	4,377	32/49/4/2/13	3,346	3,027	63.6

[a]1980 data.

2.1.1 Arkansas Power and Light

AP&L serves 469,013 retail and 25 wholesale customers covering 18,000 sq miles in the state of Arkansas. The utility serves ~50% of the state's population and 35% of its area.

AP&L is a subsidiary of Middle South Utilities Inc., which is a registered public utility holding company. The other operating subsidiaries of Middle South are Arkansas-Missouri Power Company, Louisiana Power and Light Company, Mississippi Power and Light Company, and New Orleans Public Service Inc. AP&L has installed generating capacity of 4,748 MW. The utility is summer peaking, with the winter peak load being ~62% of the summer peak load. Its 1980 annual load factor was 53.2%.

Both temperature and relative humidity are high in the summer, which has caused the saturation of residential air conditioning to increase from 46.6% in 1970 to 79.3% in 1977. During this same period the saturation of residential electric heating has increased from 5.2 to 12.5%. Average annual residential energy usage increased from 6,934 kWh in 1970 to 11,112 kWh in 1980.

2.1.2 Long Island Lighting Company

LILCO is a combination gas and electric utility providing electric service to 791,000 residential and 84,000 commercial-industrial customers. The residential class accounted for ~45% of total electric sales. LILCO also supplies natural gas to 388,000 customers. The LILCO service territory encompasses some 1,230 sq miles.

LILCO's installed generating capacity totals 3,900 MW consisting of 2,700 MW of residual oil-fired steam generation with the balance being distillate oil-fired gas turbines and diesels. The utility is summer peaking with an annual load factor of 53%.

The summers on Long Island are characterized as warm and moist. The average number of cooling degree days is 1,068.

2.1.3 Pacific Gas and Electric

PG&E's service territory covers 94,000 sq miles in northern and central California serving a population of more than 8 million. Oil and hydroelectric energy have historically been PG&E's main energy sources. The utility has 11,400 MW of installed capacity, of which 2,500 MW is hydroelectric and 900 MW is geothermal.

About 416,000 homes have central air conditioning in the PG&E service area; 85% of these are in the noncoastal climatic zones. During 1977, about 14% of PG&E's summer peak was contributed by air conditioning. The

1980 winter peak was 79% of the summer peak, and the annual load factor was 59.3%.

2.1.4 Virginia Electric and Power Company

VEPCO provides electric service to 1.25 million customers in Virginia and parts of North Carolina and West Virginia. The company also provides gas service to the Norfolk-Newport News area (excluding Portsmouth) and in an area extending from Newport News to and including Williamsburg. The company's service territory encompasses 32,000 sq miles.

VEPCO owns some 10,100 MW of generating capacity comprised of 61% coal- and oil-fired steam, 32% nuclear, 3% hydroelectric, and 4% oil- and distillate-fired combustion turbines. The company is summer peaking with a peak of 8,484 MW in 1980 but expects that within a few years its winter peak will be higher than the previous summer peak and lower than the following summer peak.

VEPCO's service area spans a variety of climatic zones ranging from the colder winters and milder summers of the Blue Ridge Mountains to the Piedmont region with its hotter summers and milder winters. VEPCO estimates that about 24,000 new residential electric heat customers are added to the system each year.

2.1.5 Wisconsin Electric Power Company

WEPCO services ~12,600 sq miles of southeastern, east central, and northern Wisconsin (including the Milwaukee area) and the upper peninsula of Michigan with an estimated population of over 2 million. The company services 726,000 residential customers and 73,000 commercial and industrial customers.

WEPCO's generating capability is 4,377 MW comprised of 990 MW nuclear, 2,718 MW coal, and 669 MW of other types. The utility's peak in 1980 occurred on July 14 at 3,346 MW.

The summers in WEPCO's service territory are mild but are characterized by high humidity. The saturation of air conditioning in existing homes is 17%, but the majority of new homes include some kind of air conditioning.

2.2 TES Equipment

The RFPs for the test program specified that the responding utility should select the near-commercial cool storage system that had the greatest probability of success in its service territory. Near-commercial was interpreted to mean that a manufacturer had obtained some field experience with the equipment, could produce a sufficient number of the units to meet the needs and time schedule of the responding utility, and would provide a warranty on the equipment during the test period.

All of the utilities that responded to the cool storage portion of the RFP proposed the equipment of one of three manufacturers. These three manufacturers were A. O. Smith Corporation, Carrier Corporation, and Calmac Manufacturing Corporation. A fourth manufacturer, Girton Manufacturing Company, became involved when Carrier Corporation declined to manufacture any additional cool storage units beyond their existing inventory. It is important to bear in mind that the cool storage equipment available for the test does not represent mass-produced, fully commercial equipment (if such equipment were available, there would be no need for the test). Rather, the cool storage systems tested represent prototype units for evaluating the viability of a particular load management concept.

Of the five utilities finally selected to participate in the cool storage tests, two utilities (AP&L and WEPCO) used A. O. Smith equipment, one utility (LILCO) used Calmac, two utilities (PG&E and one-half of VEPCO's installations) used Girton, and one utility (one-half of VEPCO's installations) used Carrier units.

All four of the cool storage systems tested are similar in concept. The systems are designed to use off-peak power to provide air conditioning during on-peak periods. The air conditioner operates during the off-peak hours to freeze a tank of water. Air conditioning is supplied to the house on demand by circulating water from the ice tank through a modified cooling coil/air handler in the house where the water absorbs the house heat load and transports it to the ice tank where the heat is absorbed by the melting ice. The ice tank can absorb large amounts of heat in the latent heat of fusion of the ice and the sensible heat of the water. A schematic of the principal components of a conventional air conditioner and of a storage air conditioner are shown in Figs. 2 and 3. The storage tank can be located either inside or outside the house. Figures 4 and 5 show typical cool storage installations for each of these locations.

Three of the systems tested in the program can be characterized as direct expansion systems. In such a system, the evaporator coil is immersed in the storage tank and, as the refrigerant expands through the

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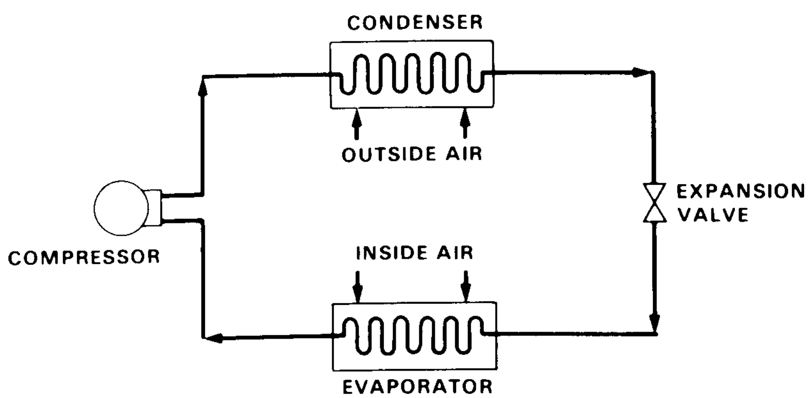

Fig. 2. Schematic of conventional air conditioner.

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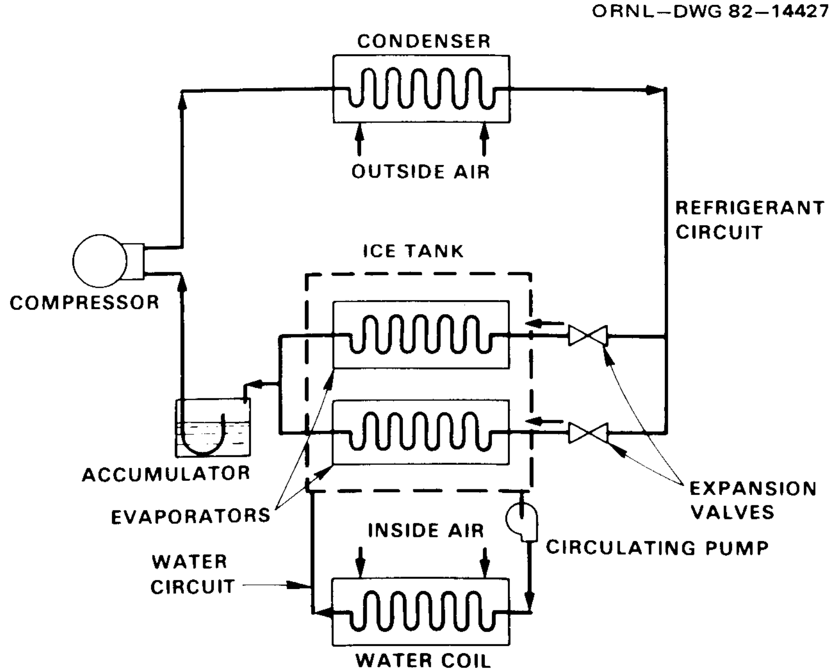

Fig. 3. Schematic of storage air conditioner.

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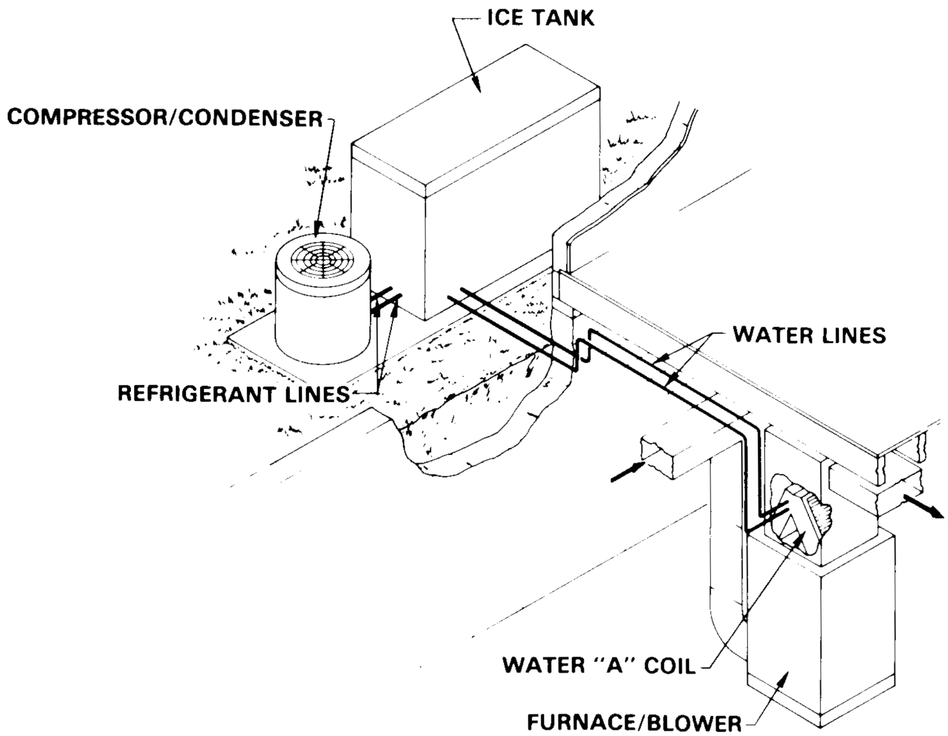

Fig. 4. Typical outside tank cool storage installation.

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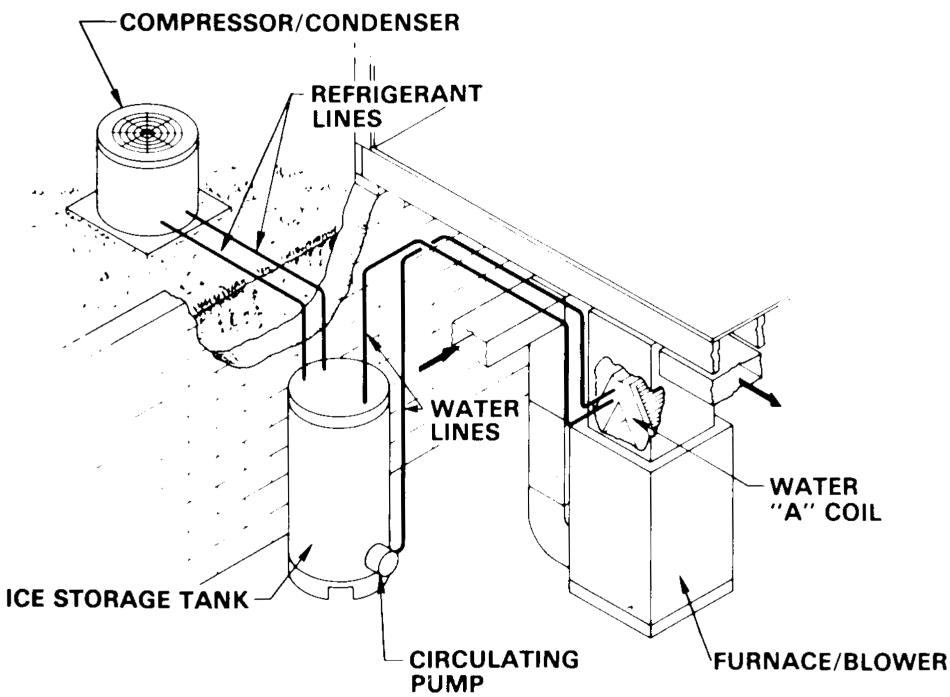

Fig. 5. Typical inside tank cool storage installation.

evaporator, ice forms directly on the evaporator coil. This type of system is shown in Fig. 3. The amount of ice formed on the evaporator coil must be controlled to allow water to circulate around the ice to meet the cooling needs of the house. A variation of this concept is used in the Calmac storage unit, which uses an evaporator coil immersed in an intermediate heat exchanger. The evaporator cools an antifreeze (ethylene glycol or methanol) solution, which is then pumped through a heat exchanger coil in the storage module, thereby freezing the stored water in the tank. This system is shown in Fig. 6. The use of an intermediate heat exchanger and antifreeze solution circulating through the storage tank allows the storage tank to freeze solid and still provide cooling. Figure 7 shows a typical Calmac installation.

None of the cool storage systems tested are packaged systems. Rather, the storage tank and associated mechanical package and controls are designed as a unit that is then mated to standard off-the-shelf residential air conditioning condensing units. Clearly, such an approach does not produce an optimum system, because there is the possibility of a mismatch between the condensing unit and the cool storage equipment. More will be said on this topic in Sect. 5.2.

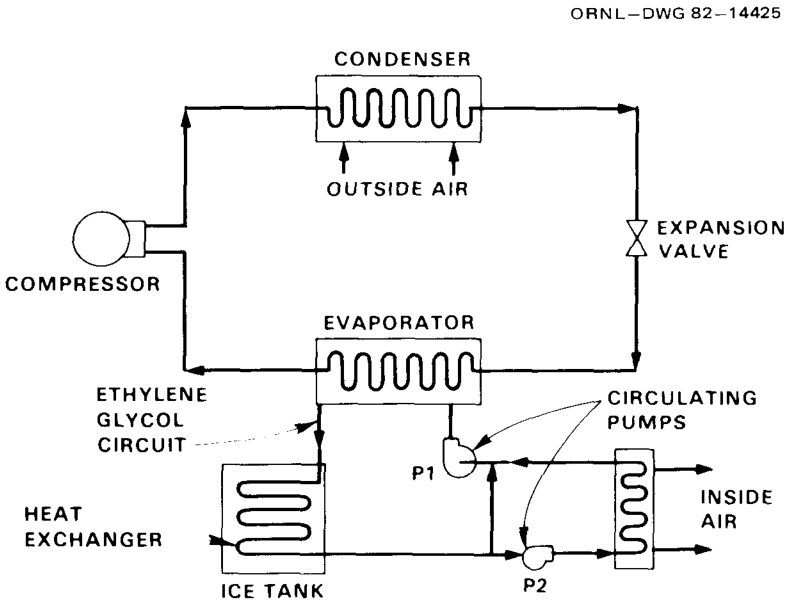

Fig. 6. Calmac system schematic.

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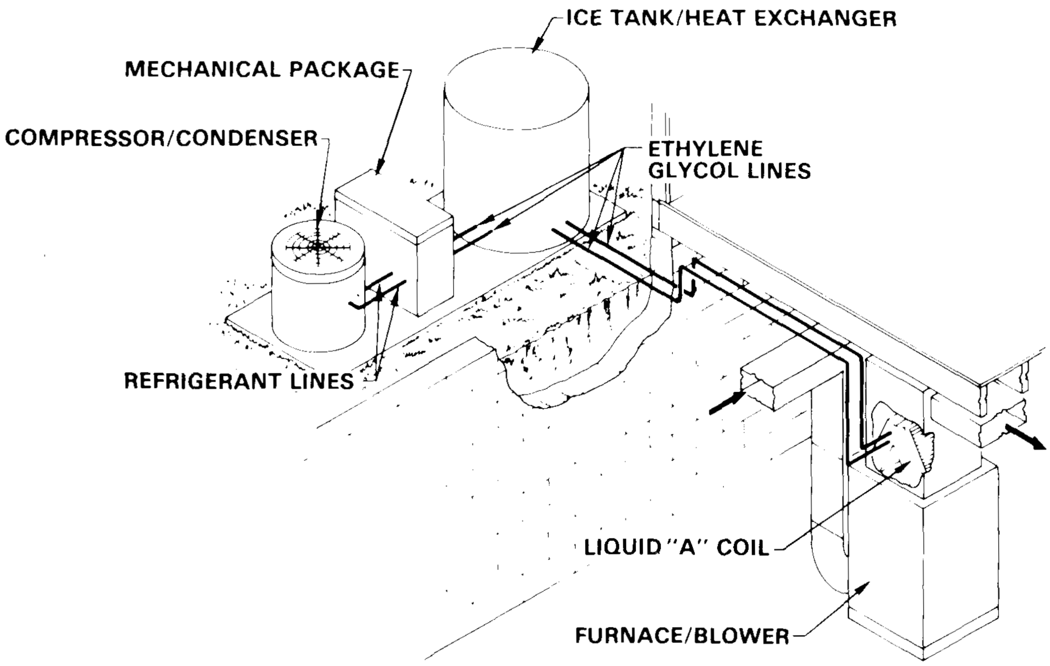

Fig. 7. Typical Calmac installation.

Although similar in concept, the four storage systems differ in the details of their design. The principal features of the four storage systems are summarized in the following sections.

2.2.1 A. O. Smith

The A. O. Smith storage tanks are modified 454-L (120-gal) water heater tanks with a serpentine evaporator coil in a vertical configuration as shown in Fig. 8. Fully charged, each storage tank has an advertised capacity of 114 MJ (108,000 Btu) of cooling. Multiple tanks can be used for larger cooling capacities.

The evaporator consists of seven circuits fed by a common expansion valve. The coil consists of 61 m (200 ft) of 9.5-mm-OD (3/8-in.) copper tubing.

The ice thickness is controlled by a mechanical pressure-actuated relay that interrupts the compressor control circuit.

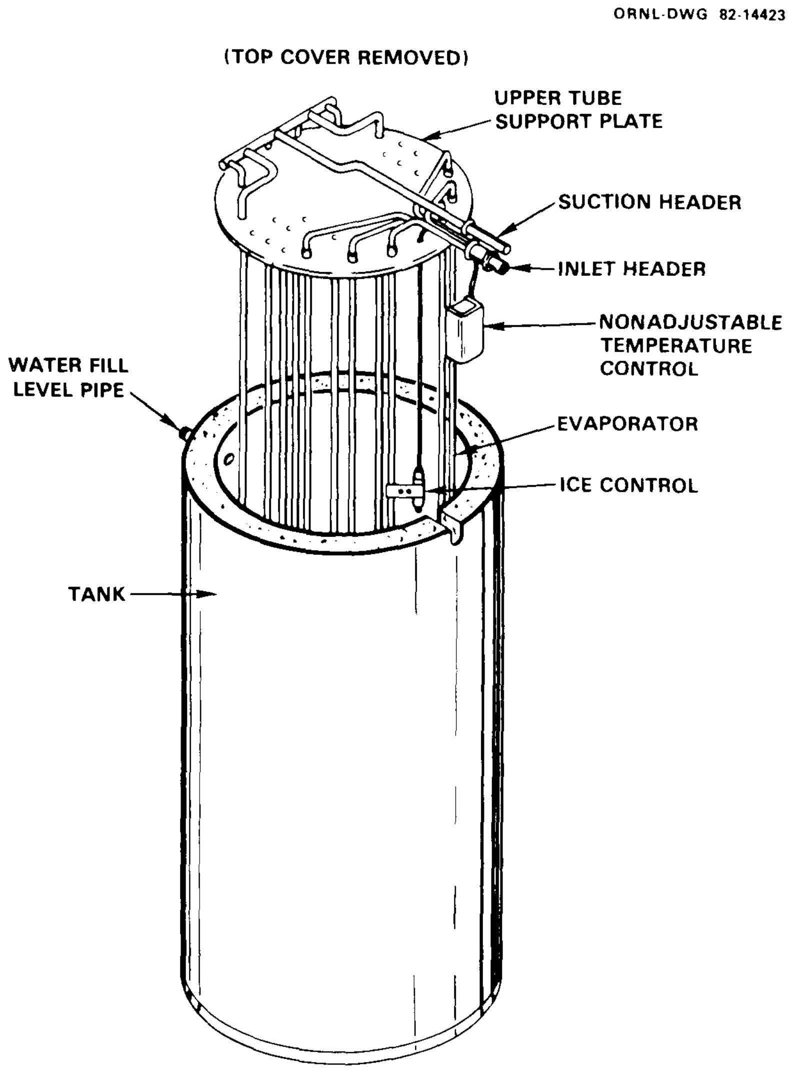

Fig. 8. A. O. Smith storage tank.

Storage tank

Capacity: , 114 MJ (108,000 Btu)

Dimensions: 749-mm (29.5-in.) diam by 1.52 m (60 in.) high

Net water volume: 408 L (108 gal)

Ice storage: 286 kg (630 lb) at 38-mm (1.5-in.) thickness

Insulation: 64-mm (2.5-in.) urethane foam

Circulating pump: 124 W

Evaporator

7 circuits fed with common expansion valve

9.5-mm-OD (3/8-in.) copper tubing – total 61 m (200 ft)

Water-side surface area: 1.77 m^2 (19 ft^2)

2.2.2 Calmac

The Calmac Icebank-32 cool storage unit consists of a 1.22 m (50 in.) high by 1.22-m-diam (48-in.) cylindrical plastic tank containing a heat exchanger coil made of coiled plastic tubing, a shell and tube heat exchanger that serves as the evaporator in the system, and the associated pumps and controls to regulate the system. The advertised cooling capacity of the tank is 380 MJ (360,000 Btu). During normal operation, the storage module freezes solid, and cooling is provided by circulating an antifreeze solution through the tank heat exchanger and the house cooling coil. If the storage capacity of the tank is depleted due to unusually heavy cooling loads, the system can provide cooling directly from the condensing unit.

Storage tank

Capacity: 380 MJ (360,000 Btu)

Dimensions: 1.22-m (48-in.) diam by 1.22 m (50 in.) high

Weight: 113 kg (250 lb) (empty)
1,216 kg (2,680 lb) (filled)

Net water volume: 984 L (260 gal)

Insulation: 25-mm (2-in.) polystyrene

Circulating pump: 249 W

Evaporator

Type: stainless steel shell and tube

Capacity: 10.5 kW

Storage tank heat exchanger

30 circuits fed from 2 headers

15.8-mm-OD (5/8-in.) polyethylene tubing

1,463-m (4,800-ft) total length

Water-side surface area: 73 m^2 (785 ft^2)

2.2.3 Carrier

The cool storage system manufactured by Carrier Corporation is similar to the A. O. Smith and Girton systems. The principal components of the system are the storage tank and control package. These are used in conjunction with a standard residential condensing unit and a chilled-water cooling coil located in the house duct system.

The rectangular tank is made of steel insulated with 51 mm (2 in.) of foam and protected by a painted steel skin. The evaporator consists of 244 m (800 ft) of 9.5-mm (3/8-in.) copper tubing positioned horizontally and arranged in 8 circuits fed by a common expansion valve.

The pumps and controls are located in a separate housing that attaches to the storage tank.

Storage tank

Storage capacity: 342 MJ (324,000 Btu)
Dimensions: Height − 1.22 m (48 in.)
Width − 0.737 m (29 in.)
Length − 2.18 m (76 in.)
Weight: 295 kg (650 lb) (empty)
1,633 kg (3,600 lb) (full)
Insulation: 51-mm (2-in.) foamed in place
Circulating pump: 93 W

Evaporator

8 circuits fed with common expansion valve
9.5-mm-OD (3/8-in.) copper tubing − total length 244 m (800 ft)
Water-side surface area: 7.3 m^2 (78 ft^2)

2.2.4 Girton

The Girton King-Zero ice storage system consists of a rectangular storage tank made with an angle iron frame and a 10-ga. hot-rolled steel tank liner. Insulation is 51-mm (2-in.) asphalted cork on bottom and sides. Covers are fabricated from galvanized sheet and contain 25 mm (1 in.) of urethane insulation. A double-embossed aluminum skin protects the sidewall insulation and doubles as the external cosmetic surface.

The tank contains two evaporator circuits each consisting of ~30.5 m (100 ft) of 19-mm (3/4-in.) schedule 40 iron pipe. The evaporator pipes are attached to steel support plates, which become the center of the two banks of ice that are generated.

The pump and control packages are mounted within an area created by an extension of the main structure frame.

Storage tank

Capacity: 304 MJ (288,000 Btu) at 51 mm (2 in.) of ice

Dimensions: Height – 1.35 m (52.5 in.)
Width – 0.711 m (28 in.)
Length – 2.90 m (114 in.)

Weight: 773 kg (1,700 lb) (empty)
2,500 kg (5,500 lb) (full)

Insulation: 51-mm (2-in.) asphalted cork

Circulating pump: 124 W

Evaporator

2 circuits with individual expansion valves

Each circuit consists of 30.5 m (100 ft) of 19-mm (3/4-in.) schedule 40 iron pipe

Water-side surface area: 3.6 m^2 (40 ft^2)

2.2.5 TES control

The control of the charging system for the A. O. Smith, Carrier, and Girton cool storage systems is similar. Condensing unit control is achieved through the use of an ice thickness sensor with overriding control exercised by the utility. In the absence of utility control, the ice thickness sensor would allow the condensing unit to operate anytime less than a full charge of ice was detected.

The utility control signal (radio, telephone, or power line carrier) operates a relay wired in series with the ice thickness sensor such that when an off control signal is sent, the condensing unit cannot operate.

A second control circuit activated by the indoor thermostat controls the operation of the water pump and indoor fan.

A number of options can be added to the basic control system. Some of the cool storage systems have a second thermostat, which senses ice tank water temperature, wired in series with the indoor thermostat. This thermostat prevents the water pump and indoor fan from operating if the tank water temperature is too high to provide useable cooling.

A second option that can be added to the basic control system is a customer override of the utility control signal. Many utilities feel that the customer must have some means of cooling the house if for some reason (e.g., control error, abnormal weather condition, or communications system failure) the stored cooling is depleted before the end of the on-peak period. The customer override switch closes a relay in parallel with the utility control relay allowing the condensing unit to operate even though commanded off by the utility.

The control system for the Calmac cool storage unit is more complicated than those of the other systems due to the presence of the intermediate heat transfer loop. The control system for the condensing unit consists of two thermostats, two relays, a 24-V transformer, and a system mode switch. The temperature sensors on the respective thermostats are connected to the thermostat body via a 7.6-m (25-ft) nonremovable capillary tube. Both temperature sensors are located about 18 cm (7 in.) below the surface of the water in the tank. The thermostat body contains a switch, a dial that permits selecting temperatures between -34.4 and 37.8°C (-30 and 100°F) to operate the switch, and a temperature differential adjustment that permits selecting differentials of 1.7 to 8.3°C (3 to 15°F) between open and closure of the switch. One thermostat (TLL) acts as a lower limit that shuts off the condensing unit when a temperature of -2.7 to -1.1°C (27 to 30°F) is reached in the storage module. The other thermostat (TO) allows the condensing unit to operate anytime the storage tank temperature exceeds 3.9°C (39°F) until the water temperature is lowered to 1.1°C (34°F).

The control scheme for the Calmac unit allows cooling to be supplied directly to the house from the evaporator without going through the ice tank heat exchanger during off-peak periods or when the storage capacity of the ice tank is depleted during on-peak periods.

Referring to the Calmac flow schematic shown in Fig. 6, in the normal on-peak operating mode when the house thermostat calls for cooling, pumps P1 and P2 are activated. P2 pumps the antifreeze from the ice tank heat exchanger through the indoor coil while P1 pumps the return from the indoor coil through the evaporator and ice tank heat exchanger back to the inlet of P2. Because in normal on-peak operation the condensing unit is not operating, the entire heat load removed from the house is absorbed by the storage tank. Routing of the antifreeze flow between pumps P1 and P2 occurs by difference in pressure drop only. The manufacturer claims that only a small portion of the flow intended for pump P2 enters pump P1 without first going through the cooling coil.

If the house thermostat calls for cooling and the temperature of the storage module exceeds 3.9°C (39°F), thermostat TO is closed, which allows the condensing unit to operate. The flow of antifreeze in the circuit is as before but now the heat load is absorbed in the evaporator. The condensing unit will continue to operate until the storage module temperature drops below 1.1°C (34°F), opening thermostat TO.

In the off-peak operating mode, cooling to the house is supplied on demand by pumps P1 and P2 as described above. However, anytime the ice tank temperature exceeds −1.1°C (30°F), the condensing unit and pump P1 are allowed to operate by thermostat TLL. If no cooling is demanded by the house or if the required cooling is less than the condensing unit capacity, the operation of the condensing unit and P1 by thermostat TLL charges the ice tank.

2.2.5 Sizing philosophy

The first step in air conditioning equipment sizing for either a conventional air conditioner or a cool storage system is to determine the heat gain characteristics of the structure to be cooled. However, from this point on the philosophies of sizing conventional air conditioners and cool storage systems are quite different.

A conventional air conditioner consists of the outdoor condensing unit and the indoor unit, which contains the air handler and evaporator coil. The indoor and outdoor units are generally matched by the manufacturer such that the compressor saturated suction temperature will be

~7.2°C (45°F) at an outdoor temperature of 35°C (95°F). These are the standard conditions at which the cooling capacity of air conditioners are rated. To size a conventional system, the structure cooling load for a cooling design day (an extreme weather condition for the given locality) is calculated. The conventional air conditioner is sized such that its rated capacity is sufficient to supply the cooling load of the house at an indoor temperature that is a few degrees higher than the normally desired thermostat set point. A slight temperature swing is allowed so that the equipment will not be so grossly oversized under less extreme weather conditions that the air conditioner experiences excessive cycling and poor humidity control.

A full storage system is designed to supply the cooling load of the house during some defined on-peak period without the condensing unit operating during the on-peak period. Such a system requires a condensing unit capable of providing a house's 24-h integrated cooling load when operated only during the off-peak period. Thus the sizing of the condensing unit must consider the total daily cooling load (not just the peak cooling load) and the length of the defined off-peak period.

The sizing of cool storage equipment is further complicated by the variation of condensing unit capacity with evaporator suction temperature. In a refrigeration system, as evaporator temperatures decrease, the cooling capacity and efficiency of the system also decrease. To make ice in a cool storage system, the evaporator suction temperature must be less than 0°C (32°F) as compared to a desired evaporator temperature of 7.2°C (45°F) in a conventional air conditioner. If the cool storage system is one that allows ice to build on the evaporator, as the thickness of the ice increases, it acts as an insulator requiring even lower evaporator temperatures to freeze any additional ice on the coil. Thus the condensing unit capacity decreases throughout the charge cycle. Evaporator temperatures less than −21.7°C (−7°F) were measured on some of the systems tested when nearing a full ice charge. Consequently the sizing of the condensing unit must consider not only the total daily cooling load and the length of the off-peak period, but the storage tank size and evaporator configuration.

Unfortunately there is not a great deal of experience with cool storage on which to base sizing recommendations. Three of the utilities

(AP&L, LILCO, and PG&E) were retrofitting cool storage to existing condensing units. Houses were selected with condensing units that were within the capacity range of the cool storage equipment [8.8 to 12.3 kW (2-1/2 to 3-1/2 tons)] at normal 7.2°C (45°F) evaporator temperatures. In most cases, houses were selected in which the existing condensing units were oversized in relationship to the calculated cooling load. An assumption implicit in this approach is that the combination of lower outside ambient temperatures while making ice and condensing units sized to meet peak loads is sufficient to compensate for the lower condensing unit rating at ice making evaporator temperatures.

Two of the utilities (WEPCO and VEPCO) installed new compressors sized to match the cool storage units. In WEPCO's case, the condensing unit manufacturers were requested to submit bids on equipment that would operate at −3.8°C (25°F) suction with an outside temperature of 35°C (95°F). The bidders were required to supply the unit's capacity, electric load, and constraints, if any, for operation under those conditions. The condensing units were then matched to the houses such that the units had adequate capacity to completely recharge the ice tank within 10 h.

A variation of the full storage concept was tested by WEPCO. A full storage system is designed for compressor operation completely off-peak and thus requires a condensing unit capable of providing a house's 24-h integrated cooling load operating only during the defined off-peak period. Such a system also requires sufficient storage capacity to meet the integrated house load during the on-peak period. In addition to requiring large condensing unit and storage capacities, if for some reason the storage is exhausted and the customer overrides the utility control signal, the full-sized condensing unit may operate on-peak.

In a partial storage system, the condensing unit is sized for nearly continuous operation on the design day rather than for the peak house load. This smaller condensing unit is in turn coupled to a partial sized storage system. Water from the tank is circulated to the house cooling coil as in the full storage system. When the capacity of the condensing unit exceeds the house cooling load, ice builds on the evaporator coils. When the cooling load exceeds the condensing unit capacity, the amount of ice in storage decreases. The storage system essentially works as a flywheel: taking or supplementing condensing unit capacity as necessary.

The obvious advantages of such a system include the capital cost savings associated with the smaller condensing unit and storage capacities. Also, in the event of a customer override, the utility will never see a full-sized condensing unit because the capacity simply is not there.

The disadvantage of such a system is that it does not completely remove compressor operation from the peak. The capacity benefits result from the difference between a condensing unit sized for continuous operation and one sized to meet peak house load.

The sizing of partial storage systems is more critical than for full storage systems because the condensing unit operates on-peak. The lowest electrical load and the lowest capacity rating will occur as the storage tank approaches a full charge. As ice is depleted and the tank warms, it is possible for the condensing unit to vary up to 125% of its nominal rating due to the higher evaporator temperatures. Under these conditions, the smaller condensing unit can look just like a conventional condensing unit to the utility system producing no on-peak load relief. Consequently condensing units in WEPCO's partial storage homes were sized at one-half of the required load as closely as available condensing units would allow.

2.3 Communications and Control

Existing utility load management systems have included a range of implementation strategies ranging from time clocks to active utility control. However, there appears to be a consensus among utilities that control strategies become more important as the penetration of load management increases.

Because it is not clear how (or whether) heat and cool storage for load management may be implemented, the test design required remote utility control of the storage systems. This allowed the utilities to test a variety of control strategies and to tailor the control strategy to storage system performance under various weather conditions as more was learned about the characteristics of heat and cool storage.

In several cases, participation in the DOE/ORNL heat and cool storage test was only one of several load management activities that a utility was involved in. This allowed the sharing of existing utility communications and control equipment and experience. Three of the five utilities used existing radio communications and control systems, one utility used a leased telephone line system, and one utility used a bidirectional power line carrier system.

AP&L used an existing radio system which consists of 25 transmitters that cover the entire service territory. The transmitters are linked to AP&L's transmission dispatch center with leased telephone lines. Initially a central message generating unit manufactured by Scientific Atlanta produced the signals that were transmitted at a frequency of 154.463750 MHz to the radio switch located on the cool storage unit. The switch is wired in series with the ice control switch and controls the operation of the condensing unit. The indoor fan and circulating pump are free to meet house cooling load on demand.

AP&L has used two types of radio control switches in its various load management projects. The Scientific Atlanta switch uses digital addressing and has 256 unique addresses. The Motorola switch receives one of 54 audible tone signals. Both switches use fail-safe operation to guard against communications system failure. An interrupt command is repeatedly sent to control the condensing unit. The switch automatically reenergizes the condensing unit when no further signals are received. Initially, all the test homes were controlled using Scientific Atlanta switches. However, problems with the switches required that they be replaced with Motorola switches in August 1980.

LILCO also used an existing Scientific Atlanta radio control system. Local logic was provided by a General Electric IR-70 programmable watthour meter. The meter was programmed to close the night timer switch, which is wired in series with the temperature thermostat that controls operation of the compressor and outside fan. The radio control system can also close the switch in series with the temperature thermostat and thus permits extending the operating strategy interval programmed into the IR-70 meter.

PG&E used a Motorola radio control system to switch the condensing units charging the Girton tank. A controller relayed command signals to a transmitter located in Fresno. Upon reception of the tone signal, the radio switch interrupted the condensing unit control circuit. The tone signals were sent every 3 min during the control period to prevent the radio switch from reenergizing the control circuit.

VEPCO used a telephone based communications and control system. Leased telephone lines connected the utility system control and data acquisition (SCADA) computer to remote terminal units (RTUs) located in selected test houses. Additional test houses were connected to these master test houses by direct burial control cable. The SCADA computer controlled a relay in each house that inhibited operation of the condensing unit. In addition to controlling operation of the TES equipment, the communications system was capable of displaying on demand analog data values from selected sensors in six master houses.

WEPCO had purchased a two-way power line carrier communication system from American Science and Engineering (AS&E) for automatic meter reading and load control. The system was also used for communications, control, and data acquisition for the cool storage test.

A central computer is connected to a receiver/transmitter located at the distribution substation via a leased telephone line. Upon command, the substation control unit imposes a 6-kHz signal on the distribution feeders to provide selective two-way data communication with transponders in the homes. Local control is provided by an auxillary relay operated by control signals from the transponder.

2.4 Data Acquisition

Because the objective of the test program was to collect reliable data to evaluate TES as a load management option, the emphasis of the data collected was on load research and economics and not on the details of storage system equipment performance. However, some knowledge of equipment performance such as degree of comfort and energy efficiency is necessary to make a proper assessment. The approach selected for this test was to instrument all the test and control homes to collect the necessary load research data, and to collect additional data on a few select homes to provide more detailed information on equipment performance. This approach led to four distinct house types based on their degree of instrumentation: test house, control house, heavily-instrumented test house, and heavily-instrumented control house. The parameters measured at the various houses by each utility are summarized in Table 3.

Within the general guidelines dictated by the test design, each utility was free to design and implement a data acquisition system compatible with its existing equipment, experience, and internal research needs. Because the benefits of load management are achieved by load shape modifications, data had to be collected on load profile as well as total energy usage. Temperature and flow data were also important to characterize equipment performance, house comfort, and energy efficiency. In addition to the data collected at individual houses, weather data for correlating with equipment performance were collected from utility weather stations, airports, and the National Weather Service.

Four of the five utilities used pulse initiating meters and temperature transducers coupled to either 2- or 4-track (1 or 3 data tracks and a time track) magnetic tape recorders to collect the data from the test. AP&L and LILCO collected data on a 15-min basis, PG&E used a 5-min basis, and VEPCO used a 30-min basis. LILCO multiplexed three temperature channels onto a single data track by consecutively recording the three temperatures and a 15-min blank space to yield sample hourly readings.

WEPCO collected its data using the two-way capabilities of the AS&E power line carrier system described earlier. Data were collected on a 15-min basis using pulse initiating meters and temperature transducers and logged directly onto computer files. On the heavily instrumented homes, four temperature channels were multiplexed onto two transponder channels to save metering costs.

Table 3. Test data parameters[a]

	AP&L	LILCO	PG&E	VEPCO	WEPCO
Total house demand	T, TH, C, CH	T, TH, CH	T, TH, C	T, TH, C	T, TH, C, CH
Condensing unit demand	T, TH, C, CH		T, TH, C	T, TH	T, TH, C, CH
Indoor fan demand	T, TH, C			T, TH	T, TH, C, CH
Circulating pump demand	T, TH		TH	T, TH	T, TH
Air conditioning system demand		T, TH, C, CH			
Water heater demand				T, TH, C	T, TH, C, CH
Outdoor air temperature	TH, CH			TH	CH
Outdoor relative humidity				TH	
Indoor air temperature	T, TH, C, CH	TH, CH	T, TH, C	T, TH	TH, CH
Indoor relative humidity	TH, CH			TH	TH, CH
Storage tank temperature	TH			TH	
Cooling coil inlet temperature	TH		TH		TH
Cooling coil outlet temperature	TH		TH		TH
Cooling coil temperature differential	T				
Conditioned air return temperature		TH, CH			
Conditioned air outlet temperature		TH, CH			
Conditioned air energy				TH	
Cooling coil energy				TH	
Water heater energy				TH	
Water preheater energy				TH	

[a] T – Test house
TH – Test house/heavily instrumented
C – Control house
CH – Control house/heavily instrumented

3. CUSTOMER SELECTION

3.1 Customer Selection Requirements

In order to make each test as meaningful as possible, the utilities were directed to select test and control home customers who were as representative as possible of the potential market for residential cool storage in their service area. The potential market for cool storage in each service area was generally determined from the utility's existing data on customer appliance stocks and trends. For example, in an area with a low saturation of air conditioning in existing homes and few retrofits, but where most new homes are being built with central air conditioning, the most likely market is new home construction. The test and control group selected should be as representative as possible of this market. (Note that the sample may not be representative of all the utility's residential customers.)

A number of constraints had to be recognized in selecting the test and control homes. Perhaps the most important of these were due to the near-commercial storage equipment that was available. All the existing cool storage equipment is designed for use with central air conditioning systems. This limitation excluded from the test homes that rely on room units for cooling. Further, the selected storage systems are also only available in a limited number of sizes, thus the homes selected had to fall within a given range of cooling loads.

A number of other criteria were also necessary due to the unique character of the tests. All participants were volunteers. The homes had to be owner-occupied because alterations to the property were necessary and because it was desirable to minimize the dropout rate. The locations of the homes were limited to a given area because of the requirement that they be within the communications and control range of the utility.

3.2 Selection Procedure

Each utility developed its own customer selection procedure based on its particular circumstances. Such factors as available information on customers, previous experience with load research studies, and marketing strategy all influenced the customer selection procedure used by each utility. Four of the five participating utilities used some combination of press conference, news release, bill insert, or mail invitation to identify potential volunteers, followed by either a mail or telephone questionnaire to screen the potential participants, and finally a field interview and inspection to verify information and determine the feasibility of test equipment installation. Because the VEPCO project was limited to new homes, its approach was to work through area homebuilders.

The screening criteria used by each utility is summarized in Table 4. The customer selection procedure used by each utility is summarized in the following paragraphs.

3.2.1 Arkansas Power and Light

Existing customer data files were used to identify customers who lived within a 40-km (25-mile) radius of Little Rock, occupied single-family homes, had lived in the house at least one year, and whose August minus May electric energy usage was between 1,000 and 1,500 kWh (this range had previously been shown to correspond to ~10.5-kW (3-ton) cooling capacity air conditioning unit). A random number program was used to select customers from this group. These customers were contacted by telephone to determine whether they were willing to participate either as a test or control home, and whether they met the basic criteria for participants. Some 1,500 customers were contacted, of which only 16 met all the criteria. The balance of the participants were selected from customers who had otherwise heard about and volunteered to participate in the program (such as neighbors and friends of contacted customers).

The majority of the test homes were selected first. The control homes were then selected to match as closely as possible the calculated cooling loads of the test homes. All customers signed an agreement to participate in the experimental program.

3.2.2 Long Island Lighting Company

LILCO held a press conference describing the project and soliciting volunteers to participate. The announcement was carried by local radio

Table 4. Customer screening criteria[a]

	AP&L	LILCO	PG&E	VEPCO	WEPCO
New/existing house	Existing	Existing	Existing	New	Existing
House size, m^2 (ft^2)	150–210 (1600–2300)	139–167 (1500–1800)	111–186 (1200–2000)	130–204 (1400–2200)	
House age, years	1–5			New	
Cooling load, kW (tons)	8.8–12.3 (2.5–3.5)	Less than 17.6 (5)	10.5–12.3 (3–3-1/2)		Less than 8.8 (2.5)
Location	Within 30 miles of Little Rock	Suffolk and Nassau Counties	Fresno	In one of 3 subdivisions, Richmond, VA	On one of 42 substations in Milwaukee

[a]All applied to single-family owner-occupied house with central split-system air conditioning.

stations, television stations, and newspapers. Some 3,000 customers responded over the next several days requesting information on the program and volunteering to participate. These customers were screened to determine if they met the initial screening criteria, and a tally of the qualified callers was kept. These customers were then contacted by phone in the order in which they had called. Information taken during the initial screening was verified, and additional information was collected. Homes that still qualified were scheduled for a field inspection, which determined the feasibility of either a test or control home installation and answered any homeowner's questions. Homes that still qualified and were interested in participating signed an agreement to be a part of the test.

3.2.3 Pacific Gas and Electric

PG&E used a mail campaign to recruit customers to participate in the cool storage test. An invitation and questionnaire describing another PG&E project on cycling air conditioners, designated "Project Power Saver," was sent to some 31,000 residential customers in Fresno. Some 2,200 of these questionnaires were completed and returned. These responses were screened to determine whether these customers would be suitable for the cool storage test.

The 161 potential participants were then contacted by local project representatives who described the cool storage project, solicited volunteers, and gathered additional information on house and air conditioner type. If the volunteer was still interested and met all the qualifying criteria, an in-home interview and inspection were done before the customer agreement was signed.

3.2.4 Virginia Electric and Power Company

The VEPCO test was unique because it was limited to new home construction and included both heat and cool storage in the same house. Rather than select customers, VEPCO selected new homebuilders to build the test houses. Customers purchased the houses in the normal manner and became participants in the program.

Area homebuilders were contacted through the offices of the Richmond Homebuilders Association and through direct contact by VEPCO personnel.

The program was discussed with 18 builders who expressed interest, and contracts were executed with 5 who agreed to provide at least 5 test and 5 matching control homes. One builder was later dropped from the program due to nonperformance.

3.2.5 Wisconsin Electric Power Company

Both a news release and bill inserts were used to solicit volunteers for the WEPCO cool storage project. Approximately 1,800 homeowners responded to the announcement and were screened over the phone. Some 600 of these were eliminated based on this initial screening. Approximately 1,200 questionnaires were sent out, and of these, 939 were completed and returned. The questionnaires were screened to identify potential participants. A field inspection of 427 homes was necessary to secure the 70 test homes and 25 control homes for the test.

3.3 Customer Incentives

By participating in the cool storage test program, a customer was subjected to a variety of intrusions and inconveniences ranging from contractors installing various pieces of storage instrumentation and control equipment, to equipment malfunctions, to metermen periodically changing data tapes. In addition to the customer incentives inherent to the program, such as participating in a major research project of public concern (the efficient utilization of electric energy) and receiving detailed information on the thermal integrity of their dwelling, it was felt that some other incentive would be necessary to stimulate customer interest in the program and compensate them for participation.

However, one of the principal advantages of using TES for load management is that it accomplishes the load management objective without requiring lifestyle changes from customers. Therefore, for the test results to be meaningful, the customer incentives offered had to avoid incentives which might promote lifestyle changes. This requirement eliminated time-of-use (TOU) rates from consideration as an incentive for the test because customers might adjust their lifestyle in response to the price signal, which would in turn alter their heating and/or cooling load profile.

Also, incentives that guaranteed the customer a lower electric bill were to be avoided because the customer might be inclined to use more energy than he would normally. Finally, if the cool storage equipment operated successfully, one measure of customer acceptance would be whether they would be willing to buy such a system. Consequently, it would be desirable to leave the equipment in place at the conclusion of the test if the homeowner desired (which also saves equipment removal costs).

Each of the five utilities designed their customer incentive package based on their individual circumstances. All of the tests included free installation and maintenance of the cool storage and test equipment. This allowed the utility to monitor the reliability and maintenance experience of the equipment. Also, because there was no assurance that the cool storage systems would all work, all participants would have the choice at the conclusion of the test of having their air conditioning systems restored to pretest conditions. In addition to these universal customer incentives, the utilities offered a range of other inducements, which are described in the following sections.

3.3.1 Arkansas Power and Light

Each test home participant received $150 at the end of each test year. Control homes received $50 at the end of each test year. At the end of the test, the test home customers had the option of free title to the storage equipment or restoration of their original system. Also, AP&L would assume responsibility for any compressor warranties that might be withdrawn because of alterations to the equipment.

3.3.2 Long Island Lighting Company

The test home customers were guaranteed that their electricity costs for air conditioning would not be more than they would have been had they not installed the TES system. (Note that this does not guarantee absolute electricity cost savings.) Further, the test customer could terminate his participation at any time. At the end of the test, storage homes had the option of purchasing the equipment for $500 or free restoration of his original system.

3.3.3 Pacific Gas and Electric

Initially, each control and test customer was offered a free water heater blanket, low-flow shower head, and a \$6/month discount on their electric bill during the cooling months of May through September. However, as discussed in Sect. 5.1, the poor performance of the cool storage equipment led to the use of an "Excess Energy Cost Adjustment." This adjustment reimbursed customers for the inefficiencies of the cool storage equipment. Calculations were based on past energy usage for that particular home and the number of cooling degree days for each billing period.

3.3.4 Virginia Electric and Power Company

Initially, test house customers were to be billed on a load management rate which was estimated to result in a \$30 average monthly energy cost savings. However, as in the case of PG&E, test customers were subsequently billed at the current rate adjusted for excess energy usage and given an additional \$30/month credit. Other adjustments were made on an individual basis for specific operating problems.

3.3.5 Wisconsin Electric Power Company

The test homes in WEPCO's project were homes that had not previously had air conditioning. Participants were able to enjoy the comforts of central air conditioning for 2 years, being responsible only for the energy costs during the study period. At the end of the study, the homeowner would have the opportunity to purchase the in-place equipment. No additional incentives were promised to customers to solicit their participation in the test.

4. EQUIPMENT INSTALLATION

4.1 Contracting

Subcontracting the installation of the TES, communications and control, and data acquisition equipment for the test turned out to be a major roadblock for several of the participating utilities. To provide some measure of control over the cost of the test, it was desirable to obtain fixed-priced subcontracts for the various tasks that were not going to be done by utility personnel, such as the installation, maintenance, and removal of the air conditioning and storage equipment. However, many heating, ventilation, and air conditioning (HVAC) contractors were reluctant to bid on a fixed-cost subcontract due in part to the fact that each project entailed some 30 to 50 units, and because there is little previous experience with this type of equipment. Many contractors felt that there was a high degree of uncertainty in the installations because of the experimental nature of the equipment. The range in bids received often reflected this uncertainty.

The experience of PG&E in trying to obtain an installation subcontractor is typical of some of the subcontracting problems that were encountered. Based on discussions with the equipment manufacturers, PG&E prepared a bid specification outlining the requirements for equipment installation. This specification was sent out March 5, 1979, to six contractors in the Fresno area. A prebid conference was held on March 8 to explain the cool storage test and provide answers to any questions the contractors might have concerning the specification or bidding procedure. Five of the six contractors originally contacted attended the prebid conference.

Only two bids were finally submitted for consideration. The difference between the two bids was 370%, and both bids were rejected.

Based on discussions with the various contractors, it was decided to revise the specifications to provide a more descriptive installation procedure, include an installation and maintenance manual, provide a listing of both test and control locations, and furnish electrical and mechanical drawings.

It was further decided to install a cool storage system at one of the test homes to serve as a model for equipment installation. In addition to providing a tangible example for prospective contractors, the test installation also alerted PG&E to some potential problems and gave it an opportunity to make some necessary modifications to the specifications.

The revised specifications were sent out in October 1979 to eight contractors in the Fresno area. A second prebid conference was held in the latter part of October to discuss specifications and show the prospective bidders the sample working system. Four contractors attended the conference.

Once again, only two bids were submitted. However, the variance between the two bids was significantly less than during the first bid, and the contract was awarded to the lower bidder.

AP&L went through a similar process of sending out a bid package, receiving poor response, installing three test units, and rebidding before obtaining a satisfactory installation contractor.

The other three utilities did not have the contracting problems experienced by PG&E and AP&L. LILCO and WEPCO were able to obtain a satisfactory response to their initial request for bids and signed a contractor on the basis of that procurement. VEPCO's situation was unique because all installations were in new homes built by select builders participating in the program. The HVAC contractor was selected based on his previous experience with cool storage, having worked with VEPCO on its Annual Cycle Energy System demonstration home.

4.2 Equipment Delivery

As described in an earlier section of this report, the cool storage systems being tested were prototype equipment and not packaged units as would be likely if cool storage were widely used. Consequently, pieces of the systems had to be ordered from different manufacturers and suppliers. This problem was complicated by the fact that, in addition to the cool storage equipment, the successful implementation of the test also required the receipt and installation of the communications and control equipment and of the data acquisition system.

Although some minor problems were experienced as a result of delays in equipment delivery, these problems were in general overshadowed by the contracting problems described in the previous section. The cool storage equipment had been selected with the ability of the manufacturer to produce the equipment on schedule as one of the selection criteria. Delays in TES equipment installation were minimized by partial shipments of orders as the equipment was produced. LILCO experienced some delays due to slow delivery of the Calmac mechanical package and the fact that several of the storage units had to be returned due to leaks in the heat exchanger coil.

In general, more problems were experienced with delays in the delivery of communications and control equipment and data acquisition equipment than with the TES equipment. Three of the five utilities, AP&L, LILCO, and PG&E, were using existing radio communications and control systems and standard magnetic tape recorders and demand meters. The only significant equipment delivery problem experienced by these utilities was that LILCO experienced some delays in receiving the temperature transmitters used in the heavily instrumented homes. Delivery was promised in April 1979, but actual delivery was not until December 1979.

VEPCO experienced delays with the delivery of the remote terminal units, control software, control relays, and Btu meters. The remote terminal units to be used in the master test houses were ordered in April 1979, and the last was delivered in March 1980. Late receipt of the software necessary for control delayed control of the first system until March 1980.

WEPCO experienced numerous delays related to the installation of the AS&E power line carrier communications system. The system was to have been installed and operational by June 1, 1979. The first partial delivery of transponders was received in July 1979, and the last transponders were not received until August 1980. Delivery of the temperature monitoring devices was also delayed due to difficulties in obtaining the equipment necessary to interface them to the AS&E system.

4.3 Installation Experience

Once the contracting and equipment delivery problems were resolved, the installation of all TES communications and control and data acquisition equipment proceeded normally with few exceptions.

4.3.1 Arkansas Power and Light

Most of the storage equipment was installed outdoors in a metal enclosure designed for the equipment. However, in six of the test houses the equipment was located under the house. The only major difference between the various test installations was the location of the cooling coil within the house and the attendant chilled-water piping.

All material and equipment for the project were required to meet all local and national building codes. No problems were encountered in meeting these requirements.

The wires for the monitoring equipment were pulled by the TES installation subcontractor to the metering panels where they were connected to the monitoring equipment and recorders by AP&L employees. The radio control switches were also installed by the installation subcontractor.

4.3.2 Long Island Lighting Company

The storage module and mechanical package were located adjacent to each other in all installations. Forty-nine were placed outside the house, and one was located in the garage. The control boxes were located inside the house within 25 ft of the storage unit due to the length of the thermostat sensor's capillary tube. The length of the thermostat capillary tube turned out to be a major installation problem because it limited the arrangement of system components. This restriction resulted in some otherwise acceptable candidate houses being deemed unacceptable.

Because the system did not require an additional power supply or permanent construction, its installation did not impinge on local building codes. No installation problems were experienced with the installation of the communication and instrumentation equipment. This equipment is in standard use at LILCO in other ongoing programs.

4.3.3 Pacific Gas and Electric

All storage units were located outside in either backyards or side yards. The physical size of the storage unit together with local code requirements limited the acceptable locations of the unit. Local codes specify minimum property line clearances and setbacks, maximum noise levels, and that the unit shall not be placed under an openable window. All guidelines were adhered to except in two cases where special permission for a variance was given.

Other problems encountered included insufficient room in the duct work in one home for the new water A-coil. A flat water coil was installed instead. At two locations the contractor had to move the air conditioner condensing unit 3 ft to accommodate the storage tank.

The installation of the communications and metering equipment did not present any significant difficulties. The radio switches were installed by the installation subcontractor and generally required less than 1/2 h per installation. The metering equipment was also installed by the installation subcontractor. The package was similar to those used by PG&E in its other load management activities.

4.3.4 Virginia Electric and Power Company

The storage equipment in the VEPCO demonstration was located in a 3- by 3.7-m (10- by 12-ft) mechanical equipment room which the builder attached to each test house. Because all houses were new construction, the problems associated with retrofitting equipment did not apply.

Local building code authorities permitted deviations where practical and cleared the installations as an experimental test project where local codes were not clear or did not address a particular matter.

Because all the communications equipment for the project is used in normal utility operations, its installation could be considered normal. However, construction scheduling was such that there was insufficient lead time for leasing and installation of the telephone data circuits. Installation of the buried control cable between master and slave houses was delayed due to obtaining right-of-way agreements from property owners. Completion of paired master and slave houses could not be coordinated with homebuilders, which delayed remote control operation.

The installation of the instrumentation equipment proceeded normally except for temperature and air flow sensors which were incorrectly installed at several test houses and subsequently required relocation. Installation of indoor sensors in occupied test houses was difficult due to the absence of homeowners.

4.3.5 Wisconsin Electric Power Company

All the installations in WEPCO's project had the storage equipment located in the basement. The installation subcontractor scheduled the installation of the TES equipment by appointment with the homeowner and secured all required permits for the installation.

The subcontractor trained his crews at the first two installations. The installation was performed by a two-man crew comprised of an electrician and sheet metal man. A refrigeration mechanic then charged and tested the completed installation. This approach allowed a two-man crew to complete an installation in less than a day. No particular installation problems were encountered.

The communication and instrumentation equipment was installed in the basement adjacent to the electrical distribution panel by the installation subcontractor. The equipment was installed as a temporary installation and wired to code. WEPCO personnel installed the temperature monitoring equipment and tested the communications and control equipment.

4.4 Installation Costs

The installed costs of the TES, communications and control, and instrumentation equipment reflect a number of circumstances unique to a test of this kind. As mentioned previously, the TES equipment available for the tests were not packaged systems, but rather near-commercial prototypes. Consequently each installation was unique, and many problems had to be solved on an individual basis. Secondly, four of the five projects involved retrofitting cool storage into existing houses and experienced the usual problems associated with any retrofit installation.

The installation subcontractors were asked to prepare a fixed-price bid for the installations. The subcontractors in general had no experience with cool storage for space conditioning, and the range in bids received by the various utilities was indicative of the uncertainty with which the subcontractors viewed this technology. Finally, the tight time schedule for the installations meant that the subcontractor would have to devote considerable resources to this one project perhaps at the expense of his other customers.

The costs of the test installations for this demonstration are summarized in Table 5. As indicated in the table, the cost of each installation is sensitive to the type of installation, the equipment used, and the experience of the installation contractor. For example, AP&L and WEPCO both used A. O. Smith tanks. However, WEPCO's tanks were generally installed in the basement while the AP&L installations required the equipment to be located outside on a slab covered by a metal equipment building. The plumbing and electrical requirements for the AP&L installations were generally greater than those of the WEPCO installations. Also, the

Table 5. Cost of test installations

	AP&L	LILCO	PG&E	VEPCO	WEPCO
TES equipment[a]	2,627 (2-tank) 3,691 (3-tank)	3,090	3,350	7,686[b]	2,223[c]
Labor	4,400	2,920	2,930	4,547[b]	1,248
Total	7,027 (2-tank) 8,091 (3-tank)	6,010	6,280	12,233	3,471
Communications and control equipment - total	100	388	80	2,831[d]	192[e]
Instrumentation	2,722	1,498	1,890	7,162[d]	1,029

[a]TES equipment includes tank, water coil, pumps, valves, controls, thermostat, ducting, miscellaneous plumbing, electrical, slab, and enclosure as necessary.

[b]VEPCO costs include heat pump system, mechanical equipment room, and installation cost common to both heat and cool storage.

[c]Average for full and half storage homes; includes new condensing unit.

[d]Equipment common to both heat and cool storage.

[e]Installation cost only.

installation subcontractor selected by WEPCO had previous experience with cool storage installations, having installed several test installations for WEPCO previous to this test. Consequently, the labor costs associated with the installation of the same storage system in the two utilities differed by more than a factor of 3.

The installed costs of the communications and control equipment reflect the fact that three of the five utilities used an existing radio control system, and the only costs associated with this test were the costs of the radio control switch and its installation on the condensing unit circuit.

In the case of WEPCO, the communication and control cost reflects only the installation cost of the transponder at the test homes because all equipment was furnished by WEPCO as a part of their system-wide power line carrier system.

The instrumentation costs given in Table 5 include the pulse initiating meters, magnetic tape recorders, transponders, temperature sensors, wiring, and other items as appropriate for both the normal and heavily-instrumented test homes. In general, the installation subcontractor placed the meter sockets and temperature probes and pulled all the wires while utility meter personnel did the final installation and checkout of the instrumentation.

5. EQUIPMENT CHECKOUT AND OPERATION

5.1 TES Performance

A detailed analysis of the results of the 1980 and 1981 cooling season is currently under way and will be presented in a subsequent report. However, some qualitative comments on the performance of the cool storage systems in the five different utilities can be made.

In general, the performance of the cool storage systems in the five projects was disappointing. Severe problems were experienced with inadequate compressor capacity, inadequate storage capacity, excessive energy consumption, high equipment failure rates, and temperature regulation. Some of the problems were unique to a particular manufacturer's equipment or installation design, while others appear to be inherent to cool storage in general. The experience of the five utilities is briefly summarized in the following sections.

5.1.1 Arkansas Power and Light

Shakedown of the cool storage installations began in May 1980. During the first week, some customers repeatedly complained about lack of cooling, even though the outdoor temperatures were still very mild. The customers who were complaining all had their chilled water lines running up the outside wall and across the attic to the water coil. Upon investigation, it was found that the water in the supply line from the tanks was draining back from the coil past the water pump and thus causing an air lock in the system. A check valve was installed on the supply line to prevent water from draining back into the tank. After this modification, complaints about lack of cooling disappeared.

The units operated off and on during May due to the mild weather, and a second problem started to appear. The problem was failure of the ice sensor, which allowed the tank to freeze solid. As originally planned, although each tank had an ice sensor, AP&L used only the sensor in one tank to shut off the system. The defective sensors were replaced, and the sensors in all tanks were wired in series so that any one of the tanks could shut off the condensing unit.

After an ice control sensor failure, it generally took from 3 to 7 d for a tank to thaw so that the evaporator could be pulled and the ice sensor replaced. During this time, the tank was isolated from the system and the cooling supplied by the remaining tank or tanks.

Ice sensors continued to fail throughout the summer. The problem was traced to the bulb that senses the thickness of the ice and operates the switch on the compressor circuit. The bulbs and/or hydraulic lines running from the bulb to the switch were either defective or damaged during installation in the tanks at the factory. Replacement of the defective sensors seemed to solve the problem.

During May, the units were allowed to run as needed. Project plans called for shutting the compressor off for 8 h a day during June. However, during June the weather became unseasonably hot and some of the ice storage units could not supply adequate cooling even when allowed to run full time.

There are usually about 1,925 cooling degree days each summer in Little Rock, but 1980 turned out to be the hottest summer on record with some 2,579 cooling degree days. The calls about inadequate cooling continued to come in, but repeated checks of the equipment verified that everything was working properly. The problem was most severe at 8 of the 26 ice storage locations. When compared with cooling demand calculations, these homes only had 20 to 25% excess condensing unit capacity (air to air) compared with the 40 to 50% excess capacity at the remaining homes. The condensing units at these 8 homes were replaced with larger units to give each house a minimum of 40% excess condensing unit capacity.

All homes were now cooled satisfactorily, but the condensing units were not being controlled for load management. In late September, the string of 100 degree plus days ended and AP&L started to cycle the condensing units — and the cooling problems returned. Many customers resorted to the manual override when stored cooling ran out. The season ended without AP&L being able to operate the storage cooling system for load management.

5.1.2 Long Island Lighting Company

LILCO's experience was somewhat similar to AP&L's. By mid-July 1980 it was apparent that all of the Calmac storage systems were operating at close to specifications. The continuing problems with insufficient cooling were therefore a result of inherent deficiencies in the system as installed. These deficiencies are described in detail in Sect. 5.3.

In addition to the problem of insufficient condensing unit and storage capacity, LILCO experienced a number of other problems with the cool storage systems. One problem was that of condensate formation. It was necessary to apply more than the normal amount of insulation to the piping carrying the ethylene glycol solution between the tank, heat exchanger, and cooling coil to prevent condensate formation. In addition, the lower than normal duct air temperatures tended to cause condensation on the cold air ducts. Because of this, it became necessary to insulate all cold air ducting in one house.

Another problem experienced with the Calmac tank was that the heat exchanger coil was not adequately secured within the tank and tended to rise as ice formed on the coil, lifting off the cover of the tank.

5.1.3 Pacific Gas and Electric

During initial startup and operational testing a number of minor problems were experienced with the cool storage system including four defective ice sensor units, one expansion valve, one circulating water pump, and several tank leaks around the manual ice thickness gauge. These problems were easily corrected. However, continued operation of the cool storage systems led to more serious equipment failures, which are discussed in more detail in the next section. Altogether 22 of the 30 test locations experienced at least one compressor failure.

Aside from the high compressor failure rate, PG&E's operating experience was similar to AP&L's and LILCO's. During periods of extreme heat, the cool storage system experienced condensing unit capacity problems. For example, the data for one particular location indicated that the condensing unit ran continuously for six consecutive days before it had produced sufficient ice to stop charging. These capacity problems led to the elimination of cycling by PG&E during periods of extreme heat.

Excessive noise was also a problem in Fresno. Some participants and participants' neighbors complained about the excessive nighttime noise caused by the near continuous operation of the condensing units.

In general, PG&E's experience was that when the cool storage systems were operating properly, temperature regulation was within acceptable limits. In several cases temperature regulation problems turned out to be equipment failure or insufficient capacity problems.

5.1.4 Virginia Electric and Power Company

VEPCO began the 1980 cooling season test with six occupied test houses. This number had increased to 29 by the end of the season. The results from these houses are similar to those of the other utilities in that problems with both condensing unit capacity and storage capacity were experienced. The unusually hot summer led to the stored cooling frequently running out in mid-afternoon, and the customer overriding the compressor control. The problem was more pronounced in houses with the Carrier tanks than with the Girton tanks.

Some problems were also experienced with temperature regulation. The chilled-water pump appeared to be oversized resulting in excess cooling capacity delivered to the cooling coil. This situation further aggravated the problem of insufficient compressor and storage capacity.

The indoor air handler that had been sized for the heat pump that was an integral part of VEPCO's system, was oversized when operated with the chilled water coil. The excessive air flow led to problems with adequate dehumidification.

5.1.5 Wisconsin Electric Power Company

WEPCO's TES operating experience was generally more positive than the other four utilities. One compressor failed on startup and was replaced. The multiple tank installations had originally had their ice sensors wired in parallel to maximize ice storage. However, unequal water flow through the tanks resulted in some tanks freezing solid. The problem was eliminated by wiring the individual ice sensors in series.

The customers in the study had very few complaints about the system, its installation, or operation. Approximately 25 storage homes had complaints of inadequate cooling shortly after installation. However, these problems were generally traced to mechanical problems which could be corrected. Five homeowners had problems with inadequate storage capacity because they exceeded the design capability of the equipment by trying to maintain an 18 to 21°C (65 to 70°F) thermostat setting. A few homeowners complained initially of the noise from the night operation of the compressor, and one compressor had to be relocated.

Temperature regulation at most homes was very good. A few thermostats required recalibration, and six homes required relocation of the fan limit switch due to short cycling in the heating mode. Even with the many minor problems that were experienced during the summer, typical comments were that the participants enjoyed the system and its obvious improvement in dehumidification.

5.2 TES Equipment Failures

Because the cool storage test involved prototypes and not proven designs, it was expected that some equipment failures would be experienced. Also, because very few units were being manufactured, the units were essentially hand built and the rigorous quality control procedures applied to fully commercial units had not been applied. Finally, because cool storage has not been widely tested, the installation subcontractor did not have a great deal of operating experience to draw on as he installed equipment produced by the various manufacturers.

The equipment failures experienced during the test can be generally categorized as related to the compressor, ice thickness sensor, circulating water pump, and all others. By far the most serious equipment problem experienced during the test was the high incidence of compressor failures. Three of the projects involved storage equipment retrofitted to existing condensing units, and the other two involve new condensing units that were installed with the storage equipment. Both old and new condensing units experienced high failure rates during the test although the problem was much more pronounced in the retrofit applications. The compressor failures experienced through the end of the 1980 cooling season included: AP&L 4, LILCO 9, PG&E 22, VEPCO 3, and WEPCO 2. For comparison purposes, only two compressor failures were reported in control homes compared to the 40 test home failures.

It is difficult to determine the exact cause of compressor failure for each location. The failure modes included locked rotors, failed valves, opened motor field windings, and even blown terminals. Discussions with various research engineers, manufacturers, HVAC consultants, HVAC contractors, and other industry personnel have identified a number of potential reasons for the high incidence of compressor failures including compressor slugging, electric motor burnout due to mechanical problems, overburdening of equipment, insufficient lubrication, improper refrigerant charge, age of compressor, and improper size and location of compressor.

Compressor slugging occurs if liquid Freon migrates through the evaporator coils and into the compressor. (This problem is discussed in more detail in the following section.) Mechanical failures such as pistons seizing could cause electric motors to burn out. Continual running of the compressors at below design temperatures could cause excessive wear and metal fatigue, especially when extended running time to build up the ice charge is required. Insufficient lubrication and improper refrigerant charging could be major contributors to compressor failure, but there is little in the way of operational experience to establish guidelines for these parameters.

An analysis of the failure data from PG&E demonstrates how difficult it has been to identify the reasons for the high compressor failure rates. The age of the compressor did not appear to be a factor because proportionately as many newer compressors as older ones failed during the cooling season. Also, compressor exposure to sun or compressor size did not correlate with compressor failure rate.

The second most frequent problem for the cool storage systems was failure of the ice thickness sensor. AP&L reported 15 ice sensor failures, PG&E reported 4, and VEPCO reported 17. Failure of the ice thickness sensor generally allowed the ice storage tank to freeze solid. When this happened, it often led to the failure of the circulating water pump due to a lack of lubrication. PG&E had 3 water pump failures, VEPCO 6, and WEPCO 10.

A variety of other equipment failures were also experienced during the test. Refrigerant leaks were a problem, and WEPCO had to replace 35 defective sight glasses that leaked. PG&E and VEPCO both reported several failures of the thermal expansion valve. PG&E had one condenser fan motor burn out and had six tank water temperature sensors fail. LILCO reported several failures of control box thermostats, control box 24-V transformers, and one mechanical package evaporator.

Two problems worthy of particular mention were tube clamp corrosion failure in the Calmac units and the use of PVC pipe for plumbing the water connections to the cooling coil. On August 18, 1980, a service visit was made to one site in LILCO's project in response to a participant complaint of the compressor short cycling. The trouble was caused by a failed hose clamp on the heat exchanger coil in the ice tank which allowed the hose to come off and permitted the ethylene glycol coolant to mix with the water. It required 12.5 man-h and 68 L (18 gal) of ethylene glycol to put the system back in operation. A visual inspection of most of the Calmac tanks showed that a majority had highly corroded clamps.

A problem was experienced by WEPCO with the use of PVC piping to circulate the cool water through the A-coil. Five homes had the PVC melt adjacent to the A-coil when the furnace was first turned on in the fall. The problem was caused by the water remaining in the cooling coil turning to steam and then condensing in the pipe. A waste valve was installed to drain the coil for winter, and the PVC was replaced.

5.3 TES Equipment Modifications

During the test a number of modifications were made to the equipment design and installation to try to correct the problems that had been experienced. The equipment modifications made at each of the projects are summarized in the following paragraphs.

5.3.1 Arkansas Power and Light

At the end of the 1980 cooling season, AP&L started looking for the cause of the lack of storage capacity in the A. O. Smith storage tanks. A tank was installed in the shop of the installation subcontractor and was connected to an 8.8 kW (2.5 ton) condensing unit. The compressor was allowed to run until it was cut off by the ice sensor. An examination of the tank revealed that the ice was forming only in about 45% of the tank as shown in Fig. 9. The cooling stored in the tank was ~63 MJ (60,000 Btu) rather than the 114 MJ (108,000 Btu) rating.

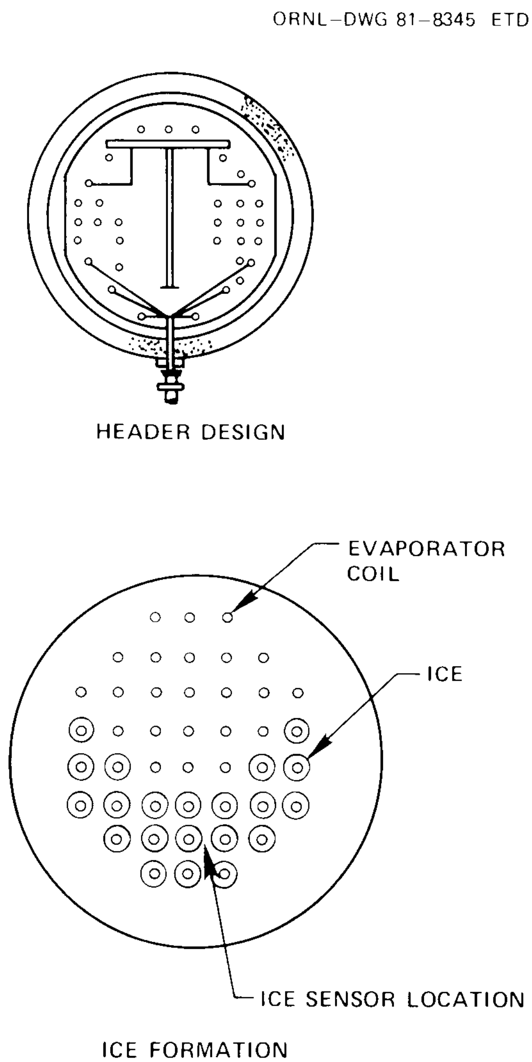

Fig. 9. Ice formation in A. O. Smith tank.

The apparent cause of the uneven ice buildup was that the evaporator coil consisted of seven unequal length circuits fed by a common expansion valve. The seven circuits were one of three types: a 4-row evaporator coil with an approximate length of 5.3 m (17.5 ft); a 6-row evaporator with an approximate length of 7.9 m (26 ft); or an 8-row evaporator with an approximate length of 10.7 m (35 ft).

When charging, ice starts forming from the supply side of the coil on the first row of each coil and moves to the next row only when ice has formed on the previous row. The ice sensor in the A. O. Smith design was located on the second row of the middle 8-row evaporator coil. Because of the unequal lengths of the evaporator coils, the ice sensor shut off the condensing units before all coils were covered with ice. Approximately 29 m (95 ft) of the evaporator never built any ice.

AP&L first tried to solve the problem by relocating the ice sensor. This was unsuccessful because it greatly increased the compressor run time with only a small increase in storage.

Next, the evaporator coil of the tank was modified to replace the three 8-row coils with six 4-row coils. This left the tank with eight 4-row evaporators and two 6-row evaporators. The ice sensor was also moved to between the third and fourth row of a 4-row coil.

The tank was refrozen, and the results were very satisfactory. The ice storage had been increased from ~63 MJ (60,000 Btu) to over 126 MJ (120,000 Btu). The efficiency of the system also increased greatly, requiring approximately the same 5-h running time as for the original tank to produce 63 MJ (60,000 Btu).

AP&L modified the evaporator coils in all tanks for the 1981 cooling season. Also, due to the repeated failure of the original ice sensors, all tanks were fitted with new ice sensors.

The only other modification made by AP&L as a result of the 1980 cooling season experience was to install a dielectric union on the supply line of each tank to prevent galvanic interaction between the galvanized supply line and the copper line circulating water to the cooling coil.

5.3.2 Long Island Lighting Company

LILCO made a number of modifications to its cool storage installations to improve their performance and reliability. The control wiring scheme was modified to preclude the possibility of interference between the house-side 24 V transformer and the control box 24 V transformer. The coolant circuit initial pressurization was increased from 138 to 207 kPa (20 to 30 psig) to avoid negative circuit pressure when the system cooled to operating temperature. The coolant circuit liquid was changed from methanol and water to ethylene glycol to preclude any fire hazard caused by coolant leakage. Nylon adapter fittings were initially substituted for polyethylene fittings at the connections to the A-coil to minimize the possibility of damage to the pipe during the heating season. The polyethylene pipe was subsequently replaced with copper tubing to the outside entrance point into the attic to minimize the possibility of breakage and water damage to the house.

5.3.3 Pacific Gas and Electric

The principal objective of the equipment modifications made by PG&E was to increase the reliability of the compressors charging the cool storage systems. Numerous compressor failures were experienced throughout the summer, and a variety of fixes were applied.

When the cool storage units were originally installed, all condensing units were retrofitted with crank case heaters and hard start kits if they did not have them.

The original installation procedure recommended by the manufacturer called for the suction line to be at least 3 m (10 ft) and not more than 15 m (50 ft) in length and for the suction and liquid line to be soldered together for 3 m (10 ft) to increase the superheat of the return gas to the compressor. The soldered section acts as a heat exchanger to protect the compressor from slugging (pumping liquid Freon) and was in addition to the existing suction line accumulator. This procedure led to problems at PG&E's initial installation by producing too much superheat, which caused the compressor to trip out on high temperature. It also resulted in excessive head pressures.

After consultation with Carrier, Girton, and the HVAC subcontractor, it was decided that the additional heat exchanger was not necessary for PG&E's application.

A second major modification was the addition of a liquid refrigerant receiver. A receiver is usually found in commercial applications but rarely in residential applications where compressors are critically charged. The receiver acts as a storage reservoir for liquid Freon to insure that the proper refrigerant charge is maintained in the system when operating with an ice storage tank.

The original installation manual called for a charge of 3.8 kg (8.4 lb) of R-22 when the ice tank was used with a Carrier Model 38RE036 condensing unit. However, the specifications provided no guidance for retrofitted systems similar to PG&E's project. Too little Freon would cause uneven and insufficient ice production in the tank. It could also cause compressor overheating and poor system efficiency. Too much Freon could cause the system to flood the accumulator, which would allow liquid Freon to enter the compressor resulting in erratic performance, high head pressures, and eventual compressor failure. The addition of the receiver allows for the expansion and contraction of Freon levels as system requirements change due to ice buildup on the evaporator coil and changing outside ambient temperatures.

The third major modification made to the cool storage system was a result of the high compressor failure rate that was experienced during the first half of the 1980 cooling season. During this period, 22 out of the 30 test homes experienced a compressor failure. It was not readily apparent what was causing the failures, so a joint meeting was held in Fresno with representatives of Carrier Corporation, Girton Manufacturing, ORNL, PG&E, and the local HVAC subcontractor to discuss the problem.

Parts of the meeting were held at several of the test locations where the operation of the cool storage systems was observed and various temperature, pressure, and current measurements were taken. After observing the systems through several startup and shutdown cycles, it was determined that upon compressor shutdown, liquid Freon was passing from the condenser and receiver through the thermal expansion valves and collecting in the bottom of the evaporator coil and accumulator. On compressor startup, liquid Freon was being sucked into the compressor causing slugging. The pressure fluctuations caused by the liquid and the resulting changes in motor load, as indicated by the current to the compressor, were quite evident.

The manufacturer had previously thought that the particular thermal expansion valve used would block the migration of the liquid when the compressor shut down. Because this was found not to be the case, a liquid line solenoid valve was added to the system as shown in Fig. 10. The valve was wired into the compressor contactor circuit so that it closes when the compressor turns off. The valve is intended to prohibit any liquid Freon from flowing into the evaporator and prevent compressor slugging.

The manufacturer recommended that any subsequent failed compressors be replaced by units which contained Carlysle series M-100 heat pump compressors. The reason given was that heat pump compressors have greater piston-to-head clearances and are more ruggedly built than the typical

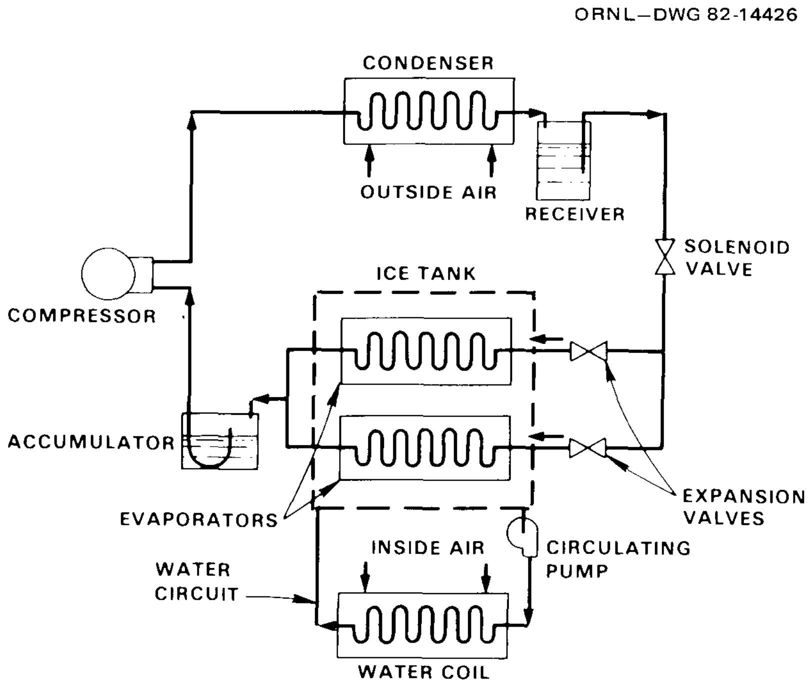

Fig. 10. Location of liquid line solenoid valve.

residential air conditioning compressors and consequently should be better able to withstand any slugging which occurs.

Several minor equipment modifications were also made during the PG&E test. A 24 V transformer was added to the storage tank control cabihet to eliminate the need for a separate 24-V line from the customer's premises. A water flowmeter was added to the chilled water supply line in the five heavily instrumented homes, and a control cabinet cover was fabricated and added to all the storage units to reduce the possibility of tampering and eliminate any potential hazards.

5.3.4 Virginia Electric and Power Company

Two of the Carrier tanks ruptured due to freezing solid when their ice sensors failed. Due to the frequent ice sensor failures during the summer in the Carrier tanks, Carrier was to provide new ice thickness sensors and control cables to be installed in the tanks. VEPCO has also planned to examine alternate ice sensor locations and tank water flow routes.

5.3.5 Wisconsin Electric Power Company

WEPCO made a number of modifications to the TES equipment to correct the operation of the equipment. As mentioned previously, the ice thickness sensors in the multiple tank installations were rewired in series to prevent any tanks from freezing solid. The water flow to the cooling coil was reduced to the minimum required to provide the calculated cooling load of the house, which prevented the test homes from being able to provide more cooling capacity than an equivalent control home. This facilitated comparison of the test and control groups.

Occasional complaints of lack of cooling at four homes were traced to problems with the circulating water pump. The pumps at these homes were lowered to provide a greater head of water, which corrected the problem.

5.4 Communications and Control Experience

Both AP&L and LILCO used the Scientific Atlanta digitally encoded message radio system for communications and control. LILCO reported some delays in the installation of the communications equipment because the binary coded messages built into the high current controller did not match the radio signal codes. It was necessary to return the units to the supplier for correction.

The radio receivers initially supplied to LILCO by Scientific Atlanta experienced a failure rate of 50% due to printed circuit board burnout as a result of insufficient clearance between boards and to poor board connections. No equipment modifications were made to the communications and control system to improve operation except to replace defective equipment.

AP&L experienced a number of difficulties with their Scientific Atlanta system. Upon installation, the radio control switches were tested at each site with a portable transmitter. At that time, 15 switches were found to be defective and were replaced.

Testing of the system from the central transmitter in Little Rock led to the discovery that all the switches were not operating correctly. Some switches would open the compressor circuit while others would only work intermittently. This intermittent operation was traced to the leased telephone lines connecting the message generator in Pine Bluff to the transmitter in Little Rock. Due to long distance switching and routing by the telephone company, the signal received by the transmitter was sometimes different from that sent by the message generator. Thus the transmitter would send out the wrong digital signal, and the radio switch would not operate.

To solve the problem, a Scientific Atlanta digital message generator was installed at the transmitter in Little Rock. The message generator was in turn tied by leased telephone lines to the computer at the transmission dispatch center in Pine Bluff.

This modification did not solve AP&L's communications problem. The message generator repeatedly failed, and after several attempts by Scientific Atlanta personnel to fix the message generator, AP&L abandoned its plans to use the digital system for this project.

All the Scientific Atlanta switches were removed in late August 1980 and were replaced with Motorola radio control switches. The Motorola radio system has been in operation at AP&L since 1977. All switches were tested and operated satisfactorily in September and were used during the summer of 1981.

PG&E also used an existing Motorola radio control system for this project. One radio switch of the 30 failed during the season and was discovered during routine data analysis at the end of the season.

The only modifications made by PG&E to the communications and control system during the test were to install a battery backup system for the Motorola controller to protect against power failures and to replace the leased telephone line between the controller and transmitter with a microwave system.

Aside from the installation and scheduling problems mentioned earlier, VEPCO reported only minor difficulties with the leased telephone line communications and control system. Minor defects in the hardware of two remote terminal units were corrected, and the computer control software was modified to accommodate changes in instrument analog ranges on six houses as well as the addresses on a number of test houses.

Intermittent operation of the first installed telephone data line was traced to telephone company switching and corrected. One installed telephone line and two slave house control cables were cut by others during excavations.

VEPCO's experience has been that 98% of commands transmitted have been received. Two percent of the commands were not executed due to equipment failure, equipment being tested, battery failure due to disconnected charging system, and other factors.

The AS&E communication system caused a number of problems during WEPCO's project. As described in Sect. 4.2, communication equipment delivery significantly delayed the collection of data, and virtually no data were collected during the 1979 cooling season. Additional problems were experienced with hardware failures, equipment modifications, and software corrections. The transponders received from AS&E required rewiring for the study, and a failure rate of 30% was normal on testing the rewired units. Delivery of the temperature monitoring devices was delayed due to difficulties in securing the necessary interface from AS&E. Once installed, the system experienced problems with noise on the system, incomplete data, or no data.

A number of equipment modifications were made by WEPCO to correct the communications and control problems that were experienced. One problem experienced was that the 6 kHz signal superimposed on the power line drowned out the AM band on the test house radio. To correct this nuisance, a filter was field installed to eliminate the transponder interference.

Originally the load controller had a built-in timer that automatically restored the load after 15 min. To eliminate repetitive off commands, a separate off and on command was programmed which required disabling the timer circuit and hard wiring the on command at all 70 storage homes.

5.5 Instrumentation Experience

In general, the conventional pulse initiating watt-hour meters and magnetic tape recording equipment used by the utilities provided acceptable reliability and accuracy. Instrumentation failures were particularly important for the three utilities using magnetic tape recorders because the normal time to collect and process the magnetic tape data can result in as much as 8 weeks of missing or erroneous data.

The most frequent problems experienced by the five utilities were related to the collection of temperature data from the test and control homes.

AP&L had few problems with their conventional magnetic tape instrumentation system. All equipment was checked and calibrated before being used in the field. During 1980, the only equipment that failed was one temperature transducer and one 3-channel frequency converter. The faulty equipment was replaced and returned to the manufacturer for repairs. No modifications were made to the system as a result of 1980's experience.

LILCO likewise reported few difficulties with their magnetic tape instrumentation system. The major problem experienced by LILCO was that the temperature transmitters used in the ten heavily instrumented test homes and ten heavily instrumented control homes were found to be faulty. Consequently the temperature data collected during the 1980 season are suspect. The only instrument modification made by LILCO was to discontinue usage of the Customer Alert Device because its indication of the operating status of the cool storage system was of no use to the participant.

The only instrumentation equipment that experienced any type of consistent malfunction in PG&E's project was the temperature-to-frequency transducer. Of the 279 transducer channels observed during the 1980 cooling season, at least 53 (19%) were partially or completely erroneous due to temperature unit failures. Although exact figures are not yet available, it is estimated that about 10% of the temperature data set was lost.

Aside from replacing the failed temperature transducer, no instrumentation modifications were made by PG&E.

VEPCO experienced a number of pulse generator printed circuit board failures on their temperature channels. These boards were replaced. While looking for the cause of the erroneous temperature data, it was discovered that the pulse generator input to the magnetic tape meters was 12,000/h instead of the specified 6,000/h. This resulted in saturation of the magnetic tape and unreliable data in the upper 20% of the scale range.

All of the temperature and humidity instrumentation was modified and recalibrated for correct output. A correction factor will be applied to all previous temperature and humidity data if feasible.

6. CUSTOMER ACCEPTANCE

Most of the customers who volunteered for the test were initially eager to participate. This is evidenced by the relative ease with which the utilities were able to secure volunteers for the test and control groups. The reasons for participation given by the customers ranged from trying to do their part for the energy crisis to trying to find a way to lower their summer electric bill.

The first objections raised by the test customers concerned the size of the TES equipment. Although the customers had been told several times about the size of the storage tanks and enclosures, several were shocked when the equipment was actually delivered. Several of AP&L's customers expressed the sentiment that they wished the metal equipment enclosure could be smaller. The most pleasing installations were where the tanks could be installed under the house or in the basement out of the customer's sight.

In general, the test customers entered the first conditioning season with high expectations. When the various equipment problems (insufficient capacity, AM radio interference, nighttime noise, compressor failures, and inadequate humidity control) cited earlier arose, the test participants were in general very understanding and patient far beyond what could be expected of a test participant. Many attributed the problems to the new nature of the equipment and considered it just a matter of time before all the bugs were worked out. Many of the customers had days when there was little or no cooling in the late afternoon and early evening. With outdoor temperatures above 38°C (100°F) and indoor temperatures above 29°C (85°F), it was surprising that the utilities did not lose most of their participants.

As the summer progressed and the various equipment problems remained unresolved, some of the test customers asked that the equipment be removed. AP&L lost two customers during the summer and another in the fall of 1980. Also during the fall of 1980, four test customers moved. AP&L was successful in persuading three of the four new owners to leave the equipment in place. LILCO converted a total of five systems back to their initial configuration at the request of the respective participants. The overriding reason the participants gave for wanting the system removed was that it did not provide a comparable level of air conditioning to that of their initial equipment.

Despite frequent complaints of inadequate cooling, none of PG&E's or VEPCO's customers asked that the equipment be removed.

WEPCO removed two systems during the study. One was removed because it was impossible to have both a humidifier and A-coil in the furnace plenum. The homeowner wanted the system but required the humidifier during the winter. The second homeowner felt that the system interfered with heating and decided that he really did not want air conditioning. Both systems were removed, and one system was installed in a new home.

The most frequent customer complaint was of inadequate cooling in the afternoon persisting into the late night. Numerous complaints of lack of cooling were received by all the utilities except WEPCO. For example, VEPCO received 72 calls for inadequate cooling. Of these 30 were found to be due to exhaustion of the available supply of ice. During the season, VEPCO accumulated 1,668 house-days of experience. Customer overrides of the utility control signal were performed 434 times or 26% of the total house-days. All homes with the Carrier ice tank were overridden daily from August 8—September 12. The homes with Carrier tanks accumulated 1,036 house-days of experience and 362 overrides for a 34.9% occurrence. Those houses with Girton tanks had 642 house-days of experience with 72 overrides for an 11.2% override rate.

WEPCO reported some initial complaints about inadequate cooling, but most of these were traced to equipment problems and corrected. Temperature regulation at most homes was good, and the typical customer comments were that they enjoyed the obvious improvement in dehumidification.

In contrast to WEPCO's experience, both LILCO and VEPCO reported customer complaints about high humidity when the system was operating. In VEPCO's case, this was probably due to the excessive air flow rate of the indoor air handler. The other utilities reported adequate temperature regulation and humidity control when the system was operating properly.

All the utilities reported customer complaints regarding noise from either the condensing unit or indoor air handler. In PG&E's case, three participants wanted to have the equipment removed because of nighttime noise. One compressor was relocated, and wooden noise baffles were constructed at the other two locations. The reduction in noise was sufficient to satisfy the three participants, and they did not withdraw from the program.

A final area of customer dissatisfaction was the high electric bills some of the customers received during the early months of the test. As discussed in Sect. 2.3, the customer incentives originally planned by the utilities did not anticipate the poor efficiencies that were exhibited by the TES equipment. In several cases, the incentives were modified to compensate the customers for the excess energy usage of the cool storage equipment.

7. RESULTS AND CONCLUSIONS

7.1 Utility Comments

7.1.1 TES performance

The results from the summer of 1980 were generally far below expectations. The loss of condensing unit capacity when operated with cool storage was much greater than expected. In addition to problems with condensing unit capacity, the A. O. Smith, Carrier, and Calmac tanks experienced problems with insufficient ice storage capacity.

Three of the five utilities reported adequate temperature regulation and humidity control when the system was operating properly. The other two, LILCO and VEPCO, reported problems with the TES systems adequately regulating humidity as installed.

The energy efficiency of the cool storage equipment was significantly poorer than any previously assumed worst case. Preliminary analysis of 1980's data indicates that some of the test homes were using more than twice as much energy for air conditioning as comparable control homes. The high energy consumption of the TES systems required several of the utilities to modify their customer incentives to compensate customers for high energy bills.

7.1.2 Equipment reliability

The TES system maintenance problems most frequently reported were compressor failure, ice thickness control sensor failure, and circulating water pump failure. Other problems reported included refrigerant leaks, expansion valve failures, control system problems, melting of PVC piping to the water coil, coolant tube clamps, and failed mechanical package evaporator.

By far the most serious reliability problem experienced during the test was the high incidence of compressor failures. A number of theories as to the cause of the failures have been proposed, and some equipment modifications were made in an attempt to alleviate the problem. However, insufficient operating experience has been accumulated to determine whether the equipment modifications were sufficient to eliminate the causes of the compressor failures.

A final consideration in the reliability of the TES system is the integrity of the storage tank itself. Several of the Carrier tanks ruptured when the tanks froze solid due to ice sensor failure. Also, the painted steel interior of the Girton tank is beginning to chip and rust. Conceivably, the floating paint and rust could clog the water circulation loop. The manufacturer-supplied rust inhibitor is of questionable effectiveness.

The participating utilities are in general agreement that the reliability of the TES equipment must be significantly improved to even be considered for commercialization.

7.1.3 Customer economics

Because the equipment available for this test program was prototypic and is not representative of future commercial mass-produced equipment, it is impossible to draw definitive conclusions as to the economic feasibility of any future cool storage system. However, the high excess energy consumption, high initial equipment cost, high installation cost, and poor reliability of the existing equipment are such that the current systems would not be economically beneficial to either the utility or its residential customers.

7.1.4 TES controllability

Operating difficulties experienced during the tests prevented the complete testing of the various control strategies that had been proposed. Remote utility control of the TES equipment has been generally satisfactory, and several utilities expressed the opinion that remote utility control would prove to be the preferred control method due to its inherent flexibility.

7.2 Commercialization Potential

The results of this test program indicate that cool storage as a load management option is not ready for commercialization in its present state of development. In this context, a system is considered to be capable of commercialization if it can be placed in the field and perform its intended function without excessive maintenance over an acceptable lifetime. Areas requiring improvement include charging capacity, storage capacity, energy efficiency, and equipment reliability.

When properly designed and installed, cool storage equipment can provide adequate or even improved space conditioning over conventional air conditioning. Areas requiring careful consideration include the advisability of retrofitting storage to existing condensing units due to the capacity derating of the condensing unit when operated with cool storage; the location and/or insulation of the storage tank to minimize standby losses; proper water flow to the cooling coil to adequately dehumidify yet not exceed the design capability of the storage equipment; and indoor air flow that is matched to the characteristics of the water cooling coil (heat pump hybrid systems may require multispeed fans).

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