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INVESTIGATION OF THE CONSERVATION POTENTIAL OF RESIDENTIAL HEAT PUMPS WITH THERMAL ENERGY STORAGE

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EXECUTIVE SUMMARY

The proposed objectives of this study were to examine the operational and economic feasibility of heat pump systems with thermal storage to:

1. Reduce annual electric cost for residential customers by operating the system during hourly periods, both summer and winter, when the most favorable coefficient of performance can be obtained.
2. Provide the potential for a reduction in peak electric utility demand, by delivering mid-day cooling from storage, with the compressor operating only during utility off-peak periods.

To meet these study objectives the investigators decided to evaluate the performance characteristics of two storage system concepts, using computer simulation techniques. Both a liquid tank storage system (HP-LTS) and a rock-bed storage system (HP-RBS) were evaluated. These two concepts are referred to in this report as Heat Pumps with Thermal Energy Storage, or simply "HP-TES" systems.

The methodology used during the HP-TES study is shown in the block diagram of Figure E-1. This study project began with three parallel activities:

1. Development of sinusoidal temperature equations for typical and worst case days based upon a review of 30 year weather data for Dallas County.

2. Definition of the physical characteristics and thermal parameters for a typical new residence in Dallas County.
3. Development of system performance equations for a typical heat pump system without storage, as a basis for comparison (HP-BASE), and performance equations for the two storage concepts HP-LTS and HP-RBS.

Items 1 and 2 above were combined to obtain transient heat-load equations which included system losses. These equations were later combined with the system performance equations [item 3 above] in the computer simulation analyses. These simulations eventually led to an understanding of the dynamic performance of three systems operating under four different weather conditions. Each computer run for the storage systems included the constraint of no compressor operation from noon until 8 p.m. during the summer months, thus providing the reduction in peak demand level.

Integral energy requirements calculated during the simulation were converted into annual operating costs for each system. Incremental installation costs and incremental performance benefits, relative to the Base system, were analyzed to derive an approximate payback period for the two storage concepts. A summary of pertinent performance and cost data is shown in Table E-1.

The results of these studies indicate that an HP-TES system will consume approximately 8-9 percent less electrical energy than a conventional heat pump installation, assuming identical load conditions. At a cost of 4.5¢ per kWh the annual savings is $30 for the rock-bed storage system and $39 for the liquid tank storage system.

The installation costs for all three systems shown in Table E-1 are based upon the assumption of 100 or more systems being installed in a newly developed residential area.

Even with the multiple installation assumption the initial cost of the two storage systems is sufficiently high to force the economic payback period into the range of 65 to 94 years. Such long payback periods are obviously not competitive with other conservation procedures available to today's homeowner.

As a result of these facts, the central conclusion of this study is that heat pump systems with thermal storage will probably not be economically attractive in future years for residential applications. This unfavorable situation for HP-TES systems would only change if there were a drastic change in residential electric rate structures, or if mass-production of thermal storage heat pumps would result in an installed cost which was about 10 percent greater than a conventional residential heat pump system.

Neither of these prospects seem likely; therefore, the investigators feel that future research and development on thermal storage applied to comfort system should be directed toward larger scale commercial and industrial chilled water/hot water systems. It is anticipated that the economies of scale for such systems might reduce the unfavorable impact of installation costs on overall project cost. This might result in payback periods which may be competitive with other energy conservation measures which are available for commercial and industrial buildings.

Based upon the results of this study the investigators recommend that DOE should not proceed with its planned demonstration of residential thermal storage systems, as described in Appendix C. Such a program would only prove once again that the payback period for small scale HP-TES systems is unacceptable. It is suggested that DOE's funding for residential thermal storage demonstrations be redirected toward large-scale thermal storage projects, the investigation of ground water source heat pump demonstrations, and further development of indirect evaporative cooling processes.

The co-investigators of this project wish to acknowledge the active involvement, encouragement, and support provided by the technical staff and management of Dallas Power & Light Company.

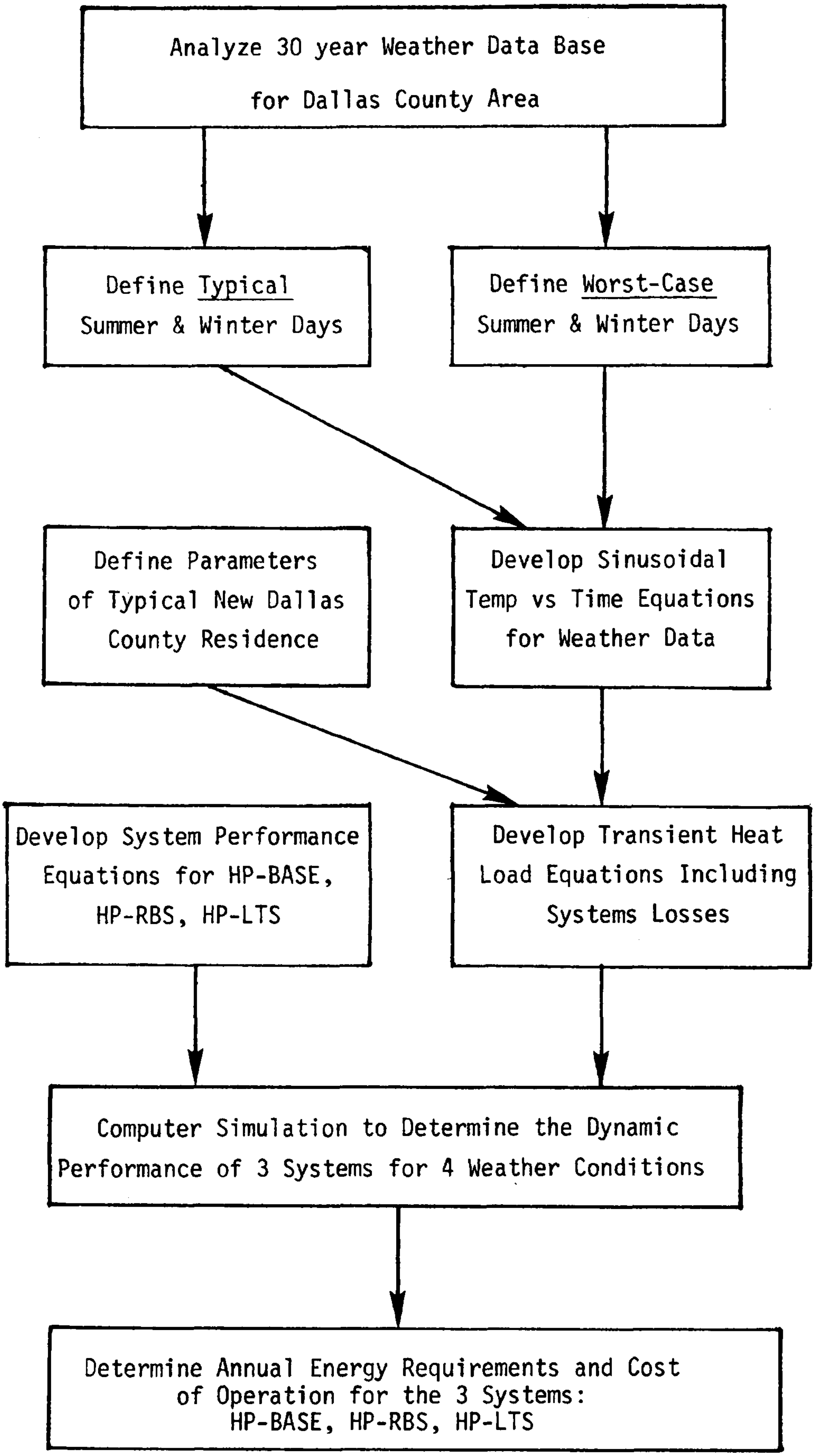

Figure E-1 Methodology of HP-TES Study.

TABLE E-1

SUMMARY OF PERFORMANCE AND COST DATA
FOR HP-TES SYSTEMS

	BASE SYSTEM	HP-RBS	HP-LTS
Heat Pump Make & Model	Carrier 38HQ134	Carrier 50PQ006	Carrier 50PQ006
Storage Medium	NA	Rock-Bed	Water
Storage Volume	NA	1000 ft^3	2500 gallons
Installation Cost Estimate	$3300	$6125	$5850
Typical Summer Day-kWh	37.07	34.20	33.75
Typical Winter Day-kWh	34.57	35.56	33.73
Summer noon to 8 p.m. Peak kW	4.22	7.57	7.57
Annual Cost of Operation, $	506	476	467
Payback Period Relative to Base system, years		94	65

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Appendix

1. INTRODUCTION

A. The Demand Peak Problem in Texas Cities

During 1978 residential use of electric power in Texas accounted for approximately one-third of all electrical energy generated within the state. Although the residential percentage of total consumption has increased only slightly over the past ten years, the consumption per customer has approximately doubled during that same time period. For example, in 1964 the average Texas residential customer used about 5100 kWh per year. By 1974, the average had risen to about 10,000 kWh per year. This increase is primarily a result of more extensive use of electrical appliances and air conditioning in the home. Census data from 1970 indicate that about half of the new homes built that year used a central air conditioning system, and this percentage has increased significantly in the past 8 years.

The continued growth of electrical demand has provided persistent pressure on Texas utilities to increase their generating capacity. In recent years the cost of increased capacity has risen dramatically to values approaching $1,000 per installed kilowatt. Much of this new capacity in the state has been installed to meet peak power requirements which occur during the summer months. The imbalance between summer and winter power loads has resulted in relatively poor utilization of the total system capital investment, and this in turn has contributed to today's higher rates for all utility customers. This seasonal imbalance of kilowatt demand is clearly evident from system load data shown in Figure 1-1, based on 1977-1978 data from Dallas Power & Light Company. Similar trends have been observed in other major Texas cities.

Peak demand in Texas cities can be correlated directly to the widespread use of electric air conditioning systems by all classes of customers served by these utilities. In fact, for many cities across the southwest region of the United States the use of residential air conditioning contributes the largest single component of load to the summer demand peak. Utility company engineers in Dallas, Houston, and Austin have recently estimated that between 30 and 40 percent of the summer peak demand is due to the use of air conditioning. Since air conditioning represents the largest single comsumer of electrical energy in the residential sector, it should be a prime target for load management and energy conservation.

One promising concept for "shaving the peak" off the summer demand curve is to operate a residential heat pump in the cooling mode during off-peak hours and store the excess cooling in a thermal storage unit for use during the peak hours. This concept, defined here as Heat Pump with Thermal Energy Storage, or HP-TES, has three potential advantages over conventional comfort systems.

1. Reduced peak demand on the local utility.
2. Improved air conditioning efficiency due to longer condenser operation using cooler night air. (Higher effective EER and coefficient of performance.)

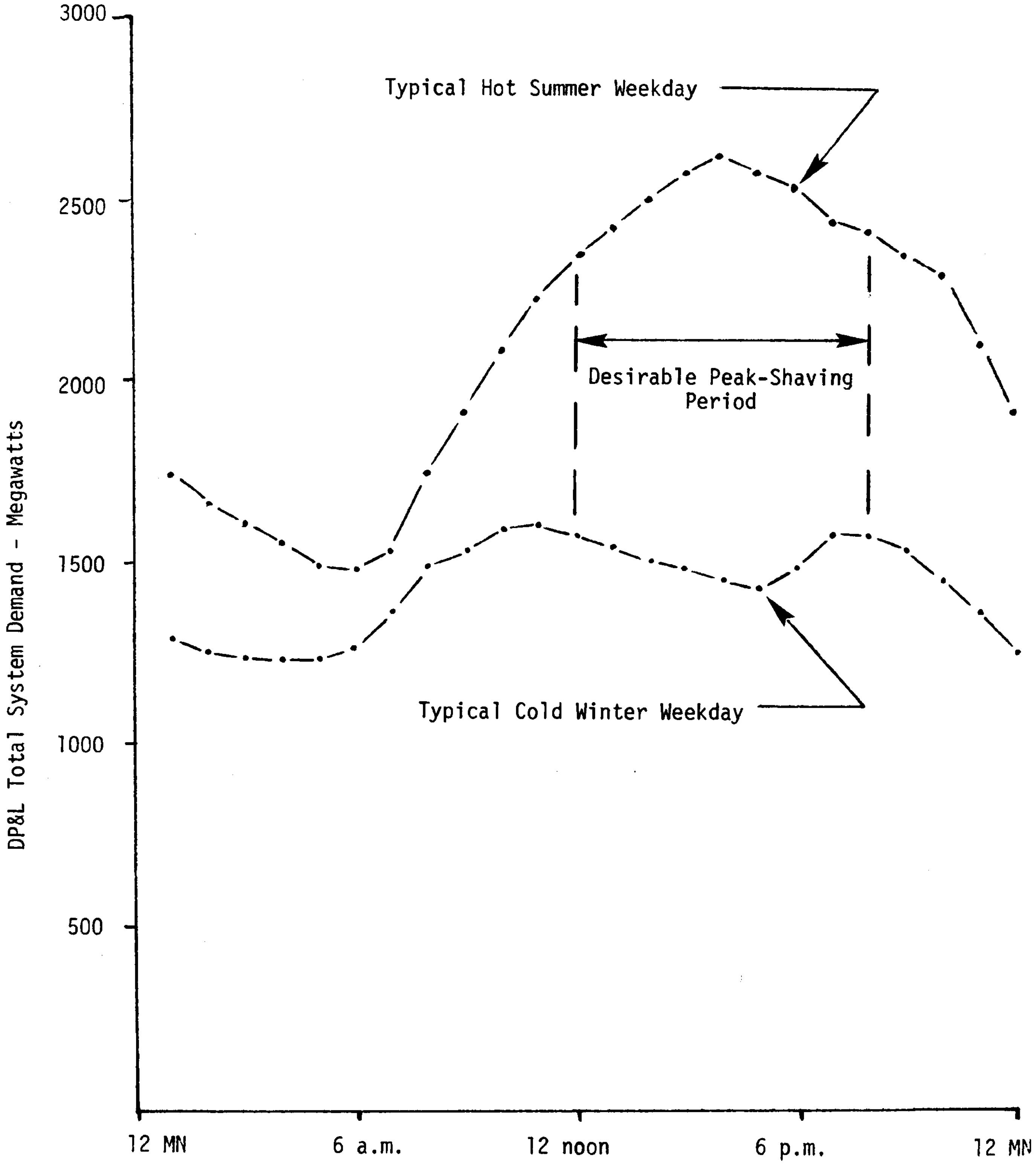

Figure 1-1 Typical Daily Demand (Dallas Power & Light Company 1977-1978 data)

3. Improved heating efficiency due to longer evaporator operation using warmer daytime air during the winter. (Higher effective coefficient of performance.)

Since all simulations of the HP-TES concept during this study were to be based upon a typical Dallas County house, the investigators carefully reviewed system load data for Dallas Power & Light Company. The purpose of this review was to examine the peak demand problem in Dallas and to determine the optimum time for peak-shaving with an HP-TES system.

First, the growth in annual peak demand was reviewed for the previous five-year period. Each of the following system peaks occurred on a day in the July to September time period.

YEAR	DP&L SYSTEM PEAK DEMAND	COOLING DEGREE-DAYS 70°F BASE
1974	2408 Megawatts	1447
1975	2354 Megawatts	1601
1976	2378 Megawatts	1339
1977	2495 Megawatts	2200
1978	2609 Megawatts	2081

It can be seen that system demand has grown by 11 percent in the past four years, and that most of the increase can be attributed to unusually hot summers in 1977 and 1978.

Next, daily power profiles were reviewed for the DP&L system, both summer and winter. The most significant data furnished by DP&L

were the "hot summer weekday" and "cold winter weekday" curves for power demand, as shown in Figure 1-1.

The hot summer day peak demand of 2609 megawatts occurred at 4 p.m., with the top 10 percent of the peak demand occurring between 12 noon and 8 p.m.. The top 10 percent of demand on the "typical summer weekday" also occurred between 12 noon nad 8:00 in the evening. Based on this information the most desirable period for peak-shaving was chosen as the eight-hour interval from 12:00 noon to 8 p.m.

The winter load profiles for DP&L demand level indicated a double peak each day as shown in Figure 1-1. The "cold winter weekday" peaks occurred at 10 a.m. and 7 p.m. and were about the same magnitude, both about 1600 megawatts. The weekend winter demand peaks were shifted an hour or two later than the weekday peaks.

It was concluded that peak-shaving in the wintertime will be of little or no value to DP&L because the summer peak is 63 percent greater than the winter peak load. Thus, it appeared that the potential value of the HP-TES concept to residential customers in the wintertime would be the opportunity to store heat during the daytime and save energy because of the higher effective source temperature for the heat pump. This mode of operation would tend to increase the winter peak demand on the utility; however, this increased peak demand level, even for widespread daytime use of heat pumps, would probably remain well below the annual summer peak demand.

B. Analysis of Weather Data For Dallas County

The accuracy of HP-TES systems analyses depends upon having truly representative weather data as a forcing function for the system simulations. The investigators began their development of representative weather data by reviewing 30 year average weather statistics for Dallas County. Information from the National Weather Service was reviewed on a month-by-month basis in terms of heating degree-days (65°F base) and cooling degree-days (70°F base).

The 30 year average data indicated that a typical heating season consisted of five months, November through March, and contained 2146 heating degree-days. Since this period is 151 days long, the average temperature was 14.2 degrees below the base of 65°F, or a temperature of 50.8°F.

The 30 year average cooling season was also five months long, May through September, and contained 1739 cooling degree-days in 153 days. Thus, the average temperature was 11.4 degrees above the 70°F base, or an average temperature of 81.4°F. The 30 year degree-day data also revealed the fact that February was the most typical heating month of the year and that June was the most typical cooling month of the year. Since the year 1969 was most representative of annual weather conditions in the past 30 years for Dallas County, the typical and worst-case temperature equations were developed by careful study of the time variations of ambient temperature during June, July, January, and February of 1969. Based upon these studies the following parameters were selected as typical and worst-case variations of ambient

Day	T_{max}	T_{min}	Amplitude	Hour of T_{max}	Hour of T_{min}
Typical Summer Day (TSD)	91.3°F	71.5°F	19.8°F	3-6 p.m.	6 a.m.
Worst Summer Day (WSD)	102.0°F	85.0°F	17.0°F	3-6 p.m.	6 a.m.
Typical Winter Day (TWD)	60.2°F	41.4°F	18.8°F	4 p.m.	6 a.m.
Worst Winter Day (WWD)	23.0°F	8.0°F	15.0°F	4 p.m.	6 a.m.

By shifting the morning low temperature to 5 a.m. and selecting 5 p.m. as a typical time for T_{max}, the variations of ambient temperature with time can be fitted to a time-dependent equation of the form:

$$T_A = \bar{T} + A \sin (\omega t + \phi)$$

where:

$\bar{T}$ is the average daily temperature

A is the half-amplitude of temperature variation

$\omega = \frac{2\pi}{24 \text{ hrs}} = 0.2618$ radians/hr

t = time since midnight, hours

ϕ = shift of T_{max} relative to 6 a.m. (11 hours) = $-\frac{11}{12}\pi$ Radians

Therefore, the assumed variations of ambient temperature for this study, based upon 30 year average weather data, are as follows:

TSD $T_A = 81.4 + 9.9 (\sin \omega t-\phi)°F$ (1-1)

WSD $T_A = 93.5 + 8.5 (\sin \omega t-\phi)°F$ (1-2)

TWD $T_A = 50.8 + 9.4 (\sin \omega t-\phi)°F$ (1-3)

WWD $T_A = 15.5 + 7.5 (\sin \omega t-\phi)°F$ (1-4)

C. Typical Residential Heating and Cooling Requirements

During the first two months of this study information was gathered from utility companies and building contractors in an effort to define the "typical new home" in Dallas County. Data were considered for new residential structures built during the last five year period. Considerable assistance in this area was received from the staff engineers at Dallas Power & Light Company. (Reference 10). The key parameters which emerged from this study of typical new homes are shown below:

TYPICAL NEW RESIDENCE IN DALLAS COUNTY, 1973-1978

Floorspace area:	1650 ft^2
Type of construction:	brick veneer and slab foundation
Insulation in ceiling and walls:	R-19 and R-11
Installed cooling capacity:	2.5 to 3 tons
Installed heating capacity:	70,000 to 100,000 Btu/hr
Number of bedrooms and baths:	3 bedrooms, 2 baths
Number of occupants:	2 to 4

Steady state analysis with a computer model for the typical residence shown above led to the following worst-case design load values.

Maximum winter load = Q_W = 56,735 Btu/hr

Ambient temperature = T_A = 8°F

Thermostat setting = T_{stat} = 73°F

Maximum summer load = Q_S = 28,826 Btu/hr

Ambient temperature = T_A = 102°F

Thermostat setting = T_{stat} = 77°F

Next, these load values were adjusted to match the more common thermostat settings of 75°F in the summer and 68°F in the winter. In addition, other loads which must be considered are the internal load of the house (people, appliances, and lights), about 2800 Btu/hr, and the latent load (summer only) due to moisture of about 3000 Btu/hr. Also, a 10 percent add-on load will be assumed for duct and piping losses.

Taking these factors into account leads to the following general load equations for the typical home during the heating and cooling seasons.

$$\text{WINTER} \quad Q_W = 1.1[52{,}371 \frac{(68 - T_A)}{\Delta T_{max}} - 2800] \text{ Btu/hr} \qquad (1\text{-}5)$$

$$\text{where } \Delta T_{max} = 68°F(\text{Stat.}) - 8°F(T_A) = 60°F$$

$$\text{SUMMER} \quad Q_S = 1.1[24{,}868 \frac{(T_A - 75)}{\Delta T_{max}} + 5800] \text{ Btu/hr} \qquad (1\text{-}6)$$

$$\text{where } \Delta T_{max} = 102°F(T_A) - 75°F(\text{Stat.}) = 27°F$$

Since the ambient temperatures are known functions of time, as developed in equations (1-1), (1-2), (1-3), and (1-4), these functions may be substituted into equations (1-5) and (1-6) to yield the following load equations:

Typical Summer Day (TSD)

$$Q_{TSD} = 1013\ [6.4 + 9.9(\sin \omega t-\phi)] + 6380 \text{ Btu/hr} \qquad (1\text{-}7)$$

Worst Summer Day (WSD)

$$Q_{WSD} = 1013[18.5 + 8.5(\sin \omega t-\phi)] + 6380 \text{ Btu/hr} \qquad (1\text{-}8)$$

Typical Winter Day (TWD)

$$Q_{TWD} = 960[17.2 - 9.4(\sin \omega t-\phi)] - 3080 \text{ Btu/hr} \qquad (1\text{-}9)$$

Worst Winter Day

$$Q_{WWD} = 960[52.5 - 7.5(\sin \omega t-\phi)] - 3080 \text{ Btu/hr} \qquad (1\text{-}10)$$

Where: $T_{A_{max}}$ occurs at 5 p.m. ($t = 17$)

$T_{A_{min}}$ occurs at 5 a.m. ($t = 5$)

$\omega = \frac{\pi}{12}$ radians/hour $\qquad \phi = \frac{11}{12}\pi$

These equations represent the dynamic thermal loads that were applied to the various heat pump systems described in the following sections.

D. Energy Storage Options for Residential Applications

For this study only two options for thermal energy storage were examined; (a) a rock-bed storage coupled with an air-to-air heat pump and (b) a liquid tank storage coupled with the same heat pump modified for liquid heating or cooling on the indoor freon circuit. Details of these two systems will be described in Sections 3 and 4 of the report. Numerous other options for residential energy storage have been examined for comparative economic feasibility in a previous study [4].

E. Practical Considerations for Control Systems

The control system for a residential application must be extremely simple;

a. to minimize initial cost to the consumer

b. to provide for ease of operation by the typical homeowner with no knowledge of the operating principles of heat pump systems and,

c. to minimize maintenance expense in these applications where preventive maintenance is infrequently performed.

Based upon discussions with firms experienced in residential installations, it appears that the simple control system should provide the following adjustments or set-points for the homeowner.

1. Switching between heating and cooling mode.
2. Adjustment of inside temperature to conform with individual comfort requirements (with multizones where applicable).
3. Automatic activation of supplemental electric resistance heating when heat pump cannot meet the total heating requirements.
4. Manual switching of system into a mode which utilizes the heat storage.
5. Manual adjustment of timing switches which open or close dampers or valves for heat storage operation. Thus, the homeowner may select a particular time of day for the storage system to operate. In the summer he might call for storage between 10 p.m. and 8 a.m. and then extraction of energy from storage at the heaviest cooling load periods in the afternoon

and early evening. The opposite procedure might be employed for winter operation.

6. An automatic mode to store and extract energy in accordance with sensing of the outdoor temperature. This automatic mode should provide for variable settings of the outdoor temperature which will activate the storage mode of operation.
7. All of the above switching operations should be simple on-off operations which either open or close the appropriate dampers or valves. Expensive proportional controls (either electric or pneumatic) cannot be justified in a typical residential application.
8. An economizer fresh air operating mode should be provided for the rock-bed storage system.

2. ANALYSIS OF THE BASELINE SYSTEM

TYPICAL RESIDENTIAL HEAT PUMP PERFORMANCE (HP-BASE)

To provide a common basis of comparison of the liquid or rock-bed storage systems, a baseline heat pump system was selected for operation without thermal energy storage. A combination of air conditioner and natural gas fired furnace could have been selected but it was felt that the current trend is toward total electric systems in new home construction. In addition, the rise in natural gas prices has made the heat pump roughly competitive in economic performance.

A commercial heat pump unit which satisfies the cooling and heating requirements discussed in Section 1C is the Carrier Model 38HQ134 and is presently installed in many homes in the Dallas area. Performance specifications for this unit are as follows:

Fan flow rate 1256 ft^3/min

Energy efficiency ratio 7.8

Total cooling 33,500 Btu/hr

ARI standard: 80°F DB, 67°F WB
indoor entering air temperature and
95°F DB outside air entering unit.

High-temperature heating 37,500 Btu/hr

ARI standard: 70°F DB $COP_H = 2.8$

Indoor air temperature, 47°F DB, 43°F WB outdoor temperature

Low temperature heating 21,000 Btu/hr

ARI standard: 70°F DB $COP_H = 2.1$

Indoor air temperature, 17°F DB
15°F WB outdoor temperature

The cooling performance under varying temperature conditions is given in Table 2-1. Heating performance under varying outside air temperatures is given in Table 2-2 for constant indoor conditions of 70°F DB, 85 percent relative humidity. Linear approximations were applied to the data of Tables 2-1 and 2-2 to obtain analytical expressions for the various performance parameters. The resulting expressions are summarized below:

Cooling Mode

$$Q_{EW} = 37{,}800 + (85-T_A)(173.3) - 535(72-T_{EW}) \text{ Btu/hr}$$

$$W = 4.28 + 0.024(T_A-85) - 0.03(72-T_{EW}) \text{ kW}$$

Heating Mode

$$Q_{HA} = 17{,}000 + 540(T_A-10) \text{ Btu/hr}$$

$$W = 2.75 + 0.033(T_A-10) \text{ kW}$$

These equations are used along with the load equations of Section 1C and selected typical and worst case days to compute overall system performance during the year. The load and ambient temperature equations are given as follows with the argument of the sine function in degrees.

Cooling Mode

Typical Summer Day (TSD) $T_A = 81.4 + 9.9 \sin(15t-165)°\text{F}$ t in hours

Worst Summer Day (WSD) $T_A = 93.5 + 8.5 \sin(15t-165)°\text{F}$ t in hours

$$\text{Load} = Q_L = 921.04T_A - 63278 \text{ Btu/hr} \quad \text{for } T_{EW} = 65°\text{F}$$

$$Q_{EW} = 48786 - 173.3\, T_A \text{ Btu.hr} \quad \text{for } T_{EW} = 65°\text{F}$$

$$W = 2.03 + 0.024\, T_A \text{ kW} \quad \text{for } T_{EW} = 65°\text{F}$$

Heading Mode

Typical Winter Day (TWD) $T_A = 50.8 + 9.4 \sin(15t-165)°F$ t in hours

Load $= Q_L = 56554 - 872.85\ T_A$ Btu/hr

A duty factor, F, was defined for the heat pump as follows:

$$F = \frac{Q_L}{Q_{EW}} \text{ (Cooling)} = \frac{Q_L}{Q_{HA}} \text{ (Heating)}$$

The above equations were used to compute the heat pump performance over 24 hour time periods for the TSD, WSD, and TWD conditions. The results are shown in Tables 2-3, 2-4, and 2-5, and Figures 2-1 2nd 2-2.

Integrated energy consumptions over the twenty four hour period are also given with appropriate quantities defined as:

$\Sigma FW\Delta t$ = total work input, kWh/day

$\Sigma Q_{EW}\Delta t$ = total unit cooling capacity, Btu/day

$\Sigma Q_L\Delta t$ = total load, Btu/day

$\Sigma(Q_{EW}-Q_L)\Delta t$ = total excess cooling capacity, Btu/day

$\Sigma Q_{HA}\Delta t$ = total unit heating capacity, Btu/day

$\Sigma Q_E(1-F)\Delta t$ = total outdoor excess capacity in heating mode, Btu/day

These integrated energies are then used to compute the seasonal and annual operating cost of the unit with the following assumptions:

1. Power cost at $0.045/kWh
2. Duct and other losses at 10 percent of total, i.e., total energy consumption is increased by 10 percent due to losses.
3. An adjustment for electric resistance supplemental heating is made by increasing winter electric consumption by 6.8 percent.

This figure was obtained by averaging the annual resistance heating costs of several Carrier units based on annual hourly operation rates supplied by Carrier Corporation.

4. 153 days are used for the cooling season, and 151 days are used for the heating season, in accordance with the climate and weather analysis presented in Section 1B.

Based on these assumptions, the operating costs are:

Typical Summer Day (TSD)

(33.696 kWh/day)(1.1)(153 days) = 5671 kWh/season

Cost at $0.045 kWh = $255.20/season (1.67/day)

Worst Summer Day (WSD)

(72.776 kWh/day)(1.1) = 80.054 kWh/day

Cost at $0.045/kWh = $3.60/day

Typical Winter Day (TWD)

(31.428 kWh/day)(1.1)(151 days) = 5220 kWh/season

Cost at $0.045/kWh = $234.90/season ($1.56/day)

Adjustment for resistance heating is 6.8 percent.

Total cost = (1.068)(234.90) = $250.87/season = $1.66/day

Annual cost, including 10 percent losses is

$255.20 + 250.87 = $506.07/year

These cost figures will be used to compare with the operating costs for the two thermal storage systems. More detailed computer results are given in Tables 2-6 to 2-9 and Figures 2-3 to 2-6.

Table 2-1

Cooling Performance of Carrier Model 38HQ134 Heat Pump

Outdoor Air Temperature, T_A, °F	Cooling, Q_{EW}, k Btu/hr Work, W, kW, COP	Indoor Wet Bulb Temperature, T_{EW}, °F		
		72	67	62
85	Q_{EW}	37.8	35.2	32.2
	W	4.27	4.15	4.00
	COP	2.59	2.49	2.36
95	Q_{EW}	35.7	33.5	30.8
	W	4.48	4.30	4.23
	COP	2.33	2.28	2.13
100	Q_{EW}	34.9	32.5	30.0
	W	4.61	4.48	4.34
	COP	2.22	2.13	2.03
105	Q_{EW}	34.2	31.5	29.1
	W	4.74	4.59	4.45
	COP	2.11	2.01	1.92
115	Q_{EW}	32.6	29.6	27.5
	W	4.99	4.81	4.67
	COP	1.91	1.80	1.73

Table 2-2

Heating Performance of Carrier Model 38HQ134 Heat Pump

Outdoor Air Temperature, °F	Heating Rate, k Btu/hr Q_{HA}	Work Input W, kW	COP_H
-10	10.0	2.3	1.27
0	14.0	2.6	1.58
10	18.0	2.9	1.82
17	21.0	3.0	2.05
20	22.0	3.0	2.15
30	26.5	3.2	2.43
40	34.0	3.8	2.62
47	37.5	3.9	2.82
50	39.5	4.1	2.82
60	45.0	4.4	3.0
70	52.0	4.7	3.24

Table 2-3

Performance of Carrier 38 HQ 134

Typical Summer Day (TSD)

Indoor at 75°F D.B., 65° W.B.

Time, t Hours	T_A, °F	Q_L Btu/hr	Q_{EW} Btu/hr	Duty Cycle F	W,kW	FW, kW	$(1-F)Q_{EW}$ Btu/hr $= Q_{EW} - Q_L$	$\frac{FW\Delta t}{\Sigma FW\Delta t}$
0	78.84	9337	35123	0.266	3.92	1.043	25690	0.0619
2	74.4	5247	35892	0.146	3.82	0.558	30652	0.0331
4	71.84	2890	36336	0.0795	3.75	0.298	33447	0.0177
6	71.84	2890	36336	0.0790	3.75	0.298	33447	0.0177
8	74.4	5247	35892	0.146	3.82	0.558	30652	0.0331
10	78.84	9337	35123	0.266	3.92	1.043	25690	0.0619
12	83.94	14052	34236	0.410	4.05	1.66	20199	0.0985
14	88.4	18142	33466	0.542	4.15	2.249	15327	0.1335
16	90.963	20503	33022	0.621	4.213	2.616	12515	0.1553
18	90.963	20503	33022	0.621	4.213	2.616	12515	0.1553
20	88.4	18142	33466	0.542	4.15	2.249	15327	0.1335
22	83.96	14052	34236	0.410	4.05	1.66	20199	0.0985

$\Sigma Q_{EW}\,\Delta t$ = 832300 Btu

$\Sigma Q_L\,\Delta t$ = 248328 Btu

$\Sigma(Q_{EW}-Q_L)\,\Delta t$ = 583972 Btu

$\Sigma WF\Delta t$ = 33.70 kWh

Table 2-4

Performance of Carrier 38 HQ 134

Worst Summer Day (WSD) Indoor at 75°F D.B., 65°F W.B.

Time, t Hours	T_A, °F	Q_L Btu/hr	Q_{EW} Btu/hr	Duty Cycle F	W, kW	FW, kW	$(1-F)Q_{EW}$ Btu/hr $= Q_{EW} - Q_L$	$\frac{FW\Delta t}{\Sigma FW\Delta t}$
0	91.3	20813	32964	0.631	4.22	2.664	12164	0.0736
2	87.49	17303	33624	0.515	4.13	2.127	16308	0.0588
4	85.29	15277	34005	0.449	4.077	1.831	18737	0.0506
6	85.29	15277	34005	0.449	4.077	1.831	18737	0.0506
8	87.49	17303	33624	0.515	4.13	2.127	16308	0.0588
10	91.3	20813	32964	0.631	4.221	2.664	12164	0.0736
12	95.7	24866	32201	0.772	4.327	3.34	7335	0.0864
14	99.51	28375	31541	0.90	4.418	3.976	3154	0.1099
16	101.71	30401	31160	0.976	4.471	4.364	748	0.1206
18	101.71	30401	31160	0.976	4.471	4.364	748	0.1206
20	99.51	28375	31541	0.90	4.418	3.976	3154	0.1099
22	95.7	24866	32201	0.722	4.327	3.34	7335	0.0864

$\Sigma Q_{EW}\Delta t$ = 701980 Btu

$\Sigma(Q_{EW} - Q_L)\,\Delta t$ = 157108 Btu

$\Sigma Q_L\Delta t$ = 544962 Btu

$\Sigma WF\Delta t$ = 72.80 kWh

Table 2-5

Performance of Carrier 38 HQ 134

Typical Winter Day (TWD) Inside Temperature = 68°F

Time, t Hours	T_A, °F	Q_L Btu/hr	Q_{EW} Btu/hr	Duty Cycle F	W, kW	FW, kW	$(1-F)Q_{HA} = Q_{HA}-Q_L$ Btu/hr	$\frac{FW\Delta t}{\Sigma FW\Delta t}$
0	48.37	14334	37719	0.38	4.016	1.526	23386	0.0971
2	44.15	18018	35441	0.5084	3.877	1.971	17423	0.1254
4	41.72	20139	34129	0.59	3.797	2.24	13993	0.1425
6	41.72	20139	34129	0.59	3.797	2.24	13993	0.1425
8	44.15	18018	35441	0.5084	3.877	1.971	17423	0.1254
10	48.37	14334	37719	0.38	4.016	1.526	23386	0.0971
12	53.23	10092	40344	0.25	4.177	1.044	30258	0.0664
14	57.45	6409	42623	0.15	4.316	0.647	36230	0.0412
16	59.88	4287	43935	0.0976	4.396	0.429	39647	0.0273
18	59.88	4287	43935	0.0976	4.396	0.429	39647	0.0273
20	57.45	6409	42623	0.15	4.316	0.647	36230	0.0412
22	53.23	10092	40344	0.25	4.177	1.044	30258	0.0664

$\Sigma Q_{HA}\Delta t$ = 857564 Btu

$\Sigma(Q_{HA}-Q_L)\ \Delta t$ = 564548 Btu

$\Sigma Q_L\Delta t$ = 293016 Btu

$\Sigma Q_E F\ \Delta t$ = 346327 Btu

$\Sigma WF\Delta t$ = 31.428 kWh

$\Sigma Q_E\ (1-F)\ \Delta t$ = 690542 Btu

Carrier 38HQ 134 Heat Pump Work Inputs No Heat Storage

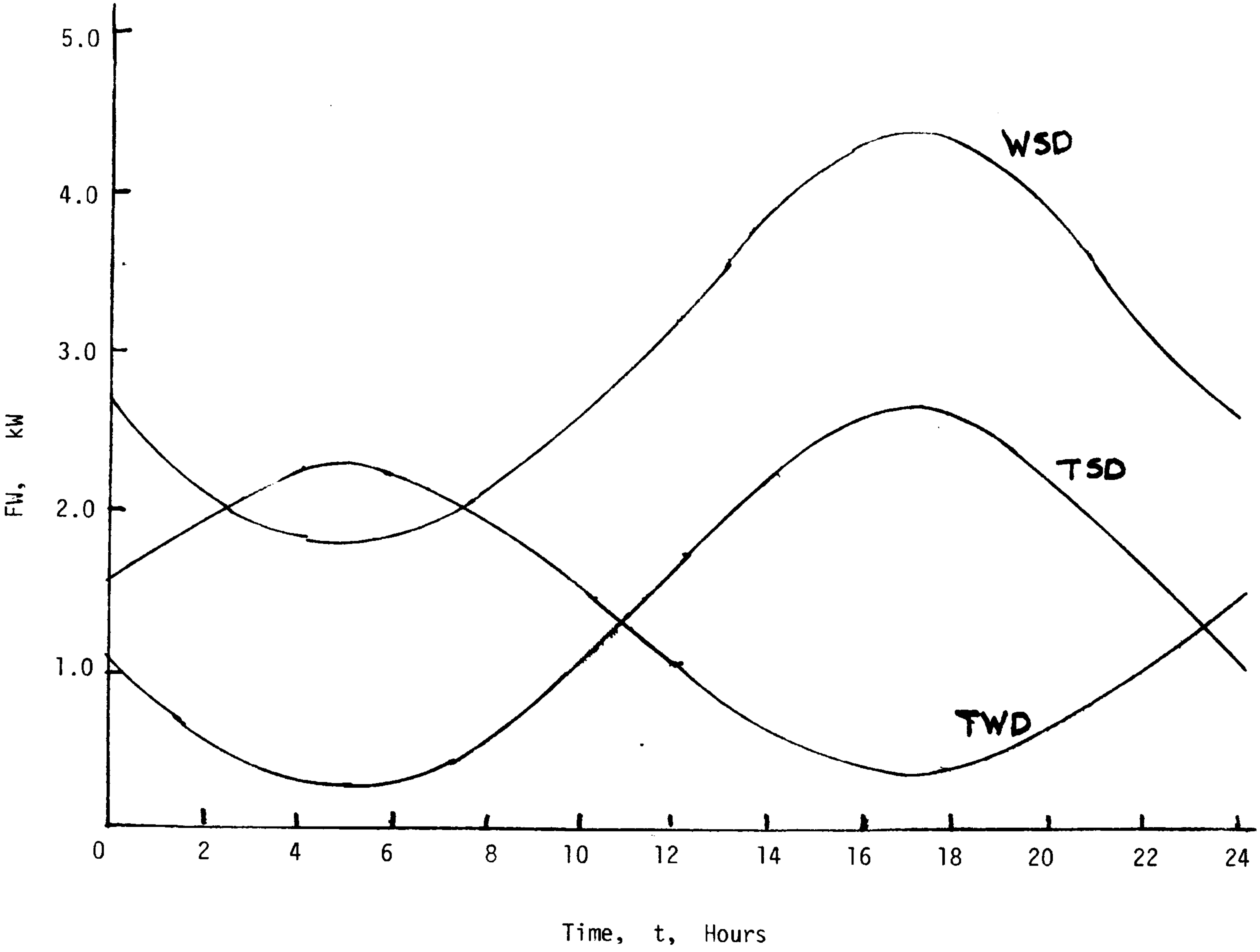

Figure 2-1

Carrier 38HQ 134 Heat Pump Heat Loads No Heat Storage

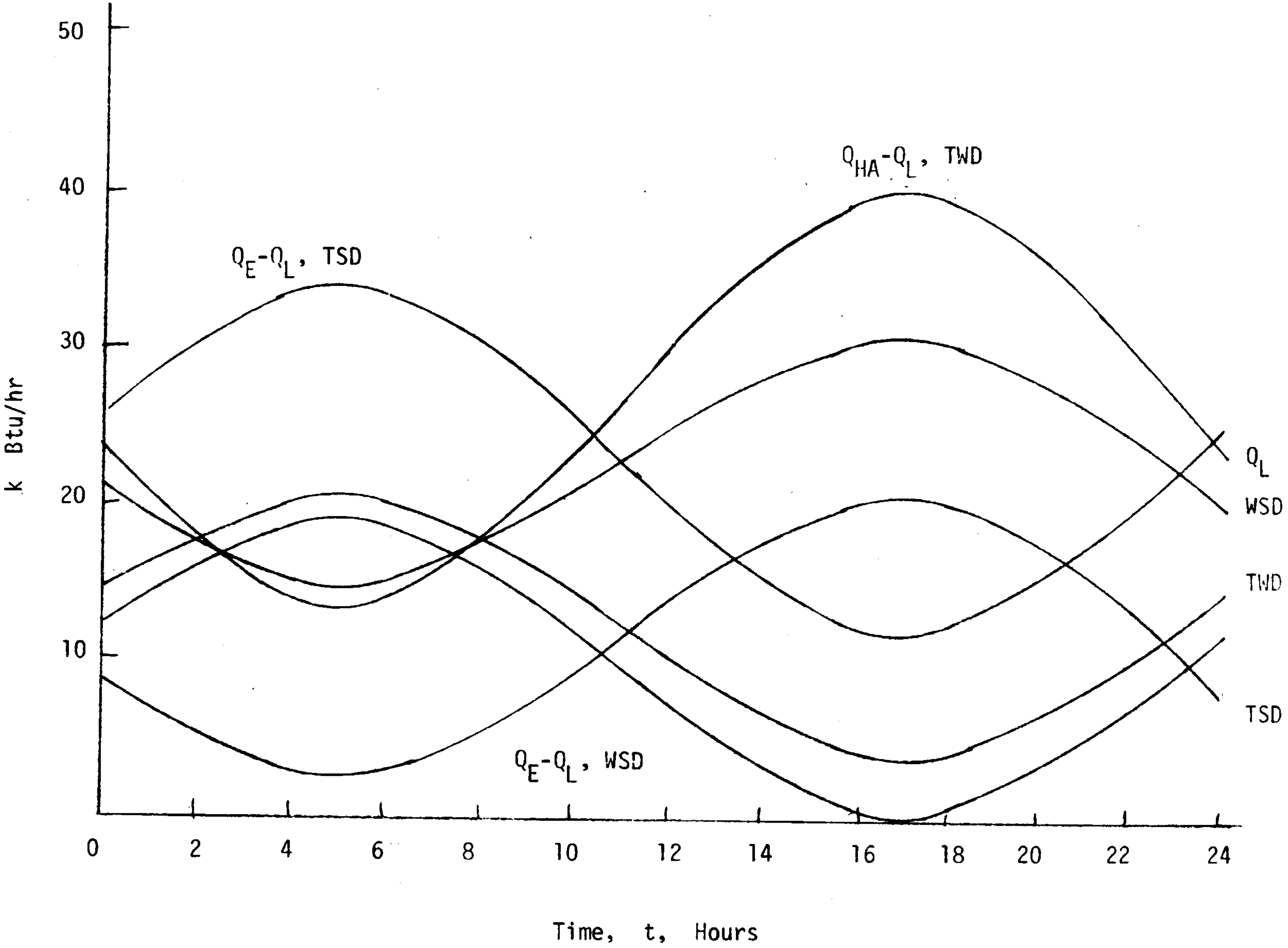

Figure 2-2

Table 2-6 HP-BASE Typical Summer Day

TIME HOUR	AV. TEMP DEG F	AV. LOAD TONS	SUM CAP BTU'S	SUM LOAD BTU'S	D'WORK KW-HRS	SUM WORK KW-HRS
0.5	78.2	0.798	17621	4790	0.531	0.531
1.0	77.0	0.698	35344	8976	0.458	0.989
1.5	75.9	0.603	53165	12597	0.391	1.380
2.0	74.8	0.517	71074	15700	0.332	1.712
2.5	73.9	0.440	89062	18343	0.279	1.991
3.0	73.1	0.375	107118	20590	0.236	2.227
3.5	72.5	0.320	125229	22513	0.200	2.427
4.0	72.0	0.279	143382	24189	0.174	2.600
4.5	71.7	0.252	161563	25699	0.156	2.756
5.0	71.5	0.238	179759	27128	0.147	2.903
5.5	71.5	0.239	197953	28562	0.148	3.051
6.0	71.7	0.254	216133	30085	0.157	3.208
6.5	72.1	0.283	234282	31782	0.176	3.384
7.0	72.6	0.325	252388	33734	0.203	3.587
7.5	73.2	0.381	270438	36018	0.240	3.827
8.0	74.0	0.448	288418	38704	0.284	4.111
8.5	74.9	0.525	306319	41856	0.337	4.448
9.0	76.0	0.613	324130	45531	0.398	4.846
9.5	77.1	0.707	341844	49776	0.465	5.311
10.0	78.3	0.809	359454	54629	0.539	5.849
10.5	79.5	0.914	376955	60115	0.617	6.467
11.0	80.8	1.023	394345	66252	0.701	7.167
11.5	82.1	1.132	411623	73045	0.786	7.954
12.0	83.4	1.240	428790	80487	0.874	8.828
12.5	84.6	1.346	445849	88561	0.961	9.789
13.0	85.8	1.446	462805	97239	1.047	10.836
13.5	86.9	1.541	479663	106482	1.129	11.964
14.0	88.0	1.627	496434	116243	1.205	13.170
14.5	88.9	1.704	513125	126465	1.275	14.444
15.0	89.7	1.770	529749	137082	1.335	15.780
15.5	90.3	1.824	546317	148023	1.386	17.166
16.0	90.8	1.865	562844	159211	1.425	18.590
16.5	91.1	1.892	579342	170565	1.451	20.041
17.0	91.3	1.906	595825	181999	1.464	21.505
17.5	91.3	1.905	612310	193430	1.463	22.968
18.0	91.1	1.890	628810	204771	1.449	24.417
18.5	90.7	1.861	645340	215938	1.421	25.839
19.0	90.2	1.819	661913	226850	1.381	27.220
19.5	89.6	1.763	678543	237431	1.330	28.550
20.0	88.8	1.696	695242	247609	1.268	29.818
20.5	87.9	1.619	712021	257320	1.198	31.016
21.0	86.8	1.531	728889	266509	1.121	32.137
21.5	85.7	1.437	745855	275129	1.038	33.175
22.0	84.5	1.335	762924	283140	0.953	34.128
22.5	83.3	1.230	780102	290518	0.865	34.993
23.0	82.0	1.121	797391	297245	0.778	35.771
23.5	80.7	1.012	814793	303317	0.692	36.463
24.0	79.4	0.904	832205	308739	0.609	37.072

Table 2-7 HP-BASE Worst Case Summer Day

TIME HOUR	AV. TEMP DEG F	AV. LOAD TONS	SUM CAP BTU'S	SUM LOAD BTU'S	D'WORK KW-HRS	SUM WORK KW-HRS
0.5	90.7	1.859	16532	11152	1.419	1.419
1.0	89.7	1.772	33153	21785	1.338	2.757
1.5	88.7	1.691	49858	31933	1.264	4.021
2.0	87.9	1.617	66638	41636	1.197	5.217
2.5	87.1	1.551	83485	50944	1.138	6.355
3.0	86.4	1.495	100391	59913	1.089	7.444
3.5	85.9	1.448	117345	68603	1.048	8.492
4.0	85.4	1.413	134334	77081	1.018	9.510
4.5	85.2	1.389	151348	85417	0.998	10.508
5.0	85.0	1.378	168374	93683	0.988	11.496
5.5	85.0	1.378	185400	101953	0.989	12.485
6.0	85.2	1.391	202412	110300	1.000	13.485
6.5	85.5	1.416	219398	118796	1.021	14.505
7.0	85.9	1.453	236348	127511	1.052	15.557
7.5	86.5	1.500	253248	136511	1.093	16.650
8.0	87.2	1.558	270090	145856	1.144	17.794
8.5	87.9	1.624	286862	155602	1.203	18.997
9.0	88.8	1.699	303559	165797	1.271	20.268
9.5	89.8	1.781	320171	176480	1.346	21.613
10.0	90.8	1.863	336694	187686	1.427	23.041
10.5	91.9	1.958	353124	199435	1.515	24.555
11.0	93.0	2.051	369459	211744	1.606	26.161
11.5	94.1	2.145	385697	224615	1.700	27.861
12.0	95.2	2.238	401840	238043	1.795	29.656
12.5	96.3	2.329	417890	252015	1.889	31.545
13.0	97.3	2.415	433851	266504	1.982	33.527
13.5	98.3	2.496	449730	281480	2.069	35.596
14.0	99.1	2.570	465532	296900	2.151	37.748
14.5	99.9	2.636	481267	312715	2.211	39.959
15.0	100.6	2.692	496943	328870	2.222	42.181
15.5	101.1	2.739	512572	345303	2.229	44.410
16.0	101.6	2.774	528165	361949	2.234	46.643
16.5	101.8	2.798	543734	378735	2.237	48.880
17.0	102.0	2.809	559290	395592	2.239	51.119
17.5	102.0	2.809	574847	412445	2.239	53.358
18.0	101.8	2.796	590418	429221	2.237	55.595
18.5	101.5	2.771	606013	445848	2.233	57.828
19.0	101.1	2.735	621647	462256	2.228	60.056
19.5	100.5	2.687	637329	478380	2.221	62.277
20.0	99.8	2.630	653070	494158	2.208	64.485
20.5	99.1	2.563	668879	509535	2.144	66.629
21.0	98.2	2.489	684766	524464	2.061	68.690
21.5	97.2	2.407	700736	538903	1.972	70.662
22.0	96.2	2.320	716795	552821	1.880	72.542
22.5	95.1	2.229	732947	566194	1.785	74.328
23.0	94.0	2.136	749195	579009	1.690	76.018
23.5	92.9	2.042	765539	591261	1.597	77.614
24.0	91.8	1.949	781979	602956	1.506	79.120

Table 2-8 HP-BASE Typical Winter Day

TIME HOUR	AV. TEMP DEG F	AV. LOAD TONS	SUM CAP BTU'S	SUM LOAD BTU'S	D'WORK KW-HRS	SUM WORK KW-HRS
0.5	47.7	1.366	18685	8195	0.876	0.876
1.0	46.6	1.456	37064	16933	0.941	1.817
1.5	45.5	1.541	55158	26180	1.002	2.819
2.0	44.6	1.619	72989	35892	1.060	3.879
2.5	43.7	1.688	90587	46019	1.111	4.990
3.0	43.0	1.747	107985	56502	1.156	6.146
3.5	42.3	1.796	125219	67277	1.193	7.340
4.0	41.9	1.833	142328	78273	1.222	8.561
4.5	41.6	1.858	159354	89419	1.241	9.803
5.0	41.4	1.870	176338	100638	1.251	11.053
5.5	41.4	1.869	193324	111853	1.250	12.304
6.0	41.6	1.856	210356	122987	1.240	13.543
6.5	41.9	1.830	227476	133964	1.219	14.763
7.0	42.4	1.791	244725	144713	1.190	15.953
7.5	43.0	1.742	262141	155163	1.152	17.105
8.0	43.8	1.681	279761	165251	1.106	18.211
8.5	44.7	1.611	297618	174919	1.054	19.265
9.0	45.6	1.533	315738	184117	0.996	20.262
9.5	46.7	1.448	334148	192802	0.934	21.196
10.0	47.8	1.356	352864	200941	0.869	22.065
10.5	49.0	1.261	371902	208509	0.803	22.868
11.0	50.2	1.164	391268	215491	0.735	23.603
11.5	51.5	1.065	410967	221884	0.668	24.272
12.0	52.7	0.968	430994	227693	0.603	24.875
12.5	53.9	0.873	451341	232932	0.541	25.415
13.0	55.0	0.783	471993	237629	0.482	25.897
13.5	56.1	0.698	492932	241816	0.427	26.324
14.0	57.0	0.620	514133	245538	0.378	26.702
14.5	57.9	0.551	535567	248845	0.334	27.036
15.0	58.6	0.492	557200	251797	0.297	27.333
15.5	59.3	0.443	578998	254456	0.267	27.600
16.0	59.7	0.406	600921	256894	0.244	27.844
16.5	60.0	0.381	622928	259183	0.229	28.073
17.0	60.2	0.369	644976	261398	0.221	28.294
17.5	60.2	0.370	667021	263618	0.222	28.516
18.0	60.0	0.383	689022	265918	0.230	28.746
18.5	59.7	0.409	710934	268375	0.246	28.992
19.0	59.2	0.448	732717	271060	0.270	29.262
19.5	58.6	0.497	754333	274045	0.300	29.562
20.0	57.8	0.558	775744	277391	0.338	29.900
20.5	56.9	0.628	796920	281157	0.382	30.283
21.0	56.0	0.706	817831	285393	0.432	30.715
21.5	54.9	0.792	838454	290143	0.487	31.202
22.0	53.8	0.883	858770	295438	0.547	31.749
22.5	52.6	0.978	878764	301305	0.610	32.358
23.0	51.4	1.075	898429	307756	0.675	33.033
23.5	50.1	1.174	917763	314798	0.742	33.775
24.0	48.9	1.271	936768	322424	0.809	34.585

Table 2-9 HP-BASE Worst Case Winter Day

TIME HOUR	AV. TEMP DEG F	AV. LOAD TONS	SUM CAP BTU'S	SUM LOAD BTU'S	D'WORK KW-HRS	SUM WORK KW-HRS
0.5	13.0	4.140	9322	24842	1.425	1.425
1.0	12.1	4.213	18400	50118	1.410	2.836
1.5	11.3	4.280	27250	75800	1.396	4.232
2.0	10.5	4.342	35891	101854	1.384	5.616
2.5	9.8	4.397	44346	128238	1.372	6.988
3.0	9.2	4.445	52641	154906	1.362	8.350
3.5	8.8	4.483	60805	181807	1.354	9.705
4.0	8.4	4.513	68870	208885	1.348	11.053
4.5	8.1	4.533	76867	236082	1.344	12.397
5.0	8.0	4.543	84832	263337	1.342	13.740
5.5	8.0	4.542	92799	290589	1.342	15.082
6.0	8.2	4.531	100802	317777	1.345	16.427
6.5	8.4	4.510	108875	344840	1.349	17.776
7.0	8.8	4.480	117051	371720	1.355	19.131
7.5	9.3	4.440	125361	398362	1.363	20.494
8.0	9.9	4.392	133833	424715	1.373	21.868
8.5	10.6	4.336	142494	450733	1.385	23.252
9.0	11.4	4.274	151366	476376	1.398	24.650
9.5	12.2	4.206	160468	501610	1.412	26.062
10.0	13.1	4.133	169815	526407	1.427	27.489
10.5	14.1	4.057	179418	550750	1.442	28.931
11.0	15.1	3.979	189284	574625	1.458	30.390
11.5	16.0	3.901	199415	598030	1.475	31.864
12.0	17.0	3.823	209807	620968	1.491	33.355
12.5	18.0	3.747	220455	643453	1.506	34.861
13.0	18.9	3.675	231347	665504	1.521	36.382
13.5	19.7	3.608	242467	687149	1.535	37.917
14.0	20.5	3.546	253797	708423	1.548	39.465
14.5	21.2	3.490	265312	729366	1.559	41.025
15.0	21.8	3.443	276987	750025	1.569	42.594
15.5	22.2	3.404	288792	770451	1.577	44.171
16.0	22.6	3.375	300698	790700	1.583	45.754
16.5	22.9	3.355	312670	810830	1.587	47.341
17.0	23.0	3.345	324675	830902	1.589	48.930
17.5	23.0	3.346	336678	850977	1.589	50.519
18.0	22.8	3.357	348645	871116	1.587	52.106
18.5	22.6	3.377	360542	891381	1.583	53.689
19.0	22.2	3.408	372336	911828	1.576	55.265
19.5	21.7	3.448	383996	932513	1.568	56.833
20.0	21.1	3.496	395494	953487	1.558	58.391
20.5	20.4	3.551	406803	974796	1.547	59.938
21.0	19.6	3.614	417901	996480	1.534	61.472
21.5	18.8	3.682	428770	1018573	1.520	62.991
22.0	17.9	3.755	439392	1041103	1.505	64.496
22.5	16.9	3.831	449759	1064087	1.489	65.985
23.0	15.9	3.909	459863	1087539	1.473	67.458
23.5	15.0	3.987	469703	1111462	1.457	68.915
24.0	14.0	4.065	479260	1135850	1.441	70.356

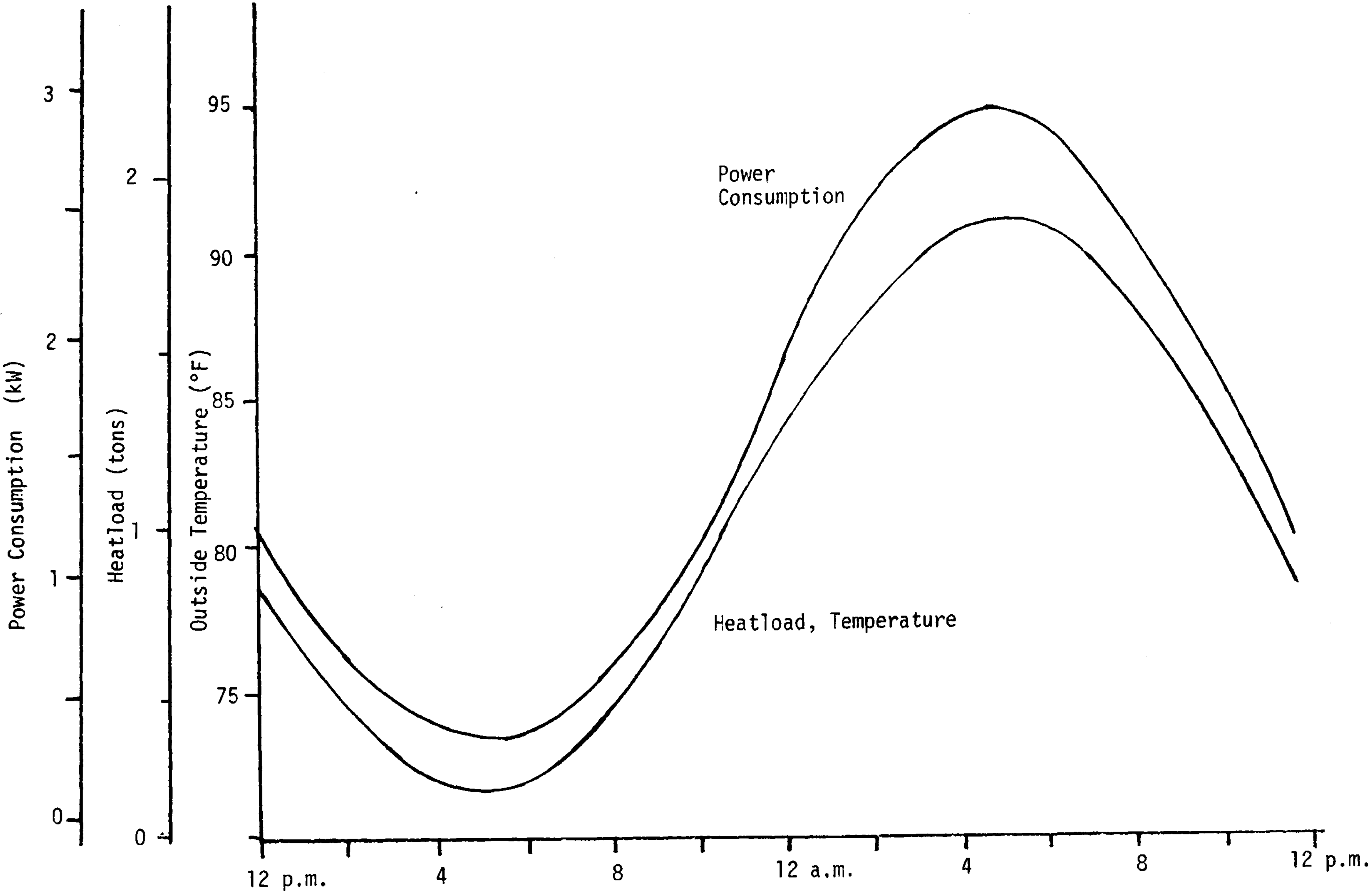

Figure 2-3 Typical Summer Day, HP-BASE.

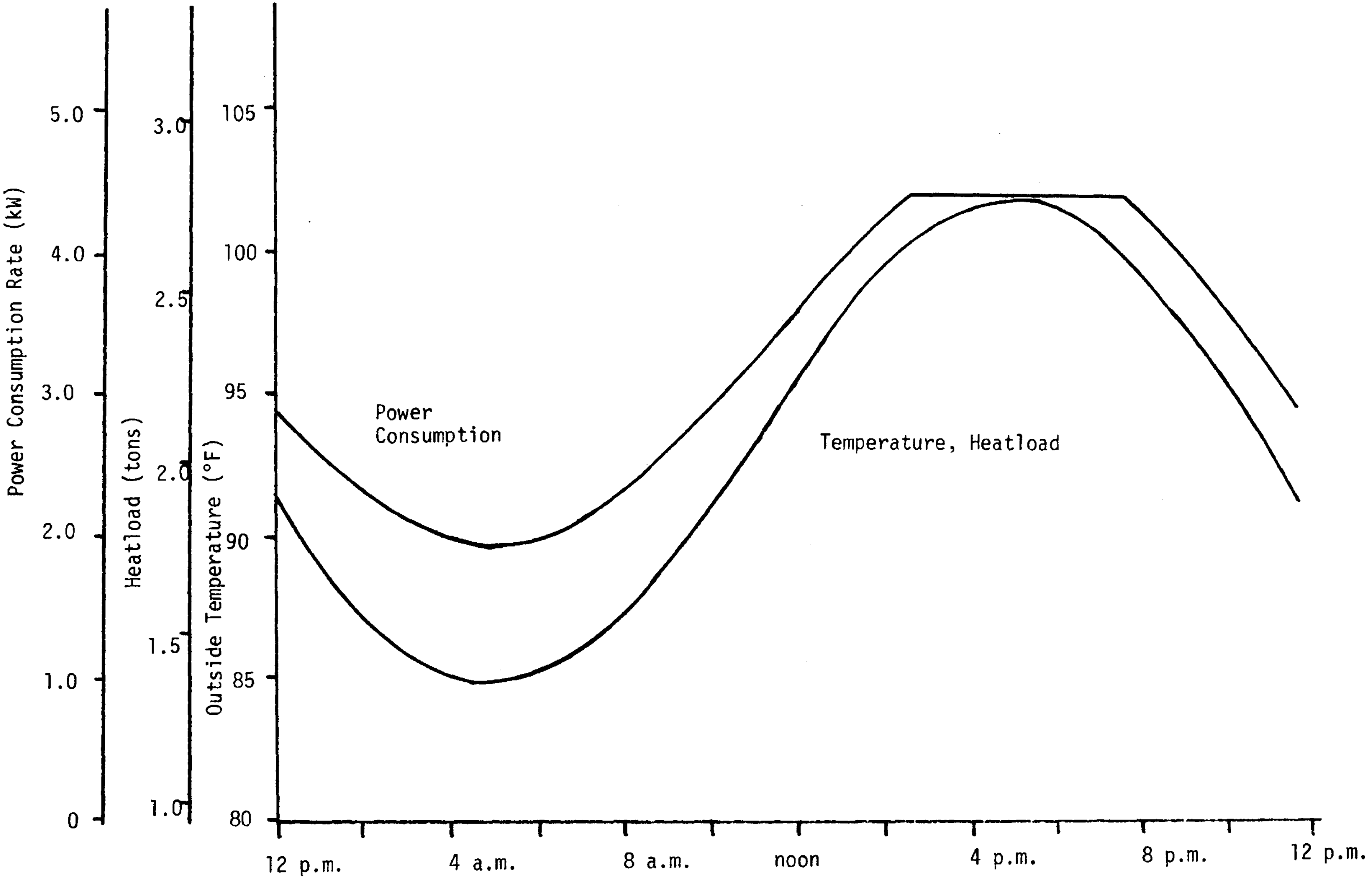

Figure 2-4 Worst Case Summer Day, HP-BASE.

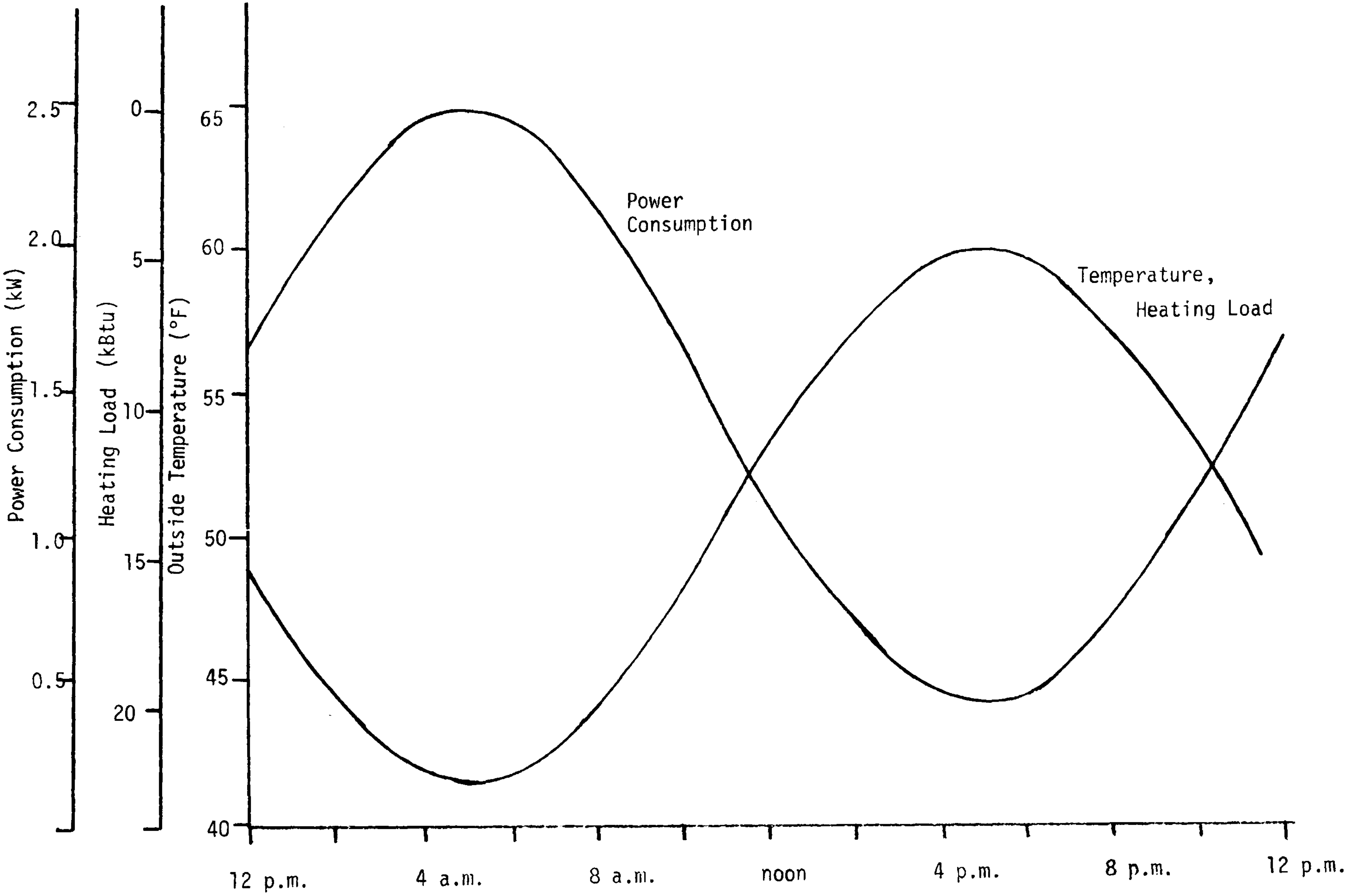

Figure 2-5 Typical Winter Day, HP-BASE.

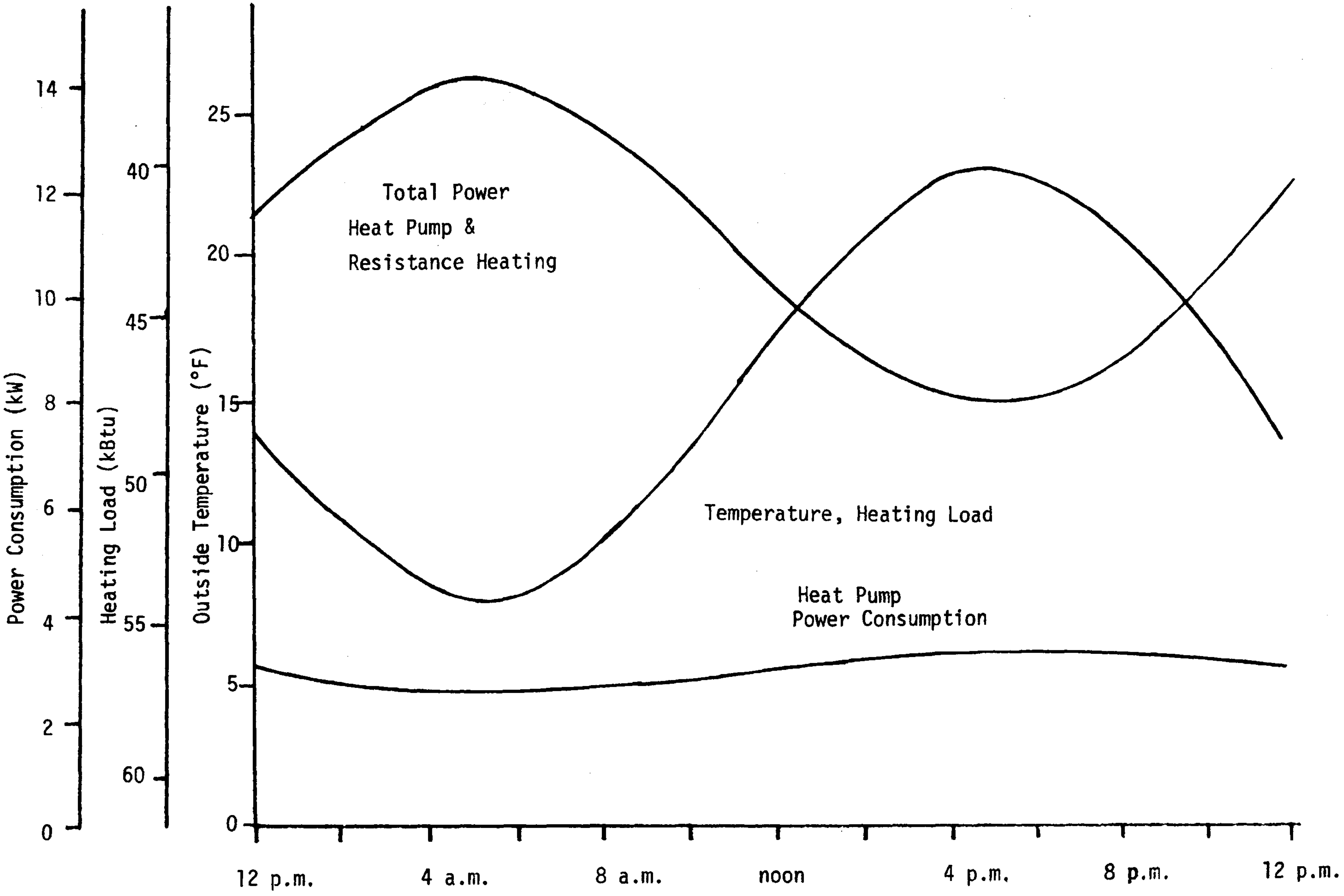

Figure 2-6 Worst Case Winter Day, HP-BASE.

3. ANALYSIS OF A HEAT PUMP WITH ROCK-BED STORAGE (HP-RBS)

A. System Concept and Configuration

Two basic storage system concepts have been selected for evaluation: a rock-bed storage system (HP-RBS) and a liquid storage system (HP-LTS). Both concepts are based upon air-source heat pumps rather than water-source heat pumps because the air source system can be installed at essentially any geographic location without regard to location of lakes, streams, or ground water.

For the rock-bed storage system there are two general options of storing energy on either the evaporator or condenser side. Depending on the method of operation, suitable damper systems must be provided to vary the storage mode at different times of the year. More detailed characterizations of the alternatives are as follows:

Heating Mode

a. Storage on evaporator side. Rocks would be heated during daytime operation, with an additional fan, and the energy recovered at night. The low temperature side of the heat pump would thereby be increased, resulting in a higher COP and higher heat output for a given electrical input.

b. Storage on condenser side. Rocks would be heated during daytime operation when heat pump has best COP. At night the energy would be recovered for direct space heating to either supplement, or supplant the heat pump, depending on load requirements. For storage on the condenser side storage temperatures would necessarily be greater than 70°F to obtain heating. The elevated storage temperature would have an unfavorable effect on storage losses.

Cooling Mode

a. Storage on condenser side. Rocks would be cooled during night operation, possibly with a condenser fan only mode. During the day the heat pump would operate at a lower condenser temperature thereby producing a higher COP.

b. Storage on evaporator side. Heat pump could run for longer night periods to cool rocks. The rocks could then be employed for direct cooling during daytime or peak load periods to reduce power consumption.

Schematic diagrams are shown for the different operational modes in Figures 3-1 and 3-2. It may be noted that various bypass arrangements may be employed with the storage system which may be actuated on a temperature and/or time basis to minimize overall work input to the unit.

Thermal Energy Storage Materials

Several candidate materials for thermal energy storage were investigated with the appropriate properties shown in Table 3-1. Most rocks have thermal capacitance values about the same as concrete or granite. Therefore, we should expect to operate with a material having a volumetric heat capacity of about 30 Btu/ft^3-°F.

Lumped Capacity Method of Analysis

Using the thermal storage properties for rocks an investigation of the suitability of a lumped capacity method of transient analysis was examined. According to Zenz and Othmer [1] the convection

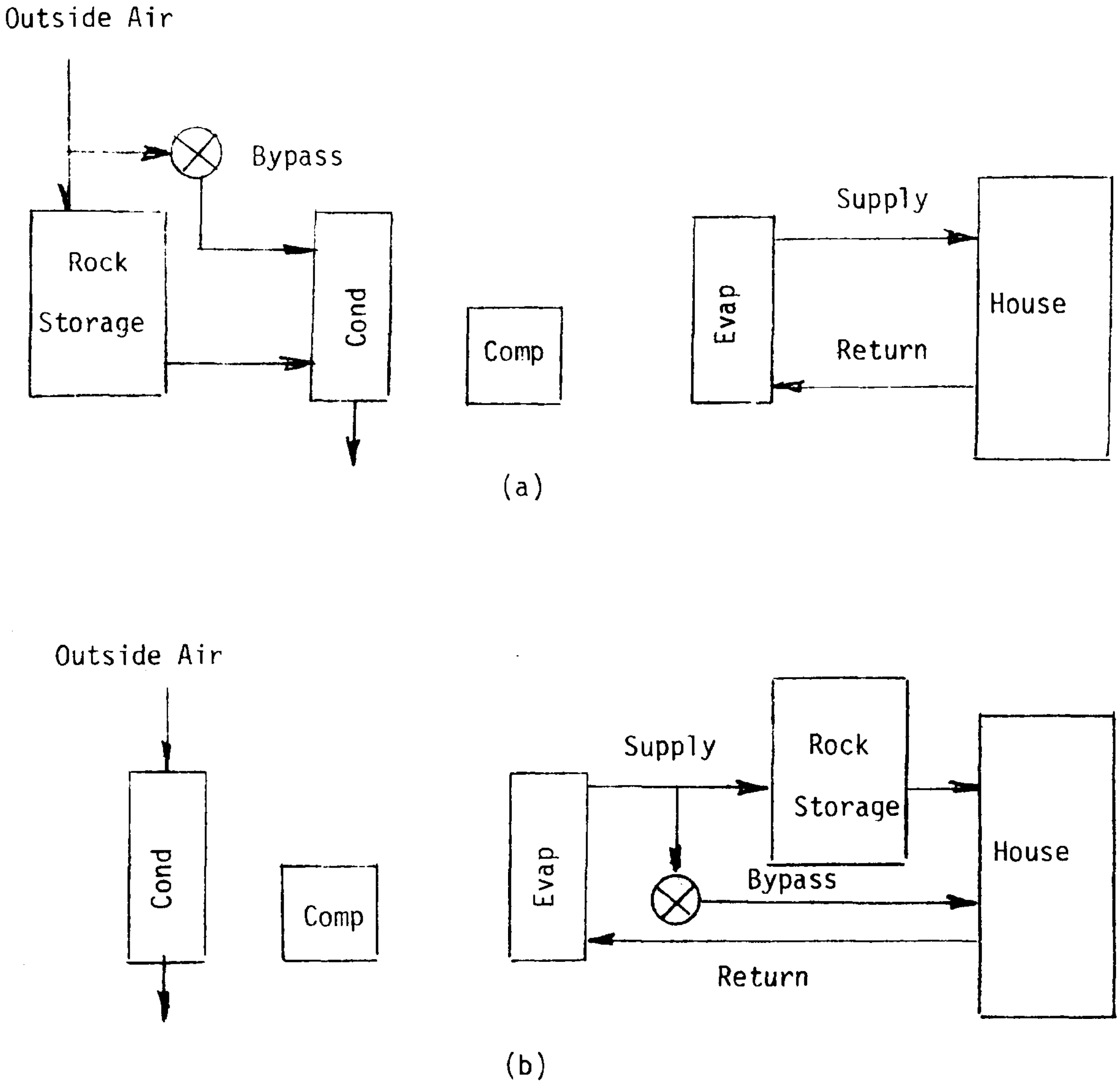

Figure 3-1 Rock-Bed Thermal Energy Storage in Cooling Mode.
(a) storage on condenser side to improve COP during heavy load periods.
(b) storage by extended operation at low load periods for reduced operation at peak loads.

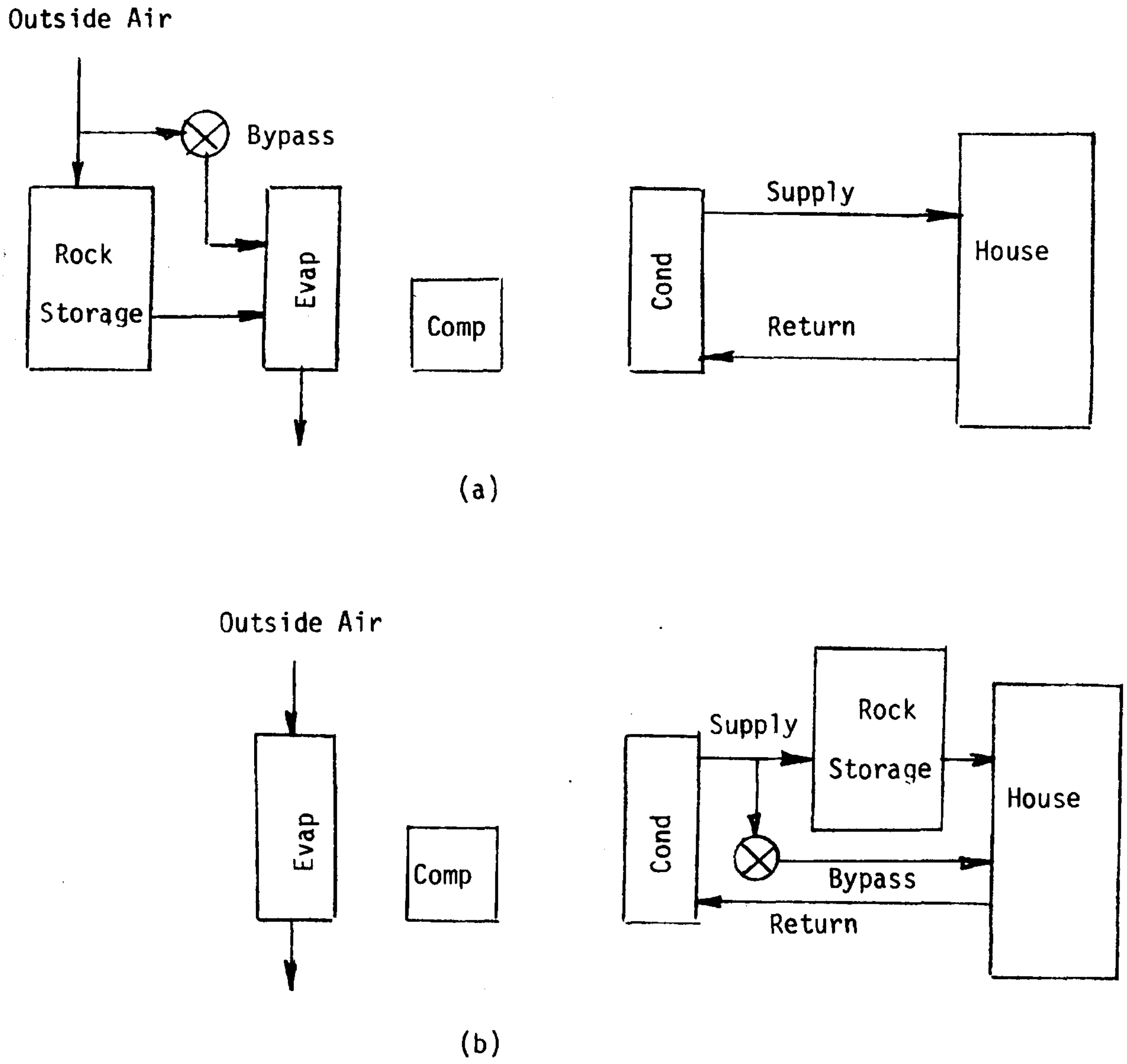

Figure 3-2 Rock-Bed Thermal Energy Storage in Heating Mode.

(a) Outside storage during warm time of day with recovery during cool times at improved COP.
(b) Storage on hot side for direct heating recovery during peak loads.

Table 3-1

Thermal Energy Storage Materials [6]

Material	Mass specific Heat, Btu/lb_m-°F	Density lb_m/ft^3	Volume specific Heat, Btu/ft^3-°F
Water	1.00	62	62
Magnetite (Fe_3O_4)	0.17	324	55
Iron (scrap)	0.11	491	54
Granite	0.19	-175	33
Brick	0.24	-125	30
Concrete	0.21	-140	29
Dry Earth	0.30	- 87	26

coefficient in a packed bed can be calculated from

$$Nu_d = 1.0\ Re_d^{0.7}\ Pr^{1/3} \tag{3-1}$$

where $Re_d = \frac{d_p \rho_f u}{\mu}$

Using a 2-in. diameter sphere as typical of the rock size and an air flow of 2000 ft^3/min across a 10x10 ft. crossection the Reynolds number based on particle diameter and superficial velocity was 307. The resulting value for the convection coefficient was 4.4 Btu/hr-ft^2-°F. The criterion for a lumped capacity analysis is given by Holman [2] as

$$\frac{h(V/A)}{k} < 0.1 \tag{3-2}$$

Using a thermal conductivity for the rock as 2.0 Btu/hr-ft-°F this parameter is calculated as 0.106 and thus we may expect to enjoy the convenience of the lumped capacity analysis method. The appropriate time constant is then calculated as

$$\Delta t = \frac{\rho c V}{hA} = 0.164\ \text{hr} = 9.85\ \text{min} \tag{3-3}$$

This is the time for the temperature of the solid to change 36.8 percent of the overall temperature difference when subjected to a step function input.

Estimate of Size of Rock Storage Bin

Using the demographic data for typical new DP&L construction and thermal capacity of the rocks it was estimated that 115.4 ft^3 of storage space would be required to store an energy of 45,000 Btu. This would provide about 1 hour of direct heating on a typical day. To provide 10 hours of direct heating would require a storage bin about 10 ft. on a side. As described previously, however, direct heating may not represent the most economical operation. We may find that other modes of heat pump operation are more favorable. In estimating the storage bin size a porosity or void space fraction of 35% was assumed along with a temperature differential of only 20°F. Larger temperature differences would produce proportionately smaller storage volumes.

Commercial Heat Pumps

A number of commercial heat pump configurations were examined. A wide range of units is available in the 5 ton (60,000 Btu/hr) cooling capacity typical of new construction in the Dallas area. Units are available with separate condenser and evaporator coils as well as separate compressor units. Others contain the compressor in the outside evaporator/condenser unit. Finally, there are a number of self-contained package units which may be connected directly to the duct system. It is this latter type of unit which appears most attractive for use with rock storage because the supplemental ductwork and damper systems can be simplified and installed in one location.

B. Commercial Heat Pump Analytical Model

The operating characteristics of a number of air-to-air heat pumps were examined for suitability to the present study. The Carrier Model 50 PQ-006 was selected for detailed modeling because of its easy adaptability to the duct systems for the final design. The general specifications and sizes of this unit, nominally a 5 ton cooling model, are as follows:

Refrigerant: R-22

Outdoor coil area: 11.7 ft^2

Outdoor fan

Nominal cfm 4000
one, 22-in. propeller
Motor: 1/2 hp, 0.8 kW

Indoor coil: 4.0 ft^2, 4 rows

Indoor fan: 10 x 9 in. size

Nominal cfm: 2000

Rpm std: 920-1300
alt: 1070-1460

Fan pulley inches std: 9.0
alt: 9.0

Motor std: 0.75 hp
alt: 1.0 hp

ARI Capacity Ratings (ARI Standard 240-75)

Cooling

2000 cfm 59,000 Btu/hr cooling EER = 7.4

Cooling rate is at 80°F DB, 67°F WB, indoor entering air temperature and 95°F DB entering outdoor unit.

Heating

62,000 Btu/hr (High Temp.) COP = 2.8

35,000 Btu/hr (Low Temp.) COP = 1.9

Heating rating is with 70°F DB indoor entering air temperature and

(High Temp.) 47°F DB, 43°F WB entering outdoor unit

(Low Temp.) 17°F DB, 15°F WB entering ourdoor unit

The detailed cooling and heating characteristics of this unit were examined along with the electrical kW input. Using the tabular data supplied by the manufacturer, operating curves were constructed and curve-fit methods were applied to obtain analytical expressions for the cooling and heating rates as functions of operating temperatures. These expressions are given below.

Cooling Cycle

The nomenclature for the cooling cycle expressions are as follows:

T_c = condenser entering DB temperature, °F

T_{EW} = evaporator entering WB temperature, °F

Q_E = evaporator cooling rate, Btu/hr

W = power input, kW

The resultant expressions are

$$W = 4.44 + 0.0427(T_{EW}-62) + 0.034\ T_c \text{ kW} \tag{3-4}$$

$$Q_E = 67500 + (85-T_c)(333.3) - 1000(72-T_{EW}) \text{ Btu/hr} \tag{3-5}$$

Heating Cycle

At low temperatures two heating and power input rates are observed depending on whether the unit is operating in an instantaneous or integrated-defrost mode. The integrated ratings take into account the heat necessary to defrost the outdoor coil. The appropriate nomenclature is given below.

Q_{HI} = Instantaneous heating rate, Btu/hr

Q_{HA} = Integrated heating rate, Btu/hr

W = power input, kW

T_o = outside DB temperature to evaporator at 70% relative humidity.

Q_{HI} = Q_{HA} for $T_o > 40°F$

COP = heating coefficient of performance = $\frac{Q_H}{W}$

The resultant analytical expressions are

<u>$40°F < T_o < 60°F$</u>

$$Q_{HI} = Q_{HA} = 55{,}000 + 950\,(T_o - 40)\ \text{Btu/hr} \qquad (3\text{-}6)$$

$$W = 6.1 + 0.06(T_o - 40)\ \text{kW} \qquad (3\text{-}7)$$

$$COP = \frac{55000 + 950(T_o - 40)}{(3413)[6.1 + 0.06(T_o - 40)]} \qquad (3\text{-}8)$$

<u>$0°F < T_o < 40°F$</u>

$$Q_{HI} = 26{,}000 + 725\,T_o \qquad \text{Btu/hr} \qquad (3\text{-}9)$$

$$Q_{HA} = 24{,}000 + 325\,T_o + 11.25\,T_o^2 \qquad \text{Btu/hr} \qquad (3\text{-}10)$$

$$W = 4.5 + 0.04\,T_o \qquad \text{kW} \qquad (3\text{-}11)$$

$$COP_I = \frac{26{,}000 + 725\,T_o}{(3413)(4.5 + 0.04\,T_o)} \qquad (3\text{-}12)$$

$$COP_A = \frac{24{,}000 + 325\,T_o + 11.25\,T_o^2}{(3413)(4.5 + 0.04\,T_o)} \qquad (3\text{-}13)$$

C. Model of Rock-Bed Storage

A simple numerical model for rock-bed storage was examined through the use of a Hewlett-Packard 9830A computer. For most practical cases the convection heat transfer coefficients are such that the air and rock temperatures are nearly the same and the equation describing the transient response of the rock-bed is

$$-A\rho_r c_r \frac{\partial T}{\partial t} = \dot{m}c_p \frac{\partial T}{\partial x} + UP(T-T_{env}) - kA \frac{\partial^2 T}{\partial x^2} \qquad (3\text{-}14)$$

The order of magnitude of the terms on the right side of this equation were examined for the following values of the parameters.

R = 20 insulation = $(1/U)$

A = $10 \times 10 = 100 \text{ ft}^2$

L = 10 ft.

P = $4 \times 10 = 40$ ft.

c_p = 0.24 Btu/lbm - °F (Air)

c_r = 0.21 Btu/lbm-°F (rock)

ρ_r = $(125)(1-0.35) = 81.3 \text{ lbm/ft}^3$ (rock)

Using these numerical values the relative magnitudes of the terms were

Environmental loss: $UP(T-T_{env}) < 40$ Btu/hr-ft.

Axial Conduction: $kA \frac{\partial^2 T}{\partial x^2} \ll 10$ Btu/hr-ft.

Energy Transport: $\dot{m}c_p \frac{\partial T}{\partial x}$: 1000 - 4000 Btu/hr-ft

Thus, it is reasonable to neglect axial conduction, and perhaps even environmental losses for calculations of the transient response of the storage bin. In these calculations, the bed temperature as a function of x-position and time is determined as well as the total bed energy accumulation (or loss) Q_S defined by

$$Q_S = \sum_i m_{ri} c_r (T_i - T_I) \tag{3-15}$$

where m_{ri} is the rock mass in the ith x-increment

$$m_{ri} = \rho_r (1-\varepsilon) \Delta x \tag{3-16}$$

and a bed porosity of $\varepsilon = 0.35$ is assumed.

T_i = rock temperature in the ith increment

T_I = initial rock temperature

c_r = rock specific heat

These potential energy sources or sinks can then be compared with the surplus or deficits involved with the heat pump as it goes through typical duty cycles.

D. Effect of Airflow Rate on Rock Bed Storage

Analytical Expressions

The equation used for calculation of nodal temperatures along the length of the rock-bed is:

$$T_m^{p+1} = (1-F)T_m^p + F*T_{m-1}^p \tag{3-17}$$

$$F = \frac{\dot{m}\, c_p \Delta t}{A\, \rho_r c_r \Delta x},$$ dimensionless grouping of rock bed and simulation program properties.

but, $\Delta x = L/n$

so $F = \frac{\dot{m} \cdot c_p n \Delta t}{A\, \rho_r c_r L}$

n = number of nodes
Δt = time step size

Defining C as $C = \frac{\dot{m}\, c_p}{A \rho_r c_r L}$ $\quad hr^{-1}$ (3-18)

This parameter embodies all the rock-bed properties and variations in determine variations in rock-bed response regardless of whether $\dot{m}$, c_p, A, ρ_r, c_r or L are changed. For the models under study:

$\dot{m}$ = 18,000 lb/hr

c_p = 0.24 Btu/lbm-°F

A = 100 ft^2

ρ_r = 91 lb/ft^3 - 140 $lb/ft^3(1-\varepsilon)$

C = 0.226 hr^{-1}

We now halve and double the mass flow rate $\dot{m}$ to determine the effects on transient response of the rock-bed. The results are summarized for a 10°F step input in Figure 3-3.

The effects of sine wave input temperatures are shown in Figures 3-4 and 3-5. The net result of this analysis, for both step and sine wave inputs, is that the rock-bed behaves in a nearly linear fashion with flow rate for energy accumulation during the first few hours of operation.

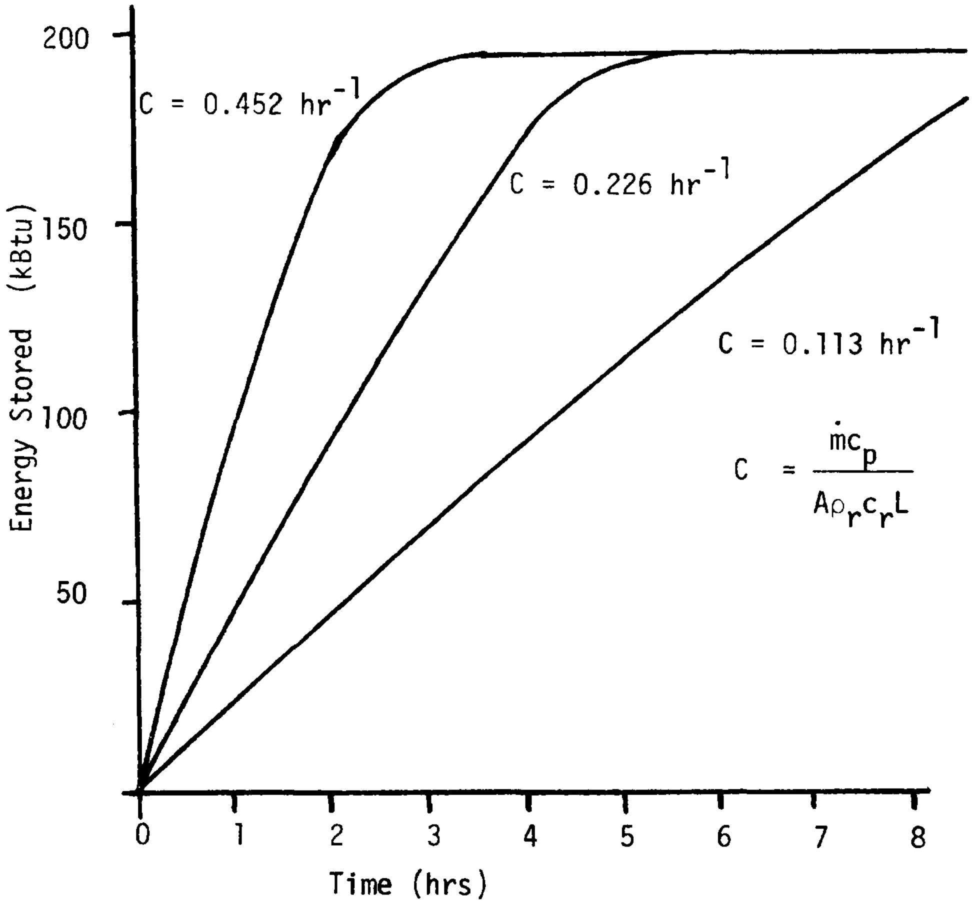

Figure 3-3 Effect of Air-flow Rate on Storage Energy with 10°F Step Input.

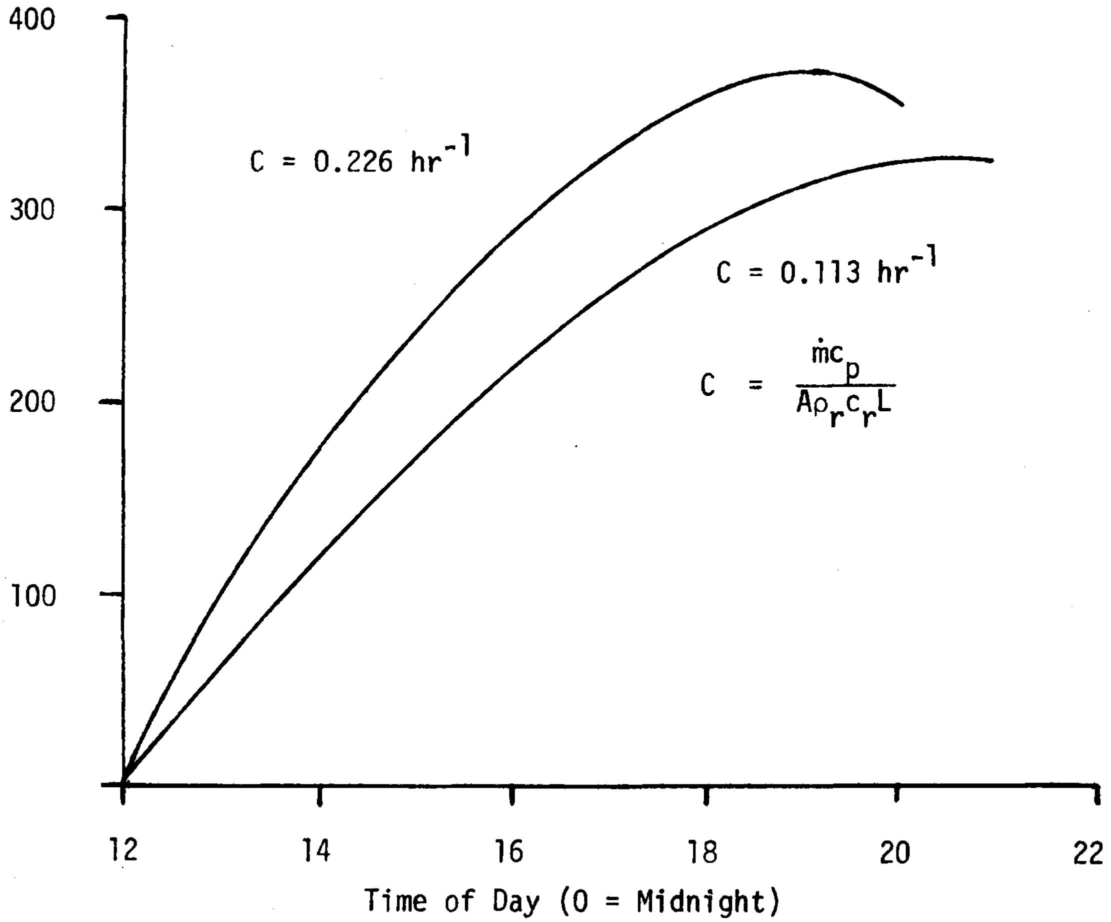

Figure 3-4 Effect of Sinusoid Inputs on Energy Storage in Rock-Bed.

$$T_A = 10 + 10 \sin[\frac{\pi}{12}(t-11)]$$

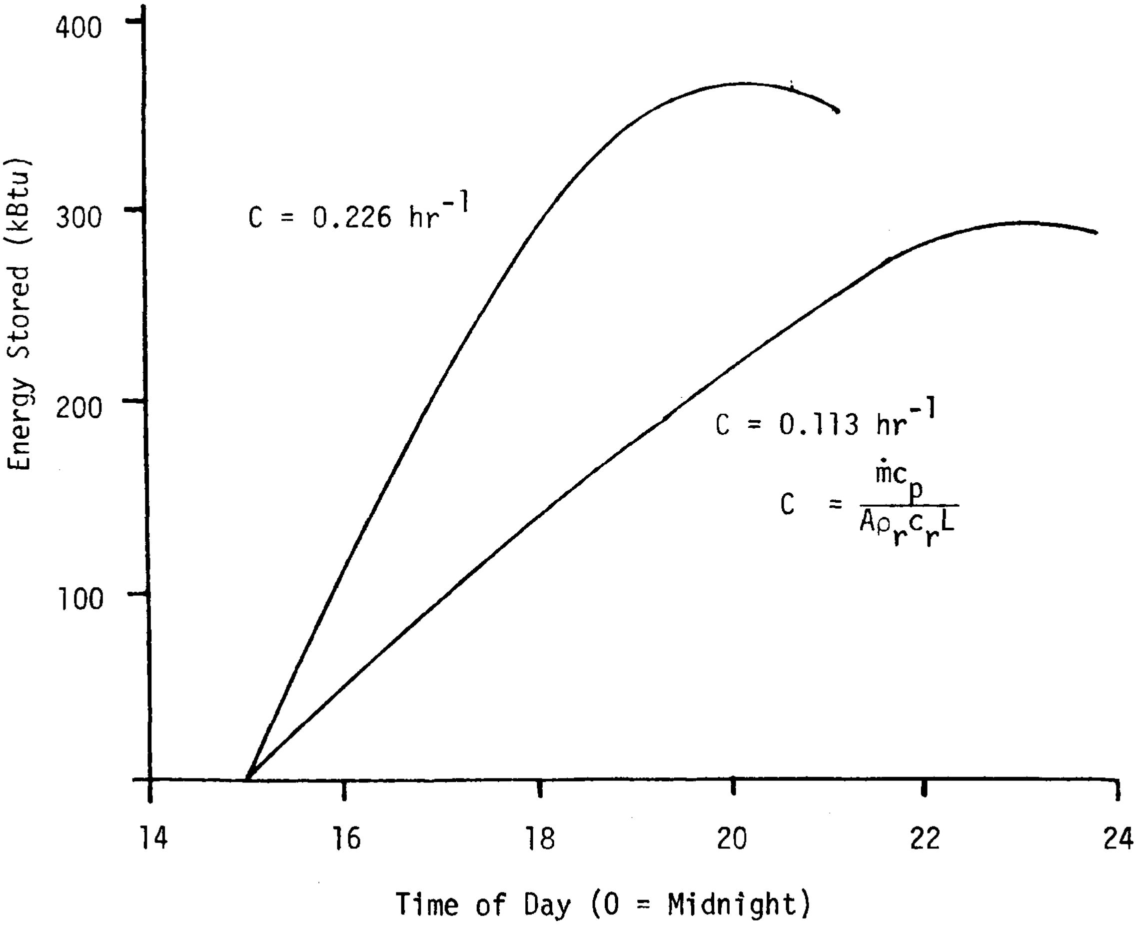

Figure 3-5 Effect of Sinusoid Inputs on Energy Storage in Rock-Bed.

$$T_A = 10 + 10 \sin[\frac{\pi}{12} (t-11)]$$

E. Rock-bed Storage Response

Analytical Expressions

The differential equation describing thermal response for the rock-bed is the following:

$$-A\,\rho_r c_r \frac{\partial T}{\partial t} = \dot{m} c_p \frac{\partial T}{\partial x} + UP(T-T_{env}) - kA\frac{\partial^2 T}{\partial x^2} \qquad (3\text{-}19)$$

Neglecting axial conduction and loss to environment terms, the equation is simplified to:

$$\frac{\partial T}{\partial t} = \frac{-\dot{m} c_p}{A\rho_r c_r}\frac{\partial T}{\partial x} \qquad (3\text{-}20)$$

where

$\dot{m}$ = mass flow of air, lbm/hr

c_p = specific heat of air, Btu/lbm-°F

A = cross sectional area of bed, ft^2

ρ_r = <u>effective</u> density of rock, lbm/ft^3

c_r = specific heat of rock, Btu/lbm-°F

Numerical Solution of Differential Equation

An approximate solution of equation (3-20) was found using finite difference approximations for the differential terms. All calculations were performed on a Hewlett Packard 9830A desk top calculator. A development of the equations used in the program follows:

The rock-bed modelled was divided into 25 equal segments and 25 temperature nodes were identified as shown in Figure 3-6.

$\dot{m}$ = 18,000 lb/hr

c_p = 0.24 Btu/lb-°F

ρ_r = 91 lb/ft^3

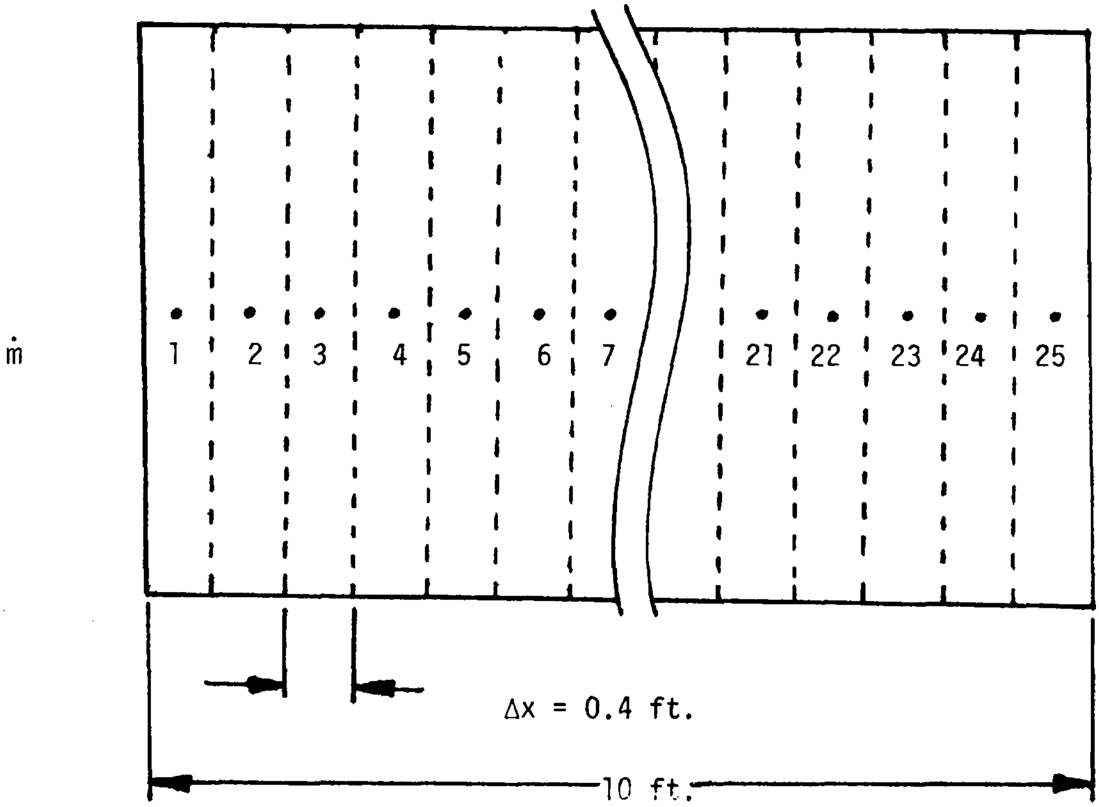

Figure 3-6 Rock-Bed Temperature Nodes.

c_r = 0.21 Btu/lb-°F

A = 100 ft^2

Node 1:

For all time >0 the temperature at node 1 equals the input air temperature.

Nodes 2-25:

Forward time differences are used to approximate $\frac{\partial T}{\partial t}$, i.e.,

$$\frac{\partial T_n}{\partial t_n} \approx \frac{T_n^{P+1} - T_n^P}{\Delta t} \qquad (3\text{-}21)$$

where the superscript and subscript correspond to time and space respectively.

$\frac{\partial T}{\partial x}$ is approximated using a backward spatial difference, or

$$\frac{\partial T}{\partial x} \simeq \frac{T_n^P - T_{n-1}^P}{\Delta x} \qquad (3\text{-}22)$$

Substituting into $\frac{\partial T}{\partial t} = -\frac{\dot{m}c_p \partial T}{A\rho_r c_r \partial x}$ and simplifying:

$$T_{n+1}^P = -\frac{\dot{m}c_p}{A\rho_r c_r}\frac{\Delta t}{\Delta x}[T_n^P - T_{n-1}^P] + T_n^P$$

or,

$$T_n^{P+1} = (1-F)T_n^P + FT_{n-1}^P$$

where $F = \frac{\dot{m}c_p \Delta t}{A\rho_r c_r \Delta x}$

Numerical Solution Program

The nodal equations developed in the previous section were programmed into a HP 9830A desk top computer to determine the thermal response of the rock-bed. Properties of the rock-bed were as previously noted.

The program incorporated 6 DO loops. Four of the loops are arranged as two unnested loops interior to two nested DO loops. The outermost loop increments with each printed output. The next loop increments with time; five time steps per printed output. The remaining two loops (both interior to the time step loop) were used to increment spatially (nodes 2 through 25) and to rename temperature values at each time for successive time steps. Two additional DO loops were used to initialize and average rock temperature. A time step of 0.05 hour (3 min) was used for most of the simulation runs. The use of a 0.01 hour (36 second) time step was demonstrated to have little effect on the results.

In addition to time and the 5 node temperatures, (nodes 1,7,13,19 and 25 temperatures were printed) the average rock temperature, energy stored in the rocks ($\Delta T*\rho*V*c_r$), energy removed from the air $[\int_0^t(T_1-T_5)*\dot{m}*c_r)dt]$ and the ratio of the preceding two terms was outputed. The last term provides a quick look at the degree of agreement between two approaches of calculating the energy exchange.

Discussion of Results

The results of the simulations run are summarized as follows: In each run presented, the initial rock temperature was 0°F. The input air temperatures used were as follows:

Run No.	Input Air Temperature	Start Time (hr)
1	10°F	0
2	10°F (Δt=0.01)	0
3	20°F	0
4	$10+10\sin[\frac{\pi}{12}(t-11)]$°F	12
5	$10+10\sin[\frac{\pi}{12}(t-11)]$°F	15
6	$10+10\sin[\frac{\pi}{12}(t-11)]$°F	18
7	$10\sin[\frac{\pi}{12}(t-11)]$°F	15
8	$10\sin[\frac{\pi}{12}(t-11)]$°F	18
9	$10\sin[\frac{\pi}{12}(t-11)]$°F	21
10	$10\sin[\frac{\pi}{12}(t-11)]$°F	3
11	$10\sin[\frac{\pi}{12}(t-11)]$°F	6
12	$10\sin[\frac{\pi}{12}(t-11)]$°F	3

The results of the analysis are discussed in terms of the individual run number.

Run 1 (Constant 10°F input air)

At infinity (or according to the simulation as early as about 8 hours from start) one would expect the entire rock-bed to change to 10°F. The corresponding change in internal energy would be:

$$\Delta U_{max} = c_r \rho_r V \Delta T = 0.21(91)(1000)(10) = 191{,}100 \text{ Btu}$$

According to the model the response of the rock bed is as shown in Figure 3-7

Run 2 (Same as Run 1 but Δt = 0.01)

In run 2 the time step was changed from 0.05 to 0.01 hour. Very little difference results. To the accuracy displayed the energy

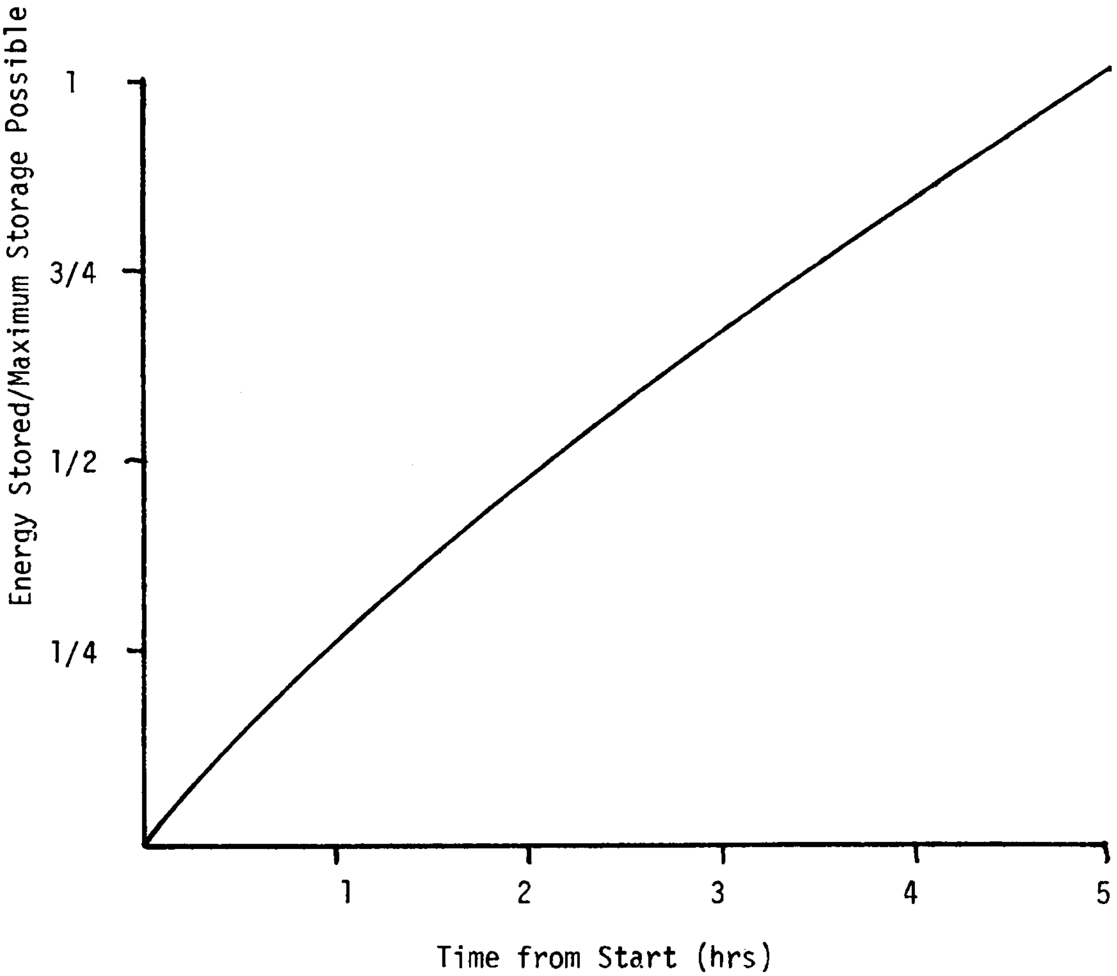

Figure 3-7 Energy Stored in Rock-Bed.

exchange during the first hour was identical to run 1. The run was terminated after 1 hour was simulated.

Run 3 (Constant 20°F input of air)

Run 3 demonstrates a linear dependence of the the rock-bed response to imposed air temperature difference. To within rounding accuracy, the outputs of run 3 are double those of run 1.

Runs 4,5, and 6

The input temperature is a sinusoid $T_1 = 10+10 \sin[\frac{\pi}{12}(t-11)]$°F with start times of 12, 15, and 18 for runs 4,5, and 6 respectively. Results are tabulated below:

Run	Start Time	Time of Max Storage	Max Energy Stored	Average Rock Temp
4	12	19.00	370 kBtu	19.37°F
5	15	20.00	359 kBtu	18.81°F
6	18	22.25	287 kBtu	15.00°F

These results look like what one would intuitively expect. It is, perhaps somewhat surprising that 97 percent (19.37/20.00) of the maximum possible energy exchange can be realized.

Runs 7,8, and 9

The input temperature is 10 $\sin[\frac{\pi}{12}(t-11)]$°F for runs 7,8, and 9 with start times of 15, 18, and 21 respectively. Results are tabulated below:

Run	Start Time	Time of Max Storage	Max Energy Stored	Average Rock Temp.
7	15	19.75	172 KBtu	9.01°F
8	18	21.75	111 KBtu	5.83°F
9	21	22.75	22 KBtu	1.14°F

Runs 10, 11, and 12

The input temperature is 10 $\sin[\frac{\pi}{12}(t-11)]$°F for runs 10, 11, and 12 with respective start times of 3, 6, and 9. The results are tabulated below:

Run	Start Time	Time of Max Storage	Max Energy Stored	Average Rock Temp
10	3	7.75	-172KBtu	-9.01°F
11	6	9.75	-111KBtu	-5.83°F
12	3	10.75	- 22KBtu	-1.14°F

Comparing these results with those of runs 7, 8, and 9 again demonstrates the exact linear dependence of the model with respect to input temperature.

F. Heat Pump Rock-Bed Storage (HP-RBS) System Simulation

Theory

Figures 3-1 and 3-2 depict schematically the HP-RBS system for summer and winter operating configurations respectively. The rock bed was sized to provide storage in the summer adequate to meet the cooling requirements of a "hot" summer day, as defined in Section 1-C, for the period between noon and 8:00 p.m. without operation of the heat pump. The heat pump analyzed for this system was a Carrier Model 50PQ006, with operating characteristics described in Section 3B.

Operation of the HP-RBS system for a typical cooling day consists of the following distinguishable modes[†]:

a. Midnight to 3:30 a.m.

Outdoor temperatures are moderate and the heat pump is operated in a conventional manner to meet the household heat load.

b. 3:30 a.m. to 6:30 a.m.

This time interval centers about the coolest time of day (5 a.m.) and the heat pump is operated at 100% duty cycle. The cooling demand of the home is met and the excess capacity is stored in the rock-bed.

c. 6:30 a.m. to 12:00 noon

Same as a.

d. 12:00 noon to 8:00 p.m.

Rock-bed stored cooling is utilized, and power consumption

[†] Storage could also have been used on the condenser side as shown in Fig. 3-1 (a) but this would entail heat pump operation during the time of day when peak loads are imposed on the power company, and this would be contrary to the central purpose of this study.

during this period is minimal. Only the evaporator fan is required to operate, which supplies cooling air to the home.

e. <u>8:00 p.m. to Midnight</u>

Same as a.

The time intervals listed above are those which were modelled for a typical cooling day. For a hot summer day, the morning storage interval is lengthened. More cooling per unit energy expended is realized by increasing the system duty cycle during the cooler part of the day. The total energy consumption of the HP-RBS system for a full typical summer day of operation is 34.2 kWh. Using the same heat pump without use of storage, the energy consumed would be 38.32 kWh or about 12% increase over the HP-RBS system. The hot summer day best illustrates the potential power peak-shaving available through use of the storage system. The maximum average power consumption rate during the noon to 8:00 p.m. period is approximately 0.80 kW for the HP-RBS. The same heat pump operated without thermal storage would have an average power consumption rate of 4.94 kW at the hottest point in the day (5 p.m.). Utility power output data (Section 1A) supplied by DP&L indicates that maximum power demand on a hot summer week day occurs just before 5 p.m.

For winter operation the rock-bed is used as a heat sink for the heat pump evaporator. Less heat transfer occurs at the evaporator that at the condenser, which enhances the effectiveness of the rock-bed for winter operation. Also, the energy storage occurs at a temperature only slightly above the outside air temperature, resulting in minimal losses. The following sequence defines the HP-RBS system operation for a typical heating day:

a. Midnight to 1:00 p.m.

The heat pump operates as required to meet the heating load, absorbing heat at the evaporator from the rock-bed. Throughout this time interval, the temperature of the air supplied to the evaporator through the rock-bed exceeds the outside air temperature.

b. 1:00 p.m. to 2:00 p.m.

The heat pump operates using outside air as its heat source. Outside air temperatures are moderate during this interval and the heat pump efficiency is high.

c. 2:00 p.m. to 6:00 p.m.

The heat pump continues to meet the heating demand using outside air as its evaporative heat source. In addition to the heat pump operation, a separate fan is used to drive ambient air through the rock-bed. At the beginning of this interval the rocks are cooler than the outside air temperature because it has been used as the evaporator heat source during the cooler part of the day. At the end of this time interval, the rocks have been restored to an average temperature nearly equal to the maximum outside temperature of the day.

d. 6:00 p.m. to Midnight

Same as a.

For typical heating days, the HP-RBS system has adequate capacity at all times of the day to avoid use of electrical resistance heating.

For the worst case heating day the rock-bed is used for the evaporator heat source for the first ten hours of the day only. The increase in heating demand results in the rock-bed having inadequate heat source potential for operating intervals of the typical heating day case. However, the frequency of occurrence of the worst case cold day is so low that it does not justify increasing the size of the rock-bed. The worst case heating day also required considerable resistance heating.

Model

A computer simulation was made for the HP-RBS system for worst case and typical days for both winter and summer operation. A Hewlett-Packard Model 9830-A desk top calculator was used for all computer simulations, with more than ample computational capability for the problem. The 9830A is programmed using BASIC computer language. Listings of the computer program statements used to generate tables of data presented are included in Appendix A.

The first step in the simulation was to develop analytical expressions describing the outside temperature as a function of time, the house heating or cooling demand as a function of outside temperature, and heat pump performance as functions of both evaporator and condenser inlet temperatures. The outside air temperature and heat load expressions are presented in Section 1-C.

In addition to developing expressions for heat pump performance, it was necessary to characterize the response of the rock-bed storage. A program discussed earlier was developed on the 9830A to solve the applicable differential equation. It was found that the rock-bed responded favorably using the air mass flow delivered by the Carrier heat pump evaporator and condenser fans. This program was later incorporated as a sub-routine in the HP-RBS system simulation.

With expressions for outside temperatures, heatloads, and characterization of the rock-bed, the next step was to build program structures to manipulate these relations to find total energy expenditures for various cooling or heating days. In each case the program contained the following:

a. A "clock". All simulations started at midnight and ended the following midnight. Logic statements in the program "looked" at the clock to make mode-of-operation decisions.

b. An expression defining the outside temperature.

c. Subroutines. For example, the rock-bed response equations and heat pump performance equaitons were grouped in separate portions of the program and were addressed by the main program body as required.

d. Counters. Cumulative energy consumption and rock-bed storage status were tracked. A sufficiently small time increment was used in the clock to permit accurate integration of the mathematical expressions used in the program.

Program listings cross-referenced to data in the report body are included in Appendix A.

To account for ducting and storage losses, the program assumed that the total heating or cooling demand was 110 percent of that defined for the typical residence. Refinement of this loss assessment was intended, however, it became apparent before that time that significant changes in total energy consumption would not be seen and that the outcome of the study would not be affected.

For each heating or cooling day multiple simulations were run to determine optimum intervals for different modes of operations. This approach results in "idealized" system operation as "real hardware"; controls could not be consistently and accurately anticipatory.

Results of Analysis

a. Typical Summer Day:

Table 3-2 is a listing of the 9830-A output for a typical cooling day and Figure 3-8 displays the results graphically. The total energy consumed during the day by the HP-RBS system is 34.2 kWh.

b. Worst Case Summer Day

Table 3-3 is the simulation result for the worst case cooling day and the results are plotted on Figure 3-9. The total energy consumption is 77.7 kWh.

c. Typical Winter Day:

The analysis results for the typical winter day are given in Table 3-4. No resistance heating is required and the energy consumed is 35.5 kWh for the 24-hour period. Figure 3-10 displays the typical heating day results graphically.

d. Worst Case Winter Day:

The results presented in Table 3-5 are for heat pump and the auxiliary fan on the rock-bed. The heat pump has inadequate capacity through most of the day and considerable resistance heating is required. The heat pump consumes 127.9 kWh and an additional 58.0 kWh of resistance heating is required. These results are plotted in Figure 3-11.

Table 3-2 HP-RBS Typical Summer Day

ROCK BED STORAGE SYSTEM TYPICAL DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON-HRS	D'WORK KW-HRS	CUM WORK KW-HRS	T ROCK DEG F
0.5	78.2	0.798	0.000	0.551	0.551	65.0
1.0	77.0	0.698	0.000	0.476	1.028	65.0
1.5	75.9	0.603	0.000	0.407	1.435	65.0
2.0	74.8	0.517	0.000	0.345	1.780	65.0
2.5	73.9	0.440	0.000	0.292	2.072	65.0
3.0	73.1	0.375	0.000	0.246	2.318	65.0
3.5	72.5	0.320	0.000	0.209	2.527	65.0
4.0	72.0	0.279	3.197	1.847	4.374	63.0
4.5	71.7	0.252	5.780	3.503	7.876	61.4
5.0	71.5	0.238	8.369	3.500	11.376	59.7
5.5	71.5	0.239	10.957	3.500	14.877	58.1
6.0	71.7	0.254	13.533	3.503	18.380	56.5
6.5	72.1	0.283	14.046	0.850	19.230	56.2
7.0	72.6	0.325	14.046	0.212	19.442	56.2
7.5	73.2	0.381	14.046	0.250	19.692	56.2
8.0	74.0	0.448	14.045	0.297	19.989	56.2
8.5	74.9	0.525	14.046	0.351	20.340	56.2
9.0	76.0	0.613	14.046	0.414	20.754	56.2
9.5	77.1	0.707	14.046	0.483	21.237	56.2
10.0	78.3	0.809	14.046	0.559	21.797	56.2
10.5	79.5	0.914	14.046	0.640	22.437	56.2
11.0	80.8	1.023	14.046	0.725	23.163	56.2
11.5	82.1	1.132	14.046	0.813	23.976	56.2
12.0	83.4	1.240	14.046	0.903	24.879	56.2
12.5	84.6	1.346	12.736	0.075	24.953	57.0
13.0	85.8	1.446	12.013	0.080	25.034	57.5
13.5	86.9	1.541	11.242	0.086	25.120	57.9
14.0	88.0	1.627	10.429	0.091	25.210	58.5
14.5	88.9	1.704	9.577	0.095	25.306	59.0
15.0	89.7	1.770	8.692	0.100	25.405	59.5
15.5	90.3	1.824	7.781	0.104	25.509	60.1
16.0	90.8	1.865	6.848	0.108	25.617	60.7
16.5	91.1	1.892	5.902	0.111	25.728	61.3
17.0	91.3	1.906	4.949	0.115	25.843	61.9
17.5	91.3	1.905	3.997	0.118	25.960	62.5
18.0	91.1	1.890	3.052	0.121	26.081	63.1
18.5	90.7	1.861	2.121	0.124	26.205	63.7
19.0	90.2	1.819	1.212	0.126	26.331	64.2
19.5	89.6	1.763	0.330	0.129	26.460	64.8
20.0	88.8	1.696	-0.435	0.245	26.705	65.3
20.5	87.9	1.619	-0.435	1.232	27.937	65.3
21.0	86.8	1.531	-0.435	1.154	29.091	65.3
21.5	85.7	1.437	-0.435	1.070	30.162	65.3
22.0	84.5	1.335	-0.435	0.983	31.145	65.3
22.5	83.3	1.230	-0.435	0.894	32.038	65.3
23.0	82.0	1.121	-0.435	0.805	32.843	65.3
23.5	80.7	1.012	-0.435	0.717	33.560	65.3
24.0	79.4	0.984	-0.435	0.632	34.192	65.3

Table 3-3 HP-RBS Worst Case Summer Day

ROCK BED STORAGE SYSTEM HOT DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON-HRS	D'WORK KW-HRS	CUM WORK KW-HRS	T ROCK DEG F
0.5	90.7	1.859	0.000	1.457	1.457	65.0
1.0	89.7	1.772	0.000	1.374	2.831	65.0
1.5	88.7	1.691	0.000	1.299	4.130	65.0
2.0	87.9	1.617	0.000	1.231	5.361	65.0
2.5	87.1	1.551	0.000	1.172	6.533	65.0
3.0	86.4	1.495	3.527	3.753	10.286	62.8
3.5	85.9	1.448	5.316	3.744	14.030	61.7
4.0	85.4	1.413	7.128	3.737	17.766	60.5
4.5	85.2	1.389	8.954	3.732	21.498	59.4
5.0	85.0	1.378	10.787	3.729	25.227	58.2
5.5	85.0	1.378	12.617	3.730	28.957	57.1
6.0	85.2	1.391	14.438	3.732	32.689	55.9
6.5	85.5	1.416	16.240	3.737	36.426	54.8
7.0	85.9	1.453	18.018	3.744	40.170	53.7
7.5	86.5	1.500	19.762	3.754	43.924	52.6
8.0	87.2	1.558	21.467	3.766	47.690	51.5
8.5	87.9	1.624	21.467	1.238	48.928	51.5
9.0	88.8	1.699	21.467	1.306	50.234	51.5
9.5	89.8	1.781	21.467	1.382	51.616	51.5
10.0	90.8	1.868	21.467	1.465	53.081	51.5
10.5	91.9	1.958	21.467	1.553	54.634	51.5
11.0	93.0	2.051	21.467	1.645	56.280	51.5
11.5	94.1	2.145	21.467	1.740	58.020	51.5
12.0	95.2	2.238	21.467	1.836	59.855	51.5
12.5	96.3	2.329	19.665	0.137	59.993	52.7
13.0	97.3	2.415	18.458	0.142	60.135	53.4
13.5	98.3	2.496	17.210	0.147	60.282	54.2
14.0	99.1	2.570	15.925	0.151	60.434	55.0
14.5	99.9	2.636	14.607	0.155	60.589	55.8
15.0	100.6	2.692	13.261	0.159	60.747	56.7
15.5	101.1	2.739	11.891	0.162	60.909	57.5
16.0	101.6	2.774	10.504	0.165	61.074	58.4
16.5	101.8	2.798	9.105	0.168	61.242	59.3
17.0	102.0	2.809	7.701	0.170	61.412	60.2
17.5	102.0	2.809	6.296	0.173	61.585	61.0
18.0	101.8	2.796	4.898	0.176	61.762	61.9
18.5	101.5	2.771	3.513	0.179	61.941	62.8
19.0	101.1	2.735	2.145	0.183	62.124	63.7
19.5	100.5	2.687	0.882	0.187	62.312	64.5
20.0	99.8	2.630	-0.383	0.396	62.707	65.2
20.5	99.1	2.563	-0.383	2.187	64.894	65.2
21.0	98.2	2.488	-0.383	2.104	66.998	65.2
21.5	97.2	2.407	-0.383	2.015	69.012	65.2
22.0	96.2	2.320	-0.383	1.922	70.934	65.2
22.5	95.1	2.229	-0.383	1.826	72.760	65.2
23.0	94.0	2.136	-0.383	1.730	74.491	65.2
23.5	92.9	2.042	-0.383	1.636	76.126	65.2
24.0	91.8	1.949	-0.383	1.544	77.670	65.2

Table 3-4 HP-RBS Typical Winter Day

ROCK BED STORAGE SYSTEM TYPICAL DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON-HRS	D'WORK KW-HRS	CUM WORK KW-HRS	T ROCK DEG F
0.5	47.7	1.366	1.128	0.824	0.824	55.3
1.0	46.6	1.456	1.607	0.879	1.703	55.0
1.5	45.5	1.541	2.113	0.930	2.633	54.7
2.0	44.6	1.619	2.644	0.977	3.610	54.3
2.5	43.7	1.688	3.198	1.018	4.628	54.0
3.0	43.0	1.747	3.772	1.054	5.682	53.6
3.5	42.3	1.796	4.362	1.084	6.766	53.3
4.0	41.9	1.833	4.964	1.106	7.872	52.9
4.5	41.6	1.858	5.574	1.121	8.993	52.5
5.0	41.4	1.870	6.188	1.128	10.121	52.1
5.5	41.4	1.869	6.801	1.128	11.249	51.7
6.0	41.6	1.856	7.411	1.120	12.369	51.3
6.5	41.9	1.830	8.012	1.104	13.473	51.0
7.0	42.4	1.791	8.600	1.081	14.554	50.6
7.5	43.0	1.742	9.173	1.051	15.605	50.2
8.0	43.8	1.681	9.726	1.015	16.619	49.9
8.5	44.7	1.611	10.257	0.973	17.592	49.6
9.0	45.6	1.533	10.763	0.926	18.518	49.2
9.5	46.7	1.448	11.243	0.874	19.392	48.9
10.0	47.8	1.356	11.695	0.820	20.212	48.7
10.5	49.0	1.261	12.117	0.763	20.974	48.4
11.0	50.2	1.164	12.508	0.704	21.679	48.1
11.5	51.5	1.065	12.869	0.646	22.324	47.9
12.0	52.7	0.968	13.198	0.587	22.912	47.7
12.5	53.9	0.873	13.496	0.530	23.442	47.5
13.0	55.0	0.783	13.738	0.476	23.918	47.4
13.5	56.1	0.698	13.738	0.421	24.339	47.4
14.0	57.0	0.620	13.738	0.372	24.711	47.4
14.5	57.9	0.551	11.069	0.730	25.440	49.0
15.0	58.6	0.492	8.571	0.693	26.133	50.6
15.5	59.3	0.443	6.017	0.663	26.797	52.2
16.0	59.7	0.406	3.440	0.641	27.438	53.8
16.5	60.0	0.381	0.944	0.626	28.063	55.4
17.0	60.2	0.369	-1.310	0.618	28.682	56.8
17.5	60.2	0.370	-3.158	0.619	29.300	58.0
18.0	60.0	0.383	-4.381	0.587	29.887	58.8
18.5	59.7	0.409	-3.916	0.242	30.130	58.5
19.0	59.2	0.448	-3.768	0.265	30.395	58.4
19.5	58.6	0.497	-3.604	0.294	30.689	58.3
20.0	57.8	0.558	-3.420	0.330	31.020	58.1
20.5	56.9	0.628	-3.213	0.372	31.391	58.0
21.0	56.0	0.706	-2.980	0.418	31.809	57.9
21.5	54.9	0.792	-2.719	0.468	32.277	57.7
22.0	53.8	0.883	-2.427	0.522	32.800	57.5
22.5	52.6	0.978	-2.104	0.579	33.378	57.3
23.0	51.4	1.075	-1.748	0.636	34.015	57.1
23.5	50.1	1.174	-1.359	0.694	34.709	56.9
24.0	48.9	1.271	-0.938	0.752	35.461	56.6

Table 3-5 HP-RBS Worst Case Winter Day

```
     ROCK BED STORAGE SYSTEM WORST CASE DAY
TIME AVG TEMP AVG LOAD  STORAGE   D'WORK  CUM WORK  T ROCK
HOUR   DEG F     TONS   TON-HRS   KW-HRS    KW-HRS   DEG F
 0.5    13.0    4.140    1.297    2.670     2.670    20.2        20613
 1.0    12.1    4.213    2.256    2.670     5.340    19.6        41225
 1.5    11.3    4.280    3.214    2.670     8.010    19.0        61837
 2.0    10.5    4.342    4.172    2.670    10.680    18.4        82450
 2.5     9.8    4.397    5.131    2.670    13.350    17.8       103062
 3.0     9.2    4.445    6.095    2.669    16.019    17.2       123652
 3.5     8.8    4.483    7.077    2.661    18.680    16.6       144110
 4.0     8.4    4.513    8.070    2.642    21.322    15.9       164212
 4.5     8.1    4.533    9.038    2.614    23.936    15.3       183805
 5.0     8.0    4.543    9.954    2.589    26.525    14.7       202949
 5.5     8.0    4.542   10.824    2.574    29.099    14.2       221817
 6.0     8.2    4.531   11.668    2.567    31.665    13.7       240558
 6.5     8.4    4.510   12.503    2.564    34.229    13.1       259242
 7.0     8.8    4.480   13.340    2.560    36.789    12.6       277864
 7.5     9.3    4.440   14.180    2.553    39.342    12.1       296360
 8.0     9.9    4.392   15.021    2.541    41.883    11.6       314632
 8.5    10.6    4.336   15.849    2.524    44.408    11.0       332605
 9.0    11.4    4.274   16.653    2.507    46.915    10.5       350264
 9.5    12.2    4.206   17.429    2.492    49.407    10.1       367658
10.0    13.1    4.133   18.106    2.486    51.893     9.6       384940
10.5    14.1    4.057   18.106    2.532    54.425     9.6       403046
11.0    15.1    3.979   18.106    2.551    56.976     9.6       421505
11.5    16.0    3.901   18.106    2.571    59.547     9.6       440319
12.0    17.0    3.823   18.106    2.590    62.137     9.6       459486
12.5    18.0    3.747   18.106    2.609    64.746     9.6       478995
13.0    18.9    3.675   18.106    2.627    67.373     9.6       498831
13.5    19.7    3.608   18.106    2.644    70.018     9.6       518974
14.0    20.5    3.546   18.106    2.660    72.677     9.6       539397
14.5    21.2    3.490   15.433    3.073 .  75.750    11.3       560070
15.0    21.8    3.443   13.462    3.056    78.806    12.5       580729
15.5    22.2    3.404   11.353    3.013    81.820    13.9       601155
16.0    22.6    3.375    9.108    2.981    84.801    15.3       621404
16.5    22.9    3.355    6.727    2.960    87.761    16.8       641535
17.0    23.0    3.345    4.249    2.950    90.711    18.3       661606
17.5    23.0    3.346    1.844    2.950    93.661    19.8       681681
18.0    22.8    3.357    0.020    2.922    96.583    21.0       701821
18.5    22.6    3.377    0.020    2.584    99.167    21.0       722085
19.0    22.2    3.408    0.020    2.617   101.784    21.0       742532
19.5    21.7    3.448    0.020    2.660   104.444    21.0       763214
20.0    21.1    3.496    0.020    2.672   107.116    21.0       783864
20.5    20.4    3.551    0.020    2.658   109.774    21.0       804260
21.0    19.6    3.614    0.020    2.642   112.417    21.0       824374
21.5    18.8    3.682    0.020    2.625   115.042    21.0       844178
22.0    17.9    3.755    0.020    2.607   117.650    21.0       863653
22.5    16.9    3.831    0.020    2.588   120.238    21.0       882784
23.0    15.9    3.909    0.020    2.569   122.807    21.0       901563
23.5    15.0    3.987    0.020    2.549   125.356    21.0       919986
24.0    14.0    4.065    0.020    2.533   127.886    21.0       938058
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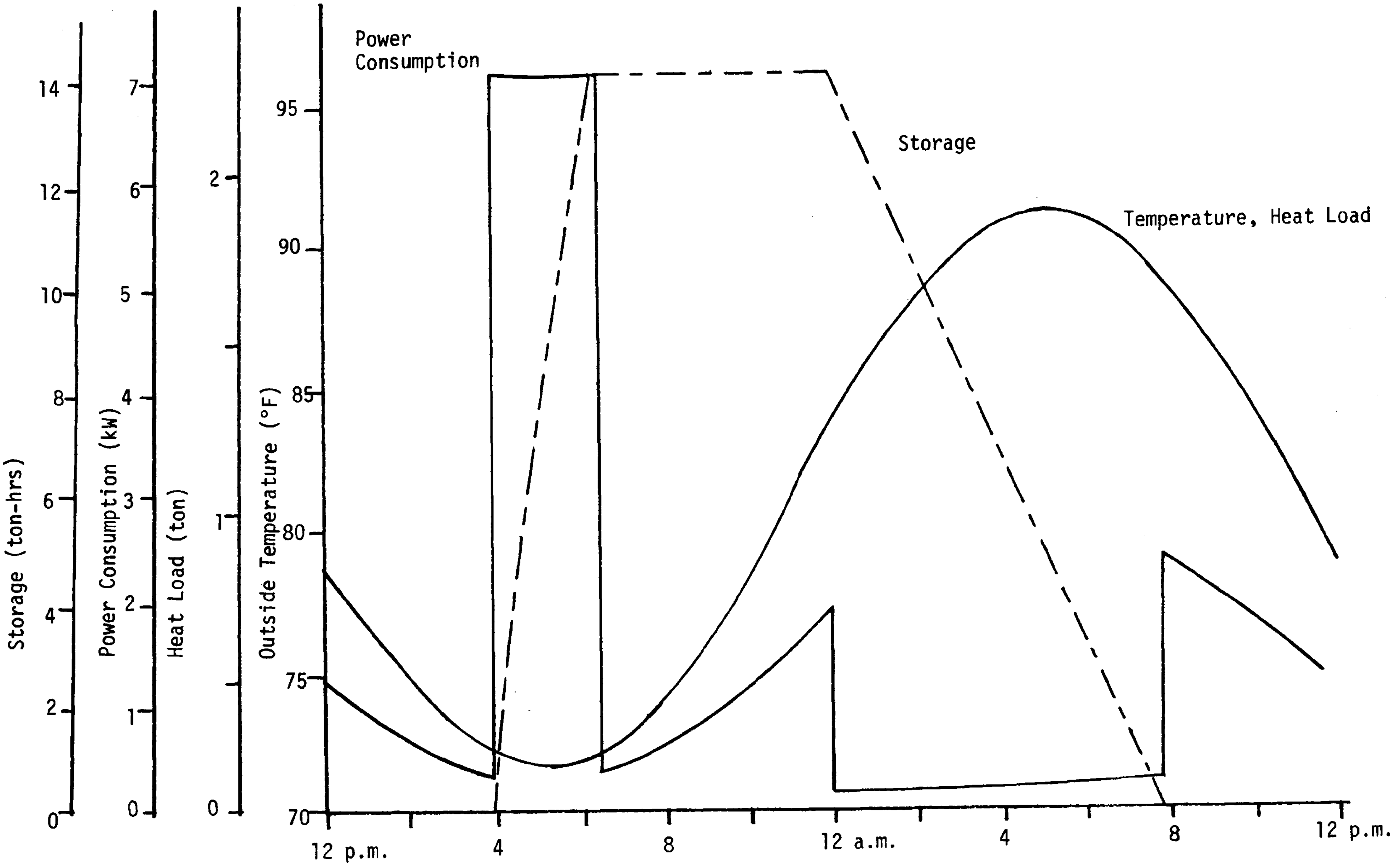

Figure 3-8 Typical Summer Day, HP-RBS.

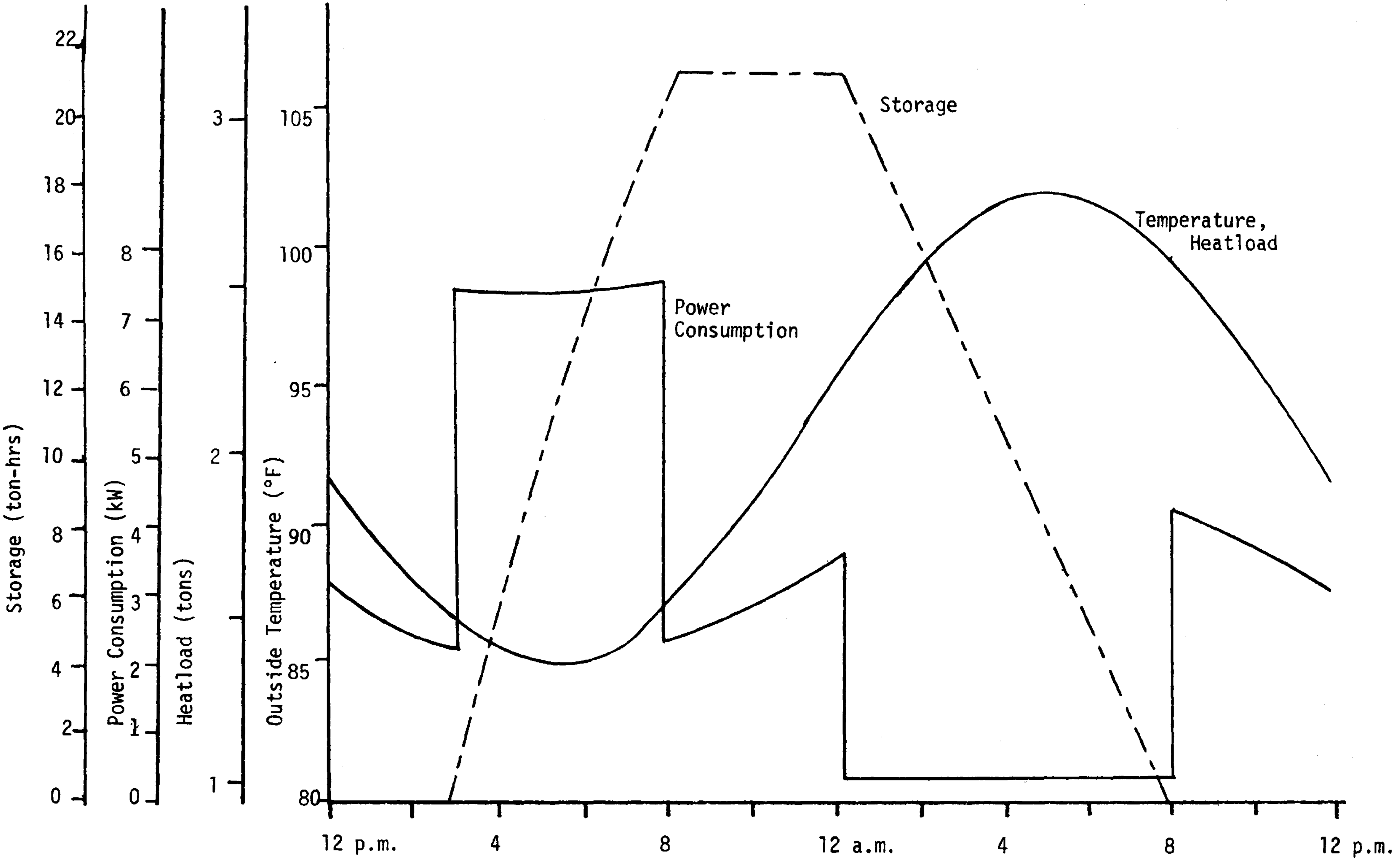

Figure 3-9 Worst Summer Day, HP-RBS.

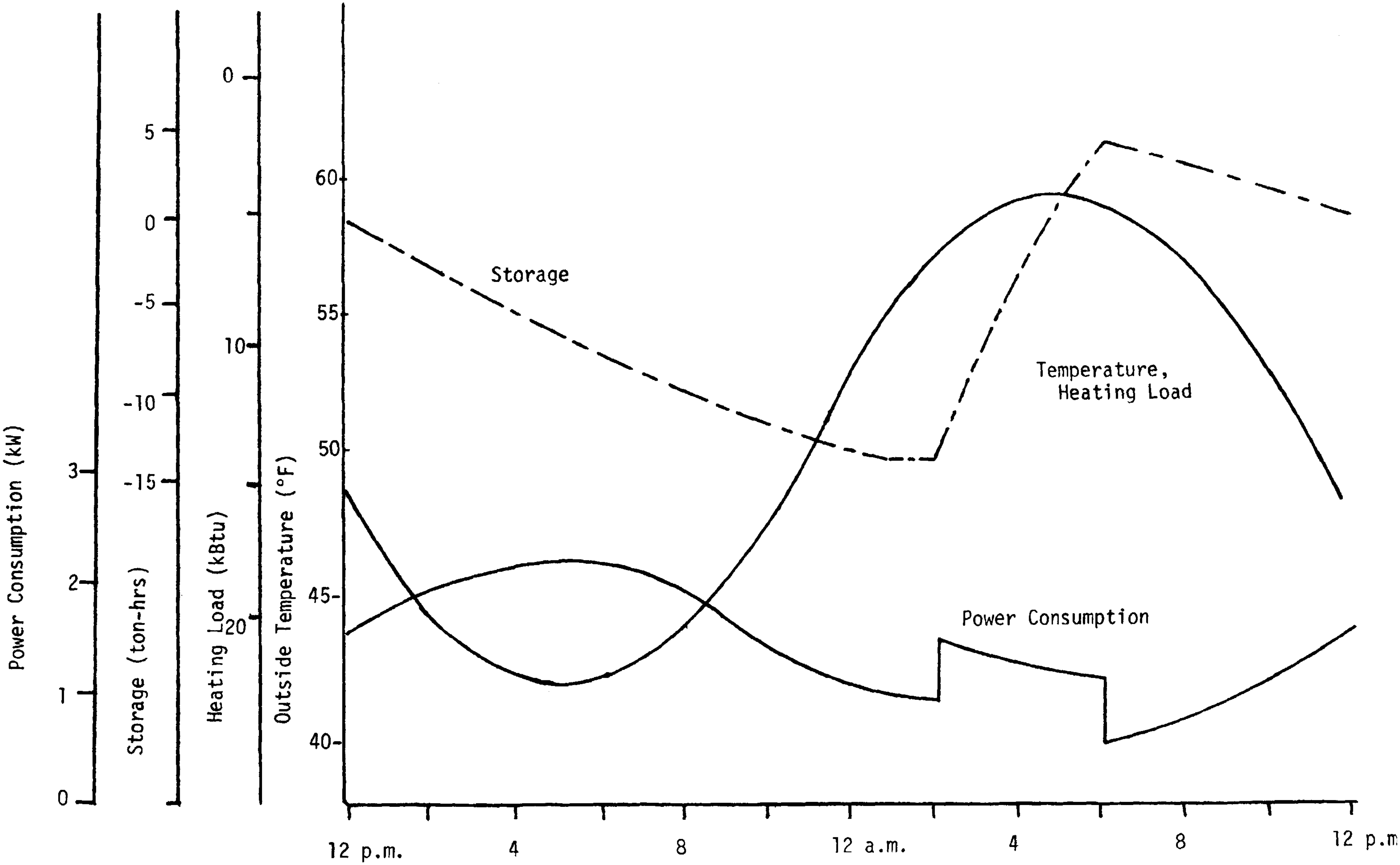

Figure 3-10 Typical Winter Day, HP-RBS.

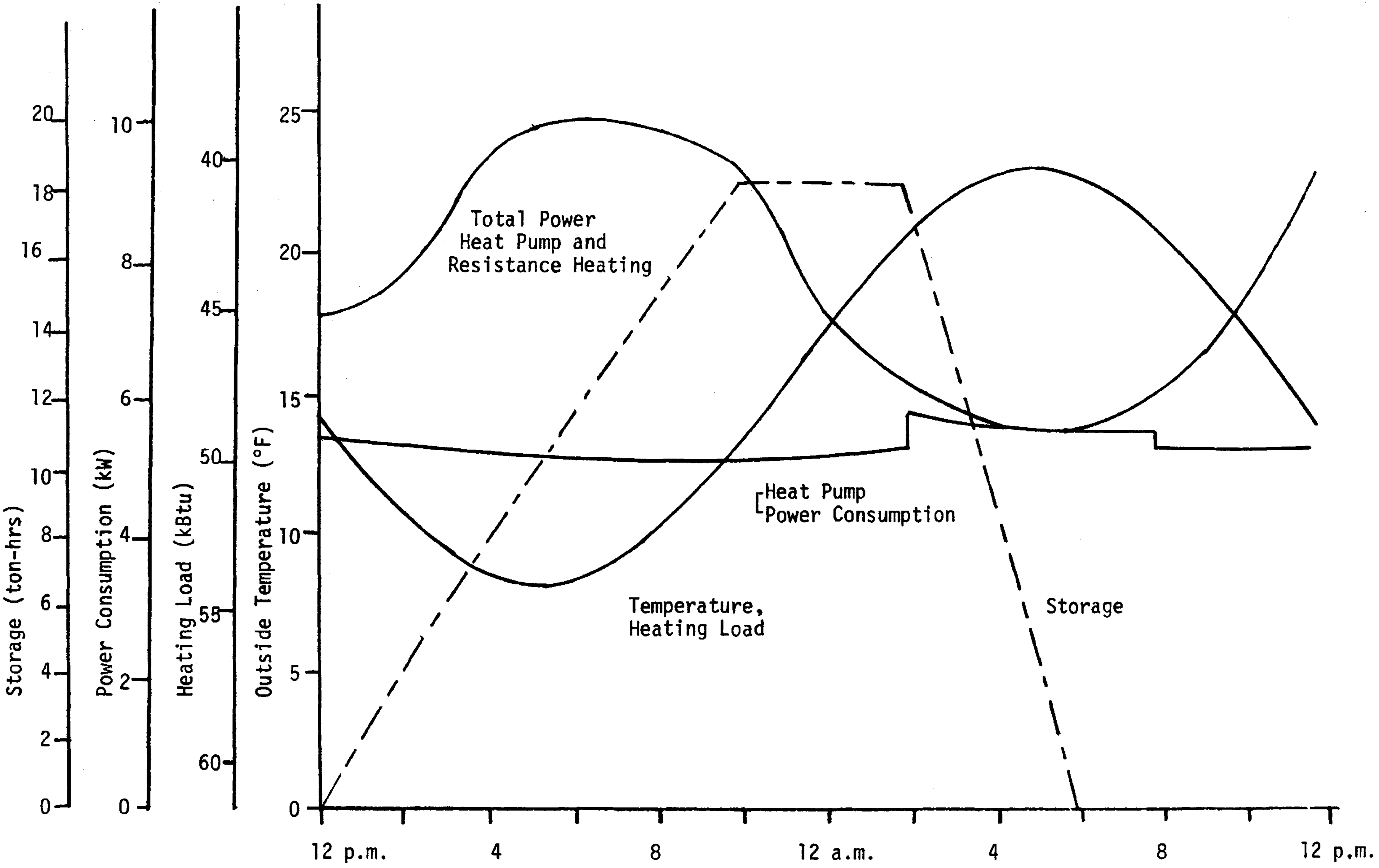

Figure 3-11 Worst Case Winter Day, HP-RBS.

4. ANALYSIS OF A HEAT PUMP SYSTEM WITH LIQUID TANK STORAGE (HP-LTS)

A. Theory of Operation

Analysis of weather data in Section 1B has shown that on worst case hot summer days a standard heat pump would operate with an effective source temperature of 75°F (indoor air) and a sink temperature of up to 102°F (outdoor air). Basic heat pump theory indicates that if this temperature difference can be reduced, the efficiency of the cooling process will be increased. Section 1B also indicates a night-time low temperature of 85°F on the hottest summer day, so the ΔT between source and sink varies from a daytime high of 27°F to a night-time low of 10°F.

The efficiency of a typical 5 ton residential heat pump system operating under the worst case daytime conditions is 7.2 Btu per watt-hour and 8.6 Btu per watt-hour under the most favorable night-time conditions indicated above. Thus, a 10,000 Btu/hr heatload would require 1.39 kW to operate the heat pump during the summer daytime high temperature, and only 1.16 kW to handle the same heatload under night-time low conditions.

Therefore, the basic theory of operation of the HP-TES system is that the heat pump is controlled to operate at maximum capacity during the coolest night hours, storing the excess cooling in the form of chilled water, and using this excess to meet daytime cooling requirements. Thus, a careful choice of operating and nonoperating time intervals for this concept should result in increased operating efficiency and reduce the peak load on the electric utility.

Referring again to Section 1B, the worst case winter day was defined to have a daytime maximum temperature of 23°F and a night-time low of 8°F. The COP for a typical residential heat pump for daytime conditions is 2.3 and about 1.9 for night-time conditions. Therefore, the storage concept can also be used to improve the thermal efficiency of a heat pump in the heating mode. In this case, it is desirable to operate the system for extended periods during the daytime, storing the excess heating capacity in the form of hot water, and then using this excess to meet night-time heating requirements.

B. Description of the Model

The system model of the HP-LTS concept is shown in Figure 4-1. The basic heat pump unit selected for this model is similar to one previously described for the HP-RBS, a Carrier 50PQ-006 unit; however, the indoor evaporator/condenser has been modified to operate as a water chiller or heater. The power and capacity equations for this unit were assumed to be identical to those used in the HP-RBS simulation, except a multiplier of 1.08 was applied to the two heating capacity equations. These changes to the performance equations are a result of more efficient heat transfer in the water-to-freon heat exchanger than in the standard air-to-freon heat exchanger. The multiplier factors were derived from comparisons of COP's and EER's for several water-source and air-source heat pumps in the 3 to 5 ton capacity range. These considerations

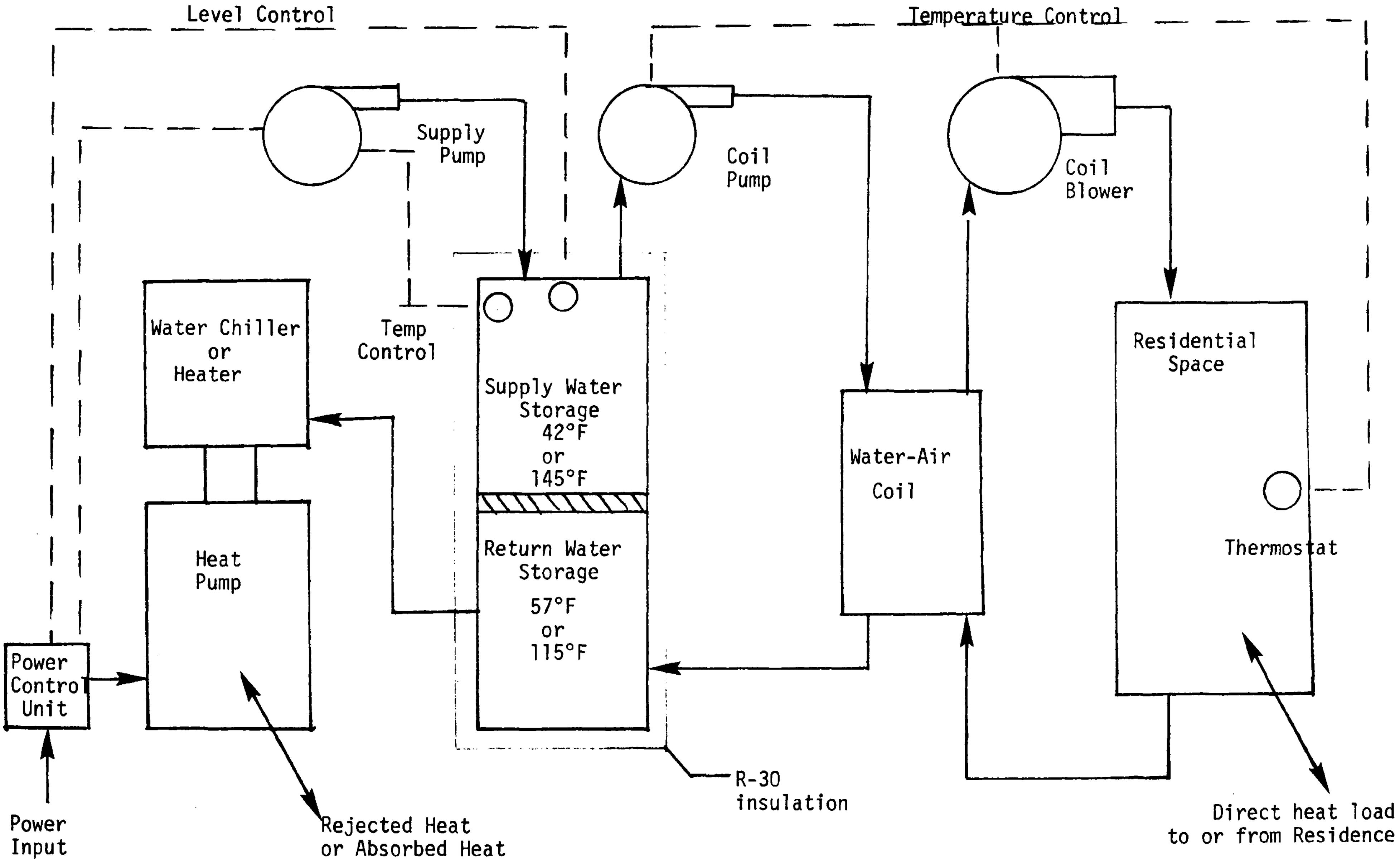

Figure 4-1 System Model: Heat Pump With Liquid Tank Storage.

lead to the following capacity equations for the HP-LTS system model:

Cooling: $Q_C = (95{,}937 - 360T_A)$ Btu/hr

Heating: $Q_H = (17{,}510 + 979T_A)$ Btu/hr
for 40°F to 60°F

$Q_H = (26{,}780 + 747T_A)$ Btu/hr
for 0°F to 40°F

Referring again to Figure 4-1, the heat pump water chiller/heater connects to a two-section storage tank with a capacity of 2200 gallons. The required storage capacity of 2045 gallons is determined by the worst case summer day storage requirement of 21.33 tons for the noon to 8 p.m. time period. In the cooling mode the three speed supply pump and thermal control sensor are used to insure that the temperature of water delivered to storage is 42°F ± 3°F under varying ambient conditions. In the heating mode, return water at 57°F or 115°F is pumped out of the lower section of the tank, cooled or heated, and then passed into the supply side of the tank. Since the volume of water within the system is constant, the insulated circular tank divider moves by differential pressure and prevents mixing of the supply and return water. The storage tank is insulated with R-30 rigid polyurethane foam.

Water is drawn from storage and passed to a water-air coil unit as required by an indoor thermostat sensor. The coil pump and coil blower operate together under the control of the thermostat. Supply and coil pumps are similar to Marsh type MDX-3, 6.7 gpm @ 105 watts.

The coil blower is rated at 1200 CFM @ 600 watts.

Overall control of the system is divided into two functions. The indoor thermostat controls the withdrawal rate of hot or cold water from storage. This action is independent of heat pump operation. The second control function is accomplished by a level control and temperature sensor located in the supply section of the storage tank. These devices activate the power control unit, which turns the heat pump on and off as required to keep the supply section of the tank full. The noon to 8 p.m. inhibit function is accomplished with a clock timer in the power control unit. Conduction losses through insulated surfaces and system ductwork are assumed to be 10% of the applied load.

C. Results of Analysis

The HP-LTS system performance was analyzed under the four load characteristics previously described; typical summer day, worst summer day, typical winter day, and worst winter day. The most important computer simulation, in terms of economic considerations, was the analysis of performance on a typical summer day. The resulting system dynamics for this condition are shown in Figure 4-2. Variations of kW demand, storage level, and applied load are shown over the 24 hour period for a typical day of cooling mode operation.

The simulation begins at midnight. The system initially operates at part load to satisfy the real time applied load. At 3:30 a.m. full system capacity is turned on and excess cooling capacity begins to be transferred into storage. The required storage capacity of 13.9 ton hours is obtained by 6:30 a.m., thus taking maximum advantage of cool night air for condenser operation. The system reverts back to part load operation, simply tracking the real time load until noon. At noon, operation of the heat pump is inhibited and all cooling is accomplished by pumping chilled water from storage. At 8 p.m. the heat pump resumes normal part load operation and continues until 3:30 a.m. the next day.

The energy required for operation of the HP-LTS during this 24-hour period was 33.75 kWh. This compares favorably with the 37.07 kWh required by the conventional heat pump system. This represents a net energy savings of 10.5 percent for the liquid storage system compared to the conventional system.

The system dynamics for typical winter operation are significantly different from summer operation, as shown in Figure 4-4. Starting at 2:00 p.m. in the afternoon the system begins to operate at full capacity, and transfer its excess heating capacity to storage. By 6:30 p.m. the storage tank is full and the system shifts back to tracking the real time load. As the coldest hours of night begin at about 10 p.m., the system starts to draw hot water from storage. This operation continues until about 10 a.m. the next morning, when the storage capacity is depleted. Then, the system resumes tracking the real time load.

The energy required for operation of the storage system during this 24-hour period was 33.73 kWh, compared to 34.59 kWh for the conventional heat pump system operating under the same typical winter day conditions. Energy savings for the storage system on this typical heating mode day was only 4.1 percent compared to the conventional system.

Worst case summer day and worst case winter day simulations are shown in Figures 4-3 and 4-5 respectively.

Annual savings for the HP-LTS system relative to the HP-BASE system were determined from the equations shown below. These equations consider a 153 day cooling season, a 151 day heating season and a 60 percent savings on the use of resistance supplement heating normally needed with the BASE system.

$$\begin{aligned}
E_{BASE} &= 153(37.07) + 151(34.59) + 1.0(0.068)(34.59)(151) \\
&= 11249 \text{ kWh/year} \\
E_{LTS} &= 153(33.75) + 151(33.73) + 0.4(0.068)(34.59)(151) \\
&= 10257 \text{ kWh/year} \\
\text{Saving} &= 991 \text{ kWh/year or } 8.8\%
\end{aligned}$$

Table 4-1 HP-LTS Typical Summer Day

LIQUID TANK STORAGE, TYPICAL SUMMER DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON HRS	D'WORK KW-HRS	CUM WORK KW-HRS
0.5	78.2	0.802	0.000	0.518	0.518
1.0	77.0	0.702	0.000	0.448	0.966
1.5	75.9	0.607	0.000	0.383	1.350
2.0	74.9	0.520	0.000	0.325	1.675
2.5	74.0	0.443	0.000	0.275	1.949
3.0	73.2	0.377	0.000	0.232	2.181
3.5	72.5	0.322	0.000	0.197	2.378
4.0	72.0	0.281	1.391	1.740	4.117
4.5	71.7	0.253	4.187	3.299	7.416
5.0	71.5	0.238	6.992	3.295	10.711
5.5	71.5	0.239	9.797	3.295	14.006
6.0	71.7	0.253	12.593	3.299	17.305
6.5	72.0	0.281	13.928	1.677	18.982
7.0	72.5	0.323	13.928	0.197	19.180
7.5	73.2	0.378	13.928	0.232	19.412
8.0	74.0	0.445	13.928	0.275	19.688
8.5	74.9	0.522	13.928	0.326	20.014
9.0	75.9	0.609	13.928	0.384	20.398
9.5	77.0	0.704	13.928	0.449	20.848
10.0	78.2	0.805	13.928	0.520	21.367
10.5	79.5	0.910	13.928	0.595	21.963
11.0	80.8	1.018	13.928	0.675	22.638
11.5	82.1	1.128	13.928	0.757	23.395
12.0	83.3	1.236	13.928	0.840	24.235
12.5	84.6	1.342	13.257	0.119	24.355
13.0	85.8	1.442	12.536	0.128	24.483
13.5	86.9	1.537	11.768	0.137	24.620
14.0	87.9	1.624	10.956	0.144	24.764
14.5	88.8	1.701	10.106	0.151	24.915
15.0	89.6	1.767	9.222	0.157	25.072
15.5	90.3	1.822	8.311	0.162	25.234
16.0	90.8	1.863	7.380	0.166	25.400
16.5	91.1	1.891	6.434	0.168	25.568
17.0	91.3	1.906	5.481	0.169	25.738
17.5	91.3	1.905	4.528	0.169	25.907
18.0	91.1	1.891	3.583	0.168	26.075
18.5	90.8	1.863	2.652	0.166	26.241
19.0	90.3	1.821	1.741	0.162	26.403
19.5	89.6	1.766	0.858	0.157	26.560
20.0	88.8	1.699	0.025	0.172	26.732
20.5	87.9	1.622	0.025	1.155	27.887
21.0	86.9	1.535	0.025	1.082	28.968
21.5	85.8	1.440	0.025	1.004	29.972
22.0	84.6	1.339	0.025	0.922	30.894
22.5	83.3	1.234	0.025	0.839	31.733
23.0	82.0	1.126	0.025	0.755	32.488
23.5	80.7	1.016	0.025	0.673	33.161
24.0	79.5	0.908	0.025	0.594	33.755

Table 4-2 HP-LTS Worst Case Summer Day

LIQUID TANK STORAGE, HOT SUMMER DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON-HRS	D'WORK KW-HRS	CUM WORK KW-HRS
0.5	90.7	1.859	0.000	1.361	1.361
1.0	89.7	1.772	0.000	1.284	2.645
1.5	88.7	1.691	0.000	1.214	3.859
2.0	87.9	1.617	0.000	1.151	5.010
2.5	87.1	1.551	0.000	1.095	6.105
3.0	86.4	1.495	1.954	3.607	9.712
3.5	85.9	1.448	3.939	3.595	13.307
4.0	85.4	1.413	5.949	3.587	16.894
4.5	85.2	1.389	7.974	3.581	20.475
5.0	85.0	1.378	10.007	3.578	24.052
5.5	85.0	1.378	12.040	3.578	27.630
6.0	85.2	1.391	14.064	3.581	31.211
6.5	85.5	1.416	16.071	3.587	34.798
7.0	85.9	1.453	18.054	3.596	38.395
7.5	86.5	1.500	20.004	3.608	42.003
8.0	87.2	1.558	21.346	2.870	44.873
8.5	87.9	1.624	21.346	1.157	46.030
9.0	88.8	1.699	21.346	1.221	47.250
9.5	89.8	1.781	21.346	1.292	48.542
10.0	90.9	1.868	21.346	1.369	49.911
10.5	91.9	1.958	21.346	1.451	51.362
11.0	93.0	2.051	21.346	1.537	52.899
11.5	94.1	2.145	21.346	1.626	54.525
12.0	95.2	2.238	21.346	1.715	56.240
12.5	96.3	2.329	20.182	0.207	56.447
13.0	97.3	2.415	18.975	0.215	56.662
13.5	98.3	2.496	17.727	0.222	56.884
14.0	99.1	2.570	16.442	0.229	57.113
14.5	99.9	2.636	15.124	0.234	57.347
15.0	100.6	2.692	13.778	0.239	57.586
15.5	101.1	2.739	12.408	0.244	57.830
16.0	101.6	2.774	11.021	0.247	58.077
16.5	101.8	2.798	9.622	0.249	58.326
17.0	102.0	2.809	8.217	0.250	58.575
17.5	102.0	2.809	6.813	0.250	58.825
18.0	101.8	2.796	5.415	0.249	59.074
18.5	101.5	2.771	4.029	0.246	59.320
19.0	101.1	2.735	2.662	0.243	59.563
19.5	100.5	2.687	1.318	0.239	59.802
20.0	99.8	2.630	0.134	0.419	60.221
20.5	99.1	2.563	0.134	2.043	62.264
21.0	98.2	2.488	0.134	1.965	64.229
21.5	97.2	2.407	0.134	1.882	66.111
22.0	96.2	2.320	0.134	1.795	67.906
22.5	95.1	2.229	0.134	1.706	69.612
23.0	94.0	2.136	0.134	1.617	71.229
23.5	92.9	2.042	0.134	1.528	72.758
24.0	91.8	1.949	0.134	1.443	74.200

Table 4-3 HP-LTS Typical Winter Day

LIQUID TANK STORAGE, TYPICAL WINTER DAY

TIME HOUR	AVG TEMP DEG F	AVG LOAD TONS	STORAGE TON-HRS	D'WORK KW-HRS	CUM WORK KW-HRS	
0.5	47.7	1.366	-0.683	0.121	0.121	8195
1.0	46.6	1.456	-1.411	0.130	0.251	16933
1.5	45.5	1.541	-2.182	0.137	0.388	26180
2.0	44.6	1.619	-2.991	0.144	0.532	35892
2.5	43.7	1.688	-3.835	0.150	0.682	46019
3.0	43.0	1.747	-4.709	0.155	0.837	56502
3.5	42.3	1.796	-5.606	0.160	0.997	67277
4.0	41.9	1.833	-6.523	0.163	1.160	78273
4.5	41.6	1.858	-7.452	0.165	1.325	89419
5.0	41.4	1.870	-8.386	0.166	1.492	100638
5.5	41.4	1.869	-9.321	0.166	1.658	111853
6.0	41.6	1.856	-10.249	0.165	1.823	122987
6.5	41.9	1.830	-11.164	0.163	1.986	133964
7.0	42.4	1.791	-12.059	0.159	2.145	144713
7.5	43.0	1.742	-12.930	0.155	2.300	155163
8.0	43.8	1.681	-13.771	0.150	2.449	165251
8.5	44.7	1.611	-14.577	0.143	2.593	174919
9.0	45.6	1.533	-15.343	0.136	2.729	184117
9.5	46.7	1.448	-16.067	0.129	2.858	192802
10.0	47.8	1.356	-16.745	0.121	2.978	200941
10.5	49.0	1.261	-17.376	0.112	3.090	208509
11.0	50.2	1.164	-17.958	0.103	3.194	215491
11.5	51.5	1.065	-18.490	0.095	3.289	221884
12.0	52.7	0.968	-18.974	0.086	3.375	227693
12.5	53.9	0.873	-19.411	0.078	3.452	232932
13.0	55.0	0.783	-19.802	0.070	3.522	237629
13.5	56.1	0.698	-20.151	0.062	3.584	241816
14.0	57.0	0.620	-20.461	0.055	3.639	245538
14.5	57.9	0.551	-19.497	1.390	5.030	248845
15.0	58.6	0.492	-16.622	3.414	8.444	251797
15.5	59.3	0.443	-13.699	3.430	11.874	254456
16.0	59.7	0.406	-10.738	3.442	15.316	256894
16.5	60.0	0.381	-7.752	3.451	18.767	259183
17.0	60.2	0.369	-4.753	3.455	22.222	261398
17.5	60.2	0.370	-1.755	3.455	25.676	263618
18.0	60.0	0.383	1.229	3.450	29.127	265918
18.5	59.7	0.409	4.187	3.441	32.568	268375
19.0	59.2	0.448	4.300	0.401	32.969	271060
19.5	58.6	0.497	4.051	0.044	33.013	274045
20.0	57.8	0.558	3.772	0.050	33.063	277391
20.5	56.9	0.628	3.458	0.056	33.118	281157
21.0	56.0	0.706	3.105	0.063	33.181	285393
21.5	54.9	0.792	2.710	0.070	33.252	290143
22.0	53.8	0.883	2.268	0.078	33.330	295438
22.5	52.6	0.978	1.779	0.087	33.417	301305
23.0	51.4	1.075	1.242	0.096	33.513	307756
23.5	50.1	1.174	0.655	0.104	33.617	314798
24.0	48.9	1.271	0.019	0.118	33.730	322424

Table 4-4 HP-LTS Worst Case Winter Day

TIME HOUR	AV. TEMP DEG F	AV. LOAD TONS	SUM CAP BTU'S	SUM LOAD BTU'S	D'WORK KW-HRS	SUM WORK KW-HRS
0.5	13.0	4.140	18260	24842	2.546	2.546
1.0	12.1	4.213	36184	50118	2.528	5.074
1.5	11.3	4.280	53791	75800	2.511	7.585
2.0	10.5	4.342	71110	101854	2.495	10.080
2.5	9.8	4.397	88171	128238	2.482	12.562
3.0	9.2	4.445	105012	154906	2.470	15.032
3.5	8.8	4.483	121671	181807	2.460	17.492
4.0	8.4	4.513	138193	208885	2.453	19.944
4.5	8.1	4.533	154622	236082	2.448	22.392
5.0	8.0	4.543	171006	263337	2.445	24.838
5.5	8.0	4.542	187392	290589	2.445	27.283
6.0	8.2	4.531	203828	317777	2.448	29.731
6.5	8.4	4.510	220362	344840	2.453	32.185
7.0	8.8	4.480	237038	371720	2.461	34.646
7.5	9.3	4.440	253898	398362	2.471	37.117
8.0	9.9	4.392	270984	424715	2.483	39.600
8.5	10.6	4.336	288330	450733	2.497	42.096
9.0	11.4	4.274	305968	476376	2.513	44.609
9.5	12.2	4.206	323924	501610	2.530	47.139
10.0	13.1	4.133	342219	526407	2.548	49.686
10.5	14.1	4.057	360868	550750	2.567	52.253
11.0	15.1	3.979	379881	574625	2.586	54.839
11.5	16.0	3.901	399260	598030	2.606	57.445
12.0	17.0	3.823	419001	620968	2.625	60.070
12.5	18.0	3.747	439095	643453	2.644	62.714
13.0	18.9	3.675	459526	665504	2.662	65.376
13.5	19.7	3.608	480274	687149	2.679	68.056
14.0	20.5	3.546	501310	708423	2.695	70.750
14.5	21.2	3.490	522603	729366	2.708	73.458
15.0	21.8	3.443	544117	750025	2.720	76.179
15.5	22.2	3.404	565812	770451	2.730	78.908
16.0	22.6	3.375	587645	790700	2.737	81.646
16.5	22.9	3.355	609571	810830	2.742	84.388
17.0	23.0	3.345	631541	830902	2.745	87.133
17.5	23.0	3.346	653510	850977	2.745	89.877
18.0	22.8	3.357	675428	871116	2.742	92.619
18.5	22.6	3.377	697249	891381	2.737	95.356
19.0	22.2	3.408	718928	911828	2.729	98.085
19.5	21.7	3.448	740422	932513	2.719	100.804
20.0	21.1	3.496	761691	953487	2.707	103.511
20.5	20.4	3.551	782700	974796	2.693	106.204
21.0	19.6	3.614	803416	996480	2.677	108.881
21.5	18.8	3.682	823815	1018573	2.660	111.542
22.0	17.9	3.755	843874	1041103	2.642	114.184
22.5	16.9	3.831	863579	1064087	2.623	116.807
23.0	15.9	3.909	882922	1087539	2.604	119.411
23.5	15.0	3.987	901898	1111462	2.584	121.995
24.0	14.0	4.065	920511	1135850	2.565	124.560

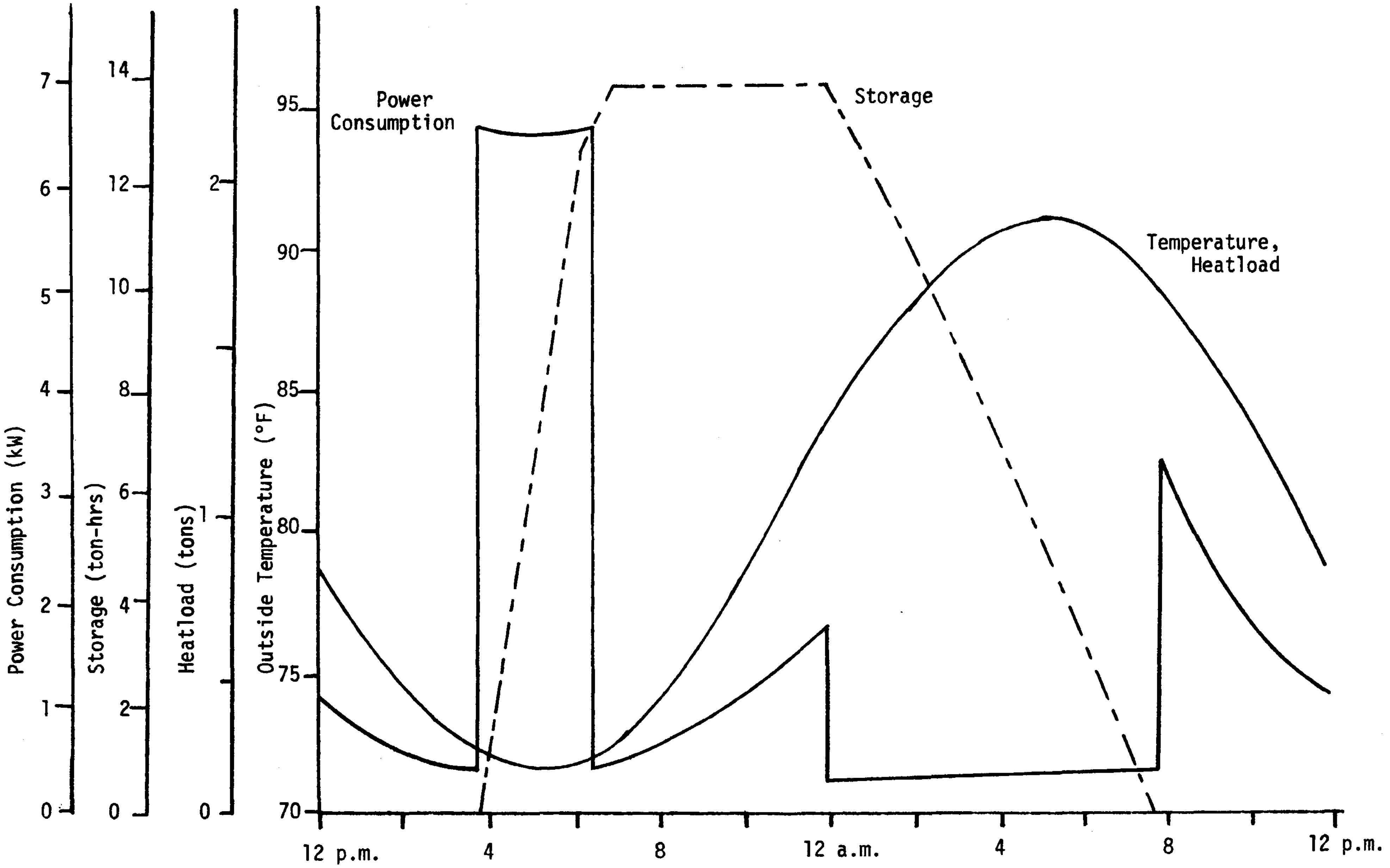

Figure 4-2 Typical Summer Day, HP-LTS

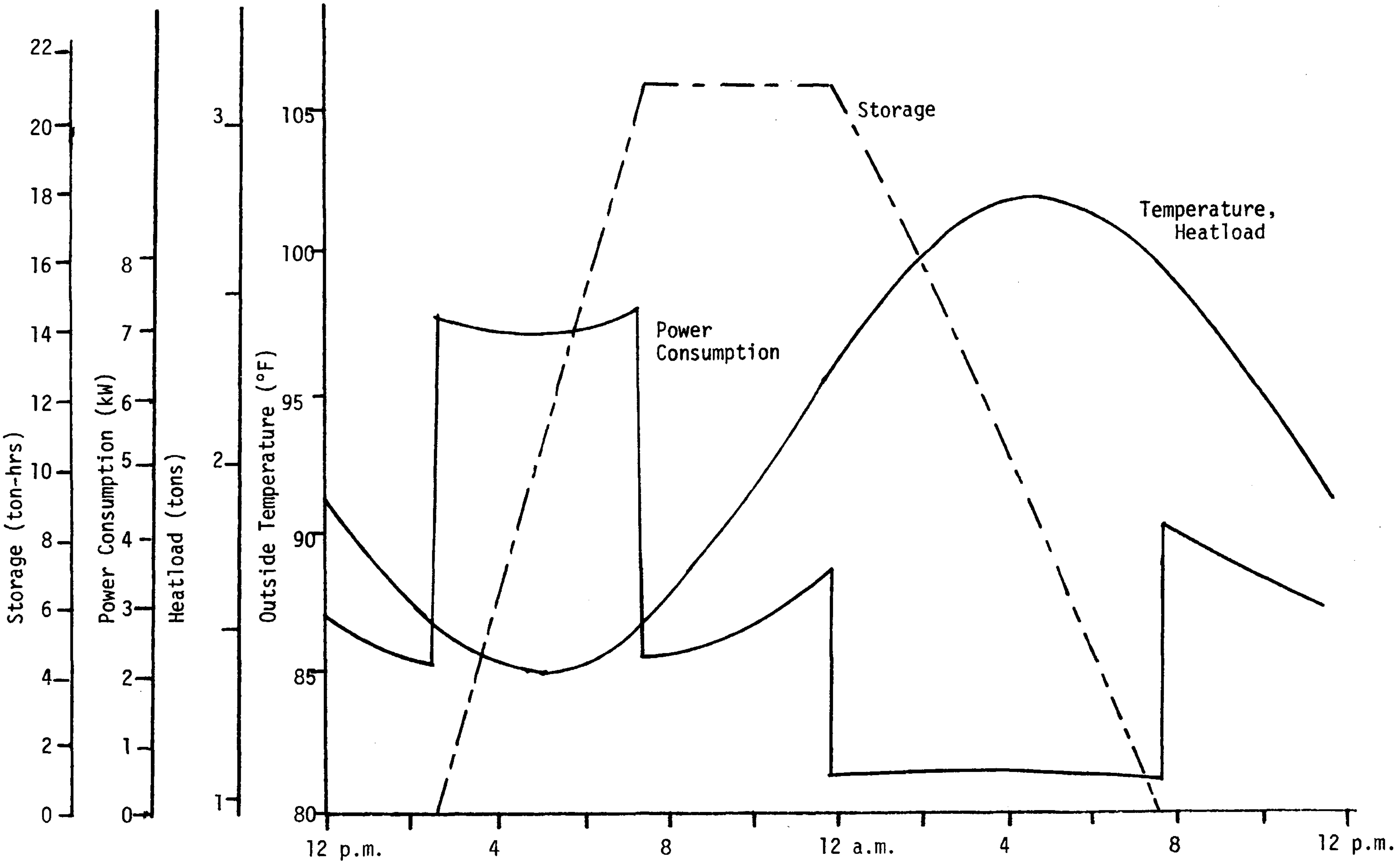

Figure 4-3 Worst Case Summer Day, HP-LTS.

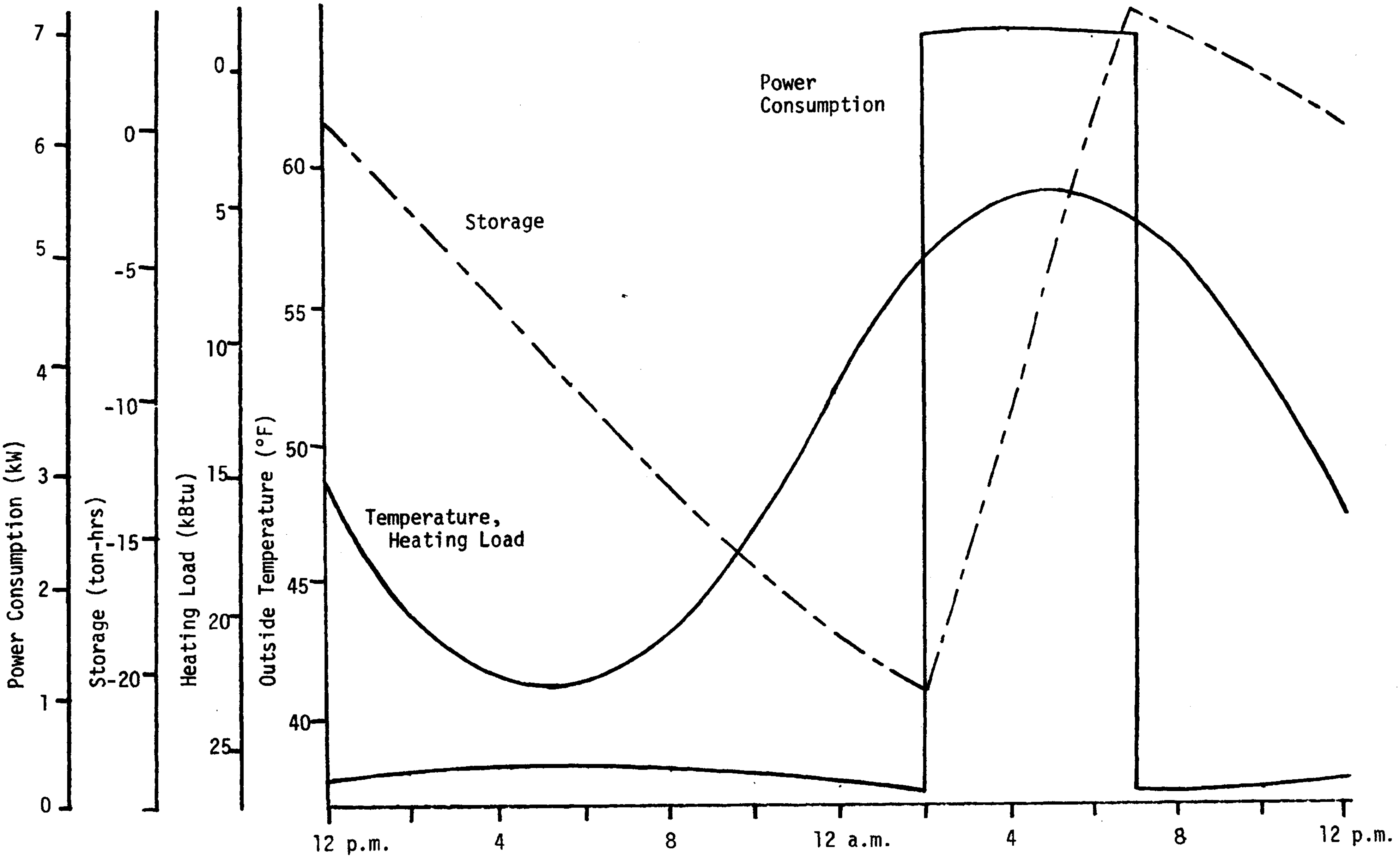

Figure 4-4 Typical Winter Day, HP-LTS.

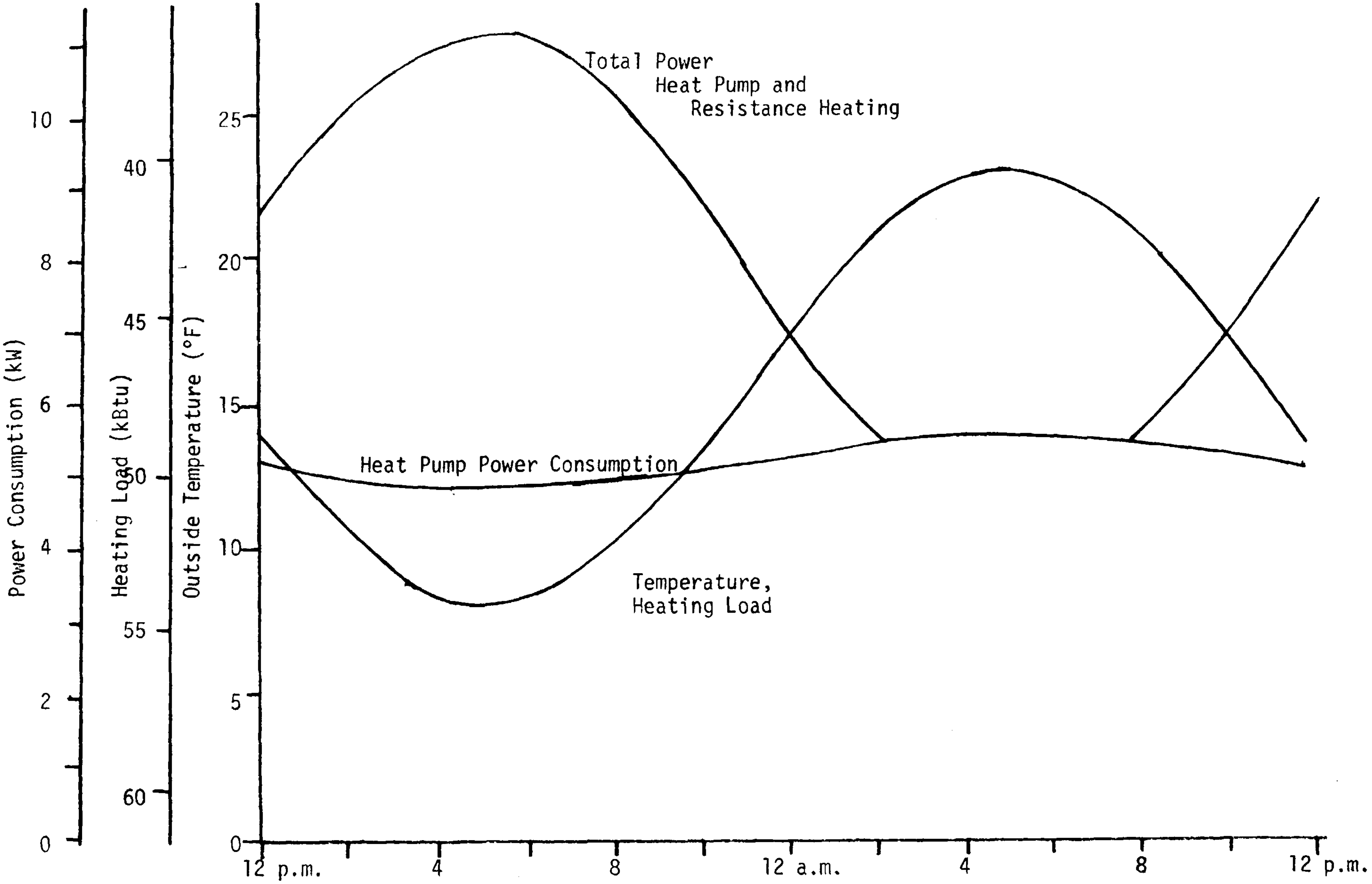

Figure 4-5 Worst Case Winter Day, HP-LTS.

5. COMPARATIVE ANALYSIS OF OPERATIONAL PERFORMANCE AND ECONOMICS

The preceding three sections have given the operating characteristics of the BASE and two thermal storage systems. The purpose of this section is to reduce these data to a common dollar base for comparison. First, let us consider the incremental capital costs associated with each of the two storage systems. These costs were obtained from consultations with air conditioning contractors and assume the following:

1. At least 100 or more installations are performed, thereby enabling quantity purchases of all parts and materials, and reduction in the costs of "learning" a new installation.
2. All system components are standard "off-the-shelf" items.

<u>Incremental Cost of Installation of HP-RBS</u>

The following incremental costs for the rock-bed system were estimated:

1.	Extra cost of Carrier 50PQ006 vs 38HQ134 Heat Pump	$ 850
2.	Extra duct work	200
3.	1000 ft^3 rock-bed storage	1,150
4.	Special dampers and controls	225
5.	Extra Labor	400
	Total incremental cost	$2,825

<u>Incremental Cost of Installation of HP-LTS</u>

The following incremental costs for the liquid tank system were estimated:

1.	Extra cost of Carrier 50PQ006 vs 38HQ134 Heat Pump	$ 850
2.	Water chiller modifications to evaporator	75
3.	Special electrical controls	175
4.	2200 gallon insulated storage tank	800
5.	Water-air coil, 2 pumps, piping	250
6.	Extra labor	400
	Total incremental cost	$2,550

These incremental costs must now be compared with the power savings over the BASE unit. For purposes of computing the savings over the BASE unit it is assumed:

1. The HP-RBS system can operate at all times of day without resistance heating.
2. The HP-LTS system will save 60 percent of the resistance heating expense of the BASE unit.
3. Power costs at 4.5¢/kWh.

The savings can then be computed as in Table 5-1.

Table 5-1

Comparative Savings of HP-TES Systems

Item	HP-BASE	HP-RBS	HP-LTS
1. TSD Energy, kWh/day	37.07	34.20	33.75
2. Season Cooling Energy, kWh	5671	5233	5164
3. TWD Energy, kWh/day	34.57	35.46	33.73
4. Resistance Heating Energy, kWh/day	2.35	0	0.92
5. Season Heating Energy, kWh	5574	5354	5232
6. Annual Energy, kWh	11245	10587	10396
7. Annual Energy Cost @ 4.5¢/kWh	$506	476	467
8. Annual Savings over BASE Unit	NA	$ 30	39
9. Annual % saving over BASE unit	NA	5.9	7.7
10. Incremental cost over BASE unit	NA	$2825	$2550
11. Years Payback (10)÷(8)		94	65

6. CONCLUSIONS AND RECOMMENDATIONS

Analyses in the foregoing sections have illustrated the demand peak problem in Texas cities and shown that it would be possible to reduce some of this peak with a heat pump-thermal energy storage system.

Rock-bed and liquid tank storage systems have been analyzed in conjunction with existing off-the-shelf heat pump equipment. Such operation is feasible from a technical standpoint, but the economic savings in power costs are not great enough to offset the increased capital expenditures for storage equipment, additional ducting, pumps, and controls. Section 5 has given comparative cost figures for the BASE, rock-bed, and liquid tank systems. The essential conclusion is that for a moderate climate like Dallas, Texas, there is not much power saving to be gained by heat pump operation during the cooler (or warmer) periods of the day. It is possible that a storage system could be economical in some commercial heat pump application with load requirements different from that for the typical residence which was studied here.

A number of heat pumps have been operated around the country in connection with solar collectors and thermal energy storage systems. We acknowledge this type of operation, but it was outside the scope of the present study.

Because the thermal energy storage systems produce only a small savings in power costs in this analysis, we do not recommend expenditure of funds for any type of demonstration project in this area. Had the results indicated a viable economic incentive, it would have been fruitful to carry the heat pump-thermal energy storage idea further by building and operating an actual system. But, it appears that there is nothing to be gained in a practical sense for such a project.

Based upon the results of this study the investigators recommend that the DOE demonstration projects described in Appendix C should not proceed. Such a program would only prove once again that the payback period for small scale HP-TES systems as used in residential applications would be unacceptable. It is suggested that DOE funding for residential thermal storage demonstrations could be more productive if redirected toward large-scale thermal storage projects, the investigation of ground water source heat pump demonstrations, and further development of indirect evaporative cooling processes.

APPENDIX A

COMPUTER PROGRAMS

Table A2-1 HP-BASE Typical Summer Day

```
10 Q9=0
20 D2=0.05
30 Q5=0
40 D1=0
50 W5=0
60 PRINT "       TIME   AV. TEMP   AV. LOAD    SUM CAP   SUM LOAD     D'WORK   SUM WORK
70 PRINT "       HOUR      DEG F       TONS      BTU'S      BTU'S     KW-HRS     KW-HRS
80 W7=0
90 J=48
100 FOR T=1 TO J
110 T2=0
120 Q6=0
130 FOR G=1 TO 10
140 D1=D1+D2
150 T1=81.4+9.9*SIN(3.141592/12*(D1-11))
160 Q1=(921.04*(T1-75)+5800)*1.1
170 Q2=Q1*D2
180 Q3=48786-173.3*T1
190 Q4=D2*Q3
200 W3=2.03+0.024*T1
205 W5=W5+W3*Q1/Q3*D2
210 T2=T2+T1/10
220 Q6=Q6+Q1/120000
230 Q5=Q5+Q4
240 Q9=Q9+Q2
250 NEXT G
260 W8=W5-W7
270 W7=W5
280 WRITE (15,290)D1,T2,Q6,Q5,Q9,W8,W5
290 FORMAT 2F10.1,F10.3,2F10.0,2F10.3
300 NEXT T
310 END
```

Table A2-2 HP-BASE Hot Summer Day

```
10 Q9=0
20 D2=0.05
30 Q5=0
40 D1=0
50 W5=0
60 PRINT "      TIME  AV. TEMP   AV. LOAD   SUM CAP  SUM LOAD    D'WORK  SUM WORK
70 PRINT "      HOUR     DEG F       TONS     BTU'S     BTU'S    KW-HRS    KW-HRS
80 W7=0
90 J=48
100 FOR T=1 TO J
110 T2=0
120 Q6=0
130 FOR G=1 TO 10
140 D1=D1+D2
150 T1=93.5+8.5*SIN(3.141592/12*(D1-11))
160 Q1=(921.04*(T1-75)+5800)*1.1
170 Q2=Q1*D2
180 Q3=48786-173.3*T1
190 Q4=D2*Q3
200 W3=2.03+0.024*T1
201 D9=Q1/Q3
202 IF (D9 <= 1) THEN 205
203 D9=1
205 W5=W5+W3*D9*D2
210 T2=T2+T1/10
220 Q6=Q6+Q1/120000
230 Q5=Q5+Q4
240 Q9=Q9+Q2
250 NEXT G
260 W8=W5-W7
270 W7=W5
280 WRITE (15,290)D1,T2,Q6,Q5,Q9,W8,W5
290 FORMAT 2F10.1,F10.3,2F10.0,2F10.3
300 NEXT T
310 END
```

Table A2-3 HP-BASE Typical Winter Day

```
10 Q9=0
20 D2=0.05
30 Q5=0
40 D1=0
50 W5=0
60 PRINT "      TIME  AV. TEMP  AV. LOAD   SUM CAP  SUM LOAD    D'WORK  SUM WORK
70 PRINT "      HOUR     DEG F      TONS     BTU'S     BTU'S    KW-HRS    KW-HRS
80 W7=0
90 J=48
100 FOR T=1 TO J
110 T2=0
120 Q6=0
130 FOR G=1 TO 10
140 D1=D1+D2
150 T1=50.8+9.4*SIN(3.141592/12*(D1-11))
160 Q1=(872.85*(68-T1)-2800)*1.1
170 Q2=Q1*D2
180 Q3=11600+540*T1
190 Q4=D2*Q3
200 W3=2.42+0.033*T1
201 D9=Q1/Q3
202 IF (D9 <= 1) THEN 205
203 D9=1
205 W5=W5+W3*D9*D2
210 T2=T2+T1/10
220 Q6=Q6+Q1/120000
230 Q5=Q5+Q4
240 Q9=Q9+Q2
250 NEXT G
260 W8=W5-W7
270 W7=W5
280 WRITE (15,290)D1,T2,Q6,Q5,Q9,W8,W5
290 FORMAT 2F10.1,F10.3,2F10.0,2F10.3
300 NEXT T
310 END
```

Table A2-4 HP-BASE Worst Case Winter Day

```
  TIME   AV. TEMP   AV. LOAD    SUM CAP   SUM LOAD    D'WORK  SUM WORK
  HOUR     DEG F        TONS      BTU'S      BTU'S    KW-HRS    KW-HRS
```

```
10 Q9=0
20 D2=0.05
30 Q5=0
40 D1=0
50 W5=0
60 PRINT "        TIME   AV. TEMP   AV. LOAD    SUM CAP   SUM LOAD    D'WORK  SUM WORK
70 PRINT "        HOUR     DEG F        TONS      BTU'S      BTU'S    KW-HRS    KW-HRS
80 W7=0
90 J=48
100 FOR T=1 TO J
110 T2=0
120 Q6=0
130 FOR G=1 TO 10
140 D1=D1+D2
150 T1=15.5+7.5*SIN(3.141592/12*(D1-11))
160 Q1=(872.85*(68-T1)-2800)*1.1
170 Q2=Q1*D2
180 Q3=11600+540*T1
190 Q4=D2*Q3
200 W3=2.42+0.033*T1
201 D9=Q1/Q3
202 IF (D9 <= 1) THEN 205
203 D9=1
205 W5=W5+W3*D9*D2
210 T2=T2+T1/10
220 Q6=Q6+Q1/120000
230 Q5=Q5+Q4
240 Q9=Q9+Q2
250 NEXT G
260 W8=W5-W7
270 W7=W5
280 WRITE (15,290)D1,T2,Q6,Q5,Q9,W8,W5
290 FORMAT 2F10.1,F10.3,2F10.0,2F10.3
300 NEXT T
310 END
```

Table A3-1a HP-RBS Typical Summer Day

```
10 DIM T[25],B[25]
20 S1=167010
30 FOR M=1 TO 25
40 D2=0.05
50 T[M]=65
60 NEXT M
70 Z=1
80 D3=10/25
90 W=9000
100 C1=0.21
110 C2=0.24
120 T2=65
130 D1=0
140 R1=91
150 A=100
160 C=W*C2/R1/A/C1
170 V=1000
180 W5=0
190 D5=3.75
200 Q5=0
210 D1=0
220 W5=0
230 W7=0
240 J=48
250 PRINT "        ROCK BED STORAGE SYSTEM TYPICAL DAY"
260 PRINT "   TIME AVG TEMP AVG LOAD  STORAGE  D'WORK  CUM WORK  T ROCK"
270 PRINT "   HOUR    DEG F     TONS  TON-HRS   KW-HRS    KW-HRS   DEG F"
280 FOR T=1 TO J
290 T2=0
300 Q6=0
310 FOR G=1 TO 10
320 D1=D1+D2
330 T1=81.4+9.9*SIN(3.141592/12*(D1-11))
340 Q1=(921.04*(T1-75)+5800)*1.1
350 Q2=Q1*D2
360 K1=(D1 <= D5 OR D1 >= 20)
370 K2=(D1>12 AND D1<20)
380 IF K1 THEN 410
390 IF ( NOT K1 AND  NOT K2) THEN 430
400 IF K2 THEN 450
410 GOSUB 630
420 GOTO 470
430 GOSUB 670
440 GOTO 470
450 GOSUB 850
460 GOTO 470
470 T2=T2+T1/10
480 Q6=Q6+Q1/120000
```

Table A3-1b HP-RBS Typical Summer Day

```
    FOR I=1 TO 25
510 T9=T[I]/25+T9
520 NEXT I
530 Q5=(65-T9)*V*R1*C1
540 Q7=Q5/12000
550 NEXT G
560 Q7=Q5/12000
570 W8=W5-W7
580 W7=W5
590 WRITE (15,600)T[1],T[3],T[5],T[8],T[10],T[13],T[16],T[18],T[21],T[23],T[2
600 FORMAT 11F7.1
610 NEXT T
620 END
630 F1=65
640 GOSUB 990
650 W5=W5+W4*Q1/Q3
660 RETURN
670 F1=65
680 GOSUB 990
690 W5=W5+W4*Q1/Q3
700 IF (Q5>S1) THEN 840
710 F=D2*C/Z/D3*(1-Q1/Q3)
720 F1=T[25]
730 GOSUB 990
740 T[1]=T[25]-Q3/W/C2
750 FOR R=1 TO Z
 50 FOR S=1 TO 25
770 B[S]=T[S]
780 NEXT S
790 FOR I=2 TO 25
800 T[I]=(1-F)*B[I]+F*B[I-1]
810 NEXT I
820 NEXT R
830 W5=W5+W4*(1-Q1/Q3)
840 RETURN
850 C9=W*C2*(75-T[1])
860 F7=Q1/C9*D2
870 W5=W5+F7*0.8
880 T[25]=75
890 F=F7*C/D3/Z
900 FOR R=1 TO Z
910 FOR S=1 TO 25
920 B[S]=T[S]
930 NEXT S
940 FOR I=1 TO 24
950 T[25-I]=(1-F)*B[25-I]+F*B[26-I]
960 NEXT I
970 NEXT R
980 RETURN
990 Q3=23830-333.3*T1+1000*F1
1000 Q4=D2*Q3
1010 W3=1.7926+0.0427*F1+0.034*T1
 320 W4=D2*W3
1030 RETURN
```

Table A3-2 HP-RBS Worst Case Summer Day

```
10 DIM T[25],B[25]
20 S1=256014
30 FOR M=1 TO 25
40 D2=0.05
50 T[M]=65
60 NEXT M
70 Z=1
80 D3=10/25
90 W=9000
100 C1=0.21
110 C2=0.24
120 T2=65
130 D1=0
140 R1=91
150 A=100
160 C=W*C2/R1/A/C1
170 V=1000
180 W5=0
190 D5=2.5
200 Q5=0
210 D1=0
220 W5=0
230 W7=0
240 J=48
250 PRINT "         ROCK BED STORAGE SYSTEM HOT DAY        "
260 PRINT '    TIME AVG TEMP AVG LOAD  STORAGE   D'WORK  CUM WORK  T ROCK"
270 PRINT "    HOUR    DEG F     TONS TON-HRS   KW-HRS    KW-HRS   DEG F"
280 FOR T=1 TO J
290 T2=0
300 Q6=0
310 FOR G=1 TO 10
320 D1=D1+D2
330 T1=93.5+8.5*SIN(3.141592/12*(D1-11))
340 Q1=(921.04*(T1-75)+5800)*1.1
350 Q2=Q1*D2
360 K1=(D1 <= D5 OR D1 >= 20)
370 K2=(D1>12 AND D1<20)
380 IF K1 THEN 410
390 IF ( NOT K1 AND  NOT K2) THEN 430
400 IF K2 THEN 450
410 GOSUB 630
420 GOTO 470
430 GOSUB 670
440 GOTO 470
450 GOSUB 850
460 GOTO 470
470 T2=T2+T1/10
480 Q6=Q6+Q1/120000
490 T9 0
```

```
500 FOR I=1 TO 25
510 T9=T[ I ]/25+T9
520 NEXT I
530 Q5=(65-T9)*V*R1*C1
540 Q7=Q5/12000
550 NEXT G
560 Q7=Q5/12000
570 W8=W5-W7
580 W7=W5
590 WRITE (15,600)T[ 1 ],T[ 3 ],T[ 5 ],T[ 8 ],T[ 10 ],T[ 13 ],T[ 16 ],T[ 18 ],T[ 21 ],T[ 23 ],T[ 2
600 FORMAT 11F6.1
610 NEXT T
620 END
630 F1=65
640 GOSUB 990
650 W5=W5+W4*Q1/Q3
660 RETURN
670 F1=65
680 GOSUB 990
690 W5=W5+W4*Q1/Q3
700 IF (Q5>S1) THEN 840
710 F=D2*C/Z/D3*(1-Q1/Q3)
720 F1=T[ 25 ]
730 GOSUB 990
740 T[ 1 ]=T[ 25 ]-Q3/W/C2
750 FOR R=1 TO Z
760 FOR S=1 TO 25
770 B[ S ]=T[ S ]
780 NEXT S
790 FOR I=2 TO 25
800 T[ I ]=(1-F)*B[ I ]+F*B[ I-1 ]
810 NEXT I
820 NEXT R
830 W5=W5+W4*(1-Q1/Q3)
840 RETURN
850 C9=W*C2*(75-T[ 1 ])
860 F7=Q1/C9*D2
870 W5=W5+F7*0.8
880 T[ 25 ]=75
890 F=F7*C/D3/Z
900 FOR R=1 TO Z
910 FOR S=1 TO 25
920 B[ S ]=T[ S ]
930 NEXT S
940 FOR I=1 TO 24
950 T[ 25-I ]=(1-F)*B[ 25-I ]+F*B[ 26-I ]
960 NEXT I
970 NEXT R
980 RETURN
990 Q3=23830-333.3*T1+1000*F1
1000 Q4=D2*Q3
  10 W3=1.7926+0.0427*F1+0.034*T1
1020 W4=D2*W3
1030 RETURN
```

Table A3-3a HP-RBS Typical Winter Day

```
10 DIM T[25],B[25]
20 D5=0
30 T5=56
40 D2=0.05
50 FOR M=1 TO 25
60 T[M]=T5
70 NEXT M
80 Z=1
90 D3=10/25
100 W=18000
110 C1=0.21
120 C2=0.24
130 T2=55
140 D1=0
150 R1=91
160 A=100
170 C=W*C2/R1/A/C1
180 V=1000
190 W5=0
200 D7=13
210 D6=14
220 D8=18
230 W7=0
240 J=48
250 PRINT "         ROCK BED STORAGE SYSTEM TYPICAL DAY"
260 PRINT "    TIME AVG TEMP AVG LOAD  STORAGE   D'WORK  CUM WORK  T ROCK"
270 PRINT "    HOUR    DEG F     TONS  TON-HRS   KW-HRS    KW-HRS   DEG F"
280 FOR T=1 TO J
290 T2=0
300 Q6=0
310 FOR G=1 TO 10
320 D1=D1+D2
330 T1=50.8+9.4*SIN(3.141592/12*(D1-11))
340 Q1=(872.85*(68-T1)-2800)*1.1
350 Q2=Q1*D2
360 K1=((D1 >= D5 AND D1<D7) OR D1>D8)
370 K2=(D1>D6 AND D1<D8)
380 IF K1 THEN 420
390 IF ( NOT K1 AND  NOT K2) THEN 450
400 IF K2 THEN 440
410 GOTO 460
420 GOSUB 660
430 GOTO 460
440 GOSUB 800
450 GOSUB 620
460 T2=T2+T1/10
470 Q6=Q6-Q1/12000
```

Table 3-3b HP-RBS Typical Winter Day

```
480 T9=0
490 FOR I=1 TO 25
500 T9=T[I]/25+T9
510 NEXT I
520 Q5=(T5-T9)*V*R1*C1
530 Q7=Q5/12000
540 NEXT G
550 Q7=Q5/12000
560 W8=W5-W7
570 W7=W5
580 WRITE (15,590)D1,T2,Q6,Q7,W8,W5,T9
590 FORMAT F8.1,F9.1,4F9.3,F9.1
600 NEXT T
610 END
620 F1=T1
630 GOSUB 920
640 W5=W5+W4*Q1/Q3
650 RETURN
660 F1=T[25]
670 GOSUB 920
680 F=D2*C/Z/D3*(Q1/Q3)
690 T[1]=T[25]-Q9/W/C2
700 FOR R=1 TO Z
710 FOR S=1 TO 25
720 B[S]=T[S]
730 NEXT S
740 FOR I=2 TO 25
750 T[I]=(1-F)*B[I]+F*B[I-1]
760 NEXT I
770 NEXT R
780 W5=W5+W4*(Q1/Q3)
790 RETURN
800 W5=W5+D2*0.8
810 T[25]=T1
820 F=D2*C/D3/Z
830 FOR R=1 TO Z
840 FOR S=1 TO 25
850 B[S]=T[S]
860 NEXT S
870 FOR I=1 TO 24
880 T[25-I]=(1-F)*B[25-I]+F*B[26-I]
890 NEXT I
900 NEXT R
910 RETURN
920 Q3=55000+950*(F1-40)
930 Q4=D2*Q3
940 W3=6.1+0.06*(F1-40)
950 Q9=Q3-3413*W3
960 W4=D2*W3
970 RETURW
```

Table A3-4a HP-RBS Worst Case Winter Day

```
10 DIM T[25],E[25]
20 T5=21
30 Q4=0
40 D6=0
50 FOR M=1 TO 25
60 D2=0.05
70 T[M]=T5
80 NEXT M
90 Z=1
100 D3=10/25
110 W=18000
120 C1=0.21
130 C2=0.24
140 T2=55
150 D1=0
160 R1=91
170 A=100
180 C=W*C2/R1/A/C1
190 V=1000
200 W5=0
210 D7=10
220 D6=14
230 D8=18
240 W7=0
250 J=48
260 PRINT "         ROCK BED STORAGE SYSTEM WORST CASE DAY"
270 PRINT "    TIME AVG TEMP AVG LOAD  STORAGE    D'WORK  CUM WORK  T ROCK"
280 PRINT "    HOUR    DEG F     TONS  TON-HRS    KW-HRS    KW-HRS   DEG F"
290 FOR T=1 TO J
300 T2=0
310 Q6=0
320 FOR G=1 TO 10
330 D1=D1+D2
340 T1=15.5+7.5*SIN(3.141592/12*(D1-11))
350 Q1=(872.85*(68-T1)-2800)*1.1
360 Q2=Q1*D2
370 K1=((D1 >= D5 AND D1<D7))
380 K2=(D1>D6 AND D1<D8)
390 IF K1 THEN 430
400 IF ( NOT K1 AND  NOT K2) THEN 460
410 IF K2 THEN 450
420 GOTO 470
430 GOSUB 680
440 GOTO 470
450 GOSUB 820
460 GOSUB 640
470 T2=T2+T1/10
480 Q6=Q6+Q1/120000
```

Table A3-4b HP-RBS Worst Case Winter Day

```
490 T9=0
500 FOR I=1 TO 25
510 T9=T[I]/25+T9
520 NEXT I
530 Q5=(T5-T9)*V*R1*C1
540 Q4=D2*Q3*D9+Q4
550 Q7=Q5/12000
560 NEXT G
570 Q7=Q5/12000
580 W8=W5-W7
590 W7=W5
600 WRITE (15,610)T[1],T[3],T[5],T[8],T[10],T[13],T[16],T[18],T[2
610 FORMAT 11F7.1
620 NEXT T
630 END
640 F1=T1
650 GOSUB 940
660 W5=W5+W4*D9
670 RETURN
680 F1=T[25]
690 GOSUB 940
700 F=D2*C/Z/D3*D9
710 T[1]=T[25]-Q9/W/C2
720 FOR R=1 TO Z
730 FOR S=1 TO 25
740 B[S]=T[S]
750 NEXT S
760 FOR I=2 TO 25
770 T[I]=(1-F)*B[I]+F*B[I-1]
780 NEXT I
790 NEXT R
800 W5=W5+W4*(D9)
810 RETURN
820 W5=W5+D2*0.8
830 T[1]=T1
840 F=D2*C/D3/Z
850 FOR R=1 TO Z
860 FOR S=1 TO 25
870 B[S]=T[S]
880 NEXT S
890 FOR I=2 TO 25
900 T[I]=(1-F)*B[I]+F*B[I-1]
910 NEXT I
920 NEXT R
930 RETURN
940 Q3=26000+725*F1
950 W3=4.5+0.04*F1
960 Q9=Q3-3413*W3
970 W4=D2*W3
980 D9=Q1/Q3
990 IF (D9 <= 1) THEN 1010
1000 D9=1
1010 RETURN
```

Table A4-1 HP-LTS Typical Summer Day

```
10 S1=167013
20 D2=0.01
30 C3=33735
40 D5=3.75
50 Q5=0
60 D1=0
70 W5=0
80 W7=0
90 J=48
100 PRINT "         LIQUID TANK STORAGE, TYPICAL SUMMER DAY"
110 PRINT "      TIME  AVG TEMP  AVG LOAD   STORAGE    D'WORK  CUM WORK"
120 PRINT "      HOUR     DEG F      TONS   TON-HRS    KW-HRS    KW-HRS"
130 FOR T=1 TO J
140 T2=0
150 Q6=0
160 FOR G=1 TO 50
170 D1=D1+D2
180 T1=81.4+9.9*SIN(3.141592/12*(D1-11))
190 Q1=(921.04*(T1-75)+5800)*1.1
200 Q2=Q1*D2
210 Q3=95937-360*T1
220 Q4=D2*Q3
230 W3=4.568+0.034*T1
240 W4=D2*W3
250 K1=(D1 <= D5 OR D1 >= 20)
260 K2=(D1>12 AND D1<20)
270 IF K1 THEN 300
280 IF ( NOT K1 AND  NOT K2) THEN 320
290 IF K2 THEN 380
300 W5=W5+(W3+0.07)*D2*Q1/Q3
310 GOTO 400
320 W5=W5+(W3+0.07)*D2*Q1/Q3
330 IF (Q5<S1) THEN 350
340 GOTO 400
350 W5=W5+(W3-0.43)*D2*(1-Q1/Q3)
360 Q5=Q5+Q4*(1-Q1/Q3)
370 GOTO 400
380 Q5=Q5-Q2
390 W5=W5+0.5*Q1/C3*D2
400 T2=T2+T1/10/5
410 Q6=Q6+Q1/120000/5
420 Q7=Q5/12000
430 NEXT G
440 W8=W5-W7
450 W7=W5
460 WRITE (15,470)D1,T2,Q6,Q7,W8,W5
470 FORMAT 2F10.1,4F10.3
490 NEXT T
490 END
```

Table A4-2 HP-LTS Worst Case Summer Day

```
10 S1=256014
20 D2=0.05
30 C3=33735
40 D5=2.5
50 Q5=0
60 D1=0
70 W5=0
80 W7=0
90 J=48
100 PRINT "          LIQUID TANK STORAGE,     HOT SUMMER DAY"
110 PRINT "       TIME  AVG TEMP  AVG LOAD   STORAGE    D'WORK  CUM WORK"
120 PRINT "       HOUR      DEG F      TONS   TON-HRS    KW-HRS    KW-HRS"
130 FOR T=1 TO J
140 T2=0
150 Q6=0
160 FOR G=1 TO 10
170 D1=D1+D2
180 T1=93.5+8.5*SIN(3.141592/12*(D1-11))
190 Q1=(921.04*(T1-75)+5800)*1.1
200 Q2=Q1*D2
210 Q3=95937-360*T1
220 Q4=D2*Q3
230 W3=4.568+0.034*T1
240 W4=D2*W3
250 K1=(D1 <= D5 OR D1 >= 20)
260 K2=(D1>12 AND D1<20)
270 IF K1 THEN 300
280 IF ( NOT K1 AND  NOT K2) THEN 320
290 IF K2 THEN 380
300 W5=W5+(W3+0.07)*D2*Q1/Q3
310 GOTO 400
320 W5=W5+(W3+0.07)*D2*Q1/Q3
330 IF (Q5<S1) THEN 350
340 GOTO 400
350 W5=W5+(W3-0.43)*D2*(1-Q1/Q3)
360 Q5=Q5+Q4*(1-Q1/Q3)
370 GOTO 400
380 Q5=Q5-Q2
390 W5=W5+0.5*Q1/C3*D2
400 T2=T2+T1/10
410 Q6=Q6+Q1/120000
420 Q7=Q5/12000
430 NEXT G
440 W8=W5-W7
450 W7=W5
460 WRITE (15,470)D1,T2,Q6,Q7,W8,W5
470 FORMAT 2F10.1,4F10.3
480 NEXT T
490 END
```

Table 4-3 HP-LTS Typical Winter Day

```
10 S1=50472
15 K2=0
20 Q9=0
30 D2=0.05
40 C3=33735
50 D5=14.31
80 Q5=0
90 D1=0
100 W5=0
110 W7=0
120 J=48
130 PRINT "         LIQUID TANK STORAGE, TYPICAL WINTER DAY"
140 PRINT "      TIME  AVG TEMP  AVG LOAD   STORAGE    D'WORK  CUM WORK"
150 PRINT "      HOUR      DEG F      TONS   TON-HRS    KW-HRS    KW-HRS"
160 FOR T=1 TO J
170 T2=0
180 Q6=0
190 FOR G=1 TO 10
200 D1=D1+D2
210 T1=50.8+9.4*SIN(3.141592/12*(D1-11))
220 Q1=(872.85*(68-T1)-2800)*1.1
230 Q2=Q1*D2
240 Q3=(55000+950*(T1-40))*1.03
250 Q4=D2*Q3
260 W3=6.1+0.06*(T1-40)
270 W4=D2*W3
280 K1=(D1 <= D5)
300 IF K1 THEN 410
310 IF K2 THEN 410
350 W5=W5+(W3+0.07)*D2*Q1/Q3
355 K2=(Q5>S1)
360 IF (Q5<S1) THEN 380
370 GOTO 430
380 W5=W5+(W3-0.43)*D2*(1-Q1/Q3)
390 Q5=Q5+Q4*(1-Q1/Q3)
400 GOTO 430
410 Q5=Q5-Q2
420 W5=W5+0.5*Q1/C3*D2
430 T2=T2+T1/10
440 Q6=Q6+Q1/120000
450 Q7=Q5/12000
460 Q9=Q9+Q2
470 NEXT G
480 W8=W5-W7
490 W7=W5
500 WRITE (15,510)D1,T2,Q6,Q7,W8,W5,Q9
510 FORMAT 2F10.1,4F10.3,F7.0
520 NEXT T
530 END
```

Table A4-4 HP-LTS Worst Case Winter Day

```
10 Q9=0
20 D2=0.05
30 Q5=0
40 D1=0
50 W5=0
60 PRINT "      TIME  AV. TEMP  AV. LOAD   SUM CAP  SUM LOAD    D'WORK  SUM WORK
70 PRINT "      HOUR     DEG F      TONS     BTU'S     BTU'S    KW-HRS     KW-HRS
80 W7=0
90 J=48
100 FOR T=1 TO J
110 T2=0
120 Q6=0
130 FOR G=1 TO 10
140 D1=D1+D2
150 T1=15.5+7.5*SIN(3.141592/12*(D1-11))
160 Q1=(872.85*(68-T1)-2800)*1.1
170 Q2=Q1*D2
180 Q3=(26000+725*T1)*1.03
190 Q4=D2*Q3
200 W3=4.5+0.04*T1
205 W5=W5+(W3+0.07)*D2
210 T2=T2+T1/10
220 Q6=Q6+Q1/120000
230 Q5=Q5+Q4
240 Q9=Q9+Q2
250 NEXT G
260 W8=W5-W7
270 W7=W5
280 WRITE (15,290)D1,T2,Q6,Q5,Q9,W8,W5
290 FORMAT 2F10.1,F10.3,2F10.0,2F10.3
300 NEXT T
310 END
```

APPENDIX B

TECHNICAL REFERENCES

REFERENCES

1. Zenz, F.A., and M.A. Othmer, Fluidization, Reinhold, 1960.
2. Holman, J.P., Heat Transfer, 4th Ed., McGraw-Hill, 1976.
3. Bywaters, R.P., et al, "Power Reduction in Residential Air Conditioning Systems Through the use of Thermal Energy Storage." Center for Energy Studies, University of Texas at Austin, March 1977.
4. Bywaters, R.P., and Hannan, D.G., "An Evaluation of Technical Options for Off-Peak Air Conditioning Systems", Center for Energy Studies, University of Texas at Austin, May 31, 1977.
5. "Cooling Storage Assessment Study", Electric Research Institute, EPRI Report EM-468, May 1977.
6. Penner, S.S., Alternate Energy Sources, Vol. II, p. 213, Addison-Wesley, 1976.
7. Eshleman, W.D., et al, "A Numerical Simulation of Heat Transfer in Rock Beds", ISES Proceedings of Annual Meeting 1977, pp. 17-21.
8. Hardy, M.P., et al. "Large Scale Thermal Energy Storage in Rock: Construction, Utilization and Economics", 12th IECEC Conf. p. 583.
9. Telkes, Maria, "Thermal Energy Storage" IECEC Record, 1975, p. 111.
10. Personal Communication with Ruben Madrid and Tom Greenhaw of Dallas Power & Light Co., November 1978.

11. McLean, J.H., and Krubsack, R.M., "Keep Your Cool" Wisconsin Electric Power Company, presented at EEI Conservation and Energy Management Conference, Washington, D.C., 1976.

12. Cummings, John, Preliminary Survey of Electric Utility Solar Projects, Electric Power Research Institute, Palo Alto, California, 1976.

13. University of Pennsylvania, Conservation and Better Utilization of Electric Power by Means of Thermal Energy Storage and Solar Heating, Philadelphia, Pennsylvania, 1973.

14. Dudley, J.C., Recondenser Off-Peak Air Conditioning System: Design and Operation, University of Pennsylvania, 1973

15. Fischer, H.C., "Ice and Water: Annual Cycle Energy System Offers Savings in Heating, Cooling," Professional Engineer, 46 (June 1976): pp. 12-15.

16. Cuplinskas, E.L., "Sizing and Application of Thermal Storage Systems," ASHRAE Journal, 17 (July 1975): pp. 31-32.

17. Cuplinskas, E.L., "A Simplified Heating-Cooling Thermal Storage System," ASHRAE Journal, 18 (April 1976): pp. 29-30.

18. Lilleleht, L.U., ed., Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, University of Virginia and ASHRAE, Charlettesville, Virginia, 1975.

19. "Cooling Demand Controls Look Good", Electrical World , 18 (July 1975): pp. 96-98.

20. Jones, J.W., and Hendrix, B.J., Residential Energy Requirements and Opportunities for Energy Conservation, Center for Energy Studies, The University of Texas at Austin, September 1975.

APPENDIX C

Article on DOE Thermal Storage Demonstration Program

AIR CONDITIONING,
HEATING & REFRIGERATION
NEWS
The weekly newspaper of the industry.

April 23, 1979

In residential buildings

8 utilities will test energy storage devices for hac

OAK RIDGE, Tenn. — Eight utilities in seven states will participate in a Department of Energy (DOE) program to demonstrate electric load management through use of thermal energy storage for heating and air conditioning in residential buildings.

The two-year program is managed by Oak Ridge National Laboratory for DOE's Division of Electric Energy Systems. The laboratory is operated by Union Carbide Corp.'s Nuclear Division for DOE.

The primary purpose of the program is to obtain data to be used by the utilities and their customers in evaluating the use of "off-peak" electric power to operate thermal energy storage devices which provide residential heating and cooling.

Utilities participating in the program are: Arkansas Power and Light Co. (Little Rock); Long Island Lighting Co. (Mineola, N.Y.); Niagara Mohawk Power Corp. (Syracuse, N.Y.); Pacific Gas and Electric Co. (Fresno, Calif.); Public Service Electric and Gas (Newark, N.J.); United Power Association (Elk River, Minn.); Virginia Electric and Power Co. (Richmond); and Wisconsin Electric Power Co. (Milwaukee).

Near-commercial heat and/or cool storage systems will be installed by the utilities in the homes of selected residential customers who are representative of those in the utility's service area. The number of systems will vary from utility to utility and will be placed in new as well as existing homes.

The systems utilize electricity to heat or cool a storage medium primarily between midnight and 7 a.m., thus avoiding the use of peak day-time electricity which is often generated by scarcer, more expensive fuels.

This type of daily load shifting would be especially useful during heavy use or "system peak" periods on the hottest and coldest days of the year when utilities often have difficulty meeting customer demand, it was noted.

Three different mediums — water, ceramic bricks, and structural concrete — will be tested in the heat storage systems.

When water is used it will be electrically heated in a well-insulated storage tank, then circulated through the existing furnace or hot water pipes and radiators of the building. Oversized hot water tanks may also be installed in some test homes to evaluate this type of storage for household water use.

The ceramic bricks will be placed in an insulated cabinet adjacent to warm air furnaces and heated by resistance elements located between the bricks. The heat will be extracted by circulating air over the ceramic material and returning it to the existing ductwork of the building.

In the structural concrete storage system, resistance elements embedded in or underneath the concrete are used to heat it. Warmth is then radiated into the living area from the heated concrete.

The cool storage systems use a conventional air conditioning unit or heat pump to freeze water in large insulated tanks. A transfer fluid is circulated from the storage tanks to cooling coils in the air-circulation system of the home when cooling is needed.

Customers participating in the program will set the desired space conditioning temperature by means of their regular thermostats, which will determine the time of heating or cooling by the system. The utility will determine the time of charging of the storage units by using a communication and control system and will instrument the homes to gather data on electrical usage and equipment performance.

In addition to the homes that receive heat or cool storage equipment, the utilities will place instruments in an equal number of control homes with conventional space conditioning systems to gather data for comparison.

The number and types of systems to be tested by each company follow:

- Pacific Gas and Electric, Arkansas Power and Light, and Wisconsin Electric Power will test 30, 35, and 70 cool storage systems, respectively.
- Public Service Electric and Gas will test 30 ceramic brick heat storage systems, and United Power will test 35 similar systems.
- Long Island Lighting will test 100 systems — 50 hot water heat and 50 ice cool storage units in separate homes.
- Virginia Electric and Power will install 40 combination heat/cool storage systems that use heat pumps in new homes in the Richmond area.
- Niagara Mohawk Power will test five different heat energy storage systems in dormitory-type structures. The five identical buildings will house more than 1,000 athletes and officials who will participate in the 1980 Winter Olympic Games at Lake Placid.

Customers who participate in the program will receive incentives ranging from lower off-peak electricity rates to the option of retaining the storage equipment at the end of the demonstration. Participants also may choose to have the storage equipment replaced by a conventional system at no extra cost.

If the program results in increased use of the utility companies' generating facilities during off-peak periods, all customers served by the utility will benefit since the need for peak generation facilities will be reduced, it was pointed out.

Other benefits will occur from shifting the electric load to a time of day when the demand on the utility system is lowest, thus allowing greater operation of the more efficient baseload electric generating plants.

This program, managed by the Electrical Energy Systems Group of ORNL's Energy Division, is one in a series of cooperative DOE-industry efforts to improve the efficiency of energy-consuming and energy-producing systems.