CONF-800524--2

MASTER

THE ANNUAL CYCLE ENERGY SYSTEM CHARACTERISTICS AND PERFORMANCE*

L. A. Abbatiello
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

DISCLAIMER

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

To be published
in the proceedings of the
International Congress on Building Energy Management
Povoa de Varzim, Portugal
May 12-16, 1980

By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering the article.

*Research sponsored by the Office of Buildings and Community Systems, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EB

DISCLAIMER

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

DISCLAIMER

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

THE ANNUAL CYCLE ENERGY SYSTEM CHARACTERISTICS AND PERFORMANCE*

L. A. Abbatiello**

**Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

The Annual Cycle Energy System (ACES) provides space heating, air conditioning, and domestic water heating while using substantially less energy than competing systems providing the same services. The ACES is based on an electrically driven, unidirectional heat pump that extracts heat from an insulated tank of water during the heating season. As the heat is extracted, most of the water freezes, and the stored ice provides air conditioning in the summer.

A single-family residence near Knoxville, Tennessee is being used to demonstrate the energy conserving features of the ACES. A second similar house, the control house, has been used to compare the performance of the ACES to both an electric resistance heating and hot water with central air conditioning system and an air-to-air heat pump system. The results of the first year's operation from November 1977 through mid-September 1978 showed that the ACES consumed 9012 kWh of electricity while delivering an annual coefficient of performance (COP) of 2.78. The control house consumed 20,523 kWh of electricity while delivering an annual COP of 1.13.

The second annual cycle was started on December 1978. The ACES was compared with an air-to-air heat pump during this period.

During the ice storage portion of this test year, December 1, 1978 to September 1, 1979, 5705 kWh of electricity was used by the ACES, compared to 12,014 kWh for the control house. The respective COPs are 1.40 for the control house with the heat pump and 2.99 for the ACES house during this period. Annual energy consumption for the test year was 6597 kWh and the annual COPs were 1.41 for the control house and 2.81 for ACES. ACES is achieving its anticipated performance.

This paper describes and defines the ACES concept and its general engineering performance as compared to conventional HVAC systems.

*Research sponsored by the Office of Buildings and Community Systems, U.S. Department of Energy under contract W-7405-eng-26 with Union Carbide Corporation.

KEYWORDS

Seasonal energy storage, latent heat cooling, low temperature thermal storage, constant capacity heat pump operation, Annual Cycle Energy System (ACES), diurnal storage.

INTRODUCTION

The Annual Cycle Energy System (ACES) project, sponsored by the U.S. Department of Energy, is designed to provide a technology that not only helps to meet the demand for electrically-based heating and cooling but does so at substantially higher efficiencies than are obtainable with alternate systems. The ACES provides space heating, air conditioning, and domestic water heating and is suitable 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, or at other times if needed. Thus, the water's heat of fusion is available as a heat source in winter and as a heat sink during periods of cooling needs. Since both the heating and cooling outputs of the heat pump are used, the resulting annual coefficient of performance (COP) is high. A simplified schematic of a typical system is shown in Fig. 1.

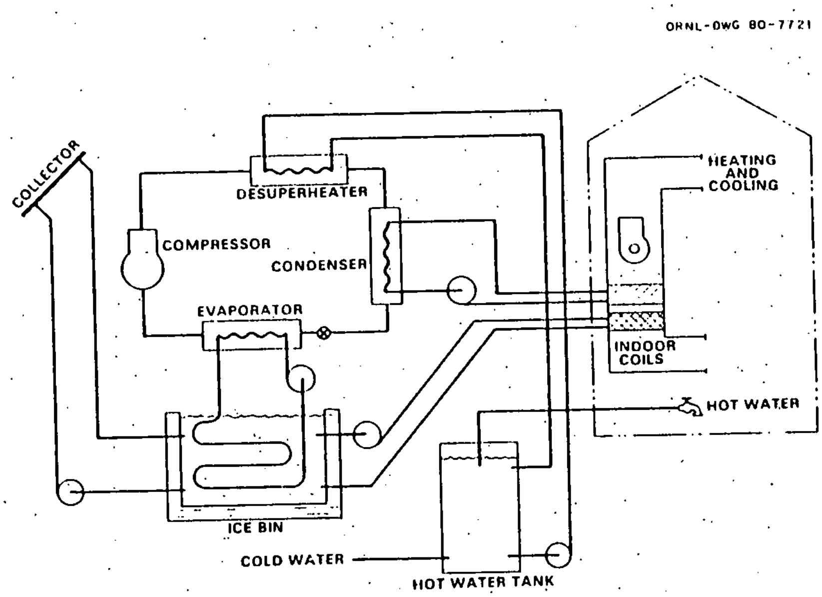

Fig. 1. Simplified schematic of ACES.

The ACES achieves maximum energy conservation in applications where the annual ice production 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 annual weather and the building usage. Provision must then be made in the ACES design to compensate for imbalances in the ice-bin heat flows. This can be done through the use of an auxiliary solar panel which provides for either the collection of heat for melting excess ice, or for rejecting heat from the ice bin to the environment when this is required during the summer.

In addition to providing high annual COPs, the ACES extends the range of heat pump feasibility to more northern climates because the heat source, the water in the storage bin at 0°C, is decoupled from the weather. That is, the system operates in the heating mode at constant efficiency and with constant capacity regardless of how low the outside temperature may drop. Thus, recourse to backup heating, e.g., electric resistance, during very cold periods is not necessary. These advantages accrue whether or not there is a need for air conditioning, but if there is not, any ice accumulated must be melted.

DEFINITIONS

The ACES concept allows the designer flexibility and choice with respect to the method of ice formation and the bin energy storage capacity. It is useful to define some terms which describe the various choices.

Ice Formation Methods

The ACES may employ either of two ice formation methods: (1) a submerged water-to-brine heat exchanger located in the ice storage bin to freeze the water surrounding the heat exchanger coils; or (2) a plate-type ice maker, which freezes water directly on the evaporator plates of the heat pump and periodically harvests the ice into the bin. Each offers certain advantages. With the brine chiller ACES, because of a higher ice packing density in the storage bin, bin volumes of approximately half the size necessary for an ice maker ACES can be used. The brine chiller ACES also has simpler refrigeration circuitry; a lower refrigerant inventory; and provides a non-freezing energy transfer fluid, the brine, for transporting heat from supplemental sources such as a solar collector panel into the storage bin. The ice maker ACES, on the other hand, eliminates the ice bin heat exchanger with its attendant costs and need for field crew installations, and makes modular design easier. The brine-chiller appears to offer significantly better reliability and economics in most applications and is therefore used as the base case for ACES designs.

Ice Bin Storage Capacity

The ACES transfers energy between the seasons of the year by storing the heat that is removed from the house during summer air conditioning operation, and then delivering the stored heat back to the house in the winter to provide space or water heating. The summer heat melts ice contained in a storage bin and the water is refrozen in the winter as the heat pump extracts energy from the bin to meet the heating needs of the house. To achieve full interseasonal energy transfer, the ice storage bin must have enough capacity to store all of the ice that can be produced during the heating season or all of the ice needed for summer air conditioning, whichever is smaller. A system with a bin of this size is defined as a full ACES. A full ACES design is characterized by an ice exhaustion date which is late in summer. In other words, stored ice cooling is contributing the maximum possible toward satisfying the cooling loads. This is graphically represented by Fig. 2.

Systems with smaller bins than those corresponding to a full ACES can, of course, be fabricated. If this is done, the amount of ambient heat that must be collected from the environment to melt surplus ice, as well as the amount of supplemental cooling that must be provided, become greater. For practical reasons, the

ORNL-DWG 79-20376

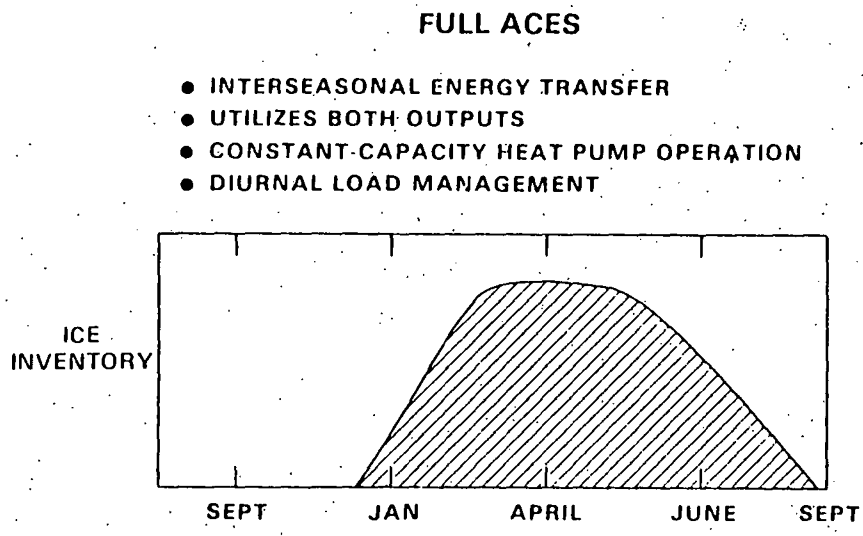

Fig. 2. Full ACES major characteristics and ice inventory history.

smallest bin that should be considered for an ACES should have a thermal capacity sufficient to allow at least two weeks of heat pump operation during the coldest month of the year without resort to ambient heat collection. A system with a bin of this size is defined as a minimum ACES. The minimum ACES is a compromise to reduce capital costs of the system, but it also reduces the energy conservation potential of the system.

The ice inventory history of a typical minimum ACES is shown in Fig. 3. The stored ice contributes a much smaller percentage of the building's cooling needs. In northern U.S. locations, the definitions of minimum and full ACES will converge resulting in only one practical bin volume which satisfies all cooling needs (i.e., full ACES). In southern U.S. locations it is not possible to produce much ice and bin volumes again approach each other. Small bin volumes in the south do not yield significant interseasonal transfer, therefore one can define these as being best characterized as minimum ACES even though they utilize all the ice which can be produced.

Ice storage can be used with systems designed to accomplish only summer air conditioning peak load management. This type of diurnal system does not qualify as an acceptable energy conserving system and we define this design as a summer load management system.

ACES OPERATIONAL EXPERIENCE

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 utilizes an ACES for heating, cooling, and domestic hot water production. The second building is an identical residence with the same orientation, differing only in that its heating and cooling are provided by a standard, commercially available air-to-air heat pump system, and its hot water is provided by conventional electric resistance heating. The two buildings are well instrumented to show direct comparison of different systems.

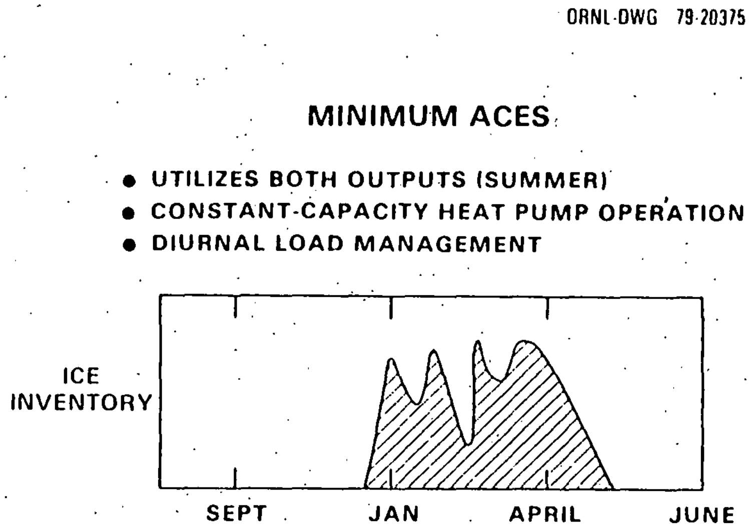

Fig. 3. Minimum ACES major characteristics and ice inventory history.

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 terminated 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 very good approximation to a full year's run. Operational performance was satisfactory during the first year, with only minor control failures causing the system to be unoperative for about two days during the entire test year.

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 ice-bin coil system was added. 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 was operated on resistance heat in the heating mode to establish base loads for the two houses. The heating loads of both houses agreed within a few percent. During the 1978-79 cycle, the control house was operated with 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 Performance

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. For the period November 1, 1977, to September 18, 1978, the ACES delivered a total of 43.0 GJ space heating, 20.9 GJ water heating, and 26.2 GJ space cooling. For this period, purchased energy was 9,012 kWh, with a resulting demonstrated annual COP of 2.78. For the same period, the system in the control house delivered 43.6 GJ space heating, 15.6 GJ water heating, and 24.5 GJ space cooling. The system was operated on electric resistance for both space and water heating, with cooling provided by a central air conditioner. The purchased energy requirement was 20,523 kWh, with a resultant annual COP of 1.13.

The maximum inventory of ice, 51,700 kg, was reached on April 1, 1978, and it provided all of the cooling needs until July 27, 1978. Up to the point that the ice inventory was depleted, the cumulative ACES COP for heating, cooling, and hot water was 3.17. To maintain cooling capacity 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/convector 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, however, it soon became apparent that the ACES in this mode of operation, in this house at this time, was less efficient that 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 controls of the system were reset so that the bin temperature stabilized very near the apparent ground temperature, about 9°C. The mechanical room was also vented directly to the outside to reduce the internal load. This improved the efficiency, but the system continued to operate below expectations, and by the end of the annual cycle the cumulative COP had fallen to 2.78.

<u>1977/1978 Weather Conditions</u>

The performance of the ACES depends on the thermal loads that the system must deliver each year. These loads are a direct result of the interaction of the weather with the building's thermal envelope, and it is appropriate to characterize qualitatively the severity of the test-year weather and to compare it with an average weather year.

Even though the TECH complex is fully instrumented to measure local climatological conditions, for long-term comparative purposes it is more convenient to use the Knoxville, Tennessee, McGhee-Tyson Airport, station 13891, weather data compiled by the National Climatic Center. The McGhee-Tyson Airport station is located within five miles of the TECH complex and has collected historical records for many years.

The severity of the heating season determines the heating loads that the system must deliver, the energy that is consumed during heating, and the production of ice that results from delivery of the heating requirements. The maximum amount of energy available for interseasonal energy transfer is limited by either the heating demands, or, if ice production exceeds bin capacity, by the bin capacity.

<u>Heating season</u>. During this test year, ice production almost exactly equaled bin capacity. The qualitative and quanitative characteristics of the weather leading to these results are described in the following paragraphs.

November 1977 was a relatively mild month, which produced only a slightly higher than normal heating demand. January and February 1978 were both severely cold months, each within the top two highest heating-demand months of the last 20 years. Collectively, these two months were the coldest two consecutive months on record for the last 20 years. January and February 1978 were recorded as requiring 1079°C-days of heating, and the record for a previous two-month period was 986°C-days for January and February 1970. The remainder of the test year heating season moderated to nearly normal conditions.

The total seasonal heating degree-days was 2104°C-days for the November 1977 to May 1978 heating season; this compares with the normal 1835°C-days anticipated for the November to May period, based on the National Climatic Center long-term average. November 1977 to May 1978 was exceptionally cold; it was the fourth coldest winter of the last 20 years.

The severe winter required the ACES to deliver far more heating than was expected on the basis of average yearly requirements. For the test year, the system should have produced an ice inventory greatly exceeding the bin capacity and requiring panel operation to melt excess ice. Bin capacity was not exceeded; because of the excessive heat leakage from the uninsulated ice bin, the bin was filled only to its maximum design capacity.

Cooling season. The test-year cooling season can be characterized as nearly normal as judged by the National Climatic Center's tabulation of cooling degree-days. Each month of the summer exhibited only slight deviations from the long-term cooling degree-day average. The only exception was September 1978, which remained hotter somewhat longer than usual. However, cooling needs were normal up to mid-September when the experiment was terminated; therefore, average cooling can be assumed even for this month.

The cooling season exhibited a total of 896°C-days as compared with 869°C-days for long-term average weather conditions. Cooling should be considered as having been average for the year.

1978/1979 Season Performance

The experiences of the 1977/78 season had indicated some areas in which system upgrading would pay significant performance dividends. The most important improvement was to increase the level of insulation in the bin, both to reduce ice loss and to make the night heat reject mode more efficient. In the control house, the heating was accomplished with the air-to-air heat pump, rather than with the resistance heating alone as used in the previous year. 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, and ran until September 30, 1979. For the period, 6597 kWh of electricity had been used by the ACES, compared to 12,861 kWh used by the control house. The respective COPs were 2.81 and 1.41. Performance to September 30, 1979, is summarized in Table 1. Equipment modifications between the first and second test year resulted in a 10% reduction in steady-state performance. This final design results in a lower-priced system.

The modified system in the ACES house operated efficiently and reliably, although some early problems with control caused about two weeks of outage in December. Heat leakage into the bin at 0°C was reduced to about 26.4 MJ/day, down from 69/MJ day from the year before. The maximum ice inventory was 54,400 kg, and it provided all of the house cooling until August 29, 1979.

1978/1979 Weather Conditions

For this year's heating season the months of December and March produced lower than normal heating demands. January and February, however, were much colder than normal, equaling the January-February 1970 period in heating demand with 984°C-days. April was nearly normal with only a 93°C-day heating requirement. The total heating degree-days for the December 1978 to May 1979 period was 1664°C-days compared to the normal 1572°C-days. This winter produced a heating demand that was 6% higher than normal.

TABLE 1 Performance summary for the Knoxville ACES complex for the period December 1, 1978 - September 30, 1979

Energy Component	Control House[a] (GJ)	ACES House (GJ)
Space Heating	31.75	31.75
Water Heating	13.75	15.82
Space Cooling	19.56	19.06
Total	65.06	66.63
Purchased Power	12,861 kWh	6,597 kWh
System COP	1.41	2.81

[a]Air-to-air heat pump with I^2R electric water heater.

The test year cooling season weather can be considered much milder than normal. May, June, and July were significantly cooler than normal while August and September were nearly normal. The cooling season exhibited 719°C-days from May through September compared to the normal 814°C-days, or a cooling demand 12% lower than normal.

SYSTEMS COMPARISONS

The air-to-air heat pump in the control house was a commercially available model, sized and installed according to conventional practices. The system was rated by the manufacturer at 9.1 kW capacity, 2.46 COP at 8.3°C outside air and 21°C inside air temperatures. Tests of the installed 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. Under these carefully instrumented conditions, the actual seasonal system performance of the heat pump was much below the ARI rated steady-state performance or the projected performance based on conventionally accepted methods. Cycling losses were found to be the dominant losses, and were so significant as to cause a decrease in system performance with increasing outside air temperatures above the house balance point.

A summary of ACES and control house operation for the two test years is presented in Fig. 4. The ice inventory history for these two years is shown in Fig. 5.

APPLICABILITY

A computer code has been developed at the Oak Ridge National Laboratory (ORNL) for computing residential building loads, for sizing ACES components, and for simulating the performance of ACES and other HVAC systems. The program, Monthly ACES Design (MAD), has been validated against field data collected at the Knoxville ACES complex. The program has subsequently been used to simulate performance for a number of HVAC systems for 115 cities in the contiguous United States. COP data for ACES and for an air-to-air heat pump system are shown in Figs. 6 and 7. Annual performance for the ACES is two to three times better in energy efficiency than for the heat pump modeled, and the ACES is applicable to all parts of the U.S. except for Southern Florida and parts of the Texas Gulf Coast, areas that have very little need for space heating.

ORNL-DWG 79-20385

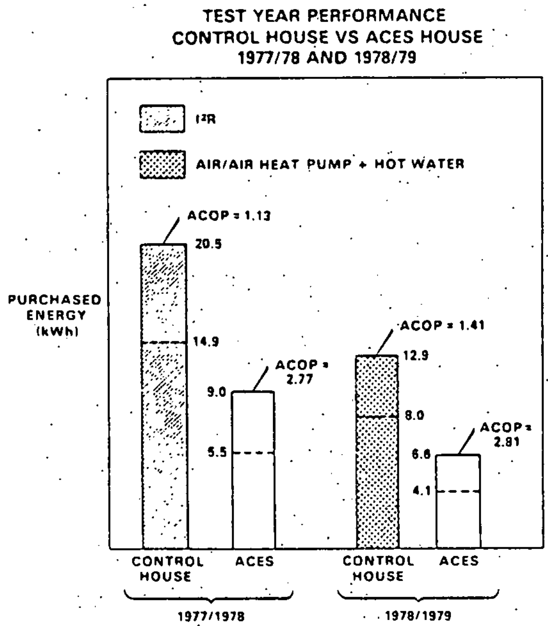

Fig. 4. ACES and conventional systems experimental performance 1977/1978 and 1978/1979.

ORNL-DWG 79-20384R

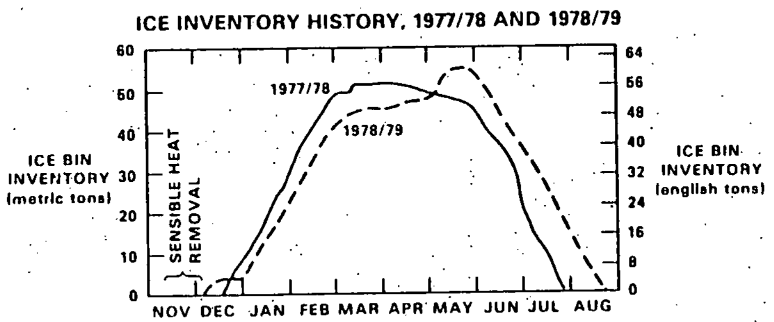

Fig. 5. Experimental ice storage history, Knoxville, Tennessee ACES house.

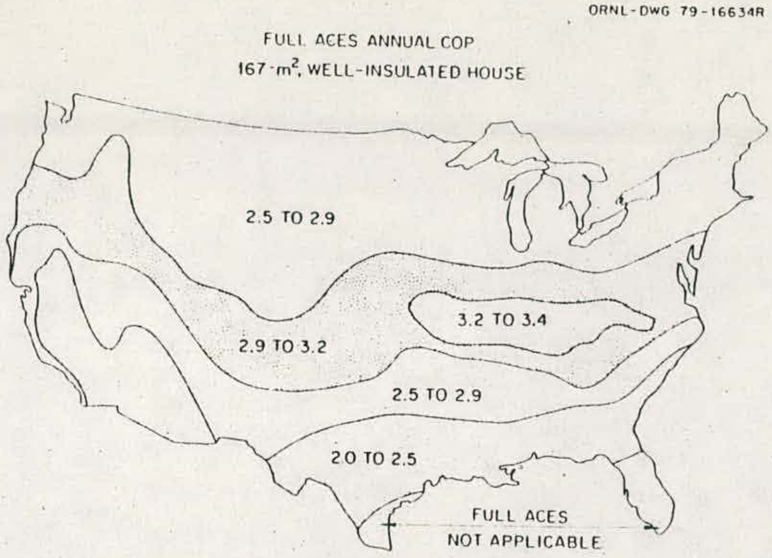

Fig. 6. Predicted full ACES annual COPs for the U.S.

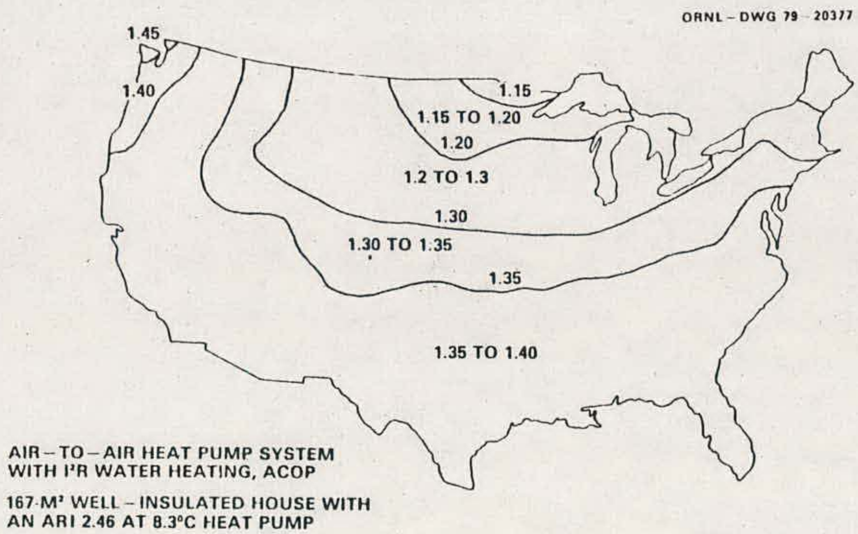

Fig. 7. Predicted air-to-air heat pump system annual COPs for the U.S.