New Modes of Heating, Ventilation, and Air Conditioning

EA-2060
Research Project 1050

Workshop Proceedings, October 1981

Tampa, Florida
January 15–17, 1979

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Section 11

THE ANNUAL CYCLE ENERGY SYSTEM

Robert E. Minturn*

The Annual Cycle Energy System (ACES) project has provided some results of actual in-field performance. The numbers I will present are real numbers; they come out of a house with an ACES in it and operating. The house is very well instrumented, and we know accurately what is going on in it. Honeywell Energy Resources Center is conducting an in-depth study of the economic competitiveness of the ACES with respect to conventional systems. This study will compare ACES with conventional systems in three different types of buildings: residential, multifamily residential, and commercial, in three different climatic zones.

The ACES has been under development by the Division of Buildings and Community Systems of the Department of Energy since about 1975. Basically, it is an assisted heat pump system with storage. Energy is provided for space heating and hot water production by extracting it from an insulated tank of water. During the heating season, the water slowly freezes, so that by the end of the season enough ice is available to provide the summer's cooling needs. All of the heat that is removed from the building during the subsequent cooling season is then stored by melting out ice in the bin. If more energy is needed for heating than is available from the bin, use is made of supplemental sources such as solar panels or outdoor air coils.

Figure 11-1 is a generalized schematic diagram of the energy flow in an ACES. The diagram is more complicated than the ACES actually is because the ACES is a flexible concept that may be utilized in a number of ways. We define two basic types of ACES, but there can be several variations even of these. One type is the full

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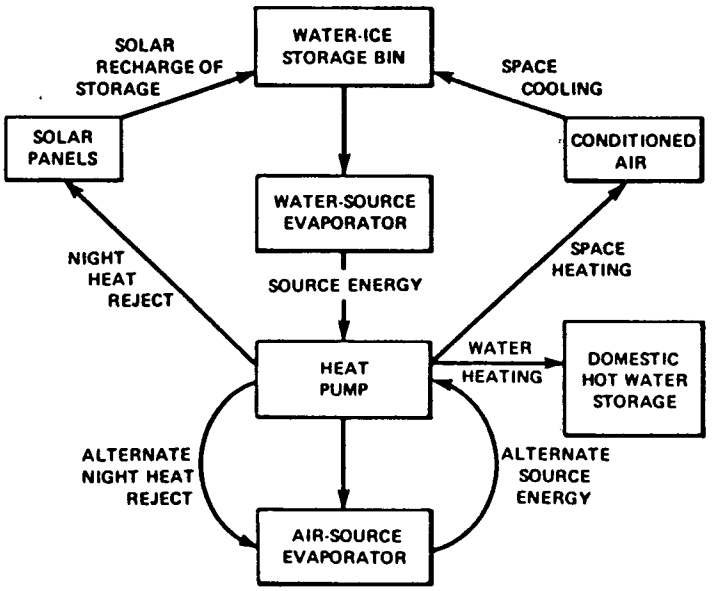

Figure 11-1. A Generalized Energy Flow Diagram for the Annual Cycle Energy System. (ORNL-DWG 78-6202)

ACES, which in the ideal case will supply all of a building's cooling needs from stored ice. The second type is the minimum ACES, which has a tank large enough only to supply all of the heating needs, without resort to supplementary sources such as solar panels, for a period of 12 consecutive days during the coldest month. We chose 12 days because we feel that, statistically, 12 days is about the maximum time an area will go without sunshine during a bad winter.

The ACES utilizes a uni-directional (heating only) heat pump that, in the basic system, gets its energy from a water source evaporator. The water is stored in a water/ice storage bin that may be located in the basement, under the patio, the garage, or wherever it is convenient to place it. It requires a large storage bin (as a rough rule of thumb, perhaps 1.25 cubic feet of storage for each square foot of floor area for a full ACES), but the cost of the storage bin is factored into the cost of the ACES when we calculate the economics of the system. Because of

the need for storage, retrofit is more expensive than installation in new construction, but it is still a possibility. In any event, the water in the storage bin provides the main source of energy to the heat pump. The energy is pumped either into conditioned air or into the domestic hot water, or both. All of the hot water needs are supplied by the heat pump at a coefficient of performance (COP) of about 3, not of 1 as obtained with resistance heating. Any time the compressor is running, a desuperheater extracts heat from the hot refrigerant and stores it in the domestic hot water tank. The rest of the useful energy in the refrigerant is then used to heat air for conditioned space, or if that is not needed, to heat additional hot water. If neither hot water or space heat is needed, of course, the compressor does not run.

Thus, during the winter, one runs the heat pump to pull energy out of the bin to condition air and heat water. If, in winter, one starts to exceed the ice storage capacity of the bin, the stored energy can be replenished through the use of solar panels simply by pumping 32° water through unglazed flat plate collectors as long as the outdoor temperature is not below 32°F. These unglazed collectors are cheap and very efficient. At 40° in Knoxville, efficiencies may exceed 100% because we pick up energy from the ambient air as well as radiant energy from the sun. Because they are efficient, one doesn't need nearly as much plate area as is common to the use of high temperature collectors. As an alternative to solar panels, a split evaporator configuration might be used. Here, if the outdoor temperature is high enough, the system would automatically switch over to an air source evaporator and operate as a conventional heat pump. When the temperature drops, and the heat pump loses capacity and efficiency, the system would revert to the water source evaporator.

In the summertime, one simply pumps ice water through the fan coil to cool the house. This is very efficient, i.e., with a COP of 12 or better, because all that is operating is a pump and a fan coil; there is no compressor operation in summer except to provide domestic hot water. If the ice is depleted during the summer because of an undersized the bin (e.g., for a minimum ACES) or because the cooling loads in summer exceed the heating loads in winter (i.e., one simply cannot make enough ice to provide the summer's needs) then one can operate the compressor at night to provide ice for cooling. This is not as efficient as operating off stored ice, but it does allow compressor operation off peak and at night when dissipation of the waste energy is most efficient.

To recapitulate, for the full ACES the storage bin is sized to be the smallest of either: (1) one large enough to store all of the ice that can be generated in the wintertime, or (2) one large enough to store all of the ice needed for summer cooling. It is possible to compensate for a mismatch between bin storage and needs either by bringing additional energy in during the winter or by rejecting excess heat during the summer. For less than full ACES, greatr reliance is placed on supplementary heating and heat rejection to the environment.

Many variations are possible in the design of an ACES. The main design problem is in sizing the water storage bin and the solar panels; since one has to provide for balanced heating and cooling loads over an entire year, the calculations are more critical than those design-day calculations common to conventional systems.

The ACES has several advantages: substantial conservation of energy (in Knoxville, in the ACES house, we are consuming about 45% of the electrical energy being used in an identical control house), reduction of peak demand, transfer of loads (summer to winter, day to night), and constant system capacity. Because the system operates only between fixed temperatures (32° in the bin and 70° in the heated space), the capacity of the compressor is independent of outdoor temperatures. Anytime it is running, it's doing so at full capacity. A full ACES doesn't need a back-up system for severe weather because its efficiency doesn't drop off when it gets cold. At Knoxville, we are getting, during actual operation, a system COP of about 2.8 for space heating only, about 3.0 for water heating only, and about 12 to 13 for space cooling from ice. For an entire yearly cycle, heating, cooling, and hot water production, we achieved an annual combined COP of about 2.8 this past year. We have improved the insulation in the ice storage tank, and expect to achieve about 3.6 in the coming year.

There are also disadvantages, and they are obvious to you. The principal one is initial cost, higher because one needs an ice storage bin and, in some cases, supplemental energy systems such as solar panels. Other components of the ACES are typical heating, ventilating and air conditioning (HVAC) components. Another major disadvantage is that nobody manufactures or markets a complete annual cycle energy system. One can buy an ice-maker heat-pump, or any of the other components of the system, but not a complete system. There is no dealer distribution network or network of trained maintenance people. These are problems primarily with residential ACES, because commercial systems are custom designed and installed anyway.

Question: You say the system operates without the need for a backup system. How many days of service do you lose if you have a major ice storm, and you're out of power 3-4 days? Then you've lost it, your thing goes down, and you can't recover it.

Answer: If power goes out, then you obviously can't run the compressor to heat your house, but then you wouldn't have power for a backup system either. Once the power comes back on, the compressor is again operative, and the system functions as if nothing had happened. The energy stored in the bin is still there, and one simply pumps it into the house and into the hot water.

Question: I guess I'm talking about the storage system deterioration during the power outage.

Answer: The storage system isn't affected by power loss. In regions where one wants to save ice for cooling, the storage bin is very well insulated. In regions where cooling is not much of a problem, but heating is, the bin is not as well insulated, and heat is gained into the bin during the heating season by transfer from the earth surrounding the bin. Incidently, one doesn't freeze the ground around the bin, even with uninsulated bins, because the bin always contains liquid water and never goes below 32°F.

Figure 11-2 is an artist's rendition of the ACES house in Knoxville. It was funded by the Department of Energy, and will eventually revert to the University of Tennessee. On the same site, there is a control house which is identical to this house and there is a similar solar house which was built by the TVA and the University of Tennessee. All are instrumented and all are monitored in the same way. The heating loads in the ACES house and the control house are remarkably similar. The loads track each other within 1% or 2% which, I'm sure, is fortuitous, but it's very nice for our purposes. The control house is heated by an air-to-air heat pump and cooled by the same system. We operated it last year on electric resistance heating because we wanted to establish a base load for the two houses. In this ACES coils are immersed in the water of the bin and there's a brine solution (methanol-water) that goes through the coils and through a heat exchanger in the mechanical package. Ice logs are formed around the coils and grow to something like 14" in diameter. We have found that loss of efficiency by going to 14" logs is something like 3% or 4%. There's an advantage to using in-bin coils because we can make the bin about half the size required with a plate-type ice-maker, which produces ice on evaporator plates above the bin and periodically causes the ice to "harvest" and to fall by gravity into the bin. Because of the packing geometry, solid ice takes up about half the volume of an equal weight of flake or sheet ice.

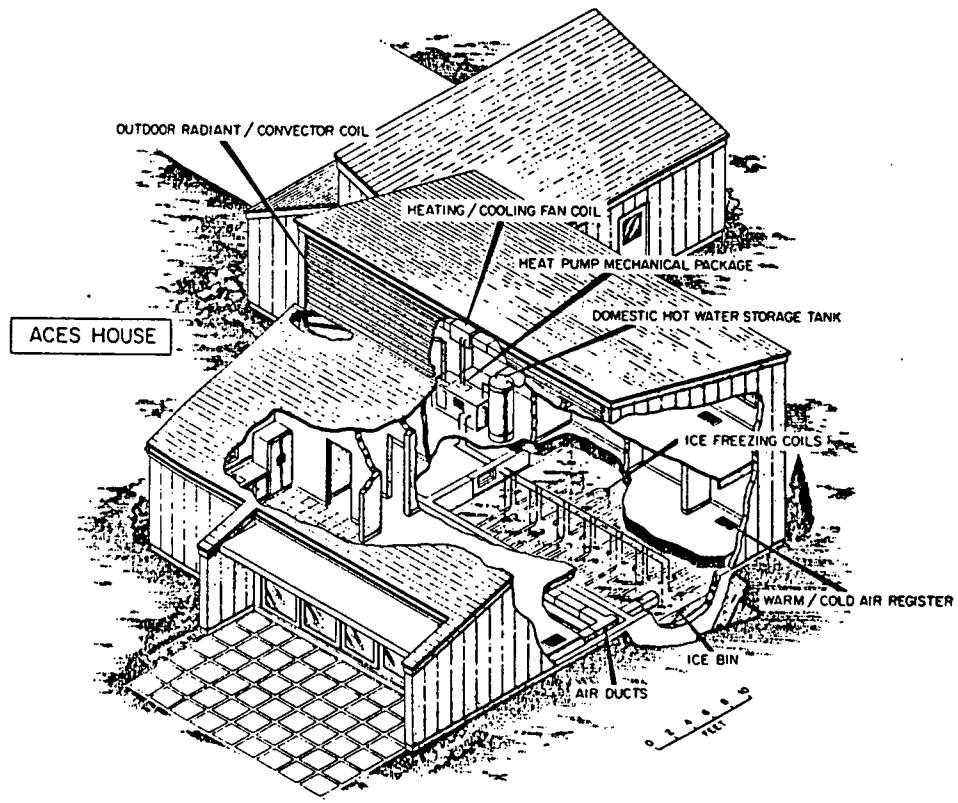

Figure 11-2. Sketch of Knoxville ACES house. (ORNL-DWG 75-11830)

Question: Are the two houses occupied?

Answer: No. The solar house is, but the ACES house and control house have programmed "people packages" in them that simulate the habits of a family of four. Seventy gallons a day of hot water is dumped on a programmed schedule down the drain, and appliance usage and people loads are synthesized. Door openings are monitored.

As I indicated, there are two ways to get heat into and out of the ice bin. One is to use submerged brine-carrying coils, as we do in the Knoxville house. The other is to use a plate-type ice-maker with the evaporator plates situated above the storage bin. In commercial ice-makers, it is customary to use hot gas defrost to harvest the ice from these plates. We do not do this because to do so is to throw away a substantial amount of useful energy. We use warm liquid refrigerant after the condenser (when it has already given up its useful energy to heat the house and provide hot water) to harvest the ice. With this technique, we are running at compressor-only COP's of 3.6 to 3.8 in the lab, which would give system COP's of about 3 for heating.

Figure 11-3 is a plot of some actual results at the Knoxville ACES house which may be of some interest to the utility representatives here. This plot shows power consumption in kilowatts as a function of the day of the week for a very cold month last January (1978). The demand (integrated hourly) for the control house is given by the dashed lines, that for the ACES house by the solid line. The control house was on I^2R. The control house demand was about 14 kW; that for the ACES about 3. (Note: the compressor for the ACES was slightly undersized for the cold weather, about 0^oF, encountered in the early part of this week. If it had been sized to carry the load, the demand would have been about 4 kW. As it was, the house temperature fell to about 65^oF, five degrees below the 70° set-point). During this same week the purchased power was 1188 kWh for the control house and 429 kWh in the ACES house.

Figure 11-4 illustrates that the ACES operates with constant efficiency and capacity. This data is for the same week as that shown in Figure 11-3, a week in which the temperature varied from about 0° early in the week to the high teens later in the week. The COP for space heating during this week was constant at about 2.8.

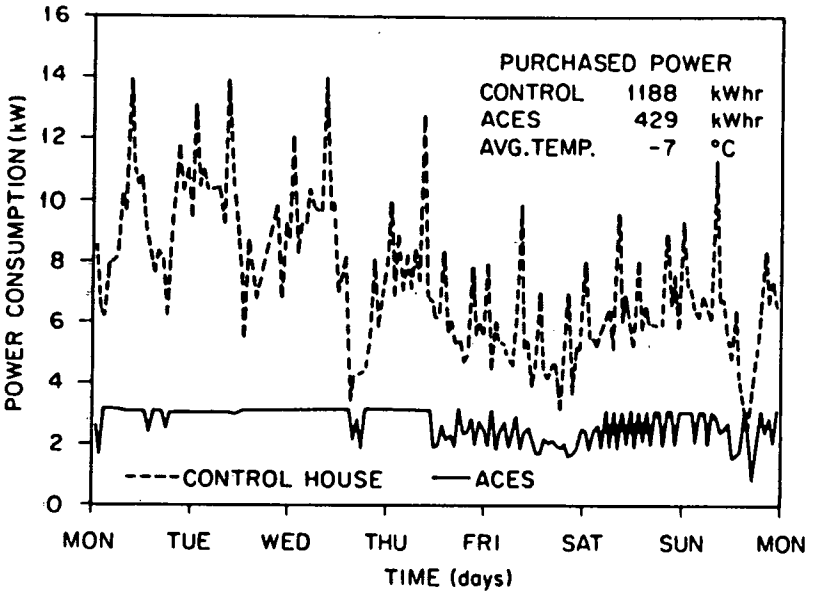

Figure 11-3. Electrical Power Demand by ACES and Control House for a Single Week in 1978. (ORNL-DWG 78-8765)

Figure 11-5 illustrates the maximum (peak) loads in kW demanded by the three houses during the annual cycle test of 1977-78. The control house, on I^2R, had a peak demand of 14.1, the ACES house 3.1 (perhaps 4), and the solar house 9.6 kW. This wasn't a particularly good year for solar energy in Tennessee because of severe winter weather. The next figure, Figure 11-6, shows the total heating season consumption of energy for the same three houses. The solar house, which used more electricity for heating than the ACES house, does not, in addition, provide ice for cooling during the next summer. Of course, both used appreciably less energy for heating than did the control house.

Question: The cooling is a benefit, entirely, right?

Answer: Yes, it's a bonus. But you must remember that the cooling is the only reason for putting in a large storage bin, and that entails capital cost up front.

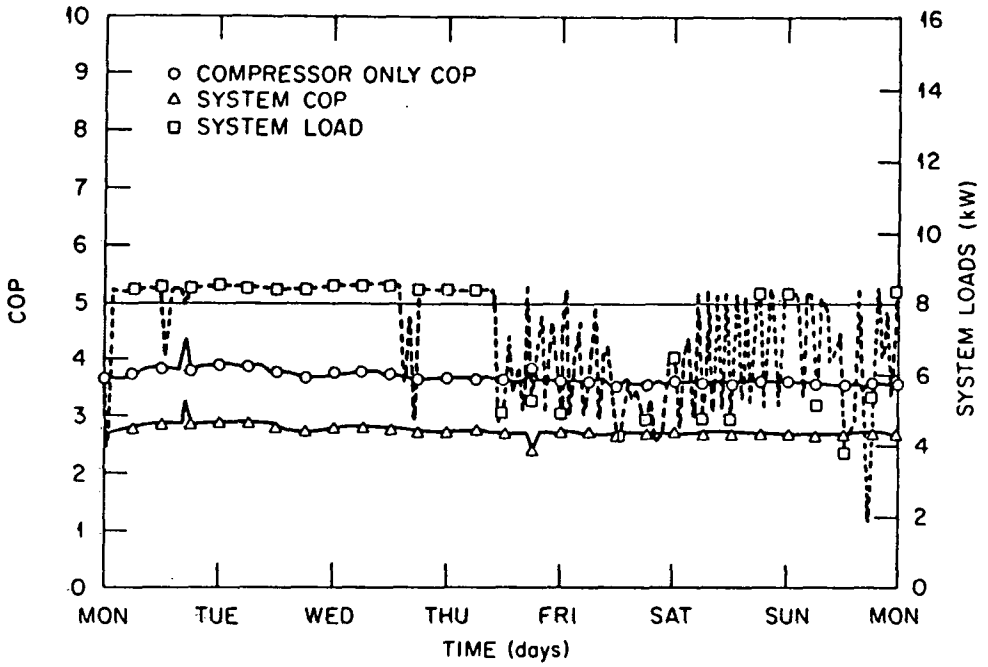

Figure 11-4. ACES Performance Analysis, Week Beginning 1/9/78. (ORNL-DWG 78-2457R)

Figure 11-7 compares the useful energy delivered by heating, cooling, and hot water and the electricity purchased for the ACES and control houses. A little more hot water was used in the ACES house because of the presence of the experimental staff, so the total energy delivered was slightly higher, while the energy purchased was considerably lower.

Figure 11-8 compares actual COP's for the two houses, and also some "what if" COP's. The actual COP for heating, cooling, and hot water production for the control house for the period stated was 1.17; that for the ACES house 2.96. If the control house had been heated with its heat pump rather than by I^2R, we estimate the annual COP would have been 1.75. If the bin of the ACES house had been better insulated, as it is now, we estimate the annual COP would have been about 3.6.

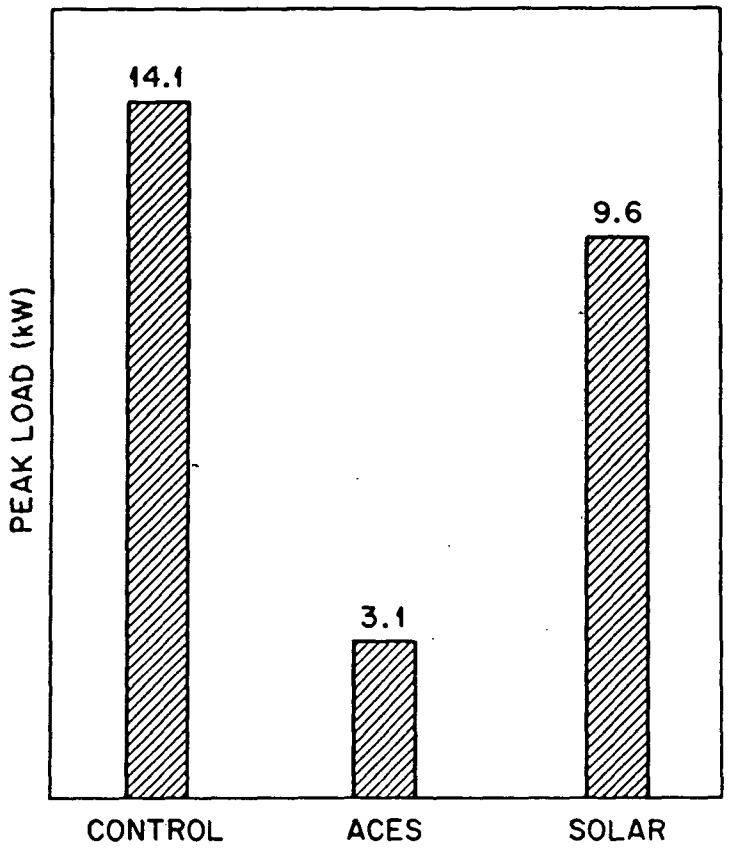

Figure 11-5. Summary of Peak Loads at the ACES, Solar and Control Houses During the 1977-78 Annual Cycle. (ORNL-DWG 78-8764)

I might comment on bin insulation. Last year, we were losing something like 75,000 Btu's worth of ice each day because of heat leakage into the bin through the walls, floor, and ceiling. This was too great a loss, and our ice inventory was depleted in late July, rather than at the end of August as we had planned. We thus had to make ice at night to provide cooling for the next day. It is very important to insulate well if you want to do cooling, even short-range cooling, because when the ice is depleted and you run your compressor, you not only have to cool down the

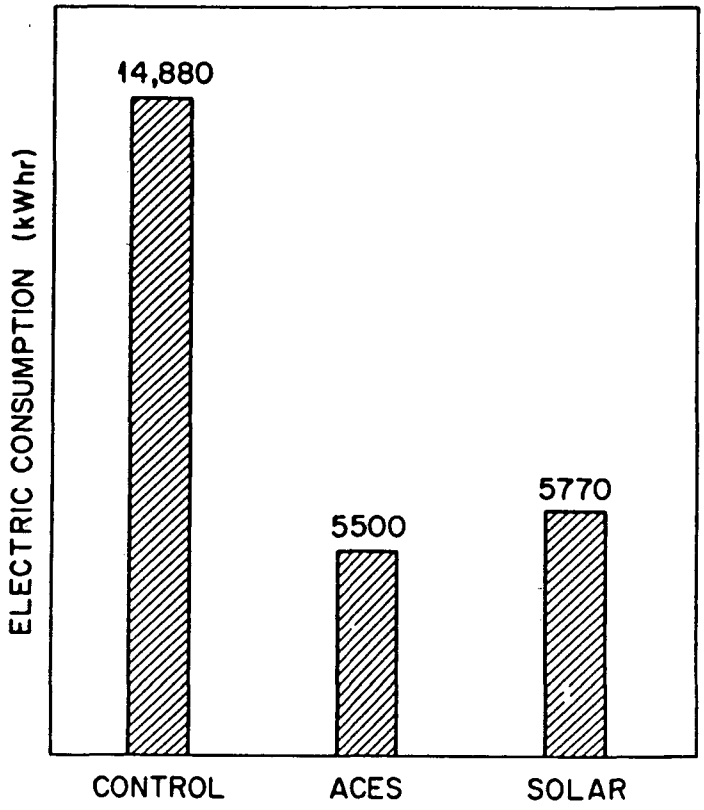

Figure 11-6. Summary of Electric Consumption for the ACES, Solar and Control Houses During the 1977-78 Heating Season. (ORNL-DWG 78-8763)

water, you also have to cool the earth surrounding the bin, and of course that is lost energy. With our new insulation, we have cut the daily losses from 75,000 Btu's/day to less than 25,000.

Question: What do you call "well insulated"?

Answer: The bin is constructed of a manufactured styrofoam block with interior voids that are filled with reinforcing rods and poured concrete. The floor was poured concrete, and the ceiling was insulated

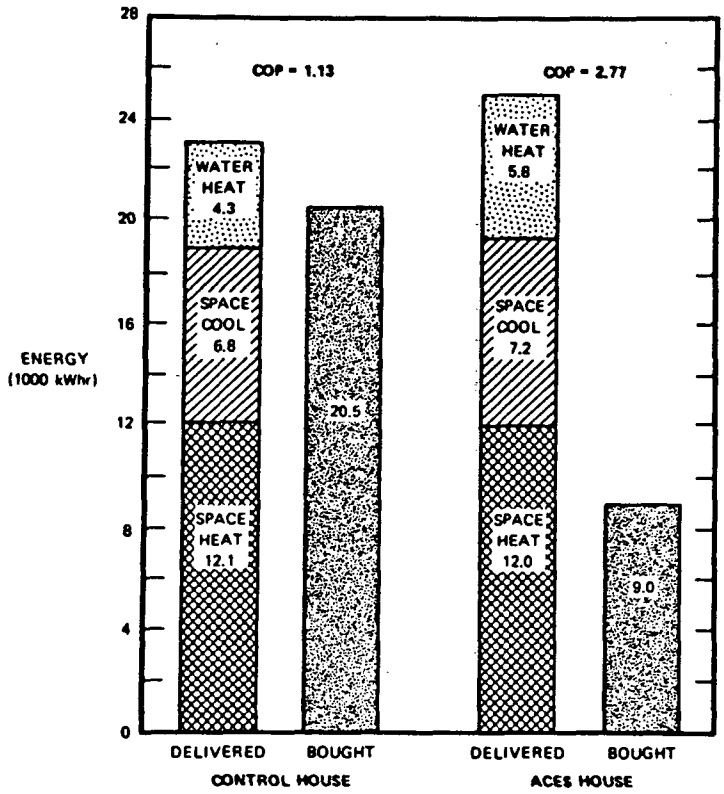

Figure 11-7. Relative Performance, Control House vs. ACES House, November 1, 1977-September 18, 1978. (ORNL-DWG 78-20052)

with fiberglass bats. We have since placed about 6 inches of rigid plastic insulation on the floor, have added 4 inches to the walls, and have replaced the ceiling with 8 inches of rigid insulation. I think the R values now run around 40.

Question: Do your COP's include heating and cooling?

Answer: I have quoted both individual COP's for heating, cooling, and hot water production, as well as annual COP's which include all three. For example, the annual COP of 3.6 we postulate for the coming year means that we will get 3.6 times more Btu's for heating, cooling, and hot water than we have to pay for in electricity costs.

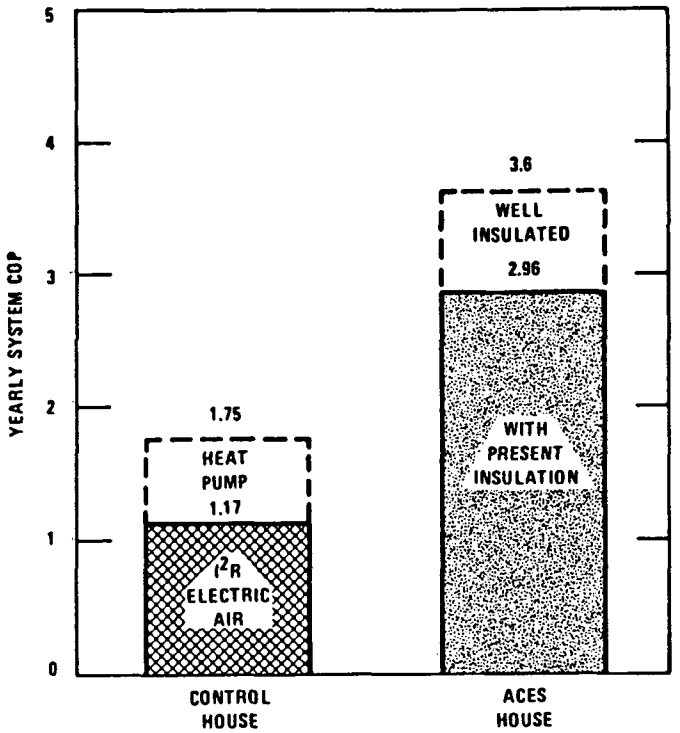

Figure 11-8. Comparison of COP's for Control and ACES houses, November 1, 1977-September 1, 1978. (ORNL-DWG 78-17248)

Question: And in the control house, that includes a conventional refrigeration system?

Answer: Yes. In that house, there is a conventional heat pump for heating and cooling, and an electric hot water heater. As I indicated, we used the I^2R part of the heat pump only for providing space heat during this first test year because we wanted to establish base loads for the two houses. During the current year, we will use the heat pump in a conventional manner for additional comparisons.

I don't want to spend much time on the economics of the ACES because, as I indicated earlier, we have a sophisticated in-depth study going on by the Honeywell Energy Resources Center. However, Figure 11-9 shows the results of some preliminary

DISCOUNT RATE ≡ 9%

FUEL COST ESCALATION RATE ≡ 6%

	PRESENT ELECTRIC RATE (c/kWhr)	
	20-YEAR BREAK EVEN	ZERO OOP* AFTER 5 YEARS
FULL ACES	5.2	6.9
PARTIAL ACES	3.2	4.2

*OUT-OF-POCKET

Figure 11-9. Estimated Comparative Economies vs. Air-Air Heat Pump. (ORNL WS-667)

in-house economic calculations. These studies show that a full ACES (maximum inter-seasonal heat transfer) might be competitive with a conventional air-to-air heat pump at electricity costs of 5.2¢/kWh or higher. The minimum ACES (storage for 12 days worst weather) might compete marginally at power costs of 3.2¢/kWh or higher. These costs were figured using a discount rate of 9% (3% over inflation) and a fuel cost escalation rate just equal to a 6% inflation rate. The two numbers under "Zero OOP After 5 Years" say simply that at electricity costs of 6.9¢/kWh a person installing a full ACES and paying for it by borrowing money which is paid back through additional mortgage payments will at the end of five years be equal to the out-of-pocket costs of a conventional air-to-air heat pump. Savings in operating costs beyond five years will leave the ACES owner with additional cash in his pocket. For the partial ACES, the equivalent power cost is 4.2¢/kWh.

More recent analyses at Oak Ridge National Laboratory (ORNL) have shown that the ACES can be marginally competitive throughout the country at power rates of about 4¢/kWh. The cost advantage of ACES at 4¢ is just marginal; people will not flock to ACES at that power cost. At higher power costs, ACES becomes more attractive, and any factors that can in effect lower the front end capital costs are going to make ACES much more attractive. I refer here to such things as tax incentives or subsidized production of equipment as an energy conservation measure.

Question: What are you assuming for equipment costs for these analyses?

Answer: For the full ACES, for a mature technology, we think the system will cost perhaps $6,000 to $7,000 more than a conventional system. For a partial ACES, these costs may be $3,000 to $4,000 more than conventional. These costs were estimated for packaged units, not prototype, one-at-a-time fabrications.

Let me summarize very briefly what the benefits of the ACES would be if we can somehow get it into the marketplace. The if is a big one because we are research people, not marketing people. The ACES will obviously reduce energy use in buildings; such a system is a great thing for energy conservation. Since the ACES can reduce peak demand on the utilities, it can be instrumental in effecting a transfer from the use of critical fuels to those fuels associated with the utilities' base load generating plants. For the customer, the technology can result in reduced energy costs. For commercial users, the ACES can reduce demand charges as well as fuel costs. For utilities with summer peaking problems, a full ACES will transfer a part of that summer load to winter. It can reduce daily peaks caused by summer cooling with conventional systems. One way that this might be implemented by utilities is for a utility to cooperate with a land tract developer to establish central ACES systems in groups of houses or apartment buildings. Perhaps the utility could own the ACES, and sell heat and cold to the surrounding customers. With this arrangement, the utility could run the compressor to its advantage, at times when demand is otherwise low.

I would like to make one comment in closing, a comment prompted by some discussions we heard earlier on high-side storage generated by I^2R heating. The Department of Energy in Washington, because it is interested in saving non-renewable fuels, is engaged in developing energy-use standards for buildings. Those standards will be conservation oriented, and as a result, it is not going to be easy to meet those standards if one uses I^2R generated storage, no matter what time of the day the heaters are run. I think the standards will, for a given type of building, place a limit on how many kilowatt hours per square foot per day one will be able to put into that building.

Question: On the first diagram you had some solar components. In the ACES house you don't have any solar collectors.

Answer: If you'll go back to Figure 11-2 you will see the solar panels, there labeled "outdoor radiant/convector coil." In this application, these are extruded aluminum tubes with fins on them, and they cost less than $5/ft^2 installed. We are also looking at flat plate collectors,

such as described elsewhere at this workshop, and these might be even less costly. We don't need panels at all at Knoxville, because the heating and cooling loads are well balanced, but we added them for experimental purposes.

Question: More of a comment than a question--it looks like you should have a wide open market on this thing--most utilities have a demand rate--if you've got one room that you want to heat or cool that an ACES can do without running a compressor--so it looks like you've got a wide open market with small commercial buildings.

Answer: You can't heat a room without running the compressor.

Question: But with a storage tank, you can.

Answer: Yes, and that's one alternative we are aware of but have not yet looked into carefully. I think in the future we will look into high-side storage. I might point out that there are some commercial-sized units now in operation. A VA nursing home in Wilmington, Delaware has an ACES in it. The Department of Energy is negotiating with the State of Maryland to incorporate an ACES into a new 71,000-square-foot office building. The VA wants to put in more units because it is pleased with the one in Wilmington. Several utilities are looking into this principle on a trial basis, using diurnal storage to get off peak. This is similar to ACES, but we limited our definition of ACES to systems providing at least 10 to 12 days storage potential. Storage times less than that are great for load management, but they don't do much for energy conservation.

Question: Are you going to put in high-side storage, and if so, how many days are you going to provide for, and will the purpose be primarily to run off-peak?

Answer: We're not sure yet about the economies of high-side storage as part of the ACES. For one thing, the compressor on the ACES runs during the heating season at a nice constant and steady rate. The utilities can count on that use, and the demand charges should not be high. In addition, high-side storage is far more difficult than ice storage. The temperature difference between the storage material and the exterior is much higher, so heat losses through the walls are much more difficult to eliminate. I think that what we would look at, at least initially, in high-side storage would be just enough low-quality energy storage to provide the incremental heat necessary to get a building started in the morning without having to go to the utility during those critical times when demand is at a maximum. That is, we could run on hot water, produced during the off-peak night hours, to carry through until the loads dropped some. The success of this would depend, of course, on the particular load curve.

Question: Are you familiar with the ACES installation by Georgia Power?

Answer: Yes, at Waycross, Georgia Power is putting an ACES in a building it is constructing. We're interested to see how that works. The ice-maker was built by a firm in Evansville, Indiana, one of the few now producing equipment for ACES installations.

Question: Harry Fischer (formerly at ORNL as an ACES consultant) has suggested discarding the ice as it is made, to lower the storage volume needed and to eliminate the need for auxiliary sources of energy to melt ice.

Answer: Yes, I'm familiar with this suggestion. Again, this idea has its main attractiveness in load management. But remember, we are interested in energy conservation, and we want that ice for air conditioning in the summer. We paid dearly to produce it, and we don't want to flush it down the drain. If we make more than we can use for cooling, then perhaps disposal is the answer. The costs of doing that will need to be compared to the cost of eliminating excess ice in the other ways I have mentioned.

DISCUSSION

Kenneth L. Baker*

This paper reports the current status of the stored cooling research conducted by Oak Ridge National Laboratory. Reported results for test homes in the Knoxville, Tennessee area suggest that storage cooling for residential applications is technically feasible. The annual cycle energy system (ACES) effectively utilizes energy that would normally be lost in the annual heating/cooling cycle thereby substantially increasing the overall system coefficient of performance (COP). Performance data reported for the control house with a conventional heat pump system are similar to findings of the recent nationwide heat pump load study sponsored by EPRI and the AEIC Load Research Committee in Research Report 432-1.

The potential for utilizing low cost low temperature solar collectors with the ACES system should also enhance the economic advantages of this form of residential space conditioning.

Several areas need further investigation:

1. Research of the ACES residential system has been primarily limited to the Knoxville climate where a favorable balance exists between heating and cooling requirements. Future research should be undertaken to verify system performance in locations with more extreme weather conditions.

2. The heat pump operation in the ACES system is different from that in a conventional heat pump system. Additional information should be developed on any effect on equipment life and maintenance costs.

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3. The concern raised in the paper regarding commercialization of the ACES system for residential use is primarily a marketing problem. The system components are commercially available equipment. No unusual technical skills for installation or maintenance were mentioned. It appears that maintenance is within the existing technical capability of reputable HVAC firms. It is possible that added features such as split evaporators and high side storage could increase sophistication of the control system to the point where highly specialized service personnel would be needed.

4. A major obstacle to commercialization of the ACES system for residential application is likely to be the initial investment. The current high cost of housing construction and high interest rates limit the attractiveness of investments that provide for economic benefits only over the long run. The mobility of the population also restricts the perceived value of cost savings that could be realized 10 to 15 years in the future.

The paper presented by Mr. Minturn is a good overview of the current findings from the Oak Ridge storage cooling project. It presents a convincing case that storage cooling research should be actively pursued in the future. This technology holds promise for conserving substantial energy in new residential structures and reducing electric generating capacity and fuel requirements for future residential air conditioning loads.