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ACES 1979
Capabilities and Potential

R. E. Minturn
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ENERGY DIVISION

ACES 1979

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Department of Energy
Division of Buildings and Community Systems

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RELATED REPORTS

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

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

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

I. G. Cantor, Investigation of Alternate Types of Water Storage Components to be Utilized in Conjunction with the ACES System, ORNL/Sub-78/14233/1 (December 1977).

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

H. C. Fischer, Development and Testing of a Single-Plate and a Two-Plate Ice-Maker Heat Pump, ORNL/CON-21 (April 1978).

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V. D. Baxter, Intermediate Report on the Performance of Plate-Type Ice-Maker Heat Pumps, ORNL/CON-23 (October 1978).

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M. L. Ballou et al., MAD: A Computer Program for ACES Design Using Monthly Thermal Loads (in preparation).

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACES 1979: CAPABILITIES AND POTENTIAL

R. E. Minturn
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ABSTRACT

The state of technological development of the Annual Cycle Energy System (ACES) as of late 1979 is reviewed, and the results of two year's operation of the ACES in the Knoxville TECH complex are presented. An assessment of the technical and economic feasibility of the ACES concept based both on field results and on analytical calculations using a computer model of ACES performance and economics applied to 115 U. S. cities is made. Areas needing further attention, especially with regard to capital cost reductions, are described.

I. SUMMARY

Since the Oak Ridge National Laboratory (ORNL) became interested in the development of the Annual Cycle Energy System (ACES) concept in mid-1974, considerable progress has been made in developing the technology, in estimating its applicability to diverse geographic areas in the United States, and in estimating its economic competitiveness with alternative systems for providing space heating and cooling and water heating to buildings. Early conjectures, designs and experimental results have been documented in a series of reports (1-8) from the Conservation Technology Group of the ORNL Energy Division; experience during the two year period September 1977 to September 1979 is summarized in this report.

For this two year period, an ACES test house and a nearly-identical control house at a Knoxville, TN, site (3,7), have been monitored continuously. For the test year 1977-78, in which the control house used electrical resistance to provide space and water heating, the ACES used just 44% of the electricity consumed at the control house. In the following year, 1978-79, a conventional heat pump heated and cooled the control house, with water again heated by a conventional electric water heater, and in this year the ACES house used about 51%

as much electricity. A computer program for the simulation of ACES and conventional system performance was developed and validated with data from the Knoxville complex. This program was then used to estimate annual coefficients of performance for these systems throughout the United States. The results indicate that ACES enjoys a strong edge in energy conservation in almost every area of the country.

Analyses have shown that the ACES can be economically competitive in the residential market at electricity prices exceeding about 4¢/kWh, and that it is presently competitive in some types of commercial buildings where demand charges and time-of-day rates are in effect. However, presently high first costs make it clear that the implementation of the ACES, with its attendant benefit to national energy conservation, will be greatly enhanced by additional research and development in areas with large potential for capital cost reduction.

II. CONCEPT DESCRIPTION AND DEFINITIONS

The ACES is designed to provide space heating, air conditioning, and domestic water heating for residences and commercial buildings. The energy transfer is by an electrically driven unidirectional heat pump that obtains its heat from water stored in an insulated underground tank. As the heat is extracted during the heating season, most of the water is frozen, and the stored ice provides air conditioning in the summer. Thus, the water's heat of fusion is available as a heat source in winter and a heat sink in summer. Since both the heating and cooling outputs of the heat pump are used, the resulting annual coefficient of performance (COP) is as high as 3.4 at the present state of equipment development.

Energy Balance Requirements

The ACES achieves maximum energy conservation in applications where the annual heating and cooling demands of a building result in a balance between heat extractions from the ice bin and heat deposits in it. In practice, an exact ice-bin heat balance from building loads alone is unlikely because the building thermal loads vary with the weather, the building usage and construction, and the lifestyle of the occupants. Provision must then be made in the ACES design to compensate for imbalances in the ice bin heat flows. In the winter, an auxiliary solar panel or outdoor air coil can be used to collect heat for melting excess ice. In the summer, the same units can be used to reject heat from the ice bin to the environment to provide additional air conditioning if required after stored ice has been depleted.

Load Management Capabilities

In addition to its function in energy conservation, the ACES has a further advantage in that it lends itself readily to load management. Because ice for air conditioning can be made and stored at night, users can take advantage of low off-peak electric rates if they are available and of substantially lower demand charges. If an appreciable fraction of the buildings being served by a utility system were to utilize the storage feature offered by the ACES, a substantial reduction in the needed generating capacity could be effected.

Bin Size Options

Heating, ventilating, and air conditioning (HVAC) systems employing the ACES concept can extend from the "full ACES," which stores either all of the ice produced during the heating season or all of the ice that can be used during the cooling season, down to the "minimum ACES" which stores only enough water to provide for a short ($\sim$ 14 days) operational period during peak winter demand. The minimum ACES is a compromise to reduce capital costs that penalizes to some extent the energy conservation potential of the system. Systems with smaller bins than those corresponding to the minimum ACES could, of course, be fabricated. Such systems would function primarily as summer load management systems (provide all-day cooling by running the compressor off-peak), but would provide little interseasonal energy transfer and cannot properly be called ACES. If properly designed, they can save some energy by providing a heating system that has a constant capacity and efficiency regardless of the outdoor air temperature.

Mechanical Equipment Options

For any size ACES, two ice formation methods can be used: (1) a brine-chiller ACES which utilizes chilled brine to freeze water around coils immersed in the storage bin; (2) a plate-type ice-maker heat pump (PTIMHP), where water is frozen directly on the evaporator plates of the heat pump, and the ice formed is periodically harvested into the bin. Both the brine-chiller and the ice-maker concepts offer certain advantages. With the former, because of a higher ice packing density in the bin, bins approximately one-half the size necessary for the ice-maker can be used. The brine-chiller ACES also has simpler internal refrigeration system circuitry, and provides a non-freezing medium, the brine, for the transfer of energy from supplementary sources such as solar panels. The ice-maker ACES, on the other hand, eliminates the ice-bin coils with their attendant costs and need for field crew installation, and makes modularization of the system by the manufacturer easier. The relative advantages of the brine-chiller and the ice-maker systems are discussed in more detail in Section IV.A.3.

III. FIELD RESULTS

A. Residential:

1. Knoxville Demonstration House

The centerpiece of the residential ACES demonstration program is a two-building complex on the campus of the University of Tennessee, just outside of Knoxville. One of the buildings is an 167-m^2 residence with an insulated 71-m^3 storage bin in the basement, and a brine-chiller ACES for heating, cooling, and domestic hot water production.[(3)] The second building is an identical residence with the same orientation, differing only in that its heating and cooling are provided by a conventional, off-the-shelf air-to-air heat pump system, and its hot water is provided by conventional resistance heating. The two buildings are well instrumented to measure heat flow and power usage. Operation of the two systems began in May 1976.

The first full annual cycle test of the systems began on November 1, 1977, and continued until September 18, 1978, at which time the experiment was concluded to allow system upgrading and modification prior to the next heating season. Because only small heating or cooling loads occur in late September and in October, the 10 months of actual operation are a good approximation to a full year's run. Reliability was good during the first year; minor control failures caused the system to be inoperative for about two days.

During late September and in October 1978, additional insulation was added to the storage bin, raising the level of insulation to R-40, and a new, more cost-effective coil system was added in the ice bin. Operation for the second test year began on December 1, 1978, and was completed on September 30, 1979.

Again, the system operated reliably and met all calculated performance goals.

During the first annual cycle test, the control house, in the heating mode, was operated on resistance heat. This established a base for comparison of the loads for the two houses, which tracked each other within a few percent. Beginning in May of 1978, the control house was heated and cooled by a conventional air-to-air heat pump. A summary of the performance of the two HVAC systems for the two seasons of operation follows.

1977/1978 Season. Because the ACES frequently provides both space and water heating simultaneously and because much of the space cooling is provided from stored ice, a by-product of heating, the true performance of the ACES must be measured in terms of the electrical energy input required and the heating and cooling supplied by the system for an entire annual cycle. The results of operation of the two houses in the Knoxville complex for the 1977/78 test year are given in Table 1. In providing essentially the same services, the ACES used just 44% as much electricity as the equipment in the control house.

Table 1. Performance summary for the Knoxville ACES complex for the period November 1, 1977, to September 18, 1978.

	Control House[a]		ACES House	
ENERGY DELIVERED	(GJ)	(10^6Btu)	(GJ)	(10^6Btu)
Space Heating	43.6	41.3	43.0	40.8
Water Heating	15.6	14.8	20.9	19.8
Space Cooling	24.5	23.2	26.2	24.8
Total	83.7	79.3	90.1	85.4
POWER PURCHASED	(kWh)		(kWh)	
November 1977	1,778		505	
December 1977	3,183		984	
January 1978	4,332		1,707	
February 1978	3,242		1,246	
March 1978	1,712		712	
April 1978	633		314	
May 1978	772		304	
June 1978	1,203		280	
July 1978	1,491		546	
August 1978	1,427		1,546	
September 1-8, 1978	750		867	
Total	20,523		9,011	
SYSTEM ANNUAL COP	1.13		2.78	

a. Electrical resistance space and water heating.

The ACES operated in three principal modes: space heating with water heating, water heating only, and space cooling from either stored ice or by night heat rejection while also satisfying water heating requirements. A detailed analysis of ACES performance through March 26, 1978, is given in Reference 7. A summary is presented below.

Heating season. The heating season began with the heat pump extracting energy from a tank full of water at 9°C, and ice began to form on the coils on December 19. By April 1, 1978, the maximum ice inventory of 51,700 kg had been reached. Although space heating and hot water demands continued throughout April, the ice inventory continuously declined because the heat leakage into the bin from the surrounding earth, equivalent to about 69 MJ/day (65,500 Btu/day) melted ice more rapidly than it was formed.

An example of system energy consumption performance in the heating season is shown in Fig. 1, which is a comparative plot of power consumed by the ACES and control houses during the week of February 13, 1978. The outstanding performance of the ACES as a constant capacity heat pump and its ability to minimize peak demand is clearly shown in Fig. 1, as well as Fig. 2, which compares the peak loads for the year for the two houses.

For the test year heating season, the ACES consumed 5,500 kWh while satisfying all hot water and space heating requirements of the house. The control house consumed 14,800 kWh during the same period, while delivering nearly identical loads. Fig. 3 illustrates this comparison.

Measured heat leakage rates into the ice storage bin were four times greater than anticipated and ice retention was much below that predicted. From the heating season results, it became apparent that additional insulation was needed in the bin to reduce heat leakage and that a scheme for limiting water heating during periods of peak space heating demand should be adopted.

The measured COP for water heating and space heating during the heating season was 2.73, very close to the predicted seasonal performance.

Transition season. During April and May, the transitional months between the heating and cooling seasons, the only significant load supplied by the system was for hot water; heating and cooling needs were small. The ice formed as a by-product of hot water production was not great enough to compensate for heat leakage into the bin, and as a result, the ice inventory declined during the transition season. The COP for water heating during the transition season was 2.4.

Cooling with stored ice. By mid-May, with about 47,000 kg of ice remaining in the bin, cooling loads became significant. The stored ice provided all of the cooling needs until July 27, 1978, equivalent

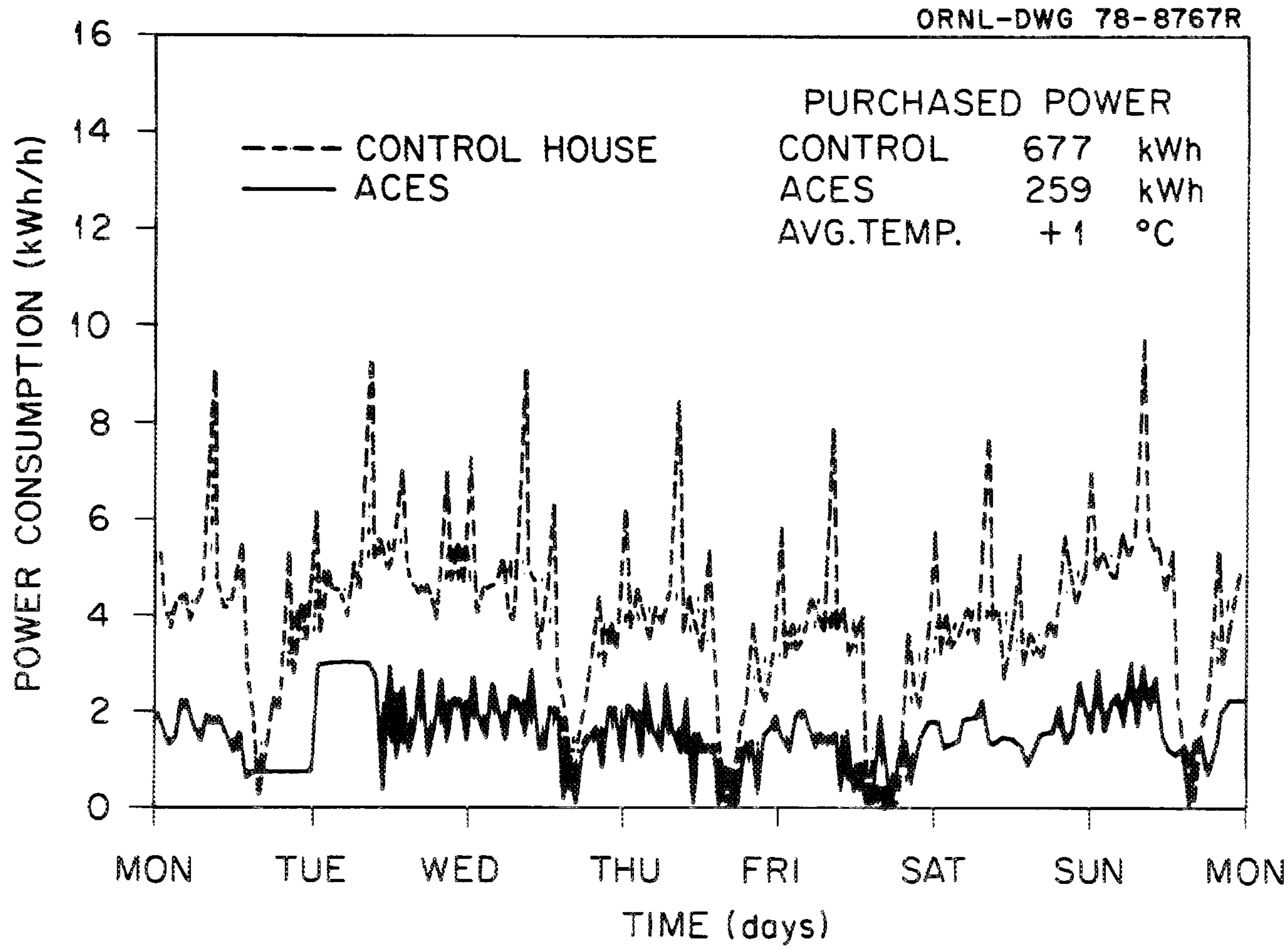

Fig. 1. Comparison of ACES and control houses heating power consumption for the week beginning February 13, 1978.

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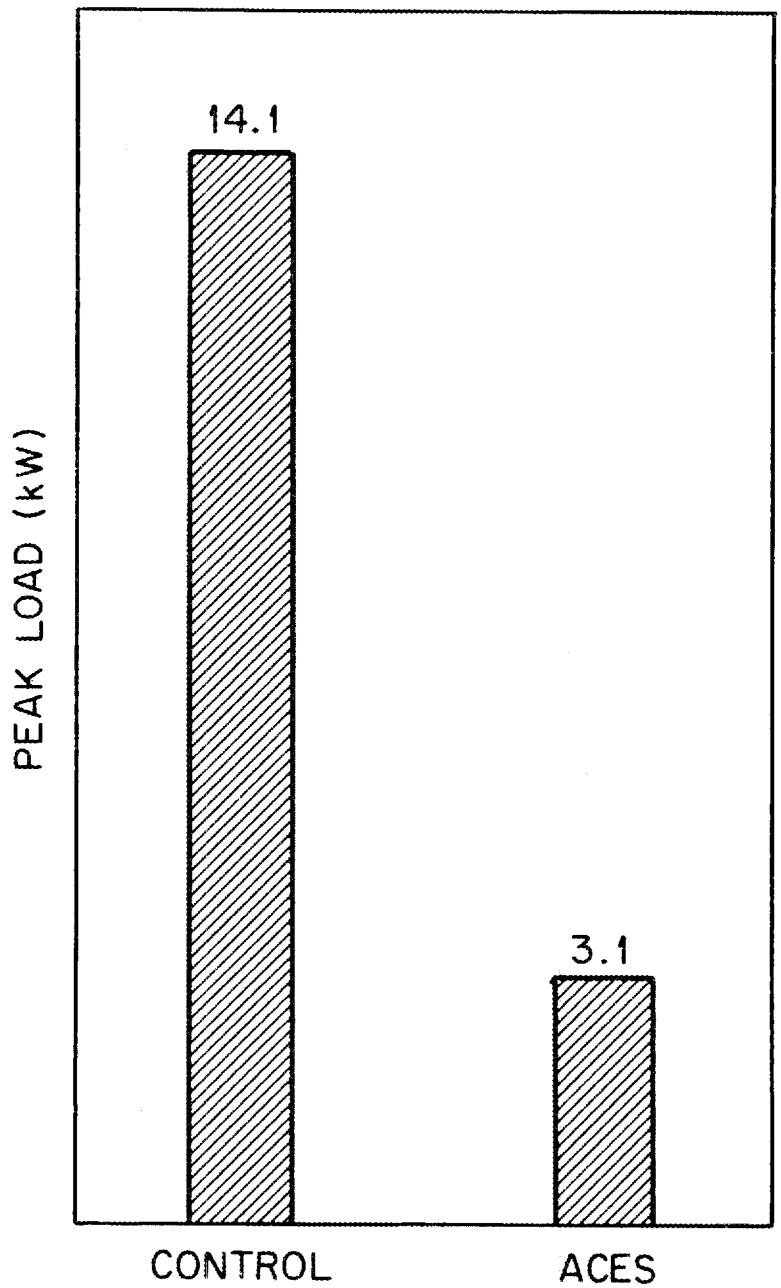

Fig. 2. Comparison of heating season peak utility load in ACES and control houses. (Electrically heated control house.)

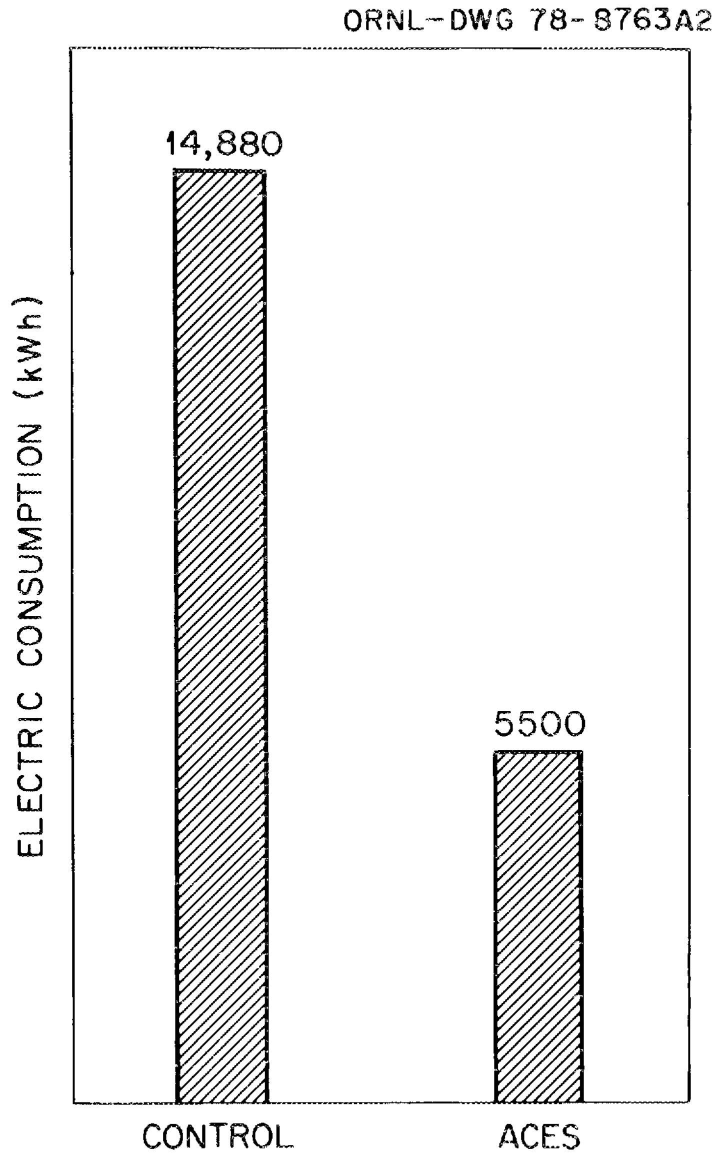

Fig. 3. Comparison of 1977-78 heating season energy consumption in ACES and control houses. (Electrically heated control house.)

to about 13.3 GJ (12.6 x 10^6 Btu) of cooling. This relatively low figure, equal to only 68% of the design cooling storage capacity of the bin, reaffirmed the need for greater bin insulation.

Figure 4 illustrates the energy consumption pattern during cooling with stored ice; the spikes on the ACES curve indicate periods of compressor operation to produce hot water. Some additional cooling capability is, of course, a by-product of the compressor operation. During the particular week covered by Fig. 4, the ACES used only 18% as much purchased electricity as the heat pump air conditioner and electric water heater in the control house. Peak values for ACES were about 2.4 kWh/h; those for the control house about 5.5 kWh/h.

Cooling by night heat rejection. Up to the point the ice ran out, the ACES COP for heating, cooling, and hot water was 3.17, the highest cumulative COP reached during this annual cycle. To maintain cooling capability after the ice was exhausted, the compressor was run at night to cool the water in the bin, and the waste heat was rejected by the solar panel. Performance in this mode of operation was expected to be about equal in efficiency to an air-to-air heat pump, but to have the potential advantage of compressor off-peak operation.

In practice, it soon became apparent that the ACES in this mode of operation, in this house at this time, was less efficient than the conventional system in the control house. This was caused by heat leakage into the bin and the large internal load the mechanical package imposed upon the building cooling load; not only was the ACES being required to cool the house, but it was also cooling a large amount of earth surrounding the bin. To minimize heat leakage, the set points of the system were changed so that the bin temperature was controlled at about 9°C, very near the apparent ground temperature. Also, the mechanical room was vented directly to the outside to reduce internal load.

Fig. 5 illustrates power consumption for the two houses during a typical week when the ACES was in the night heat reject mode. For the entire cooling period, from ice and from reject heat mode operation, the ACES consumed 3,240 kWh compared to 4,810 kWh by the control house.

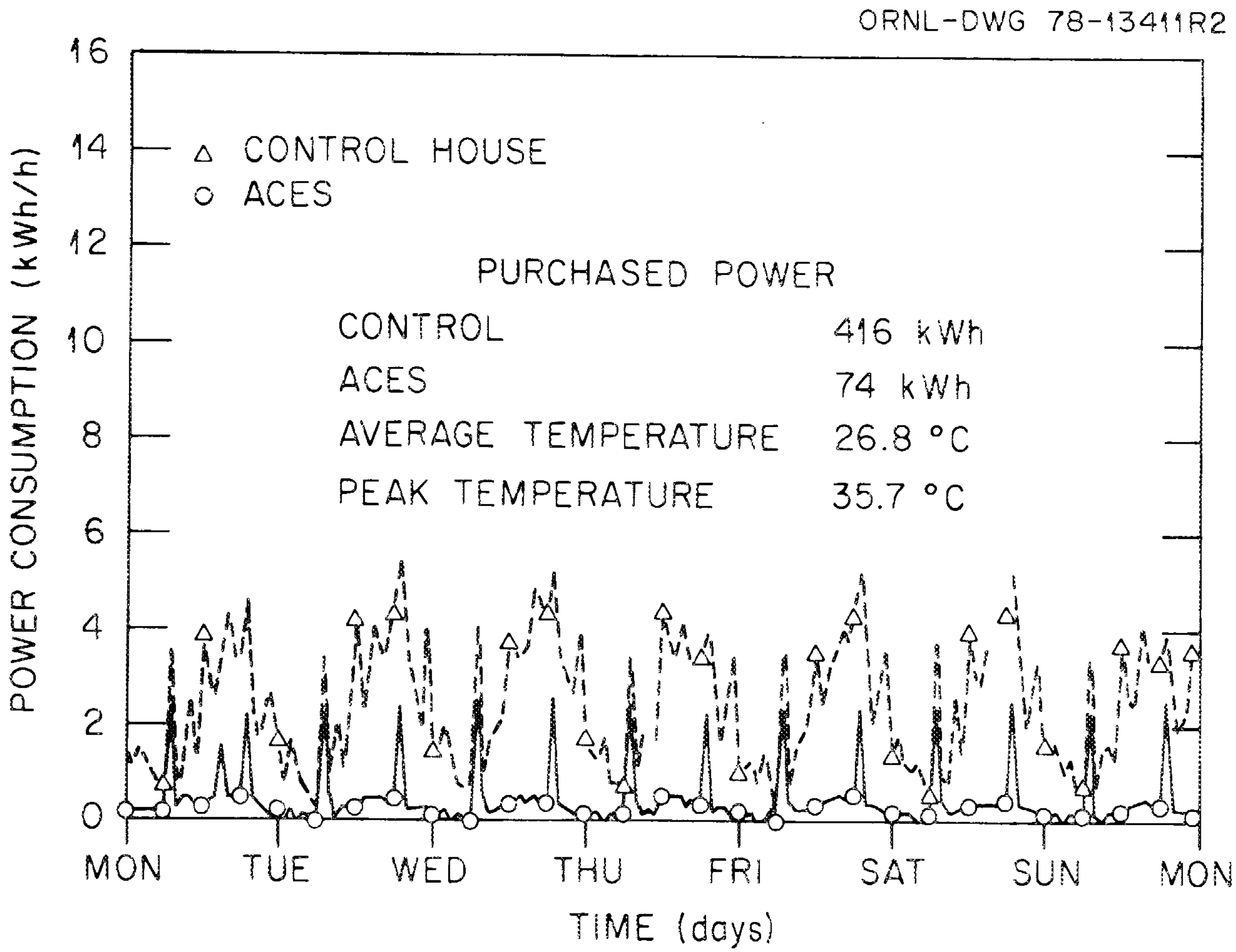

Fig. 4. Comparison of ACES and control houses cooling power consumption for week beginning June 26, 1978. ACES cooling was with stored ice.

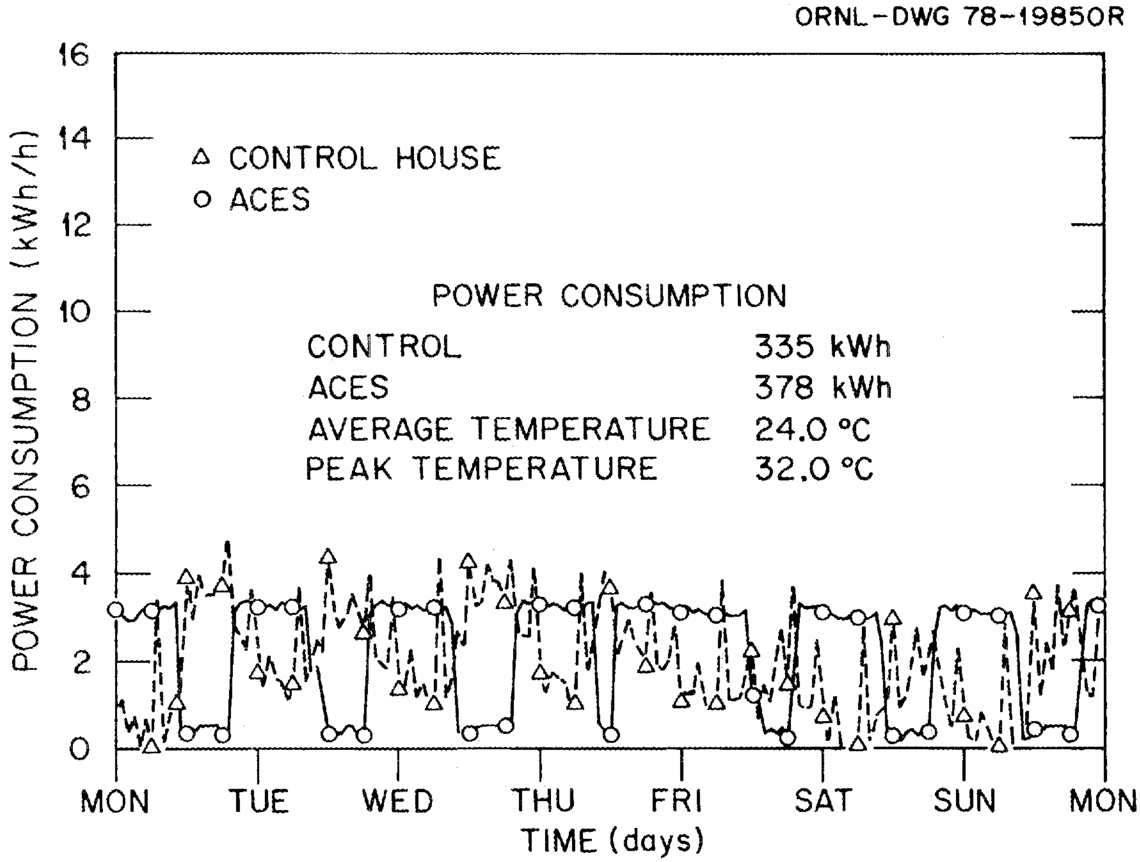

Fig. 5. Comparison of ACES and control houses cooling power consumption for week beginning September 11, 1978. ACES cooling was by night heat rejection.

By the end of the annual cycle, the cumulative COP, 3.17 at ice exhaustion, had fallen to 2.78.

1978/1979 Season. The experiences of the 1977/1978 season had indicated some areas in which system modifications would pay significant performance dividends. Most important was to increase the level of insulation in the bin, so as to both reduce ice loss and make the night heat reject mode more efficient. A more cost-effective, but slightly less efficient, in-bin heat exchanger was installed, and the compressor was replaced with a larger unit. The data acquisition system was also upgraded to increase both capacity and reliability. In the control house, provision was made for heating with an air-to-air heat pump, rather than with the resistance heating used previously. Hot water in the control house continued to be produced by a conventional electric water heater.

The modified system was put into operation, and the second annual cycle started on December 1, 1978. The steady-state COP for water and space heating for the ACES was measured to be 2.50 vs about 2.66 for the previous mechanical package; the degradation was attributable mainly to the less efficient compressor and ice-bin heat exchanger combination.

For the period December 1, 1978 to September 30, 1979, 6,597 kWh of electricity had been used by the ACES, compared to 12,861 kWh for the control house. The respective COPs were 2.81 and 1.41. Performance to September 30, 1979, is summarized in Table 2.

Heating season. The air-to-air heat pump in the control house is a General Electric "Weathertron," sized and installed according to conventional practices. The ARI rating of the system is 32.7 MJ/h (31,000 Btu/h), 2.46-COP at 8.3^{o}C (47^{o}F) outside air and 21^{o}C (70^{o}F) inside air. In-place tests of the equipment confirmed this rating under steady-state conditions. The data acquisition system monitored the heat pump indoor and outdoor unit power and the hot water supplied to the control house.

The operation of the air-to-air heat pump in the control house under well-instrumented conditions revealed the following:

1. Actual seasonal system performance is much below the ARI rated performance or the projected performance based on methods that do not account for cycling, frosting, and defrosting losses.

2. Cycling losses are the dominant losses, and are so significant as to result in actually decreasing system performance with increasing outside air temperatures above the house balance point. For example, the space heating only seasonal performance factor (SPF) was 1.65 in January 1979 but only 1.42 the following April.

Contrary to common practice with air-to-air heat pumps, the ACES in the Knoxville demonstration house uses a liquid line solenoid valve which maintains refrigerant pressure differences across the compressor

Table 2. Performance summary for the Knoxville ACES complex for the period December 1, 1978 to September 1, 1979.

	Control House[a]		ACES House	
ENERGY DELIVERED	(GJ)	(10^6Btu)	(GJ)	(10^6Btu)
Space Heating	32.85	31.13	32.85	31.13
Water Heating	13.75	13.03	15.82	14.99
Space Cooling	19.18	18.18	19.17	18.17
Total	65.78	62.34	67.84	64.29
POWER PURCHASED				
December 1978	1,670		997	
January 1979	2,542		1,538	
February 1979	2,037		1,121	
March 1979	1,160		610	
April 1979	611		284	
May 1979	476		215	
June 1979	1,023		278	
July 1979	1,015		249	
August 1979	1,462		534	
September 1979	857		892	
Total	12,853		6,718	
SYSTEM ANNUAL COP	1.41		2.81	

a. Air-to-air heat pump with electric resistance water heater.

and prevents refrigerant migration during the off-cycle. Because of this, the ACES does not suffer any detectable losses due to cycling.

The modified system in the ACES house operated efficiently and reliably, although some early problems with the control system caused about two weeks of outage in December. Heat leakage into the 0°C bin was reduced to about 26.4 MJ/day (25,000 Btu/day), down from the 69 MJ/day (65,500 Btu/day) formerly. Sensors beneath and around the bin indicated higher earth temperatures than formerly, reflecting the higher level of bin insulation. A new water heating control logic prevented some excessive water heating that had occurred during the previous winter heating season. By the end of the heating season, the ice inventory reached about 90% of design capacity, and some ice generation continued as a byproduct of hot water production.

Transition and cooling seasons. During April and May, little space heating was demanded, and hot water was produced at a COP of 2.2. In early May, a test run of heat rejection by means of the solar/convector panels on the south side of the ACES house brought the ice inventory to 105% of design capacity.

By mid-May, cooling loads became significant and stored ice provided all of the cooling needs, amounting to 14.1 GJ, until August 24, 1979. The test year COP to that date was 3.0; the ACES COP for cooling and hot water to the end of August was about 5.2. Following depletion of the ice, cooling was done through September 30, 1979, by chilled water produced by nighttime operation of the compressor. The COP for space cooling and water heating during this period was 1.7. For the entire cooling season, the ACES house COP was 3.37 while the control house COP was 1.45.

Thus, modifications in the Knoxville ACES house have worked as expected and results from the demonstration complex have continued to provide confirmation of the technical feasibility and the striking reduction in energy consumption made possible by the concept. Operation has been reliable, and the effect of system design on performance is now adequately understood.

B. Commercial:

To date the DOE ACES Implementation Program has not involved the design and construction of ACES in commercial-sized installations. To our knowledge, the only commercial heat-pump-based system with ice storage which has a storage bin large enough to effect any inter-seasonal transfer of energy, is the "Energy Bank" system (9,10) at the Nursing Home on the campus of the Veterans Administration Hospital in Wilmington, Delaware. With this system, the installed bin is somewhat smaller than that needed to qualify as a "minimum ACES" under the definition of Section II of this report. The ACES in this 60-bed, 2700-m^2 facility was put into operation in July 1978, and incorporates a 566-m^3 ice storage bin and about 140-m^2 of unglazed aluminum solar panels.

Although the Energy Bank has supplied both heating and cooling to the nursing home, a number of problems have arisen and much reliance has been placed to date on the contingency back-up system. The major problem area seems to be in system control, and as a result proper use of the solar panels and the outdoor air coil as supplementary heat sources seems not to have been made. The solar panel appears, furthermore, to be too small to meet design loads. The VA is working with the equipment manufacturer and the controls supplier to get the equipment working properly so that a true assessment of the concept as applied to larger buildings can be made. From preliminary information, ORNL calculates an annual COP of about 2.9 for the facility when all components are operating properly.

A number of diurnal cooling load management systems with ice storage are under evaluation by several utilities and other commercial firms (11). Although such installations do not save much energy, they do utilize equipment similar in many respects to that needed for ACES, and may, consequently, expedite the development of ACES in commercial sizes.

IV. RESIDENTIAL ACES

From an engineering point of view, the ACES is a technically sound system for reducing energy use in residential buildings without requiring any changes in the lifestyles of the occupants. Economically, the residential ACES appears to be potentially competitive with other electrically driven systems at electricity costs exceeding about 4¢/kWh. It is not presently competitive because mass-produced mechanical packages are not available. Technical and economic considerations are both discussed in more detail below.

A. Technical Feasibility

1. Fuel and energy conservation. The field results which were presented in Section III show that the residential ACES can save appreciable amounts of electricity over competing electrically driven systems such as resistance heating and air-to-air heat pumps with electric water heaters. In addition, a recent independent study (12), commissioned by the ACES Program, indicates that the ACES can lower primary fuel usage over a number of conventional systems which provide the same services. Table 3 presents some energy use estimates for four different HVAC systems and two ACES configurations for a 167-m^2 well-insulated house in three representative cities.

Table 3. Estimates of annual primary fuel usage[a] (in GJ) for different HVAC systems in a 167-m^2 well-insulated residence.[b]

	Location		
HVAC System	Philadelphia	Atlanta	Minneapolis
Full ACES	87	68	127
Minimum ACES	96	97	130
Gas heat & hot water, electric AC	140	111	193
Oil heat, electric AC and hot water	174	142	223
Air/air heat pump, electric hot water	176	140	265
Resistance heat & hot water, electric AC	272	189	384

[a]Assumes a 30% efficiency in generating and transmitting electricity to home.

[b]Derived from Reference 12.

A subcontracted study (13) by the Research Foundation of the National Association of Homebuilders (NAHB) has concluded that the ACES is compatible with all popular house types. We have subsequently used the technical data generated in the Knoxville facilities to estimate the applicability of the ACES as a conservation tool to other regions of the United States. Fig. 6 shows the range of expected annual COPs for full ACES installed in well-insulated 167-m^2 homes for different regions of the country. The annual COP is, of course, a direct measure of the services delivered with respect to energy purchased, and as such reflects both the needs of the house and the design of the system which provides the services.

In the calculations used to generate these COPs, a high-performance ACES mechanical package, optimally installed and operated, with little cycling losses during the winter, was assumed. All pumps and fans are assumed to be of the highest efficiency obtainable, and the energy losses from the pumps and from the compressor are assumed to be vented into the house during the winter and rejected to the outdoors during the summer. The ice storage bin is assumed to be below grade and insulated to R-40. The system modal COPs used in the calculations are as follows:

Heating season COP	= 2.55
Stored ice cooling COP	= 12.7
Summer water heating COP	= 2.68
Bin heat rejection COP	= 2.01

As Fig. 6 shows, the annual COPs for full ACES residential installations range from a low of about 2.0 in some southern states to a high of about 3.4 in the east-central part of the country. Only two areas appear impractical for ACES applications, southern Florida and part of the Texas gulf coast. These areas are unsuitable because of the lack of appreciable space heating loads, but they might benefit from diurnal summer cooling load management using ice storage/heat pump systems. For minimum ACES installations, the values of Fig. 6 would range from about 2.0 to 2.9.

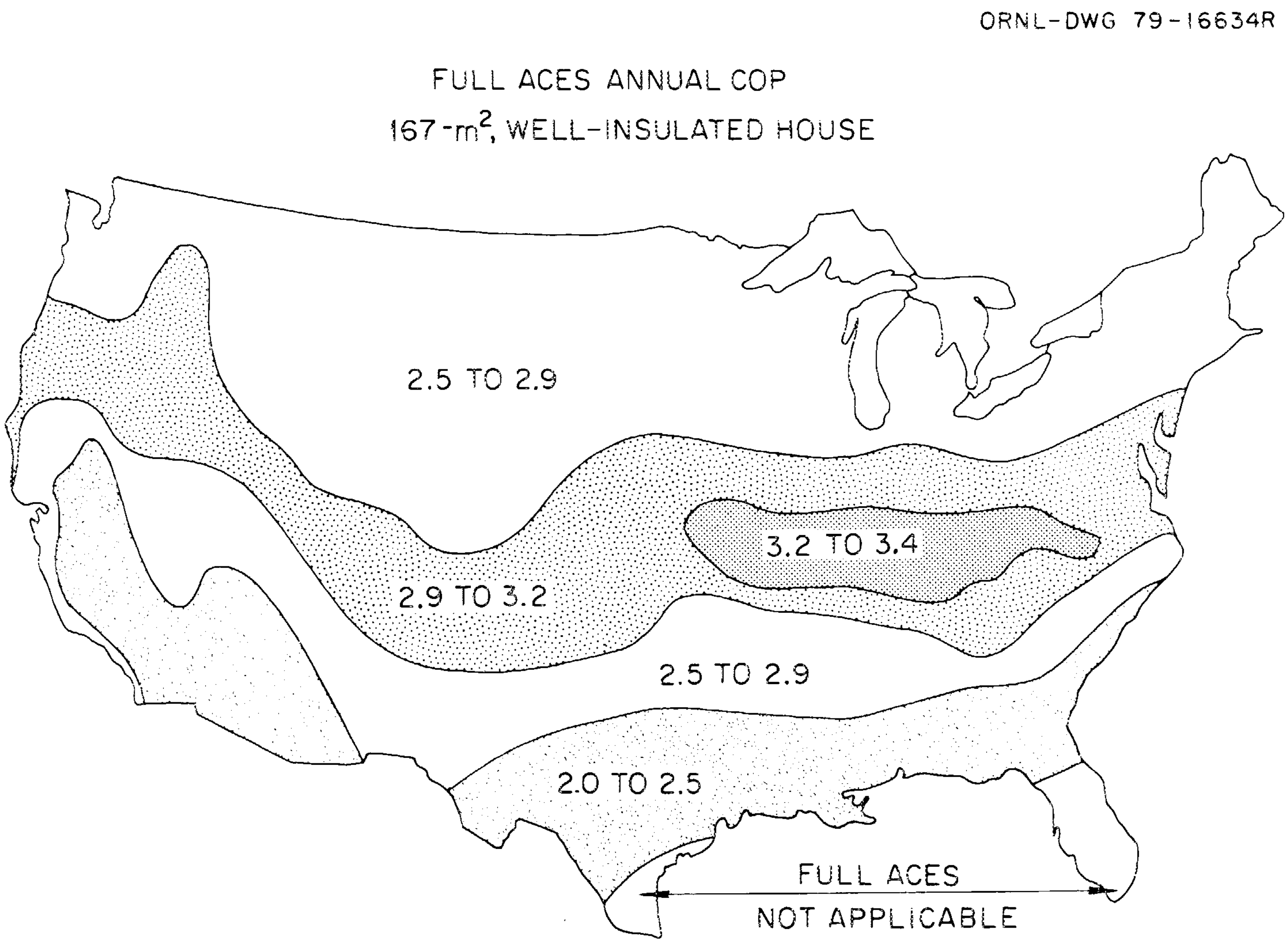

Fig. 6. Estimated annual COPs in regions of Full ACES applicability.

To put the COP values of Fig. 6 into perspective with competitive HVAC systems, we have calculated seasonal performance factors for a standard, presently available air-to-air heat pump (ARI COP = 2.46 at 8.3^{o}C, 1.7 at -8.3^{o}C). The computer model used to calculate the SPFs for the air-to-air system was validated with data taken at the control house in the Knoxville complex. The validation results are given in Table 4, which shows that the computer model represents the heat pump system reasonably well.

Table 4. Comparison of calculated and measured SPFs for an air-to-air heat pump in a 167-m^2 control house at Knoxville, Tennessee.

Quantity	Measured[a]	Calculated
Heating only SPF	1.6	1.52
Cooling only SPF	1.6	1.49
Annual COP (including I^2R water heating)	1.4	1.35

[a]For the period May 1978 through April 1979.

Following validation of the model, annual COPs for the system including water heating by I^2R were calculated for 114 U.S. cities, and a summary plot of the results is given in Fig. 7.

Comparison of Figs. 6 and 7 reveal that the ACES is potentially superior to the standard air-to-air heat pump in all areas in which the ACES can be applied. In most areas of the country, the ACES' annual COP exceeds that of the standard heat pump and resistance water heater by a factor of two or more. If a desuperheater water heater were used instead of a resistance heater, the annual COPs in Fig. 7 would be increased by three or four tenths of a point, still much below that for the ACES. Because much research is currently being conducted on heat pumps, future performance will certainly exceed that shown in Fig. 7, but even small improvements in efficiency will be very costly to develop. Moreover, most improvements that one can visualize for the air-to-air

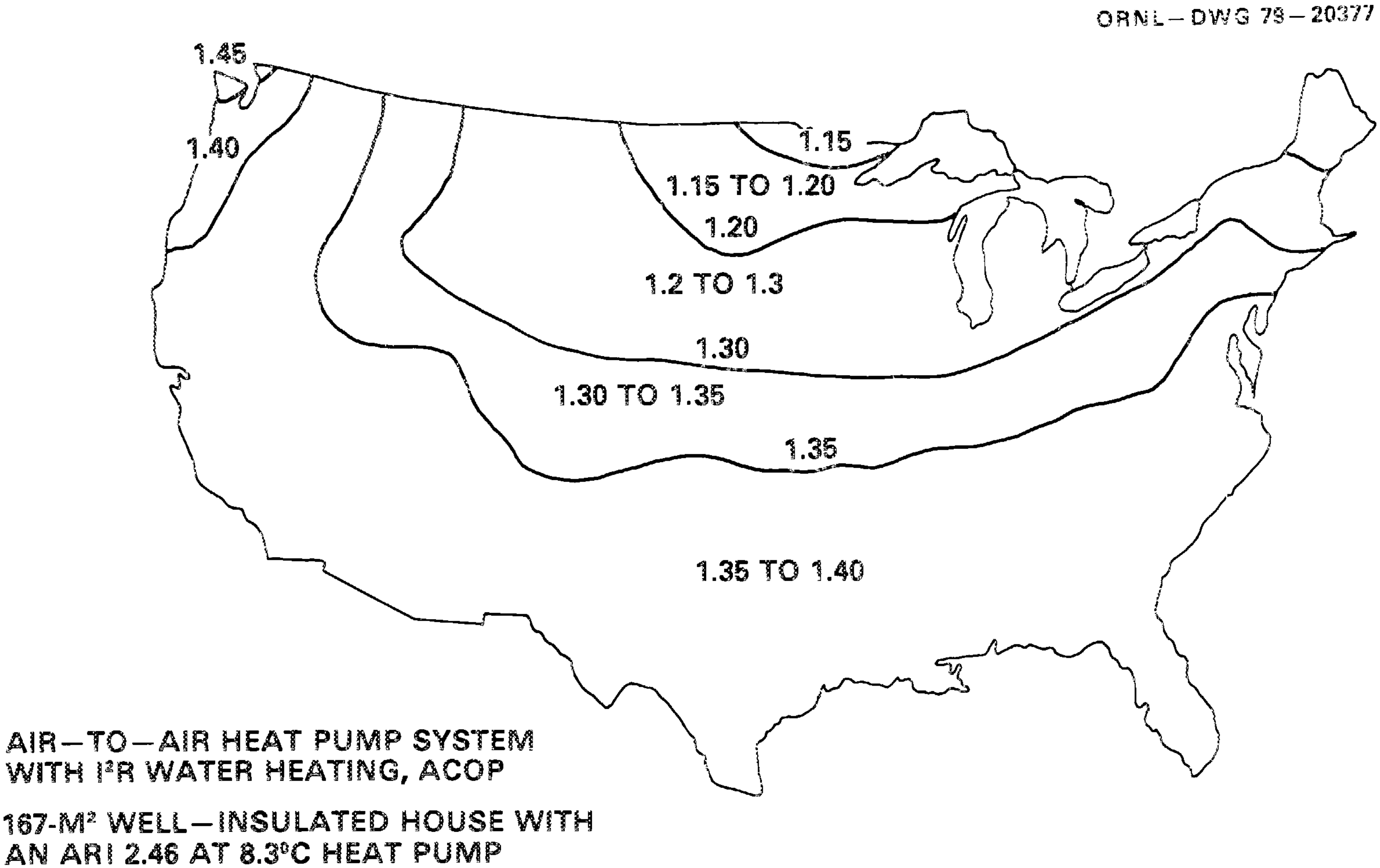

Fig. 7. Estimated annual COPs for a standard air-to-air heat pump and electric resistance water heater.

heat pump will also benefit the ACES, which is, of course, heat pump based.

2. System design and availability. The recent development of a residential ACES design handbook (14) has shown that a generalized design methodology can be written that is applicable nationwide, and that graphs, tables, and approximations can be constructed which provide time-saving computational short cuts without a significant sacrifice in accuracy. Reference (14) contains ACES theory as well as other information necessary to design and size rapidly a wide variety of annual cycle energy systems.

The residential ACES design handbook is predicated on the assumption that the necessary mechanical packages (compressor, heat exchangers, air coil, etc.) are fabricated and available from manufacturers. This is not currently true, although a few companies now produce plate type ice maker heat pumps in small commercial sizes. All of the components necessary for the system can be purchased, however, and a dedicated individual with knowledge of refrigeration technology could, in principle, fabricate an ACES. However, widespread utilization of the ACES concept must await greater participation by manufacturers and distributors.

3. Brine-chiller versus ice-maker. As indicated in Section II, two ice formation systems can be used in the ACES, the brine-chiller and the plate type ice-maker. Early intuitive expectations that the ice-maker would enjoy a thermodynamic advantage over the brine-chiller, because of elimination of the intermediate brine loop and of thinner ice at the heat exchanger, have not been borne out in practice. The two systems operate with nearly equal efficiencies; the evaporation and condensation temperatures under operating conditions are very similar for the two systems. The degradation of performance expected from the thicker ice characteristic of the brine-chiller is compensated for by the larger ice-water surface area for heat transfer as the ice logs grow in diameter and by the lower temperature differential across the walls of the heat exchanger.

Another advantage expected of the ice-maker, this one economical, also failed to materialize. The ice-maker system requires no ice-bin coils, with their attendant material, fabrication and installation costs, and hence should be cheaper. However, to store an equivalent amount of energy the ice-maker requires a bin more than twice the size of the brine-chiller system because (1) the ice packing fraction, or fraction of total bin volume occupied by the ice when most closely packed, is about one-half that of the solid ice formed on the coils, and (2) the heat leakage into the resulting larger bin is enhanced because of the greater area exposed to the warm ground by the walls and floor of the tank. The added cost of the extra storage volume more than balances the cost of coils in the brine chiller system as shown in Fig. 8, which is a plot based on climatic data for 110 U.S. cities of estimated ice-maker initial system costs relative to the brine chiller (the horizontal line) as a function of bin size. For the smaller bin (5-15 m^3), the ice-maker system costs exceed the brine chiller costs by only a few percent, but for larger sizes the disparity may reach 30% or more.

We have operated a prototype brine-chiller system for more than two years at the ACES house in Knoxville. It has performed efficiently and reliably throughout this period. We do not have similar experience with ice-maker systems in the field, although we have pursued their development for a number of years in the laboratory. Recent research has led to a simplified ice-harvesting system (essentially free of energy penalty) that shows promise with respect to reliability and compressor longevity, but extensive trials in the field have not been conducted. However, since there appears to be little or no engineering or economic advantage to the ice-maker system, there is little incentive at this time to pursue its development further.

4. Areas for technical improvements. In spite of engineering progress to date, a number of engineering areas still need development or testing.

a. While experience has been gained with individual components, totally integrated minimum ACES systems (mechanical package, solar panel, storage bin, and system control) have not been assembled or field tested. Minimum systems offer a somewhat greater

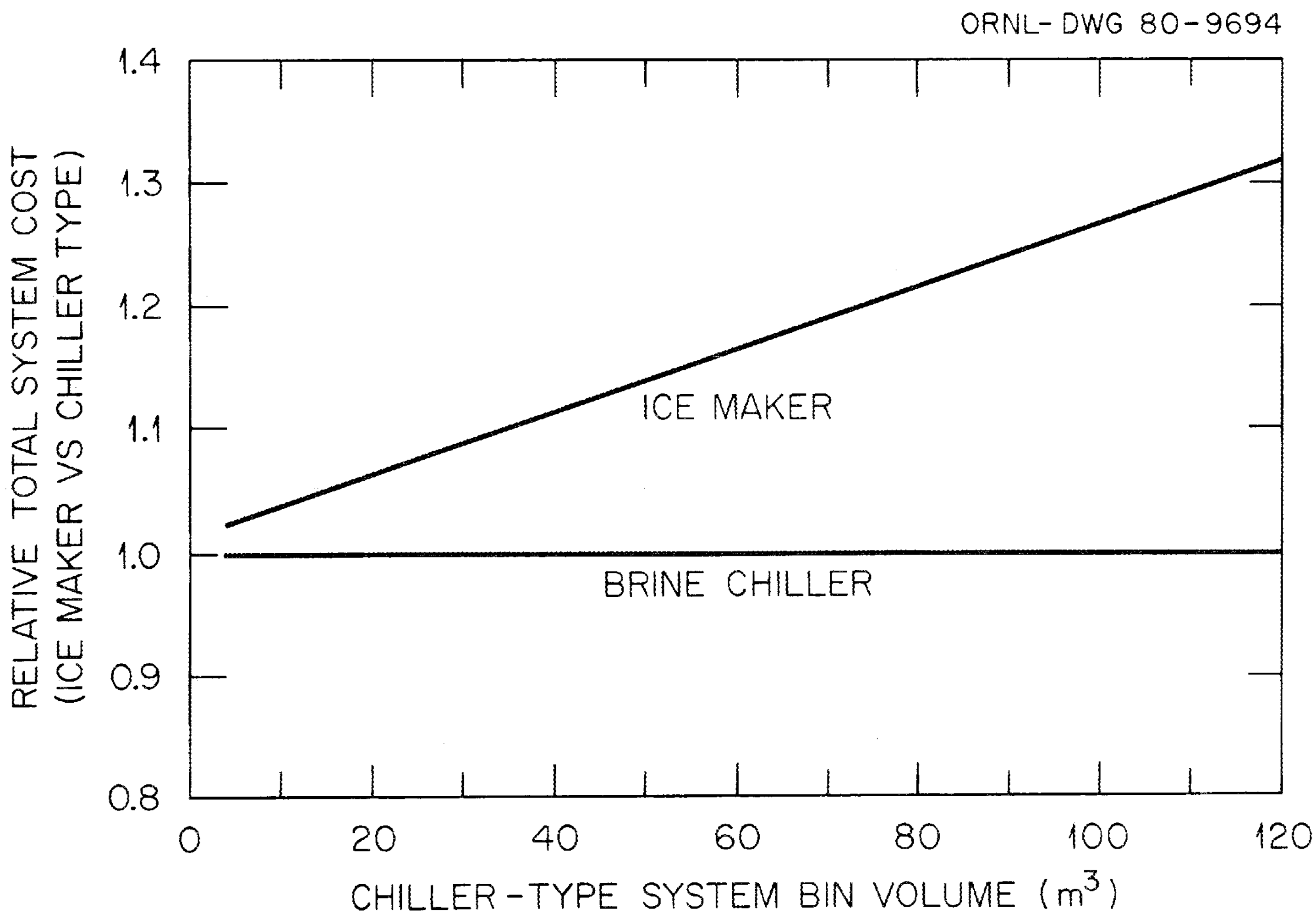

Fig. 8. Relative total system costs, ice maker vs chiller type for residential ACES mechanical package alternatives.

technical challenge than full ACES systems because they place a greater reliance on supplemental sources of heat.

b. Supplemental heat collecting systems, used for ACES operation in northern areas to melt unneeded ice, are in need of further development. Solar sources, the most widely used and studied, are expensive, prone to malfunction, and weather dependent. Optional sources, such as ground or air/water split evaporators, need to be evaluated for possible use in the ACES concept.

c. The ice storage bin is an indispensable component of the ACES, and it is also a major source of the increased capital costs incurred by the system. Construction concepts to lower costs and to provide more efficient use of the energy storage space available need to be developed.

d. Other schemes for decreasing capital and operating costs without undue sacrifice in energy efficiency need to be evaluated. Examples of these are:

   (1) the configuration of the brine-chiller system to use the heat pump to provide energy from the outside air to heat space and/or to melt excess ice when outside temperatures warrant it, and

   (2) the utilization of a small storage tank in conditioned space to store heat in winter and cold in summer, both from nighttime, possibly off-peak, compressor operation.

B. Economic Feasibility

At the present time, the prototype status of ACES, combined with its need for peripheral components (storage bin, supplemental heat source, etc.) not required by conventional systems, makes it initially more costly than conventional systems. The ACES life cycle costs, however, are comparable with those of alternative conventional systems. The ACES benefits make it worthwhile to investigate ways to remove it from prototype status and to lower as far as possible all incremental costs. The benefits foreseen are: to the country, a potentially significant reduction in the use of critical fossil fuels and a commensurate decrease in an unfavorable balance of trade; to the utility, a tool for load management, both seasonal and diurnal, and an opportunity to serve more new customers for a given addition to generating capacity; and, to the homeowner, lower utility bills.

Table 5 gives some estimated mature system costs and energy savings data for New York City, a city in which weather and fuel cost conditions are favorable for ACES. We compare a full ACES to an air-to-air heat pump because the heat pump is more efficient than resistance heating with electric air conditioning. The ACES would not fare as well against systems utilizing natural gas at prices prevailing mid-1979.

Table 5 shows that in New York the full ACES costs $7,935 more to buy and install than the competing heat pump, but saves $882 per year in fuel costs at present prices. Dividing the costs by the savings per year gives a simple payback period of 9 years. Table 6 gives similar information for the same city for the minimum ACES. Here the incremental cost is $7,735, the annual savings $865, and simple payback period again about 9 years. For the minimum ACES, the bin costs are lower, but the solar panel costs are higher. For this geographic area, the full and minimum ACES have nearly identical performance and economic properties.

To achieve a payback period of, say, five years in New York, the full ACES total cost would have to be reduced by about $3,500, assuming the same performance and the same fuel prices, or, alternatively, electricity costs in New York would have to increase to 12¢/kWh. For a minimum ACES, the reductions would have to total about $3,400. The major potentially reducible cost items are the storage tank and coils and the solar panels, which total $6,044 for the full ACES and $5,804 for the minimum. A reduction of about 40% in the projected costs for these items would bring the total cost of the system into a range yielding a reasonable simple payback period.

Table 5. Cost and energy savings data for New York, New York (electricity costs assumed to be 6.65 ¢/kWh)

Item	Full ACES	Air-to-air heat pump	Difference
System Costs:			
Mechanical package	$ 2,616	$2,165	$ 451
Storage tank	2,386	0	2,386
In-bin coils	558	0	558
Solar panels	3,100	0	3,100
Hot water tank	150	150	0
Control system	300	50	250
Auxiliary pumps	0	0	0
Ductwork	1,000	1,000	0
Backup system	90	0	90
Miscellaneous	1,100	0	1,100
Totals	$11,300	$3,365	$7,935
Energy use, kWh/yr	9,400	22,666	13,266
Energy cost, $/yr	625	1,507	882

Table 6. Cost and energy savings data for New York, New York (electricity costs assumed to be 6.65 ¢/kWh)

Item	Minimum ACES	Air-to-air heat pump	Difference
System Costs:			
Mechanical package	$ 2,616	$2,165	$ 451
Storage tank	1,904	0	1,904
In-bin coils	0	0	0
Solar panels	3,900	0	3,900
Hot water tank	150	150	0
Control system	300	50	250
Auxiliary pumps	100	0	100
Ductwork	1,000	1,000	0
Backup system	90	0	90
Miscellaneous	1,040	0	1,040
Totals	$11,100	$3,365	$7,735
Energy use, kWh/yr	9,660	22,666	13,006
Energy cost, $/yr	642	1,507	865

The Energy Tax Act of 1978, as modified by the Crude Oil Windfall Profit Tax Act of 1980, provides for a 40% federal income tax credit on the first $10,000 of costs for solar systems, for a maximum tax credit of $4,000. If a similar credit were applied to ACES, which we believe to be equally as beneficial to energy conservation as solar, the simple payback period, with respect to the air-to-air heat pump, could be reduced to 6.0 years for the full ACES, even if other cost reductions were not made, and assuming the same credits applied to the heat pump. If the credit did not apply to the standard heat pump, the ACES payback period would decrease to 4.5 years. In addition, several states have tax credit programs for conservation measures. California law, for example, provides a 55% income tax credit up to a $3000 maximum for solar system costs. If a similar credit were applied to ACES costs in the New York area, after federal credits, the payback period would drop to 3.8 years if the credit also applied to the standard heat pump, and to a very attractive 2.6 years if it did not. The effect of tax credits on the payback period of the minimum ACES, in the example under consideration, would be almost identical to that for the full ACES.

In addition to simple payback calculations, the economics of any two HVAC systems can be compared for any given period. The result can be expressed by a coefficient of economics (COE), which is the ratio of the present worth of a selected "base" system to the present worth of the system which is to be compared, or "new" system. This is:

$$\text{COE} = \frac{\text{Present Worth, Base System}}{\text{Present Worth, New System}}$$

In this expression, the "present worth" of a system is defined as the total, in today's dollars, of the investment (capital) cost, plus the yearly fuel consumption times the present fuel cost times a present worth factor plus the present worth of all maintenance costs. The present worth factor, given by:

$$\text{PWF} = \left(\frac{1 + i}{d - i}\right)\left[1 - \left(\frac{1 + i}{1 + d}\right)^{N}\right] ,$$

relates the real fuel escalation rate i, the real discount rate d, and the presumed system lifetime N. In essence, the present worth of a system is the number of today's dollars that would be required to prepay all owning and operating costs for the life of the system. In the present calculations, the real cost escalation rate for electricity was assumed to be 0.02, while the real discount rate (or cost of money) is assumed to be 0.04, or 4% above the inflation rate. The presumed lifetime, N, is 20 years. Under these assumptions, the present worth factor is 16.41.*

The base system used in this analysis is a properly-sized air-source heat pump of conventional performance (ARI rating COP = 2.46 at 8.3°C), combined with an electric water heater. This base system is capable of providing the same heating, cooling and hot water services that an ACES can provide. Other base systems could be used.

Two ACES configurations were evaluated with respect to the base heat pump system for 15 representative U.S. cities, assuming power costs of 4¢ and 7¢/kWh and 20-year lifetimes. The first configuration was the full ACES, and the engineering results are given in Table 7, the economic results in Table 8. As expected, the ACES was superior in annual efficiency (ACOP) to the base system in all cities considered. With respect to economics, the full ACES was marginal at 4¢/kWh, but enjoyed a distinct competitive edge at 7¢/kWh.

The second ACES configuration evaluated was one which was sized so as to be most economically competitive with the base system, provided that the ACES could not provide less storage than that associated with a defined "minimum" ACES (see Section II). Because of the paramount importance of first costs, the "most economical" ACES is often also the minimum ACES. In Table 9, minimum ACES ACOPs are somewhat lower than those of the full ACES, but still very much better than those of the base system. The economic status of the ACES has improved somewhat (Table 10), but electricity prices of 4¢/kWh are still too low to encourage consumer acceptance of the concept.

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*A more detailed report on the comparative economics of several HVAC systems is presently under preparation.

Table 7. Calculated Engineering Data for a Brine Chiller Full ACES and an Air/Air Heat Pump System with Electric Hot Water Heating, Each in a Well-Insulated 167-m^2 House.

City	Air/Air ACOP	ACES ACOP	Ice Bin Vol (M^3)	Solar Panel (M^2)	ACES Energy Use (kWh)
Denver, CO	1.32	2.85	38	11	9270
Atlanta, GA	1.36	3.03	68	0	6733
Boise, ID	1.39	2.91	19	73	8711
Indianapolis, IN	1.34	2.96	71	8	8890
Minneapolis, MN	1.23	2.87	40	94	11,660
Kansas City, KS	1.36	3.42	109	0	7424
Syracuse, NY	1.31	2.86	38	45	9881
Oklahoma City, OK	1.37	2.99	84	0	7984
Philadelphia, PA	1.38	2.99	60	10	7984
Knoxville, TN	1.37	3.18	70	0	6437
Nashville, TN	1.35	3.21	81	0	6897
Houston, TX	1.36	2.08	19	0	10,679
Richmond, VA	1.37	3.14	75	0	6670
Seattle, WA	1.44	2.77	12	15	7346
Madison, WI	1.28	2.88	43	57	10,895

Table 8. Calculated Economics for Full ACES. Coefficients of Economics Relative to Air/Air Heat Pump Systems with Electric Hot Water Heating.

City	Est. System Initial Cost[a] $	20-yr Present Worth Power @ 4¢/kWh $	20-yr Present Worth Power @ 7¢/kWh $	Full ACES COE Power @ 4¢/kWh	Full ACES COE Power @ 7¢/kWh
Denver, CO	10,464	18,511	23,076	0.97	1.20
Atlanta, GA	9,539	15,921	19,236	0.90	1.13
Boise, ID	10,460	18,141	22,430	0.92	1.15
Indianapolis, IN	11,542	19,340	23,718	0.91	1.15
Minneapolis, MN	14,084	23,701	29,442	0.96	1.23
Kansas City, KS	12,213	19,049	22,704	0.89	1.15
Syracuse, NY	11,364	19,813	24,678	0.96	1.20
Oklahoma City, OK	10,877	18,080	22,012	0.90	1.13
Philadelphia, PA	10,769	17,973	22,054	0.89	1.11
Knoxville, TN	10,013	16,200	19,370	0.89	1.12
Nashville, TN	10,733	17,222	20,619	0.90	1.14
Houston, TX	6,426	15,398	20,656	1.00	1.13
Richmond, VA	9,925	16,266	19,550	0.90	1.13
Seattle, WA	7,157	13,877	17,446	1.00	1.17
Madison, WI	12,688	21,803	27,168	0.96	1.22

a. Total installed system costs including ductwork. Cost of air/air heat pump reference system assumed to be $3032.00.

Table 9. Calculated Engineering Data for a Brine Chiller Minimum ACES and an Air/Air Heat Pump System with Electric Hot Water Heating, Each in a Well-Insulated 167-m^2 House.

City	Air/Air ACOP	Min ACES ACOP	Ice Bin Vol (M^3)	Solar Panel (M^2)	ACES Energy Use (kWh)
Denver, CO	1.32	2.69	17	16	9815
Atlanta, GA	1.36	2.33	11	6	8748
Boise, ID	1.39	2.66	17	25	9541
Indianapolis, IN	1.34	2.54	18	27	10,377
Minneapolis, MN	1.23	2.76	27	148	12,120
Kansas City, KS	1.36	2.43	17	17	10,455
Syracuse, NY	1.31	2.74	21	72	10,338
Oklahoma City, OK	1.37	2.27	14	7	10,533
Philadelphia, PA	1.38	2.58	17	30	9249
Knoxville, TN	1.37	2.38	14	15	8597
Nashville, TN	1.35	2.35	13	11	9406
Houston, TX	1.36	1.97	6	1	11,247
Richmond, VA	1.37	2.33	11	8	8978
Seattle, WA	1.44	2.73	12	15	7346
Madison, WI	1.28	2.72	24	93	11,529

Table 10. Calculated Economics for Minimum ACES. Coefficients of Economics Relative to Air/Air Heat Pump System with Electric Hot Water Heating.

City	System Initial Cost[a] ($)	20-yr Present Worth Power @ 4¢/kWh ($)	20-yr Present Worth Power @ 7¢/kWh ($)	Minimum ACES COE Power @ 4¢/kWh	Minimum ACES COE Power @ 7¢/kWh
Denver, CO	9299	17,705	22,538	1.01	1.23
Atlanta, GA	7089	14,795	19,102	0.97	1.14
Boise, ID	8991	17,217	21,915	0.97	1.17
Indianapolis, IN	9295	18,069	23,178	0.98	1.18
Minneapolis, MN	15,310	25,229	31,197	0.91	1.16
Kansas City, KS	8754	17,579	22,727	0.97	1.15
Syracuse, NY	11,319	20,068	25,158	0.95	1.18
Oklahoma City, OK	7965	16,842	22,028	0.97	1.13
Philadelphia, PA	9036	17,070	21,624	0.93	1.13
Knoxville, TN	7688	15,293	19,527	0.94	1.11
Nashville, TN	8059	16,196	20,827	0.95	1.13
Houston, TX	6103	15,449	20,987	0.99	1.11
Richmond, VA	7174	15,030	19,451	0.97	1.14
Seattle, WA	7426	14,210	17,827	0.96	1.15
Madison, WI	12,891	22,421	28,098	0.94	1.18

a. Total installed system costs including ductwork. Cost of installed air/air heat pump reference system assumed to be $3032.00.

For comparison purposes, the performance and economics of six different electrically based systems were calculated for a single city, Knoxville, Tennessee, again at power costs of 4¢ and 7¢/kWh. The systems compared were (1) electric furnance, electric air conditioning and electric resistance (I^2R) hot water; (2) the base system, which was an air/air heat pump with I^2R hot water; (3) advanced air/air heat pump with I^2R hot water;(4) present-day high performance air/air heat pump with desuperheater hot water; (5) minimum ACES; and (6) full ACES. The annual COP and electrical energy consumption of each of these systems are listed in Table 11. The two ACES configurations consume less electricity, on an annual basis, than any of the other systems, while delivering the same house loads.

The economic evaluation of the six systems is given in Table 12. At 7¢/kWh, the two ACES configurations are economically superior, on a life-cycle basis, to all other electrically driven systems considered. The advanced air/air heat pump with a desuperheater will have a COE of about 1.16, making it an economically attractive alternative. However, it is anticipated that the COE of the ACES can be improved by reducing first costs. The ACES will continue to save appreciable energy even over this advanced system, which will have an estimated annual COP of about 1.80.

Thus, with the ACES, the initial costs are large and the payback periods are relatively long. However, the annual benefits beyond the payback period will be appreciably greater than for the alternative system considered, and the cumulative benefit over the life of the system is for ACES also much greater. In addition, even in the life cycle cost analyses made above, the ACES is perhaps being penalized unjustly. No credit is given for "salvage" value. The ice storage bin accounts for about 30% of the incremental costs for the ACES, and was assumed to have a lifetime of 20 years. In practice, however, the bin will last as long as the house - it would be made of steel-reinforced concrete and insulated with high grade material - and it seems reasonable to assume that energy storage will be as valuable in twenty years as it is today.

V. COMMERCIAL ACES

The applicability of ACES in large commercial buildings depends more upon the design and use of the particular building than it does upon its

Table 11. Estimated energy consumption of HVAC systems (Knoxville, Tennessee)[a]

	Type of System	ACOP	Annual Energy Usage (kWh)
1.	Electric furnace, electric air conditioning, I^2R hot water.	1.11	18,400
2.	A/A heat pump (2.46)[b], I^2R hot water.	1.37	14,928
3.	A/A heat pump (3.20)[b], I^2R hot water.	1.54	13,273
4.	A/A heat pump (2.75)[b], desuperheater hot water.	1.62	12,669
5.	Minimum ACES, brine chiller type.	2.38	8,557
6.	Full ACES, brine chiller type	3.18	6,437

a. Well-insulated, 167-m^2 single-family residence with annual loads of 8,942 kWh, 6,835 kWh and 4,710 kWh for space heating, space cooling and water heating, respectively.

b. ARI rated steady-state COP at +8.3^{o}C.

Table 12. HVAC system relative 20-year economics (Knoxville, Tennessee)[a]

Type of System	System Cost ($)	20-Year Present[c] Worth ($) at Power Costs of 4¢/kWh	7¢/kWh	Coefficient of Economics (COE) at Power Costs of 4¢/kWh	7¢/kWh
1. Electric furnace, electric air conditioning, I^2R hot water.	2933	15818	24878	0.91	0.87
2. A/A heat pump (2.46)[b], I^2R hot water.	3032	14376	21727	1.00	1.00
3. A/A heat pump (3.20)[b], I^2R hot water.	3492	13749	20284	1.05	1.07
4. A/A heat pump (2.75)[b], desuperheater hot water.	3422	13537	19778	1.06	1.10
5. Minimum ACES, brine chiller type.	7688	15293	19526	0.94	1.11
6. Full ACES, brine chiller type.	10013	16200	19370	0.89	1.12

a. Well-insulated 167-m^2 single-family residence with annual loads of 8,942 kWh, 6,835 kWh and 4,710 kWh for space heating, space cooling and water heating, respectively.

b. ARI steady state COP rating at +8.3°C.

c. The 20-year present worth values include maintenance costs, and a present worth factor of 16.41 is assumed.

geographical location. Because of high internal loads, in most large office buildings, the cooling loads are higher than the heating loads. This circumstance, coupled with the disproportionately low requirement for hot water, as compared to residential installations, greatly reduces the possibility for interseasonal transfer of energy in large amounts. For special applications, however, such as motels, hotels, restaurants, and hospitals, the use of ACES may be very attractive.

To our knowledge, the only commercial-sized installation of a heat-pump based HVAC system with enough ice storage to be called an ACES is the VA's Nursing Home in Wilmington, Delaware (see Section III B). Even this system, which barely qualifies as a "minimum" ACES, has not been in operation long enough to generate any real data with respect to energy conservation. There are, however, reasons to conclude that ACES in commercial buildings will be a viable technology in those cases where building usage and climatic factors combine to give a favorable balance of heating and cooling loads. These reasons are discussed on the following pages.

A. Technical Considerations

The Honeywell economic study (12) indicates that the ACES can save primary fuel usage in a typical 5574-m^2 office, as shown in Table 13. Certain other types of buildings, such as hospitals, hotels, motels and restaurants, should do even better, because they generally have appreciably higher hot water loads, and thus better loads balance.

Table 13. Annual primary fuel usage[a] (in GJ) for different HVAC systems in a typical 5574-m^2 office building.[b]

HVAC System	Philadelphia	Atlanta	Minneapolis
Full ACES	2,448	2,680	2,026
Minimum ACES	3,049	2,886	2,553
Gas heat & hot water, electric AC	3,280	3,320	2,760
Oil heat, electric AC & hot water	3,102	3,218	2,617
Resistance heat & hot water, electric AC	4,009	4,389	4,220

[a]Assumes 30% efficiency in generating and delivering electricity to building.

[b]Derived from Reference 12.

HVAC systems for large buildings are custom designed and assembled by contractors accustomed to dealing with sophisticated systems, so an ACES should present no insurmountable problems to them. Some major components of the mechanical package, such as compressors, pumps, refrigerant valves and the like, are presently available in a number of sizes from commercial manufacturers, but the outdoor air coils are not. The commercial ACES design handbook, now under development, will lead the A/E to the appropriate configuration of systems, and once the ACES is installed and operational, the professional building staff will be available to keep the system in operating condition.

B. Economic Considerations

Since the components necessary for commercial-sized ACES are, in the main, standard pieces of equipment, they are available from commercial manufacturers (Carrier, Trane, York, and others) at competitive prices. In addition, since both the heating and cooling outputs of the ACES heat pump are utilized, total system costs may be lowered because it is not necessary to install one system for heating and another for cooling. Large users of electricity, such as building operators, can take advantage of the ACES' capacity to shift loads (both heating and cooling) to off-peak, and thus, to times of lower energy costs. They can also drastically reduce the impact of demand charges by operating a system of constant capacity and efficiency, with little need to resort to high-demand back-up systems during periods of unfavorable weather. Because of its energy storage features, the ACES can be used effectively to manage a building's internal loads, moving waste heat from one area for use as needed at another time or place.

An important conclusion of the Honeywell study of ACES economics (Ref. 12) is that some configurations of commercial-sized ACES are economically competitive with conventional systems at today's prices, and that competitive position will improve with time. The reader is referred to the Honeywell report for details.

VI. FUTURE POTENTIAL FOR ACES DEVELOPMENT

The engineering results presented in Section IV.A.1. lead to the conclusion that few, if any, technological alternatives show as much promise as ACES for future energy conservation in the heating and cooling of buildings. The Department of Energy, through its Office of Buildings and Community Systems, has, in addition to its ACES program, undertaken a vigorous program for the development of other heat pump systems. In the area of electric heat pumps, the goals for these are increases of 25 to 40% in the heating SPFs over those currently obtained in standard practice. The ACES would, however, increase annual efficiencies by two or three hundred percent over competing electric systems, including the new generations of heat pump systems that do not provide storage. Most future improvements in standard heat pump efficiency and reliability, such as better compressor design, gas-fired or Stirling-engine-driven configurations, or the use of other than the Carnot thermodynamic cycles, will also benefit the ACES.

The fact remains, of course, that strong motivation must exist before a society will adopt a new technology in place of an old and familiar one. The strongest and most persistent motivating force appears to be money. At the present time, heat pump systems offer a life-cycle savings of about 20% over electric resistance systems, and appear to be receiving increased public acceptance. So too, the ACES, not withstanding its "good for the nation" advantages in the saving of critical fuels, must carry definite economic advantages as well.

Closer approaches to the absolute efficiency limits of the thermodynamic cycles upon which heat pump technology is based will be small and only painfully derived. Future economic returns for the ACES can be enhanced appreciably if losses of usable energy can be reduced, or if system front-end (capital) costs can be substantially decreased. At present energy prices, it appears that front-end costs should be reduced even if it entails some sacrifice in operating efficiency. The following sections describe areas in which research and development along these lines are contemplated.

A. Improvements in System Design

It is anticipated that ACES will benefit from any significant improvements in the thermodynamic efficiencies of refrigeration equipment, but it is also possible that better ways to configure and apply the ACES concept can be found. Computer programs are now available which can model ACES performance, and determine its relative economics. These programs will be used to identify building types, system control strategies, and alternative system configurations that will maximize both energy conservation and economic attractiveness for ACES in a given geographic location.

One such possibility is the configuration of the ACES to take greater advantage of time-of-day rates should they become more common. Under present design, the full ACES can contribute to utility load leveling on a seasonal basis, and can be used for summer diurnal load management after the stored ice is depleted. Recent analyses of the economics of diurnal storage have indicated, however, that the procedure has its drawbacks. Each day enough extra ice must be made to compensate for both the (significant) heat leakage from the surrounding earth into the large storage bin and for the heat losses from the compressor, the pumps, and the fan motors into the conditioned space. This results in practice in a daily cooling COP less than that of a conventional central air conditioner. However, by the inclusion of a small storage tank, within the conditioned space, two advantages might accrue. If, or when, time-of-day rates become available, the compressor could be operated during the winter-time off-peak hours to store enough hot water, from the high-side output of the heat pump, to provide all daily space and water heating needs. Any heat leakage from the small bin would be into conditioned space, where it is needed, and no energy would be wasted in storage. The ice by-product from compressor operation would be stored, as before, in the large bin for summer use.

In the summer, after the stored ice in the large bin is depleted, the compressor will again operate off-peak, and the cold-side output would be stored in the form of ice in the small bin for air conditioning as needed. As in previous summer load management schemes, the high side output, if not needed for domestic hot water, would be rejected to the outside air. Again, since the small tank will be in conditioned space, any heat transfer from the house into the bin to melt ice will result in cooling the house, a desired condition.

This diurnal load leveling scheme will probably be of economic benefit to the homeowner only if time-of-day rates with significant on-peak/off-peak differentials come into being. Although at the present time such rates are far from common, they may become far more prevalent if the cost of new generating capacity by the utilities continues to increase as it has in the last several years.

B. Changes in Storage Tank Design

Storage tanks are a necessary component of the ACES, but storage needs differ in the winter from those in summer, and they differ from region to region as well. In the winter, unfrozen water must be available in the tank to serve as a heat source, and a smaller tank will suffice to provide the necessary energy if the tank is designed to enhance ground heat flow through the walls to melt ice. In the summer, however, the retention of ice to provide cooling becomes the major consideration. Hence, in summer, a well insulated tank is needed to prevent the melting of ice by ground heat. The two needs, heating and cooling, are opposed as far as the insulating qualities of the tank wall are concerned. To date, no effort has been directed at modeling and testing an underground uninsulated tank, containing within it a well-insulated smaller bin. The uninsulated tank could, perhaps, be coupled with additional ground heat input systems to further decrease the needed volume (see below).

C. Development of Supplementary Heat Sources

The purpose of the supplementary heat source system is to supply environmental energy to the bin at a rate adequate to keep the accumulated ice from exceeding bin capacity. ACES work to date on the heat input system has been restricted to the evaluation and field testing, at one location, of unglazed solar/convector panels. These panels and their associated plumbing also constitute a major part of the incremental costs of the ACES, and alternative environmental energy collection systems may be economically more viable.

Ground heat is a potential energy source that appears to offer several advantages, among which is the fact that ground temperatures a few feet below the frost line are relatively constant, independent of time of day and cloud cover, and vary little with season of the year. A number of possible ground source systems need to be evaluated, including (1) the bin-within-bin, described above, where the uninsulated bin walls and floor act as the collector, (2) interruptible soil-to-bin conductive heat pipes, (3) pumped fluid heat exchange through horizontal pipes buried well below the frost line, and (4) pumped fluid heat exchange through vertical pipes.

Another alternative that might be used to reduce capital costs, although causing an increase in purchased energy use, would be to make fuller use of the compressor in the ACES package. Whereas in the present ACES designs, the compressor operates only to pump energy from the tank for space heating or domestic hot water production, in the "multi-use-heat pump system" the compressor could be operated in any one of the following modes, depending upon the outdoor temperature:

(1) to pump heat from the bin to conditioned space or domestic water;

(2) to pump heat from exterior air to conditioned space or domestic water;

(3) to pump heat from exterior air to the bin to melt out excess ice; and

(4) to pump heat from conditioned space to outside air (air conditioning), when stored ice has been depleted and cooling is needed.

In many parts of the country, mode (3) might eliminate the need for solar panels or for other supplemental heat systems. Mode (4) would provide a more economical method of cooling after ice depletion than is now used (i.e., the nighttime generation and storing of chilled water or ice in the big bin for later use), yet preserve the load management capability of the system for use in regions where off-peak electrical power rates are available. With a brine-chiller system, the above modes could be realized without reversing the flow of heat pump refrigerant, necessary in the conventional heating/cooling heat pump configuration.

D. Development of a Dual Evaporator Heat Pump for ACES Application

An ACES configuration that shows promise for reducing bin size, and thus first costs, is being developed under an ACES program subcontract at the Engineering Experiment Station of the University of North Dakota, Grand Forks. This configuration utilizes a dual, air-water, evaporator; some of the energy needed for space and water heating during the winter is extracted from ambient air, by means of an outdoor evaporator, on those days warm enough to make this mode of operation more efficient than the process of extracting heat from the 0°C ice bin. At the University, an either-or (parallel) configuration of evaporators was tested first and found to be unsatisfactory because the refrigerant values available for residential-sized systems could not prevent refrigerant migration into the colder evaporator. These refrigerant inventory problems led to tests on series evaporators, wherein the refrigerant is subcooled in the first evaporator and evaporated in the second. The order of evaporators is reversed when the system is switched from air to water source, or vice versa.

Experimental work is continuing on this ACES scheme; it is being field tested in a home in Crookston, Minnesota during the winter 1979/80.

VII. CONCLUSIONS

Among systems using conventional fuels, the ACES is the most energy-efficient system yet demonstrated to provide year-round heating, cooling, and domestic hot water services for residences. It is at least twice as efficient, on an annual basis, as an air-to-air heat pump, and as heat pump technology improves, most of the improvements can be carried into ACES technology as well. Although it has not yet had an extended operational history, the ACES appears to be a reliable system, compatible with today's homes and lifestyles. Long term reliability should be at least as good as that for heat pump systems, for the ACES is subjected to less extreme conditions during operation.

As perceived by the homeowner, the ACES has, at present, three main drawbacks: (1) the need for a storage tank of appreciable volume; (2) the need for solar panels or some other supplemental heat source; and (3) high capital costs. The first cannot be eliminated; indeed, the storage and interseasonal transfer of energy is the fundamental basis of the ACES concept. However, the impact of the tank on aesthetics and inconveniences to the homeowner can be minimized by proper design and placement. Ever though it is cheaper to place the tank in the basement, we do not encourage this. First, it takes space that might be of value for family use, and second, it might lead to moisture or condensation problems. But tanks can easily be located in out-of-the-way places, such as under patios, driveways, garages or carports, or can be buried in the yard and landscaped over. The only requirements are that the tank should be insulated, not too far from the equipment room, and the interior should be accessible for service and inspection.

Solar panels or other supplemental heat sources are needed in all areas of the country in which heating needs exceed to an appreciable extent the cooling needs. We have indicated in the text that alternatives to solar panels exist, and that these are being, or should be, evaluated and tested. The elimination of solar panels will probably cause a decrease in system cost as well as decreasing an aesthetic problem for the architect or homeowner.

The third perceived drawback, higher capital costs, is not so easily dismissed. The ACES does cost more, and it will continue to do so. Appreciable reductions in front-end costs appear possible, but even with the most optimistic of these, simple payback periods will not soon reach the three to five year periods sometimes assumed necessary, except perhaps in a very few areas with restricted access to natural gas and very high electricity costs.

But the ACES <u>can</u> save appreciable amounts of non-renewable fuels if the technology gains widespread acceptance, and because of this it can play a significant role in energy conservation in the future. Every increase in the real cost of energy will bring ACES a little closer to the point that economics will favor its adoption. Every utility district that institutes time-of-day rates that really reflect the incremental cost of on-peak fuels and of new generating capacity will make the ACES economically more viable. And finally, as in the case of solar, the government can hasten the day when ACES will survive on its energy conservation merits alone, by providing financial incentives in the form of tax rebates or the like to nurture the implementation of this high cost, but high rewards technology.

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