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ECONOMICS, TESTING, AND EVALUATION OF AN EXHAUST AIR HEAT PUMP FOR R-2000 (TIGHT) HOUSES

J.W. Linton, P.E.
ASHRAE Associate Member

ABSTRACT

Three balanced airflow ventilation devices were evaluated, an exhaust and supply fan (E&SF), air-to-air heat exchanger (ATAHE), and exhaust air heat pump (EAHP), which can be used to increase the ventilation rate in an R-2000 (tightly constructed) type house.

A prototype of the EAHP, which uses a combination of heat pipe and heat pump, was built and tested.

A frosting and nonfrosting version of the EAHP were evaluated. The nonfrosting version provided the best overall performance. The capacity of the nonfrosting unit, using an additional 1 kW electric resistance heater at low outdoor temperatures, ranged from 7500 Btu/h (2.2 kW) at 59 F (15°C) outdoor temperature to 13400 Btu/h (3.93 kW) at -13 F (-25°C). The coefficient of performance (COP) of the nonfrosting unit (including the electric resistance heater at low outdoor temperatures) had a maximum of 4.8 at 14 F (-10°C) and a minimum of 2.4 at -13 F (-25°C).

INTRODUCTION

In the past, Canadians have relied on the natural infiltration of outside air through cracks and other openings to ventilate their homes during the heating season. Since the early 1970s and the advent of steeply rising energy costs, houses have been built to substantially reduce air leakage and the home heating bill. A new standard for Canadian housing has been set by the R-2000 Super Energy Efficient Housing.

Although significant energy savings have been realized, the reduction in the rate of natural ventilation has created a concern for air quality. It has been found that if the ventilation rate of a house is lowered to below 0.5 of an air change per hour (ACH), problems with indoor air quality can arise (Scheuneman 1982; Tenwolde et al. 1984). With such a low rate of fresh outdoor air entering the house (and a correspondingly low rate of "stale" air leaving the house), pollutants and moisture can build up to what may be unacceptable levels.

The need for controlled ventilation in the home, together with the need for energy conservation, has focused attention on heat recovery from exhaust air.

This paper evaluates three different mechanical devices that could be used to increase the ventilation rate of tightly built R-2000 type houses. The three devices are an exhaust and supply fan (E&SF), an air-to-air heat exchanger (ATAHE), and an exhaust air heat pump (EAHP). A prototype of the EAHP, which uses a combination of heat pipe and heat pump to extract energy from stale exhaust air and preheat incoming fresh air, was built and tested to determine its suitability for commercial development (see Figure 1 for a general equipment

J.W. Linton is a Research Officer, Division of Mechanical Engineering, National Research Council Canada, Ottawa, Ontario, K1A 0R6

arrangement). The three ventilation devices considered would be classified as balanced, where the airflow rate out of the house equals the airflow rate drawn into the house by the device, and hence the pressure inside the house is affected very little.

COMPARISON OF VENTILATION DEVICES

To allow comparison of the three devices, a house with a natural infiltration rate of 0.2 ACH was considered. (This infiltration rate would be typical of tightly constructed R-2000 houses.) The comparison house chosen was a detached, split-entry style house with a heated basement. This house was considered typical of the new R-2000 type construction and was designed to meet usual R-2000 construction specifications. (A more detailed description of the house and method of determining the heat loss is described in Appendix A.)

For this comparison, the energy required to heat and ventilate the house was determined for three cities in Canada. Vancouver, Montreal, and Saskatoon were chosen to represent the range of climates experienced in this country with heating degree-days [65 F (18°C) base] of 5412 (3007), 8047 (4471), and 10938 (6077), respectively.

The test conditions for the ventilation devices were based on CSA Standard C439-M1985, "Standard Methods of Test for Rating the Performance of Heat Recovery Ventilators." The low temperature ventilation performance was determined at a supply air temperature of -13 F (-25°C) with a relative humidity of 50% to 100%. The exhaust air was maintained at a temperature of 71 F (21.6°C) with a relative humidity of 40%.

In each location, three different heating and ventilating strategies were examined. In all cases, the house relied on a gas or electric furnace as the primary heating device; oil heating was not considered because less than 1% of R-2000 houses are constructed with oil heating systems. For the base case, ventilation of the house was accomplished with exhaust and supply fans. In the two other cases, the exhaust and supply fans were replaced by an exhaust air heat recovery device; either an air-to-air heat exchanger or an exhaust air heat pump. CSA Standard C444 - M1985, "Installation Guidelines for Heat Recovery Ventilators," was used as the installation guide for the ventilators.

For the ATAHE, a constant energy recovery of 60% of the heat available from the exhaust air is assumed. All the ventilation devices are assumed to run continuously during the heating season (approximately 6552 hours). With the EAHP, the evaporator (exhaust) and condenser (supply) fans run continuously, and the compressor would operate on demand from the house thermostat.

The costs of various fuels on a regional basis were supplied by the Energy Statistics Handbook (Energy, Mines and Resources Canada). Table 1 shows the cost of energy produced and includes an estimate for typical seasonal furnace efficiency values. As the new generation of high efficiency gas furnaces increases in its market share, the cost of energy from gas will decrease slightly.

Table 2 is a comparison of the energy costs and simple payback associated with the ventilation device when compared to the base case (E&SF) for a gas furnace and an electric furnace. The table shows that the ATAHE is economically attractive at all locations. The EAHP is also economically attractive with the exception of a gas heated house in western Canada where the energy cost ratio between electricity and gas is >2.

Estimates of the capital costs and installation costs for each device are given in Table 3. The capital cost of the E&SF and ATAHE are typical for the Canadian market. The EAHPs capital cost was based on actual construction costs of the prototypes, with a factor to allow for cost reduction of a manufactured unit. The installation costs are based on typical contractor estimates for new construction.

The heating provided by the EAHP for the different locations is summarized in Table 4. The table shows that the EAHP can provide a substantial portion of the house heating requirements. All tabulated costs indicated are in Canadian dollars.

THE EXHAUST AIR HEAT PUMP

The prototype EAHP was built by the Low Temperature Laboratory, National Research Council Canada (see Figure 1 for general equipment layout and Figure 2 for as-built component layout).

Two versions of the EAHP were investigated, one using an air defrost system to clear the evaporator when frosting became excessive, the second using an evaporator pressure regulator to limit the evaporator temperature to a minimum of 30 F (-1.1°C), which eliminated the need for any defrosting.

Heat Pipe

The heat pipe was included in the EAHP for the following reasons:

1. It allowed the refrigeration system to be smaller than an EAHP without the heat pipe.

2. The heat pipe preheats the supply air before reaching the condenser. This helps to alleviate the problem of low condensing pressure, and it also keeps the suction temperature up.

The heat recovery effectiveness of the heat pipe was initially selected at 30%. This would allow maximum energy recovery from the exhaust air but would not frost the heat pipe coil at low outdoor temperatures. It would also maintain the exhaust air temperature high enough to defrost the evaporator if it became frosted.

Heat Pump

The preliminary design specifications for the main heat pump components (i.e., compressor, condenser, and evaporator) were established, and the equipment was selected using a heat pump system design method (Hawken et al. 1984) that has proved to be reliable in predicting the performance of real heat pump systems. Sizing of the major EAHP components was based on the following criteria:

-- Heat Source: 150 SCFM (70.8 std L/s) airflow exhaust from the house at 71 F (21.6°C) and 40% RH

-- Heat Sink: 150 SCFM (70.8 std L/s) airflow supplied to the house at -13 F to 59 F (-25°C to 15°C) and 50% to 100% RH

-- Working Fluid: R12 (dichlorodifluoromethane) evaporating in the range of 22 F to 35.6 F (-5.5°C to 2°C) and condensing in the range of 90 F to 120.5 F (32.2°C to 49.1°C)

EXHAUST AIR HEAT PUMP OPERATING CONTROLS

Automatic Operation

The EAHP is normally operated by the first stage of a two-stage room thermostat. The second stage of the thermostat will energize the house heating system if the EAHP cannot maintain the set temperature. The thermostat stops and starts the heat pump compressor. The supply and exhaust fans in the EAHP will operate continuously, providing fresh air and exhausting stale air from the house.

Electric Heater

A 1 kW electric heater was included in the EAHP to ensure that the temperature of the fresh air supplied to the house does not fall below 70 F (21.1°C) (see Figure 1 for location).

The electric heater was installed upstream of the heat pump condenser as a means of head pressure control at low supply air temperatures.

Automatic Defrost (Frosting EAHP)

The frosting version of the EAHP requires periodic defrost at outdoor temperatures below 14 F (-10°C). The defrosting of the heat pump evaporator was accomplished by stopping the heat pump compressor and allowing warm exhaust air from the house (after it exits the heat pipe) to defrost the coil. There is a drain pan under the evaporator and heat pipe to remove moisture from the EAHP.

The defrosting of the EAHP was initiated by an air pressure differential switch with pressure sensing points located between the inlet to the heat pipe and the outlet of the evaporator. The pressure switch would initiate a defrost when the pressure differential reaches the set point, which indicates the evaporator coil is blocked with frost.

CONSTRUCTION OF THE EXHAUST AIR HEAT PUMP

All the components of the EAHP were purchased from outside suppliers as off-the-shelf items where possible or were built to the design specifications provided. The major components were mounted on the base plate of the steel case (see Figure 2 for as-built component layout).

The physical size of the EAHP was determined by the size and position of the major components. The heat pipe determined the width and height, and the spacing of the coils and fans determined the length. Figures 3 and 4 are photographs of the EAHP during construction.

TESTING OF THE EXHAUST AIR HEAT PUMP

The purpose of testing the EAHP was to provide an accurate assessment of its operation at the specified indoor and outdoor temperature ranges.

The prototype EAHP was tested in a psychrometric calorimeter. The calorimeter consists of two rooms, one to simulate outdoor conditions, and the other to simulate indoor conditions. The test loop for the EAHP is shown in Figure 5.

The EAHP was located in the indoor test chamber. Exhaust air was drawn from the indoor room through the EAHP and then through an airflow meter and supplementary fan to the outdoor room. The outdoor test chamber was used as the source for conditioned fresh air. The outdoor air was drawn through the EAHP and then through an airflow meter and supplementary fan and into the indoor test chamber. The inlet and outlet temperatures of the supply and exhaust airstreams were measured by a thermocouple grid in the air ducts.

Test Requirements

The main requirements of the testing were as follows: (1) establishment of the actual operating performance of the EAHP as a complete unit, i.e., the difference in temperature between inlet and outlet on the supply and exhaust sides; (2) measurement of electrical power usage of the compressor, heater, and supply and exhaust fans; (3) determination of the energy input to incoming fresh air; (4) determination of the coefficient of performance (COP); (5) observation of the defrost frequency for the frosting EAHP and the effectiveness of the air defrost in clearing the evaporator coil; and (6) determination of which version (frosting or nonfrosting) is the best choice for commercialization.

COMMISSIONING

The electrical controls were checked for proper operation and the refrigerant system checked for leaks and evacuated. The vacuum in the refrigeration system was broken with refrigerant 12 and the compressor was started.

After the heat pump was operating with the correct refrigerant charge, the evaporator was allowed to frost in order to set the differential air pressure switch and the defrost termination thermostat.

Commissioning Problems

One of the major commissioning problems discovered during initial testing at low temperature was frosting of the exhaust side of the heat pipe. The heat pipe specification to the manufacturer was for a nonfrosting design to avoid defrosting problems, and this limited its effectiveness to about 30%. After the frosting problem was observed, the heat pipe was tested without the heat pump operating and was found to be 57% effective. Because no allowances were made in the design of the EAHP to defrost the heat pipe, and a more effective heat pipe would adversely affect the operation of the heat pump, it was decided to derate the heat pipe to the specified 30% effectiveness. The heat pipe was made up of individual aluminium finned tubes and was three rows deep. It was derated by drilling a hole in the end of selected tubes and releasing the refrigerant inside the tube. The entire first row of the heat pipe was drilled, and the effectiveness of the heat pipe was reduced to 36%. This proved to be sufficient to keep the tubes frost free at -13 F (-25°C) outdoor air temperature.

RESULTS OF TESTING

The EAHP performed very well with no problems evident in its operation. The heat pump system operated for extended periods in a wide variety of outdoor and indoor temperatures and humidities without difficulty.

The air defrost system selected was very effective in clearing the frosted evaporator, and the method of initiating and terminating the defrosts worked without difficulty.

The evaporator on the nonfrosting EAHP (with evaporator pressure regulator) remained frost free for all the conditions tested, and there were no operating problems when the regulator was used. The regulator comes factory preset at the required pressure, and no field adjustments to the regulator were required.

Frosting versus Nonfrosting EAHP

Two versions of the EAHP were tested, a frosting evaporator type with air defrost system and a nondefrosting evaporator type with an evaporator pressure regulator.

Figures 6, 7, and 8 compare the capacity of the two versions during one cycle (from startup after defrost to completion of defrost) of the frosting EAHP at -13 F (-25°C), 1.4 F (-17°C), and 14 F (-10°C) outdoor temperature (these figures are for 71 F (21.6°C) and 40% RH indoor conditions).

Figure 6 shows that at -13 F (-25°C) the frosting evaporator has slightly more capacity over the complete cycle (including the defrost period when the heat pump is shut off) than the nonfrosting evaporator. At about 1.4 F (-17°C) outdoor temperature there is no difference in capacity over the complete cycle between the two version (see Figure 7). Above this temperature, the nonfrosting unit has more capacity over the complete cycle. The frosting version still required a defrost period of about four minutes every hour at 14 F (-10°C) (Figure 8). The total hours of operation below 1.4 F (-17°C) is very low at most locations and the nonfrosting version would therefore provide the greater total energy savings.

The nonfrosting version also has several practical advantages over the frosting evaporator. The electrical controls are simplified when defrosting is not required, and the nonfrosting unit would not require an air pressure differential switch, defrost relay, defrost termination thermostat, and heater relay. The defrost controls are also a source of possible service problems that can be eliminated from the nonfrosting unit.

Figure 9 is a comparison of capacity between the frosting and nonfrosting EAHP (frosting version capacity is the average capacity achieved throughout the cycle). The figure shows that the capacity of the EAHP increases as the outdoor temperature falls, which is

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APPENDIX A
Characteristics of House Model

The standard house chosen for comparison of various ventilation practices is meant to represent a typical detached house with heated basement that has been constructed to conform to R-2000 type specifications. The insulation values, size of south-facing windows, etc., were taken from the typical figures given in a monitoring report of constructed R-2000 houses across Canada (Dumond 1984). Two adults and two children are assumed to occupy the house. The following references were used as a guide when determining the heat loss of the house (Cane 1979; Dumont, et al. 1982). The house heating requirement was calculated for the various temperature increments (bins) at each location. Details are given below:

Mechanical ventilation for winter conditions	0.5 ACH
Air infiltration for winter conditions	0.2 ACH
Living area	1,141 ft^2 (106 m^2)
Basement area	1,141 ft^2 (106 m^2)
Total house volume, for 8 ft (2.44 m) ceiling	18,267 ft^3 (517 m^3)
Thermal conductance of building skin above grade	123.5 Btu/h·F (65.3 W/°C)
Below-grade heat loss (assumed constant)	1,365 Btu/h (0.4 kW)
Gain from appliances, lights, people, and sun (assumed constant)	5,292 Btu/h (1.55 kW)
Loss due to a total ventilation rate of 0.7 ACH	340 Btu/h·°F (179.7 W/°C)

Cane, R.L.D. September 1979. "A modified bin method for estimating annual heating requirements of air source heat pumps." ASHRAE Journal: 60-63.

Dumont, R. December 1984. "R-2000 home monitoring report, interim monitoring results," Division of Building Research, Saskatoon, National Research Council Canada.

Dumont, R.; Lux, M.E.; and Orr, H.W. September 1982. R-2000 Energy Analysis Program, Rev. 4.02.2, based on NRC Hotcan 2.0 DBR Computer Program No. 49, Division of Building Research, National Research Council Canada.

TABLE 1

Energy Costs in 1987 dollars

	VANCOUVER B.C.		SASKATOON SASK.		MONTREAL QUE.	
	GAS[1]	ELECT.[2]	GAS	ELECT.	GAS	ELECT.
ENERGY COST $/Btu × 10^6 ($/GJ)	8.25 (7.82)	16.09 (15.25)	7.16 (6.79)	16.44 (15.58)	11.00 (10.43)	13.48 (12.78)

1. Gas prices are for June 1987 and for a monthly consumption of 10,000 ft^3 (282 m^3). Energy value of gas is 1,000 Btu/ft^3 (37.259 MJ/m^3). Average furnace efficiency of 70% is assumed.

2. Electricity prices are based on the average bill for a consumption of 750 kWh/month as of June 1987.

3. Information supplied by Energy Mines & Resources, Energy Statistics Handbook.

TABLE 2

Comparison of Energy Costs Associated with Ventilation Device

	GAS FURNANCE			ELECTRIC FURNACE		
Location and recovery device used	Cost of heating & ventilation (1987$)	Energy cost savings of recovery device compared to base case (1987$)	Simple pay back period for recovery device (yrs)	Cost of heating & ventilation (1987$)	Energy cost savings of recovery device compared to base case (1987$)	Simple pay back period for recovery device (yrs)
MONTREAL, Que						
Base case	606.00	-	-	734.00	-	-
ATAHE	382.00	224.00	3.3	459.00	275.00	2.7
EAHP	303.00	303.00	4.4	323.00	411.00	3.3
SASKATOON, Sask.						
Base case	572.00	-	-	1246.00	-	-
ATAHE	380.00	192.00	3.9	806.00	440.00	1.7
EAHP	471.00	101.00	13.3	640.00	606.00	2.2
VANCOUVER, B.C.						
Base case	272.00	-	-	466.00	-	-
ATAHE	155.00	117.00	6.4	267.00	199.0	3.7
EAHP	161.00	111.00	12.1	161.00	304.00	4.4

TABLE 3

Estimated Cost of Ventilation Devices

	E&SF	ATAHE	EAHP
Capital Cost (1987 $)	150	800	1400
Installation Cost (1987 $)	700	800	800
Total Cost (1987 $)	850	1600	2200

TABLE 4

Heating Provided by Exhaust Air Heat Pump for Heating Season

	Vancouver B.C.	Montreal Que.	Saskatoon Sask.
Useful heat supplied by EAHP Btu × 10^6 (GJ)	29.6 (31.27)	44.3 (46.79)	55.1 (58.19)
Heating required by house Btu × 10^6 (GJ)	29.6 (31.27)	52.6 (55.47)	73.3 (77.39)
Percentage of house heating load met by EAHP	100	84.4	75.2

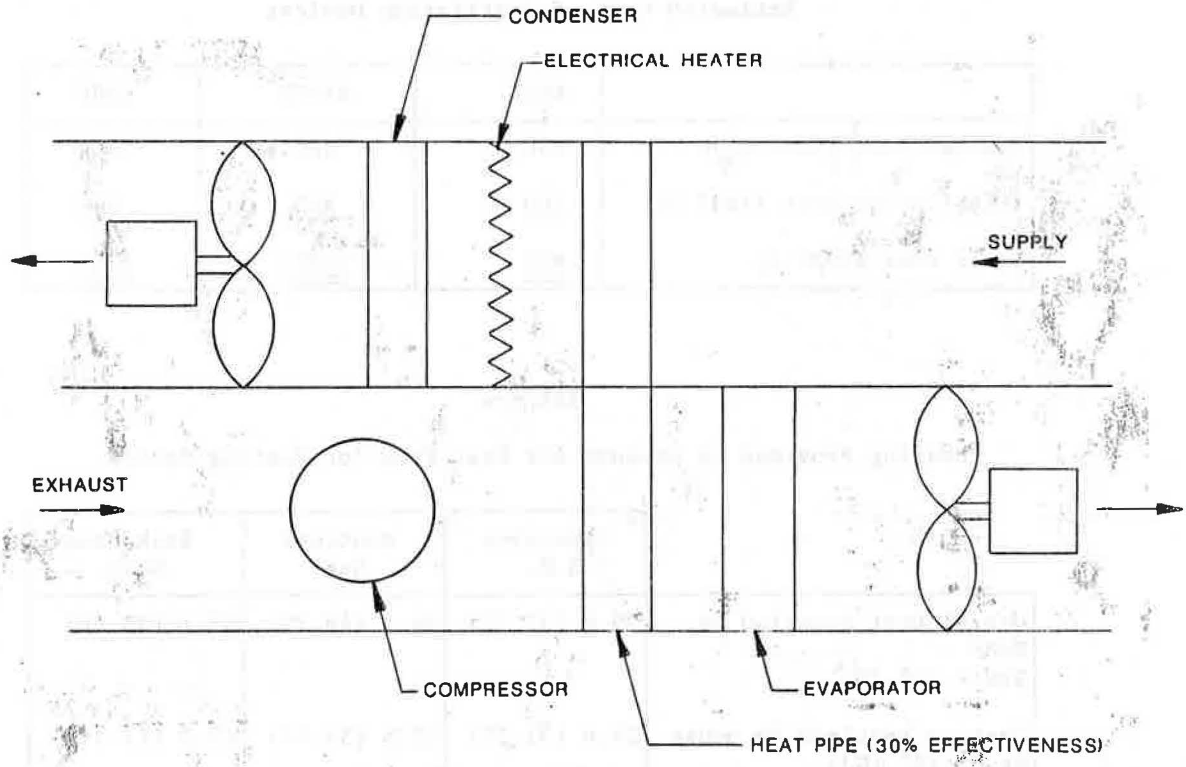


Figure 1 Exhaust air heat pump equipment arrangement

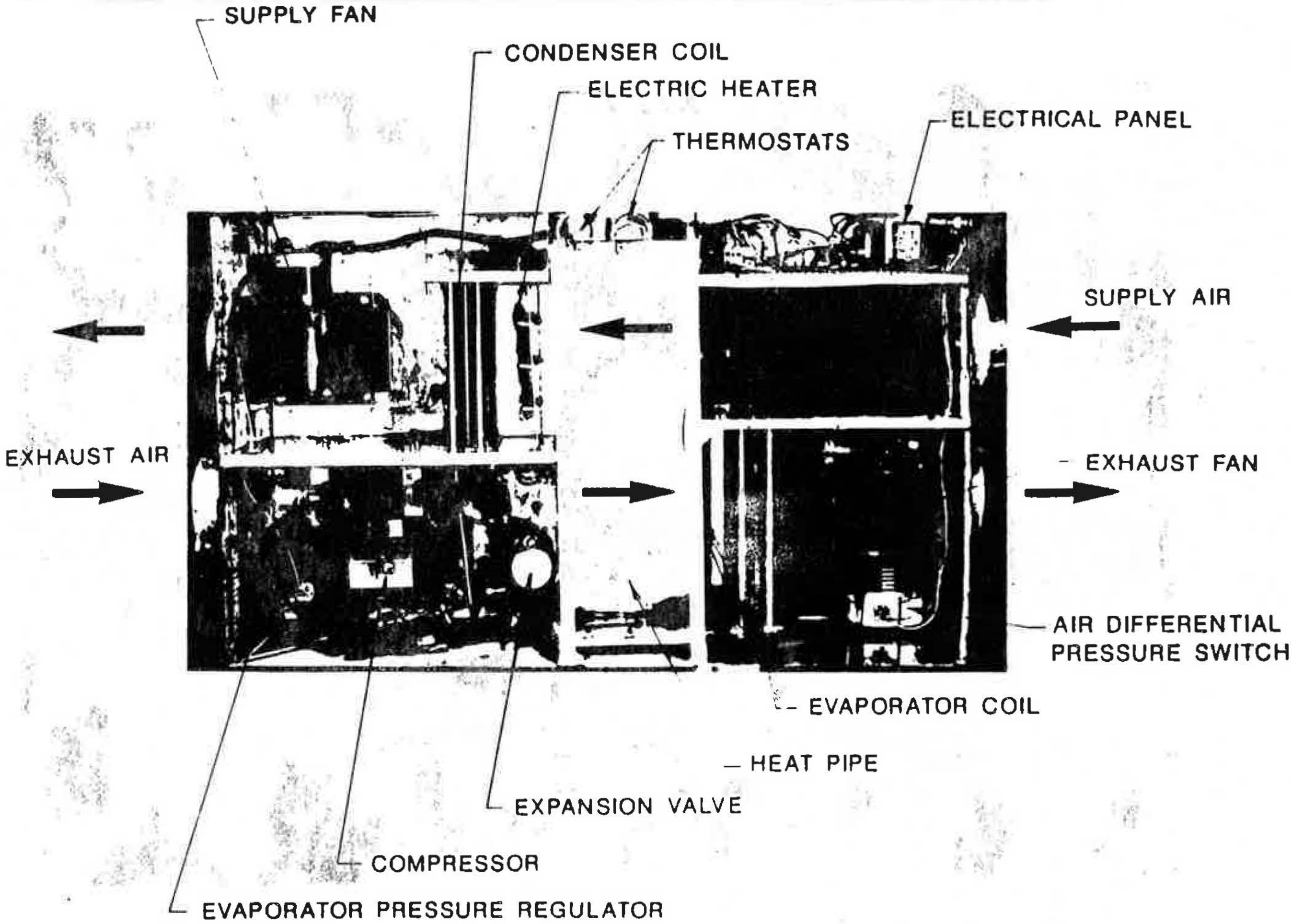
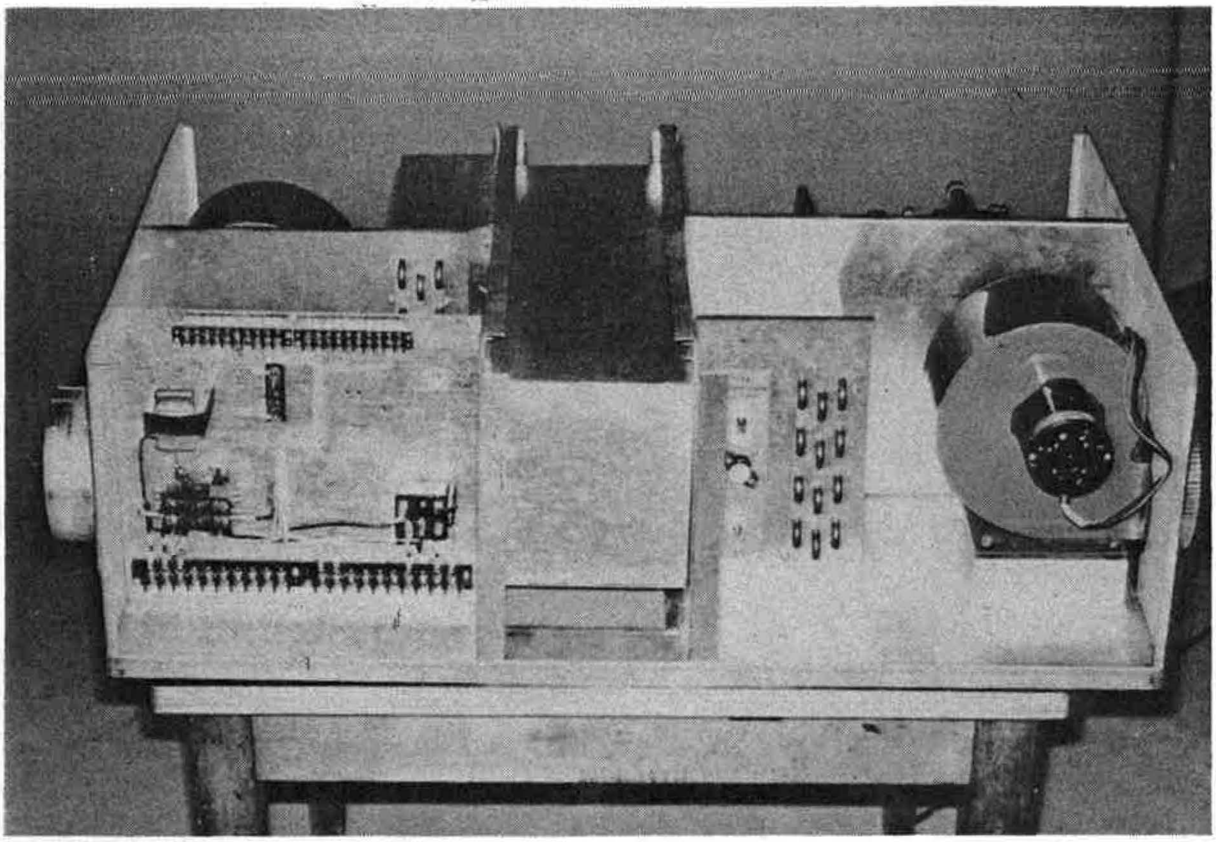


Figure 2 Exhaust air heat pump as built layout (plan)



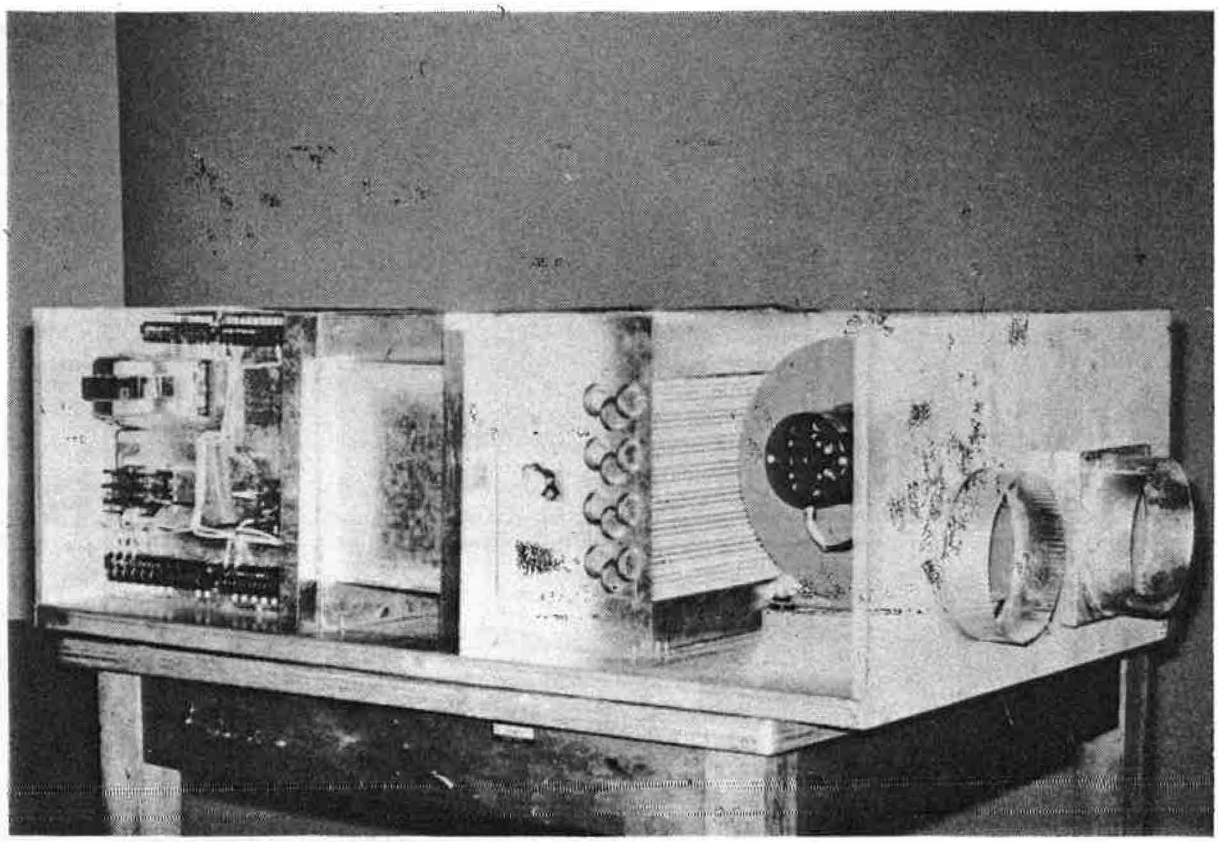
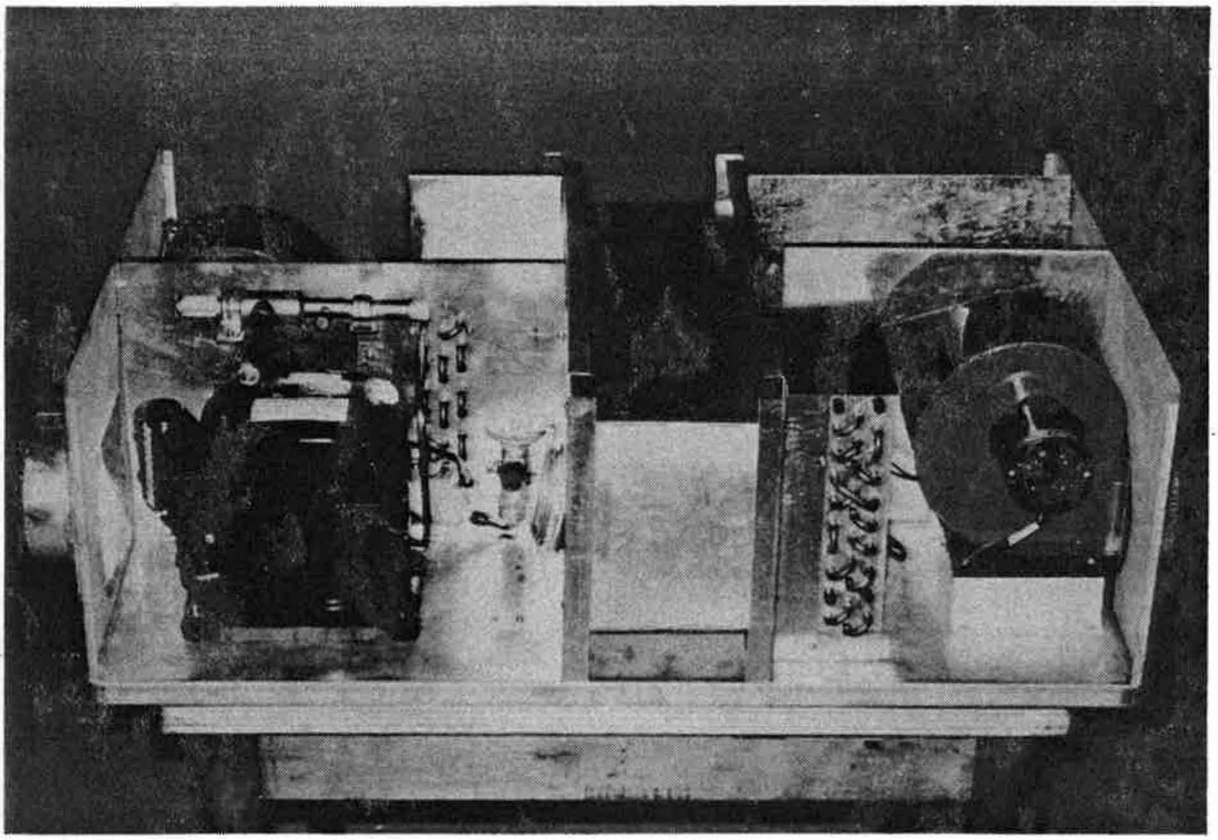


Figure 3 EAHP during construction (supply air side)



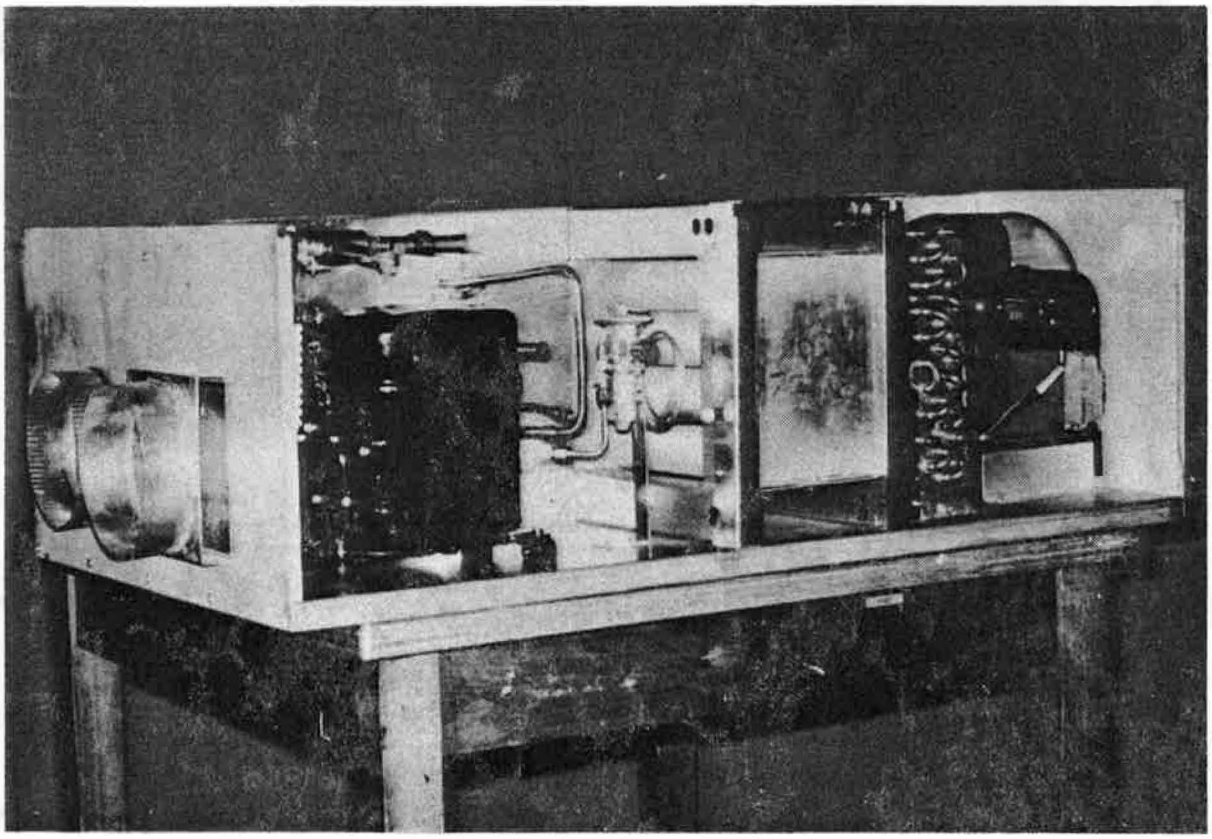


Figure 4 EAHP during construction (exhaust air side)

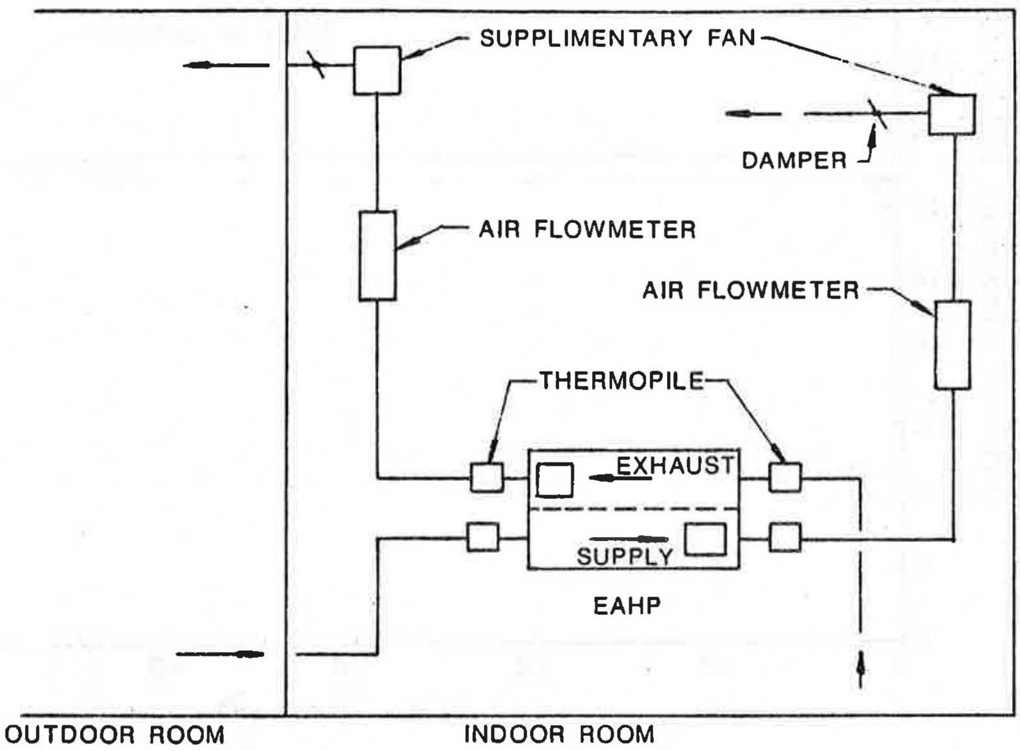


Figure 5 Layout of test loop in psychrometric calorimeter

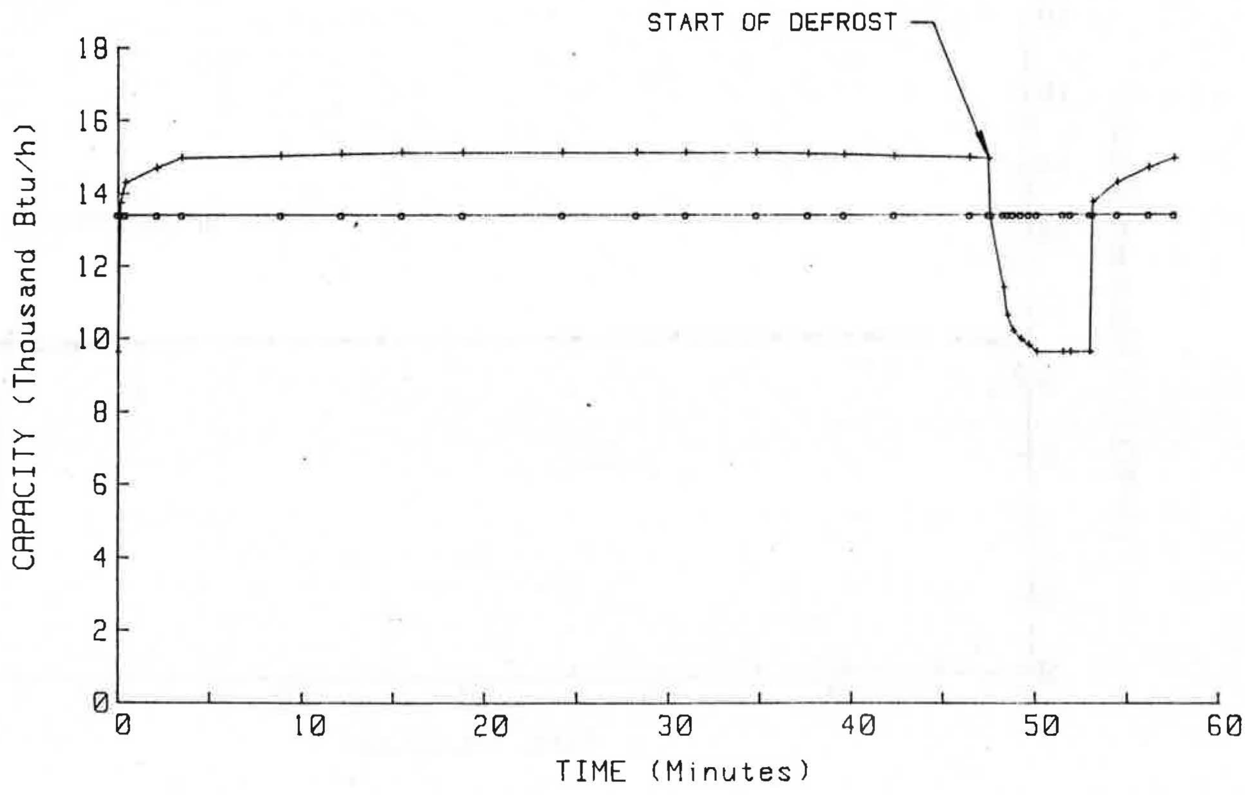


Figure 6 Comparison of capacity for non-frosting and frosting EAHP during one cycle at -13 F (-25°C) outdoor temperature (+ frosting; o non-frosting)

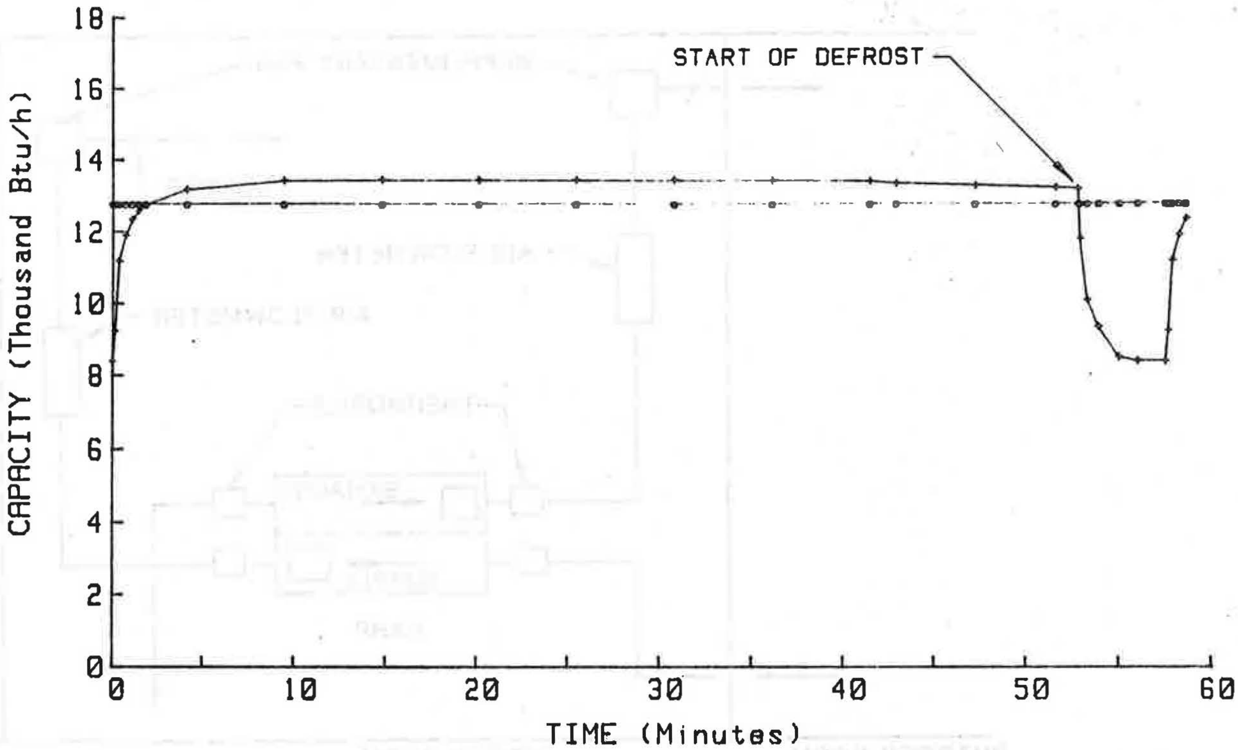


Figure 7 Comparison of capacity for non-frosting and frosting EAHP for one cycle at 1.4 F (-17°C) outdoor temperature (+ frosting; o non-frosting)

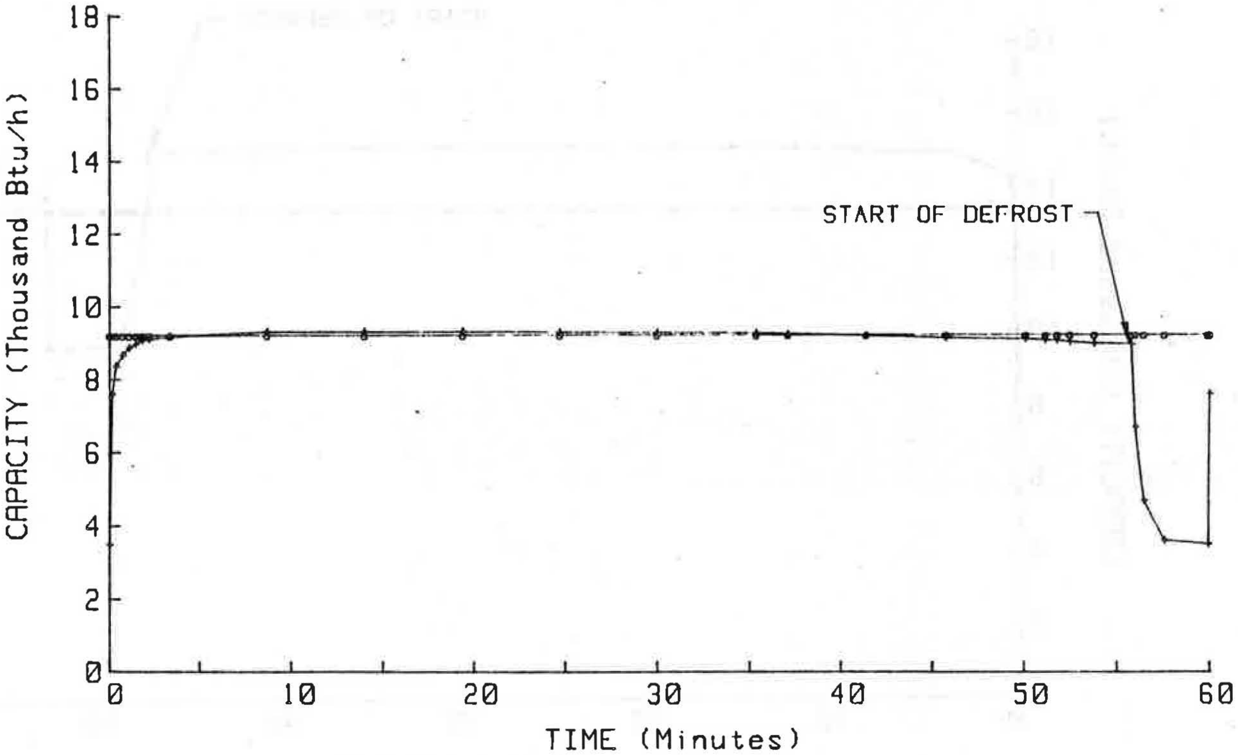


Figure 8 Comparison of capacity for non-frosting and frosting EAHP for one cycle at 14 F (-10°C) outdoor temperature (+ frosting; o non-frosting)

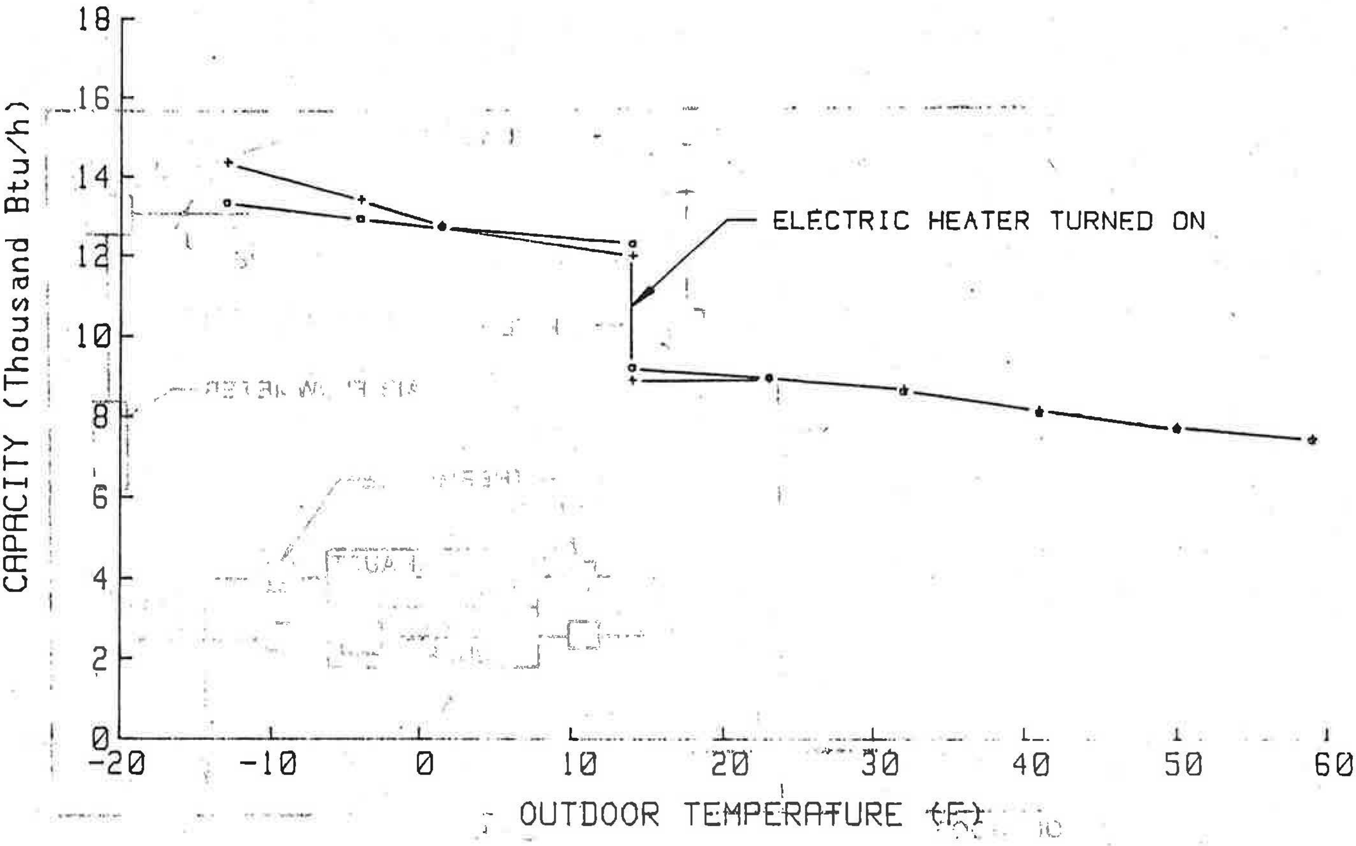


Figure 9 Comparison of capacity for non-frosting and frosting EAHP vs. outdoor temperature (+ frosting; o non-frosting)

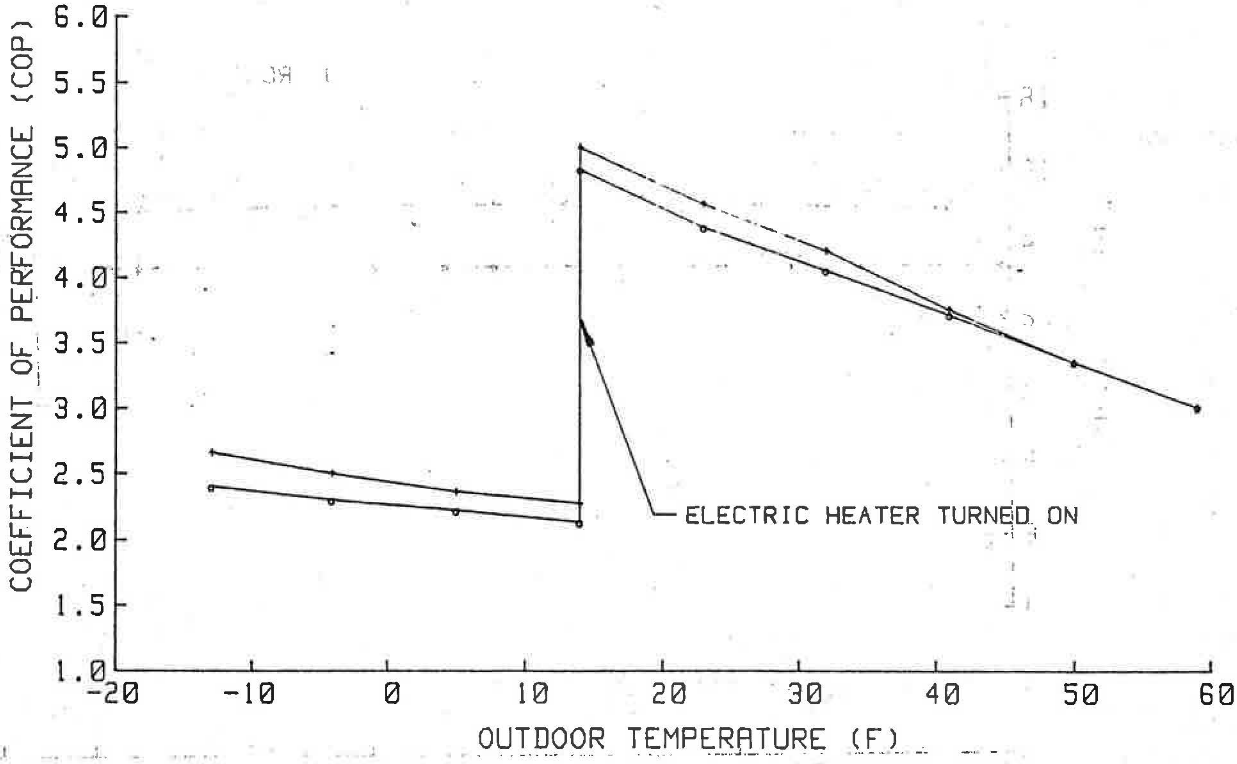


Figure 10 Comparison of COP for non-frosting and frosting EAHP vs. outdoor temperature (+ frosting; o non-frosting)