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Add-on Heat Pump for Residential Applications - Estimation of the Savings

Lance N. McCold

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UNION CARBIDE CORPORATION
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ADD-ON HEAT PUMP FOR RESIDENTIAL APPLICATIONS - ESTIMATION OF THE SAVINGS

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ACRONYM AND VARIABLE DEFINITIONS

A_{bn}	burner on factor, function of cycle time that the furnace burner is on
ABP	application balance point, the outdoor temperature below which the heat pump has insufficient heating capacity to maintain the house at the thermostat setting, (°F)
AOHP	add-on heat pump
AS	annual dollar savings from use of add-on heat pump excluding maintenance and service ($/year)
ASDL	annual dollar savings divided by design load, AS/DL ($-h/yr-$10^3$Btu)
ASDLEP	annual dollar savings divided by DL and electricity price, ASDL/EP ($-h-kWh/yr-$10^3$Btu-¢)
balance point	the outdoor temperature above which a house needs no heating (frequently assumed to be 65°F)
C_D	empirical correction factor for heating effect vs 65°F (18.3°C) heating degree days (References 8 and 10)
C_f	empirical savings correction factor
COP	coefficient of performance, the ratio of heat output to energy input
COP17	heat pump COP at 17°F
COP47	heat pump COP at 47°F
DCCF	frost/defrost capacity correction factor
DECF	frost/defrost efficiency correction factor
DL	design load (10^3Btu/h), as used here it is HEUR times the difference between the balance point temperature and outdoor design temperature (ODT)
EBP	economic balance point, the outdoor temperature below which it is less expensive to run the furnace alone than the AHOP (°F) EP electricity price (¢/kWh)
E_{utl}	utilization efficiency, heat added to forced-air system inlet air divided by the chemical and electrical energy input FC furnace heating capacity (10^3 Btu/h)
FCCF	furnace capacity correction factor, correction to values of ASDL in the proposed audit procedure

FE	furnace efficiency
FLF	furnace load factor
FP	fuel price (¢/kWh)
FRT	fraction of cycle the furnace runs
HPC	heat pump heating capacity (Btu/h)
HPC17	heat pump heating capacity at 17°F (Btu/h)
HPC47	heat pump heating capacity at 47°F (Btu/h)
HPRT	fraction of cycle the heat pump runs
HEUR	heating energy use rate, the rate of heat loss increase with increase of indoor/outdoor temperature difference (Btu/h-°F)
L	building heat loss rate (Btu/h)
ODT	outdoor design temperature, for the purposes of this report it is taken to be the temperature of the lowest temperature bin with one or more hours (°F)
PF	fuel price correction factor for step 6 of the proposed audit procedure
Q	building heat capacity (Btu/°F)
RFC	Rated furnace capacity (Btu/h), this is the fuel consumption capacity of the furnace it is usually given on the furnace nameplate
SSFE	steady state furnace efficiency
T	temperature (°F)
t	time
ΔT_f	change of thermostat temperature during furnace operation
ΔT_{hp}	change of thermostat temperature during heat pump operation
ΔT_z	change of thermostat temperature while no equipment runs
Δt_f	duration of furnace part of cycle
Δt_z	duration of no heat part of cycled

ABSTRACT

The Residential Conservation Service (RCS) program requires large gas and electric utilities to offer energy audits to residential customers. An auditor must examine the customer's house and advise the homeowner on the advisability of a minimum menu of energy conservation measures. State governments have the option of adding measures for utilities within their jurisdiction. The add-on heat pump is a state-added measure in Florida and Wisconsin.

The add-on heat pump (AOHP) is a heat pump which is added onto an existing oil- or gas-fired forced-air heating system. This work was performed to assess the characteristics and potential value of AOHPs and to develop an audit procedure for use by those states which have added the AOHP to the basic audit.

This report presents an analysis of the operation of add-on heat pumps. Based on the AOHP operating characteristics a bin-hour method of estimating annual operating savings is developed and explained. This method is used to examine the sensitivity of AOHP savings to equipment capacities and efficiencies, fuel prices and climate. Based on the sensitivity analysis, a simplified AOHP savings estimation procedure, suitable for auditor use, is presented.

AOHP annual operating savings depend very strongly on fuel prices and climate. In mild climates, add-on heat pumps pay for themselves slowly unless fuel prices are quite favorable. For oil at $1/gallon and electricity at 6¢/kWh simple payback periods (not including maintenance costs) of 6-100 years were estimated. In cool climates with relatively high heating fuel prices and low electricity prices AOHPs may be attractive.

1. INTRODUCTION

The Residential Conservation Service (RCS) program was established by the Department of Energy as required by the National Energy Conservation Policy Act of 1978. RCS requires large gas and electric utilities to offer an audit to residential customers. An auditor must examine the customer's house and advise the homeowner on the advisability of a minimum menu of energy conservation and renewable resource measures. State governments have the option of adding measures for utilities within their jurisdiction. The add-on heat pump (AOHP) is a state-added measure in Florida and Wisconsin.

The RCS Model Audit was developed under the direction of the Department of Energy (DOE) as an aid to utilities providing audits to their customers. Oak Ridge National Laboratory (ORNL) was involved in developing the Model Audit and is presently involved in making improvements.[1] One of ORNL's tasks was to evaluate the dollar savings achieveable with the add-on heat pump and develop an audit procedure for the add-on heat pump. This report documents the work done in support of this effort.

An add-on heat pump (AOHP) is an electric heat pump added to an existing forced air system with a fossil-fired furnace. Because heat pumps require relatively large air flow rates through the indoor coil, applications will generally be limited to systems which already have a central air conditioner. The heat pump will replace the air conditioner. The advantage of an add-on heat pump is that the heat pump has high efficiency and heating capacity in mild weather. Both the efficiency and heating capacity of the heat pump decline in cold weather while fossil-fired furnace has an essentially fixed heating capacity but its efficiency increases as the weather gets colder because it cycles less frequently. When the weather is mild, the heat pump part of the AOHP system operates. When the weather is cold, the fossil fuel-fired furnace will operate. The temperature at which the

switchover from heat pump to furnace occurs is at or near the temperature below which the furnace operates less expensively than the heat pump.

This study had two purposes. One purpose was to develop a procedure for estimating AOHP dollar savings for use by an auditor. Most of this report is concerned with development of the audit procedure. Section 2 is concerned with development of a mathematical model for estimating annual dollar savings resulting from use of an AOHP instead of a furnance. Section 2 describes the characteristics of the components of add-on heat pumps and describes the overall operating characteristics of the AOHP as modeled. Model Audit procedures are intended to provide estimates which are accurate to within about 20% but with special caution against over estimating the value of a conservation measure. The approximations and assumptions made in Section 2 were made in this context and therefore may not be applicable in other contexts.

The other purpose for this study was to assess the potential benefits of AOHP use. Section 4 discusses the locations and conditions under which AOHPs are likely to be attractive. The assessment is based on the sensitivity analysis presented in Section 3. Besides indicating where AOHPs are likely to be economically attractive, the sensitivity analysis displays relationships between parameters which affect AOHP performance. These relationships are used to develop a simplified procedure which an auditor could use to estimate AOHP annual savings (Section 5).

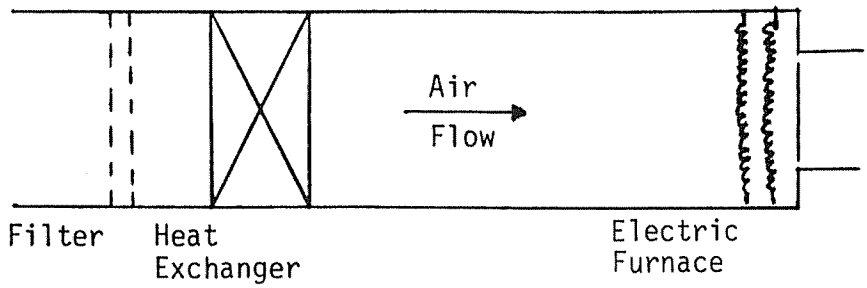
2. ADD-ON HEAT PUMP DESCRIPTION, BEHAVIOR AND OPERATION

2.1 Description

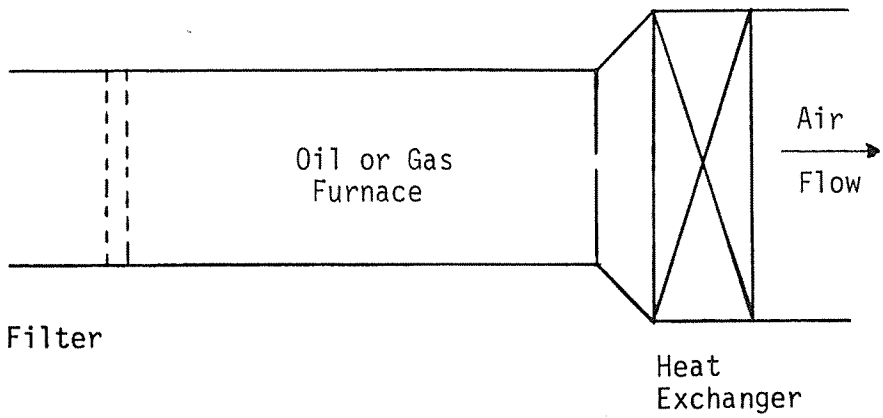
The add-on heat pump is very similar to the conventional heat pump. They both consist of an indoor coil, an outdoor coil, a compressor, and a supplemental furnace. The principle difference is that the conventional heat pump uses the electric resistance furnace while the add-on heat pump uses the fossil-fuel fired furnace. An important difference is that the electric furnace is downstream of the conventional heat pump heat exchanger, but the fossil-fuel-fired furnace is upstream of the add-on heat pump heat exchanger (Fig. 2.1). This difference is necessary for safety reasons. In summer, a heat pump is used as an air conditioner. Condensate (water) collects on the heat exchanger and is sometimes carried downstream. If the furnace is down stream, the condensate deposited on it may cause corrosion. As corrosion proceeds, the furnace may develop leaks from which combustion products may leak into the living space.[2] Because the add-on heat pump heat exchanger is down- stream of the furnace and operates at a lower temperature than the furnace, the furnace and the heat pump do not operate simultaneously.

Both add-on heat pumps and conventional heat pumps use thermostats with two stages of heating. When the house temperature drops to the thermostat set point, the thermostat calls for the first stage of heating and the heat pump begins operating. The heat pump runs until the house temperature rises to about 0.3°C (.5°F) above the set point where the thermostat shuts the heat pump off. If the heat pump does not have enough heating capacity to keep the house warm, the temperature falls until the thermostat's second stage calls for supplemental heat at about 0.56°C (1.0°F) below the set point.

When supplemental heat is needed, the operations of the conventional heat pump and the add-on heat pump are different. The conventional heat pump continues to operate while the electric furnace provides the needed supplemental heat. When the add-on heat pump



Conventional Heat Pump



Add-On Heat Pump

Fig. 2.1. Schematic representations of conventional and add-on heat pumps.

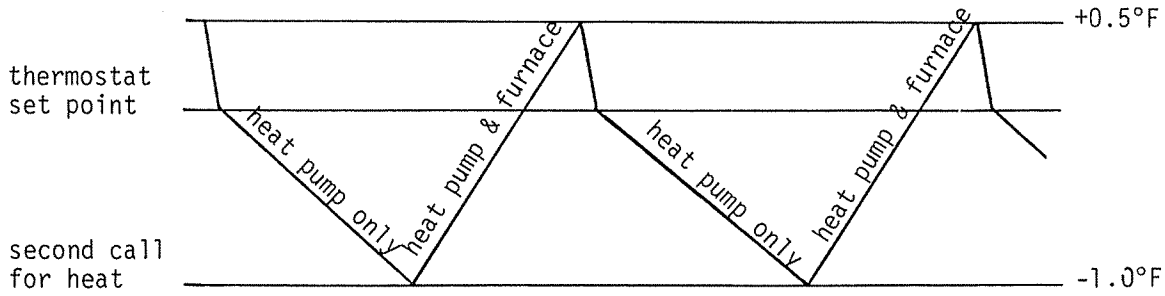
thermostat's second stage calls for heat, the heat pump is turned off and the furnace is turned on (because the heat pump and furnace do not run simultaneously). The furnace continues to operate until the house temperature rises to about 0.28°C (0.5°F) above the thermostat set point and the furnace is switched off. No equipment operates until the house cools to the thermostat set point where the first stage call for heat starts the heat pump operating. These cycles are illustrated in Fig. 2.2.

There is another difference between the operations of the conventional heat pump and the add-on heat pump. The coefficient of performance (COP) of an electric furnace is 1.0 and a heat pump COP is above 1, except at very low outdoor air temperatures. Conventional heat pump operating costs are minimized by running the heat pump down to the lowest possible outdoor air temperatures. This is not usually the case with add-on heat pumps. As the add-on heat pump efficiency declines at low outdoor air temperatures, the furnace efficiency increases. There is generally an outdoor air temperature, called the economic balance point (EBP), below which it is less expensive to operate the furnace than the heat pump. The EBP depends on the cost of fuel and electricity, the efficiencies and capacities of furnace and heat pump, and the heat loss characteristics of the house. The add-on heat pump is supplied with an outdoor thermostat which, if properly set, will prevent heat pump operation at outdoor temperatures below the economic balance point.

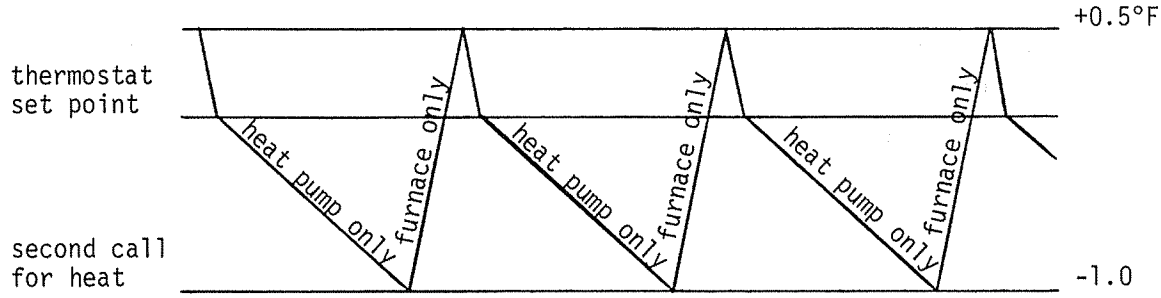
Section 2.2 is concerned with the details of AOHP behavior. Section 2.3 discusses the AOHP savings model. Those readers who are not interested in these details may wish to skip ahead to Section 2.4 which presents an example of AOHP operating characteristics.

2.2 Equipment Behavior

Furnaces and heat pumps frequently operate when the building heat loads are less than the heating capacity of the equipment. In order to keep the house temperature in the desired range, heat pumps and



Conventional Heat Pump with 5kW Electric Furnace



Add-On Heat Pump With 70,000 Btu/h Furnace

Figure 2.2 Conventional and Add-on Heat Pump Operation Cycles Below the Application Balance Point, but above the AOHP's Economic Balance Point

furnaces cycle on and off. This cycling has an important effect on equipment efficiency. Start up and shut down operation of a furnace or heat pump is considerably less efficient than steady running. Consequently, the longer a furnace or heat pump runs in an on- off cycle, the more efficiently it operates. The frequency of on-off cycles and the duration of the on part of the cycle are related to the building heat load, the equipment capacity, the thermostat deadband, and the thermal inertia of the building. The fraction of an on-off cycle during which a heat pump runs is equal to or greater than the building heat load divided by the heat pump capacity.

For a particular heat loss rate, a building with a large thermal inertia will have a longer on-off cycle and consequently it will have longer on periods. In principle, it is possible to calculate the cycling behavior of a furnace or heat pump for a given house under any condition; however, for this study the required data and effort are not warranted. In what follows, published data on cycling performance of particular furnaces and heat pumps are used to represent the typical behavior of these equipment.

2.2.1 Furnace efficiency and heating capacity

Although it is widely recognized that cycling affects furnace efficiency, little experimental work has been done to characterize the relationship between efficiency and cycling in conventional forced-air furnaces.[3,4] The relationship between furnace efficiency and cycling presented here is based entirely on a study of an 80,000 Btu/h (23.5 kW) gas furnace in a mobile home performed by Goldschmidt et al.[3] Their results are used to characterize gas, oil and propane furnaces for this study.

Goldschmidt et al. define a utilization efficiency (E_{utl}) which is the total heat added to the forced air system inlet air divided by the sum of the chemical energy input (i.e., fuel) and the electrical energy input (i.e., electricity used by the blower motor). They also define a burner on factor (A_{bn}) which is the total time

that the burner is on during a furnace cycle divided by the duration of the cycle. In terms of these parameters, they present an equation for a quadratic least squares fit to their efficiency measurements:

$$E_{utl} = 0.44 + 0.46\ A_{bn} - 0.22\ (A_{bn})^2 \qquad (2.1)$$

This gives a steady state furnace efficiency (SSFE) of 0.68 when $A_{bn} = 1$.

The above equation is not precisely the form we desire, but it is adequate enough for our purposes. Goldschmidt's utilization efficiency is slightly different from the term we would prefer to use because it includes the blower motor energy use in the furnace input. Ideally, we would have furnace fuel efficiency and furnace electric energy use as a function of operating conditions.

The blower motor in their installation consumed electricity at the rate of 120 W, so the error introduced to Eq. 2.1 if interpreted as an estimate of furnace fuel efficiency is less than 1%. In some cases the blower motor will be as large as 500 W. Since the per unit energy price of electricity is higher than the price of furnace fuel the cost of operating the furnace will be slightly underestimated by ignoring the blower motor electricity consumption. Hereafter, the expression "furnace efficiency" (FE) is used instead of utilization efficiency (E_{utl}) for convenience.

The burner on factor, A_{bn}, is also not ideal. A more convenient parameter is the furnace load factor (FLF), defined as the ratio of the heat delivered to the house during a period of time to the heat output of the furnace if it had run steadily during that time period. Furnace capacity probably does decrease at small values of A_{bn} but it certainly does not decline as much as furnace efficiency. Assuming that A_{bn} is equal to FLF, that is assuming that furnace heating capacity is constant, introduces a small underestimation of furnace efficiency.

For use in Section 3, Equation (2.1) is extrapolated to furnaces with different steady-state efficiencies. This extrapolation has the form:

$$FE = \frac{SSFE}{0.68} (0.44 + 0.46\ FLF - 0.22\ FLF^2) \qquad (2.2)$$

There are other ways Eq. 2.1 could be modified for furnaces with SSFE's different than 0.68, but Eq. 2.2 is the simpliest modification and we have no data or other knowledge to suggest that a more complicated modification can be justified.

The terminology of fuel burning furnaces is confusing in one aspect. Furnaces are rated by their fuel consumption rate, not by their heat output rate. For instance, the 80,000 Btu/h furnace discussed above consumes fuel at the rate of 80,000 Btu/h but its maximum heat output rate is only 68% of that, or 54,400 Btu/h. In what follows, the furnace capacity (FC) will be the heat output rate of the furnace and the rated furnace capacity (RFC) will be the fuel consumption rate of the furnace.

2.2.2 Heat pump cycling

As with furnaces, heat pump efficiency is reduced by cycling. Parken et al. did extensive tests of heat pump behavior under part-load conditions on an 11 kW (37,000 Btu/h) split system air-to-air unitary heat pump.[5] The approximation of heat pump cycling behavior presented here is based on their findings. Figure 2.3 presents a simplification of their findings on heat pump cycling COP degradation. The curve shown in Fig. 2.3 is very close to their curve for load factors down to 0.25. For load factors between 0.1 and 0.25, our curve slightly overstates the efficiency of a cycling heat pump. For load factors below 0.1, our curve is pure extrapolation since Parken et al. present no data in this region. Some approximations have a straight line between 0.7 at heat pump load factor of 0 and 1.0 at a

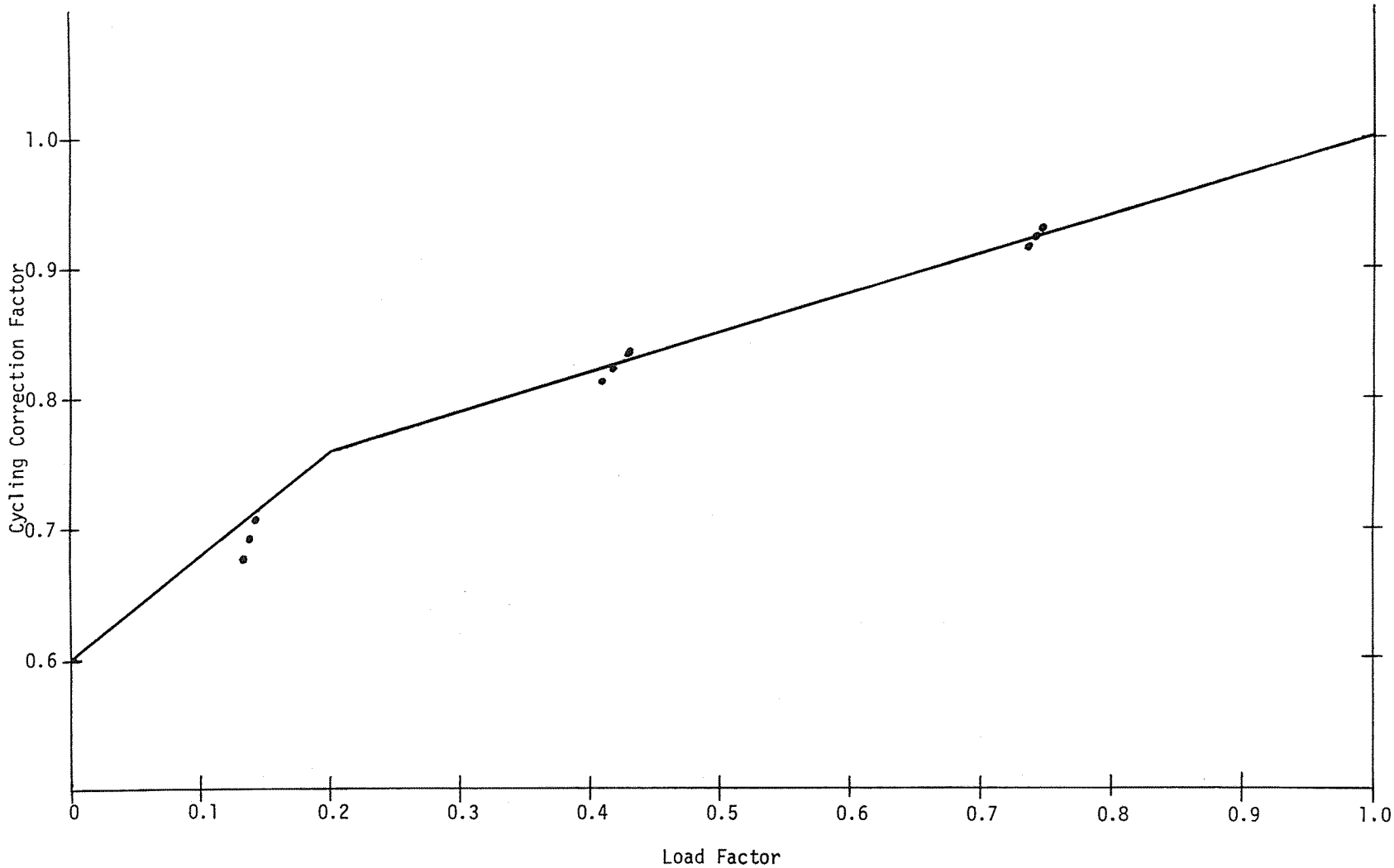


Figure 2.3. Cycling Correction to Heat Pump Coefficient of Performance

load factor of 1.0; this is simpler than Fig. 2.3 but does not agree with Parken et. al. The points indicated on Figure 2.3 are the values measured by Parken et al.

2.2.3 Heat pump defrost cycles

The heat pump evaporator (the evaporator during heating, but condenser during cooling) frequently operates below the freezing point of water. During these times, frost may form on the evaporator as moisture is condensed out of the air and frozen. Because ice buildup on the evaporator prevents the free-flow of air through it and reduces heat transfer, the heat pump must periodically defrost the evaporator. At these times, the flow of refrigerant is reversed, the evaporator is heated, and the condenser is cooled until the ice on the evaporator is eliminated. During this defrost period, the heat pump is cooling the indoor coil and supplemental heat must be used to prevent distribution of cold air through the house. Both the frost buildup and the defrost process reduces the effective COP and heating capacity of the heat pump. Parken et al. studied a heat pump which defrosts in response to frost buildup on the evaporator. (Some heat pumps defrost at regular timed intervals whether the heat pump needs defrosting or not; these heat pumps are not considered here.) Parken et al. measured heat pump performance degradation during frost buildup-defrost cycles. They found several useful facts about heat pump frosting/defrosting performance. The first is that if outdoor relative humidity is below 50%, essentially no frost/defrost degradation of heat pump heating capacity or efficiency occurs. Also, at outdoor relative humidities above 73%, frost/defrost degradation occurs but its extent does not depend on relative humidity approximately halfway between 73 and 50% relative humidities. The practical value of this fact is that at relative humidity below 50% frost/defrost degradation need not be considered, and at relative humidity above 73% frost/defrost degradation takes place to an extent that is independent of relative humidities. In this analysis we have assumed the frost/no-frost point

to be 60% relative humidity, approximately halfway between 73 and 50% relative humidities. Another important finding is that frosting does not occur at outdoor temperature above about 5.6°C (42°F) or below about -11.1°C (12°F). Other heat pumps will have slightly different characteristics but these characteristics were used as typical.

Parken et al. presented a figure showing the ratio of average heat pump capacity over a frost/defrost cycle to the manufacturer's reported capacities for various temperatures. This ratio is called the frost/defrost capacity correction factor (DCCF) here. On examination of their data, we concluded that, for outdoor relative humidities over 60%, DCCF could be adequately represented by a linear relationship which has a value of 1.0 at -11.1°C (12°F) and 0.8 at 18.3°C (45°F). For outdoor relative humidities below 60% and for outdoor temperatures above 7.2°C (45°F) or below -11.1°C (12°F), DCCF is assumed to have a value of 1.0.

A similar figure for the ratio of measured average COP over a frost/defrost cycle to manufacturer's reported COP is also presented by Parken et al. This ratio is called the frost/defrost efficiency correction factor (DECF). From their data, we concluded that for outdoor relative humidities over 60%, DECF could be approximated by a linear relationship with a value of 1.0 at -12.2°C (10°F) and a value of 0.84 at 5.6°C (42°F). As for DCCF, DECF has a value of 1.0 at outdoor relative humidities below 60% and at outdoor temperatures above 5.6°C (42°F) and below -12.2°C (10°F).

2.2.4 Heat pump capacity

While heat pump capacity is reduced by frost/defrost cycles, it is reduced much more significantly by low outdoor air temperatures. Steady-state heat pump capacities for most heat pumps are available from the Air Conditioning and Refrigeration Institute (ARI) at outdoor air temperatures of 8.3°C (47°F) and -8.3°C (17°F). In most cases, the heat pump capacity at 17°F (HPC17) is between 50-60% of the heat pump capacity at 47°F (HPC47). At outdoor temperatures of -27.8°C (-18°F),

heat pump capacities are generally about 25% of HPC47. Consequently, heat pumps in sensibly designed installations are able to meet only a small part of the building heat load at low outdoor air temperatures.

Figure 2.4 shows a plot of ratios of heat pump capacities at various temperatures to HPC47 for 11 General Electric heat pumps.[6] This ratio is called the temperature capacity correction factor (TCCF). The curve drawn through the data points on this figure shows the values of TCCF used in the procedures presented in section 3 and appendix A.

2.2.5 Heat pump coefficient of performance

Heat pump COP is also strongly affected by cold weather. For instance, a heat pump with a steady state COP at 47°F (COP47) of 2.75 will have its COP reduced to 1.0 at some outdoor temperature in the vicinity of -17.8 to -28.9°C (0.0 to -20°F).

Figure 2.5 shows manufacturer-reported COPs for three heat pumps at a range of temperatures.[6] For each of these three heat pumps, a straight line fits the data quite well for temperatures of 8.3°C (47°F) and below, except for very low temperatures. At low temperatures where COP drops below about 1.1 or 1.2, the straight line approximation to the COP curve slightly underestimates the heat pump COP. At temperatures above 8.3°C (47°F) the COP is a little greater than the COP47, but does not seem to depend strongly on temperature. For the purposes of the procedure presented in section 3, we have developed a method to estimate the steady state COP from the COP at 47°F and the COP at 17°F (COP17) available from ARI. For temperatures below 8.3°C (47°F) the COPs are taken to lie on a straight line which passes through COP47 and COP17. Where the previous step gives a COP of less than 1.0, the COP of 1.0 is used instead. At temperatures about 8.3°C (47°F), the steady-state COP is taken to be 1.03 x COP47.

A reviewer pointed out that not all heat pump's COPs level off above 47°F. He suggested that where it does occur, it occurs because

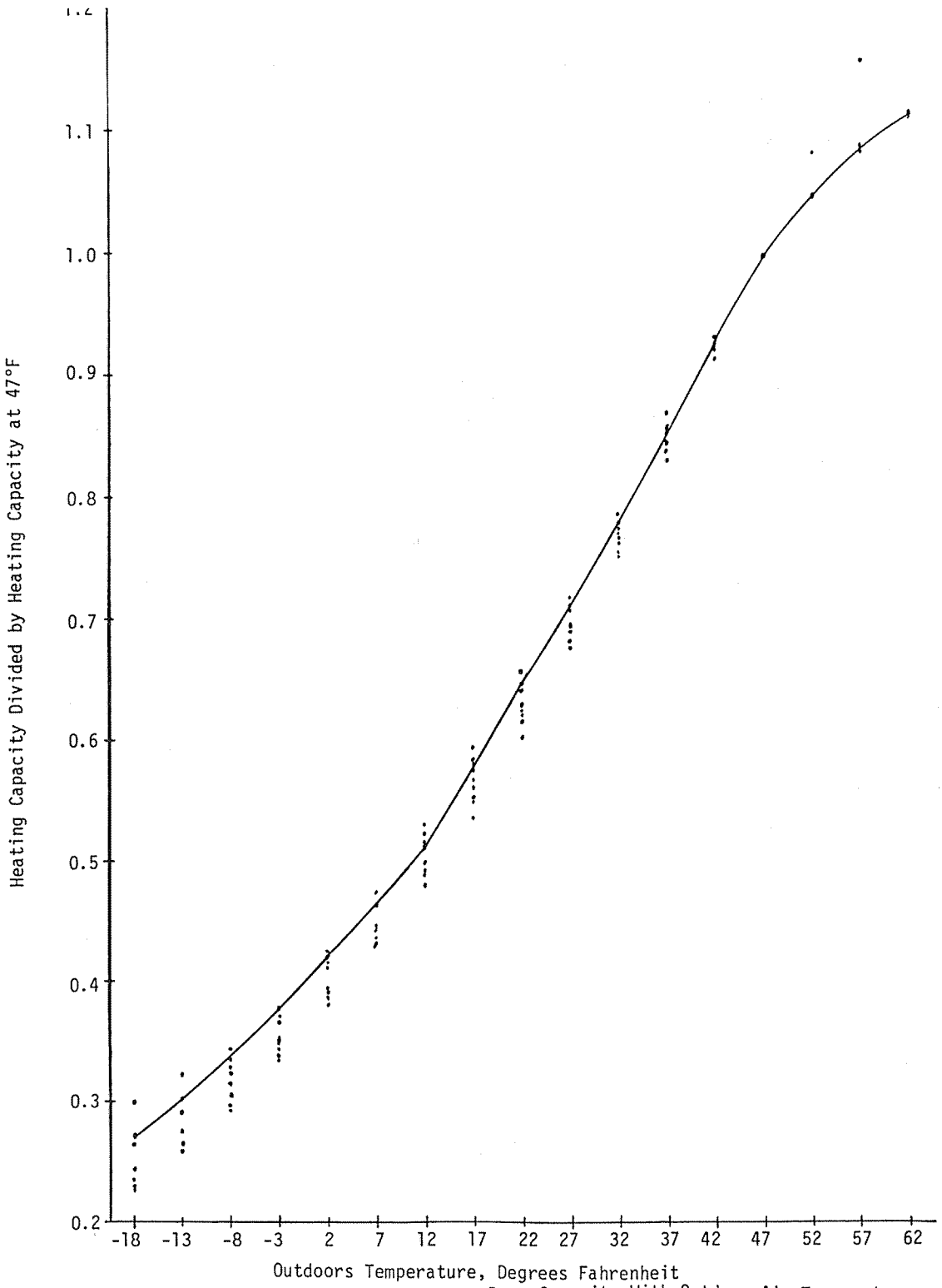


Figure 2.4 Variation of Steady State Heat Pump Capacity With Outdoor Air Temperature

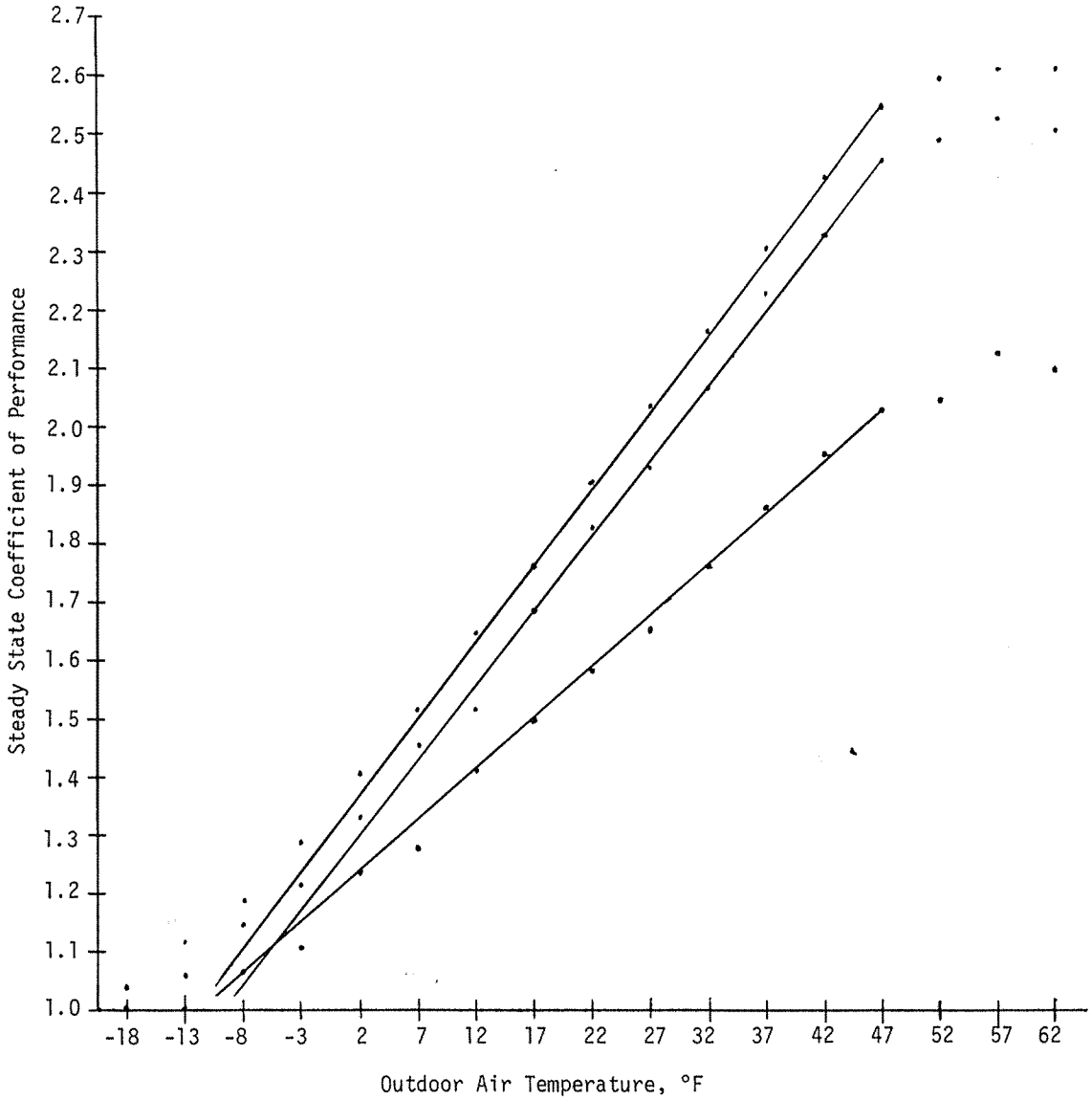


Figure 2.5 Variation of Heat Pump Steady State COP With Outdoor Air Temperature

heat exchangers are sized too small to efficiently accomodate the increased capacity at these temperatures. This implies that more efficient heat pumps may not display this leveling of COP above 47°F. Other estimates of COP above 47°F could be justified; however, the estimate above is preferred for this study because it is not expected to overestimate AOHP savings for most commercially available AOHPs. Also, the errors introduced by this approximation are generally small since possible COP errors will be largest in the temperature range from 55°F to 65°F where the heat pump operates relatively little.

2.2.6 Add-on heat pump

The behavior of the add-on heat pump is essentially determined by the behaviors of the component furnace and heat pump. The novel feature of an add-on heat pump is the special mode of operation, described above, in which the heat pump and furnace take turns heating the building. This special mode of operation may be used if the heat pump does not have sufficient capacity to keep the house warm but is less expensive to operate than the furnace. However, even when the heat pump operation is less expensive than the furnace operation, this special mode may not be less expensive than straight furnace operation, because in the alternating mode the efficiencies of both heat pump and furnace are degraded by the cycling involved in the alternating mode. An example of this will be presented in the next section.

As explained in the sections on cycling, detailed consideration of the thermal inertia of the building is beyond the scope of this study. Consequently, cycling estimates for the alternating mode of add-on heat pump operation gives the fraction of time each unit runs and not the duration of the cycle. The analysis of AOHP cycling and the thermostat characteristics assumed here follows Schulze.[7]

The alternating mode cycle consists of three parts: the heat pump running, the furnace running, and neither running. The fraction of the time that the heat pump runs we call HPRT. The fraction of the time

that the furnace runs we call FRT. The fraction of the time during which neither the heat pump nor furnace runs we call Z. With these definitions, we write Eq. 2.3, which accounts for the entire cycle.

$$HPRT + FRT + Z = 1 \tag{2.3}$$

Since the heat added to the building is equal to the heat loss by the building, we can write Eq. 2.4.

$$(HPRT \cdot HPC) + (FRT \cdot FC) = L \tag{2.4}$$

where

HPC is the heating capacity of the heat pump,

FC is the heating capacity of the furnace,

L is the net building heat load provided by the heating system.

These two equations allows us to write the equation in terms of FRT and Z.

$$FRT\ (HPC - FC) + (Z \cdot HPC) = HPC - L \tag{2.5}$$

A second equation relating FRT and Z can be derived by considering the heat capacity of the building (Q, Btu/°F or Wh/°C) and the changes in building temperature accommodated by the thermostat (ΔT) for the heat pump, furnace, and the nonheating parts of the cycle (Δt_{hp}, Δt_f, Δt_z). While the furnace is running, the time rate of change of building temperature can be written:

$$\frac{dT}{dt} = \frac{(FC - L)}{Q} \tag{2.6}$$

If during the furnace part of a cycle, the building temperature changes by ΔT_f then the duration of that part of the cycle is

$$t_f = \frac{Q \cdot \Delta T_f}{(FC-L)} \tag{2.7}$$

The comparable equation for the no heat part of the cycle is

$$t_z = \frac{Q \cdot \Delta T_z}{-L} \tag{2.8}$$

Recognizing that the ratio of Z to FRT is equal to the ratio of Eq. 2.8 to Eq. 2.7, we get:

$$Z/FRT = t_z / t_f = \frac{\Delta T_z (L - FC)}{\Delta T_f \cdot L} \tag{2.9}$$

Substituting Eq. 2.9 into Eq. 2.5, we get Eq. 2.10 for FRT.

$$FRT = \frac{HPC - L}{(HPC - FC) - (\Delta T_z / T_f)(HPC/L)(FC - L)} \tag{2.10}$$

With an equation for FRT, HPRT can be calculated with Eq. 2.4, which we have rearranged below.

$$HPRT = \frac{L}{HPC} - FRT \frac{FC}{HPC} \tag{2.11}$$

The above equations for HPRT and FRT are used in the procedure presented in the next section. The heat rates (HPC, FC, L) are either input to the procedure or calculated from the input. But ΔT_z and ΔT_f are readily measurable since they depend on thermostat characteristics. For our purposes, we have used what are believed to be typical values: -0.5°F for ΔT_z and 1.5°F for ΔT_f. Figures 2.6 and 2.7 show graphs of HPRT and FRT for various ratios of L/FC and HPC/FC. No values of FRT or HPRT are presented for values of HPC/FC

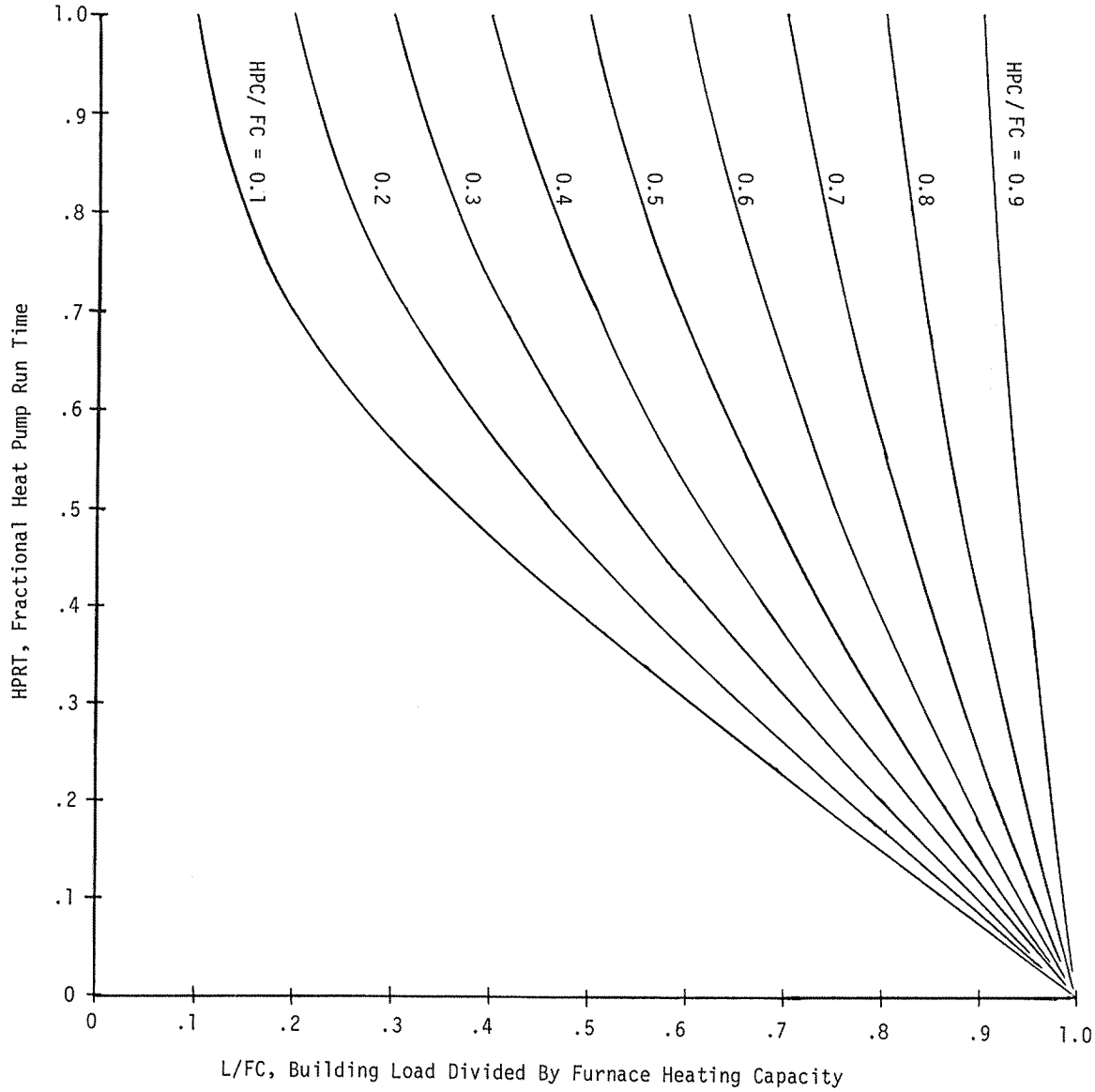


Figure 2.6 Dependence of HPRT on Furnace and Heat Pump Capacities and Building Heat Load

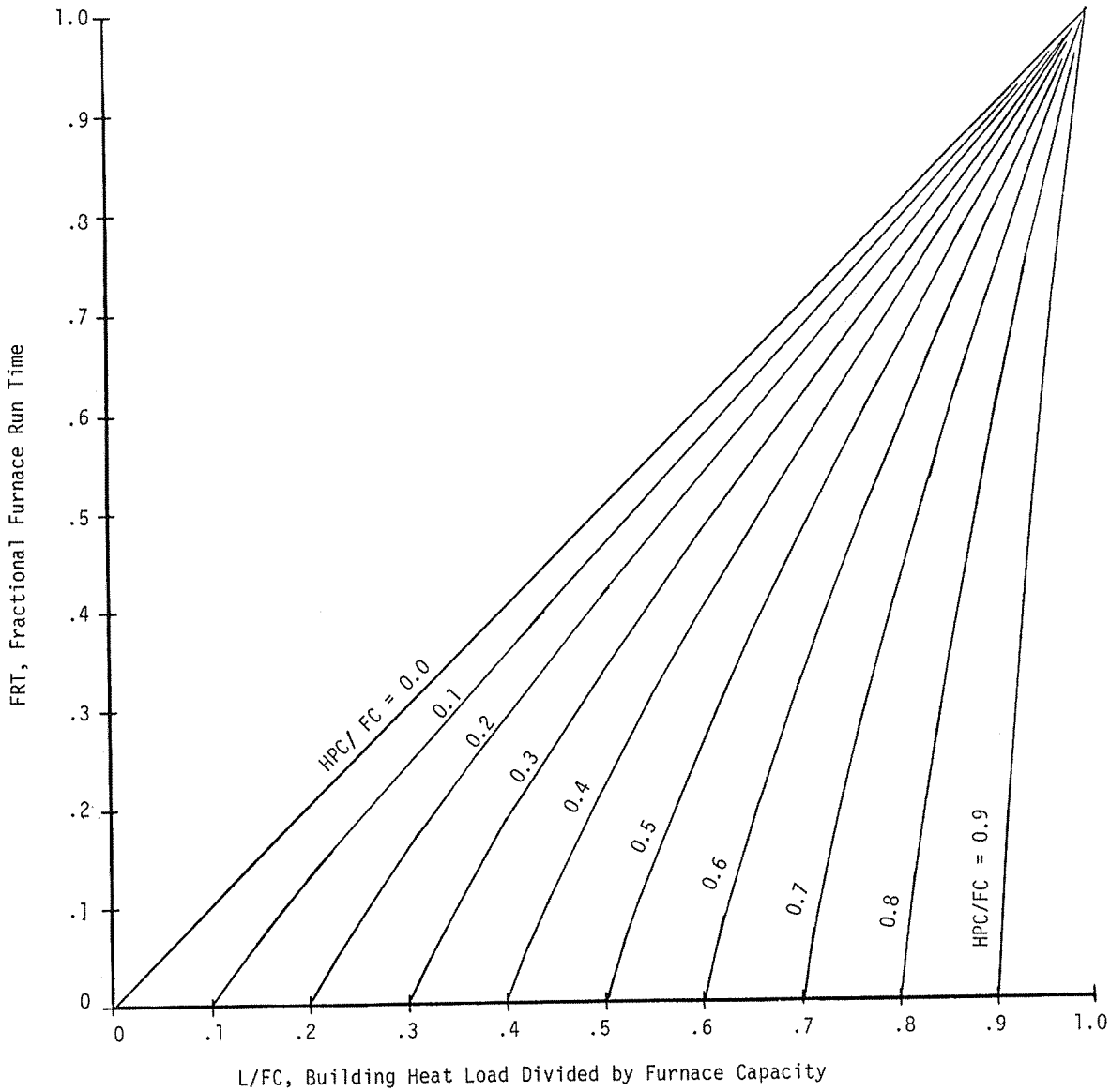


Figure 2.7 Dependence of FRT on Furnace and Heat Pump Capacities and Building Heat Load

greater than L/FC because Eqs. 2.10 and 2.11 are only applicable where the heat pump capacity (HPC) is less than the building heat loss rate (L).

An example illustrates the behavior of Eqs. 2.10 and 2.11. A hypothetical installation has a furnace capacity (FC) of 58,000 Btu/hr. If at an outdoor temperature of 42°F, the building load (L) is 18,400 Btu/hr and the heat pump capacity (HPC) is 17,600 Btu/hr, then the value of HPC/FC is 0.30 and L/FC is 0.32. The values of FRT and HPRT are 0.03 and 0.95, respectively. At an outdoor temperature of 12°F, L equals 42,000 Btu/hr and HPC is 12,000 Btu/hr; HPC/FC is 0.21 and L/FC is 0.73. At these conditions, FRT and HPRT are 0.68 and 0.23, respectively.

2.3 Bin-Hour AOHP Savings Model

A bin-hour model of AOHP dollar savings was developed. The bin-hour method was judged to have sufficient accuracy for this study and to offer a considerable savings in computational effort compared to an hour-by-hour simulation. The model calculates operating saving by subtracting the estimated operating cost of the AOHP from the estimated operating cost of a stand-alone furnace. No estimate of energy savings is made because the decision for or against an AOHP is presumed to be made on economic grounds. (Under some circumstances the AOHP may use more electric power plant fuel energy than it saves of furnace fuel energy.)

Bin weather data consists of the average number of hours per year during which the air temperature is in each of several ranges. The bin weather data used has 5 F° wide bins. For example, the number of hours in the 42°F bin is the average number of hours in a year in which the outdoor air temperature is equal to or greater than 40°F and less than 45°F. Table 2.1 lists the bin temperature data for the 10 cities examined in this report. Data for 67 other cities are available from ASHRAE Handbook of Fundamentals[8] (also listed in Appendix B) and data for a large number of cities are available from Air Force Manual 88-29, "Engineering Weather Data".[9] The AOHP savings model is a variant of

Table 2.1. Average number of hours in each 5°F temperature bin for 10 cities

Location	62°	57°	52°	47°	42°	37°	32°	27°	22°	17°	12°	7°	2°	-3°	-8°	-13°	-18
Chicago, IL	653	592	569	543	591	800	822	551	335	196	117	85	59	25	12	3	
Dallas, TX	693	656	629	576	504	371	231	91	34	17	4	1					
Denver, CO	783	731	678	704	692	717	721	553	359	216	119	78	36	22	6	1	1
Fresno, CA	921	1006	1036	952	673	426	168	34									
Knoxville, TN	746	675	672	689	648	590	456	217	101	41	21	7	2				
Miami, FL	452	277	147	71	26	4											
Portland, OR	1001	1316	1274	1271	1238	772	343	123	40	10	4	1					
Seattle, WA	750	1272	1462	1445	1408	914	427	104	39	20	3						
Syracuse, NY	723	717	656	641	651	720	830	547	392	282	190	102	55	23	5	2	2
Washington, DC	740	673	690	684	790	744	542	254	138	54	17	2					

1981 Handbook of Fundamentals, American Society of Heating Air-Conditioning and Refrigeration Engineers, page 28.8.

Note: Each bin spans a 5°F range; for example the number of hours in the 57° bin is the number of hours the temperature is equal to or above 55°F and less than 60°F.

the "classical bin method" described in ASHRAE Handbook of Fundamentals.[8] The AOHP savings model includes calculations for furnace operation, heat pump operation and for the operating mode where the furnace and heat pump alternate in keeping the house warm. The AOHP savings model makes two departures from the "classical bin method." The first departure is to note that C_D is not necessarily the appropriate correction factor for the bin method. C_D corrects for several errors in the heating degree day method which are not introduced by the bin method. For example as Reeves notes: "The degree day is based on the mean of the daily extreme temperatures, so that a day with extremes of 75°F and 55°F registers no degree days, although heating may well have been required for part of the day."[10] Since the bin method uses the average number of hours at various outdoor temperatures instead of the average of the extreme daily temperatures this error is not introduced. On the other hand the bin method does not account for building thermal inertia effects which might result in no heat being used on such a day. Other errors introduced by one but not the other of the two methods could be noted.

The point is that while the bin method shares some of the errors of the degree day method and hence probably requires a correction factor like C_D it is unlikely that the appropriate correction factor has the same value as C_D in any particular climate. The AOHP savings model acknowledges this problem by introducing a bin method correction factor C_B.

The second departure from the "classical bin method" is how the correction factor is used. An example in the ASHRAE Handbook of Fundamentals uses C_D to reduce the building heat load. There seems to be little or no justification for this use of C_D. In the degree day method, C_D is a correction to the overall heating energy consumption. To apply the correction factor to the buiding heat load estimates in the bin method is to imply that these estimates are the entire source of the bin method errors. An obvious error which is not

due to building heat load estimates errors is the lumping of temperatures into 5°F bins. Finally, reducing the building heating load by multiplying by a correction factor introduces errors in the bin method by making heating equipment appear (for the calculations) to be oversized. The AOHP savings model uses a correction factor, C_B, to reduce the annual operating savings in a manner analogous to the use of C_D in the degree day method to reduce energy consumption estimates. Unfortunately, while ASHRAE presents estimates for C_D no estimates of C_B are available.[8] Values of C_B could be calculated in a manner similar to that used to calculate C_D. Because no empirical estimates of C_B are available, the local value of C_D is suggested for use as the value of C_B.

The AOHP savings model is presented in two forms in Appendices A and B. Appendix A presents step-by-step instructions for manually calculating AOHP savings. This procedure is long and tedious because there is a large number of calculations to be made, but those readers wishing to understand the AOHP savings model will find it instructive. Since the AOHP savings model calculations are lengthy, a Fortran computer program for the model was developed. A listing of this program and samples of the required data files are given in Appendix B.

2.4 Sample Calculation

Some understanding of the AOHP savings model and of AOHP behavior can be gained by examining an output of the Fortran computer program of the model (Figure 2.8). Most of the material at the top of the sample output is a repetition of input data or parameters which are ratios of input parameters. Two parameters which are not repetitions of input are the heat pump application balance point (ABP) and the seasonal efficiencies. The ABP is found as calculations are being performed by interpolation between bin temperatures to the approximate temperature where the HPC (column G) equals the building heat load (L) (column C).

HEAT LOSS CHARACTERISTIC= 800.0(BTU/H/DEG F)
RATED FURNACE CAPACITY= 102.35(MBTU/H) STEATY STATE FURNACE EFFICIENCY= 0.68
FURNACE HEATING CAPACITY= 69.60(MBTU/H)
47 DEG. F HEAT PUMP CAPACITY= 46.40(MBTU/H)
COP47= 2.75 COP17= 1.95
BALANCE POINT= 65.00(DEG F)

FUEL TYPE=OIL PRICE= 1.00/GAL
ELECTRICITY= 6.00(C/KWH)
FUEL PRICE RATIO (EP/FP) = 2.45

CORRECTION FACTOR(CB) = .70

DESIGN LOAD = 46.4*10**3 BTU/H, HPC47/DL = 1.00, FC/DL = 1.50

CITY NUMBER=72 CITY=WASHINGTON, DC

APPLICATION BALANCE POINT = 27. DEGREES F.

SEASONAL EFFICIENCIES (BASE FURN, AOHP FURN, HP) = 0.56 0.58 1.97

A TEMP	B BINHR	C L	D FLF	E FE	F DCOSTF	G HPC	H SHPCOP	I DCFCOP	J LODF	K CCOP1	L HPCOP1
62.	740.000	2.400	0.034	0.456	5.377	51.782	2.833	1.000	0.046	0.637	1.805
57.	673.000	6.400	0.092	0.480	5.099	50.437	2.833	1.000	0.127	0.702	1.987
52.	690.000	10.400	0.149	0.504	4.862	48.674	2.833	1.000	0.214	0.764	2.164
47.	684.000	14.400	0.207	0.526	4.660	46.400	2.750	1.000	0.310	0.793	2.181
42.	790.000	18.400	0.264	0.546	4.485	35.264	2.617	0.840	0.522	0.857	1.883
37.	744.000	22.400	0.322	0.565	4.334	33.686	2.483	0.860	0.665	0.899	1.921
32.	542.000	26.400	0.379	0.583	4.203	31.830	2.350	0.890	0.829	0.949	1.984
27.	254.000	30.400	0.437	0.599	4.090	29.974	2.217	0.910	0.000	0.000	0.000
22.	138.000	34.400	0.494	0.614	3.992	28.165	2.083	0.940	0.000	0.000	0.000
17.	54.000	38.400	0.552	0.627	3.908	26.077	1.950	0.960	0.000	0.000	0.000
12.	17.000	42.400	0.609	0.639	3.836	23.942	1.817	0.990	0.000	0.000	0.000
7.	2.000	46.400	0.667	0.649	3.775	21.483	1.683	1.000	0.000	0.000	0.000

A TEMP	M DCOST1	N HPCVFC	O FRT	P FEFF	Q HPRT	R CCOP2	S HPCOP2	T DCOST2	U BASEN	V ADOHPE	W DSHRT
62.	3.325	0.000	0.000	0.000	0.000	0.000	0.000	0.000	27.981	17.302	0.311
57.	3.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	64.352	38.107	0.307
52.	2.772	0.000	0.000	0.000	0.000	0.000	0.000	0.000	102.236	58.288	0.298
47.	2.751	0.000	0.000	0.000	0.000	0.000	0.000	0.000	134.473	79.391	0.259
42.	3.187	0.000	0.000	0.000	0.000	0.000	0.000	0.000	191.015	135.734	0.134
37.	3.123	0.000	0.000	0.000	0.000	0.000	0.000	0.000	211.628	152.513	0.119
32.	3.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	176.222	126.758	0.110
27.	0.000	0.431	0.016	0.447	0.977	0.993	2.003	3.085	92.537	69.804	0.092
22.	0.000	0.405	0.196	0.522	0.737	0.921	1.804	3.869	55.532	53.815	0.017
17.	0.000	0.375	0.338	0.570	0.570	0.871	1.631	4.057	23.745	23.745	0.000
12.	0.000	0.344	0.455	0.604	0.447	0.834	1.500	4.042	8.102	8.102	0.000
7.	0.000	0.309	0.559	0.629	0.347	0.804	1.354	3.984	1.027	1.027	0.000

ANNUAL SAVINGS= 226.98
ANNUAL BASE ENERGY BILL= 762.19
ANNUAL ADD ON HP ENERGY BILL= 535.21
ANNUAL SAVINGS/DESIGN LOAD= 4.8919 ($/YR)/(10**3 BTU/H) ASDLEP = 0.8153 ($/YR)/(10**3 BTU/H)/(C/KWH)

Figure 2.8 Sample Output of the Add-on Heat Pump Savings Estimation Computer Program

The seasonal efficiencies are calculated by dividing the furnace and heat pump delivered heats by the energies consumed by the furnace and heat pump for the year (all the bins). The furnace-only (base furn) efficiency is, as may be expected, substantially less than the steady-state furnace efficiency (SSFE). However, this furnace is substantially oversized (FC/DL = 1.50); a smaller furnace would have a higher seasonal efficiency. Though not apparent from this example, the seasonal efficiency of the furnace as it operates in the AOHP configuration may be higher or lower than it is when the furnace operates alone. The AOHP-furnace seasonal efficiency would be higher than in this example if it did not operate in combined heat pump-furnace mode in the 27° and 22°F temperature bins. (Compare the values of furnace efficiency, FE, for columns E and P for the 27° and 22°F bins.) In cases where the furnace runs with the heat pump to lower temperatures, the furnace seasonal efficiency may be lower than the furnace-only seasonal efficiency.

Comparison of the steady-state heat pump COP's (COP47 and COP17) with the seasonal heat pump COP is interesting. The seasonal COP is closer to the 17°F COP (COP17) than to COP47. Examination of the heat pump COP illustrates both the operation of the AOHP and the characteristics of the procedure. Figure 2.9 illustrates the relationship between steady state COP, cycling, defrost cycles, and actual operating COP (as computed by this method). The curve titled "steady-state heat pump COP" is a plot of the numbers from column H of Fig. 2.8. The curve titled "net COP" is from column L for temperatures above 27°F and from column S for temperatures below 32°F. The change from column L to column S occurs at the application balance point. Below the COP curves are curves for the defrost and cycling correction factors and a curve which is the product of the two. These two correction factors are the multiplicative corrections to the steady state heat pump COP which yield the actual heat pump COP.

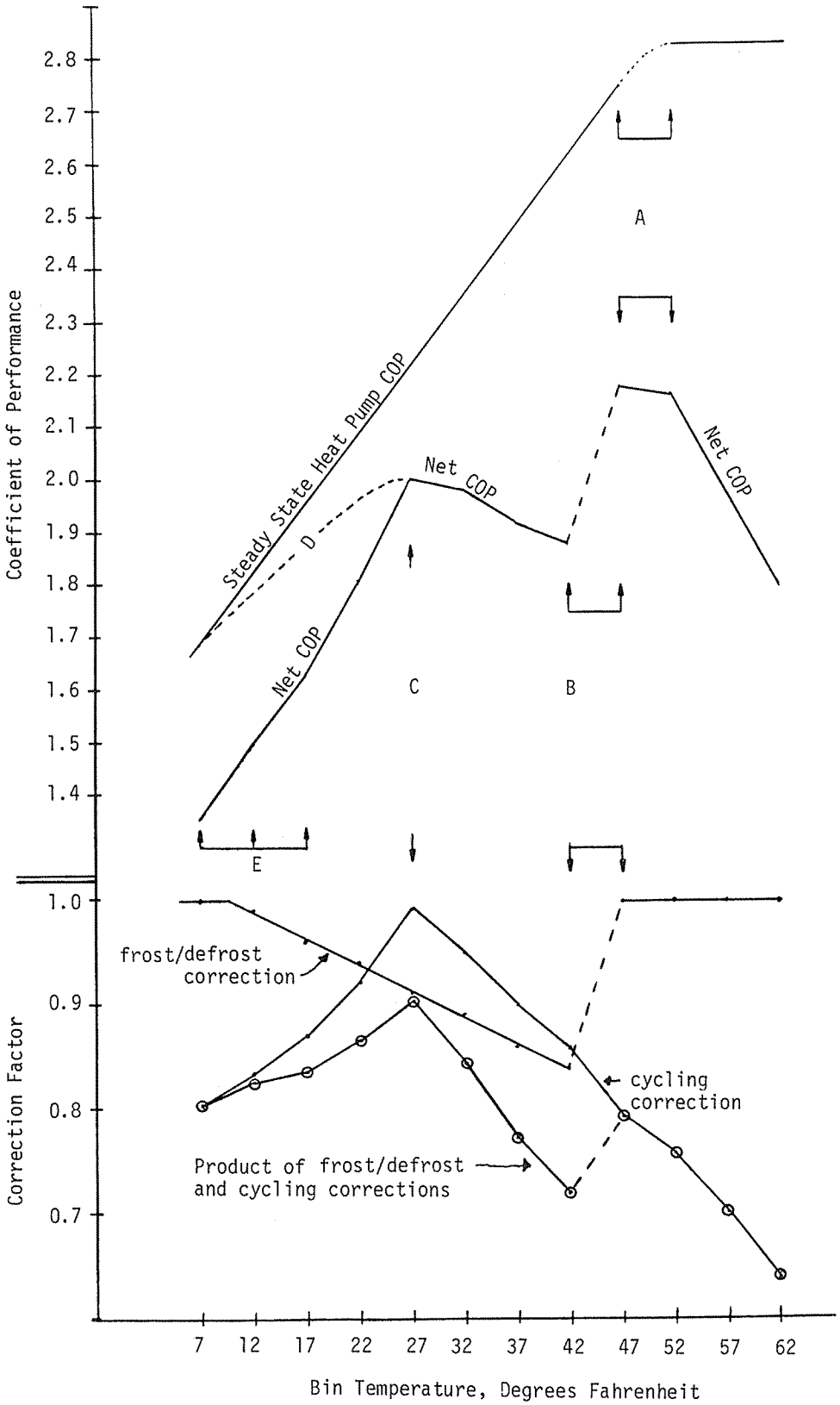


Fig. 2.9 Heat Pump Coefficient of Performance and Factors which Affect It

At temperatures of 52°F and above, the model approximates steady state heat pump COP as essentially constant. (As discussed in Section 2.2.5, not all heat pumps exhibit this behavior.) For the temperatures of region 'A' and above, the difference between steady state and actual COPs is due to the cycling which results from the heat pump's excess heating capacity (compare columns C and G on Fig. 2.8).

In region 'B' on Fig. 2.9, frost/defrost losses become a factor in the COP. The dotted lines in the COP and frost/defrost correction factor curves in region 'B' are intended to indicate that we don't really know what happens there. Across region B, heat pump COP declines precipitiously with decreasing temperature in spite of the effects of reduced cycling losses. (Compare the curves from frost/defrost, cycling, and product of cycling and frost/defrost corrections.) Between 42°F and 27°F, the heat pump COP increases gradually notwithstanding a continual decline of the steady state COP.

Point 'C' (Fig. 2.9) is the application balance point. Above this point the heat pump cycles because it has excess heating capacity. Below point 'C' the heat pump cycles because it must operate alternately with the furnace. Below point 'C' the heat pump COP declines rapidly due to the combined effects of the declining steady state COP and the cycling correction factor. If this were a conventional heat pump installation with the electric furnace downstream of the heat pump coil (Fig. 2.2) the actual COP would follow a curve like 'D' since the heat pump would only cycle for defrost.

Region 'E' of Fig. 2.9 is the temperature range where the heat pump drops out and the furnace provides all the heat in the example of Fig. 2.8. Columns F, M, and T of Fig. 2.8 are delivered heat cost in cents per kWh. By delivered cost we mean the cost of the fuel and/or electricity required to provide a kWh of heat to the building. Column F is the delivered heat cost for the furnace-only operation. Columns M and T are the delivered heat cost by the AOHP if the heat pump is operating. Comparison of columns F and T show that the AOHP is less expensive to operate than the furnace in the 27° and 22°F bins, but

the furnace alone is less expensive at lower temperatures. The AOHP is equipped with an outdoor thermostat (mentioned earlier) which turns the heat pump off when the furnace is less expensive to operate. The last three bins for column V are the same as those of column U because the furnace is providing all the heat in both cases.

Column W (Figure 2.8) is the ratio of the dollars saved by the AOHP to the hours run by the heat pump. It can be thought of as a measure of heat pump productivity. Because we have chosen to evaluate the AOHP on the basis of operating costs only, this factor is not a part of the savings calculations. If some use were made of maintenance or capital costs, this parameter might be useful. For example, if the wear on a heat pump were known to cause maintenance costs at the rate of 2¢/h of run time, then the heat pump should not be operated down to 22°F where the productivity of the heat pump is only 1.7¢/h.

3. AOHP PERFORMANCE SENSITIVITY ANALYSIS

A sensitivity analysis of AOHP performance was carried out using the computer version of the AOHP savings model. The sensitivity analysis served two purposes. The first was to illuminate which parameters affected annual savings most strongly. The second purpose was to look for a simplified method of estimating AOHP savings such as could be used by an auditor. Readers not interested in these details will find most of these results summarized in Section 4.

3.1 Functional Dependence

The variables which determine the annual savings (AS) have been discussed elsewhere. By way of summary, the functional form of AS can be written as:

$$AS = f\ (\text{climate, FC, SSFE, FP, HPC47, COP47, COP17, EP, DL}) \qquad (3.1)$$

Simple considerations lead us to expect that the annual savings are proportional to the design load. A house with twice the heating needs should be able to achieve twice the savings (dollars) if other factors are appropriately scaled. If we define ASDL to be the annual savings (AS) divided by the design load (DL), it turns out that ASDL can be written as a function of FC/DL and HPC47/DL instead of FC, DL and HPC47. Also, since the cost of heat from the furnace is proportional to the fuel price and inversely proportional to the furnace efficiency ASDL can be written as a function of FP/SSFE. We can write ASDL as Eq. 3.2.

$$ASDL = f\ \left(\text{climate}, \frac{FC}{DL}, \frac{FP}{SSFE}, \frac{HPC47}{DL}, \text{COP47, COP17, EP}\right) \qquad (3.2)$$

The advantage of this formulation is readily apparent. The annual operating savings of one AOHP application may be simply scaled up or down for another building provided the furnace and heat pump capacities are scaled up or down at the same rate.

The annual savings also depend on fuel and electricity prices in a simple way. If both electricity and fuel prices were to double, the annual savings should double. To take advantage of this, we created a new variable which is annual savings (AS) divided by design load (DL) and electricity price (EP) called ASDLEP. The functional form of ASDLEP is given by Eq. 3.3.

$$\text{ASDLEP} = f\left(\text{climate}, \frac{\text{FC}}{\text{DL}}, \frac{(\text{FP/SSFE})}{\text{EP}}, \frac{\text{HPC47}}{\text{DL}}, \text{COP47}, \text{COP17}\right) \qquad (3.3)$$

This formulation allows simplified treatment of a variety of fuel and electricity prices, and furnace efficiencies.

Figure 3.1 shows annual heating fuel bills for two fuels (and fuel prices) and a range of electricity prices for both the furnace only and the AOHP. This figure shows that for any particular electricity price the annual savings depends strongly on the price of the fossil fuel being displaced. For instance, with electricity at 6¢/kWh, oil furnace-AOHP savings are about $200/yr while gas furnace-AOHP savings are less than $30/yr. Note that while annual savings depend on furnace fuel prices, for these fuel prices and electricity price below 6¢/kWh the annual heating bill is relatively little affected by the cost of the furnace fuel. One way to understand this figure is to see that, with an AOHP, the annual heating fuel bill will be approximately that of the least expensive heating mode. Figure 3.2 shows the value of the formulation of Eq. 3.3. The curve on Fig. 3.2 includes both oil and gas furnace-AOHP savings. For values of FP/EP between 0.35 and 1.2, ASDLEP can be approximated by the linear equation indicated on the figure. The curved tail (values of FP/EP less than 0.35) is of little practical value because, for the small values of ASDLEP in this region, AOHPs will not save enough money to justify the investment. The curve or the equation can be used to find annual savings estimates after fuel or price changes without using the AOHP savings model again.

In the subsections which follow, annual savings (AS) will be discussed since their meanings are most easily grasped. Values of ASDL will be included on some figures to remind the reader of the importance

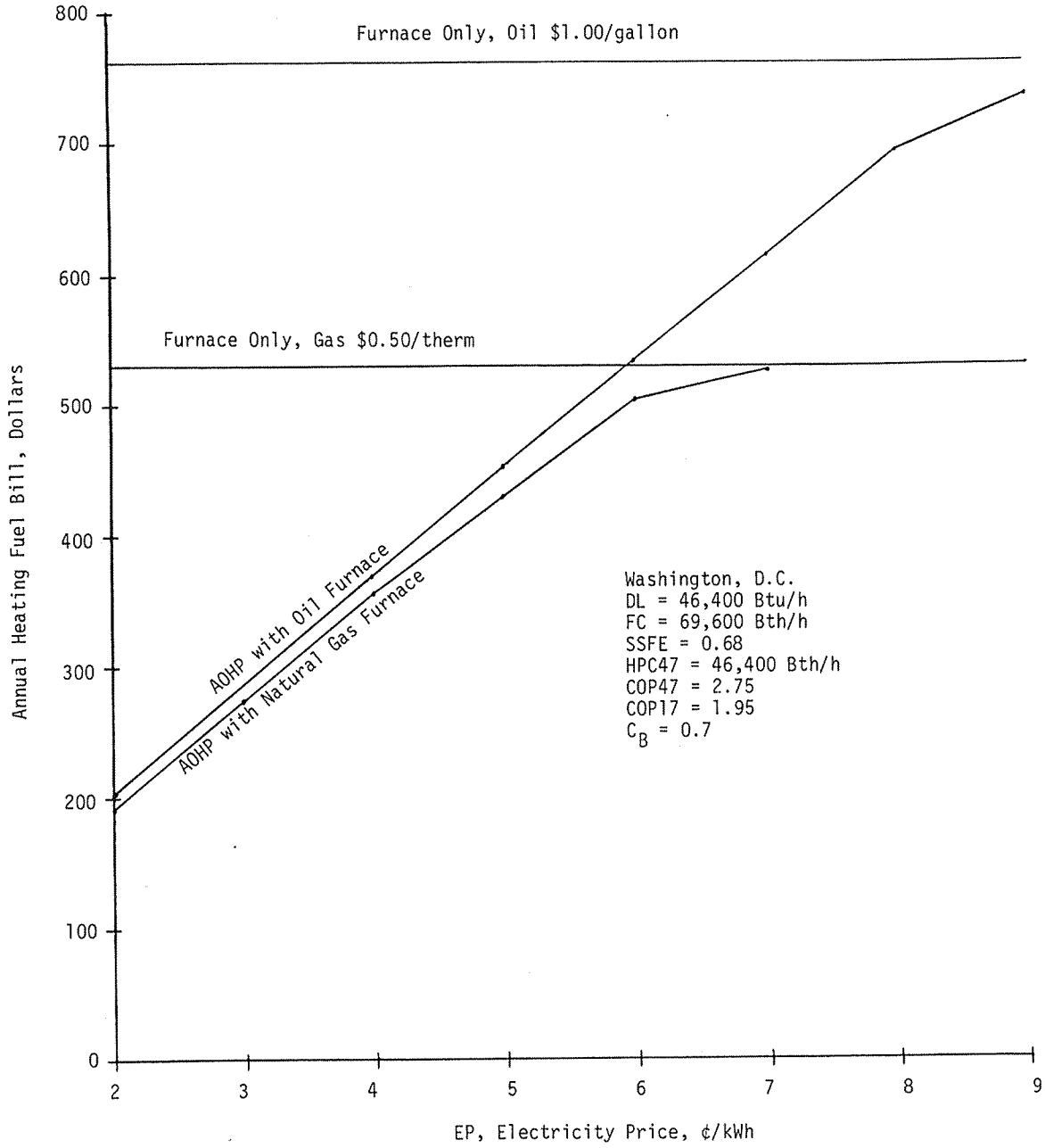


Figure 3.1 Annual Heating Fuel Bills for Two Fossil Fuels (and Prices) And a Range of Electricity Prices

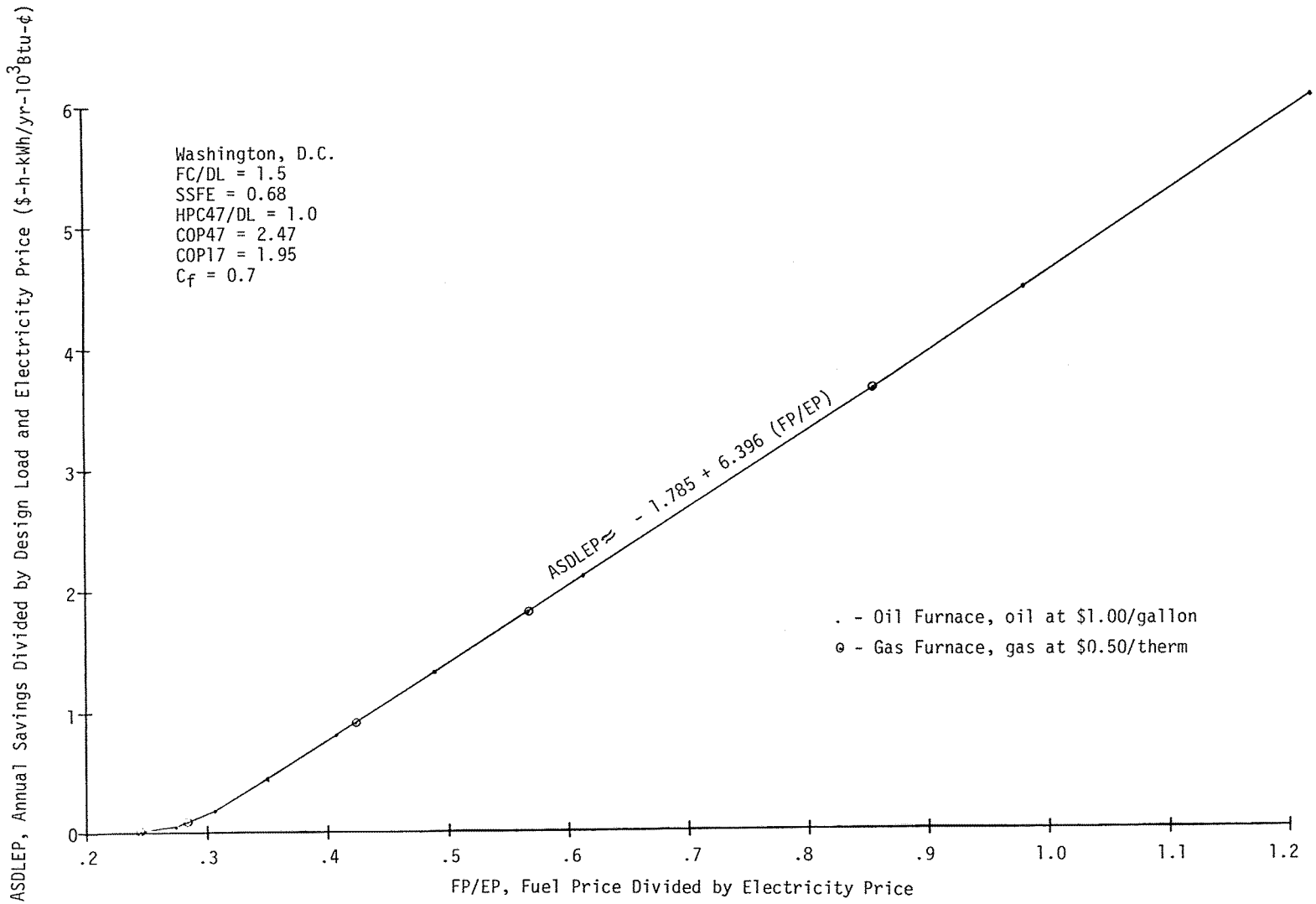


Figure 3.2 Variation of ASDLEP With the Ratio FP/EP

of building heat load to annual savings. In the following subsections, EP and FP are held constant so ASDLEP may be calculated from ASDL easily.

3.2 Base Case

For the sensitivity analysis, we selected a base case which could be expected to be near the middle of the range of AOHP application variables. Table 3.1 lists the characteristics of the selected base case. Note that the values of ODT and DL are based on the bin weather data (Table 2.1) and are not the same as the ASHRAE values of design temperature or design load. Any other formulation of DL could have been used.

In section 3.1, we noted the relationship between ASDLEP and FP/EP. In th next few sections, we will examine the behavior of annual savings with variations in other parameters individually and, in some cases, together.

Table 3.1. Base case characteristics

Location: Washington, DC	Outdoor Design Temperature (ODT): 7°F
HEUR: 800 Btu/h-°F Balance Point: 65°F Correction Factor (C_B): 0.7	Design Load (DL): 46,400 Btu/h
Furnace Fuel: Oil Fuel Price (FP): $1.00/gal (= 2.45¢/kWh equivalent to gas @ $0.72/therm) Steady State Furnace Efficiency (SSFE): 0.68	
Rated Furnace Capacity (RFC): 102,400 Btu/h	Furnace Heating Capacity (FC): 69,000 Btu/h; FC/DL = 1.5
Electricity Price (EP): 6.0¢/kWh 47°F Heating Capacity (HPC47): 46,400 Btu/h Heat Pump COP @ 47°F (COP47): 2.75 Heat Pump COP @ 17°F (COP17): 1.95	FP/EP = 0.41 HPC47/DL = 1.0

3.3 Climate

We examined annual savings in ten cities across the country. The results are displayed on Table 3.2. Since our concern here is the effects of climate, the fuel prices used for Table 3.2 are those of the base case (Table 3.1). The annual savings presented in the table are for comparison purposes and must be modified to account for actual fuel and electricity prices if AS or ASDL values are desired for these cities.

Two facts are readily apparent from Table 3.2. Places with small heating bills are going to have small annual savings. In Miami, if electricity were free, the annual savings from heat pump use could not be more than $55. Similarly, Dallas and Fresno have relatively small values of annual savings. The other apparent feature is that the percent savings are all in the range of 26 to 40% with the higher values in the milder climates. The warmer the climate the larger the fraction of the weather which occurs in the temperature ranges where the heat pump is most efficient.

Comparisons between certain cities show other interesting effects. For example, Chicago, Denver, and Syracuse have base fuel bills between about $1100 and $1200. Both Chicago and Syracuse have savings of about 26% of base fuel bills. Denver, however, has about 32% savings. This difference is due to the fact that Denver has a dry winter climate where heat pump frosting seldom occurs. If Fig. 2.9 had been for Denver weather the central dip in the net COP curve would have been absent.

Another interesting comparison is Washington, Portland, and Dallas. Portland's base heating bill is about 20% larger than Washington's, but Portland's annual savings are about 36% larger than Washington's. This can be understood by comparing the distribution of hours amongst the bins, Figure 3.3. Only 17% of Portland's hours are

Table 3.2. Effect of climate on annual savings

City	Design Temp. (°F)	Annual Base Fuel Bill ($)	Annual Savings ($)	% Savings**	Simple payback period† (years)
Miami, FL	37	55	19	40	105
Dallas, TX	7	458	152	33	13
Fresno, CA	27	539	169	34	12
Knoxville, TN	2	676	211	31	9
Washington, DC	7	762	227	30	9
Portland, OR	7	910	308	34	6
Seattle, WA	12	1004	329	33	6
Chicago, IL	-13	1094	286	26	7
Denver, CO††	-18	1127	361	32	6
Syracuse, NY	-18	1206	311	26	6

*This table is based on the base case parameter values of Table 4.1. It should be especially noted that these values are based on $1.00/gal oil and 6.0¢/kWh electricity and a house with an HEUR of 800 Btu/h-°F.

**These % savings values depend on fuel and electricity prices and furnace and heat pump efficiencies.

†These simple payback periods assume an installed AOHP cost of $2,000 and no maintenance costs.

††Dry winter climate assumed, therefore no defrost degradation was included.

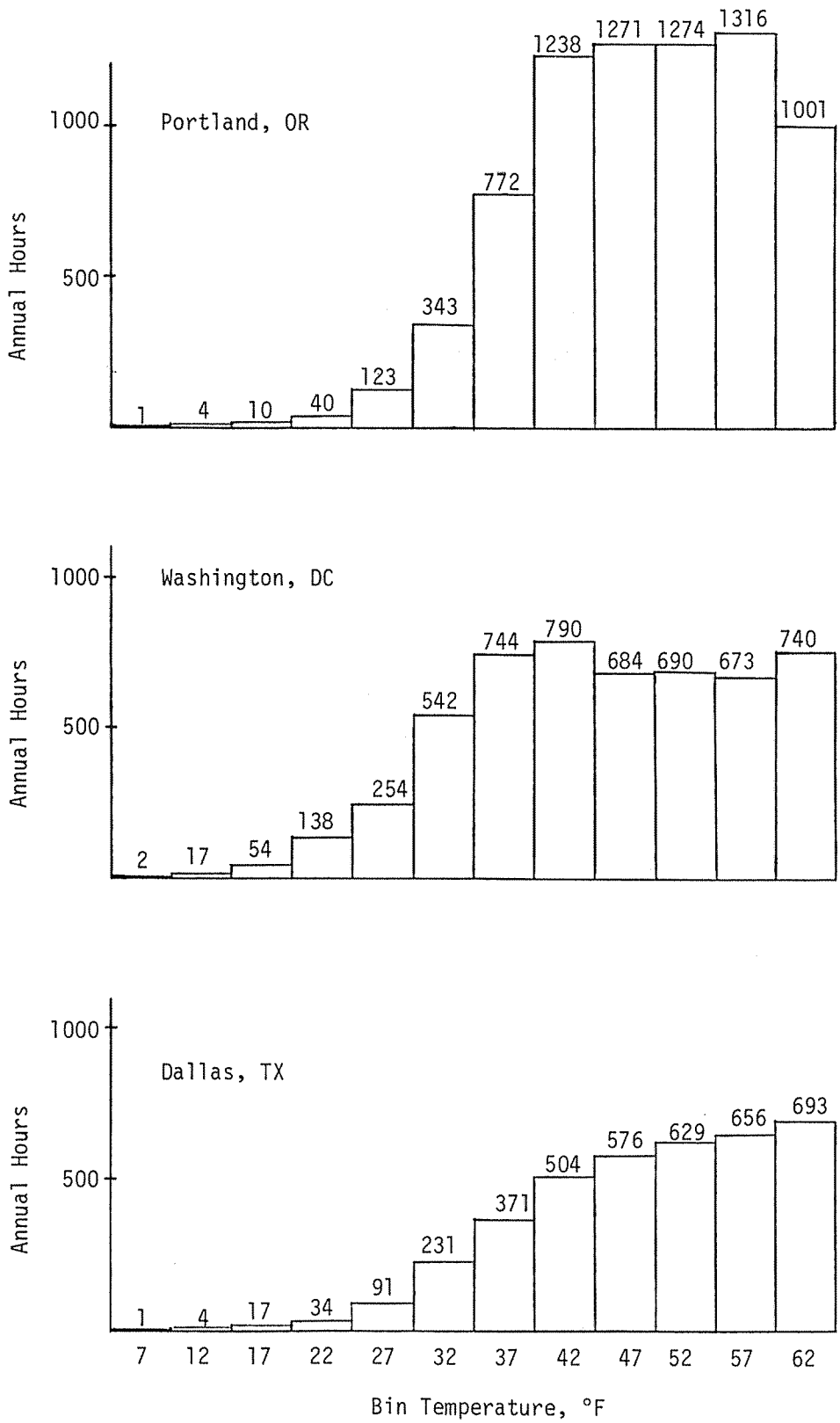


Figure 3.3 Distribution of Bin Hours for, Portland, OR, Washington, DC, and Dallas, TX

below 40°F, while 31% of Washington's hours are below 40°F. Dallas has half of Portland's base heating bill but it also has half of Portland's annual savings since, like Portland, a large fraction of the heating hours are at warmer outdoor temperatures.

3.4 Purchase and Maintenance Costs

The annual savings of the AOHP are the focus of most of this report. However, purchase and maintenance costs are extremely important to the overall attractiveness of the AOHP. The installed cost of a heat pump is about $2,000 excluding the duct work.[11] Central air conditioners cost about $1,000. Both these costs are variable depending on location, manufacturer, size and efficiency of the unit. Two installation situations need to be considered. The first is that an operational air conditioner is replaced by an AOHP. Since little if any salvage value can be expected from a used central air conditioner, the cost of the AOHP will be about $2,000. The second situation is that the existing air conditioner has failed or has deteriorated to such an extent that it must be replaced. If the air conditioner is going to be replaced, then the decision of whether or not to replace it with an AOHP should be based on the additional cost incurred by doing so; that is, about $1,000.

Heat pump maintenance and repair costs are known to be higher than those of air conditioners. A study by Nephew and Abbatiello estimates maintenance costs for various heating/cooling/domestic hot water systems.[12] By their estimate, a heat pump system has maintenance costs of about $50 per year more than an air conditioner with electric resistance heat. Collie reports that some manufacturers' heat pump compressors fail on average 2-2.5 times as often as others.[13] He also reports that even within a group of manufacturers with a particular average heat pump compressor failure rate there is a considerable scatter of failure rates. He concludes that "specifying an average compressor failure rate may not always be very meaningful." Perhaps the biggest risk involved in an AOHP or any heat pump is the possibly large maintenance costs.

Table 3.3 presents estimated simple payback period for add-on heat pumps for two net heat pump costs and two annual maintenance costs. The ten cities listed in Table 3.3 are presented to display climatic effects, not local fuel prices; every result on this table is based on electricity at 6¢/kWh and oil at $1.00/gal. The two net AOHP costs refer to the two cases; replacing a failed or deteriorated air conditioner and replacing an air conditioner in good condition. The two annual maintenance costs are intended to represent an average case and a rather pessimistic case. It is apparent that in mild climates like Miami almost any maintenance costs will preclude eventual payback of investment in an AOHP. In moderate climates like Washington, D.C., investment in an AOHP can be attractive provided maintenance and net purchase cost is low. However, unexpectedly high maintenance costs can seriously erode the attractiveness of the AOHP. In the more severe climates where annual savings are higher, the AOHP looks more attractive. Indeed, if a seven or eight year payback period is acceptable, a homeowner might consider replacing an operating air conditioner if he is confident that maintenance costs will remain low. Once again Tables 3.2 and 3.3 are based on the fuel prices of Table 3.1; local fuel prices can dramatically change the picture.

In general it appears that the AOHP will be most attractive when the existing air conditioner needs replacement or major repairs. Table 3.3 also shows that higher than normal maintenance costs can seriously erode AOHP savings. A prospective AOHP purchaser may be able to minimize his risks of excessive maintenance costs by using suppliers with good reputations. Perhaps a more secure arrangement is possible with a service or maintenance contract from the heat pump contractor.

3.5 Effects of Heat Pump Capacity

Figure 3.4 illustrates that annual savings are relatively insensitive to the capacity of the heat pump for values of HPC47/DL between 0.7 and 1.2. At higher heat pump capacities, the savings decline slowly. At lower heat pump capacities, the savings decline more quickly; reduced by about 20% at HPC47/DL = 0.5. This finding has important implications for sizing of heat pumps but the results for

Table 3.3 Effect of Maintenance costs on simple payback period

City	Net AOHP Cost*: Added Annual Maintenance:**	Simple payback period† $1000 $50	$1000 $150	$2000 $50	$2000 $150
Miami, FL					
Dallas, TX		10		20	
Fresno, CA		8		17	
Knoxville, TN		6	16	12	33
Washington, DC		6	13	11	26
Portland, OR		4	6	8	13
Seattle, WA		4	6	7	11
Chicago, IL		4	7	8	15
Denver, CO		3	5	6	9
Syracuse, NY		4	6	8	12

*The $1000 net AOHP cost represents the situation where an air conditioner needing major repairs is replaced by an AOHP. The $2000 net AOHP cost represents the case where an operational air conditioner is replaced by an AOHP.

**The $50 added annual maintenance cost is considered a reasonable low-maintenance and repair average cost based on Reference 12. The $150 added annual maintenance cost reflects the facts that some manufacturers have average repair rates that are fully twice that of other manufacturers and that there is a considerable scatter of repair rates about the average.

†Based on oil at $1.00/gal and electricity at 6¢/kWh, not local prices.

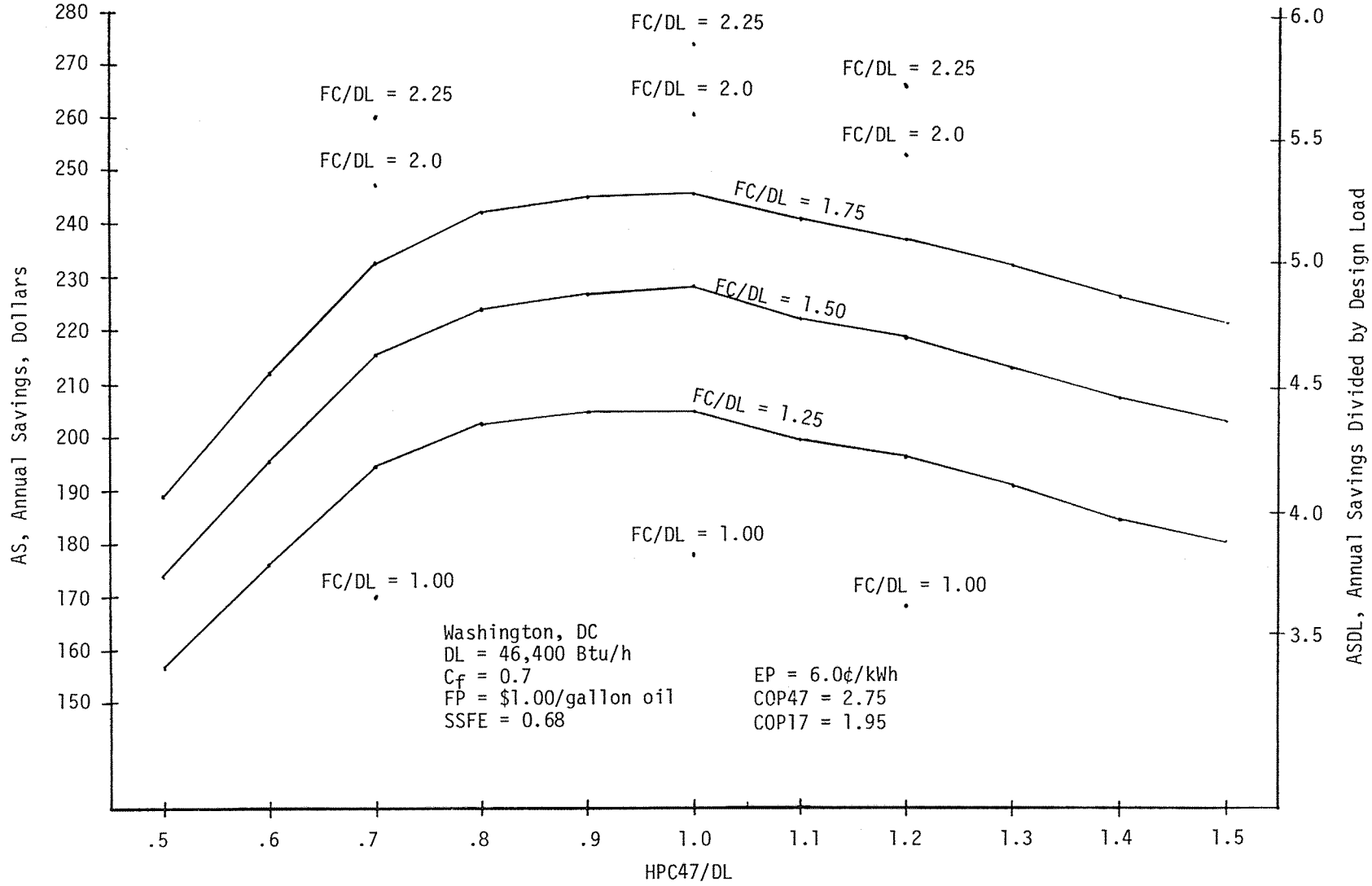


Figure 3.4 Dependence of Annual Savings on Furnace and Heat Pump Heating Capacities

this example in Washington, DC are not directly transferable to other locations. The general patterns will be repeated in other locations but the bounds of insensitivity may be different.

Heat pumps are used to meet both the heating and cooling loads. Since heat pumps are provided with auxillary heat sources, heat pumps are usually sized to satisfy the peak cooling load. Figure 3.4 shows that, within limits, installing a heat pump with cooling capacity to meet the peak cooling load should cause little reduction in savings. In this example, a heat pump of about 3.75 ton capacity provides about the maximum annual savings. However, use of 2.5 to 4.5 ton heat pumps reduce the annual savings by no more than about $10. This allows considerable latitude in meeting the design cooling load.
This result also has implications for the economics of heat pumps.

Where, as is usually the case, the maximum rate of return on investment (ROI) is desired, the smallest heat pump which captures most of the savings is preferable. In the example (Fig. 3.4) a heat pump of about 2.5 ton capacity would be preferred since the additional cost of a larger capacity heat pump would yield very little additional savings. However, the need to meet peak cooling loads may preclude using such a small heat pump.

3.6 Effects of Furnace Capacity

Figure 3.4 also displays useful information on furnace heating capacity (FC) effects. This figure shows that annual AOHP savings are larger for furnaces with more excess capacity. The savings for a furnace with FC/DL = 1.75 are substantially larger than for a furnace with FC/DL = 1.25.

Inspection of this figure shows that each increment of furnace capacity has less effect than the preceeding increment. For instance, for an AOHP with HPC47/DL = 1.0 and a furnace with a capacity of 2.25 DL, the annual savings will be $13 more than for an application to a furnace with FC = 2.0 DL. By comparison, the annual savings for a furnace with FC = 1.50 DL will be $23 greater than for a furnace with FC = 1.25 DL.

The similarity of the three curves on Fig. 3.4 (FC/DL = 1.75, FC/DL = 1.50 and FC/DL = 1.25) suggests that furnace capacity affects annual savings about the same regardless of the value of HPC47/DL. In order to explore this possibility, we calculated the ratio of AS at various values of FC/DL with AS at FC/DL = 1.50, at three values of HPC47/DL. Table 3.4 displays the results.

Table 3.4 Annual savings ratios* for various FC/DL and HPC47/DL values

FC/DL	0.7	1.0	1.2
2.25	1.205	1.205	1.215
2.00	1.148	1.148	1.156
1.75	1.079	1.081	1.084
1.50	1.0	1.0	1.0
1.25	0.903	0.902	0.898
1.00	0.790	0.785	0.770

*Compared to AS at FC/DL = 1.5.

Results show that excess furnace capacity causes increased annual savings to an extent which only depends weakly on heat pump capacity.

3.7 Effects of Furnace and Heat Pump Efficiencies

Add-on heat pump savings depend strongly on the efficiency of the furnace to which the heat pump is added. Annual savings also depend, though somewhat less pronouncedly, on the heat pump efficiency. Figure 3.5 shows the annual heating fuel bill for a fossil-fuel fired furnace as a function of steady-state furnace efficiency. For this example, replacing an inefficient furnace with an efficient furnace can save nearly as much money as installing an AOHP.

Figure 3.5 also shows add-on heat pump heating bills as a function of SSFE for three heat pump COPs. It is readily apparent that, for this example, the AOHP heating bill depends very little on SSFE in this

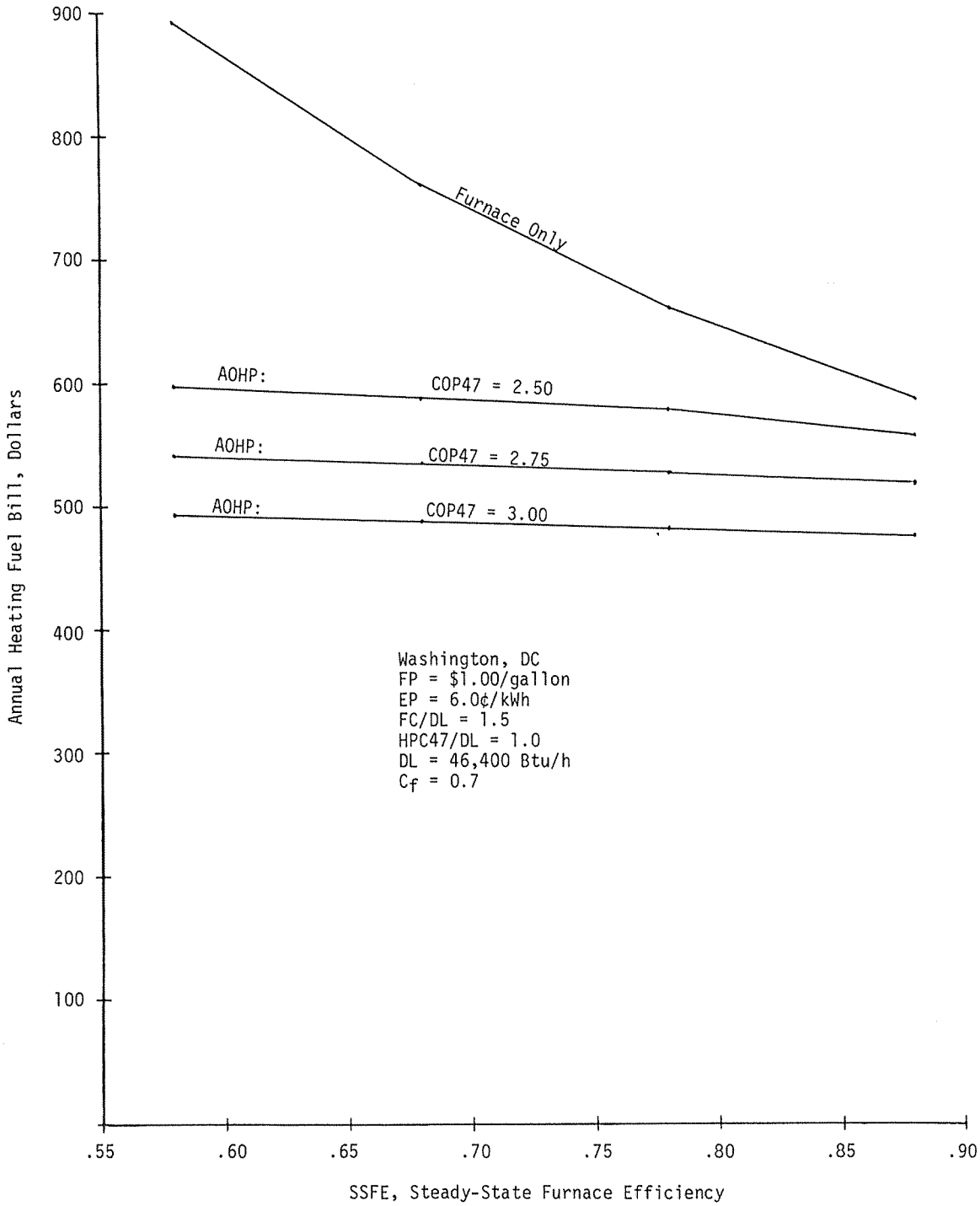


Figure 3.5 Annual Heating Fuel Bill Dependence on Furnace Efficiency and Heat Pump COP

range. It also appears that increasing the COP47 from 2.50 to 2.75 or from 2.75 to 3.00 reduces the annual heating bill by about $50. This $50 figure, with the consumers preferred payback criterion, gives an indication of how much more the consumer should pay for a higher efficiency heat pump.

This figure also shows that the annual savings (the difference between the furnace-only curve and the AOHP curve) is highly dependent on furnace efficiency. Another observation is that a householder with an inefficient furnace may choose to install a high efficiency furnace (SSFE > 0.85) or he may choose to add on a heat pump, but there is little economic advantage in doing both. A homeowner who has an efficient furnace will find little advantage in adding an AOHP, at least in this example.

Figure 3.6 displays annual savings (AS) as a function of SSFE and heat pump COP. This figure does not show the savings achievable by replacing an inefficient furnace but it shows annual savings in a simple manner where AOHP savings alone are of interest. This form of presentation is used in the proposed audit procedure discussed in Section 5.

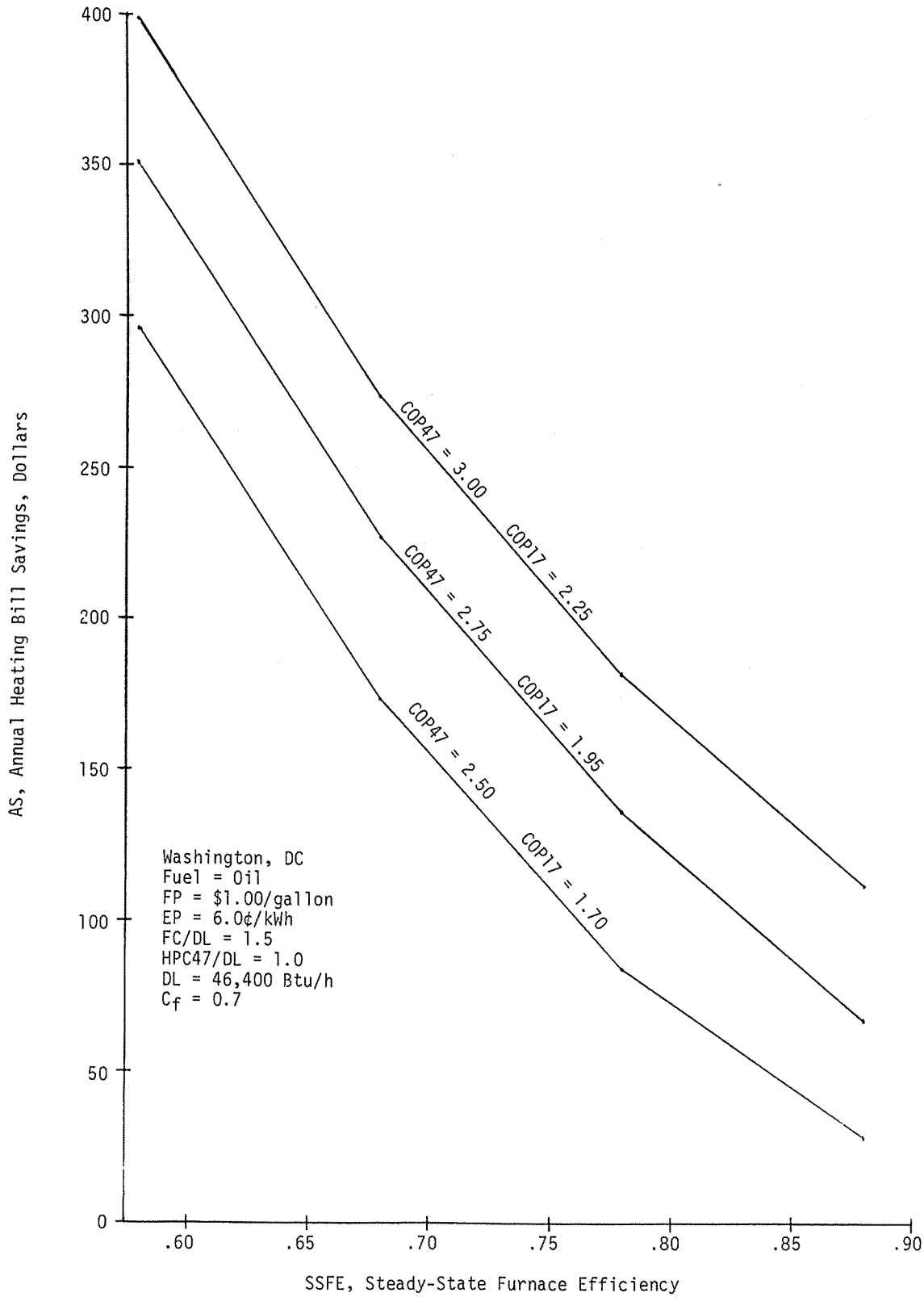


Figure 3.5 Annual Savings Dependence on Furnace Efficiency and Heat Pump COP

4. AOHP ASSESSMENT

The homeowner who is interested in the add-on heat pump will want to know whether it is advantageous for him to invest in it. The proposed audit procedure described in the next section provides a tool for easy estimation of AOHP savings (if the local utility has prepared the auditor's data). There are, however, a number of places where AOHPs can be seen to be quite unattractive. This section discusses in qualitative terms the locations and conditions for which AOHPs will be attractive or unattractive.

The first concern for the prospective AOHP user is whether it can be applied to his house. Most houses with a central oil- or gas-fired forced-air furnace <u>and</u> air-conditioner will be able to use an AOHP. Some houses with a central oil- or gas-fired forced-air furnace <u>without</u> an air-conditioner will be able to use an AOHP. There are, however, many possible problems, especially if the air conditioning capabilities of the AOHP are to be used. The cost of an AOHP applied where no air conditioning exists will often be much higher than considered here.

A typical AOHP with installation can be expected to cost $2000 and up. In order for an AOHP to pay for itself in a reasonable period of time, it must be able to save considerably on the annual fuel bill. Table 3.2 shows that, even if an AOHP is assumed to require no maintenance or repairs, small annual heating fuel bills as in Miami, or even in Dallas or Fresno, make for a long time to pay off the investment in the AOHP.

If an existing air conditioner requires replacement, then the effective cost of an AOHP can be somewhat lower than the $2000+ mentioned above. For instance, if replacing the existing air conditioner costs $1000 then the effective cost of an AOHP may be more like $1000. Where the AOHP is only marginally attractive, the homeowner may wish to wait and reconsider the AOHP when his existing central air conditioner needs replacement.

Heat pumps are generally recognized to require more maintenance than air conditioners and furnaces. A reasonable average estimate for

this extra cost is $50 per year. Some people have had much worse than average luck with their heat pumps. Table 3.3 shows estimates of simple payback periods for two net AOHP costs and two annual maintenance costs. The point to notice on this table is that if the simple payback period is fairly attractive (say three to four years) at a low maintenance cost then the payback period will be higher but not unreasonable if maintenance costs are unexpectedly high. On the other hand, if the payback is relatively slow at a low annual maintenance cost then higher maintenance costs can make the AOHP a poor investment.

Fuel and electricity prices are also very important. Figure 3.1 shows annual heating bills with and without an AOHP for two fuels and various electricity prices. For this example, it is apparent that if the furnace burns natural gas there is very little advantage to using an AOHP if the electricity price is much above 5¢/kWh. At 6¢/kWh, an AOHP can save over $250 per year if the furnace burns oil. In places with very high electricity prices, such as some of the states in the northeastern United States, even a relatively expensive fuel like oil may not make the AOHP attractive.

Other factors which strongly affect AOHP savings are the efficiencies of the furnace and heat pump. Figure 3.5 shows annual heating bills for several furnace efficiencies and heat pump COPs. This figure shows that add-on heat pumps and high efficiency furnaces are somewhat in competition. A homeowner with a fairly inefficient furnace can save a few hundred dollars per year by installing an AOHP or he can replace his existing furnace with a very high efficiency furnace and achieve similar savings. Higher or lower fuel and electric prices can of course change the relative competitive advantages. The relative costs of AOHP and high efficiency furnace are also important. Figure 3.5 also shows that the COP of the heat pump can make a substantial difference in AOHP savings. The prospective AOHP purchaser should consider the price and savings differences between AOHPs with different COPs so as to decide which will give him the preferred return on his investment. One other factor to consider is that if electricity prices were to increase more quickly than fuel prices the savings from

the high efficiency AOHP would be eroded less than those of the low efficiency model.

Other factors which affect AOHP savings are furnace and heat pump heating capacities. Oversized heating equipment causes excessive cycling which in turn reduces efficiency. Where an excessively large furnace is in place the advantage of an AOHP or furnace replacement is increased. Installation of a relatively small AOHP can save by reducing the purchase price and by operating efficiently; however, the cooling requirements of a house usually determine the size of heat pump required.

5. PROPOSED AUDIT PROCEDURE

An audit procedure needs to be simple to use yet reasonably accurate (within 20%). Variations of climate and fuel prices across the country make it a formidable task to estimate AOHP savings for all parts of the country. The proposed audit procedure presumes that the utility or company doing the audits will make certain preliminary calculations and provide the results to their auditors.

The desired result of an audit is an estimate of how much money an AOHP will save the homeowner each year. The procedure described below estimates operating savings, but does not include corrections for maintenance costs. The homeowner will best be served by an audit which provides realistic local estimates of maintenance costs and, perhaps, recommendations on what to look for in a heat pump.

5.1 Audit Procedure

The proposed audit procedure makes extensive use of the sensitivity analysis (Section 3). Equation 3.1 shows the variables which are needed to estimate AOHP annual savings. Since climate and electricity prices are essentially constant for a given locale, these parameters can be built into the information provided the auditor. Some utilities may wish to consider only high-COP add-on heat pumps, so COP47 and COP17 can be fixed. Alternatively, information about the relative savings of heat pumps with different COPs can be provided as in Fig. 3.6. Equation 3.2 can be used to provide annual savings estimates for houses with different heat loss rates or design load (DL).

In order to estimate AOHP annual savings, the auditor must collect certain information. The furnace heating capacity (FC) and steady state efficiency (SSFE) are needed. The furnace heating capacity is approximately equal to the rated furnace capacity (the rated fuel consumption rate of the furnace), possibly listed on the nameplate, multiplied by the SSFE.

The heating design load (DL) is proportional to the heating energy use rate (HEUR) estimated as a part of the audit process. The DL is calculated by multiplying HEUR by a temperature difference between indoors and outdoors. ASHRAE recommends using the actual design indoor air temperature and a value from their table of outdoor design temperatures for calculating the temperature difference. This study has used 65°F for the indoor temperature, as it is the balance point temperature presently used by the Model Audit. The outdoor design temperature has been taken to be the temperature of the coldest bin with one or more hours in an average year. Any choice of design indoor and outdoor temperatures can be used as long as it is used consistently by the auditor and those parties preparing the local data for the auditor.

As shown in Fig. 3.4, heat pump capacity affects AOHP annual savings. The heat pump capacity is usually determined by the need to meet the cooling needs of the house during summer months. In some places the relation between heating and cooling loads will be such that annual savings will be fairly insensitive to HPC47 (as on Fig. 3.4 for HPC47/DL between 0.7 and 1.2). Where this situation does not exist, the auditor will have to estimate the heat pump heating capacity. The Air Conditioning and Refrigeration Institute (ARI) ratings usually give HPC47 to be 0 to 10% larger than the rated cooling capacity of a heat pump.[14] The auditor can find or estimate the required cooling capacity, and estimate HPC47 as equal to the rated cooling capacity.

Ater determining HPC47, DL and SSFE, the auditor can go to a figure like Fig. 5.1 for an estimate of ASDL. A figure like Fig. 5.1 for ASDL would be provided to the auditor by the utility or company doing the audits. The utility would prepare the figure by using the AOHP savings model (Appendix A or B), local climatic data and local fuel prices.

Figure 5.1 may be more complicated than needed. For instance a utility may wish to recommend purchase of only high efficiency heat pumps and the curves for COP47 equal to 2.75 and 2.50 could be deleted. Or, if ASDL is no more affected by the range of expected values of HPC47/DL than is shown in this example for HPC47/DL between 0.7 and

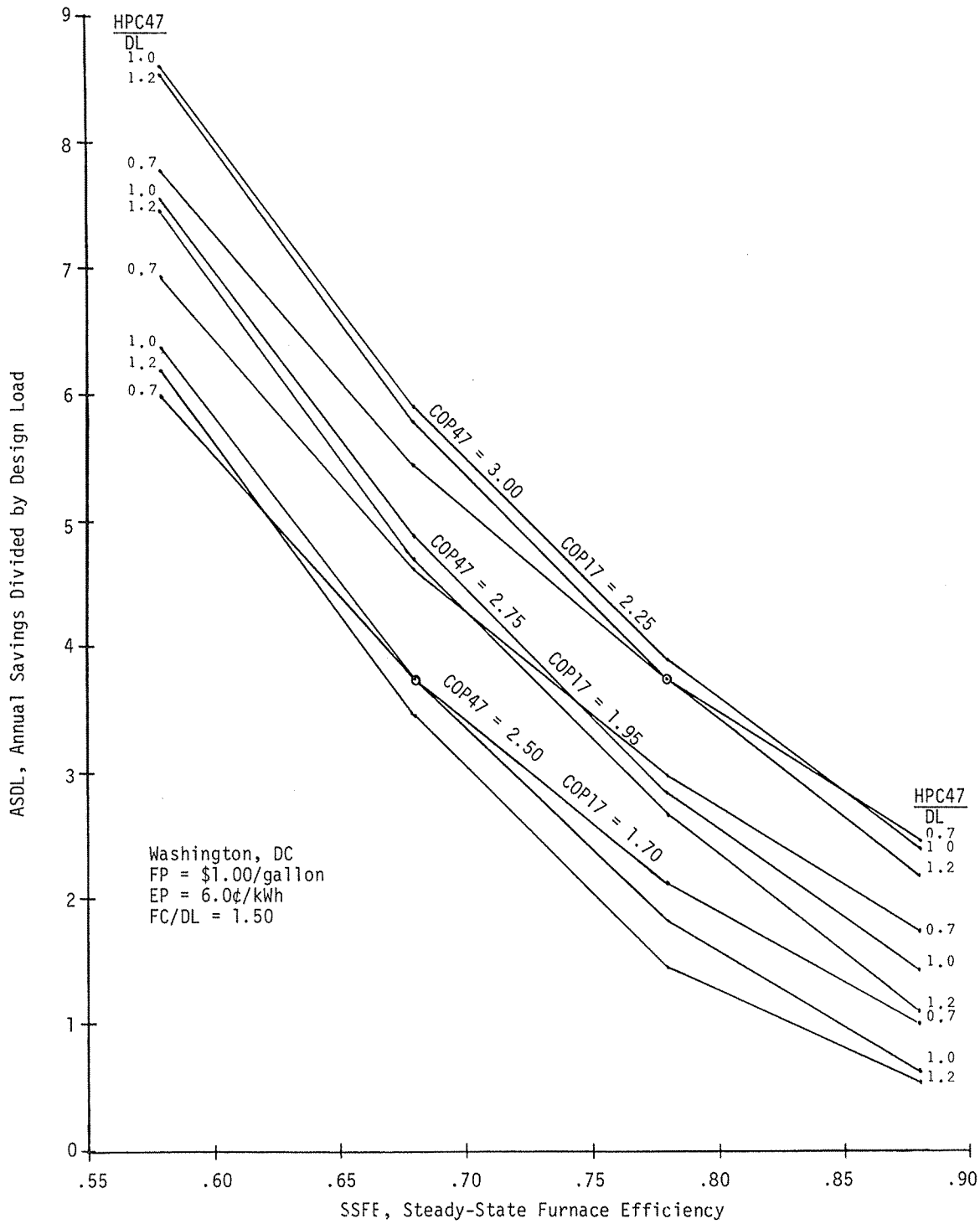


Figure 5.1 Dependence of Annual Savings on Heat Pump COP and Steady-State Furnace Efficiency

1.2, then a single curve might be used for each COP value instead of the several in Fig. 5.1. If other heating fuels were in use in a locale, then a Figure like 5.1 could be prepared for each fuel.

One other correction is needed. Figure 5.1 is based on a FC/DL ratio of 1.5, but other values of FC/DL may be expected. Table 3.4 shows that a multiplicative factor can correct annual savings for FC/DL ratios for a range of HPC47/DL ratios. A table like Table 5.1 with furnace capacity correction factors (FCCF) should be provided for the auditor. The AOHP annual savings (AS) can then be calculated by Eq. (5.1)

$$AS = ASDL \times FCCF \times DL \qquad (5.1)$$

Table 5.1 Furnace capacity correction factors

FC/DL	Correction factor, FCCF
2.25	1.21
2.00	1.15
1.75	1.08
1.50	1.00
1.25	0.90
1.00	0.79

5.2 An Example

A simple example may clarify the use of Fig. 5.1 and Table 5.1. A house in Washington, DC has an oil furnace with a heating capacity (FC) of 90,000 Btu/h (26.4 kW) and a measured steady state efficiency (SSFE) of 60%. The house has a HEUR of 700 Btu/h-°F and a design load (DL) of 52.2×10^3 Btu/h (15.3 kW). The peak cooling load is 44,400 Btu/h (13.0 kW), so a 47°F heat pump heating capacity (HPC47) of 44,400 Btu/h (13.0 kW) is assumed. At this point a standard heat pump size may be selected but using the peak cooling load for HPC47 will introduce little error. Also, assume that the higher efficiency heat pump with

COP47 of 3.0 is to be considered. HPC47/DL equals about 0.85. Heating oil costs $1.00/gallon and electricity costs 6¢/kWh. On Fig. 5.1, we find 7.7 for the ASDL for this combination of COP47, SSFE and HPC47/DL. The ratio FC/DL is 1.72 so we get a FCCF value of 1.08 from Table 5.1. Putting this all together, we find that the annual AOHP savings is $434 (7.7 x 1.08 x 52.2).

5.3 Preparation of Local Data

The company or utility preparing to use the proposed audit procedure in a locale will need to prepare a body of data for the auditor. This subsection presents suggestions for the preparation of that data.

The first task is to find what values of HPC47/DL will generally be found in the area of interest. This is usually determined by the relative sizes of the peak cooling and heating loads. Where cooling is not anticipated, other criteria, such as those suggested in the preceeding sections, may be used.

With typical values of HPC47/DL found, a figure like Fig. 5.1 can be prepared using the computer program listed in Appendix B. It may be that a utility will choose to audit for only the most efficient add-on heat pumps. In that case, the curves for COP47 = 2.75 and COP47 = 2.50 will be unnecessary. If the expected range of HPC47/DL is large or if the value of ASDL changes rapidly as HPC47/DL changes (for example, see Fig. 3.4 for HPC47/DL less than 0.7), then it may be necessary to include curves for more than three values of HPC47/DL on the figure like Fig. 5.1. The figure should be prepared using local weather data and electricity and fuel prices.

A table like Table 5.2 or a figure with the same information should be prepared to account for furnace oversize conditions different than the FC/DL used in preparing the figure discussed above. Our experience with the furnace capacity correction factor (FCCF) indicates that it is not very sensitive to the values of HPC47/DL. If this is not true for the applications of interest, a more complicated table or figure may be prepared to account for HPC47/DL as well as FC/DL.

Preparing the data for this procedure will require at least 20 calculations, however more calculations should be seriously considered to verify that the procedure is as well behaved in the location of interest as in our example. In any case, an automated calculation, like the Fortran program in Appendix B, will make preparation of the audit procedure data more convenient.

6. SUMMARY

The goals of this study were to evaluate the potential savings of add-on heat pumps and to develop a simple annual savings estimation procedure suitable for use by an auditor. In order to achieve these goals, the behavior of the AOHP was described and modeled (Section 2) and a sensitivity analysis on AOHP performance was performed (Section 3).

Add-on heat pumps can save significant amounts of money in cases where the existing furnace is not very efficient and electricity prices are not too high. For the ten cities considered (assuming 6¢/kWh and $1/gallon oil), we found annual savings ranging from about $20 to $360. Judgements about add-on heat pump economic attractiveness depends on the rate of return on investment desired by the homeowner. Simple payback periods ranged from 6 to 105 years assuming a $2,000 capital cost and no maintenance costs (Table 3.2). Maintenance costs can be $50 or more per year and can significantly influence the attractiveness of the AOHP (Table 3.3). On the other hand, since a heat pump is a dual purpose machine, careful consideration should be given to the allocation of capital costs between heating and cooling. For instance, if a central air conditioner <u>needs</u> to be replaced and an AOHP is purchased to replace it, then the annual savings should be compared to the incremental additional cost of the AOHP above the replacement air conditioner, not the full cost of the heat pump.

The AOHP performance sensitivity analysis revealed several interesting AOHP characteristics:

(1) Add-on heat pump savings are very dependent on furnace efficiency, and fuel and electricity prices.

(2) In the range examined, heat pump efficiency affects AOHP savings but much less than furnace efficiency.

(3) Furnace oversize has an important effect on AOHP savings because the greater the excess furnace capacity, the lower the seasonal furnace operating efficiency.

(4) There is a range of heat pump capacities in which annual savings do not vary significantly. AOHP performance declines rapidly for higher and lower heat pump capacities. This range of savings insensitivity exists because over a range of heat pump capacity, cycling inefficiencies at higher outside temperature are somewhat offset by improved heat pump performance at lower outside temperatures and vice versa.

(5) Some climates are more favorable for AOHP applications than others. Climates with mild winters may find add-on heat pumps unattractive unless an air conditioner is being replaced and AOHP savings must only pay for the increment which a heat pump adds to the air conditioner cost. Climates with many hours at mild outdoor temperatures where the heat pump is most efficient have larger savings than climates with more cold weather even if the two climates have the same number of heating degree days.

The proposed audit procedure (Section 5) is quite simple but it requires a data base to be prepared for the auditor's use. The auditor's data base should be prepared using local bin weather data, local fuel and electricity prices, and a knowledge of the relationships between peak heating and cooling loads in the area.

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APPENDIX A
ADD-ON HEAT PUMP ANNUAL SAVINGS MODEL
MANUAL METHOD

This appendix describes a manual method of the add-on heat pump annual savings model. It is presented for those who cannot use the Fortran version in Appendix B and must either make the calculations manually or write a program in some other language.

The annual AOHP savings estimation procedure consists of two parts. The first part is collection of the data indicated by Table A.1. The meanings of the preliminary data for Table A.1 are self evident except for the correction factor, C_B. This factor is discussed at length in Section 2.3. The best value of C_B for any particular locale must be based on experience in that locale. Use of 0.7, the ASHRAE modified degree-day method C_D or a locally derived C_D as a first estimate of C_B will give reasonable results with little risk of overestimation of benefits.

Table A.1. Preliminary Data

House

Location _____

Balance point (if unknown, use 65°F) _____

Rate of heat loss increase with increase inside/outside temperature difference (HUER) _____ (Btu/h-°F)

Correction factor, C_B (suggested default is 0.7 or local C_D)

_____

Heat Pump

Capacity @ 47°F _____ thousands of Btu/h

COP @ 47°F _____

COP @ 17°F _____

Electricity price _____ ¢/kWh

Furnace

Rated furnace capacity (RFC) _____ thousands of Btu/h

Steady state furnace efficiency (SSFE) _____ (default 0.7)

Furnace heating capacity (FC = RFC x SSFE) _____ thousands of Btu/h

Fuel type (select the appropriate one) and price:

Natural gas _____, $_____ per therm x 3.41 = ¢ _____ per kWh

Propane _____, $_____ per gallon x 3.75 = ¢ _____ per kWh

Oil _____, $_____ per gallon x 2.45 = ¢ _____ per kWh

The second part of the procedure is calculation of furnace and AOHP performance by completing the form illustrated in Fig. A.1. The instructions for completing the form are listed below:

A. Delete bin temperatures which are irrelevent. That is, if average year has no temperatures below -10°F then delete -13 and -18.

B. Use local values or values from the ASHRAE Handbook of Fundamentals or from Air Force Manual 88-29.

C. These values can be calculated in several ways, but the values should be those for the house being considered. If the HEUR of the house is known, that is, heat loss as a function of outside air temperature (Btu/h-°F and the balance point, °F) then these values can be easily calculated. For instance, if the balance point is 65°F (a frequently assumed value) and the heat loss characteristic (HUER) is 800 Btu/h-°F, then the building heat load for the 62°F bin is 2400 Btu/h [800 Btu/h-°F x (65°F - 62°F)]. Similarly, for the 57° bin the building heat load is 6400 Btu/h [800 Btu/h-°F x (65°F - 57°F)].

D. Calculate the furnace load factors (FLF) by dividing the building heat load (L) by the furnace heating capacity (FC). Keep three digits to minimize round-off errors in subsequent steps.

E. Calculate the furnace efficiency (FE) with the following equation:

$$FE = SSFE \cdot (0.6471 + 0.6765 \cdot FLF - 0.3235 \cdot FLF^2) \qquad (A.1)$$

If SSFE is unknown, assume some value such as 0.7.

F. Calculate the delivered cost of heat by dividing the fuel price (in ¢/kWh, from the Table 3.2) by the furnace efficiency (column E).

G. Determine the heat pump capacities for the relevant bin-temperatures. Use manufacturer's data if available for the unit of interest. Otherwise, the values can be approximated by multiplying the manufacturer's 47°F heat pump capacity by the appropriate correction factors on Table A.2. Use the "Normal Climate" column except in areas with very dry winter air (relative humidity usually below 60%).

For climates with very dry winter air, use the "Dry Climate" column of Table A.2. If a particular manufacturer's capacity curves for the appropriate temperatures are to be used, correct them for defrost capacity losses by multiplying them by the values in the "Defrost Correction" column. For dry winter climates, make no correction to the manufacturer's capacity data.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Bin Temperature	Number of Bin Hours	Building Heat Load	Furnace Load Factor	Furnace Efficiency	Delivered Cost of Furnace Heat	Heat Pump Capacity	Steady State Heat Pump COP	Frost/Defrost Correction to COP	Heat Pump Load Factor	Cycling Correction to COP	Net Heat Pump COP	Delivered Cost of Heat Pump Heat	Heat Pump Capacity / Furnace Capacity	Furnace Run Time	Furnace Efficiency	Heat Pump Run Time	Cycling Correction to Heat Pump COP	Net COP of Heat Pump	Delivered Cost of Heat	Base Case Annual Energy Bill	Add-on Heat Pump Energy Bill	Savings Per Hour of Heat Pump Running Time
	h	kBtu/h			¢/kWh	kBtu/h						¢/kWh							¢/kWh	$	$	$/h
62								1.0														
57								1.0														
52								1.0														
47								1.0														
42								0.84														
37								0.86														
32								0.89														
27								0.91														
22								0.94														
17								0.96														
12								0.99														
7								1.0														
2								1.0														
-3								1.0														
-8								1.0														
-13								1.0														
-18								1.0														

Totals _____
Correction Factor ___
Savings _____

Fig. A.1 Add-on heat pump savings calculations table.

H. If manufacturer's data on steady-state heat pump COPs are available for the relevant bin temperatures, use that data. If such data is not available, find the 47° and 17°F COP ratings of the selected heat pump model. For temperatures above 47°F multiply the 47° COP by 1.03. For temperatures below 47°F interpolate between 47°F and 17°F COPs. For example, if the 47° and 17°F COPs are 2.80 and 1.90, respectively, then the heat pump COP of each (5°F) bin would be (2.8 - 1.9) ÷ 6 less than the heat pump COP of the next warmer bin. Continue reducing COPs of each bin by the same amount until a COP of 1 or less is reached. Any COP less than 1 calculated by this method should be replaced by a COP value of 1 in column H.

I. The COP frost/defrost correction factor is applicable in most climates. For dryer winter climates (where the winter relative humidity is usually below 60%), skip this factor or set all values to 1.

Columns J through M should be calculated only for bins where the value in column C is less than (or equal to) the value in column G.

J. Calculate heat pump load factor which is the fraction of the heat pump's capacity required to meet the building heat load. The heat pump load factor is equal to the value in column C divided by the value in column G.

K. When operating at less than full load, heat pumps cycle on and off. This cycling is controlled by the thermostat. The cycling reduces the efficiency of the heat pump. Figure 2.3 presents efficiency corrections as a function of load factor (column J.)

   For each bin find the load factor in column J. Find cycling correction factor which corresponds to that load factor on Fig. 2.3. Enter the value from Fig. 2.3 into column K.

L. The net COP of the heat pump is the product of the values in columns H, I, and K. In dry climates (where the winter relative humidity is below 60% as in G above), column I should <u>not</u> be included.

M. Calculate the delivered cost of heat from the heat pump by dividing the cost of electricity (from the preliminary data form) by the net heat pump COP in column L.

Columns N through T are for calculations on the combined mode in which heat pump and furnace run alternatively to maintain the house temperature because the heat pump has insufficent capacity yet is less expensive to operate than the furnace. While the heat pump may be less expensive to operate than the furnace, the combined mode is sometimes

more expensive than the furnace alone. Columns N through T need be completed only for those bins where the values of certain columns have the following relationships:

$$C > G \text{ and } F > T.$$

Once a temperature is found where the value in column F is less than the value in column T this condition will hold for all lower temperature bins.

N. Calculate the ratio of the heat pump capacity (HPC) to the furnace capacity (FC); divide the value of column G by the furnace heating capacity (FC).

O. The furnace run time is comparable to the furnace load factor (column D). Since in this mode both the furnace and heat pump run (alternately) a different formula is required. The furnace run time fraction (FRT) may be calculated with the following equation:

$$FRT = \frac{1 - \frac{L/FC}{HPC/FC}}{\frac{1 + 2L/FC}{3L/FC} - \frac{1}{HPC/FC}} \qquad (A.2)$$

where L/FC is equal to FLF of column D, and HPC/FC is the ratio of heat pump capacity to furnace capacity, column N. Figure 2.7 allows the user to find values of FRT graphically.

P. The furnace efficiency is calculated as in step E but the values of furnace run time (FRT) from column O should be used in place of the values of furnace load factor from column D.

Q. The heat pump run time is comparable to the heat pump load factor (column J). The heat pump run time fraction (HPRT) may be calculated with the following equation:

$$HPRT = \frac{L/FC - FRT}{HPC/FC} \quad . \qquad (A.3)$$

The value of HPRT may also be taken from Fig. 2.6.

R. Given the heat pump run time from column Q, the cycling correction to the heat pump COP may be read from Fig. 2.3.

S. The heat pump COP is calculated by multiplying the values from columns H, I, and R. In dry climates the defrost correction factor (column I) should be omitted.

T. The delivered cost of heat from the combination heat pump is calculated by the following equation:

$$\text{Heat Cost} = \frac{\left[\frac{HPC}{COP} \times HPRT \times ECOST\right] + \left[\frac{FC}{FEFF} \times FRT\right]}{L} \qquad (A.4)$$

where: HPC is the heat pump capacity (column G),
EP is the price of electricity (¢/kWh),
FC is the furnace heating capacity,
FEFF is the furnace efficiency (column P),
FP is the furnace fuel cost (¢/kWh), and
L is the building heat load (column C).

Columns V through X are used to calculate the annual fuel expenditures for the base case and the add-on heat pump case, and to estimate the savings from the add-on heat pump case.

U. The base case annual energy bill is the product of the values from columns B, C and F divided by 341.3.

V. The add-on heat pump annual energy bill is the product of the values from columns B, C, and the least of F, M, or T; divided by 341.3.

W. (Optional.) Calculate the AOHP dollar savings per hour of heat pump run time for each bin by subtracting the value in column V from the value in column U then dividing the difference by the product of the building heat load (column C) and the heat pump load factor (column J) or the heat pump run time (column O), as appropriate.

This parameter is needed only if an estimate of the maintenance costs per hour of heat pump run time is available.

Final Step:

Total columns U and V. Subtract the column V total from the column U total and multiply by the correction factor (C_B). This is the annual savings expected from this add-on heat pump application.

APPENDIX B

ADD-ON HEAT PUMP COMPUTER PROGRAM SAVINGS ESTIMATION

```
C       PROGRAM TO COMPUTE THE SAVINGS DUE TO ADD-ON HEAT PUMP.
C       MODIFIED TO PROCESS AS MANY CITIES AS REQUESTED.
C       THIS VERSION ACCESSES BIN HOUR DATA SET FOR ALL CITIES
C       AND RUNS THE PROGRAM FOR GIVEN FURNACE AND HEAT PUMP SPECS.
C       BINHR:   AVERAGE NUMBER OF BIN HOURS, BIN TEMPERATURES ARE
C                FOR 62,57,52,47,42,37,32,27,22,17,12,7,2,-3,-8,
C                -13, AND -18.
C       L:      BUILDING HEATING LOAD
C       FLF:    FURNACE LOAD FACTOR
C       FE:     FURNACE EFFICIENCY
C       DCOSTF: DELIVERED COST OF FURNACE FUEL
C       HPC:    HEAT PUMP CAPACITY
C       SHPCOP: STEADY STATE HEAT PUMP COP(COEFFICIENT OF PERFORMANCE)
C       DCFCOP: COP FROST/DEFROST CORRECTION FACTOR
C       LODF:   LOAD FACTOR
C       CCOP1:  CYCLING CORRECTION FACTOR TO COP
C       HPCOP1: NET HEAT PUMP COP
C       DCOST1: DELIVERED COST OF HEAT PUMP HEAT
C       HPCVFC: RATIO OF HEAT PUMP CAPACITY TO FURNACE CAPACITY
C       FRT:    FURNACE RUN TIME
C       FEFF:   FURNACE EFFICIENCY BASED ON THE RUN TIME
C       HPRT:   HEAT PUMP RUN TIME
C       CCOP2:  CYCLING CORRECTION FACTOR TO COP BASED ON HPRT
C       HPCOP2: NET HEAT PUMP COP BASED ON CCOP2
C       DCOST2: DELIVERED COST OF HEAT PUMP WITH FEFF AND HPCOP2
C       BASEN:  BASE CASE ANNUAL ENERGRY BILL
C       ADOHPE: ADD ON HEAT PUMP ENERGY BILL
C       DSHRT:  DOLLAR SAVING PER HOUR OF HEAT PUMP RUN TIME
C       CCF:    CAPACITY CORRECTION FACTORS
C       CB:     CORRECTION FACTOR ON ANNUAL SAVINGS
C
        REAL LODF, L
        LOGICAL DEBUG
        DIMENSION BINHR(17),L(17),FLF(17),FE(17),DCOSTF(17),HPC(17)
     1  ,SHPCOP(17),DCFCOP(17),LODF(17),CCOP1(17),HPCOP1(17)
     2  ,DCOST1(17),HPCVFC(17),FRT(17),FEFF(17),HPRT(17),CCOP2(17)
     3  ,HPCOP2(17),DCOST2(17),BASEN(17),ADOHPE(17),DSHRT(17)
     2  ,CCF(17,2),FUELF(3),CITY(4),FTYPE(3,3),FUNIT(2,3),TEMP(17)
        NAMELIST/LOCA/LOCBEG,LOCEND
C
C       LOC(130) CONTAINS ICITY NO. ASSOCIATED WITH CITIES TO BE RUN.
C
        NAMELIST/FACT/HTLOSC,HPC47,COP47,COP17,KLIMAT,BALPT,RFC,SSFE
C
C       HTLOSC: HEAT LOSS COEFFICIENT
C       HPC47:  47 DEG F. HEAT PUMP CAPACITY
C       COP47:  HEAT PUMP COP FOR 47 DEG F.
C       KLIMAT: KLIMAT=1     FOR NORMAL REGION
C               KLIMAT=2     FOR DRY REGION
C       BALPT:  BALANCE POINT
C       COP17:  HEAT PUMP COP FOR 17 DEG F.
C       RFC:    RATED FURNACE CAPACITY (MBTU/H)
C       FC:     FURNACE HEATING CAPACITY (=RFC*SSFE), (MBTU/H)
C       SSFE:   STEADY STATE EFFICIENCY OF FURNACE
```

```
C
      NAMELIST/FUEL/FUELPR,ITYPE,ECOST
C
C             ECOST:  ELECTRICITY PRICE
C             ITYPE:  1:      NATURAL GAS
C                     2:      PROPANE GAS
C                     3:      OIL
C             FUELPR: FUEL PRICE OF THE TYPE INDICATED BY ITYPE.
C
      DATA CCF/1.116,1.087,1.049,1.000,0.760,0.726,0.686,0.646,0.607
     1        ,0.562,0.516,0.463,0.420,0.376,0.336,0.302,0.273
     2        ,1.116,1.087,1.049,1.000,0.929,0.856,0.780,0.711
     3        ,0.646,0.579,0.516,0.463,0.420,0.376,0.336,0.302,0.273/
C    4        ,1.000,1.000,1.000,1.000,0.818,0.848,0.879,0.909,0.939
C    5        ,0.970,7*1.000/
      DATA DCFCOP/4*1.0,0.84,0.86,0.89,0.91,0.94,0.96,0.99,6*1.0/
      DATA FUELF/3.41,3.75,2.45/,FTYPE/'NATUR','AL GA','S    ',
     1 'PROPA','NE   ','     ','OIL  ',2*'     '/
     2 ,FUNIT/'/THER','M    ','/GAL ','     ','/GAL ',
     3 '     '/,DEBUG/.XXXX./
      DATA CB,HDD,SSFE/0.0,0.0,0.68/
      DATA UBASE,DBASE,UF,DF,UHP,DHP/6*0.0/
      DATA TEMP/62.,57.,52.,47.,42.,37.,32.,27.,22.,17.,
     1 12.,7.,2.,-3.,-8.,-13.,-18./
C
C     INPUT
C
      OPEN(UNIT=20,FILE='ADOHP.TMP')
      READ(20,LOCA)
      READ(20,FACT)
      READ(20,FUEL)
      IF(LOCEND.EQ.0)LOCEND=LOCBEG
      NLOC=LOCEND - LOCBEG +1
C
C     FURNACE HEATING CAPACITY DEFINED:
        FC = RFC * SSFE
C
      WRITE(5,1200)HTLOSC,RFC,SSFE,FC,HPC47,COP47,COP17,BALPT
 1200 FORMAT('0HEAT LOSS CHARACTERISTIC=',F8.1,'(BTU/H/DEG F)'/
     1 ' RATED FURNACE CAPACITY=',F10.2,'(MBTU/H)',3X,
     2 ' STEATY STATE FURNACE EFFICIENCY=',F6.2/
     3 ' FURNACE HEATING CAPACITY=',F8.2,'(MBTU/H)'/
     4 ' 47 DEG. F HEAT PUMP CAPACITY=',F10.2,'(MBTU/H)'/
     5 ' COP47=',F5.2, '     COP17=',F5.2/
     6 ' BALANCE POINT=',F6.2,'(DEG F)')
      FPR = ECOST/FUELPR/FUELF(ITYPE)
      WRITE(5,1300)(FTYPE(I,ITYPE),I=1,3),FUELPR,
     1 (FUNIT(I,ITYPE),I=1,2),ECOST,FPR
 1300 FORMAT('0FUEL TYPE=',3A5,
     1 '      PRICE=',F5.2,2A5/
     2  ' ELECTRICITY=',F5.2,'(C/KWH)'/
     3  ' FUEL PRICE RATIO (EP/FP) = ',F5.2)
C
C     SET THE VALUE OF CB (CORRECTION FACTOR).
```

```
C     IF CB IS SPECIFIED THAT VALUE IS USED.
C     IF CB IS NOT SPECIFIED BUT HDD IS ;CB IS CALCULATED.
C     IF NEITHER CB NOR HDD IS SPECIFIED, CB DEFAULTS TO 0.7.
C
        IF(CB .LE. 0.0) GO TO 1350
        IF(HDD .EQ. 0) GO TO 1350
        CB = 0.85 - (0.15/5000)*HDD
        IF(HDD .GT. 5000) CB=0.6 + (.05/4000)*(HDD - 5000)
        IF(HDD .GT. 9000) GO TO 1350
        GO TO 1400
 1350   CB = 0.7
 1400   WRITE(5,1450) CB
 1450   FORMAT('0CORRECTION FACTOR(CB) = ',F4.2)
C
        OPEN (UNIT=21,FILE='BINHR.DAT')
        DO 500 NCITY=1,LOCEND
        READ(21,3000,END=999)ICITY,CITY
        READ(21,3100)NBIN,(BINHR(I),I=1,NBIN)
 3000   FORMAT(I4,4A5)
 3100   FORMAT(I4,(14F5.0))
        IF(ICITY .LT. LOCBEG) GO TO 500
C
        DL = HTLOSC*(BALPT- 62. +(NBIN-1)*5)/1000
        R1 = HPC47/DL
        R2 = FC/DL
        WRITE(5,3200) DL, R1, R2
 3200   FORMAT('0DESIGN LOAD =',F5.1,'*10**3 BTU/H, ',
     1          '   HPC47/DL = ',F4.2,
     2          ',    FC/DL = ',F4.2)
C
        WRITE(5,1500)ICITY,(CITY(I),I=1,4)
 1500   FORMAT('0CITY NUMBER=',I2,4X,' CITY=',10A5)
C
        SUBFAC=(COP47 - COP17) * 5.0/30.0
        FCOST=FUELF(ITYPE) * FUELPR
        DO 20 I=1,NBIN
        FRT(I)=0.
        DCOST1(I)=0.
        HPRT(I)=0.
        DCOST2(I)=0.
 20     LODF(I)=0.
C
        DO 100 I=1,NBIN
C
C       ***   C   ***  BUILDING HEATING LOAD
C
        L(I)=HTLOSC * (BALPT - 62. + (I-1)*5)/1000.0
C
C       ***   D   ***  FURNACE LOAD FACTOR
C
        FLF(I)=L(I)/FC
C
C       ***   E   ***  FURNACE EFFICIENCY
C
```

```
      FE(I)=SSFE *(0.6471 + 0.6765 *FLF(I) - .3235 * FLF(I)*FLF(I))
C
C     ***   F   ***   DELIVERED COST OF FURNACE FUEL
C
      IF(FE(I).NE.0.)DCOSTF(I)=FCOST/FE(I)
C
C     ***   G   ***  HEAT PUMP CAPACITY
C
      HPC(I)=HPC47 * CCF(I,KLIMAT)
C
      IF(HPC(I) .GT. L(I)) GO TO 17
      IM1 = I - 1
      IF(HPC(IM1) .LE. L(IM1)) GO TO 17
      ABP = 72. - 5.*I + 5.*(L(IM1) - HPC(IM1))/
     1            (L(I) - L(IM1) - HPC(I) + HPC(IM1))
      WRITE(5,1700) ABP
 1700 FORMAT('0APPLICATION BALANCE POINT = ',
     1         F4.0,' DEGREES F.')
 17   CONTINUE
C
C     ***   H   *** STEADY STATE HEAT PUMP COP
C
      SHPCOP(I)=COP47 * 1.03
      IF(I .LT. 4) GO TO 15
      SHPCOP(I)=COP47 - SUBFAC * (I-4)
      IF(SHPCOP(I) .LT. 1.0)SHPCOP(I)=1.0
C
C     ***   I   *** COP FROST/DEFROST FACTORS
C
 15   IF(KLIMAT .EQ. 2)DCFCOP(I)=1.0
C
C     ***   J   *** LOAD FACTOR
C
      IF(L(I) .LE. HPC(I))LODF(I)=L(I)/HPC(I)
      IF(L(I) .GT. HPC(I)) GO TO 25
C
C     ***   K   *** CYCLING CORRECTION TO COP
C
      IF(LODF(I) .LE. 0.2)CCOP1(I)=0.6 + 0.8*LODF(I)
      IF(LODF(I) .GT. 0.2)CCOP1(I)=0.76 + 0.3*(LODF(I) - 0.2)
C
C     ***   L   *** NET HEAT PUMP COP
C
      HPCOP1(I)=SHPCOP(I) * DCFCOP(I) * CCOP1(I)
C
C     ***   M   ***  DELIVERED COST OF HP HEAT
C
      DCOST1(I)=ECOST/HPCOP1(I)
C
C     N - T ARE COMPUTED ONLY WHEN C > G AND F > M.
C
 25   IF(L(I) .LE. HPC(I) .OR. DCOSTF(I) .LE. DCOST1(I)) GO TO 35
C
C     ***   N   ***  RATIO OF HPC TO FC
```

```
C
      HPCVFC(I)=HPC(I)/FC
C
C     ***   O   ***   FURNACE RUN TIME
C
      HPCFC=1./HPCVFC(I)
      FRT(I)=(1. - FLF(I)*HPCFC)/((1./FLF(I)  + 2.)/3. -HPCFC)
C
C     ***   P   ***   FURNACE EFF BASED ON THE RUN TIME
C
      FEFF(I)=SSFE*(.6471 + .6765*FRT(I)-.3235*FRT(I)*FRT(I))
C
C     ***   Q   ***   HEAT PUMP RUN TIME
C
      HPRT(I)=(FLF(I) - FRT(I))/HPCVFC(I)
C
C     ***   R   ***   CYCLING CORRECTION TO HP COP BASED ON HPRT
C
      IF(HPRT(I) .LE. .2)CCOP2(I)=.6 + .8*HPRT(I)
      IF(HPRT(I) .GT. .2)CCOP2(I)=.76 + .3*(HPRT(I) - .2)
C
C     ***   S   *** HEAT PUMP COP BASED ON CCOP2
C
      HPCOP2(I)=SHPCOP(I) * DCFCOP(I) * CCOP2(I)
C
C     ***   T   ***  DELIVERED COST OF HEAT PUMP WITH FURNACE
C
      DCOST2(I)=(HPC(I)*HPRT(I)*ECOST/HPCOP2(I) +
     1 FC*FRT(I)*FCOST/FEFF(I))/L(I)
C
C     ***   U   ***   BASE CASE ENERGY BILL
C
 35   BASEN(I)=BINHR(I) * L(I) *DCOSTF(I)/341.3
C
C     ***   V   ***   ADD ON HEAT PUMP ENERGY BILL
C
      IF(DCOST1(I) .EQ. 0.0)AMIN=AMIN1(DCOST2(I),DCOSTF(I))
      IF(DCOST2(I) .EQ. 0.0)AMIN=AMIN1(DCOST1(I),DCOSTF(I))
      IF(AMIN .EQ. 0.0)AMIN=DCOSTF(I)
      ADOHPE(I)=BINHR(I) * L(I) * AMIN/341.3
C
C     ***   W   ***   DOLLAR SAVINGS PER HEAT PUMP RUN TIME
C
      IF(LODF(I) .EQ. 0.0) GO TO 45
      DSHRT(I)=(BASEN(I)-ADOHPE(I))/(BINHR(I)*LODF(I))
 45   IF(DCOST2(I) .EQ. 0.0 .OR. HPRT(I) .EQ. 0.) GO TO 50
      DSHRT(I)=(BASEN(I)-ADOHPE(I))/(BINHR(I)*HPRT(I))
C
C     PRELIMINARIES FOR SEASONAL EFFICIENCIES
C
 50   BIN = BINHR(I)
      UBASE = UBASE + BIN*FLF(I)*FE(I)
      DBASE = DBASE + BIN*FLF(I)
C
```

```
      IF(DCOST2(I) .GE. DCOSTF(I)) GO TO 55
      UF = UF + BIN*FRT(I)*FEFF(I)
      DF = DF + BIN*FRT(I)
C
      UHP = UHP + BIN*(LODF(I)*HPCOP1(I) + HPRT(I)*HPCOP2(I))
      DHP = DHP + BIN*(LODF(I) + HPRT(I))
C
      GO TO 100
 55   UF = UF + BIN*FLF(I)*FE(I)
      DF = DF + BIN*FLF(I)
C
 100  CONTINUE
C
C     CALCULATE SEASONAL EFFICIENCIES
C
      SEFE1 = UBASE/DBASE
      SEFE2 = UF/DF
      SECOP = UHP/DHP
C
      WRITE(5,1800) SEFE1,SEFE2,SECOP
 1800 FORMAT('OSEASONAL EFFICIENCIES (BASE FURN, AOHP FURN',
     1        ', HP) = ',F6.2,F8.2,F8.2)
C
C     PRINTOUT THE INTERMEDIATE VALUES AND TOTAL VALUES.
C
      IF(.NOT.DEBUG)GO TO 350
      WRITE(5,1900)
 1900 FORMAT('O',4X,'A',6X,'B',9X,'C',9X,'D',9X,'E',9X,'F',9X,
     1 'G',9X,'H', 9X,'I',9X,'J',9X,'K',9X,'L'/5X,
     2 'TEMP',3X,'BINHR',5X,'L  ',7X,'FLF',7X,'FE',8X,'DCOSTF',4X,
     3 'HPC',7X,'SHPCOP'4X,'DCFCOP',4X,'LODF',6X,'CCOP1',5X,
     4  'HPCOP1')
C
      DO 200 I=1,NBIN
      WRITE(5,2000)TEMP(I),BINHR(I),L(I),FLF(I),FE(I),DCOSTF(I),
     1 HPC(I),SHPCOP(I),DCFCOP(I),LODF(I),CCOP1(I),HPCOP1(I)
 2000 FORMAT(1X,3X,F4.0,11(F10.3))
 200  CONTINUE
C
      WRITE(5,2100)
 2100 FORMAT('O',4X,'A',6X,'M',9X,'N',9X,'O',9X,'P',9X,'Q',9X,
     1 'R',9X,'S',9X,'T',9X,'U',9X,'V',9X,'W'/5X,
     2 'TEMP',3X,'DCOST1',4X,'HPCVFC',4X,'FRT',7X,'FEFF',6X,
     3 'HPRT',6X,'CCOP2',5X,'HPCOP2',4X,'DCOST2',4X,'BASEN',
     4  5X,'ADOHPE',4X,'DSHRT')
C
      DO 300 I=1,NBIN
 300  WRITE(5,2000)TEMP(I),DCOST1(I),HPCVFC(I),FRT(I),FEFF(I)
     1 ,HPRT(I),CCOP2(I),HPCOP2(I),DCOST2(I),BASEN(I),ADOHPE(I)
     2 ,DSHRT(I)
C
C     TOTAL U AND V AND FIND ANNUAL SAVINGS.
C
 350  TBASEN=0.0
```

```
      TADOHP=0.0
      DO 400 I=1,NBIN
      TBASEN=TBASEN + BASEN(I)*CB
      TADOHP=TADOHP + ADOHPE(I)*CB
 400  CONTINUE
C
      ANNSAV=TBASEN - TADOHP
      ASDL = ANNSAV/DL
      ASDLEP = ASDL/ECOST
      WRITE(5,2200)ANNSAV,TBASEN,TADOHP,ASDL,ASDLEP
 2200 FORMAT('OANNUAL SAVINGS=                ',F7.2/
     1        ' ANNUAL BASE ENERGY BILL=      ',F7.2/
     2        ' ANNUAL ADD ON HP ENERGY BILL= ',F7.2/
     3        ' ANNUAL SAVINGS/DESIGN LOAD=   ',F9.4,
     4        ' ($/YR)/(10**3 BTU/H)',
     5        '     ASDLEP = ',F7.4,
     6        ' ($/YR)/(10**3 BTU/H)/(C/KWH)')
 500  CONTINUE
 999  STOP
      END
```

INPUT DATA FILE ADOHP.TMP

```
&LOCA LOCBEG=XX,
      LOCEND=YY
       &END
&FACT HTLOSC=800. ,HPC47=46.4 ,COP47=2.75,       COP17=1.95,
 SSFE=0.68    KLIMAT=1,BALPT=65.,RFC=102.35  &END
&FUEL FUELPR=1.00  ,    ITYPE=3, ECOST=6.0      &END
```

BIN WEATHER DATA FILE BINHR.DAT

1ALBANY, NY
17 740. 708. 652. 625. 647. 769. 793. 574. 404. 278. 184. 110. 63. 32.
10. 5. 4.
2ALBUGUERQUE, NM
14 719. 651. 687. 734. 741. 689. 552. 346. 154. 66. 21. 4. 1. 1.
3ATLANTA, GA
12 823. 784. 735. 676. 598. 468. 271. 112. 44. 19. 8. 2.
4BAKERSFIELD, CA
8 966. 977. 908. 746. 541. 247. 77. 7.
5BIRMINGHAM, AL
12 805. 742. 668. 614. 528. 433. 292. 143. 69. 17. 6. 3.
6BISMARK, ND
17 614. 606. 563. 520. 518. 604. 653. 550. 474. 371. 338. 292. 278. 208.
131. 77. 80.
7BOISE, ID
14 643. 702. 786. 798. 878. 829. 522. 307. 148. 53. 26. 14. 6. 2.
8BOSTON, MA
15 804. 781. 766. 757. 828. 848. 674. 429. 256. 151. 74. 35. 4. 9.
1.
9BUFFALO, NY
15 760. 700. 666. 624. 647. 756. 849. 602. 426. 267. 170. 81. 5. 24.
2.
10BURLINGTON, VT
17 703. 694. 655. 603. 637. 716. 752. 561. 491. 336. 272. 216. 135. 81.
39. 17. 8.
11CASPER, WY
17 592. 642. 606. 670. 782. 831. 806. 683. 495. 324. 200. 116. 73. 45.
30. 15. 5.
12CHARLESTON, SC
10 889. 787. 651. 576. 434. 321. 192. 79. 27. 5.
13CHARLESTON, WV
14 767. 689. 661. 667. 607. 633. 630. 356. 252. 135. 73. 22. 7. 1.
14CHARLOTTE, NC
12 839. 752. 730. 684. 634. 515. 360. 166. 64. 23. 5. 2.
15CHATTANOOGA, TN
13 775. 722. 713. 679. 642. 553. 414. 228. 113. 45. 14. 4. 2.
16CHICAGO, IL
16 653. 592. 569. 543. 591. 800. 822. 551. 335. 196. 117. 85. 59. 25.
12. 3.
17CINCINNATI, OH
15 726. 639. 611. 599. 627. 698. 711. 460. 249. 131. 68. 44. 18. 8.
2.
18CLEVELAND, OH
15 732. 641. 638. 607. 620. 754. 806. 578. 355. 201. 111. 47. 22. 11.
2.
19COLUMBUS, OH
16 720. 648. 622. 603. 658. 730. 772. 502. 280. 169. 94. 40. 20. 10.
4. 1.
20CORPUS CHRISTI, TX
9 748. 551. 444. 302. 180. 83. 27. 9. 3.
21DALLAS, TX
12 693. 656. 629. 576. 504. 371. 231. 91. 34. 17. 4. 1.
22DENVER, CO
17 783. 731. 678. 704. 692. 717. 721. 553. 359. 216. 119. 78. 36. 22.

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 6.   1.   1.
23DES MOINES, IA
17 681. 600. 585. 512. 510. 627. 747. 557. 405. 281. 211. 152. 104.  59.
23.   8.   1.
24DETROIT, MI
15 695. 633. 592. 566. 595. 808. 884. 618. 377. 248. 131.  61.  17.   4.
 1.
25EL PASO, TX
11 749. 760. 687. 611. 494. 369. 233. 104.  34.  10.   2.
26FT. WAYNE, IN
16 699. 608. 569. 552. 601. 725. 905. 596. 381. 205. 124.  69.  40.  19.
 6.   1.
27FRESNO, CA
 8 921.1006.1036. 952. 673. 426. 168.  34.
28GRAND RAPIDS, MI
16 712. 647. 571. 565. 554. 742. 938. 690. 469. 293. 172.  78.  31.  10.
 1.   1.
29GREAT FALLS, MT
17 636. 754. 822. 830. 832. 813. 698. 533. 355. 218. 167. 136. 118. 101.
68.  51.  62.
30HARRISBURG, PA
14 737. 692. 635. 659. 722. 888. 749. 427. 222. 125.  52.  18.   4.   1.
31HARTFORD, CT
16 751. 752. 649. 575. 683. 807. 825. 552. 370. 233. 153.  77.  33.  11.
 3.   2.
32HOUSTON, TX
10 772. 681. 570. 452. 291. 141.  64.  18.   4.   2.
33INDIANAPOLIS, IN
16 722. 585. 586. 579. 605. 712. 791. 551. 293. 152.  97.  60.  35.  13.
 3.   2.
34JACKSONVILLE, FL
 9 879. 692. 530. 355. 288. 154.  83.  24.   2.
35JACKSON, MS
13 790. 677. 618. 605. 484. 367. 224. 103.  41.   6.   2.   2.   1.
36KANSAS CITY, MO
14 601. 572. 553. 562. 628. 625. 591. 407. 265. 175.  99.  51.  21.   4.
37KNOXVILLE, TN
13 746. 675. 672. 689. 648. 590. 456. 217. 101.  41.  21.   7.   2.
38LAS VEGAS, NV
10 699. 786. 769. 716. 591. 396. 194.  44.   7.   1.
39LITTLE ROCK, AR
12 725. 672. 638. 669. 605. 509. 363. 172.  50.  25.   5.   1.
40LOS ANGELES, CA
 62193.1904.1054. 428. 107.  10.
41LOUISVILLE, KY
15 693. 654. 619. 634. 649. 703. 631. 332. 169.  97.  45.  25.   8.   3.
 1.
42LUBBOCK, TX
14 688. 700. 642. 618. 620. 546. 490. 346. 180.  86.  33.   7.   5.   1.
43MEMPHIS, TN
12 715. 690. 618. 633. 614. 532. 374. 196.  74.  25.  10.   4.
44MIAMI, FL
 6 452. 277. 147.  71.  26.   4.
45MILWAUKEE, WI
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17 749. 634. 585. 591. 611. 774. 913. 659. 421. 285. 176. 116. 83. 47.
18. 4. 3.
46MINNEAPOLIS, MN
17 695. 602. 588. 482. 500. 560. 632. 609. 514. 383. 311. 246. 186. 119.
62. 31. 16.
47MOBILE, AL
10 882. 698. 609. 506. 377. 214. 109. 49. 7. 3.
48NASHVILLE, TN
15 738. 697. 637. 619. 627. 565. 463. 263. 132. 67. 28. 9. 3. 1.
1.
49NEW ORLEANS, LA
9 850. 692. 621. 449. 282. 128. 47. 9. 2.
50NEW YORK, NY
13 754. 745. 722. 796. 838. 858. 603. 330. 188. 2. 26. 10. 1.
51OKLAHOMA CITY, OK
14 717. 643. 645. 611. 641. 570. 468. 287. 173. 77. 36. 12. 3. 1.
52OMAHA, NB
16 606. 558. 539. 543. 543. 655. 663. 511. 390. 287. 189. 135. 93. 40.
15. 1.
53PHILADELPHIA, PA
12 735. 710. 663. 701. 758. 818. 654. 335. 189. 100. 32. 9.
54PHOENIX, AZ
8 767. 769. 659. 540. 391. 182. 57. 8.
55PITTSBURGH, PA
15 799. 678. 637. 587. 631. 688. 774. 569. 360. 233. 159. 60. 30. 7.
1.
56PORTLAND, ME
17 780. 808. 760. 748. 772. 839. 820. 599. 408. 293. 190. 109. 60. 29.
15. 5. 1.
57PORTLAND, OR
121001.1316.1274.1271.1238. 772. 343. 123. 40. 10. 4. 1.
58RALEIGH, NC
12 848. 762. 707. 672. 638. 527. 410. 236. 103. 38. 11. 1.
59RENO, NV
15 572. 690. 845. 909. 890. 829. 733. 530. 387. 227. 101. 37. 15. 4.
1.
60RICHMOND, VA
13 784. 745. 690. 673. 699. 632. 478. 285. 138. 67. 19. 2. 1.
61SACRAMENTO, CA
81071.1329.1298.1049. 701. 355. 93. 8.
62SALT LAKE CITY, UT
14 614. 635. 682. 685. 755. 831. 798. 564. 328. 158. 80. 41. 16. 2.
63SAN ANTONIO, TX
12 789. 669. 569. 445. 387. 190. 94. 31. 11. 4. 1. 1.
64SAN FRANCISCO, CA
71264.2341.2341.1153. 449. 99. 10.
65SEATTLE, WA
11 750.1272.1462.1445.1408. 914. 427. 104. 39. 20. 3.
66SHREVEPORT, LA
11 772. 679. 619. 609. 516. 361. 200. 72. 23. 6. 2.
67SIOUX FALLS, SD
17 669. 605. 522. 498. 501. 625. 712. 585. 520. 448. 293. 208. 152. 102.
59. 43. 18.
68ST. LOUIS, MO

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15 646. 575. 585. 578. 620. 671. 650. 411. 219. 134.  77.  40.  15.   7.
 1.
69SYRACUSE, NY
17 723. 717. 656. 641. 651. 720. 830. 547. 392. 282. 190. 102.  55.  23.
 5.   2.   2.
70TAMPA, FL
 8 877. 570. 345. 216. 137.  48.  10.   1.
71WACO, TX
11 701. 622. 651. 558. 501. 354. 216.  84.  24.   3.   1.
72WASHINGTON, DC
12 740. 673. 690. 684. 790. 744. 542. 254. 138.  54.  17.   2.
73WICHITA, KS
15 641. 603. 589. 592. 611. 584. 607. 426. 273. 161.  85.  45.  14.   3.
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