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Community Systems

Design Report for the ACES DEMONSTRATION HOUSE

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J. C. Moyers
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OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ANNUAL CYCLE ENERGY SYSTEM — DEMONSTRATION HOUSE DESIGN REPORT

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ANNUAL CYCLE ENERGY SYSTEM — DEMONSTRATION HOUSE DESIGN REPORT

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Abstract

A 2000 ft^2 single family residence will be constructed in first quarter 1976 to demonstrate the energy conserving features of additional insulation, the Annual Cycle Energy System (ACES), and an automatic economy cycle in the cooling season. The design specifications for the house and for the ACES components are given. ACES is a water-to-air heat pump system with ice and thermal storage. The calculated loads and predicted performance of the system along with the calculated performance of conventional systems are presented. The design calculations indicate that ACES can supply the space heating, space cooling, and the domestic hot water for about 42% of the electrical consumption required by a system composed of an electric furnace, electric air conditioner, and an electric water heater and for about 54% of the electrical consumption of an air-to-air heat pump and an electric water heater.

DESIGN REPORT FOR
ANNUAL CYCLE ENERGY SYSTEM DEMONSTRATION HOUSE

E. C. Hise

1. Summary

The Annual Cycle Energy System (ACES) demonstration house is one of a complex of three houses — the ACES, the Solar, and the Base Line being built to explore and demonstrate energy conservation in housing. This complex is being constructed on the campus of the University of Tennessee in Knoxville as a cooperative venture of the Energy Research and Development Administration, represented by the Oak Ridge National Laboratory, the University of Tennessee, and the Tennessee Valley Authority. The three houses are of identical floor plan and, insofar as possible, of identical construction. They are two story, frame construction, 2000 ft^2 with three bedrooms, and two baths.

The three energy conserving features of the ACES house are the additional insulation, the integrated space conditioning and water heating system (ACES), and the automatic economy cycle in the cooling season.

The additional insulation described in 2.1 as compared to the identical house insulated to the *HUD Minimum Property Standards* for this climate reduced the design heating load to 61% and the annual heating consumption to 46%.

The ACES combines a heat pump, thermal storage, and solar assistance to provide a space heating and cooling and water heating system that balances the energy requirements for these services over a whole year. The heating is supplied by heat pumping from the

thermal storage in the form of a tank of water. During the winter season this water is converted to ice. During the summer the ice provides the space cooling. Solar assistance provides an additional heat source and a condenser provides an additional heat sink to provide an annual energy balance as various climates and buildings require. The ACES can supply the space heating, space cooling, and the domestic hot water for about 42% of the electrical consumption required by a system composed of an electric furnace, electric air conditioner and electric water heater or about 54% of the electrical consumption of an air-to-air heat pump and electric water heater.

The economy cycle during the cooling season further reduces the energy consumption by the ACES installation (by automatically cooling with outside air instead of refrigeration whenever the conditions are suitable) to 83% of that required by the ACES installation without the economy cycle.

Thus, the ACES demonstration house incorporating these three features is predicted to use for space heating, space cooling, and water heating 24% of the electricity that the same house with conventional insulation, electric furnace, electric air conditioner, and electric water heater would use to supply these same services. To state it another way, the projected cost of heating cooling, and hot water for the ACES house is about the same as the average operating cost for an electric water heater. The electrical consumption and costs for various combinations are shown in Table 1.1.

Table 1.1 Comparative electrical consumption and costs

Characteristics of house and system	Annual kWhrs consumed for space heating/cooling and water heating	Annual cost of electricity @ 2.0¢/kWhr	Annual cost of electricity @ 3.5¢/kWhr
Conventional insulation electric furnace, A/C, water heater	20,850	$417.00	$729.75
Conventional insulation electric heat pump, water heater	14,411	288.22	504.39
Conventional insulation ACES	7,522	150.44	263.27
Conventional insulation ACES, economy cycle	6,732	134.64	235.62
Additional insulation electric furnace, A/C, water heater	14,093	281.86	493.26
Additional insulation electric heat pump, water heater	11,133	222.66	389.66
Additional insulation ACES	5,967	119.34	208.85
Additional insulation ACES, economy cycle	4,979	99.58	174.27

2. Systems Description

2.1 The Building

2.1.1 Architectural. The ACES demonstration house is one of a complex of three houses being built near Knoxville, Tennessee to explore energy conservation in housing. The three are the ACES house, the Solar house, and the Base Line house. It is the design intent that the three houses be identical in floor plan, appearance, construction, and thermal characteristics; insofar as the differing requirements of the heating/cooling systems permit. The houses themselves (the thermal envelope) will be energy conserving and present the mimimum of barriers to acceptance by the building industry and the public.

The house is a two level, plus partial basement, frame structure having about 2000 ft^2 of living space distributed among three bedrooms, two baths, living-dining room, kitchen, utility room, and entry hall. Figures 2.1, 2.2, and 2.3 are the floor plans for the basement and first and second floor. Figure 2.4 is an elevation cross section.

2.1.2 Thermal Envelope. The thermal envelope of the house is better insulated than is conventional or than is required by *HUD Minimum Property Standards* for this climate zone. The insulation and the resulting U values for the demonstration house as designed and to *HUD* Standards are given in Table 2.1. Areas and exposure are given in Table 2.2. Construction details are given in Table 2.3.

The basement walls and the crawl space foundation are of reinforced concrete poured in styrofoam forms. The resulting composite has an overall thermal resistance of R=16 $hr\text{-}ft^2\text{-}°F\text{-}Btu^{-1}$ (U=0.062 $Btu\text{-}hr^{-1}\text{-}ft^{-2}\text{-}°F^{-1}$). The Foam Form is described in Fig. 5.1.

2.2 The Annual Cycle Energy System

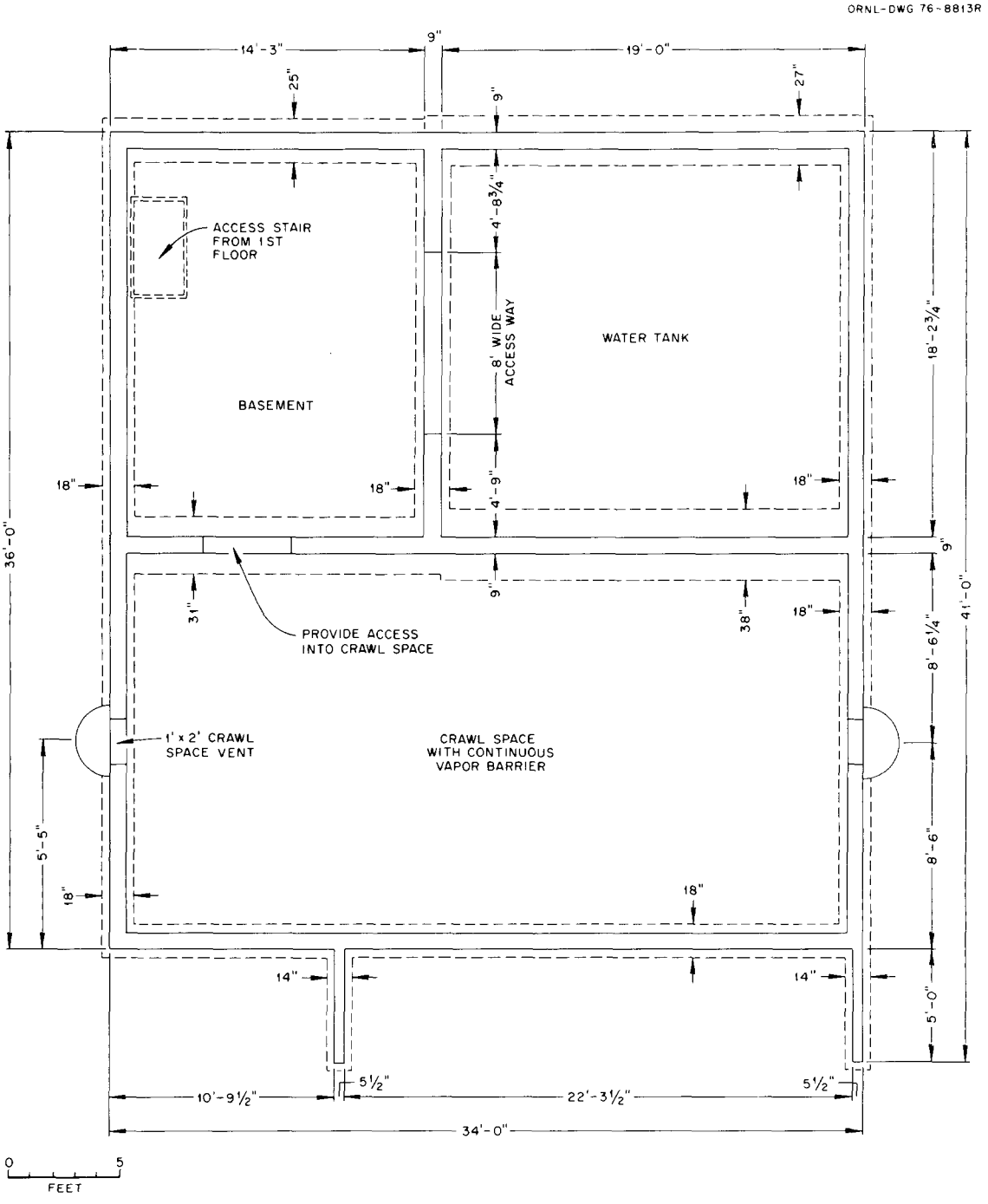

Fig. 2.1 Basement plan

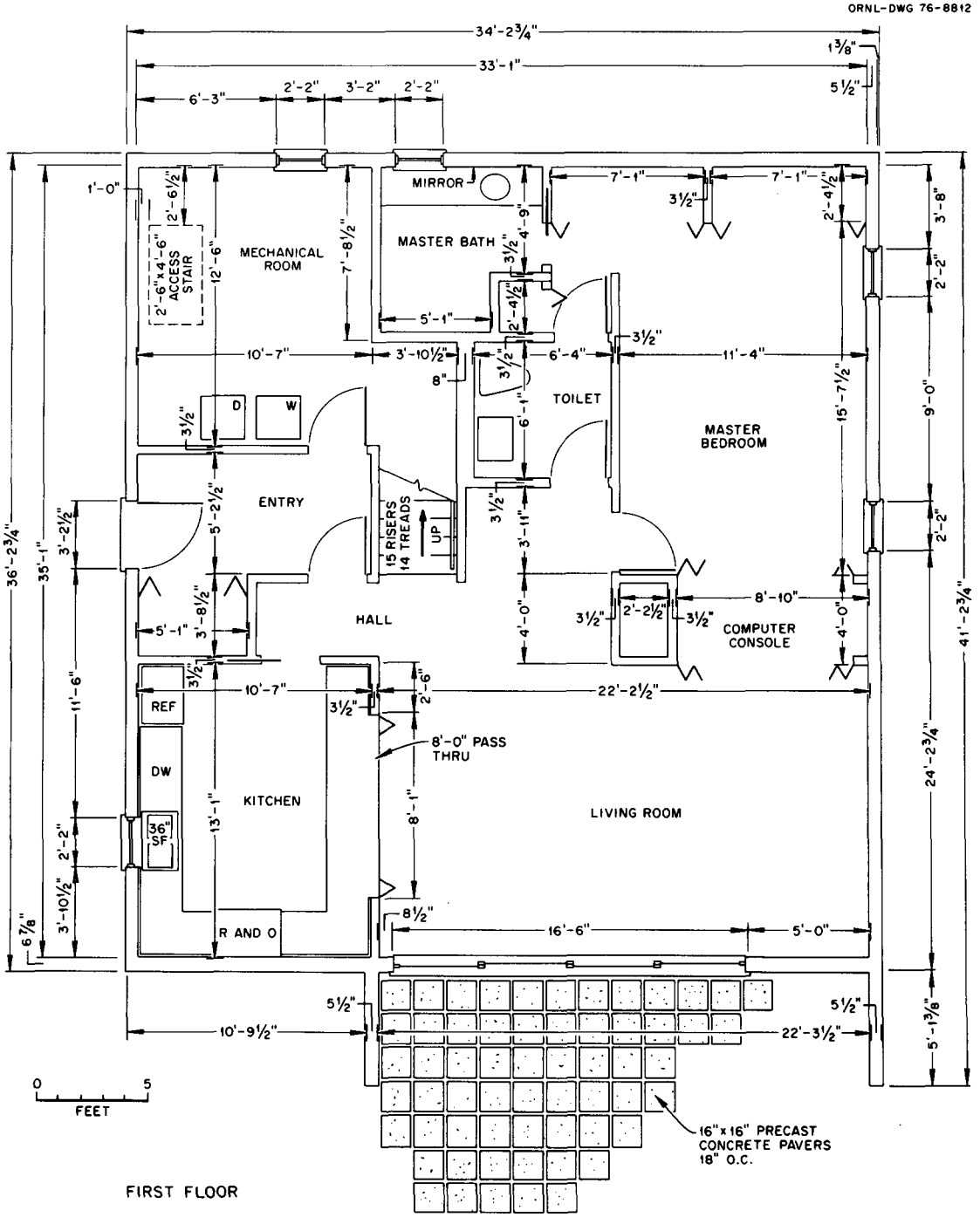

Fig. 2.2 First floor plan

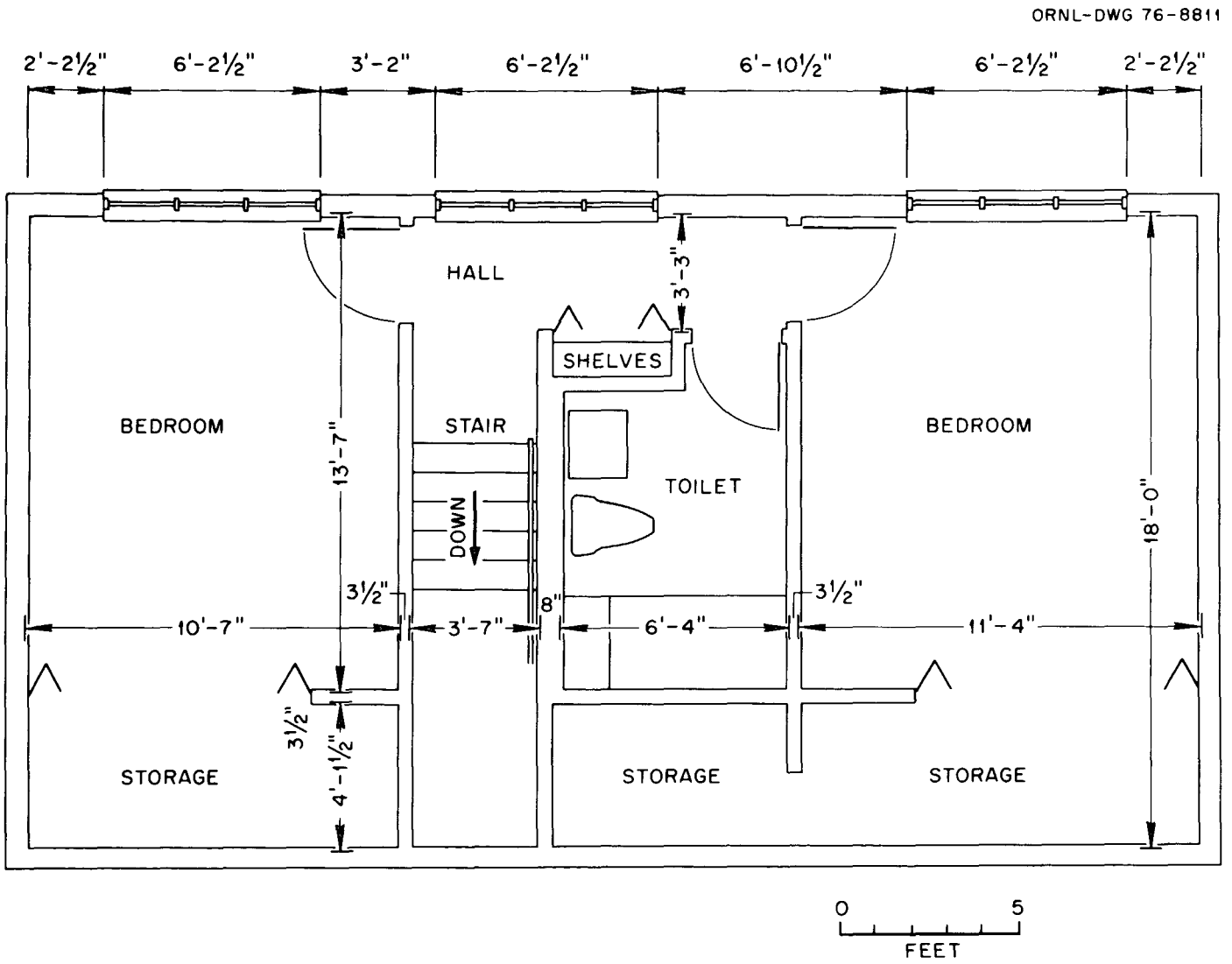

Fig. 2.3 Second floor plan

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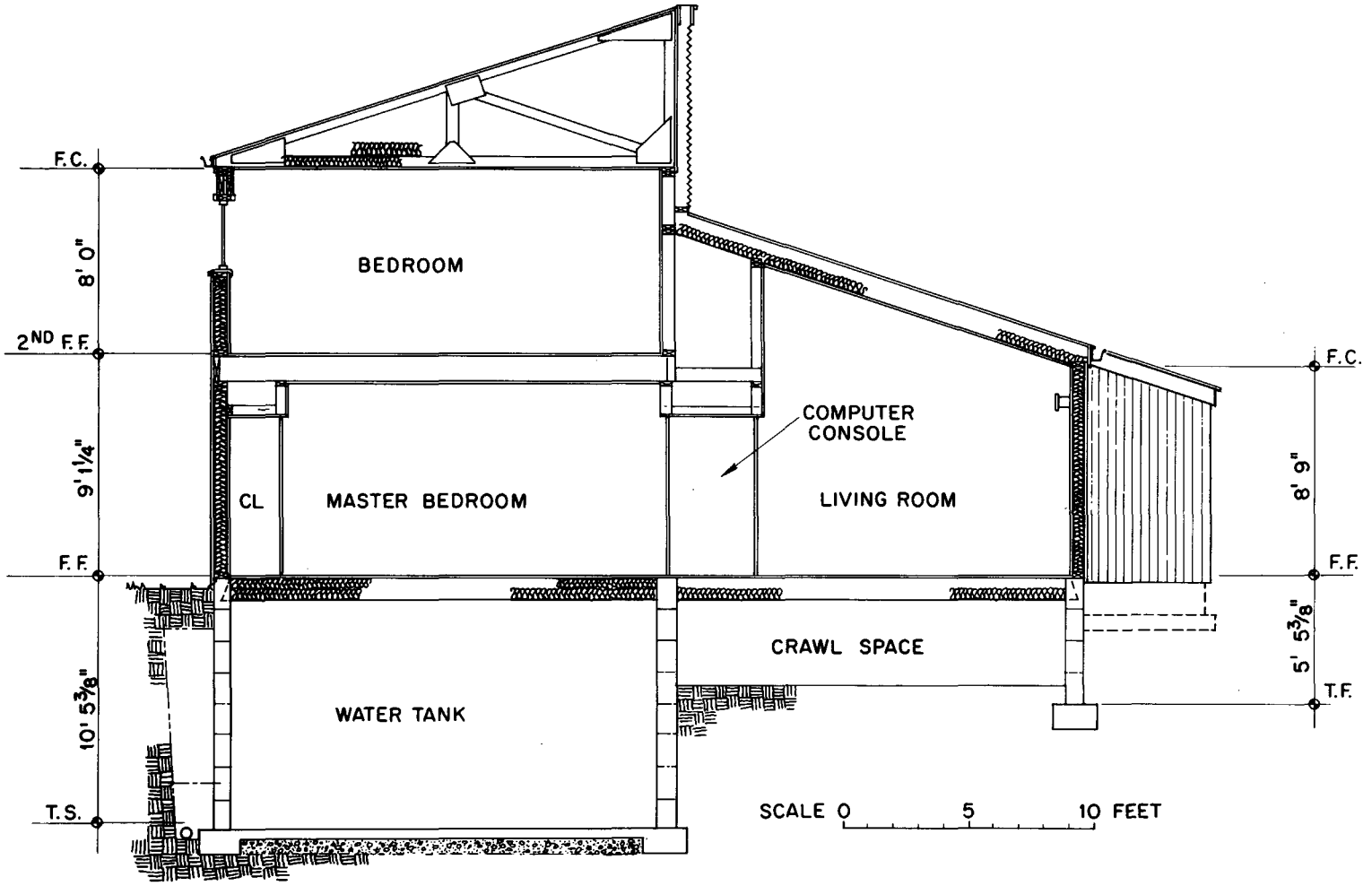

Fig. 2.4 Section

Table 2.1 Insulation details

	Demonstration house		HUD minimum property standards	
	Insulation	Btu/hr ft^2°F	Insulation	Btu/hr ft^2°F
Sidewalls	5 1/2 in.	0.045	Not specified	0.08
Ceiling, flat	12 in.	0.024	———	0.05
Ceiling, cathedral	9 in.	0.032		
Floor (wood floor over crawl)	6 in.	0.040	———	0.10
Windows	Double glazed	0.58	Single glazed	1.12
Basement and crawl space		0.062	———	——

Table 2.2. Areas and exposures

	Area ft^2
Floor	
1st floor	1160
2nd floor	594
Subfloor	
Finished basement	222
Storage bin	327
Crawl space	550
Opaque walls	
North exposure	498
East exposure	448
South exposure	282
West exposure	438
Windows	
North exposure	68
East exposure	17
South exposure	90
West exposure	7
Doors	
West exposure	20
(South exposure sliding glass door included in window areas)	

Table 2.3 Construction details

Exterior walls	- 1/2 in. gypsum board, 2 x 6 studs 16" O.C. with 5 1/2 in. glass fiber batt insulation, 25/32 in. fiber board sheathing, 5/8 in. exterior plywood.
Ceiling	- (760 ft^2 flat) 1/2 in. gypsum board, 2 x 4 trussed joists with 12 in. glass fiber batt insulation.
	- (367 ft^2, horizontal projection, cathedral) 1/2 in. gypsum board, 2 x 12 rafters with 9 in. glass fiber batt insulation, 2 1/2 in. vented air space, 5/8 in. plywood sheathing, building paper, asphalt shingles
Roof	- (over flatt ceiling, 760 ft^2) 2 x 4 trussed rafters, 5/8 in. plywood sheathing, building paper, asphalt shingles.
Floor	- carpet or sheet vinyl, 5/8 in. particle board underlayment, building paper, 5/8 in. plywood subfloor, 2 x 12 joists with 5 1/2 in. air gap and 6 in. glass fiber insulation.
Windows	- double glazed wood frame.
Door	- metal cased, 1 3/4 in. urethane foam core, with magnetic weather seal.

Note: The equivalent insulation value for the exterior walls can be achieved by several other means. One system would be 2 x 4 studs, 3 1/2 in. glass fiber batt insulation, and 1 in. to 1 1/2 in. of foam insulation sheathing having a K factor of around 0.18.

The Annual Cycle Energy System (ACES) is an integrated space heating and cooling and domestic water heating system. Its major elements are:

1) a high efficiency heat pump with refrigerant-to-brine heat exchangers on both the evaporating and condensing side;
2) thermal storage on the low temperature (evaporator) side;
3) an auxiliary heat source and sink;
4) a forced air circulating system with a fan coil for space heating and cooling;
5) a refrigerant to water heat exchanger for heating and a tank for storing domestic hot water.

The arrangement of these components in the house is shown pictorially in Fig. 2.5 and a flow schematic is shown in Fig. 2.6. The piping drawn in solid lines is all contained within the mechanical package. The dashed lines represent brine piping to components located externally to the mechanical package. The heat pump (compressor) always extracts heat from the evaporator (20% methanol brine cooler) which in turn extracts heat from the ice storage bank via the circulating brine system. The heat pump always discharges its heat to one or more of the three high temperature heat exchangers; the desuperheater, the hot water condenser, and the space heating condenser. Thus, the refrigerant cycle is completely contained within the mechanical package and is a nonreversing cycle.

Space heating is accomplished by circulating brine from the heating condenser through the fan coil and transferring the heat to the living space by the circulating air system. Space cooling is accomplished by circulating brine from the ice storage bank through the fan coil and transferring heat to it from the circulating air system.

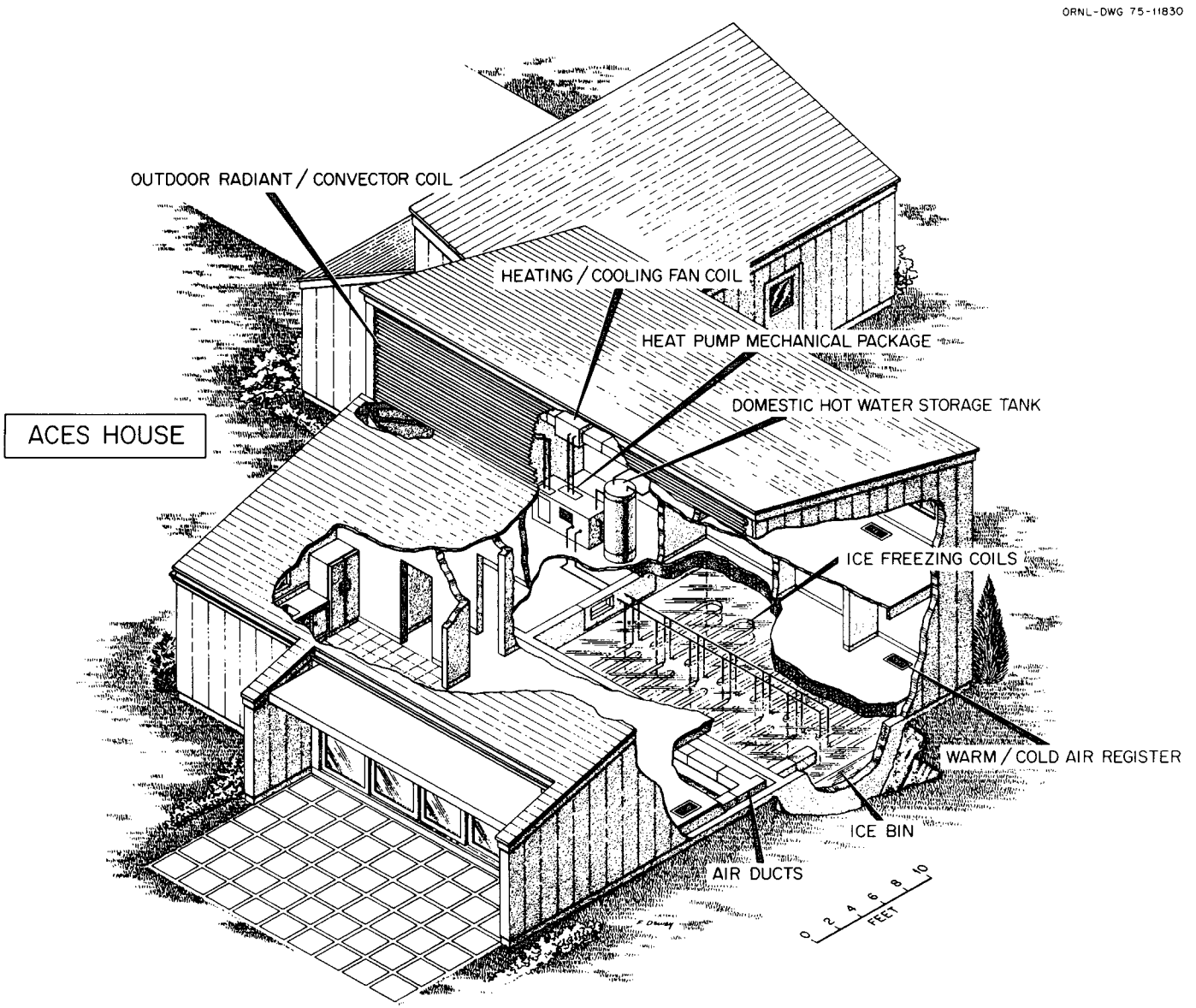

Fig. 2.5 Pictorial

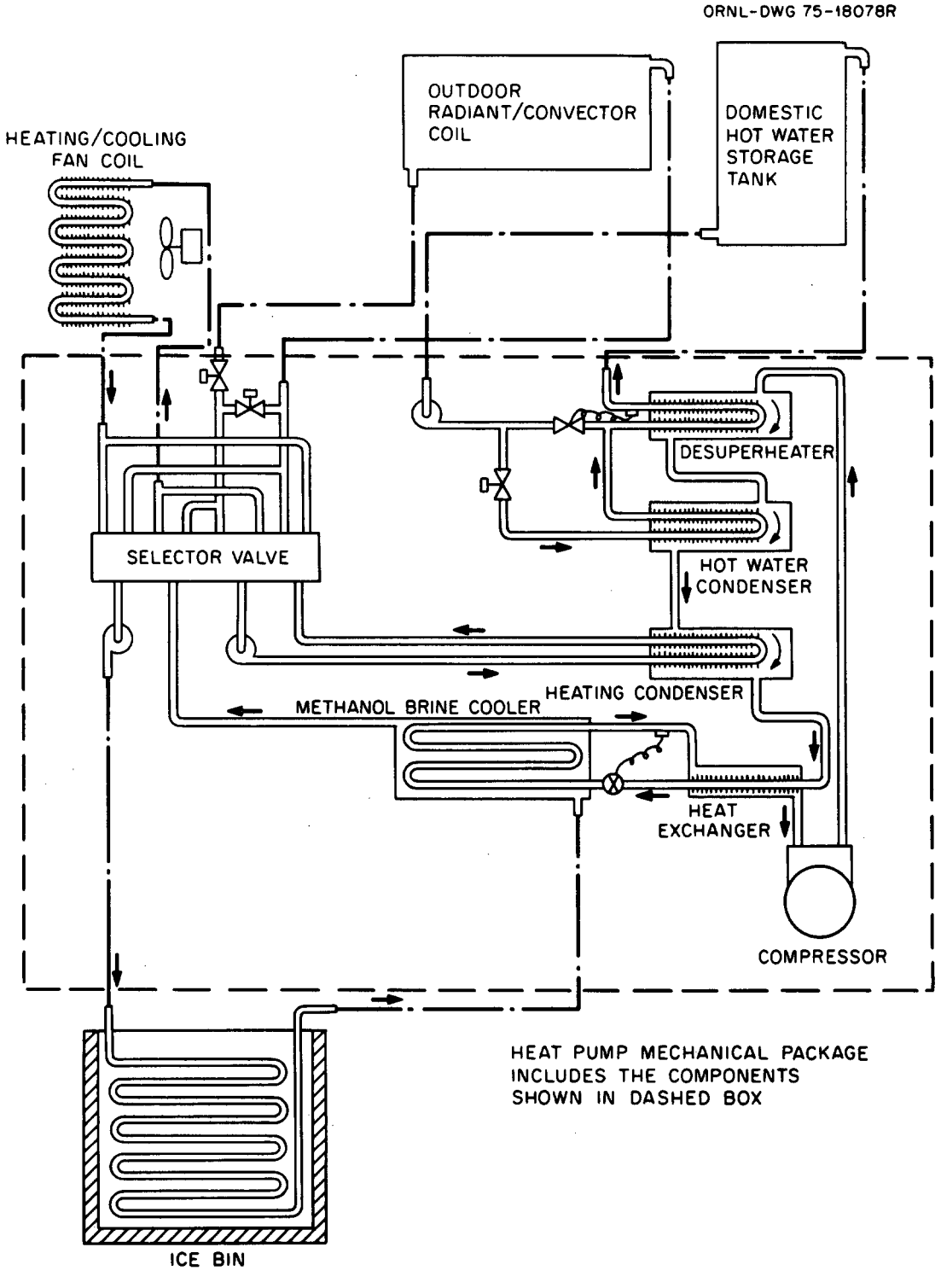

Fig. 2.6 System schematic

The selector valve chooses the brine circuit for heating or cooling as required. The domestic water is heated by recirculation through the desuperheater during the heating season and through the desuperheater and the hot water condenser during the cooling season.

The radiant/convector panel is circuited to be able to accept or reject heat as needed. During the heating season, the panel can accept solar and convective heat and deposit it in the ice bank via the circulating brine system. This mode of operation can be automatically selected when needed (for instance, if the ice inventory exceeds 80% of the bank capacity). Ice formation is restricted to 80% of bank capacity to avoid expansion damage to the container. During the cooling season, the panel can reject heat convectively from the space heating condenser via the circulating brine system. This mode of operation can be automatically selected when needed (for instance, if the ice inventory is exhausted, the bank temperature exceeds 34° and outdoor ambient is below 80°). This mode permits compressor operation under favorable conditions for heat rejection and off the usual utility peak load.

2.3 The Economy Cycle

In any building the internal loads — that is the heat from lighting, cooking appliances, etc.; the heat from the occupants; and the solar energy entering through the windows and structure — will hold the indoor temperature above the outdoor temperature. The outdoor temperature at which the internal loads will maintain the desired indoor temperature is called the break-even temperature. This break-even temperature is a function of the size of the building, the degree of insulation, and the internal loads and thus can vary widely with different buildings.

However, for any building there is that span of outdoor temperatures below the desired indoor temperature and above the break-even temperature for which the building will require cooling. The conventional air conditioning system must supply this cooling by refrigerating the indoor air. However, if the system is equipped with an economy cycle the cooling will be supplied by ventilating with outdoor air thus expending only blower energy and no refrigeration energy. For the demonstration house in the Knoxville climate this span of temperature occurs enough of the cooling season that the economy cycle will save about 6 million Btu or 25% of the required air conditioning.

In the demonstration house the heating-cooling duct system is equipped with a motor operated damper and so arranged that when in the normal position the blower circulates indoor air through the coil and in the economy cycle position the blower draws outside air into the house, discharges indoor air outside, and bypasses the coil. The control system places the damper in the economy cycle position whenever the room thermostat requires cooling and the outdoor thermostat recognizes that the cooling can be accomplished by ventilation.

3. System Performance

3.1 Heating-Cooling Loads and Seasonal Requirements

3.1.1 Design Conditions. The overall objective of the demonstration program is to minimize the energy required to provide the indoor comfort conditions. That energy requirement depends in part upon the efficiency with which the heating-cooling system supplies the heating and cooling requirements imposed by the specified indoor design conditions, the climate, and thermal envelope.

The specified indoor design conditions are:

1) winter — 70°F dry bulb (d.b.), no humidity control;

2) summer — 78°F dry bulb (d.b.), 60% relative humidity;

3) internal electrical load schedule averaging 1 kWhr;

4) daily occupancy schedule varying from 2 to 4 people;

5) ventilation rate of 0.5 air changes per hour.

The climate in Knoxville, Tennessee is:

1) latitude — 35° 5';

2) winter design temperature — 17°;

3) summer design temperature — 95°db, 77°wb;

4) winter degree days — 3500;

5) summer full load air conditioning hours — 1000.

The thermal envelope of the demonstration house is as described in Tables 2.1, 2.2, and 2.3 and all of the design calculations are based on that thermal envelope. In addition, load calculations were performed assuming a thermal envelope built to the *HUD Minimum Property Standards* as described in Table 2.1. Although there is no present plan to build a house insulated to the minimum property standards it is useful to calculate the loads and system performance in order to be able to separate the magnitude of the contribution of each of the energy conserving features and to be able to present analytically the performance of the ACES in a house insulated to those standards.

3.1.2 Design Loads. In order to be able to properly size space heating and cooling equipment as well as to provide a standard basis for comparison, it is conventional to calculate the design heating and cooling loads for the winter and summer design temperatures. These loads represent the Btu per hour that must be supplied to or removed

from the building to maintain the design indoor temperature when the outdoor is that specified as the design temperature for that area. The local outdoor design temperatures are based on weather data and are available from the local weather bureau or in compilations in many handbooks including the *ASHRAE Fundamentals Handbook*. These loads are a function of the building and temperatures only and are independent of whatever heating and cooling system are chosen to supply the loads.

The design heating and cooling loads for the demonstration house and for a house insulated to the minimum property standards are given in Table 3.1. The resulting design heating load for the ACES house is about 61% of that for the conventionally insulated house and the design cooling load is about 80%. The lower heating-to-cooling ratio for the demonstration house reflects the fact that in a well insulated house, internal loads supply a larger portion of the total heating requirement.

3.1.3 Seasonal Requirements. While the design loads give the load on the heating or cooling system at design conditions and permit sizing the equipment to be able to supply that load they do not indicate the total amount of heating or cooling required during the season. In order to estimate the energy consumed by a building over the year and, for ACES, to estimate the required size of the energy storage bin it is necessary to estimate the seasonal heating and cooling requirements in terms of the total Btu to be supplied during the heating season and the total Btu to be removed during the cooling season. This estimation must be based on the compiled weather data for the area. Several computational methods are available. The computer method used in this design is based on hourly weather data recorded for Knoxville for the eight years from 1955 through 1962. The heating or cooling load each hour is calculated by the

Table 3.1. Design heating and cooling loads and seasonal requirements[a]

	Insulated to minimum property standards	Demonstration house	Demonstration house with economy cycle
Design heating load Btu/hr	29,790	18,235	18,235
Design cooling load Btu/hr	23,760	19,000	19,000
Seasonal heating requirement 10^6 Btu	43.8	20.3	20.3
Seasonal cooling requirement 10^6 Btu	22.7	24.1	17.1

[a]The requirements are for year 5 of the weather tape and are representative, although not necessarily average.

procedure suggested in the *ASHRAE Fundamentals Handbook*, 1972 edition, and those loads are summed for the entire season. The results of these calculations for one year are shown in Table 3.1 and for eight years in Table 3.2.

The heating requirement for the ACES demonstration house is only 46% of that for the conventionally insulated house, but the cooling requirement is 106%. This again reflects the effect of internal loads. As discussed earlier in Section 2.3, the lower heat transmission rate of the demonstration house results in a lower break-even temperature of 72.5°F (the outdoor temperature at which the internal loads will maintain an indoor temperature of 78°), as compared to the break-even temperature of 74.0°F for the conventional house. The lower heat transmission rate also results in a lower cooling load at summer outdoor design condition. This is shown graphically in Fig. 3.1. Below 78° (where the two cooling lines cross) the conventional house will require less cooling and although the conventionally insulated house has a higher cooling load above this crossover temperature, the demonstration house has more cooling hours. The Knoxville climate has many cooling hours below this crossover temperature of the two houses, with the paradoxical result that the demonstration house having 80% of the design cooling load of the conventional house also has 106% of the seasonal cooling consumption.

Commercial building design has long been faced with a high internal-load-to-envelope-transmission ratio and the resulting low cooling break-even temperature. The design response is the "economy cycle" which turns off the refrigeration system and draws in outside air whenever outside air temperature is low enough to hold the building at the indoor design temperature. The demonstration house can be held at indoor design temperature by circulating 1200 cfm of outdoor air, if outdoor air is at

Table 3.2. Calculated performance of the ACES demonstration house

	Annual consumptions							
	Btu 10^6				kWhrs			
		Space cooling			With economy cycle			
Year[a]	Space heating	Without economy cycle	With economy cycle	Water heating	Heat pump	Auxiliaries	Maximum ice inventory tons	Minimum tank size ft^3
1955	19.7	22.9	16.8	16.2	4952	785	21	921[a]
1956	17.2	21.4	15.1	16.2	3592	736	52	2280
1957	16.9	22.8	16.3	16.2	4048	750	40	1754
1958	23.9	21.7	15.4	16.2	4245	903	56	2456
1959	20.3	24.1	17.1	16.2	4138	842	51	2236
1960	25.0	21.5	15.1	16.2	4326	929	56	2456
1961	20.4	15.7	10.0	16.2	3484	739	54	2368
1962	22.2	23.5	16.6	16.2	4233	891	56	2456

[a]Year 1 performance assumes startup on January 1. The following years assume continuous operation.

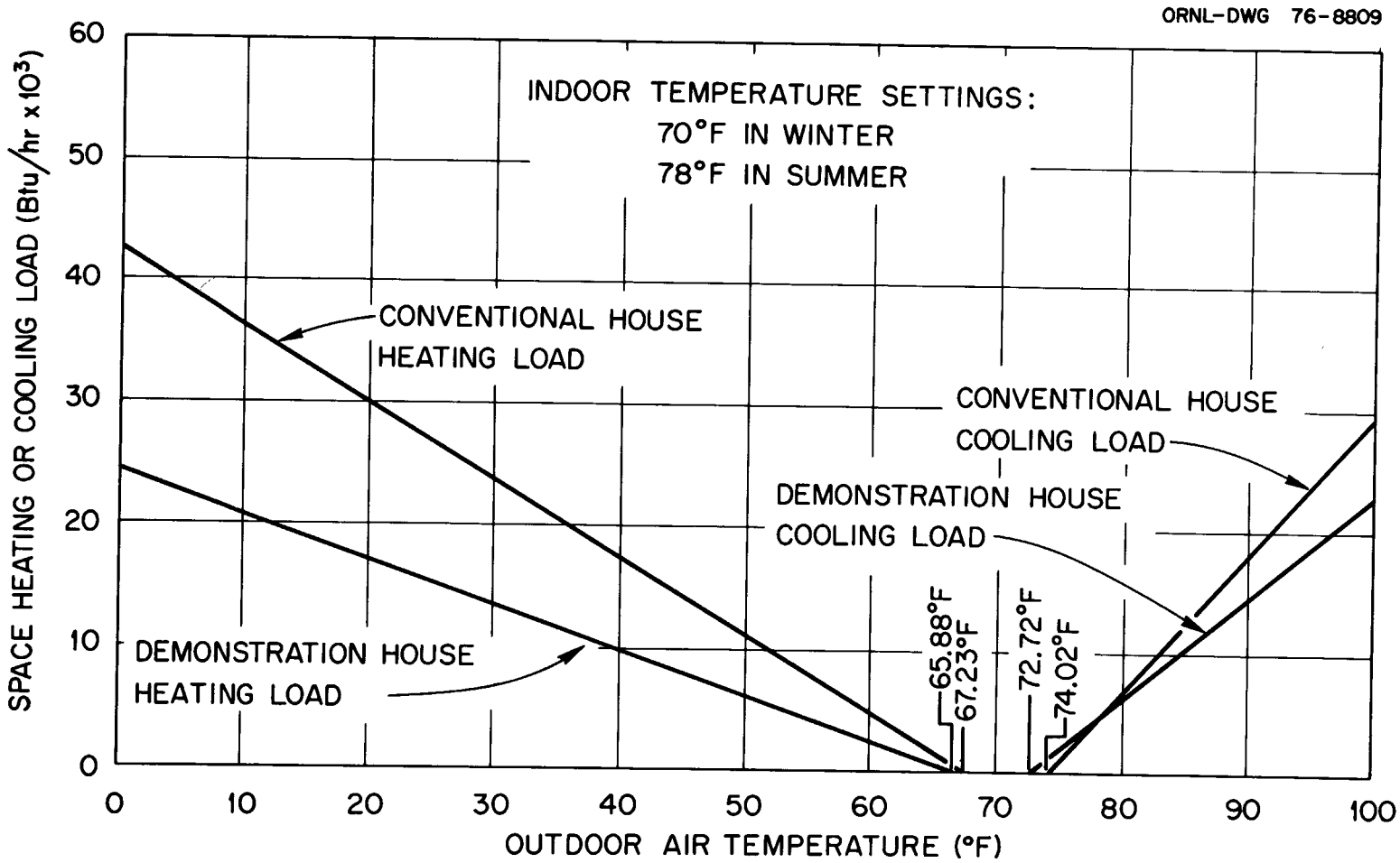

Fig. 3.1 Heating and cooling load

about 74.5^{o} in the daytime or 75.5^{o} at night. The effect on the seasonal cooling requirement of the demonstration house by the economy cycle is shown in the third column of Table 3.1. This economy cycle is a design feature of the demonstration house and will be accomplished by a motor operated damper in the air duct controlled by an outdoor thermostat.

The design conditions for the demonstration house then are those of the third column of Table 3.1 reflecting the heavier than conventional insulation and the "economy cycle."

3.2 Predicted Energy Consumption

The seasonal requirements for space heating and cooling discussed in 3.1.3 are a function of the thermal envelope of the building and of the indoor and outdoor temperatures. The energy consumed in supplying those requirements is a function of the heating-cooling system. Since ACES integrates service water heating with space heating-cooling it must supply all three and therefore the energy comparisons that follow include that for water heating.

The demonstration house incorporates the three energy conserving measures of the thermal envelope, the ACES, and the economy cycle. The energy consumption is calculated for various configurations to evaluate the contribution of each of these measures.

Table 3.3 shows the seasonal requirements of heating, cooling, and water heating for the two different thermal envelopes and shows the electrical energy consumption required to satisfy these requirements with various systems. This table was calculated for the weather data of calendar year 1959 and assumes continuous operation from the preceding

Table 3.3 Comparative energy consumption of different systems loads are for year 1959 of Table 3.2

Insulated to HUD minimum property standards				Insulated to demonstration house standards				
		Energy consumption			Energy consumption			
Seasonal requirements		Resistance heat, elec. A/C, elec. water heater	Heat pump, electric water heater	Seasonal requirements	Resistance heat, elec. A/C, elec. water heater	Heat pump, electric water heater	ACES	ACES with economy cycle
	10^6 Btu	kWhrs	kWhrs	10^6 Btu	kWhrs	kWhrs	kWhrs	kWhrs
Space Heating	43.8	12,837	6,418	20.3	5,920	2,960		
Space Cooling	22.7	3,243	3,243	24.1	3,423	3,423		
Water Heating	16.2	4,750	4,750	16.2	4,750	4,750		
Total kWhrs		20,830	14,411		14,093	11,133	5,967	4,979

year. The demonstration system will actually begin operation upon completion of the house in the second quarter of 1976 which will be at the end of the heating season. The first true annual cycle of operation will be from about November 1976 to November 1977. Table 3.2 displays the results of the performance calculations for the demonstration house for the years of 1955 through 1962 with a system start-up on January 1 of 1955. Thus 1955 might approximate the first year of operation and any of the following years might represent the first full annual cycle of the demonstration house.

3.3 Control Modes

The Annual Cycle Energy System can be operated in different control modes to accommodate to different requirements to the climate, the structure, the occupants, and the choice of installed equipment. The system in the demonstration house was designed to provide full annual cycle heating and cooling for this house in this climate; however, certain control and equipment flexibility is provided to permit simulating operation in other climates and with different system arrangements.

3.3.1 Design Mode. The system will be operated on design for two full years. During the heating season, all of the heat required for space heating and water heating will be withdrawn from the ice storage bank with no contribution from the radiant/convector unless through unusual weather or system operation the ice inventory exceeds 80% of the capacity of the ice storage bank. In that event, solar energy will be collected until the ice inventory is reduced below 80%. During the

cooling season, the space cooling will be accomplished by circulating the chilled brine from the ice storage bank coils through the fan coil. If the ice is exhausted before the end of the cooling season, as is probable in a year having a mild winter and hot summer, the compressor will be permitted to operate at night when the air temperature falls below a predetermined temperature of about 80° to chill the water and perhaps make ice. The thermal storage capacity of the water between 35° and 45° is 1.5×10^{6} Btu which is sufficient to supply about a week of cooling. Over half the hours in July and August are below 80°. Thus, any compressor operation required in the summer will be at a relatively low rejection temperature and off the normal utility peak. During either the heating or cooling season, the compressor is permitted to operate to remove heat from the ice storage bank to heat domestic water under control of the hot water tank thermostat.

3.3.2 Cold Climate Mode. In climates or installations where the heating load considerably exceeds the cooling load the ice bin is sized to store adequate ice for the cooling season but not large enough to provide the full heating requirements. The deficiency of available heat from the ice bin is made up by the radiant/convector panel. Calculations based on the weather data from virtually any of the northern cities show that over the winter there is adequate solar energy available at low temperatures to melt ice or, in a sense, recharge the bin even though there are protracted periods when little or no solar energy is available. The bin provides the thermal flywheel through these periods in addition to storing ice for the cooling season. In this mode the system will function as follows: at the beginning of the heating season the radiant

convector will be operated whenever its outlet temperature is above the bin temperature. This will raise the bin temperature, the evaporator temperature and the Coefficient of Performance (COP) of the heat pump. When the output of the radiant convector is less than the heat required the bin temperature will drop and ice will be formed. At a predetermined time late in the heating season the control system will turn off the radiant/convector and all of the heat will be obtained from the bin thus forming the ice inventory for the cooling season. If the ice investory should exceed 80% of the bin capacity, the radiant/convector will be automatically reactivated to maintain it at or about 80%. This control is described in 5.8.

3.3.3 Warm Climate Mode. In climates or installations where the cooling load considerably exceeds the heating load the bin is sized to supply the heating load and the system is controlled during the heating season to draw all the heating requirement from the bin. The ice formed is used for space cooling. When the ice is exhausted the compressor is permitted to operate, whenever outdoor ambient is below a predetermined temperature, to chill the bin and form ice. The thermal storage capacity of the bin is adequate to carry the cooling load during those periods when outdoor ambient is above the predetermined temperature for efficient heat rejection.

4. Load Management

The ACES requires less installed electrical generating capacity than other electric heating systems because its heating coefficient of performance (COP) is high and independent of outdoor ambient. During the cooling season after the ice is exhausted, the compressor demand approximates that of a conventional properly sized air conditioner; however, the low temperature storage permits the compressor to be operated at the most advantageous time rather than during the hottest hours of the day. During both the heating and cooling season the domestic hot water is heated at a COP of about three thus reducing the demand for that service.

The amount of heating energy that must be supplied by any system, of course, varies inversely with the ambient temperature, however, the electrical energy input required to supply that heat is a function of the efficiency of the system. Resistance heating has a COP of one and therefore its peak demand is the electrical equivalent of the peak heat

load. The conventional air-to-air heat pump efficiency or COP varies with outdoor temperature. Its seasonal COP in Knoxville climate is two or more and thus its annual consumption will be half or less than that of the resistance system. However, on the "coldest day" its COP approaches one and therefore its peak demand approaches that of the resistance system. The ACES heating COP remains at about three, because it has a constant temperature heat source, and therefore its peak demand is about 1/3 that of the resistance or air-to-air heat pump systems. Table 4.1 shows the "coldest day" heating load for the demonstration house and the hourly electrical consumption of each system. The

Table 4.1 Peak hourly electrical consumptions heating season - Demonstration house - three systems Knoxville, Tennessee weather data

Heating load Btu/hr	Peak hourly consumption kWhrs			Date
	Resistance heat	Heat pump[a]	ACES[b]	
26,513	7.8	6.5 - 7.8	3.1	Feb. 1958
28,000	8.2	6.8 - 8.2	3.2	Jan. 1961
30,502	8.9	7.5 - 8.9	3.3	Dec. 1962

[a]Heat pump consumption assumes a COP of 1 to 1.2 during coldest hour.
[b]ACES consumption includes water heating, conventional systems do not.

instantaneous peak demand for each of the heating systems could be higher than the hourly consumption but it is assumed that for residential loads the hourly consumption approximates the diversified peak load. The consumption for ACES includes heating the domestic hot water. The other two systems probably should have some coincident water heating peak added.

During that part of the cooling season in which the ACES can supply the cooling load from stored ice the electrical consumption is only that required for the circulating pump and blower and is much less than that for a conventional air conditioner. However, for a demand analysis it is necessary to consider also a situation in which the stored ice is consumed and cooling is supplied by compressor operation. In this situation the ACES efficiency is approximately that of a good conventional air conditioner and its consumption and demand will be approximately the same. However, the conventional system must supply the cooling load as it occurs, whereas the ACES compressor can operate during the coolest hours of the day or the week and store the cooling effect for use as needed. Thus this load can be managed, if necessary, to be completely off the utility peak. Figure 4.1 is a plot of a day's cooling load for the demonstration house, the approximate consumption curve for a conventional air conditioner and the consumption curve for ACES with stored ice and after the ice is exhausted.

5. Component Specifications and Design Data

5.1 General

The mechanical installation isometric, Fig. 5.1, indicates the location and relative size of the components and the routing of the piping.

ORNL-DWG 76-8808R

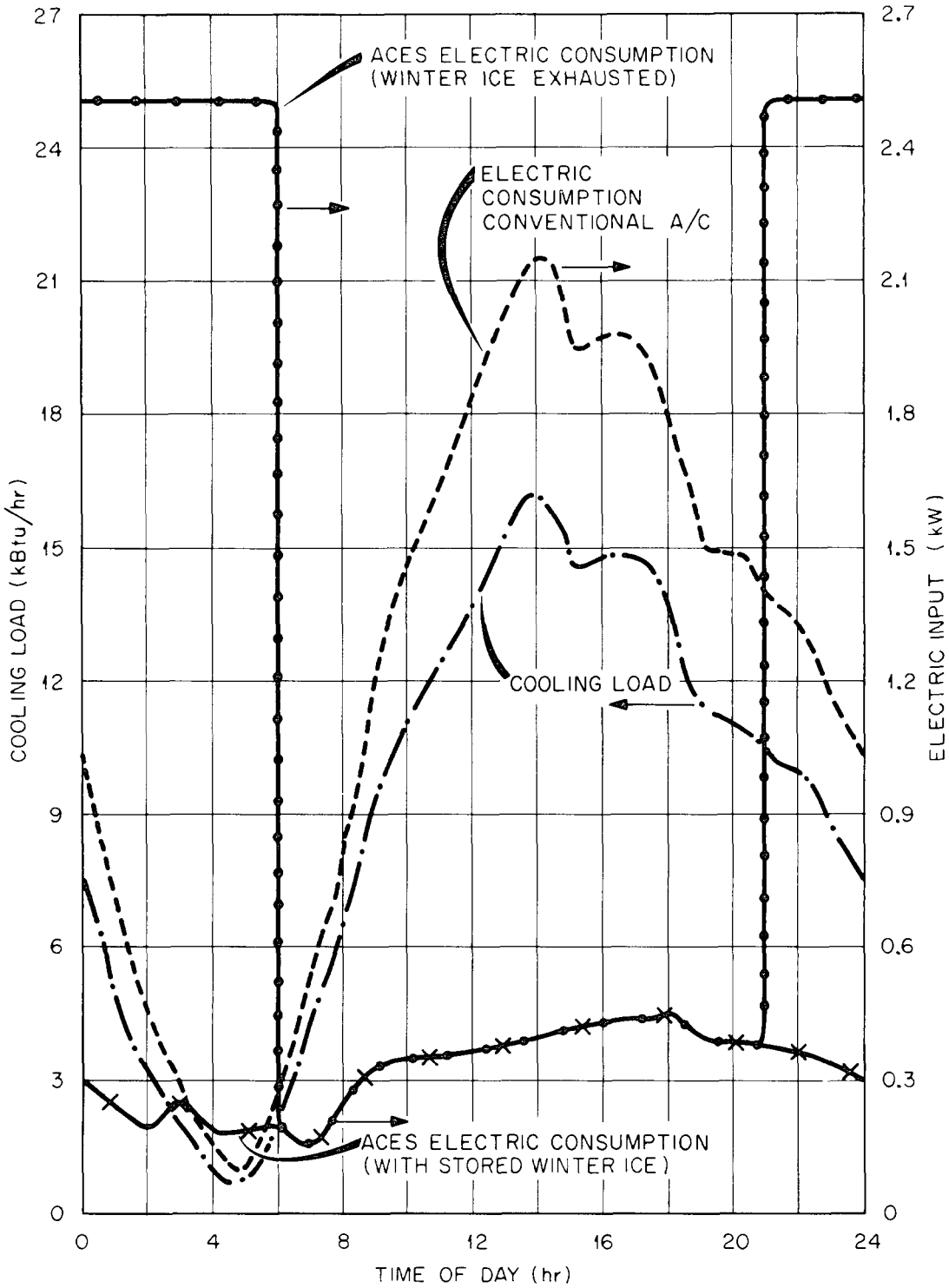

Fig. 4.1 Energy consumption vs. cooling load

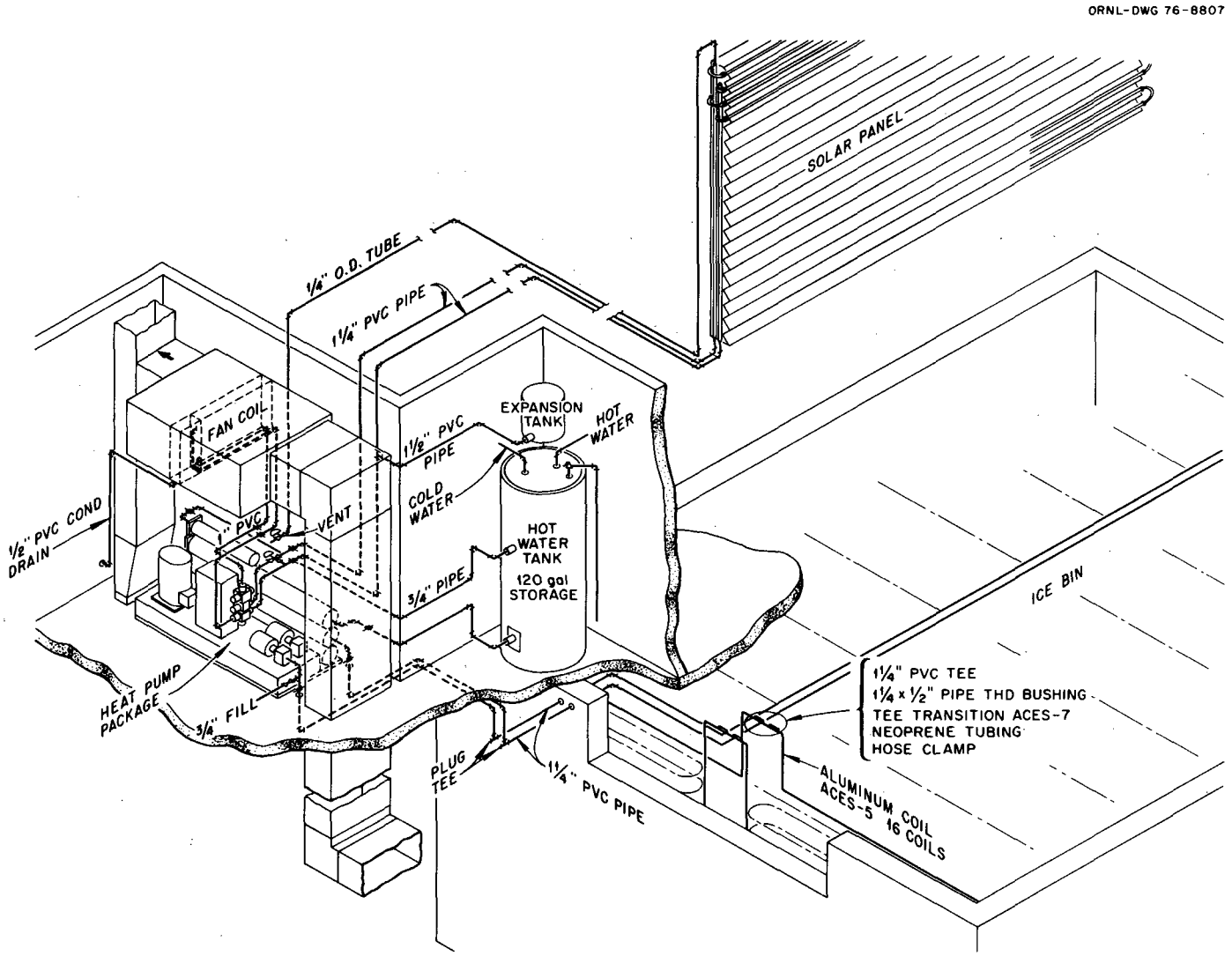

Fig. 5.1 System Isometic

5.2 The Mechanical Package

The mechanical package was custom assembled by Bohn Aluminum and Brass. The factory test performance is shown in Fig. 5.2 and 5.3. It contains the heat pump (the refrigerant compressor), the desuperheater, the water heating condenser, the space heating condenser, the brine cooler (evaporator), the circulating pumps, and the control valves. The heat exchangers are aluminum construction and there are no copper bearing materials in any brine circuits:

cooling capacity	25,000 Btu/hr @ 25° brine outlet
heating capacity	30,000 Btu/hr @ 25° brine outlet 105°F condensing
dimensions	5 ft long x 3 1/2 ft high x 3 ft deep
compressor design load watts	3500
refrigerant	R-22
total pump watts	455

5.3 Ice Storage Bank

The ice storage tank is constructed as an integral part of the basement/foundation of the house. The floor slab and footings are a continuous pour (no expansion joint). Poured into the footings are vertical reinforcing bar stubs, a 2 in. x 4 in. key to tie the vertical walls, and a 1 in. x 4 in. rubber water stop. The walls are a reinforced concrete monolith poured in Foam Form essentially as described in Fig. 5.4. The floor and walls are finish coated with an asphalt-urethane preparation (Lion Oil NOKORODE 705) primarily to prevent chemical

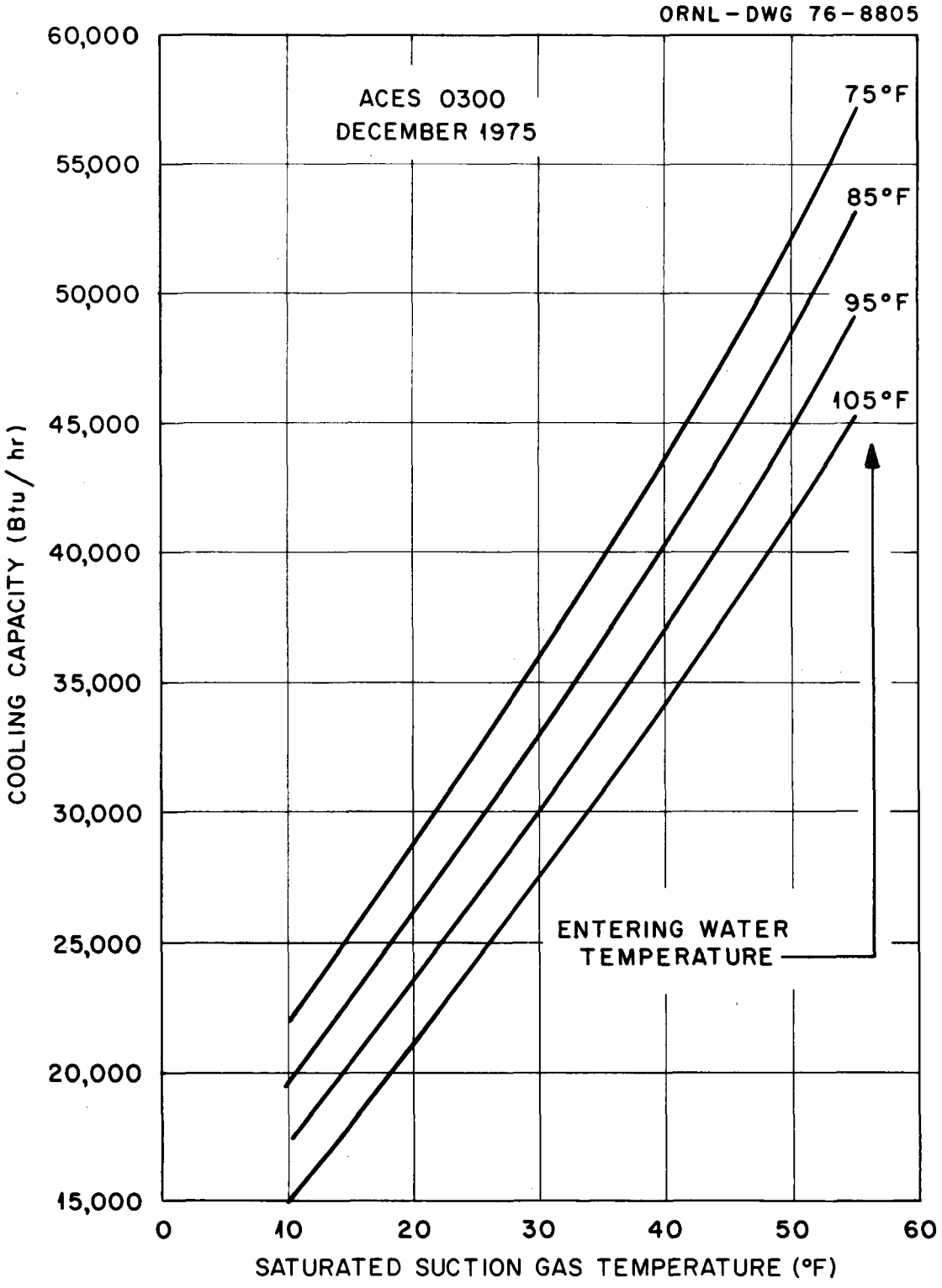

Fig. 5.2 Mechanical package performance

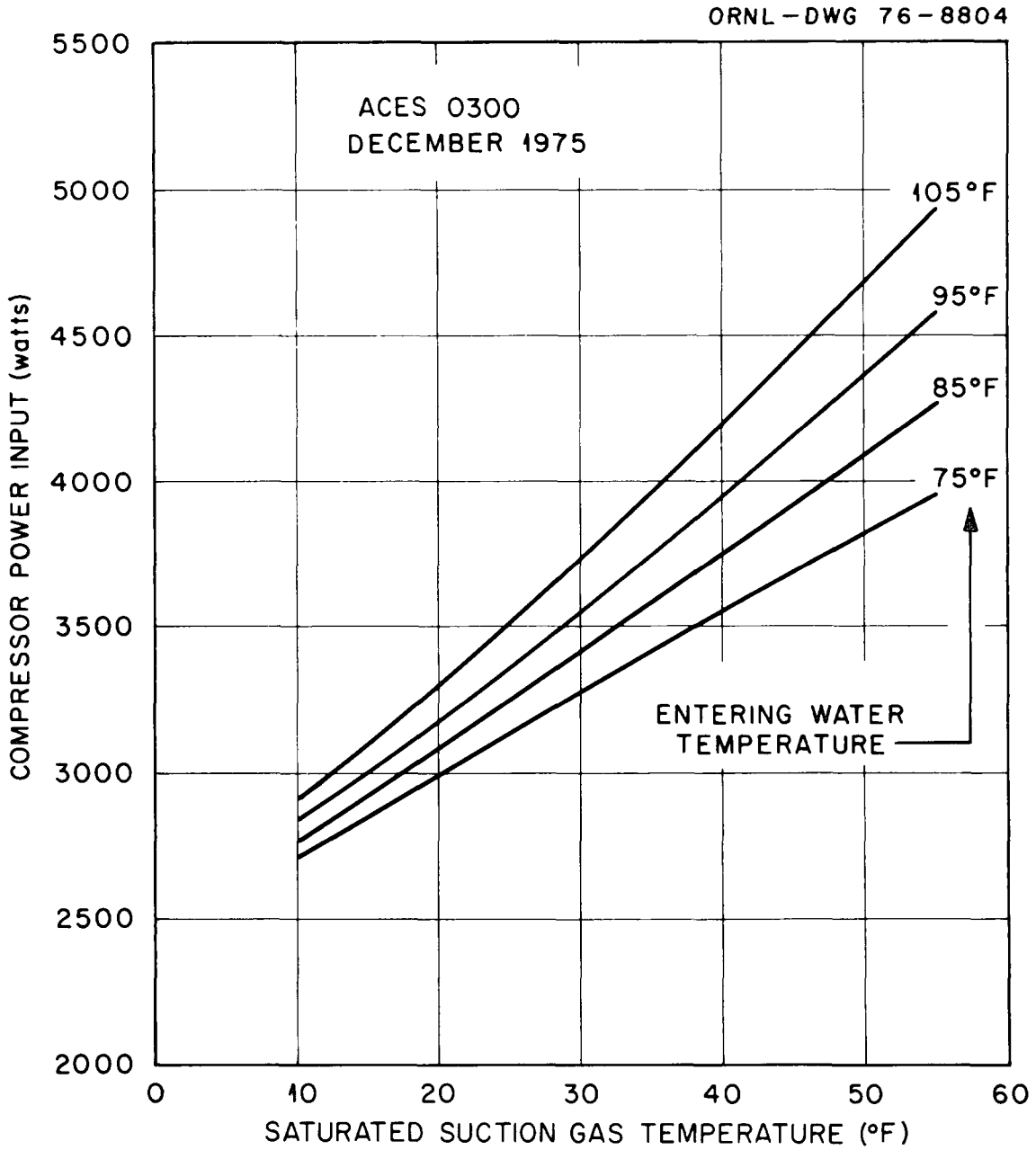

Fig. 5.3 Mechanical package performance

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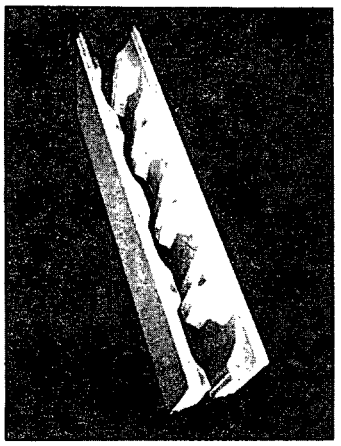
FOAM FORM® BLOCK

For On The Site Construction Of INSULATED STORAGE TANKS For Hot Water or Ice

FOAM FORM blocks are in stock in the 6" core size (9" outside) and each block has a face area of 5.33 sq. ft. Block dimensions are 48" long by 16" high and thickness (over insulation) is 9". Weight per block is approximately 4 pounds. These blocks consist of two parallel molded sections of expanded polystyrene insulation held together by expanded metal ties. Our Part No. 5878.

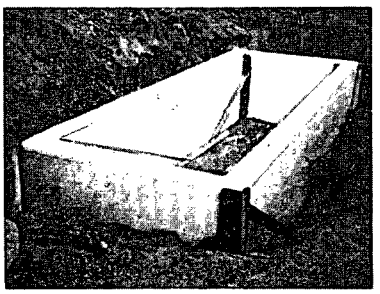


To construct a tank of any size required, soil is excavated and a reinforced concrete slab poured. In pouring the slab, vertical steel rods are positioned to pass through the center of the Foam Form blocks. Foam Form blocks are then assembled (tongue and groove) by dropping over the verticle rods. Horizontal steel reinforcing rods are laid inside each tier of Foam Form blocks. Corners are easily formed by mitring at 45°. Temporary bracing is used to keep corners and walls true while pouring.

The surface may then be covered inside and out with "Block Bond" or equivalent to waterproof the foam insulation. Or a vinyl liner may be used.

By use of Foam Form, a poured concrete tank may be constructed on the job to exactly fit the application and with a minimum of expense for forms.

The form becomes the permanent insulation and the insulating value is approximately R 16.



It is useful for most water or ice storage requirements, including the ACES (Annual Cycle Energy System) since it provides great flexibility and excellent insulation and relatively low cost.

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Fig. 5.4 Foam Form

interaction between the concrete and water and as an added waterproofing. The top or cover is the floor above with 12 in. fiberglass batts between the floor joists.

dimensions	19 ft x 17.5 ft x 7.5 ft fill level (2500 ft^3)
maximum permissable ice inventory	2000 ft^3
total heat of fusion available	16.5×10^6 Btu
sensible heat between 45^oF and 32^oF	2.1×10^6 Btu
average daily cooling load range	100,000 – 250,000 Btu/day

5.4 Ice Building Coils

The coils are constructed of an extruded aluminum tube (Fig. 5.5) having an outside diam of 1/2 in. and an integral axial fin of an overall width of 3 in. The tubing is mounted on support structures that extend from the tank floor to the floor joists overhead to support the weight or resist the bouyancy as the case may be.

tubing quantity	1950 ft
number of parallel circuits	16
center distance	13 in.
maximum permitted ice diam	13 in.
thermal loading	12 Btu/ft hr
brine to water ΔT @ maximum ice dia	9°

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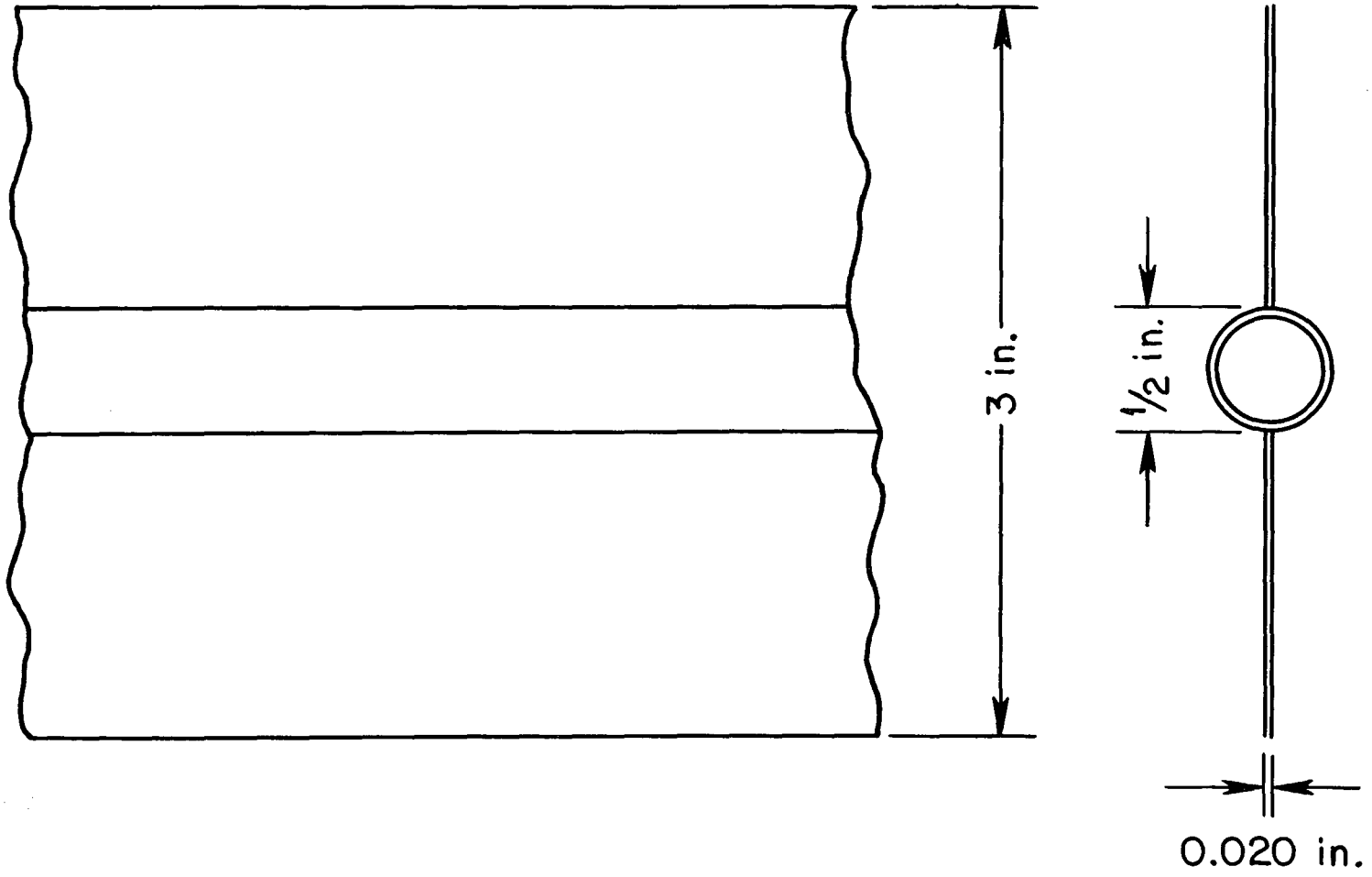

Fig. 5.5 Radiant/convector and ice coil tubing

5.5 Radiant/Convector Panel

The radiant/convector panel occupies a south-facing vertical break in the roof about 8 ft high and 34 ft long (see Fig. 2.5). The tubing is that shown in Fig. 5.2. The support members are 2 in. x 6 in. wood studs cut to a sawtooth form to orient each tube fin 30° from the vertical (normal to the noon sun at winter solstice) and separate them vertically to prevent shadowing. The tubes are nailed to the studs through the fins. The supply and return headers are at one end and return bends at the other to form 13 parallel circuits. No glazing or insulation is installed and free convective air flow is permitted through the panel. The tubes are painted a flat brown.

number of tubes	26
length of tubes	32 ft
radiant surface area	208 ft^2
convective surface area	415 ft^2
design convective coefficient	2 Btu/ft^2, hr, $^{\circ}F$
average incident solar 15 Dec. — 15 Feb.	9000 Btu/ft^2, week
average convective energy 15 Dec. — 15 Feb.	240 Btu/ft^2, week
average total available energy 15 Dec. — 15 Feb.	9480 Btu/ft^2, week or 2×10^6 Btu/week for the whole panel
average house requirement	1.2×10^6 Btu/week

5.6 Fan Coil

The fan coil unit located in the main air duct contains the finned tube brine coil, the circulating air blower, and the motorized damper for the economy cycle.

face area	2.5 ft^2
number of rows	6
liquid side pressure drop	6 ft
liquid flow	6-8 gpm
air flow	1200 cfm
air side pressure drop	0.25 in H_2O

5.7 Brine

The circulating brine is 20% methanol and 80% water.

freezing point	4.5^oF
boiling point	182^oF
density	60.4 lb/ft^3
specific heat	0.97 Btu/lb, ^oF

5.8 System Control

The external control for the system is like any other space heating-cooling system, a room thermostat having a heating and a cooling temperature setting. The internal control system is different, but of about the same complexity as that of a conventional air-to-air heat pump.

The required sensing elements are the room thermostat, the hot water storage tank thermostat, an outdoor temperature thermostat, a radiant/convector thermostat, and an ice inventory sensor.

The primary control functions are as follows:

1) Space heating demand - signaled by the room thermostat turns on the compressor, the brine circulating pumps, and the circulating air blower;

2) Water heating demand - signaled by the hot water storage tank thermostat turns on the compressor, the brine circulating pumps, and the water circulating pump. During the heating season this mode would seldom occur because the compressor operation for space heating will supply adequate hot water;

3) Space cooling demand, chilled brine - signaled by the room thermostat turns on the chilled brine circulating pump and the circulating air blower;

4) Space cooling demand, economy cycle - coincident signal from the room thermostat, indicating space cooling demand, and from the outdoor thermostat indicating that the demand can be satisfied with outdoor air, operates the motor operated damper and turns on the circulating air blower. Outdoor air is drawn into the house (through a screened and filtered louver) and house air discharges outside to cool the house without using the chilled brine.

The secondary control functions, which may or may not occur during a season are as follows:

1) Full ice bin - an ice inventory in excess of 80% during the heating season signaled by the ice inventory sensor indicates the need for supplementary heat to the ice bin. A coincident signal of available supplementary heat to the radiant/convector thermo-

stat will cause brine to circulate between the ice bin and radiant/convector to melt ice. The 80% setting leaves an adequate safety factor for bad weather. Safety instrumentation prevents the compressor from operating if the ice inventory exceeds 90%. Reaching the 80% point could rationally occur only late in the heating season; however, assuming it to occur in January creates no problems. The heat of fusion of the ice available between 80% and 90% is about 2×10^6 Btu and the heat of compression increases this to 3×10^6 Btu. The energy available from the radiant/convector during the month of January is about 8×10^6 Btu. Thus, the capacities of the storage bin and radiant convector far exceed the requirements of the house. The operating schedule assures that the eventuality of reaching 80% capacity could occur only late in the cooling season. Three sets of instruments will prevent the ice from exceeding 90%.

The demonstration house system has three independent methods of determining the ice inventory. One is a set of conductivity probes that directly measure the thickness of the ice on the tubes. The second is a bin water level measurement that infers the ice inventory by the increased volume. The third is a refrigerant suction pressure sensor. The refrigerant evaporating temperature and pressure decreases as the ice diameter increases. When the pressure drops below a predetermined point the pressure switch prevents the compressor from operating. The nature of the ice formation is such that there is never an adequate quantity of trapped water to cause damage if a freeze up should occur. The

ice forms around the tubes and the spaces between the intersecting ice cylinders always has communication to the free surface so that the expansion resulting from freezing results only in the water level rising.

2) Exhausted ice bin - an exhausted ice inventory during the cooling season signaled by an ice bin temperature above $32^{o}F$ indicates the need for supplementary compressor operation. A coincident signal that the radiant/convector thermostat is below 80° turns on the compressor and the brine circulating pumps permitting the system to refrigerate the bin and reject heat to the radiant/convector panel. Again, the thermal storage between 33° and 45° is adequate to provide space cooling through several hot days when rejection may not be possible. However, the exhaustion of ice would normally occur at the end of the cooling season when cool nights should permit heat rejection.

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