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Economic Efficiency in the Sizing of Residential Heat Pumps

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Economics and Regulatory Technology Division
Washington, DC 20234

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

The work in this report was conducted by the Applied Economics Group of the Building Economics and Regulatory Technology Division, in the Center for Building Technology, National Engineering Laboratory, at the National Bureau of Standards. This effort was supported by the Department of Energy (DoE) under Interagency Agreement No. 77-A-01-6010, Task Order A008-BCS.

ABSTRACT

This report provides a methodology for determining the optimal heat pump size, in terms of heating output capacity, for residential installations having annual heating requirements significantly greater than annual cooling requirements. The optimal size heat pump is defined as the size for which total present value, life-cycle heating and cooling costs (including equipment costs) are minimized. Incremental energy savings from increasing the output capacity of the heat pump are calculated using hourly simulation models of heat pump and building performance developed at the National Bureau of Standards (NBS). The dollar value of the incremental savings, in present-value, life-cycle terms, is then calculated and compared with incremental costs to determine the optimal heat pump size. A base case analysis of an 1800 square-foot house in the Chicago climate shows that a slightly larger heat pump size than would typically be selected for air conditioning purposes alone is optimal for the assumptions specified. A number of sensitivity analyses are performed to show the effects of changes in load size, degradation coefficients, power utilization efficiency, economic assumptions and geographic location on the optimal heat pump size.

Key words: Benefit-cost analysis; energy conservation; equipment selection; equipment sizing; heat pump; life-cycle costs.

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SI CONVERSION

Because the energy analysis in this report is based directly on the NBS Test Procedure for Heat Pumps operated in the heating and cooling modes and on the capacities of heat pumps as typically rated by U.S. manufacturers, compatible U.S units of measurement are used throughout this report. Since the United States is a signatory to the Eleventh General Conference on Weights and Measures, which defined and gave official status to the Metric SI system, the following conversion factors are provided to assist users of SI units.

Metric Conversion Factors

Length:	1 inch (in) = 25.4 millimeters (mm) 1 foot (ft) = 0.3048 meter (m)
Area:	1 ft^2 = 0.092903 m^2
Volume:	1 ft^3 = 0.028317 m^3
Fluid Capacity:	1 gallon (gal) = 3.78541 liters (L)
Temperature:	1°F = 9/5°C + 32
Temperature Interval:	1°F = 5/9°C or K
Mass:	1 pound (lb) = 0.453592 kilogram (kg)
Mass per unit Length:	1 lb/ft = 1.48816 kg/m
Mass per unit Area:	1 lb/ft^2 = 4.88243 kg/m^2
Mass per unit Volume:	1 lb/ft^3 = 16.0185 kg/m^3
Energy:	1 Btu = 1.05506 kilojoules (kJ)
Heat Flow Rate:	1 Btu/h = 0.293071 Watt (W)
Specific Heat:	1 Btu/(lb)(°F) = 4.1868 kJ/(kg)(K)
U-value:	1 Btu/(ft^2)(h)(°F) = 5.67826 W/(m^2)(K)
R-value:	1 (ft^2)(h)(°F)/Btu = 0.176110(m^2)(K)/W

1. INTRODUCTION

1.1 PURPOSE AND SCOPE

The heat pump has become increasingly popular as a residential space heating and cooling system since the oil embargo in the early 1970's. In general, heat pumps are significantly more energy efficient than electric resistance heaters, although they have a considerably higher initial cost. Occasional curtailments in the availability of new natural gas hookups, improved reliability of heat pump components, their ability to function as central air conditioners, a general trend toward electric heating in new houses, and rising electricity prices have all contributed toward the increasing popularity of the heat pump. While in 1965 only 20 percent of new single-family houses were heated with electricity and 25 percent had central air conditioning[1], in 1978 approximately 50 percent had electric heat and 60 percent had central air conditioning[2]. The use of heat pumps rose from insignificant levels in the 1960's to 25 percent of new housing in 1978.[2]

The heating and cooling output capacities of a heat pump are closely related due to the dual nature of the system. Traditionally, heat pumps have been sized to properly match design cooling loads and indeed this requirement provides a minimum sizing constraint. Heating loads in excess of the heating output capacity can be satisfied using supplemental electric resistance heating. However, this sizing procedure has been questionable from an economic standpoint in geographic regions where annual heating requirements are significantly greater than annual cooling requirements. As will be demonstrated in this report, the seasonal heating efficiency of a larger size heat pump is generally somewhat greater, and operating costs somewhat lower, than of a smaller size heat pump in colder than average climates. Thus the purpose of this report is to identify factors which make the use of a larger size heat pump cost effective on a life-cycle basis and to determine the optimal size heat pump from a life-cycle cost minimization viewpoint.

The scope of this report is limited to analysis of air-source, one-speed heat pumps in the 2.0 to 5.0 ton[3] output range. Supplementary electric resistance heating is assumed to be used to assure a proper match with heating requirements. Heating and cooling loads for a residential building and corresponding system efficiencies are calculated hourly for an entire year in order to determine the

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[1] Bureau of the Census, Characteristics of New One-Family Homes: 1974, Construction Reports - Series C25, U.S. Department of Commerce, Washington, D.C., 1975.

[2] Bureau of the Census, Characteristics of New Housing: 1978, Construction Reports - Series C25-78-13, U.S. Department of Commerce, Washington, D.C., 1978.

[3] One ton of heating or cooling output equals 12,000 Btu per hour (Btu/hr). In this report the heating output capacity is designated at 47°F outdoor temperature.

annual energy use for each heat pump size examined. Some preliminary guidelines for the optimal sizing of residential heat pump systems are developed. However, more research will be required in order to provide a comprehensive set of guidelines that can be validated for field use.

1.2 TECHNICAL BACKGROUND

Basically, a heat pump is an air conditioner which can operate in a reverse mode in order to "pump" heat from the outside air to the inside air even though the outdoor temperature is lower than the indoor temperature. (While the outside air may be cold relative to the inside air, it is still "warm" relative to absolute zero.) The output capacity of a heat pump, in terms of thermal units per hour, depends in part on the indoor-outdoor temperature differential. For any given indoor temperature, the colder the outdoor temperature, the lower the heating capacity of the heat pump. Similarly, the higher the outdoor temperature, the lower the cooling output capacity. The ratio of the heat output to (or removed from) the conditioned space to the electrical input, when expressed in common thermal units, is called the coefficient of performance (COP). For any given indoor temperature, the lower the outdoor temperature, the lower the COP in the heating mode. Similarly, the higher the outdoor temperature, the lower the COP in the cooling mode.

Since the space heating requirements of a house increase as the outdoor temperature decreases (given some indoor temperature and fixed internal and solar heat gains), the heat pump will not be able to satisfy all of the heating requirements below some outdoor temperature. The outdoor temperature at which the heat pump output just meets the space heating requirements is called the "balance point" of the heat pump. This balance point concept is shown in figure 1. In this figure the hourly heating load of a given house and the hourly output capacity of a given heat pump system are shown on the vertical axis as a function of the outdoor temperature on the horizontal axis. The intersection of these two curves, T_{B1}, determines the balance point for this system. To the right of this point, the difference between heating requirements and output capacity must be provided by a supplementary heating system. This supplementary system is usually made up of electric resistance strip heaters in the indoor air handler. These strip heaters are less efficient, and thus more costly in terms of electric energy per unit of heat output, than the heat pump itself for outdoor temperatures above approximately -20°F. At temperatures below -20°F the heat pump should be shut off and the entire heating load will be met by the supplementary system.

The balance point of a given heat pump, and thus the amount of supplementary heat required, is a function of the rated output capacity of the heat pump at any given outdoor temperature. Increasing the capacity of a heat pump for a given house will result in less supplementary heating, since the balance point will be significantly lower. This is demonstrated in figure 1, where a second heat pump of twice the capacity of the first is shown together with the unchanged space heating requirements of the same house. The balance point has been reduced from T_{B1} to T_{B2}. No supplementary heating is required at all between T_{B1} and T_{B2}. In addition, those heating loads occurring below T_{B2} can be satisfied with less supplementary heat since the output of the larger heat pump is greater, reducing seasonal kWh requirements further.

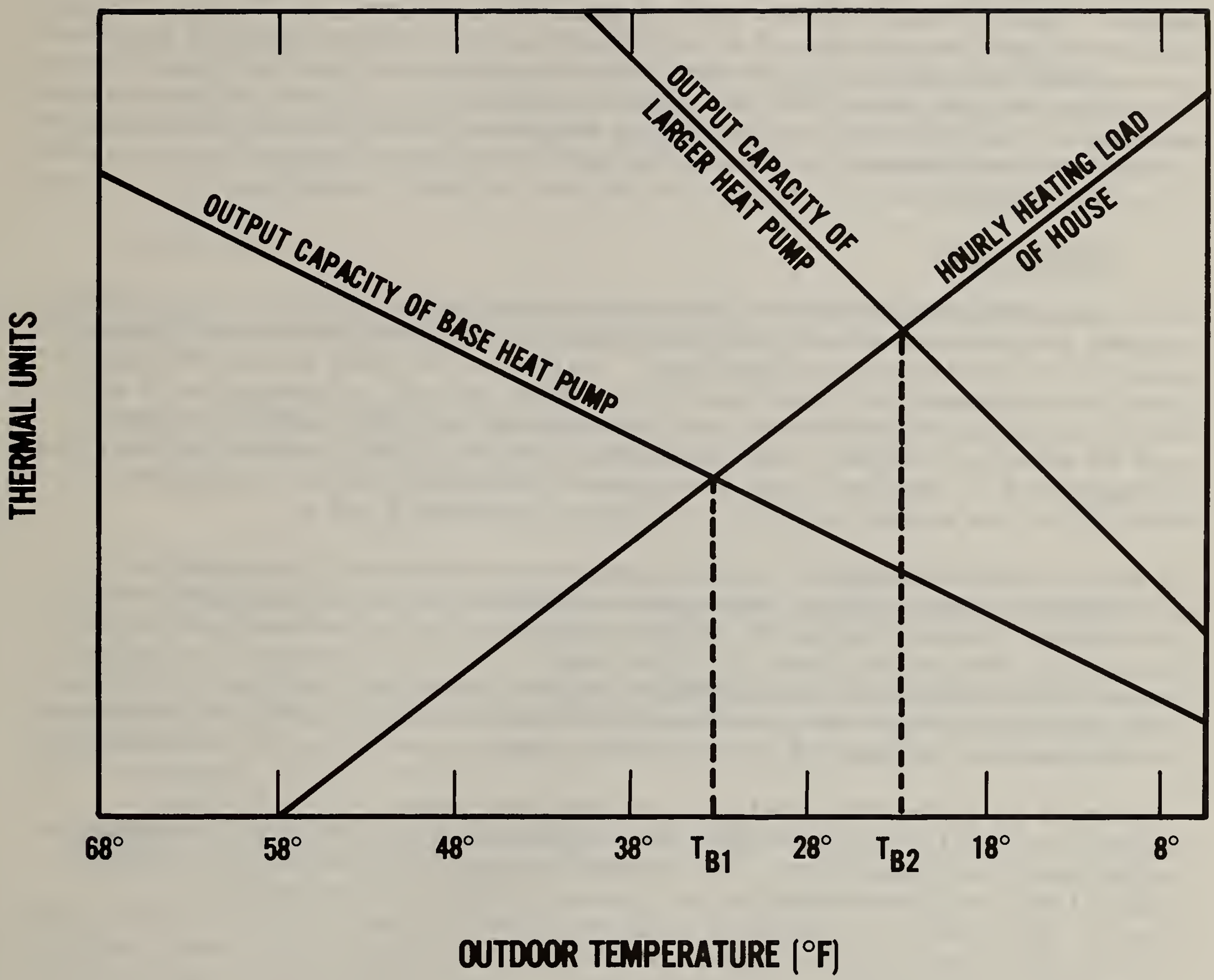

Figure 1. Balance Point of Heat Pump as a Function of Heating Output Capacity

The actual seasonal reduction in kWh requirements, relative to electric resistance heating, resulting from a heat pump in any given installation will depend upon the heating load of the house, the performance characteristics of the heat pump system used, and the local climatic conditions during the heating season. Each of these factors will be explored in this report, using hourly simulation data in all cases. In addition, the operation of the heat pump in the cooling cycle will be considered, since oversizing of the heat pump with respect to cooling loads will increase kWh consumption in the cooling mode and may reduce its ability to control indoor humidity. While the increase in kWh consumption requirements in the cooling mode is estimated in this report, the potential degradation of humidity control has not been quantified.

1.3 ORGANIZATION

This report has five sections. This introduction is section 1. In section 2, a model for simulating heat pump performance in both the heating and cooling modes on an hourly basis is described. This model is based on the NBS heat pump test procedure [3,5] and requires computer support for execution if more than a few hours of performance are to be simulated. (The computer program used to calculate the heat pump performance for each size examined is described in Appendix A.) Section 2 can be skipped if the reader wishes to proceed directly to the actual analytical results in sections 3 and 4.

In section 3 the procedure for determining the optimal heat pump size is developed and demonstrated. The base case example is for a heat pump of known performance characteristics in an 1800 square-foot house located in Chicago. The heating and cooling loads for this house are calculated using the National Bureau of Standards Load Determination Program, NBSLD [4], and Test Reference Year, TRY [6], climate records. Specific assumptions are made as to the cost per kWh and the incremental costs of heat pumps in the 2.0 to 5.0 ton range.

In section 4, sensitivity analyses are made with respect to load sizes, degradation coefficients, steady-state efficiency characteristics, energy price projections, heat pump costs, and climate location. In section 5, a summary, conclusions, and recommendations for future research are provided.

2. MODELING HEAT PUMP PERFORMANCE

In this section the equations used to model the energy utilization of a heat pump are presented. These equations are based on testing and rating procedures developed at NBS by Parken, Kelly, and Didion [3,5]. Energy utilization is modeled hourly based on the outdoor temperature and the coincident heating or cooling load in that hour. Energy utilization is then integrated for both heating and cooling operations over the entire year. The equations for modeling heat pump performance in the heating mode are modeled first, followed by those for the cooling mode.

2.1 HEATING MODE

In this report, the known heat pump characteristics used in simulating the heating performance of a typical one-speed heat pump on an hourly basis are the following[1]:

Output Capacity	at	17°F	(CAP17)	in Btu/hr,
" "	"	47°F	(CAP47)	in Btu/hr,
Input Power	"	17°F	(POW17)	in kW,
"	"	47°F	(POW47)	in kW,

a coefficient of degradation (less than 1.0) resulting from cycling when heating load is less than heat pump capacity (C_D), and a coefficient of degradation due to frosting (C_F).

In addition, it is convenient to have symbols for capacity at 35°F (CAP35), and power at 35°F (POW35). These values are calculated in terms of the heat pump characteristics given above by linear interpolation and (in the case of capacity) adjustment by C_F. Thus,

$$CAP35 = (0.4 * CAP17 + 0.6 * CAP47) * C_F, \text{ and}$$
$$POW35 = (0.4 * POW17 + 0.6 * POW47).$$

The procedure for modeling the hourly energy utilization of a heat pump is based on three elementary functions of the outdoor temperature in hour j (T_j) and the corresponding hourly heating load of the house (HL_j). These three functions determine the output capacity (in Btu), the power input (in Watts), and the part-load factor of a heat pump in each hour that a heating load exists.

(a) <u>Capacity Function</u>. The capacity function, denoted $CAP(T_j)$, is piecewise linear. At $T_j = 17°F$ the function has a change in slope, but is continuous. At $T_j = 45°F$ the function has a change in slope and a discontinuity. The parameters used in defining the function are:

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1 These characteristics are typically rated by the manufacturer using a standardized testing and calculation procedure.

CAP17,
A_1 = [CAP47 - CAP17]/30, and
B_1 = [CAP35 - CAP17]/18.

The domain of the function, T_j, is divided into three intervals:

for $T_j \leq 17°F$, $CAP(T_j) = CAP17 + A_1\ (T_j - 17°F)$,
for $17°F < T_j \leq 45°F$, $CAP(T_j) = CAP17 + B_1\ (T_j - 17°F)$, and
for $T_j > 45°F$, $CAP(T_j) = CAP17 + A_1\ (T_j - 17°F)$.

The functional relationship between capacity in the heating mode and T_j is shown in figure 2 for specified values of CAP17, CAP47, and C_F.

(b) Part-Load Factor. The power function is defined in terms of the part-load factor for heating (PLF_h). Thus the latter function is described first.

For the outdoor temperature in hour j (T_j), the heating output capacity of a given heat pump ($CAP(T_j)$) can be calculated using the formula in paragraph (a) above. Now define for hour j the heating load factor (X_j):

$$X_j = \frac{HL_j}{CAP(T_j)} \text{ or 1.01 whichever is less,}$$

where HL_j is the heating load in Btu for a given house in hour j.

The part-load factor for heating in hour j is then defined in terms of the known parameter C_D (which will always be less than one) and the value of X_j:

$$PLF_h(X_j) = 1 - C_D\ (1 - X_j).$$

The part-load factor is used only when $T_j > 45°F$.[1]

(c) Power Function. The power function ($POW(T_j)$) is continuous and piecewise linear for $T_j \leq 45°F$. The function undergoes a change in slope at $T_j = 17°F$; for $T_j > 45°F$ power is a nonlinear function of T_j and $PLF_h(X_j)$.

The parameters used in defining the function $POW(T_j)$ are:

POW17,
A_2 = [POW47 - POW17]/30,
B_2 = [POW35 - POW17]/18, and
$PLF_h(X_j)$.

The domain of the power function is determined by both the outdoor temperature (T_j) and the heating load factor (X_j), the second component entering only when

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[1] In the final version of the testing and rating procedure, the part-load factor was extended to outdoor temperatures below 45°F as well. However, the analysis in this report was completed before the testing and rating procedures were finalized.

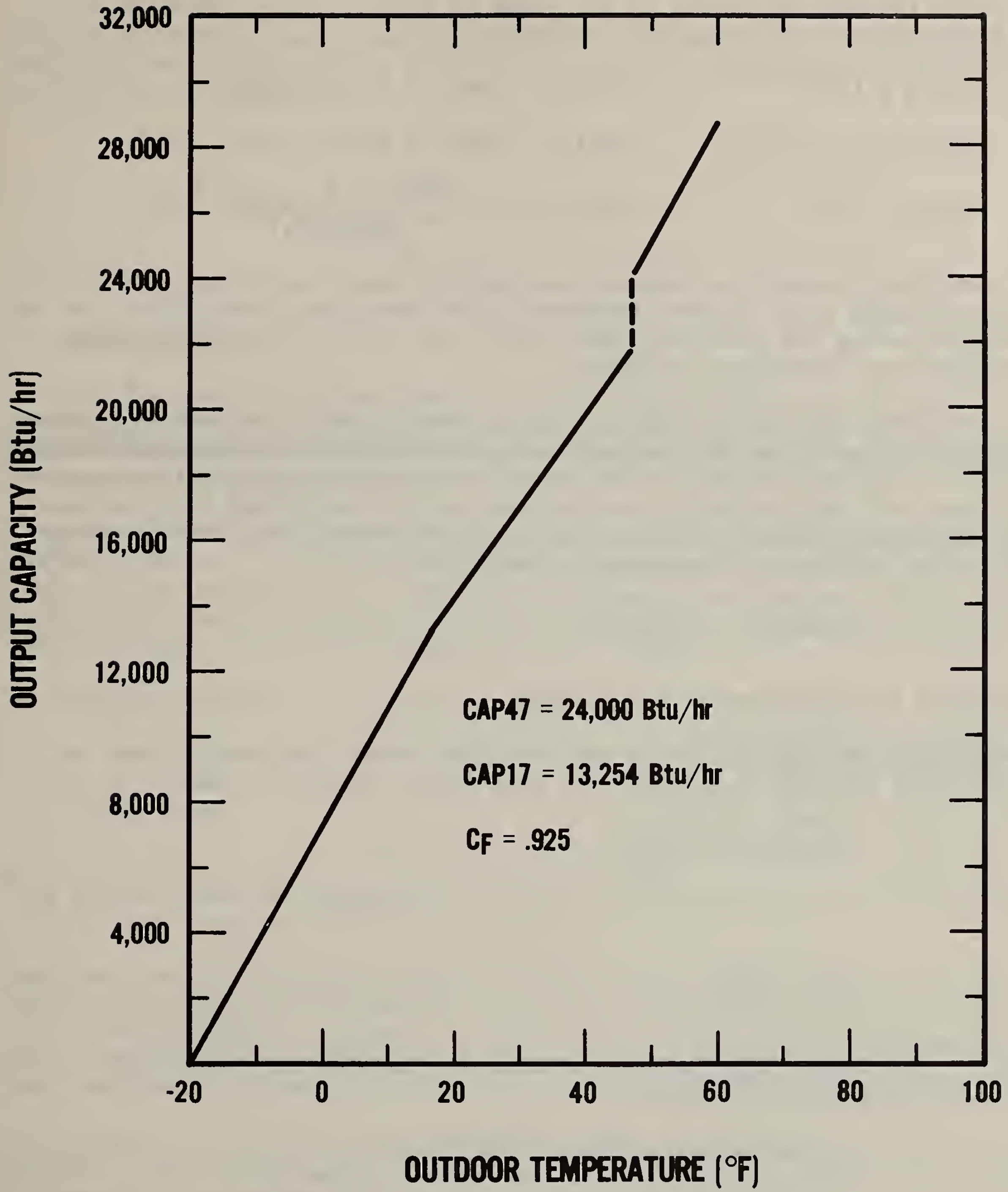

Figure 2. Output Capacity of Heat Pump in Heating Mode as a Function of Outdoor Temperature

$T_j > 45°F$ through its effect on the value of PLF_h. The T_j component of the domain is divided into three intervals:

for $T_j \leq 17°F$, $\quad POW(T_j) = POW17 + A_2 \, (T_j - 17°F)$

for $17°F \leq T_j \; 45°F$, $\quad POW(T_j) = POW17 + B_2 \, (T_j - 17°F)$, and

for $T_j > 45°F$, $\quad POW(T_j, X_j) = [\dfrac{POW17 + A_2 \, (T_j - 17°F)}{PLF_h \, (X_j)}]$.

The electrical energy requirements and coefficient of performance (COP) for a given heating load, outdoor temperature and heat pump installation can be determined using the functions described above, given that the heat pump characteristic parameters are known.

Note that when the electricity required to operate the heat pump is greater than that of operating the supplementary electric resistance heating strips to provide the same output, it is assumed that the heat pump will automatically shut off and the entire heating load will be satisfied with the electric resistance strips. In other words, it is assumed that the heat pump will not be operated at temperatures for which

$$POW(T_j) > \frac{CAP(T_j)}{3413} ,$$

where 3413 is the number of Btu per kWh.

Denote by E_j the electricity in kWh required to meet the heating load in hour j. For any hour j at which the temperature is so low that

$$POW(T_j) > \frac{CAP(T_j)}{3413} ,$$

set

$$E_j = \frac{HL_j}{3413} .$$

That is, the space heating load in hour j is met entirely by electric resistance heating. Otherwise

$$E_j = POW(T_j) + \frac{HL_j - CAP(T_j)}{3413} \text{ for } X_j = 1,$$

and

$$E_j = (X_j) \, [POW(T_j)] \text{ for } X_j < 1.$$

The heating COP of the heat pump for any hour j in which there is a heating load is calculated as:

$$COP_j = \frac{HL_j}{(E_j)(3413)} .$$

Annual electricity requirements for heating are obtained by summing E_j over all hours of the year for which $HL_j > 0$. The heating seasonal performance factor (HSPF) is calculated as:

$$HSPF = \frac{\sum_{j=1}^{8760} HL_j}{\sum_{j=1}^{8760} (E_j)(3413)} \quad \text{for all } HL_j > 0.$$

2.2 COOLING MODE

Section 2.1 provides the methodology used to model the energy-related performance of a heat pump in the heating mode. In this section the corresponding methodology for determining the performance of the same heat pump in the cooling mode is presented.

The parameters of the equation used to calculate energy utilization in the cooling mode are a function of the design characteristics of the heat pump, and thus will be different for different heat pumps. The characteristics that are used in this report to model the cooling performance of a one-speed heat pump on an hourly basis are as follows:[1]

Output Capacity at an outdoor temperature of 75°F (CAP75) in Btu/hr,
" " " " " " " 85°F (CAP85) in Btu/hr,
" " " " " " " 95°F (CAP95) in Btu/hr,
" " " " " " " 115°F (CAP115) in Btu/hr,
Input Power " " " " " 75°F (POW75) in kW,
" " " " " " " 95°F (POW95) in kW, and

a coefficient of degradation resulting from cycling when cooling load is less than heat pump capacity (C_D).

The procedure for modeling energy utilization with a heat pump in the cooling mode is based on three elementary functions of the outdoor temperature in hour j (T_j) and the hourly cooling load of the house (CL_j). As for the heating mode, these three functions determine the output capacity, the power input, and the part-load factor of the heat pump in each hour that a cooling load exists.

(a) Capacity Function. The capacity function, denoted $CAP(T_j)$, is piecewise linear. At T_j = 85°F and T_j = 95°F the function has a change in slope, but is continuous. The parameters used in defining the function are:

---

1 These characteristics are sufficient to model the performance of a specific heat pump in the cooling mode in that the capacity and power functions can be approximated using these rating points. Other rating points may be more appropriate for other heat pump systems but the underlying model will be the same.

CAP75,
CAP85,
CAP95,
CAP115,
SC_1 = [CAP85 - CAP75]/10,
SC_2 = [CAP95 - CAP85]/10, and
SC_3 = [CAP115 - CAP95]/20.

The domain of the function, T_j, is divided into three intervals:

for $65°F < T_j \leq 85°F$, $CAP(T_j) = CAP75 + SC_1 (T_j-75°F)$,
for $85°F < T_j \leq 95°F$, $CAP(T_j) = CAP85 + SC_2 (T_j-85°F)$, and
for $95°F < T_j \leq 115°F$, $CAP(T_j) = CAP95 + SC_3 (T_j-95°F)$.

The functional relationship between capacity in the cooling mode and T_j is shown in figure 3.

(b) Part-Load Factor. The power function is defined in terms of the part-load factor for cooling (PLF_c). Thus, the latter function is described first.

For the outdoor temperature in hour j (T_j) the output capacity of the heat pump under consideration ($CAP(T_j)$) can be calculated using the formula in paragraph (a) above. Now define for hour j the cooling load factor (X_j):

$$X_j = \frac{CL_j}{CAP(T_j)} \text{ or 1.0, whichever is less,}$$

where CL_j is the cooling load in Btu of the house in hour j.

The part-load factor for cooling in hour j is then defined in terms of the parameter C_D (which will always be less than one) and the value of X_j:

$$PLF_c(X_j) = 1 - C_D (1-X_j).$$

(c) Power Function. The power function, denoted $POW(T_j,X_j)$, is a nonlinear function of T_j and $PLF_c(X_j)$.

The parameters used in defining the function $POW(T_j,X_j)$ are:

POW75,
SP = [POW95 - POW75]/20, and
$PLF_c(X_j)$.

The domain of the power function is determined by both the outdoor temperature and the cooling load factor (X_j), the second component entering through its effect on the value of PLF_c:

$$POW(T_j,X_j) = \left[\frac{POW75 + SP\ (T_j-75°F)}{PLF_c(X_j)}\right] .$$

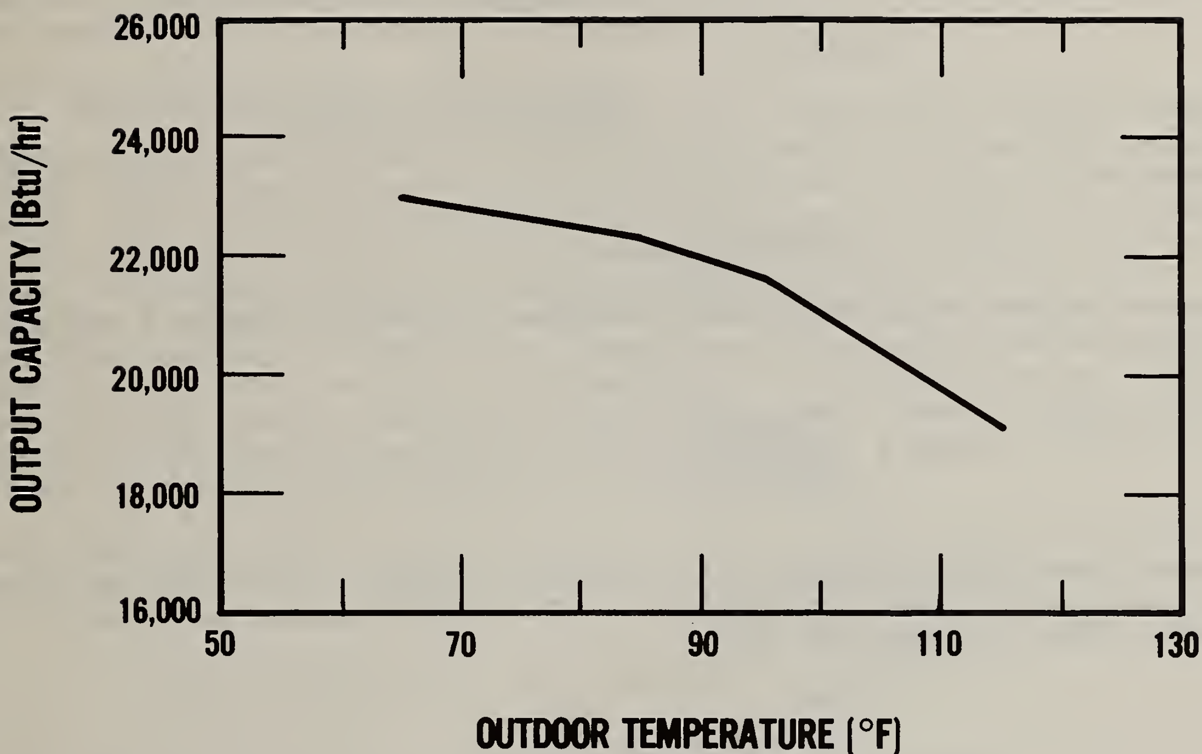

Figure 3. Output Capacity of Heat Pump in Cooling Mode as a Function of Outdoor Temperature

The electric energy requirement in hour j (P_j) and coefficient of performance (COP) for a given cooling load, outdoor temperature and heat pump installation can be expressed in terms of the functions described above as follows:

$$\text{If } CL_j > CAP(T_j) \text{ then}$$

set

$$P_j = POW(T_j,1).$$

(Note that the cooling load is not fully met in such an hour.)

Otherwise

$$P_j = (X_j)\ POW(T_j,X_j).$$

The cooling COP of the heat pump for any hour j in which there is a cooling load is calculated as:

$$COP_j = \frac{(X_j)CAP(T_j)}{(3413)(P_j)}.$$

Annual electricity requirements for cooling are obtained by summing the P_j over all hours in the year at which $CL_j > 0$. The cooling seasonal performance factor (CSPF) is calculated as:

$$CSPF = \frac{\sum_{j=1}^{8760} (X_j)CAP(T_j)}{\sum_{j=1}^{8760} (3413)(P_j)} \quad \text{for all } CL_j > 0.$$

3. DETERMINATION OF AN OPTIMAL HEAT PUMP SIZE

In section 2, a methodology was described for calculating the electric energy needed to meet the annual heating and cooling requirements of a house when a one-speed heat pump of known performance characteristics is to be installed. In this section, the optimal size heat pump (in terms of output capacity) is determined for a given set of assumptions, including performance characteristics, geographic location, annual heating and cooling requirements, energy costs, heat pump costs, and the expected useful lifetime of the heat pump. In the following section these assumptions will be varied in order to determine the sensitivity of the results to these assumptions.

3.1 SELECTION OF OPTIMAL SIZE EQUIPMENT

The general economic objective in selecting equipment to perform a given task is to choose equipment capable of achieving that task at minimum total present-value, life-cycle cost.[1] This objective is valid both for selecting equipment size as well as for selecting among qualitatively different types of equipment (e.g., heat pumps from different manufacturers or of different efficiency ratings). However, this report focuses entirely on the selection of the optimal size heat pump in terms of its thermal output capacity, given specific operating conditions and economic assumptions. (In all cases, the heat pump must be large enough to match the design cooling load. However, supplementary electric resistance heat strips will be used to assure that any heating load in excess of the heat pump capacity is fully satisfied.)

For a heat pump, total present-value life-cycle cost (TC) can be calculated as:

$$TC = IC + \sum_{t=1}^{n} EC_t/(1+D)^t + \sum_{t=1}^{n} MC_t/(1+D)^t - S_n/(1+D)^n$$

where IC = initial installed equipment cost,
EC_t = energy cost in year t,
MC_t = maintenance cost in year t,
n = study period, i.e. the expected life of the heat pump,
D = discount rate, and
S_n = salvage value at the end of the study period.

In evaluating the life-cycle cost of a given heat pump type, the expected life and maintenance cost are not assumed to vary significantly with variations in output capacity only. In addition, the salvage value of the heat pump at the end of its useful life is assumed to be insignificant. As a result, the two key parameters that will determine the optimal size heat pump are the difference

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[1] In order to properly compare the life-cycle costs of such alternatives, a common time horizon or study period must be used. If the alternatives considered have different expected lives, cost adjustments (e.g., prorating) must be made to bring them to a common life.

in initial installed cost for alternative output capacities and the change in life-cycle energy costs. Changes in energy costs are in turn a function of the change in seasonal heat pump performance for both heating and cooling due to selecting a heat pump of different output capacity, the annual heating and cooling requirements of the house, the projected price of electricity over the life of the heat pump, and the discount rate.

The initial installed cost of a heat pump is a function of heat pump size, typically increasing at a constant or slightly increasing rate as capacity increases, as shown in the top of figure 4. Therefore, when a given size heat pump is acceptable in a particular application, the alternative of a larger heat pump need only be considered if the net amount of electricity saved by the heat pump increases with the heat pump size. It will be shown that in colder than average geographical locations, annual electricity consumption typically decreases as the heat pump size is increased, but at a decreasing rate, as shown at the top of figure 4. Therefore, as long as the present dollar value of the additional (or "incremental") energy savings attributable to a given increase in heat pump size exceeds the additional (or incremental) heat pump costs incurred, total life-cycle costs will be reduced by increasing the heat pump size, as seen to the left of output capacity $\overline{C}$ figure 4. These incremental savings and costs are shown graphically at the bottom of figure 4. However, because incremental heat pump costs are constant or increasing while incremental energy savings are declining as the heat pump size is increased, beyond some point the incremental costs will exceed the corresponding incremental dollar savings, resulting in an increase in total life-cycle costs. Thus the optimal size heat pump ($\overline{C}$)is that size for which the incremental present-value dollar energy savings (compared to the next smaller size) just equals the corresponding incremental cost of that size increase. Note that at $\overline{C}$ in figure 4, the ratio of incremental savings to incremental costs is 1.0.

In practice, heat pump sizes do not vary continuously as shown in figure 4. An optimal size heat pump from the set of available sizes is therefore the largest one for which the ratio of present-value incremental savings to incremental heat pump cost (both measured from the immediately smaller size heat pump available) is larger than or equal to 1.0. This incremental savings-cost approach will be used to identify the optimally sized heat pump in each case examined in the report because incremental costs and savings can often be more accurately identified than total costs and savings.

3.2 ENERGY AND DOLLAR SAVINGS AS A FUNCTION OF HEAT PUMP SIZE

In this subsection an example of the effects of heat pump size on annual energy requirements is discussed and the resulting energy savings are translated into present-value dollar terms. The example is based on specified design characteristics representative of a product line of six commercially available one-speed heat pumps ranging in size from 2.0 tons (24,000 Btu/hr output capacity at 47°F outdoor temperature) to 5.0 tons (60,000 Btu/hr). The capacity and power characteristics have been adjusted so that (1) the increments of size follow a regular pattern, and (2) small variations in the coefficient of performance (COP, the ratio of energy output to energy input) at any given temperature are eliminated, thereby isolating the effects of changes in size from changes in COP characteristics.

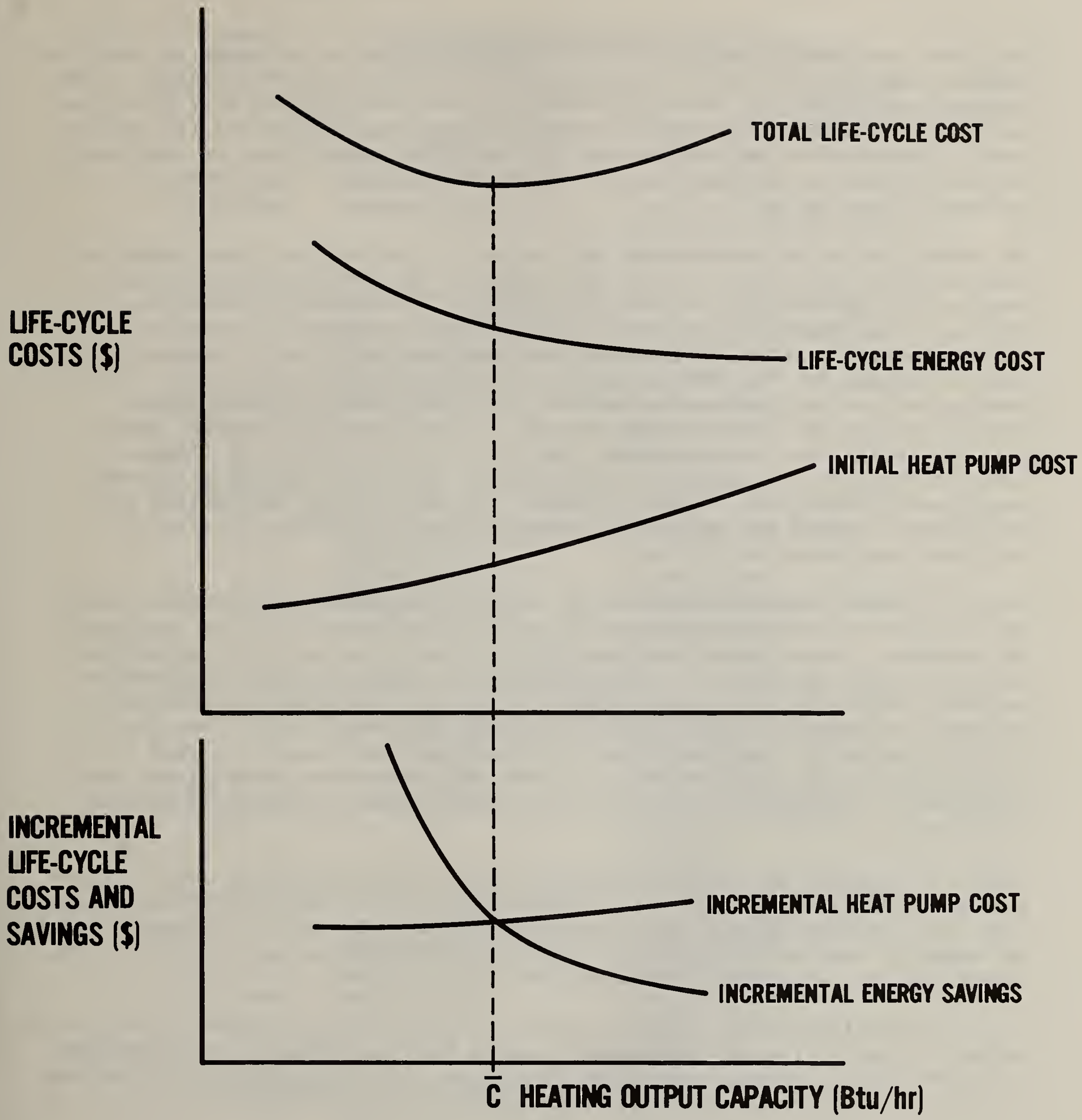

Figure 4. Life-Cycle Heating-Related Costs as a Function of Output Capacity

The given performance characteristics related to capacity and power at specified outdoor temperatures, used in calculating the annual energy requirements of the six heat pump sizes, are shown in table 3.1. Note that for the base case, the coefficient of degradation resulting from cycling, C_D, is 0.25 and the coefficient of degradation due to frosting, C_F, is 0.925. Sensitivity of the results to variation in the degradation coefficients and the power input will be examined in section 4.

The annual energy utilization (in kWh) of each of the six heat pump sizes was calculated for both space heating and cooling of an 1800 square-foot house, based on the methodology outlined in section 2. The computer program used in this heat pump simulation is listed in Appendix A. Chicago was selected as the geographic location for the base case analysis, as it has a reasonably typical climate for the northern half of the continental United States. Hourly heating and cooling loads were simulated for a well insulated and tightly constructed one-story house using the NBS Load Determination Program, NBSLD [4], and hourly Test Reference Year, TRY [6], climate records for Chicago. Table 3.2 provides the physical description of the house, including relevant operational assumptions. Table 3.3 shows the annual energy utilization for heating and cooling and the corresponding seasonal performance factors for each heat pump size.

Table 3.3 shows that the annual energy utilization for heating decreases while the energy utilization for cooling increases as the capacity of the heat pump is increased. Accordingly, the seasonal performance factor (SPF) for heating increases while the SPF for cooling decreases. (Cooling energy requirements increase because cycling losses increase as the air conditioning capacity is increased relative to cooling loads.) It will be demonstrated in section 4.6 that increasing the heat pump capacity beyond the basic capacity needed to satisfy the cooling requirements of a house will not always reduce total energy consumption, especially if annual cooling requirements exceed annual heating requirements.

Table 3.4 provides the incremental annual kWh savings for each increase in heat pump size, based on the difference between total annual energy utilization for each heat pump size and the next smaller size from table 3.3 As expected, equal increases in heat pump size result in positive, but increasingly smaller, energy savings as the overall size is increased.

The corresponding present-value life-cycle dollar savings are shown in the third column. These savings are calculated using a base year price of $0.04 per kWh, a 10-year life, a nominal rate (i.e., including inflation) of kWh price increase of 12 percent per year, and a 15 percent nominal discount rate.[1]

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[1] A 15 percent nominal discount rate is approximately equal to a four percent real discount rate if the rate of general inflation averages 11 percent. A 12 percent nominal increase in electricity prices is approximately equal to a one percent real increase in electricity prices if the rate of general inflation averages 11 percent. The four percent real discount rate and one percent real price increase in electricity prices are consistent with other residential energy conservation reports prepared for DoE by NBS.

Table 3.1 Heat Pump Performance Characteristics used in Base Case Analysis

Nominal Size	Performance Characteristics[a] Heating	Cooling
2.0 tons	CAP17=13,254 Btu/hr CAP47=24,000 " POW17=2.157 kW POW47=2.705 "	CAP75=22,615 Btu/hr CAP85=22,313 " CAP95=21,600 " CAP115=19,138 " POW75=2.29 kW POW95=2.70 "
2.5 tons	CAP17=16,567 Btu/hr CAP47=30,000 " POW17=2.697 kW POW47=3.381 "	CAP75=28,269 Btu/hr CAP85=27,891 " CAP95=27,000 " CAP115=23,922 " POW75=2.87 kW POW95=3.38 "
3.0 tons	CAP17=19,880 Btu/hr CAP47=36,000 " POW17=3.236 kW POW47=4.057 "	CAP75=33,923 Btu/hr CAP85=33,469 " CAP95=32,400 " CAP115=28,706 " POW75=3.43 kW POW95=4.05 "
3.5 tons	CAP17=23,194 Btu/hr CAP47=42,000 " POW17=3.775 kW POW47=4.733 "	CAP75=39,577 Btu/hr CAP85=39,047 " CAP95=37,800 " CAP115=33,491 " POW75=4.01 kW POW95=4.73 "
4.0 tons	CAP17=26,507 Btu/hr CAP47=48,000 " POW17=4.315 kW POW47=5.409 "	CAP75=45,230 Btu/hr CAP85=44,626 " CAP95=43,200 " CAP115=38,275 " POW75=4.58 kW POW95=5.40 "
5.0 tons	CAP17=33,134 Btu/hr CAP47=60,000 " POW17=5.393 kW POW47=6.761 "	CAP75=56,538 Btu/hr CAP85=55,782 " CAP95=54,000 " CAP115=47,844 " POW75=5.72 kW POW95=6.75 "

a C_D = 0.25 and C_F = 0.925 for all sizes (base case).

Table 3.2 Physical Description of Base House

- Single-family detached house - one story over crawl space.
- 1800 square feet floor and ceiling areas.
- Other surface areas:

Component	S	W	N	E
	Areas by orientation (ft^2)			
Wall	292	294	322	294
Windows/sliding glass door	100	-	50	-
Door	-	-	20	-

- Insulation levels:

Ceiling	Walls	Floor	Windows/sliding glass door
R-38	R-13	R-19	Double Glazed

- Infiltration rates = approximately 0.6 air changes/hr at Δt = 25°F and 7.5 MPH windspeed; 1.0 air changes/hr at Δt = 50°F and 15 MPH windspeed.
- Thermostat settings: 68°F heating, 78°F cooling.
- Natural ventilation used when sufficient to keep house below 78°F.
- Windows are 50 percent shaded during summer months.
- Occupants: 2 adults, 2 children.
- Lights and equipment heat output scheduled hourly.
- Annual heating requirements computed for Chicago: 51.1 million Btu = 14,972 kWh at an efficiency of 1.0 (i.e., electric resistance heating).
- Annual cooling requirements computed for Chicago: 8.0 million Btu.

Table 3.3 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Base Case[a] (Chicago)

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SCF)	
	Heating[b]	Cooling[c]	Total	Heating	Cooling
2.0	8722	1008	9729	1.72	2.33
2.5	8399	1040	9439	1.78	2.26
3.0	8196	1057	9253	1.83	2.23
3.5	8069	1074	9143	1.86	2.19
4.0	7989	1085	9075	1.87	2.17
5.0	7905	1102	9007	1.89	2.14

[a] 1800 square-foot house, $C_D = 0.25$, $C_F = 0.925$.

[b] Annual heating requirements = 51.1 million Btu; electric resistance equivalent = 14,972 kWh.

[c] Annual cooling requirements = 8.0 million Btu.

Table 3.4 Energy and Dollar Savings Data by Heat Pump Size: Base Case (Chicago)

(1)	(2)	(3)	(4)	(5)
Heat Pump Size (Tons)	Incremental Savings (kWh/yr)	Incremental Savings ($, Life Cycle)[a]	Total Heating Savings[b] ($, Life Cycle)	Hours Cooling Load Exceeds Capacity
2.0	-	-	$2169	6
2.5	290	$101	2281	0
3.0	186	65	2351	0
3.5	110	38	2395	0
4.0	69	24	2423	0
5.0	68	24	2452	0

[a] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[b] Total heating savings relative to electric resistance heating.

(Sensitivity analyses of kWh price projections, discount rates, and expected lifetimes is discussed in section 4.5).

The present dollar value (P.V.) over a given study period (10 years in this case) of each unit of energy used or saved annually was evaluated using the following formula:[1]

$$\text{P.V.} = (\$/\text{unit}) \left(\frac{1+P}{D-P}\right) \left(1 - \left(\frac{1+P}{1+D}\right)^{L}\right) \qquad (3.1)$$

where P = annual rate of energy price increase
D = discount rate, and
L = lifetime or study period

Thus the present dollar value of a kWh saved each year over ten years is

$$(\$0.04/\text{kWh}) \left(\frac{1.12}{0.15-0.12}\right) \left(1 - \left(\frac{1.12}{1.15}\right)^{10}\right) = \$0.347 \text{ kWh.}$$

As with kWh savings, the dollar-valued savings attributable to equal increases in heat pump capacity are positive but decline as the overall capacity is increased.

Table 3.4, column four, provides the present-value, life-cycle dollar savings for each heat pump size (heating only) relative to the use of electric resistance heat only. For any heat pump size selected, these savings must be at least as great as the difference between (1) the total installed cost of the heat pump, including expected maintenance, and (2) the cost of separate air conditioning equipment (if needed) and conventional electric resistance heating equipment, including expected maintenance and repairs in both cases.[2] If they do not exceed this difference, the heat pump is not a cost-effective alternative to separate central air conditioning and electric resistance heating equipment. (In such a case the economically optimal heat pump size is zero.)

Table 3.4, column five, displays the number of hours per year in which the cooling load is not fully satisfied by the heat pump size shown. Typically, central air conditioners and heat pumps are sized so as to satisfy the entire cooling load of a house 97.5 percent of the hours in which there is a cooling load. According to the cooling load analysis performed with NBSLD and the TRY climate data for Chicago, there are approximately 800 hours per year in which a cooling load exists (i.e., the space temperature will rise above 78°F unless the air conditioner is turned on). Thus the 2.0 ton heat pump will apparently satisfy the criterion typically used in selecting an appropriate heat pump size. Again note that this is a well-insulated and tightly constructed house.

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1 If P=D, the formula is modified to P.V. = (\$/unit) (L).

2 In comparing alternative equipment costs, it is important to adjust these costs in order to reflect the same expected lifetimes.

3.3 HEAT PUMP COSTS AS A FUNCTION OF SIZE AND THE SELECTION OF AN OPTIMAL SIZE HEAT PUMP

In the previous subsection calculations of incremental energy and dollar-value savings were shown for a wide range of heat pump sizes in Chicago. In this section we will discuss how to use this information together with information on the incremental cost of additional heat pump capacity in order to determine an optimum heat pump size, i.e., the heat pump size which will minimize total life-cycle costs.

Table 3.5 provides representative cost data[1] for a heat pump with approxmately the same performance characteristics as those shown in table 3.1. These costs include both the outdoor compressor and indoor coil units plus the refrigerant tubing. No change in cost for the thermostat is expected so this cost is not needed. Installation costs are expected to be similar for each size as well, although a slightly larger concrete pad would be needed for the larger sizes and the heavier weight may require additional lifting capability at the site. In addition, no change in duct size is attributed to the increased heat pump sizes. On the other hand, no savings from potential reductions in supplementary heating strips is credited to the larger heat pump sizes. In general, these latter assumptions will be reasonable if the optimal heat pump size does not greatly exceed the heat pump size that would be selected using more conventional procedures.

Based on the cost data shown in table 3.5, a 24,000 Btu/hr heating output capacity heat pump would cost approximately $1150, uninstalled. The average incremental cost per 1000 Btu/hr heating output capacity above 24,000 Btu/hr is approximately $17 up to 36,000 Btu/hr ($200/(36-24.5)=$17). Above 36,000 Btu/hr the average incremental cost per 1000 Btu/hr is $25 ($705/(64-36)=$25). Table 3.6 shows the estimated cost of the six heat pump sizes examined in section 3.2, calculated using this incremental cost data and rounded to the nearest ten dollars. In addition, table 3.6 shows the incremental cost estimated for each heat pump size above the 2.0 ton unit.

This incremental cost data can now be compared with the incremental dollar savings for identical increases in heat pump size. The incremental savings attributable to the 2.5 ton heat pump over the 2.0 ton heat pump in table 3.4 ($100) is slightly larger than the incremental cost of that change. A further increase in size generates incremental savings less than incremental costs, making the 2.5 ton heat pump the optimal heat pump size in this example. At higher incremental costs or lower kWh costs, the 2.0 ton size would be optimal. (This is the size that would likely have been selected if the heat pump size was selected to satisfy the cooling criterion only.) In order for the 3.0 ton heat pump size to be optimal, the price per kWh would have to be increased to $0.062 (100/65 x $.04) given the other assumptions made in this example.

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[1] These costs were taken from the Sears, Roebuck, and Co., "Spring-Summer 1979" catalogue.

Table 3.5 Heat Pump Cost Data, Unadjusted[a]

Heating Output Capacity (1000 Btu/hr at 47°F)	Cost (1979 $) (Rounded to nearest dollar)
24.5	1155
30	1255
36	1355
42	1500
49	1730
64	2060

a These costs include outdoor unit, indoor coils, and connecting tubing only. Installation costs are not included here, but are assumed to remain relatively constant as the capacity increases.

Table 3.6 Heat Pump Cost Data, Adjusted[a]

Heating Output Capacity		Total	Incremental
Nominal	1000 Btu/hr at 47°F	Cost ($)	Cost ($)
2.0 tons[b]	24	1150	
2.5 tons	30	1250	100
3.0 tons	36	1350	100
3.5 tons	42	1500	150
4.0 tons	48	1650	150
5.0 tons	60	1950	300

a Based on table 3.5.

b 1 ton = 12,000 Btu/hr.

In section 4 the effects of alternative assumptions regarding the size of heating and cooling loads, performance characteristics, incremental heat pump costs, energy costs, and geographic location on optimal heat pump sizes will be examined in more detail.

4. SENSITIVITY OF OPTIMAL HEAT PUMP SIZE TO CHANGES IN BASE CASE ASSUMPTIONS

The previous sections describe a model of heat pump performance and show how to use the results of the model to select a heat pump that will minimize the life-cycle cost of the heat pump. In this section the variation in heat pump energy utilization with respect to changes in load conditions, changes in degradation coefficients, and increases in steady-state efficiency will be investigated. Incremental energy and dollar savings will then be recalculated in each case in order to determine the effects of these changes on the optimal heat pump size. In addition, the effects of alternative heat pump costs and energy price projections on the optimal heat pump size will be considered. Finally, the effects of changes in geographic location on both energy utilization and optimal heat pump sizes will be examined. All calculations of total kWh utilization and seasonal performance factors are shown in Appendix B.

4.1 EFFECTS OF CHANGES IN LOAD SIZE

The heat pump simulation analyses described in section 3 were repeated for a house with a 100 percent increase in hourly heating loads and a 50 percent increase in hourly cooling loads relative to the base case. A doubling of hourly heating loads can be attributed to a combination of factors, including a larger house, less insulation, greater air infiltration rates, more (non-south facing) glass area, less solar gains through windows, and smaller internal loads than were modeled in the base house. Except for increased glass area on east and west walls, these factors will have significantly less effect on increases in cooling loads than on heating loads. While a computer simulation could be used to quantify these interrelationships, the proportion of increase in cooling requirements to heating requirements is quite sensitive to the assumptions made about each of these modeling parameters. The outdoor temperature profile, performance characteristics and economic assumptions were the same as used in the base case in section 3. Incremental reductions in annual kWh consumption and present-value, life-cycle energy costs were then calculated for each of the five heat pump sizes greater than the basic 2.0 ton unit. The results of this analysis are reported in table 4.1.

In comparing table 3.4 with the new data reported in table 4.1, one can see that the incremental savings in energy and dollars for each increase in heat pump size are significantly greater in the latter. These incremental dollar savings from increasing the size of the heat pump are greater than the incremental heat pump costs (reported in table 3.6) through the 4.0 ton heat pump size. The optimal size heat pump for the larger house in Chicago under the energy and equipment cost assumptions made is thus the 4.0 ton heat pump. Had the heat pump size been based on the cooling load criteria only, the 2.5 ton heat pump would have been selected.

4.2 EFFECTS OF CHANGES IN DEGRADATION COEFFICIENTS

In describing the model of heat pump performance in section 2, two degradation coefficients were identified among the given heat pump characteristics: (1) the coefficient of degradation that results from cycling when heating or cooling loads are less than the heat pump capacity during that hour (C_D); and (2) the

Table 4.1 Energy and Dollar Savings Data by Heat Pump Size: Chicago; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$3182	76
2.5	1152	$400	3609	14
3.0	885	307	3931	6
3.5	640	222	4165	0
4.0	471	163	4336	0
5.0	613	213	4561	0

[a] A 100 percent increase in hourly heating loads and a 50 percent increase in cooling loads relative to the base case. See table B.1 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.2 Energy and Dollar Savings Data by Heat Pump Size: Chicago; Base Loads; $C_F=0.925$, $C_D=0.15$[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2182	6
2.5	307	$106	2294	0
3.0	197	68	2366	0
3.5	119	41	2410	0
4.0	74	26	2438	0
5.0	78	27	2468	0

[a] See table B.2 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

the coefficient of degradation due to frosting (C_F) of the outdoor coils when the outdoor temperature is between 17 and 47°F. For the computations of heat pump energy utilization reported in section 3 the values of these parameters were taken as $C_D = 0.25$ and $C_F = 0.925$.

Other conditions held constant, a decrease of C_F would result in a heat pump yielding smaller energy savings, and a decrease in C_D would result in a heat pump yielding larger energy savings. However, the magnitude of the effect of given changes in the degradation coefficients on the total and incremental energy savings from larger size heat pumps is not immediately apparent. To get some indication of how sensitive heat pump energy utilization is to variation in these degradation coefficients, the energy savings for heat pumps with coefficients different from those used in section 3 were calculated. The same climate data, load data and heat pump performance characteristics (other than degradation coefficients) described in section 3 were used. Results are shown in table 4.2 for a C_D of 0.15 and a C_F of 0.925, in table 4.3 for a C_D of 0.25 and a C_F of 0.850, and in table 4.4 for a C_D of 0.15 and C_F of 0.850.

In comparing these three tables with table 3.4, note that incremental savings due to increasing the output capacity of the heat pump are slightly greater in all three cases. The cost-effectiveness of each heat pump size is increased assuming no change in the cost of the heat pump. However, given the heat pump cost data shown in table 3.6, in no case is this increase large enough to increase the optimal size heat pump above 2.5 tons.

4.3 EFFECTS OF IMPROVEMENTS IN STEADY-STATE EFFICIENCY

In this subsection the effects of increasing the overall steady-state heat pump energy utilization efficiency are examined. This is accomplished by changing the performance characteristics of the heat pump so that it will achieve the same output capacity at any given outdoor temperature with a smaller power input. Specifically, the power inputs for each heat pump size and outdoor temperature shown in table 3.1 are reduced by 10 percent and the simulation analysis described in section 2 is repeated. The results of these new simulations are shown in table 4.5.

Incremental energy and dollar savings for each heat pump size are increased significantly (from 16 to 35 percent) relative to the base case. However, as in the previous sensitivity analyses with respect to degradation coefficients, the increase in incremental savings is not sufficient to change the optimal heat pump size from the 2.5 ton unit. On the other hand, an increase in the cost of the higher efficiency heat pump, relative to the retail cost data used in the base case analysis, may reduce the optimal size heat pump to 2.0 tons.

4.4 EFFECTS OF ALTERNATIVE HEAT PUMP COSTS

In subsection 3.3, retail price data from a major department store catalog were used to estimate the costs of the six heat pump sizes examined. By comparing the incremental heat pump cost for each increase in output capacity with the corresponding incremental dollar savings, the optimal size heat pump for the base case example was found to be 2.5 tons. Thus the incremental cost of

Table 4.3 Energy and Dollar Savings Data by Heat Pump Size: Chicago; Base Loads; C_F=0.850, C_D=0.25[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2023	6
2.5	318	$110	2144	0
3.0	196	68	2218	0
3.5	115	40	2264	0
4.0	71	25	2293	0
5.0	68	24	2322	0

[a] See table B.3 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.4 Energy and Dollar Savings Data by Heat Pump Size: Chicago; Base Loads; C_F=0.850, C_D=0.15[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2036	6
2.5	334	$116	2159	0
3.0	208	72	2233	0
3.5	124	43	2280	0
4.0	78	27	2309	0
5.0	78	27	2338	0

[a] See table B.4 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.5 Energy and Dollar Savings Data by Heat Pump Size: Chicago; Base Loads; Power Input Reduced by 10 Percent[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2379	6
2.5	337	$117	2506	0
3.0	218	76	2588	0
3.5	133	46	2639	0
4.0	86	30	2672	0
5.0	90	31	2708	0

[a] See table B.5 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

additional output capacity is an important determinant of the optimal heat pump size, as long as increasing the heat pump size reduces annual energy costs. In general, the higher the cost per additional unit of output capacity, the smaller the optimal size heat pump tends to be; the lower the cost per additional unit of output capacity, the larger the optimal size heat pump tends to be. However, variation in the heat pump size is constrained by the need to satisfy the space cooling and dehumidification requirements of the dwelling unit as well. These lower and upper size constraints, respectively, are best determined on a site-by-site basis by an experienced air-conditioner installer. In addition, since heat pump sizes vary by discrete units of capacity, relatively small changes in unit capacity costs may not be sufficient to change the optimal heat pump size in many instances.

4.5 EFFECTS OF ALTERNATIVE ENERGY PRICE PROJECTIONS, DISCOUNT RATES, AND LIFE EXPECTANCIES

In computing the present-value, life-cycle savings in dollars due to each kWh hour saved annually, the current price per kWh was assumed to be $0.04. In addition, a 12 percent per year increase in electricity prices, a 15 percent discount rate and an expected lifetime of 10 years were assumed. Using equation 3.1, these assumptions resulted in a 10-year present-dollar-value of $0.347 for each kWh saved per year. The effects of an increase or decrease in this life-cycle kWh price factor on the incremental dollar savings shown in tables 3.4 and 4.1 through 4.5 can be readily computed by multiplying the annual incremental energy savings in kWh by the new factor.[1]

The life-cycle dollar savings are directly proportional to the price per kWh in the base year, i.e., a doubling of the price per kWh would result in a doubling of dollar savings. However, due to the exponential nature of equation 3.1, the life-cycle dollar savings are not directly proportional to the rate of kWh price increase, the discount rate, nor the expected lifetime. Table 4.6 provides constants of proportionality derived using equation 3.1 for selected variations in these factors. The life-cycle kWh price factor based on the 12 percent kWh price increase, 15 percent discount rate, and 10-year life can then be adjusted by simple multiplication to reflect changes in these three factors (e.g., $0.347 x 0.91 = $0.316 for a 10 percent increase in annual kWh price instead of a 12 percent increase).

Note that a 15 percent decrease in the life-cycle kWh cost factor (from $0.347 to $.29) will reduce the optimal heat pump size by one-half ton in all cases examined in sections 3 and 4. A 56 percent increase in the life-cycle kWh price factor (to $0.54) is needed to raise the optimal heat pump size to 3.0 tons in the base case example in table 3.3. A 42 percent increase in the same factor (to $0.49) is needed to made the 5.0 ton heat pump size cost effective in the example shown in table 4.1 (increased heating and cooling loads).

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[1] The total dollar savings relative to electric resistance heating can be recomputed by dividing the figure shown by $0.347 and multiplying by the new life-cycle kWh price factor.

Table 4.6 Adjustment Factors for Alternative Economic Assumptions[a]

I. 10 Percent Discount Rate

Price Escalation Rate (%)	Expected Life (years) 7	10	12	15
8	0.75	1.04	1.23	1.50
10	0.81	1.15	1.38	1.73
12	0.87	1.27	1.56	2.00
14	0.93	1.41	1.76	2.33
16	1.00	1.56	1.99	2.72

II. 15 Percent Discount Rate

Price Escalation Rate (%)	Expected Life (years) 7	10	12	15
8	0.63	0.83	0.94	1.09
10	0.68	0.91	1.05	1.23
12	0.73	1.00	1.17	1.41
14	0.78	1.10	1.31	1.61
16	0.84	1.21	1.46	1.86

[a] Base case = 10-year life, 12 percent kWh price increase, 15 percent discount rate, UPW* = 9.672.

4.6 EFFECTS OF GEOGRAPHIC LOCATION

In this section heat pump energy utilization will be calculated for the same six heat pump sizes examined in sections 3 and 4 in seven additional geographic locations in the United States where calculated annual heating requirements exceed calculated annual cooling requirements.[1] NBSLD [4] and Test Reference Year [6] climate data tapes were used to calculate annual heating and cooling requirements and the hourly heating and cooling load profile for the same 1800 square-foot house in each location. The heat pump energy utilization is then computed for each size heat pump in each house using the corresponding outdoor temperature data. The heat pump performance characteristics shown in table 3.1 are used for these simulations. Incremental energy and dollar savings for each increase in heat pump output capacity are calculated and the optimal heat pump size is identified for each location.

No sensitivity analyses for changes in degradation coefficients nor power input will be performed since these have relatively small effects on incremental savings. However, incremental savings and optimal heat pump sizes for a house with significantly increased heating and cooling loads will be calculated.

4.6.1 Optimal Size Heat Pump for Base House

Table 4.7 shows the annual heating and cooling requirements for the base house (see table 3.2) in eight U.S. cities, including Chicago, based on NBSLD analysis and the TRY climate records in each case. The kWh-equivalent heating requirements are shown for each location, corresponding to the 1.0 efficiency of electric resistance heating. In addition, the number of hours annually in which a cooling load occurs in the base house is shown. Tables 4.8 through 4.14 show the incremental energy and dollar savings attributable to increasing the output capacity of the heat pump as indicated for each location (except Chicago). In all cases, the 2.0 ton heat pump will satisfy the space cooling requirements in 97.5 percent of the cooling hours. In all locations except Seattle, increasing the output capacity beyond 2.5 tons increases the seasonal performance factor for heating (HSPF) thereby reducing electricity demand for heating. In Seattle, because approximately 85 percent of the heating degree days are above 45°F, increasing the heat pump output capacity causes severe penalties with regard to part-load (cycling) performance. The 2.0 ton heat pump size appears to be optimal in this case. (Coincidentally, Seattle has much lower electricity prices than most other locations in the United States as well, which also tends to hold the optimal heat pump size to the minimal acceptable size.)

In both Washington, D.C. and Atlanta, decreases in the seasonal performance factor for cooling along with relatively high annual cooling requirements result in little or no net energy savings on an annual basis. As a result, increasing

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1 In installations where annual cooling requirements exceed annual heating requirements, increasing the heat pump size typically results in no net annual energy savings because of the increase in part-load performance losses.

Table 4.7 Annual Energy Requirements for Base House[a]

Location	Annual Heating Requirements (kWh)	Annual Heating Requirements (million Btu)	Annual Cooling Requirements (million Btu)	Annual Cooling Hours
Seattle, Washington	10990	37.5	2.2	240
Atlanta, Georgia	5403	18.4	17.4	1491
Washington, D.C.	8786	30.0	16.8	1561
Kansas City, Missouri	12706	43.4	20.5	1711
Chicago, Illinois	14972	51.1	8.0	811
Boston, Massachusetts	15229	52.0	6.6	632
Madison, Wisconsin	19518	66.6	6.0	633
Minneapolis, Minnesota	25527	87.1	10.9	1013

[a] Based on NBSLD analysis using TRY climate data and assumptions shown in table 3.2.

Table 4.8 Energy and Dollar Savings Data by Heat Pump Size: Seattle; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2044	0
2.5	- 6	-$ 2	2049	0
3.0	-11	- 4	2047	0
3.5	-12	- 4	2045	0
4.0	- 9	- 3	2042	0
5.0	-13	- 4	2039	0

[a] See table B.6 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.9 Energy and Dollar Savings Data by Heat Pump Size: Atlanta; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$ 961	1
2.5	-21	-$ 7	979	0
3.0	-23	- 8	985	0
3.5	-34	- 12	987	0
4.0	-24	- 8	987	0
5.0	-38	- 13	987	0

[a] See table B.7 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.10 Energy and Dollar Savings Data by Heat Pump Size: Washington, D.C.; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$1498	1
2.5	47	$ 16	1538	0
3.0	25	9	1561	0
3.5	-1	0	1573	0
4.0	-4	- 1	1580	0
5.0	-20	- 7	1586	0

[a] See table B.8 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.11 Energy and Dollar Savings Data by Heat Pump Size: Kansas City; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$1730	33
2.5	245	$ 85	1848	0
3.0	153	53	1920	0
3.5	86	30	1967	0
4.0	53	19	1997	0
5.0	44	15	2030	0

[a] See table B.9 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.12 Energy and Dollar Savings Data by Heat Pump Size: Boston; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2398	0
2.5	387	$134	2541	0
3.0	207	72	2618	0
3.5	97	34	2657	0
4.0	42	15	2674	0
5.0	20	7	2686	0

[a] See table B.10 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.13 Energy and Dollar Savings Data by Heat Pump Size: Madison; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2420	1
2.5	416	$144	2572	0
3.0	262	91	2667	0
3.5	172	60	2731	0
4.0	124	43	2776	0
5.0	166	58	2838	0

[a] See table B.11 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.14 Energy and Dollar Savings Data by Heat Pump Size: Minneapolis; Base Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2316	6
2.5	573	$199	2531	0
3.0	420	146	2685	0
3.5	302	105	2799	0
4.0	214	74	2879	0
5.0	260	90	2977	0

[a] See table B.12 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.15 Energy and Dollar Savings Data by Heat Pump Size: Seattle; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$3661	13
2.5	633	$220	3888	6
3.0	331	115	4007	0
3.5	161	56	4066	0
4.0	61	21	4089	0
5.0	21	7	4099	0

[a] See table B.13 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

the heat pump output capacity above 2.0 tons in these two locations does not appear to be either an energy conserving nor cost-effective procedure.

In Kansas City, the incremental energy savings for increasing the heat pump from 2.0 to 2.5 tons ($84) are less than the $100 cost calculated in section 3.3. The 2.0 ton system appears to be optimal here. However, higher energy costs (e.g., $0.05/kWh), a more efficient heat pump, larger annual heating requirements, or lower incremental heat pump costs would likely increase the optimal size to 2.5 tons.

In the remaining locations (Boston, Madison, and Minneapolis) the incremental savings for the 2.5 ton heat pump are all significantly higher than the incremental cost. The optimal size for Boston and Madison is shown to be 2.5 tons under the assumptions made. For Minneapolis, the 3.0 ton heat pump size is optimal. (While the dollar savings from increasing the heat pump size from 3.0 to 3.5 tons in Minneapolis is approximately $104, the corresponding incremental cost is assumed to be $150.)

Based on the analysis of heat pump sizing effects in these seven locations, plus the base case example for Chicago in section 3.3, it was found that the optimal heat pump size exceeded the minimum acceptable size (2.0 tons) in four locations (Chicago, Boston, Madison and Minneapolis). In each location the house modeled had annual heating requirements (AHR) exceeding 50 million Btu. In addition, the house in Kansas City with AHR of 43 million might be included if kWh costs were raised slightly (e.g., to $0.05/kWh). In the other three locations examined (where the houses modeled all had AHR less than 40 million Btu), it is unlikely that the economically optimal heat pump size will ever exceed the minimum acceptable size needed for air conditioning purposes. Thus it appears that serious consideration should be given to increasing the size of a heat pump above the minimum acceptable size if the AHR of the house in which it is to be installed are greater than approximately 40 million Btu. For AHR between approximately 40 and 80 million Btu, a one-half ton increase should be considered. Above approximately 80 million Btu, a one-ton increase in heat pump size should be considered.

In the following subsection, the optimal heat pump size for houses with increased heating and cooling requirements will be considered in order to provide additional data for such guidelines.

4.6.2 Optimal Size Heat Pump for House with Increased Heating and Cooling Loads

In subsection 4.1 the optimal size heat pump was shown to increase significantly with increases in hourly heating and cooling loads, based on the Chicago TRY climate data. Specifically, doubling the hourly heating loads and increasing hourly cooling loads by one half raised the optimal size heat pump from 2.5 to 4.0 tons, while the minimum acceptable size was increased from 2.0 to 2.5 tons. In this subsection, hourly heating and cooling loads are increased by the same proportions in the seven additional locations shown in table 4.7. Annual kWh requirements for heating and cooling are calculated for each of the six heat pump sizes, based on their performance characteristics as listed in table 3.1. Incremental kWh and dollar value savings due to increasing output capacities are calculated for the five heat pump sizes greater than 2.0 tons. As in section 3, dollar value savings are based on 10-year savings at $0.04 per kWh, with a 12 percent increase per year in electricity costs and a 15 percent discount rate. Results of these analyses for the increased heating and cooling loads are shown in tables 4.15 through 4.21, corresponding to the base house in tables 4.8 through 4.14.

In all seven cases, increasing the heat pump output capacity reduces annual kWh consumption throughout the range of sizes examined. In addition, the minimum heat pump size which satisfies the hourly cooling loads in 97.5 percent of the hours in which cooling loads occur is larger than the base case in all locations. The optimal heat pump size, based on the assumptions made in section 3 (including an incremental cost per one-half ton increase in output capacity of $100 up to 3.0 tons and $150 above 3.0 tons) exceeds the minimum size in all cases except for Atlanta. In Atlanta, the optimal size would be 2.0 tons if a minimum sizing constraint did not require a 3.0 ton unit for cooling purposes. For Seattle and Washington, D.C. the optimal size is 3.0 tons, while the minimum acceptable size is 2.5 tons in both cases. For Kansas City the optimal heat pump size is 3.5 tons, while the minimum acceptable size is 3.0 tons. For Boston and Madison it is 4.0 tons, versus a minimum acceptable 2.5 ton size. For Minneapolis the optimal size is 5.0 tons, while the minimum acceptable size is 3.0 tons. In Kansas City, Boston, and Madison, a small increase in dollar savings would increase the optimal heat pump size one step further. Significantly higher incremental costs will reduce the optimal level in many cases. For example, a 15 percent increase in incremental costs would reduce the optimal heat pump level to the minimum level in Seattle, Washington, D.C., and Kansas City. However, in the coldest locations (Boston, Madison, and Minneapolis) incremental costs would have to be increased by three to four hundred percent before the optimal size would coincide with the size selected for cooling capacity alone.

The results of this analysis correspond quite well with those of the previous subsection in terms of the correlation between annual heating requirements and increased capacity needed for optimal heat pump sizing relative to the minimum acceptable size. Below 40 million Btu, no increase in sizing is warranted. Between 40 and 80 million Btu, a one-half ton increase should be considered. Further analysis of the results in this subsection implies that for AHR between approximately 80 and 100 million Btu, a one ton increase should be considered, while above 100 million Btu, a one and one-half ton increase in heat pump capacity may be optimal. In the most extreme case (AHR of 174 million Btu in Minneapolis), a two ton increase was shown to be optimal.

While these AHR intervals may provide some preliminary guidelines for the optimal sizing of heat pump systems, it must be recognized that incremental capacity costs, kWh prices, and present-value factors should play an important role in the decision-making process for heat pump selection. Higher unit capacity costs than those used (see table 3.5 and 3.6) would tend to raise the AHR intervals shown proportionally. Higher kWh prices and higher present-value factors would tend to lower them in inverse proportion.

Table 4.16 Energy and Dollar Savings Data by Heat Pump Size: Atlanta; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$1601	224
2.5	208	$72	1739	41
3.0	178	62	1832	1
3.5	86	30	1889	0
4.0	43	15	1922	0
5.0	24	8	1958	0

[a] See table B.14 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.17 Energy and Dollar Savings Data by Heat Pump Size: Washington, D.C.; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2461	205
2.5	488	$169	2694	34
3.0	333	116	2840	1
3.5	196	68	2934	0
4.0	128	45	2996	0
5.0	156	54	3077	0

[a] See table B.15 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.18 Energy and Dollar Savings Data by Heat Pump Size: Kansas City; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$2467	423
2.5	701	$243	2811	139
3.0	633	220	3081	33
3.5	498	173	3290	1
4.0	417	145	3459	0
5.0	581	202	3696	0

a See table B.16 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

b Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

c Total heating savings relative to electric resistance heating.

Table 4.19 Energy and Dollar Savings Data by Heat Pump Size: Boston; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$3390	61
2.5	1325	$460	3873	15
3.0	1088	377	4262	0
3.5	851	295	4567	0
4.0	641	222	4796	0
5.0	799	277	5083	0

a See table B.17 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

b Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

c Total heating savings relative to electric resistance heating.

Table 4.20 Energy and Dollar Savings Data by Heat Pump Size: Madison; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$3411	53
2.5	1390	$482	3912	9
3.0	1107	384	4306	1
3.5	852	296	4610	0
4.0	642	223	4839	0
5.0	857	298	5145	0

[a] See table B.18 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

Table 4.21 Energy and Dollar Savings Data by Heat Pump Size: Minneapolis; Increased Loads[a]

(1) Heat Pump Size (Tons)	(2) Incremental Savings (kWh/yr)	(3) Incremental Savings ($, Life Cycle)[b]	(4) Heat Pump Savings[c] ($, Life Cycle)	(5) Hours Cooling Load Exceeds Capacity
2.0	-	-	$3097	152
2.5	1301	$452	3591	34
3.0	1143	396	4008	6
3.5	939	326	4352	0
4.0	770	267	4630	0
5.0	1195	415	5062	0

[a] See table B.19 in Appendix B for corresponding annual energy utilization and seasonal performance factors.

[b] Based on $0.04 per kWh price in base year, 10-year life, 12 percent annual increase in kWh price, 15 percent discount rate.

[c] Total heating savings relative to electric resistance heating.

These guidelines are preliminary in nature, however, because they do not address the important relationship between the heating and cooling requirements of the building in which the heat pump is to be installed. The effects of an oversized cooling capacity on proper dehumidification must also be addressed. Additional research is needed to provide a more comprehensive set of guidelines for field usage.

5.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER RESEARCH

The size of a residential heat pump in terms of its output capacity in the heating and cooling modes is typically selected to match design cooling loads rather than design heating loads. Supplementary electric resistance strip heating is generally added to match heating loads in excess of the heat pump capacity. However, this supplementary heat source is less efficient than the heat pump itself at outdoor temperatures above approximately -20°F. As a result, an increase in the heating capacity of the heat pump (i.e., selecting a larger size heat pump), by reducing supplementary heating requirements, may increase the seasonal heating efficiency of the overall heating system in many cases.

The purpose of this report is to identify factors which make the use of larger size heat pumps cost effective in residential applications and to determine the economically optimal heat pump size as a function of these factors. The economically optimal heat pump size is defined as that heat pump size available for which total owning and operating costs on a life-cycle cost basis are minimized while satisfying design cooling loads. As a result, the optimal size cannot be smaller than the size selected to match design cooling loads using conventional selection procedures.

This report uses an hourly simulation model of heat pump performance, heating and cooling load data for two house sizes for an entire calendar year, performance characteristics typical of a commonly available heat pump, and representative cost data to determine the optimal size heat pump in a variety of geographic locations with significant annual heating requirements. In addition, a number of sensitivity analyses are performed in order to demonstrate the effects of changes in certain factors on the optimal heat pump size. Over the range of variation tested, only changes in the size of the space heating and cooling loads, the geographic location of the house, and the price of electricity had a significant effect on the optimal heat pump size.

In the cases studied, annual heating requirements must be approximately 50 million Btu before the optimal heat pump size exceeds the minimum acceptable size for cooling purposes by one-half ton or more. In addition, annual heating requirements exceed annual cooling requirements by nearly three to one in all such cases. Higher electricity costs or more efficient heat pumps would tend to lower the annual heating requirements needed to increase the optimal size heat pump above the minimum. On the other hand, substantially higher incremental heat pump costs than those used would tend to hold the optimal level closer to the minimum acceptable size.

For houses with annual heating requirements above 80 million Btu, a one ton increase in capacity should be considered. Above 100 million Btu, the optimal heat pump capacity may be one and one-half tons or more greater than the minimum acceptable size for cooling. However, when such large increases in capacity are considered, care must be taken to assure that dehumidification requirements can be adequately met without significant increases in cooling energy usage.

In milder climates such as in Seattle and Atlanta, increasing the heat pump size can actually lower seasonal heating efficiency because reductions in part-load efficiency (from cycling on and off) due to oversizing at the higher outdoor temperatures tend to offset increases in efficiency at lower temperatures. Similarly, increasing the heat pump size in all cases tends to reduce seasonal cooling efficiency because of oversizing relative to the actual cooling requirements.

The scope of this report is limited primarily to the development of a methodology for the economic sizing of residential heat pumps and some parametric analysis to determine the sensitivity of optimal heat pump size to many of the important assumptions required. This research could be expanded to address several areas of additional concern:

(1) The results of this report are based on an hour-by-hour analysis of heating and cooling loads and heat pump performance in residential applications in eight locations. Such a detailed analysis would be prohibitively costly for most new heat pump installations. Generalized guidelines based on estimates of annual heating and cooling requirements, readily available climate parameters, electricity costs and heat pump costs are needed so that the findings in this report can be made more useful for field usage.

(2) This report investigated the economic efficiency of a one-speed heat pump. A variable-speed heat pump should yield greater energy savings than the one-speed heat pump because it reduces loss of performance at higher temperatures resulting from equipment cycling. An economic investigation of the extent to which this potential energy saving will pay for the greater initial cost of the variable-speed heat pump as well as the optimal sizing of the latter should be conducted.

(3) In installations with small annual cooling requirements, a heating-only heat pump may be an attractive alternative to a reversible heat pump since it will have a higher seasonal performance factor. Heating-only heat pumps are not currently being manufactured because of low demand. However, an economic analysis of the superior performance of the heating-only heat pump, including sizing considerations, may provide an increased incentive for manufacturing such a system.

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Appendix A. Listing of Computer Program for Heat Pump Sizing Analysis

This appendix gives a listing of the computer program used to calculate the electricity needed to meet heating-cooling loads and the present value of energy saved by a heat pump.

List of Symbols in the Program

Symbol	Interpretation	Line of first Occurrence
C1	Coefficient of degradation due to frosting	4
C2	Coefficient of degradation resulting from cycling when heating load is less than heat pump capacity	5
SENER	Sum of electric energy used to meet heating load	81
SENEC	Sum of electric energy used to meet cooling load	82
SHL	Total heating load	83
SXCI	Total cooling load	91
JE	Number of hours cooling load exceeds capacity	92
T	Dry bulb temperature	100
XL	Sensible load	101
XLL	Latent load	101
TB	Temperature below which heat pump is not used	90
SHL	Sum of heating load	103 (initialized 83)
SXCI	Sum of cooling load	121 (initialized 91)
SPF	Seasonal performance factor, heating load	128
SPC	Seasonal performance factor, cooling load	129
SENET	Total energy used, heating plus cooling	130
SVG	Present value of savings on heating load	132
SENRM	Marginal energy savings, heating plus cooling	136
SVGM	Present value of total marginal savings	137

Listing of Computer Program

```
 1.   C         ...^HPJLFL.MAINU...
 2.             DIMENSION DB(24),DUM(24),XL(24),XLL(24)
 3.             INPUT=9
 4.             C1=.925
 5.             C2=.250
 6.       3100  WRITE (6,15) C1,C2
 7.             DO 150 K=1,6
 8.             GO TO (2110,2120,2130,2140,2150,2160,2170),K
 9.       2110  CONTINUE
10.             CAP17=13254
11.             CAP47=24000
12.             POW17=2.157
13.             POW47=2.705
14.             CAP75=22615
15.             CAP85=22313
16.             CAP95=21600
17.             CAP15=19138
18.             POW75=2.29
19.             POW95=2.70
20.             GO TO 2000
21.       2120  CONTINUE
22.             CAP17=16567
23.             CAP47=30000
24.             POW17=2.697
25.             POW47=3.381
26.             CAP75=28269
27.             CAP85=27891
28.             CAP95=27000
29.             CAP15=23922
30.             POW75=2.87
31.             POW95=3.38
32.             GO TO 2000
33.       2130  CONTINUE
34.             CAP17=19880
35.             CAP47=36000
36.             POW17=3.236
37.             POW47=4.057
38.             CAP75=33923
39.             CAP85=33469
40.             CAP95=32400
41.             CAP15=28706
42.             POW75=3.43
43.             POW95=4.05
44.             GO TO 2000
45.       2140  CONTINUE
46.             CAP17=23194
```

Heat pump

design parameters

(lines 9 through 79)

Table 3.1

```
      CAP47=42000
      POW17=3.775
      POW47=4.733
      CAP75=39577
      CAP85=39047
      CAP95=37800
      CAP15=33491
      POW75=4.01
      POW95=4.73
      GO TO 2000
 2150 CONTINUE
      CAP17=26507
      CAP47=48000
      POW17=4.315
      POW47=5.409
      CAP75=45230
      CAP85=44626
      CAP95=43200
      CAP15=38275
      POW75=4.58
      POW95=5.40
      GO TO 2000
 2160 CONTINUE
      CAP17=33134
      CAP47=60000
      POW17=5.393
      POW47=6.761
      CAP75=56538
      CAP85=55782
      CAP95=54000
      CAP15=47844
      POW75=5.72
      POW95=6.75
 2170 CONTINUE
 2000 SENFR=0.
      SENFC=0.
      SHL=0.
      CAP35=(.4*CAP17+.6*CAP47)*C1               Heating performance
      POW35=(.4*POW17+.6*POW47)                  parameters
      A1=(CAP47-CAP17)/30.
      B1=(CAP35-CAP17)/18.
      A2=(POW47-POW17)/30.                       Subsection 2.1
      B2=(POW35-POW17)/18.
      TB=17.+((3413.*POW17-CAP17)/(A1-3413.*A2))
      SXC1=0.
      JE=0
      SC1=(CAP85-CAP75)/10.                      Cooling performance
      SC2=(CAP95-CAP85)/10.                      parameters
      SC3=(CAP15-CAP95)/20.
      SP=(POW95-POW75)/20.                       Subsection 2.2
      DO 100 I=1,367
      READ (INPUT,END=999) DB,DUM,DUM,DUM,XL,XLL
      DO 90 J=1,24
      T=DB(J)
      HL=(XL(J)+XLL(J))
      IF (HL.LT.0.) GO TO 290
      SHL=SHL+HL
      IF (T.LE.TB) GO TO 70
```

```
      VAL=CAPCTY(T)
      X1=HL/VAL
      X=AMIN1(1.0,X1)
      POW1=POWER(T,X,C2)
      ENERX=ENER(VAL,POW1,HL,X)
      GO TO 80
   70 ENERX=HL/3413.
   80 SENER=SENER+ENERX
      GO TO 90
```

Energy use
heating load hour

Subsection 2.1

```
  290 CL=-HL
      VAL=CAPC(T)
      X1=CL/VAL
      IF (X1.LE.1.0) GO TO 260
      JE=JE+1
      CL=VAL
  260 X=AMIN1(1.0,X1)
      SXCL=SXCL+CL
      POW1=POWC(T,X,C2)
      ENERX=X*POW1
      SENEC=SENEC+ENERX
```

Energy use
cooling load hour

Subsection 2.2

```
   90 CONTINUE
  100 CONTINUE
  999 CONTINUE
      SPF=SHL/(3413*SENER)
      SPC=SXCL/(3413.*SENEC)
      SENET=SENER+SENEC
      CALL LCCF(FLC)
      SVG=FLC*(SHL/3413.-SENER)
      IF (K.GE.2) GO TO 130
      SENR1=SENET
  130 CONTINUE
      SENRM=SENR1-SENET
      SVGM=FLC*SENRM
      WRITE (6,7) K
      WRITE (6,11) SENER,SPF
      WRITE (6,41) SENEC,SPC
      WRITE (6,23) SENET
      WRITE (6,17) SVG
      WRITE (6,19) SENRM
      WRITE (6,21) SVGM
      WRITE (6,31) JE
      SENR1=SENET
      REWIND INPUT
  150 CONTINUE
    7 FORMAT (16H0HEAT PUMP SIZE=,I2)
   11 FORMAT (7H SENER=,F10.1,7H   SPF=,F9.4)
   15 FORMAT (5HIFCD=,F10.4,8H   PLCD=,F10.4)
   17 FORMAT  (19H HEAT PUMP SAVING=$,F10.1)
   19 FORMAT (7H SENRM=,F9.1)
   21 FORMAT (7H SVGM=$,F8.1)
   23 FORMAT (7H SENET=,F10.1)
   31 FORMAT (37H HOURS COOLING LOAD EXCEDES CAPACITY=,I4)
   41 FORMAT (7H SENEC=,F10.1,7H   SPC=,F9.4)
      STOP
      FUNCTION CAPCTY(T)
      IF (T.LE.17.) GO TO 1000
      IF (T.GT.45.) GO TO 1000
      CAPCTY=CAP17+B1*(T-17)
```

Heating capacity

```
      GO TO 1010
 1000 CAPCTY=CAP17+A1*(T-17)                  Subsection 2.1 (a)
 1010 RETURN
      FUNCTION POWER(T,X,C2)
      IF (T.GT.17) GO TO 1100                 Heating power
      POWER=POW17+A2*(T-17)
      GO TO 1120
 1100 IF (T.GT.45.) GO TO 1110
      POWER=POW17+B2*(T-17)                   Subsection 2.1 (c)
      GO TO 1120
 1110 PLF=1.0-C2*(1.0-X)
      POWER=(POW17+A2*(T-17))/PLF
 1120 RETURN
      FUNCTION ENER(VAL,POW1,HL,X)            Heating electricity use
      IF (X.GE.1.0) GO TO 1200
      ENER=X*POW1
      GO TO 1210
 1200 ENER=(HL-VAL)/3413+POW1                 End Subsection 2.1
 1210 RETURN
      FUNCTION CAPC(T)
      IF (T.GT.85) GO TO 1010                 Cooling capacity
      CAPC=CAP75+SC1*(T-75.)
      GO TO 1000                              Subsection 2.2 (a)
 1010 IF (T.GT.95) GO TO 1020
      CAPC=CAP85+SC2*(T-85.)
      GO TO 1000
 1020 CAPC=CAP15+SC3*(T-95.)
 1000 RETURN
      FUNCTION POWC(T,X,C2)                   Cooling power
      PLF=1.0-C2*(1.0-X)
      POWC=(POW75+SP*(T-75.))/PLF
      RETURN                                  Subsection 2.2 (c)
      END
```

Subroutine to Calculate the Present Value of an Annual Expenditure per kWh of Electricity Over Ten Years (Subroutine called in main program at line 131.)

```
C       ...CHPJLFL.LCCF...
        SUBROUTINE LCCF(FLC)
        DIMENSION FD1(9),FD2(9),FD3(9),DF(9)
        P1=.04
        NB=1
        FD1(1)=.07
        FD2(1)=.1
        FD3(1)=10.
        FLC=0.
        CDF=1.
        DO 150 I=1,NB
        DF(I)=(1.+FD1(I))/(1.+FD2(I))
        IF (DF(I).NE.1.) GO TO 100
        FLC=FLC+CDF*FD3(I)
        GO TO 150
  100   Y1=EXP(FD3(I)*ALOG(DF(I)))
        BPVF=DF(I)*(1.-Y1)/(1.-DF(I))
        PVF=CDF*BPVF
        FLC=FLC+PVF
        CDF=CDF*Y1
  150   CONTINUE
        FLC=P1*FLC
        RETURN
        END
```

Appendix B. Annual Heating and Cooling Energy Utilization by Heat Pump Size: Sensitivity Analysis

Table B.1 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Chicago; Increased Loads; C_F=0.925, C_D=0.25[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	20771	1389	22160	1.44	2.48
2.5	19539	1469	21008	1.53	2.39
3.0	18612	1510	20122	1.61	2.34
3.5	17937	1545	19482	1.67	2.29
4.0	17444	1568	19012	1.72	2.25
5.0	16796	1602	18398	1.78	2.20

a Annual heating requirements = 102.2 million Btu; electric resistance equivalent = 29944 kWh. Annual cooling requirements = 12.0 million Btu.

Table B.2 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Chicago; Base Loads; C_F=0.925, C_D=0.15[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	8683	952	9635	1.72	2.47
2.5	8358	971	9329	1.79	2.43
3.0	8153	979	9131	1.84	2.41
3.5	8024	988	9013	1.87	2.38
4.0	7944	994	8937	1.88	2.37
5.0	7858	1002	8860	1.91	2.35

a Annual heating requirements = 51.1 million Btu; electric resistance equivalent = 14972 kWh. Annual cooling requirements = 8.0 million Btu.

Table B.3 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Chicago; Base Loads; C_F=0.850, C_D=0.25[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	9140	1008	10148	1.64	2.33
2.5	8790	1040	9830	1.70	2.26
3.0	8577	1057	9634	1.75	2.23
3.5	8444	1074	9519	1.77	2.19
4.0	8362	1085	9448	1.79	2.17
5.0	8278	1102	9380	1.81	2.14

[a] Annual heating requirements = 51.1 million Btu; electric resistance equivalent = 14972 kWh. Annual cooling requirements = 8.0 million Btu.

Table B.4 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Chicago; Base Loads; C_F=0.850, C_D= 0.15[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	9101	952	10054	1.65	2.47
2.5	8749	971	9720	1.71	2.43
3.0	8533	979	9512	1.75	2.41
3.5	8400	988	9388	1.78	2.38
4.0	8317	994	9310	1.80	2.37
5.0	8231	1002	9233	1.82	2.35

[a] Annual heating requirements = 51.1 million Btu; electric resistance equivalent = 14972 kWh. Annual cooling requirements = 8.0 million Btu.

Table B.5 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Chicago; Base Loads; Power Input Reduced by 10 Percent[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	8112	907	9019	1.85	2.59
2.5	7746	936	8682	1.93	2.52
3.0	7512	952	8464	1.99	2.47
3.5	7364	967	8331	2.03	2.44
4.0	7268	977	8245	2.06	2.41
5.0	7164	991	8155	2.09	2.38

[a] Annual heating requirements = 51.1 million Btu; electric resistance equivalent = 14972 kWh. Annual cooling requirements = 8.0 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.6 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Seattle; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	5097	285	5381	2.16	2.29
2.5	5082	293	5375	2.16	2.22
3.0	5088	298	5386	2.16	2.19
3.5	5096	302	5398	2.16	2.16
4.0	5102	305	5407	2.15	2.13
5.0	5111	310	5420	2.15	2.11

[a] Annual heating requirements = 37.5 million Btu; electric resistance equivalent = 10990 kWh. Annual cooling requirements = 2.2 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.7 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Atlanta; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	2633	2108	4741	2.05	2.42
2.5	2581	2181	4762	2.09	2.34
3.0	2564	2222	4785	2.11	2.30
3.5	2558	2261	4819	2.11	2.26
4.0	2556	2286	4843	2.11	2.23
5.0	2557	2325	4881	2.11	2.19

[a] Annual heating requirements = 18.4 million Btu; electric resistance equivalent = 5403 kWh. Annual cooling requirements = 17.4 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.8 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Washington, D.C.; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	4468	2112	6579	1.97	2.33
2.5	4351	2181	6533	2.02	2.26
3.0	4287	2221	6508	2.05	2.21
3.5	4251	2258	6509	2.07	2.18
4.0	4231	2283	6514	2.08	2.15
5.0	4214	2320	6534	2.08	2.12

[a] Annual heating requirements = 30.0 million Btu; electric resistance equivalent = 8786 kWh. Annual cooling requirements = 16.8 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.9 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Kansas City; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	7720	2527	10247	1.65	2.37
2.5	7379	2624	10002	1.72	2.28
3.0	7171	2678	9849	1.77	2.24
3.5	7035	2728	9764	1.81	2.20
4.0	6949	2761	9710	1.83	2.17
5.0	6855	2812	9666	1.85	2.13

[a] Annual heating requirements = 43.4 million Btu; electric resistance equivalent = 12706 kWh. Annual cooling requirements = 20.5 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.10 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Boston; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	8316	822	9138	1.83	2.35
2.5	7903	848	8752	1.93	2.27
3.0	7682	863	8544	1.98	2.24
3.5	7570	877	8447	2.01	2.20
4.0	7519	886	8405	2.03	2.18
5.0	7485	900	8385	2.03	2.14

[a] Annual heating requirements = 52.0 million Btu; electric resistance equivalent = 15229 kWh. Annual cooling requirements = 6.6 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.11 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Madison; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	12542	755	13298	1.56	2.33
2.5	12103	778	12881	1.61	2.26
3.0	11829	790	12620	1.65	2.22
3.5	11645	803	12448	1.68	2.19
4.0	11514	810	12324	1.70	2.17
5.0	11336	822	12158	1.72	2.14

[a] Annual heating requirements = 66.6 million Btu; electric resistance equivalent = 19518 kWh. Annual cooling requirements = 6.0 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.12 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Minneapolis; Base Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	18851	1367	20219	1.35	2.34
2.5	18231	1414	19645	1.40	2.26
3.0	17785	1440	19225	1.44	2.22
3.5	17459	1465	18923	1.46	2.19
4.0	17228	1481	18709	1.48	2.16
5.0	16944	1505	18449	1.51	2.13

[a] Annual heating requirements = 87.1 million Btu; electric resistance equivalent = 25527 kWh. Annual cooling requirements = 10.9 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.13 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Seattle; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	11426	394	11819	1.92	2.43
2.5	10771	415	11187	2.04	2.34
3.0	10429	427	10856	2.11	2.29
3.5	10259	436	10695	2.14	2.24
4.0	10192	442	10634	2.16	2.21
5.0	10163	451	10614	2.16	2.17

[a] Annual heating requirements = 75.0 million Btu; electric resistance equivalent = 21980 kWh. Annual cooling requirements = 3.3 million Btu. C_F = 0.925, C_D = 0.25.

Table B.14 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Atlanta; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	6189	2880	9070	1.75	2.58
2.5	5793	3070	8863	1.87	2.49
3.0	5525	3160	8685	1.96	2.42
3.5	5362	3237	8598	2.02	2.36
4.0	5265	3290	8556	2.05	2.32
5.0	5161	3371	8532	2.09	2.27

[a] Annual heating requirements = 36.9 million Btu; electric resistance equivalent = 10806 kWh. Annual cooling requirements = 26.1 million Btu. C_F = 0.925, C_D = 0.25.

Table B.15 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Washington, D.C.; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	10477	2894	13371	1.68	2.49
2.5	9807	3076	12883	1.79	2.39
3.0	9384	3165	12549	1.87	2.33
3.5	9115	3239	12354	1.93	2.28
4.0	8935	3290	12225	1.97	2.24
5.0	8701	3368	12069	2.02	2.19

[a] Annual heating requirements = 60.0 million Btu; electric resistance equivalent = 17572 kWh. Annual cooling requirements = 25.2 million Btu. C_F = 0.925, C_D = 0.25.

Table B.16 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Kansas City; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	18300	3351	21651	1.39	2.52
2.5	17309	3641	20951	1.47	2.43
3.0	16530	3788	20318	1.54	2.37
3.5	15927	3893	19820	1.60	2.31
4.0	15441	3962	19403	1.65	2.27
5.0	14755	4066	18822	1.72	2.21

[a] Annual heating requirements = 86.7 million Btu; electric resistance equivalent = 25412 kWh. Annual cooling requirements = 30.8 million Btu. C_F = 0.925, C_D = 0.25.

Table B.17 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Boston; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	20684	1133	21817	1.47	2.50
2.5	19293	1199	20492	1.58	2.41
3.0	18172	1232	19404	1.68	2.35
3.5	17293	1260	18553	1.76	2.30
4.0	16633	1279	17912	1.83	2.26
5.0	15805	1308	17113	1.93	2.21

[a] Annual heating requirements = 104.0 million Btu; electric resistance equivalent = 30458 kWh. Annual cooling requirements = 9.9 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.18 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Madison; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	29204	1046	30250	1.34	2.47
2.5	27757	1103	28860	1.41	2.38
3.0	26621	1132	27753	1.47	2.33
3.5	25745	1156	26901	1.52	2.28
4.0	25086	1173	26259	1.56	2.25
5.0	24204	1197	25402	1.61	2.20

[a] Annual heating requirements = 133.2 million Btu; electric resistance equivalent = 39036 kWh. Annual cooling requirements = 9.0 million Btu. $C_F = 0.925$, $C_D = 0.25$.

Table B.19 Annual Heating and Cooling Energy Utilization by Heat Pump Size: Minneapolis; Increased Loads[a]

Heat Pump Size (Tons)	Annual Energy Utilization (kWh)			Seasonal Performance Factors (SPF)	
	Heating	Cooling	Total	Heating	Cooling
2.0	42127	1865	43991	1.21	2.49
2.5	40702	1989	42690	1.25	2.40
3.0	39498	2049	41548	1.29	2.34
3.5	38509	2100	40609	1.33	2.29
4.0	37705	2133	39838	1.35	2.25
4.5	36460	2184	38643	1.40	2.20

[a] Annual heating requirements = 174.2 million Btu; electric resistance equivalent = 51054 kWh. Annual cooling requirements = 16.4 million Btu. $C_F = 0.925$, $C_D = 0.25$.

FEDERAL INFORMATION PROCESSING STANDARD SOFTWARE SUMMARY

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02. Summary prepared by (Name and Phone)
Joel Levy (301) 921 x2607

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05. Software title
Program for Heat Pump Sizing Analysis

06. Short title

07. Internal Software ID
MAINU

08. Software type
[ ] Automated Data System
[X] Computer Program
[ ] Subroutine/Module

09. Processing mode
[ ] Interactive
[X] Batch
[ ] Combination

10. Application area

General:
[ ] Computer Systems Support/Utility
[ ] Scientific/Engineering
[ ] Bibliographic/Textual
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[X] Other

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Life-cycle cost of different heat pump sizes.

11. Submitting organization and address
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Building Economics and Regulatory Technology Div.
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13. Narrative

From data on hour by hour heating and cooling loads and weather conditions the program calculates electricity saved by use of given size heat pump. On the basis of electricity price data and the discount rate these life-cycle savings on electricity are converted to their present value. Comparison with heat pump costs then allows selection of heat pump size maximizing net savings.

14. Keywords
Benefit-cost analysis; energy conservation; equipment selection; equipment sizing; heat pump; life-cycle costs.

15. Computer manuf'r and model	16. Computer operating system	17. Programing language(s)	18. Number of source program statements
UNIVAC 1108	EXEC 8	FØRTRAN IV	195 MAIN 24 Sub

19. Computer memory requirements	20. Tape drives	21. Disk/Drum units	22. Terminals
Max. 32K	1	None	NA

23. Other operational requirements
None

24. Software availability
Available [X] Limited [ ] In-house only [ ]
Applied Economics Group
Bldg. 226, Rm. A319
National Bureau of Standards
Washington, D.C. 20234

25. Documentation availability
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Bldg. 226, Rm. A319
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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This report provides a methodology for determining the optimal heat pump size, in terms of heating output capacity, for residential installations having annual heating requirements significantly greater than annual cooling requirements. The optimal size heat pump is defined as the size for which total present value, life-cycle heating and cooling costs (including equipment costs) are minimized. Incremental energy savings from increasing the output capacity of the heat pump are calculated using hourly simulation models of heat pump and building performance developed at NBS. The dollar value of the incremental savings, in present-value, life-cycle terms, is then calculated and compared with incremental costs to determine the optimal heat pump size. A base case analysis of an 1800 square-foot house in the Chicago climate shows that a slightly larger heat pump size than would typically be selected for air conditioning purposes alone is optimal for the assumptions specified. A number of sensitivity analyses are performed to show the effects of changes in load size, degradation coefficients, power utilization efficiency, economic assumptions and geographic location on the optimal heat pump size.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Benefit-cost analysis; energy conservation; equipment selection; equipment sizing; heat pump; life-cycle costs.

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