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Optimal night setback control of a residential heatpump heating system.

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OPTIMAL NIGHT SETBACK CONTROL OF A RESIDENTIAL HEATPUMP HEATING SYSTEM

by

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ABSTRACT

A design for an optimum night setback thermostat has been developed which can operate effectively with a residential heatpump heating system. The design incorporates a predictor of outside temperature to enable projection of residence heating demand and heatpump output to determine the most economical time to begin morning recovery. A Fortran based dynamic computer simulator of a residence and heatpump system with controlling thermostat was written and tuned to the characteristics of the author's residence. Using the simulator, the energy savings from the optimum night setback thermostat is shown to be most pronounced at moderate to higher outside temperatures, with heating energy consumption for a 24-hour period reduced by as much as 15 % over that without thermostat setback. On days which are quite cold (with outside temperature dipping below -10.0 deg. C), the energy savings achievable with the optimum night setback thermostat reduces to zero, and may even require greater energy consumption than without setback if the prediction of outside temperature is not close to the actual temperatures which occur during recovery. It is estimated that the optimum night setback thermostat operating with a heatpump system in the Bethlehem, Pennsylvania area would yield an annual reduction in heating energy consumption of between 5 and 8 percent, for a reduction in the thermostat setting from a daytime reference of 21.1 degrees Centigrade to a night reference of 15.6 degrees Centigrade.

BACKGROUND

The air-to-air heatpump system has become accepted as an energy efficient means of residential heating during the last decade. The conventional setback thermostat has contributed to energy conservation when coupled with either a fossil fueled or electric furnace heating system. However, the conventional setback thermostat which is used with these heating systems would not yield an optimum energy savings if coupled with a heatpump system. This is due to the fact that a sudden increase of the thermostat reference in the morning would cause the heatpump (high efficiency) and auxiliary backup heat (low efficiency) to both come "on", reducing the net efficiency of recovery. Therefore, the optimum design of a night setback thermostat to operate in conjunction with a heatpump heating system is the consideration of this thesis.

The air-to-air residential heatpump heating system operates on the same principle as a conventional refrigeration system, in that it uses electrical energy to extract heat from a low temperature area (outside) and "pump" it to an area which is at a higher temperature (interior of the residence). A typical system is shown in Illustration 1. The amount of heat which can be "pumped" into the residence (heatpump output) is basically a function of the outside temperature, as shown in Figure 1 for a Carrier Heatpump Model 38HQ940/134 operating at steady-state (Reference 1 - the heatpump installed in the author's residence). The efficiency of the heatpump system arises

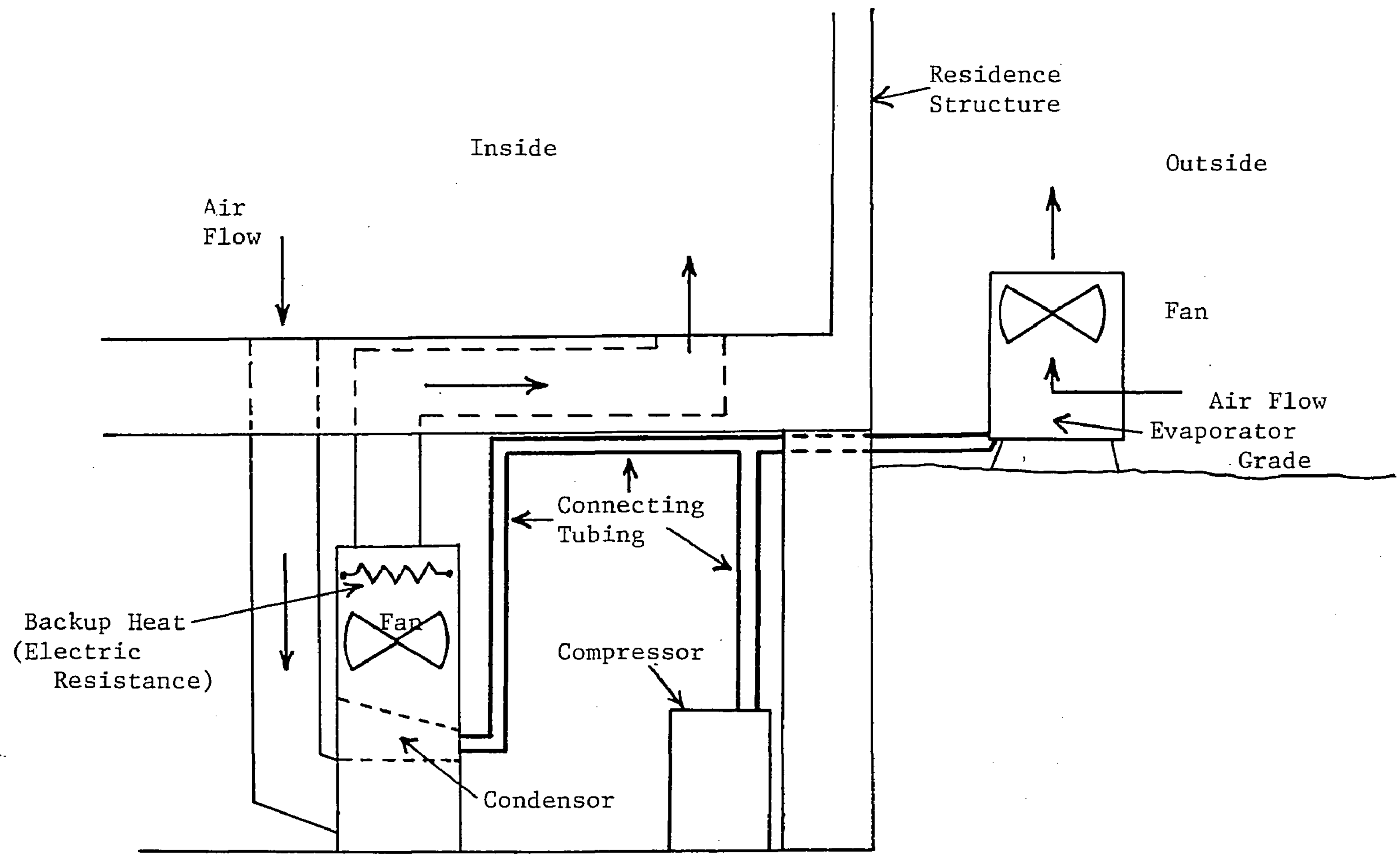


Illustration 1. TYPICAL RESIDENTIAL HEATPUMP INSTALLATION

from the fact that for each unit of energy consumed in operation, more than that same amount of energy is extracted from the outside air and supplied to the residence as heat. The ratio of heatpump output to the energy consumed (Coefficient Of Performance - COP) is also a function of outside temperature as shown in Figure 2 for the same heatpump system operating at steady-state.

The curve in Figure 1 shows a significant change in the slope at an outside temperature of between 0 and +5 degrees Centigrade. This is due to ice buildup (frosting) on the outside coil (evaporator) of the heatpump system. This phenomenon occurs at temperatures below +5 degrees Centigrade. The frosting of the evaporator reduces the amount of heat which can be extracted from the outside air and "pumped" into the residence. Therefore, periodically, the heatpump is reversed to "pump" heat from the residence to the outside coil and melt the ice. The curves in Figures 1 and 2 reflect the defrosting requirement and show the average output and COP for the specific heatpump system.

Figure 1 also shows the residence demand curve as a function of outside temperature. The outside temperature at which the heatpump output and residence demand curves intersect is called the "Balance Point". When outside temperature is above the "Balance Point" the heatpump will cycle "on" and "off" upon demand to maintain residence temperature at the desired thermostat setting. When outside temperature is below the "Balance Point" the heatpump will remain "on" and a form of auxiliary backup heat (electric resistance heat in the case of this study) is cycled "on" and "off" to maintain residence temperature at a second thermostat setting which is at a slightly lower temperature than the first. The COP of the electric resistance backup heat is somewhat less than 1.0 due to losses in air handling ductwork within the residence.

Whenever the heatpump cycles "on" there is a period of time before the nominal steady-state output is reached. The transient operation is shown in Figure 3 for the heatpump mentioned above and is nearly five minutes in duration. During this transient period the electrical energy input required is essentially that of steady-state (a very short response in reaching the steady-state input requirement). Therefore, with required input immediately reaching steady-state and output reaching steady-state at some later time, the heatpump COP is reduced during the transient period.

The conventional thermostat with night setback automatically reduces the thermostat setting to a lower level at a desired evening hour and restores the setting to daytime reference at a desired morning hour. The reference changes occur as steps at the desired times. Such thermostat step changes, if sufficiently large (more than 2.8 degrees centigrade for the author's heatpump system and thermostat), to a heatpump system would cause the backup heat to come "on" (at a COP of less than 1.0) in addition to the heatpump itself. Recovery in the morning would therefore occur primarily by the backup heat with a net usage of electrical energy during a 24-hour period conceivably greater than that of the heatpump system maintaining the residence at the daytime reference temperature without night setback. The optimum mode of operation would be to setback the thermostat in the evening (as a step) and turn the heatpump system back "on" (heatpump only, with possible assistance from backup heat if needed near the end of the recovery) at precisely the right predicted time to have the residence temperature restored by the desired hour of the morning. This conceptualization is in agreement with the "principle of optimality" from Optimal Control Theory (Reference 2), which states:

> "An optimal policy, or optimal control strategy, has the property that, whatever the initial state and the initial decision, the remaining decisions must form an optimal control strategy with respect to the state resulting from the first decision".

The determination of the optimal time at which to turn "on" the heatpump is the objective of the optimum night setback thermostat which is considered by this thesis.

PROCEDURE

The objective of this study was to develop a form of night setback thermostat that would achieve optimum energy savings when operated with a residential heatpump heating system. To do this required essentially two steps: 1) determine a predictor of outside temperature which permits residence demand to be forecast for the remaining night time hours and 2) develop a model of the residence and heatpump with which the optimum thermostat could be simulated, to establish its effectiveness.

TEMPERATURE PREDICTOR

The temperature predictor is divided into two parts: a deterministic portion and a stochastic portion. The deterministic portion is based on the statistical average descriptions of seasonal and daily temperature variations. The stochastic portion is based on the dynamic characteristics of the difference between the deterministic portion and the actual measured temperature.

Temperature data required for this study were obtained from records kept by the National Weather Service at the Allentown-Bethlehem-Easton Airport. Actual outside average daily temperatures for each day from November 1977 through October 1978 were obtained and are presented in Appendix A. Presented in Appendices B and C are the hourly recorded temperatures for the months of January and October 1978 respectively.

The deterministic portion of the temperature predictor was computed based on two parts: a seasonal variation and a daily variation. The seasonal variation was chosen to be represented by a sinusoid with the daily variation represented by a Fourier Series.

The sinusoid to represent the seasonal temperature variation was established by averaging the daily temperatures to form a monthly average and then fitting a sinusoid to this data with the goal of good agreement in the winter months. Figure 4 shows the sinusoid plotted with the mathematical expression for the sinusoid. In the equation, time, t , is expressed in hours since 12:00 midnight of January 1, 1978.

The Fourier Series to represent the daily temperature variations was established by averaging the hourly temperatures for each hour over the entire month (January and October separately) and then computing the first three Fourier Series coefficients to best fit the composite daily variation. Figure 5 presents the actual and Fourier Series fit for the daily temperature variations for January and October 1978, with the mathematical expressions for each presented below. In the equations, time, t , is expressed in hours since 12:00 midnight of the average day.

Fourier Series - January 1978

$$Temp(t) = ((-0.5691 - 1.3351 * \cos(0.2618 * t) + 0.5603 * \cos(0.5236 * t) - 0.0925 * \cos(1.0472 * t) - 2.2145 * \sin(0.2618 * t) + 0.7778 * \sin(0.5236 * t) + 0.1154 * \sin(1.0472 * t)) - 32.0 * 5.0 / 9.0$$

Fourier Series - October 1978

$$Temp(t) = ((6.4216 - 6.6624 * \cos(0.2618 * t) + 1.9706 * \cos(0.5236 * t) + 0.1321 * \cos(1.0472 * t) - 5.0667 * \sin(0.2618 * t) + 0.4395 * \sin(0.5326 * t) + 0.2862 * \sin(1.0472 * t)) - 32.0 * 5.0 / 9.0$$

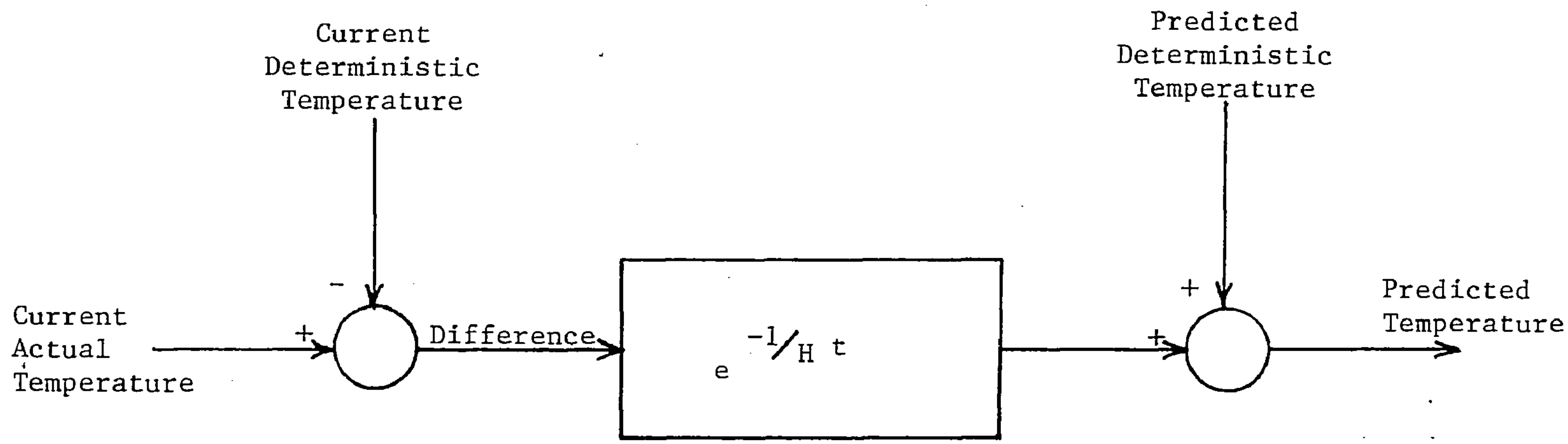
A stochastic term for the temperature predictor was computed from the difference between the deterministic portion (seasonal and daily variations included) and actual measured temperature on an hourly basis. The difference is considered as stationary random. From this difference an autocorrelation function was formulated as shown in Figures 6 and 7 for January and October 1978 respectively. The equations shown on each figure are the mathematical expressions selected to represent the autocorrelation functions, where, t , is the time since the current time.

The temperature predictor was then formed as the sum of the deterministic portion and the stochastic portion operating on the difference in temperature between the current actual temperature and the deterministic calculated current temperature. Illustration 2 shows the basic configuration of the temperature predictor with the stochastic term constants for January and October 1978.

SYSTEM MODEL

The heat transfer within the author's residence and between the residence and its surroundings was modeled. The model was implemented into a digital computer program (simulator) in which the characteristics of the heatpump system, thermostat and residence surroundings were also included. The computer program was then tuned to actual conditions measured from the residence. Finally, the simulator was exercised with standard, conventional setback and optimum setback thermostats to establish the advantages of the setback thermostats.

A Lumped-Heat-Capacity system was selected to model the personal residence of the author. The basic model configuration is shown in Illustration 3. The differential equations governing the heat transfer model are given in Appendix D. Specific quantities calculated for the various terms in the differential equations, including composite densities, specific heats and inverse heat transfer coefficients, are presented in Appendix E. The respective terms for each of the individual materials used in the residence structure were obtained from Reference 3.



January 1978 : H = 18.59

October 1978 : H = 17.00

t is time since current time in hours

Illustration 2. TEMPERATURE PREDICTOR DIAGRAM

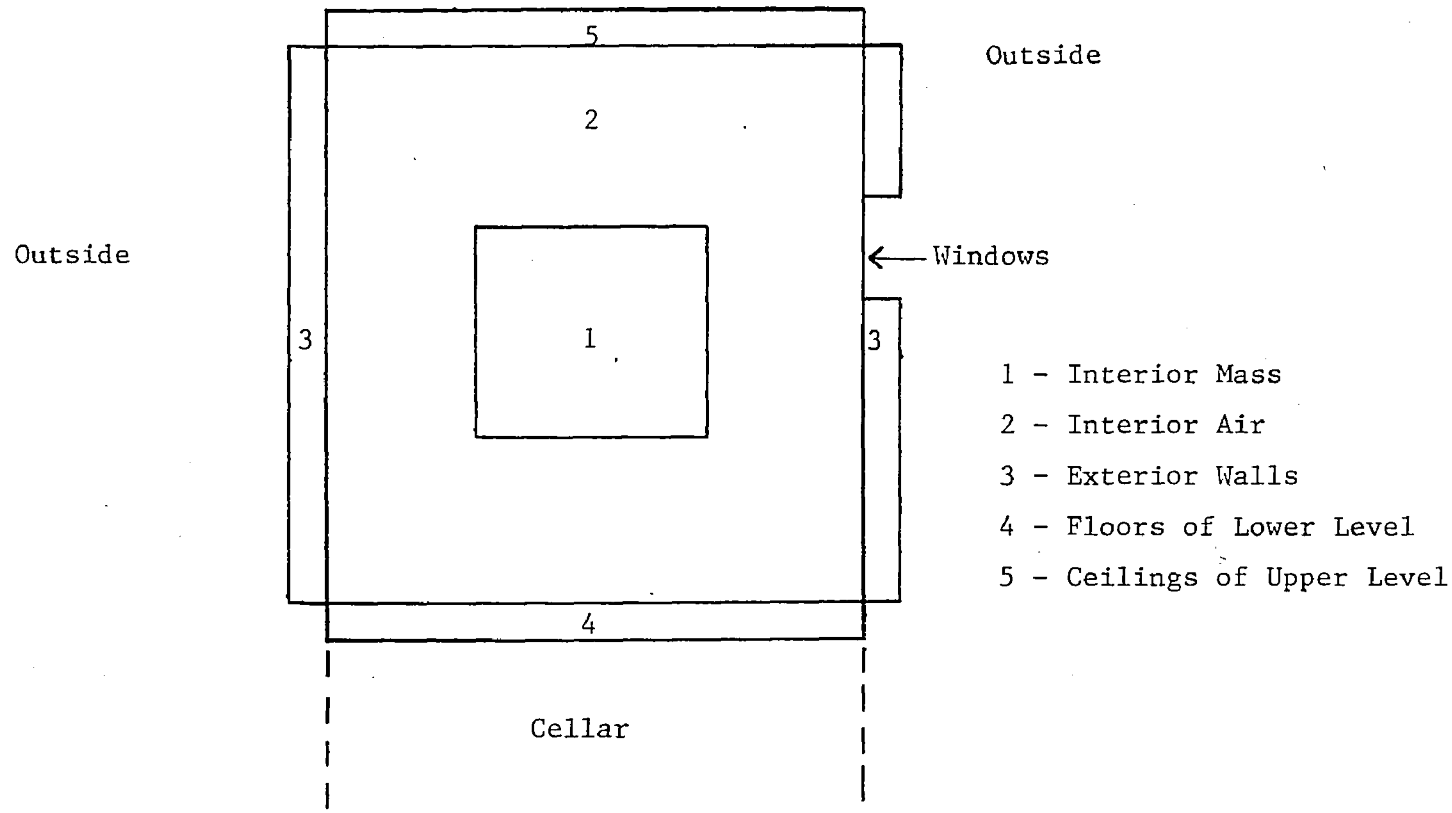


Illustration 3. LUMPED-HEAT-CAPACITY MODEL OF RESIDENCE

A Fortran based digital computer simulator was written to simulate the residence (Lumped-Heat-Capacity system) under actual temperature conditions operating in conjunction with a heatpump heating system and controlling thermostat. The simulator was designed to calculate the various temperatures of the residence model by computing the temperature derivatives at one minute intervals and employing a 2nd order Runge-Kutta integration routine. The listing of the computer simulator is on file in the office of the Department of Mechanical Engineering and Mechanics, Lehigh University, along with a sample listing of the computer simulator inputs. There are five basic modes of simulator operation:

Mode 1. Standard thermostat operation - no setback.

Mode 2. Standard thermostat operation - no setback but with backup heat locked out during specified hours of operation.

Mode 3. Conventional setback thermostat operation - setback and setup as step changes, to reduce thermostat reference during specified hours of operation.

Mode 4. Manually controlled thermostat operation - setback at a specified time with recovery at specified starting hour by heatpump only followed by backup heat at separately specified starting hour.

Mode 5. Optimum setback thermostat operation - setback with temperature predictor used to determine when recovery by combination of heatpump and backup should start.

The optimum thermostat (Mode 5) runs through the following basic steps:

1) The thermostat waits a period of time before beginning the procedure below for initiating recovery. The wait period was preselected and at no time did it arbitrarily force the recovery to begin too late.

2) The thermostat formulates an outside temperature projection, based on the current temperature and the difference between the current temperature and the deterministic temperature for this time, from the current time until four hours past the desired recovery time.

3) The thermostat assumes the heatpump is turned "on" now and projects interior air temperature until recovery time.

4) If the daytime reference interior air temperature is reached before the required recovery time, a next time to check for optimal recovery is calculated and the program waits until this time before beginning at Step 2 again. If the interior air temperature does not reach daytime reference by the required recovery time, the thermostat proceeds.

5) The time to turn "on" the auxiliary backup heat (in addition to the heatpump) to have the residence interior air temperature at daytime reference by the required recovery time is computed. The simulator proceeds from this time to recovery assuming both heatpump and backup heat are "on".

6) Energy required to begin recovery now, obtain daytime reference temperature by recovery time (using backup heat if necessary) and continue normal heatpump system operations for four hours past recovery time is calculated.

7) A second projected energy usage (following the Step 3 through 6 procedure) is calculated assuming a 15 minute wait before recovery is initiated and using the same outside temperature projection.

8) The two energies are compared. If the current energy is smaller, recovery is initiated at the current time by turning "on" only the heatpump. If the current energy is larger, the system waits for 15 minutes before it begins at step 2 again.

9) If the recovery was initiated, the thermostat will wait and periodically check to see whether the backup heat is required to attain daytime reference interior air temperature by the required recovery time. The procedure followed is to again project temperature from the current time until recovery time and assume backup is turned "on" now (in addition to the

heatpump already "on"). If daytime reference temperature is reached before the recovery time, then the system waits a period of time based on the difference in time between when projected daytime reference interior air temperature was reached and the desired recovery time. If daytime reference is just reached or not reached by recovery time, then the backup is turned "on" immediately.

Only operating modes 1, 3, 4 and 5 were required and exercised for purposes of this study. Typical 24-hour summary outputs of the simulator oparating in modes 1, 3 and 5 are on file in the office of the Department of Mechanical Engineering and Mechanics, along with the Fortran listing of the computer simulator and simulator input listings. In addition to the 24-hour summary output, expanded output, which gives information every integration time step, is available from the simulator.

The simulator was tuned to the author's residence and heat-pump system under three specific conditions:

* During a temperature decay of the residence with the heating system manually shut "off".

* During dynamic cycling of the heatpump system at approximately 9 degrees Centigrade outside temperature.

* During dynamic cycling of the heatpump system at approximately 1 degree Centigrade outside temperature.

Tuning of the simulator was accomplished by varying the thermal capacitance of components (walls, floors, ceilings, etc.) of the Lumped-Heat-Capacity model of the residence. This adjusted the rate of change of temperature of each of the model components. Thermal capacitance was adjusted by varying only the density of each component. Comparison of Appendices E and F show the required changes in densities to obtain good model-actual agreement under the above three specific conditions. In general it was necessary to increase the thermal capacitance of the interior mass (by a factor of 2.4) and interior air (by a factor of 4.1) while reducing the thermal capacitance of the walls (by a factor of 12.2), floors (by a factor of 2.1) and ceilings (by a factor of 28.9). This amount of tuning, although the net effect on residence weight (density * volume) was only a 12.4 % increase, is attributed to a shortcoming in applying the Lumped-Heat-Capacity analysis to the residence. The shortcoming is that the analysis assumes internal resistance of the bodies to heat transfer is low compared with the external resistance (Reference 4). In fact, most of the resistance of the outside walls is in the central insulation layer, which has little thermal capacitance; and most of the thermal capacitance is in the drywall, which has little thermal resistance. A composite model of the structure is suggested, which requires further investigation.

1) Tuning during temperature decay.

Temperatures within the residence as well as the outside temperatures were monitored for a four and one-half hour period, during which time the heating system was manually shut "off". After tuning, good agreement between actual decay of temperatures within the residence and simulator decay of temperatures was achieved, as shown in Figures 8 through 12. Differences in starting points between actual and simulated structure temperatures were due to initialization within the simulator.

All temperatures were taken using scientific thermometers of one-quarter degree Centigrade accuracy. The thermometers were located as described in Table 1.

The simulator was operated in Mode 3 to simulate this decay situation. The model was setup at nominal conditions and the thermostat then setback to a low reference during the simulation. Calculated residence temperatures were obtained from the expanded data output of the simulator.

2) Tuning during dynamic cycling.

Residence temperatures, outside temperatures and heatpump cycling operation by the thermostat were monitored for a period of time in excess of one hour during each of two tests at different outside temperatures. After tuning, reasonable

SIMULATOR TEMPERATURE	EXPERIMENTAL LOCATION
T1 - Interior Mass	Embedded in interior wall.
T2 - Interior Air	At location of conventional thermostat.
T3 - Walls	Embedded in exterior wall.
T4 - Floors	Embedded in floor over cellar.
T5 - ceilings	Embedded in exterior ceiling.
TOUT - Outside	In protected area approximately 3 meters from residence.
TCEL - Cellar	In area approximately 7 cm. below first floor insulation.

Table 1. LOCATIONS OF EXPERIMENTAL TEMPERATURE MEASUREMENT WITHIN RESIDENCE

agreement between actual and simulator heatpump cycling was achieved, as shown in Figures 13 and 14.

All temperatures were taken using scientific thermometers of one-quarter degree Centigrade accuracy. Thermometers were again located as described in Table 1.

The simulator was operated in Mode 1 to simulate the cycling situation. The model was setup at nominal conditions and allowed to run for the required time. Heatpump cycling and residence temperatures were obtained from the expanded output of the simulator.

The simulator was exercised in manual Mode 4 to demonstrate the advantages of night setback and illustrate the optimum combinations of heatpump and backup heat during recovery to reduce energy consumption. The optimum thermostat (Mode 5) was then used with the simulator to find the optimum recovery starting time under actual temperature conditions during four 48-hour periods (January 6,7 ; January 10,11 ; January 24,25 and October 9,10 1978).

RESULTS

A reduction in the energy consumption of a residential heat-pump heating system can be achieved with the use of an optimum night setback thermostat. In some instances a reduction in energy consumption is achievable with a conventional setback thermostat also. However, the benefit of setback (optimal or conventional) becomes questionable on severly cold days. It should also be noted that optimum thermostat control may not contribute any savings and may in fact require greater energy usage than no setback on nights in which the outside temperature drops significantly below the projection and more backup heat than projected is required.

The simulator was operated in Mode 4 (manual setback with recovery starting at an arbitrarily specified time by heatpump only and later assisted by backup heat starting at a second arbitrarily specified time) to demonstrate the savings of setback and controlled recovery for both deterministic and actual outside temperature profiles on January 1. In each case the simulator was started at 12:00 midnight with specified nominal initial conditions and thermostat setback from 21.1 degrees Centigrade to 10.0 degrees Centigrade. Recovery was stipulated to be completed by 7:00 am with interior air temperature at the desired daytime reference of 21.1 degrees Centigrade.

For the case of an outside temperature profile composed of the seasonal and daily variations for January 1, minimum energy for recovery is shown in Figure 15 to be achieved with a recovery starting time of approximately 4:15 am. Table 2 presents a breakdown of the time of operation and energy consumed for each of the cases presented in Figure 15. With the optimum thermostat as designed with the temperature predictor, it was possible to locate a recovery starting time of 3:47 am. This point is marked with an "X" on Figure 15. The true minimum was not found due to the limitation in the optimal setback thermostat which only computes energy consumption during recovery and for four hours following recovery. Had the optimal thermostat computed energy consumption for the entire day, the true minimum would have been found.

For the case of the actual temperature profile for 1/1/78, minimum energy for recovery is shown in Figure 16 to be achievable at two separate recovery starting times of approximately 3:40 am and 4:15 am. The two separate times arise from the characteristics of the actual temperature profile during recovery (see Appendix B). Table 3 presents a breakdown of the time of operation and energy consumed for each of the cases presented in Figure 16. With the optimum thermostat, a recovery starting time of 3:30 am was found best, and is indicated by an "X" in Figure 16.

Presented in Figure 17 is the interior air temperature profile for three of the cases in Figure 16. This figure indicates how

RECOVERY STARTING TIME	OPERATING TIME DURING RECOVERY (Minutes)		OPERATING ENERGY FOR DAY (Joule * 10**6)		
	HEATPUMP	BACKUP	HEATPUMP	BACKUP	TOTAL
No setback	-	-	215.0	-	215.0
1:04 am	356	-	205.4	-	205.4
2:30 am	270	6	198.5	3.6	202.1
3:00 am	240	9	195.0	5.4	200.4
3:30 am	210	12	192.8	7.2	200.0
4:00 am	180	17	189.3	10.2	199.5
4:30 am	150	23	185.7	13.8	199.5
5:00 am	120	33	181.7	19.8	201.5
5:30 am	90	48	178.0	28.8	206.8
5:55 am	65	65	173.5	38.4	211.9

Table 2. HEATPUMP SYSTEM - RECOVERY TIME AND 24-HOUR ENERGY USAGE WITH THERMOSTAT SETBACK - DETERMINISTIC OUTSIDE TEMPERATURE PROFILE JANUARY 1

RECOVERY STARTING TIME	OPERATING TIME DURING RECOVERY (Minutes) HEATPUMP	BACKUP	OPERATING ENERGY FOR DAY (Joule * 10**6) HEATPUMP	BACKUP	TOTAL
No setback	-	-	202.0	-	202.0
1:30 am	330	-	190.3	-	190.3
2:30 am	270	4	186.7	2.4	189.1
3:00 am	240	6	184.5	3.6	188.1
3:30 am	210	9	181.1	5.4	186.5
4:00 am	180	13	179.3	7.8	187.1
4:30 am	150	18	175.7	10.8	186.5
5:00 am	120	25	171.8	15.0	186.8
5:30 am	90	37	168.7	22.2	190.9
6:02 am	58	58	162.8	33.6	196.4

Table 3. HEATPUMP SYSTEM - RECOVERY TIME AND 24-HOUR ENERGY USAGE WITH THERMOSTAT SETBACK - ACTUAL OUTSIDE TEMPERATURE PROFILE 1/1/78

recovery is achieved in each case and the interaction of the residence and heatpump following recovery. In Figure 17, the heatpump cycles between interior air tempertures of 21.1 degrees Centigrade and 20.0 degrees Centigrade under normal operation following recovery. Backup heat would cycle "on" if interior air temperature dropped to 18.3 degrees Centigrade and cycle "off" once the air temperature reached 20.0 degrees Centigrade. During recovery, however, the heatpump and backup heat (when used) both remained "on" until the 21.1 degrees Centigrade reference was reached at 7:00 am.

Four 48-hour runs were made with the simulator to demonstrate the comparable benefits of both conventional and optimum setback thermostats with the heatpump heating system. For each run the daytime reference thermostat setting was 21.1 degrees Centigrade with setback to 15.6 degrees Centigrade between the hours of 11:00 pm and 6:30 am (arbitrarily selected as thermostat setup time) for the conventional setback thermostat and between the hours of 11:00 pm and optimal recovery time as determined by the optimum setback thermostat. Table 4 presents these results.

It is evident from comparison of Tables 4 and 5 that on a severly cold day (1/10/78 - a day in which the outside temperature profile also deviated siginficantly from the projected profile) there is no benefit from the use of either conventional or optimum setback thermostats. This is due to the large amounts of backup heat required to restore the residence temperature following the setback

		ENERGY CONSUMPTION FOR 24-HOUR PERIOD (JOULE * 10**6)					
		FIRST DAY			SECOND DAY		
DAYS SIMULATED	SIMULATOR MODE	HEATPUMP	BACKUP	TOTAL	HEATPUMP	BACKUP	TOTAL
1/6/78 & 1/7/78	1	148.4	-	148.4	164.6	-	164.6
	3	125.3	12.0	137.3	143.6	11.4	155.0
	5	140.4	-	140.4	150.7	3.6	154.3
1/10/78 & 1/11/78	1	254.2	10.8	265.0	248.1	-	248.1
	3	204.1	84.5	288.6	202.3	58.2	260.5
	5	241.7	18.9	260.6	235.9	9.0	244.9
1/24/78 & 1/25/78	1	236.3	34.2	270.5	161.0	-	161.0
	3	188.8	98.9	287.7	137.5	13.2	150.7
	5	217.9	56.7	274.6	157.4	-	157.4
10/9/78 & 10/10/78	1	96.9	-	96.9	70.7	-	70.0
	3	82.4	4.8	87.2	56.2	4.8	61.0
	5	84.4	-	84.4	59.9	-	59.9

Table 4. HEATPUMP SYSTEM ENERGY CONSUMPTION WITH STANDARD, CONVENTIONAL SETBACK AND OPTIMUM SETBACK THERMOSTATS

	OUTSIDE TEMPERATURE (Deg. C)					
	FIRST DAY			SECOND DAY		
DAYS SIMULATED	AVG	MAX	MIN	AVG	MAX	MIN
1/6/78 & 1/7/78	2.7	7.2	-1.1	0.6	1.7	-0.6
1/10/78 & 1/11/78	-10.1	-7.8	-13.3	-6.8	-3.9	-9.4
1/24/78 & 1/25/78	-8.0	-0.6	-16.1	1.1	2.8	-2.2
10/9/78 & 10/10/78	8.3	15.0	2.8	11.9	21.7	1.7

Table 5. OUTSIDE TEMPERATURE SUMMARY FOR 48-HOUR SIMULATIONS

period, regardless of the length of the setback period. On days of cold to moderate outside temperatures (1/11 & 24/78) the optimum setback thermostat contributes to energy savings whereas the conventional setback thermostat yields a greater energy consumption than even the standard thermostat. This is due to the conventional setback requirement of relatively large amounts of inefficient backup heat to complete recovery as compared with larger amounts of efficient heatump heat energy with the optimum thermostat. During those periods which are at higher outside temperatures (10/9 & 10/78), regardless of the actual outside temperature profile, both setback thermostats contribute to energy savings, although, the optimum thermostat yields the greatest savings. During those periods which are at moderate outside temperatures yet deviating from the projected temperature profile (1/6, 7, 25/78), the benefit from the optimum setback thermostat compares closely with that of the conventional setback thermostat, both generating an energy savings.

In addition to reduced energy consumption the setback thermostat, whether conventional or optimum, yields a savings in terms of reduced heatpump wear through a reduction in the number of starts as seen in Table 6. This savings is present in the optimum thermostat, however, it was not a design criteria consideration in the optimizing routine used in the simulator.

The reduction in consumed energy for the conventional and optimum thermostats is given in Table 7 for the days simulated. On a

DAYS SIMULATED	SIMULATOR MODE	NUMBER OF HEATPUMP STARTS FIRST DAY	SECOND DAY
1/6/78 & 1/7/78	1	64	62
	3	38	30
	5	46	36
1/10/78 & 1/11/78	1	0	8
	3	2	6
	5	2	5
1/24/78 & 1/25/78	1	13	63
	3	12	35
	5	13	50
10/9/78 & 10/10/78	1	55	40
	3	38	26
	5	38	25

Table 6. HEATPUMP CYCLING WITH STANDARD, CONVENTIONAL SETBACK AND OPTIMUM SETBACK THERMOSTATS

DAYS SIMULATED	SIMULATOR MODE	PERCENT CHANGE IN TOTAL CONSUMED ENERGY FROM STANDARD THERMOSTAT FIRST DAY	SECOND DAY
1/6/78 & 1/7/78	3	-7.5%	-5.8%
	5	-5.4%	-6.3%
1/10/78 & 1/11/78	3	+8.9%	+5.0%
	5	-1.7%	-1.3%
1/24/78 & 1/25/78	3	+6.4%	-6.4%
	5	+1.5%	-2.2%
10/9/78 & 10/10/78	3	-10.0%	-13.7%
	5	-12.9%	-15.3%

Table 7. ENERGY SAVINGS WITH CONVENTIONAL SETBACK AND OPTIMUM SETBACK THERMOSTATS

composite basis the optimum setback thermostat improved the energy consumption over that of the conventional setback thermostat. It is realized that the 6:30 am recovery time specified for the conventional setback thermostat was not early enough for the colder days and was too early for the warmer days; however, the averge 6:30 am time was selected considering the homeowners probable lack of attention to altering the recovery time with regard to the average outside temperature. Therefore, on the colder days the conventional setback thermostat is not achieving the desired residence daytime temperature soon enough, making the energy savings look better than expected; and on the warmer days the conventional setback thermostat is achieving the daytime temperature sooner, making the energy savings look worse than expected.

CONCLUSIONS AND RECOMMENDATIONS

The optimum thermostat strongly appears to contribute to reductions in average heating energy consumption of a residential heatpump system. The amount of energy reduction achieved in practice would be dependent on the severity of the weather (how much temperature deviates from a projected profile and how cold the average temperatures are) and the amount of thermostat setback which can be tolerated. The author estimates, from the results of this study, but without a detailed evaluation requiring additional simulator runs, that a projected 5% to 8% annual reduction in heating energy could be achieved with the optimum thermostat (with a 5.6 degree Centigrade thermostat setback between 11:00 pm and 7:00 am) as compared to the standard thermostat.

It is recommended that the following additional items be considered for further investigation:

1) The Lumped-Heat-Capacity model of the residence should be examined to determine the reasons which necessitated the drastic shifting of thermal capacitance within the residence to achieve model and actual data agreement. Composite models of the residence sub-structures (walls, floors, ceilings, etc.) should be considered.

2) The effect of additional capacitive heat storage within the

residence should be examined. The capacitive heat storage could either be inherent in the structure or be intentionally designed into the heating system. The largest potential benefit would follow from utilizing the improved efficiency of the heatpump at higher outside temperatures (during the day, for example) by storing the heat and then using it during periods of lower outside temperatures (during the night, for example). Another benefit requiring less storage would come through reduced cycling, increasing the average COP and increasing the life of the heatpump system.

3) Consideration should be given to improving the temperature prediction within the model. One suggestion would be to include some form of weather forecast. A second suggestion would be to incorporate the recent temperature history into the prediction (as in a Kalman filter) rather than just the present temperature.

4) True stochastic optimal control considers the consequences of error in the prediction. Including this concept would improve the average performance of the optimum thermostat at the expense, perhaps, of the peak performance improvements of the optimum thermostat as developed in this thesis.

5) Suggested in Figure 17 is an alternative strategy to be followed in recovery. Instead of satisfying the upper bound of normal thermostat control, satisfy the lower bound, as shown in the figure. In this way the comfort of the residence, following recovery, is better assured while still gaining the benefits of reduced heatpump cycling and decreased energy consumption.

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4. J. P. Holman, HEAT TRANSFER - SECOND EDITION, McGraw-Hill Book Company, 1963.

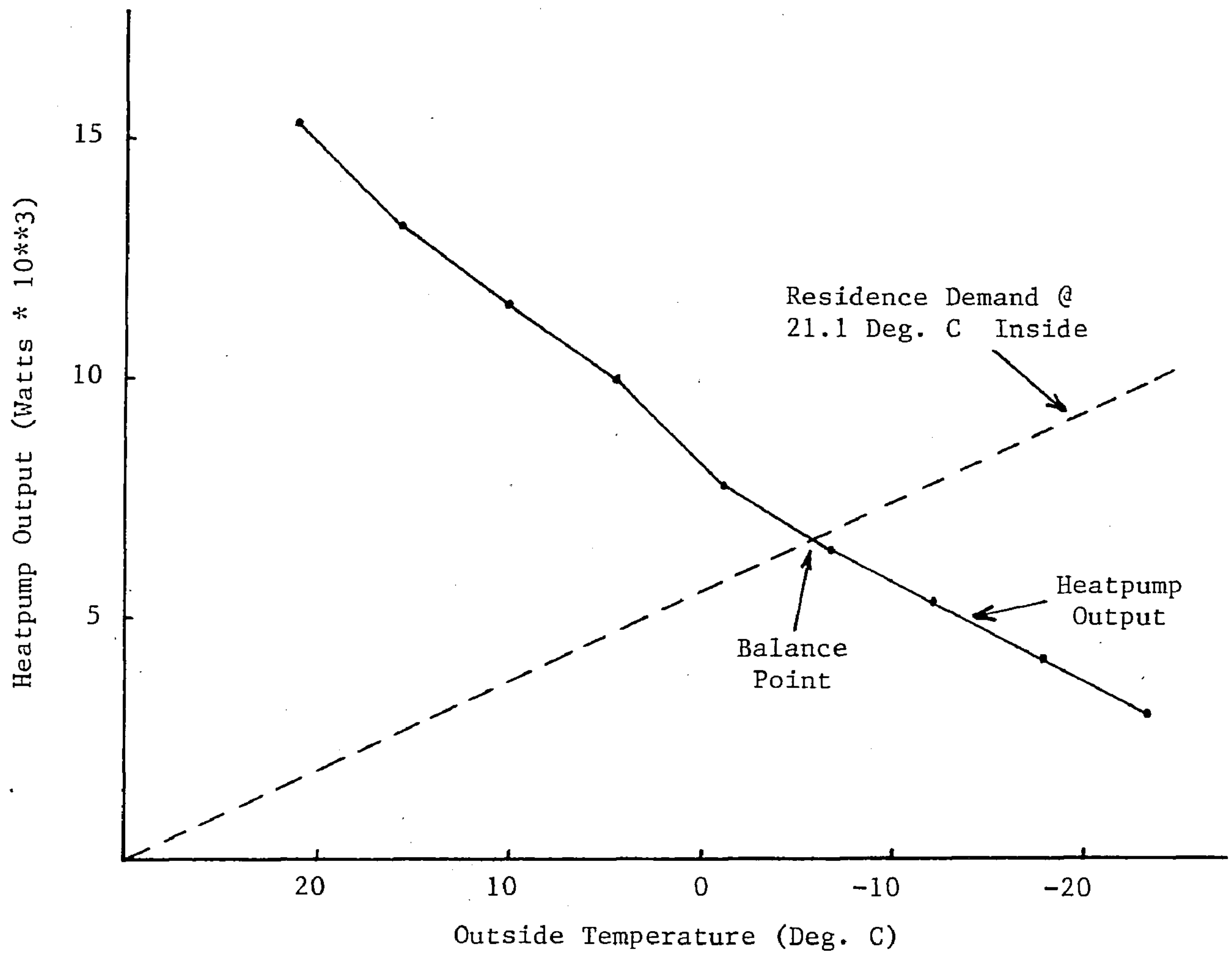


Figure 1. HEATPUMP OUTPUT AND RESIDENCE DEMAND

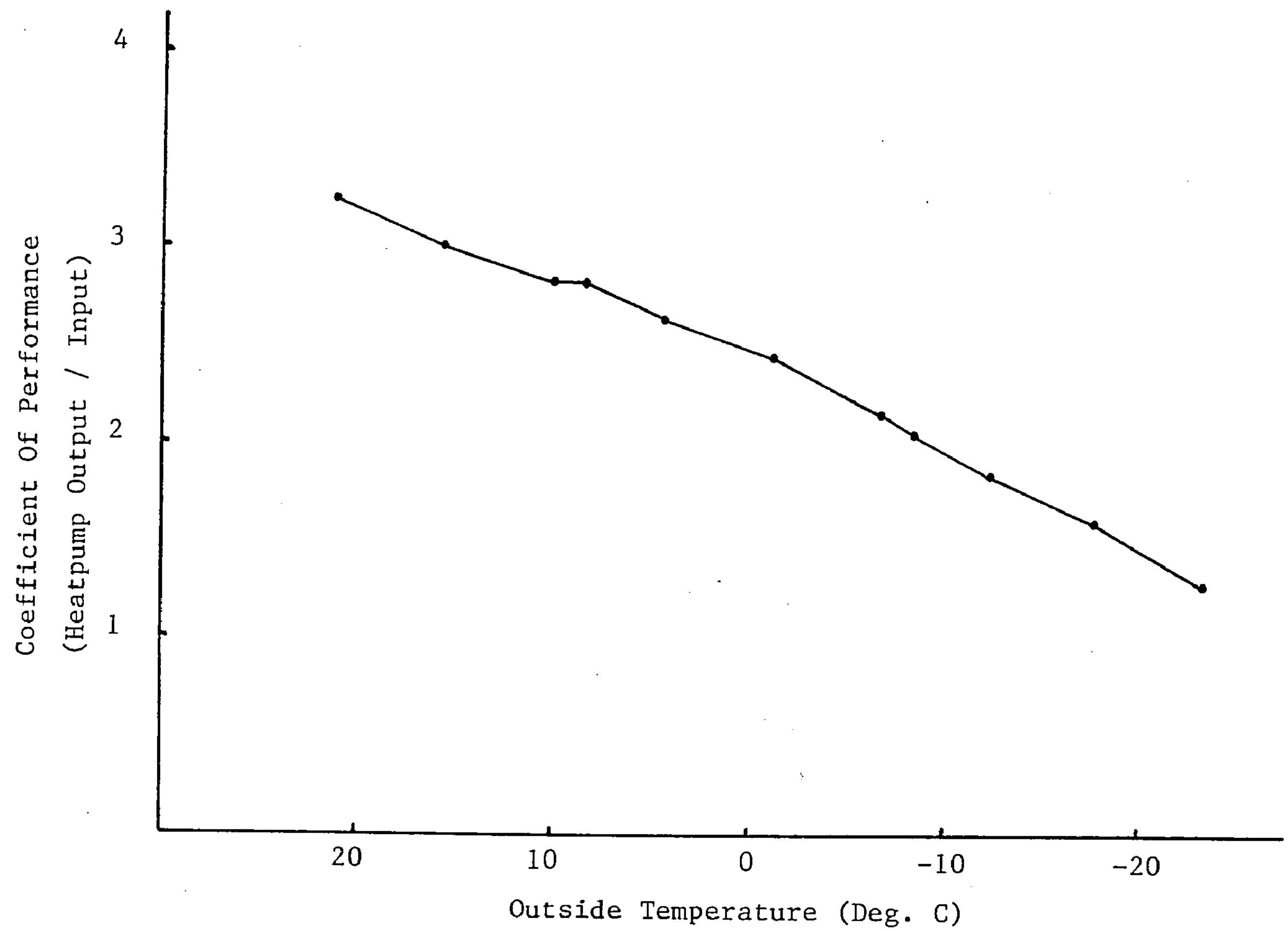


Figure 2. HEATPUMP COEFFICIENT OF PERFORMANCE

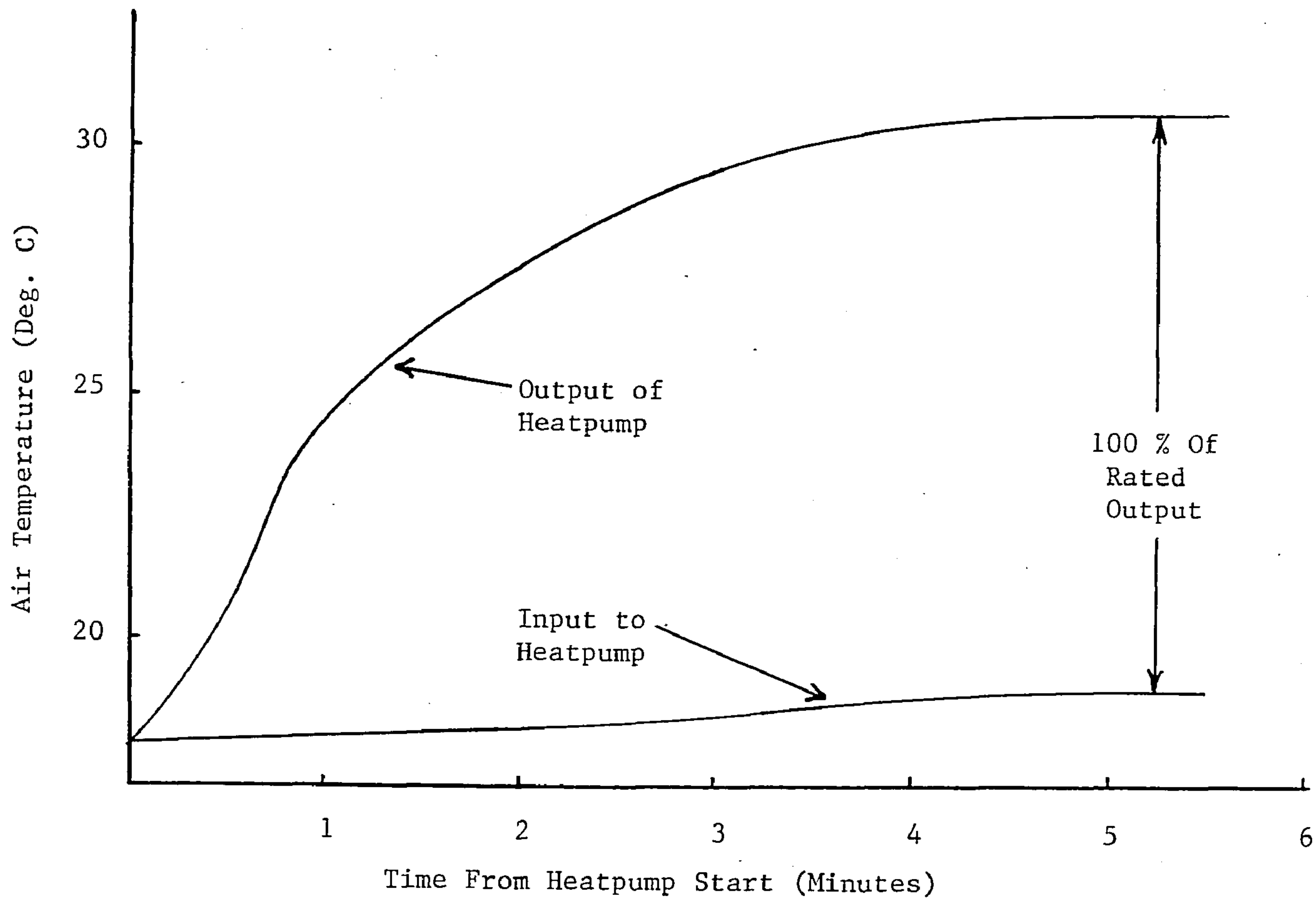


Figure 3. HEATPUMP TRANSIENT OPERATION - STARTUP

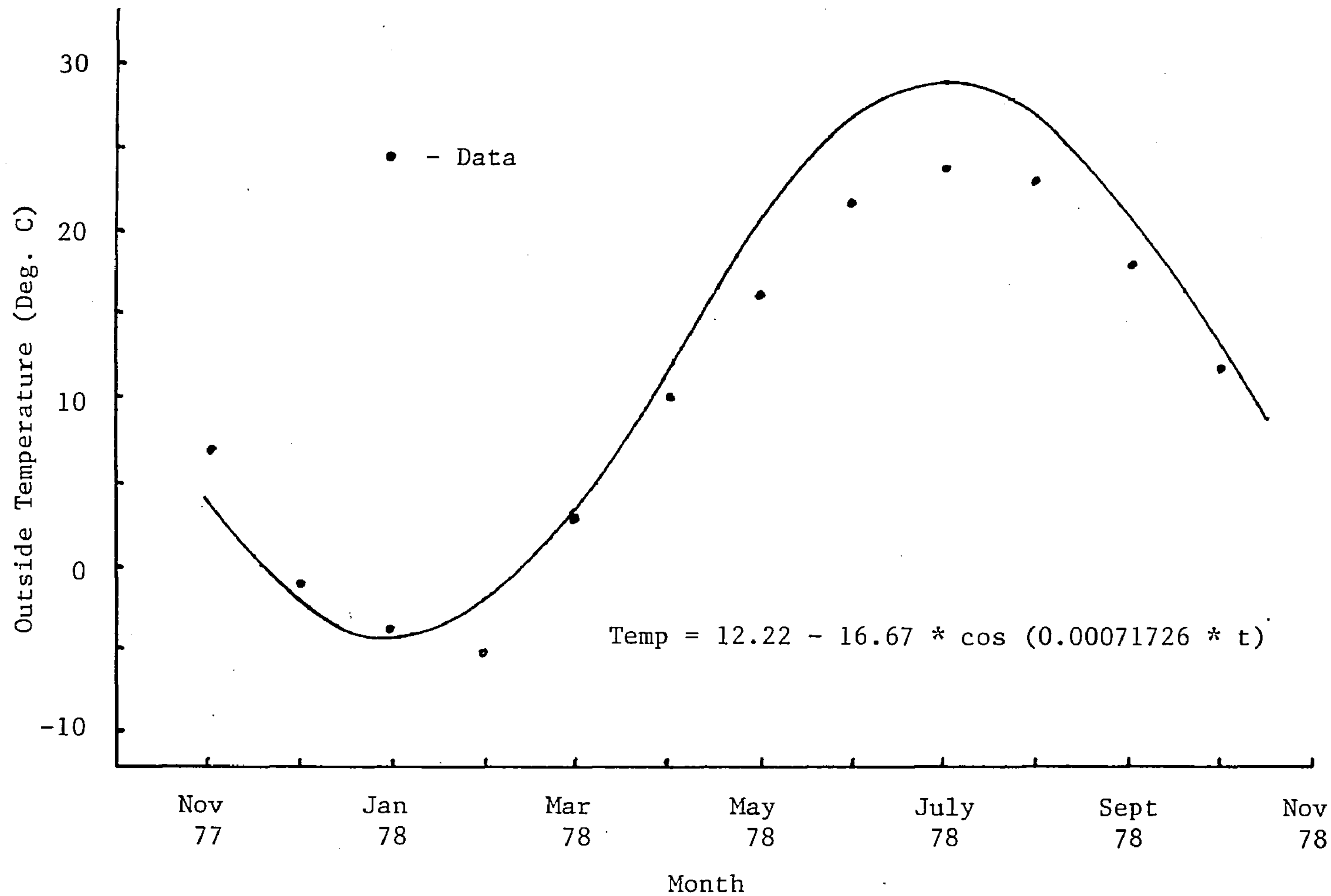


Figure 4. SEASONAL PART OF DETERMINISTIC TEMPERATURE PREDICTOR

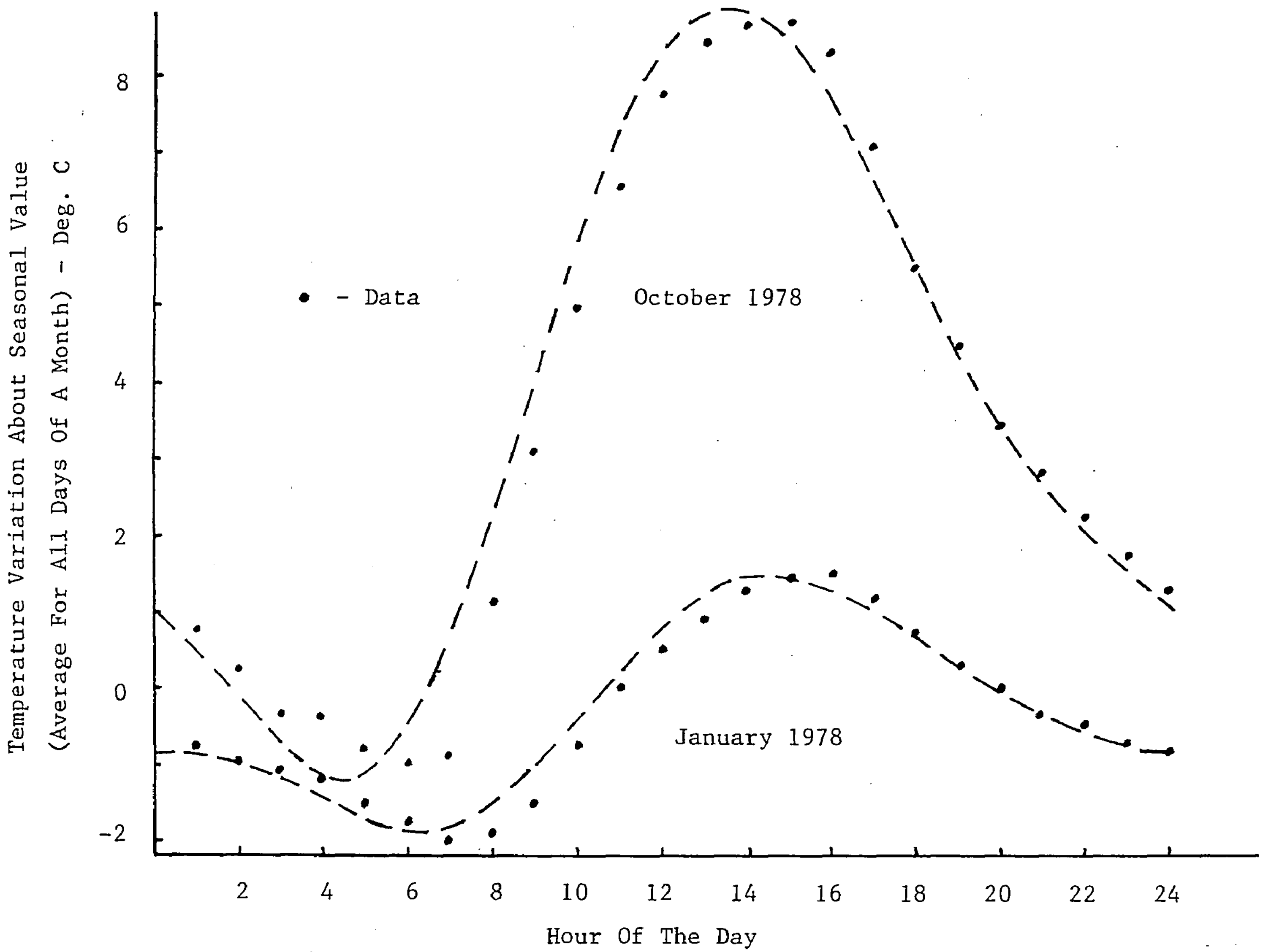


Figure 5. 24-HOUR PART OF DETERMINISTIC TEMPERATURE PREDICTOR - JANUARY AND OCTOBER 1978

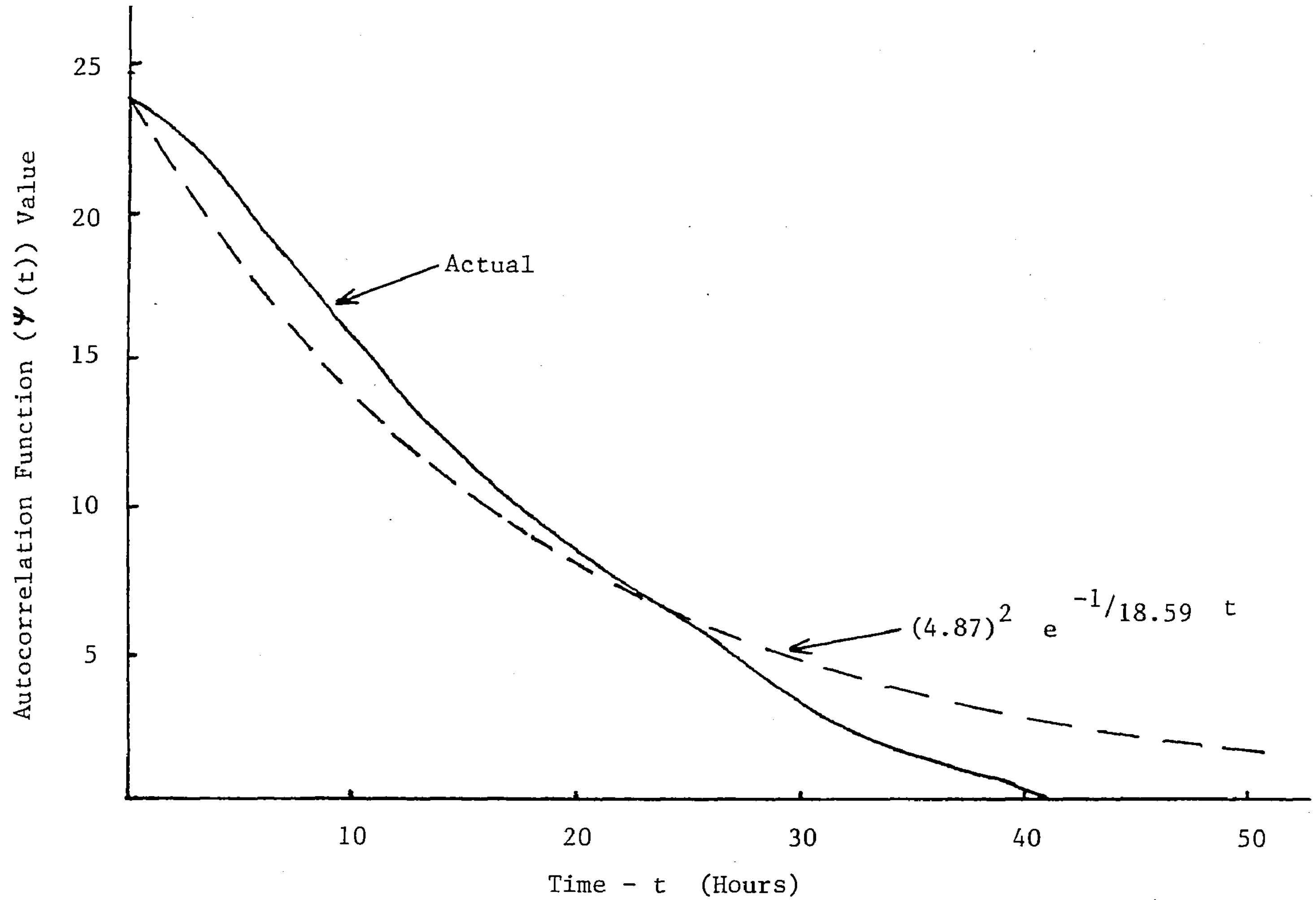


Figure 6. AUTOCORRELATION OF TEMPERATURE ERROR - JANUARY 1978

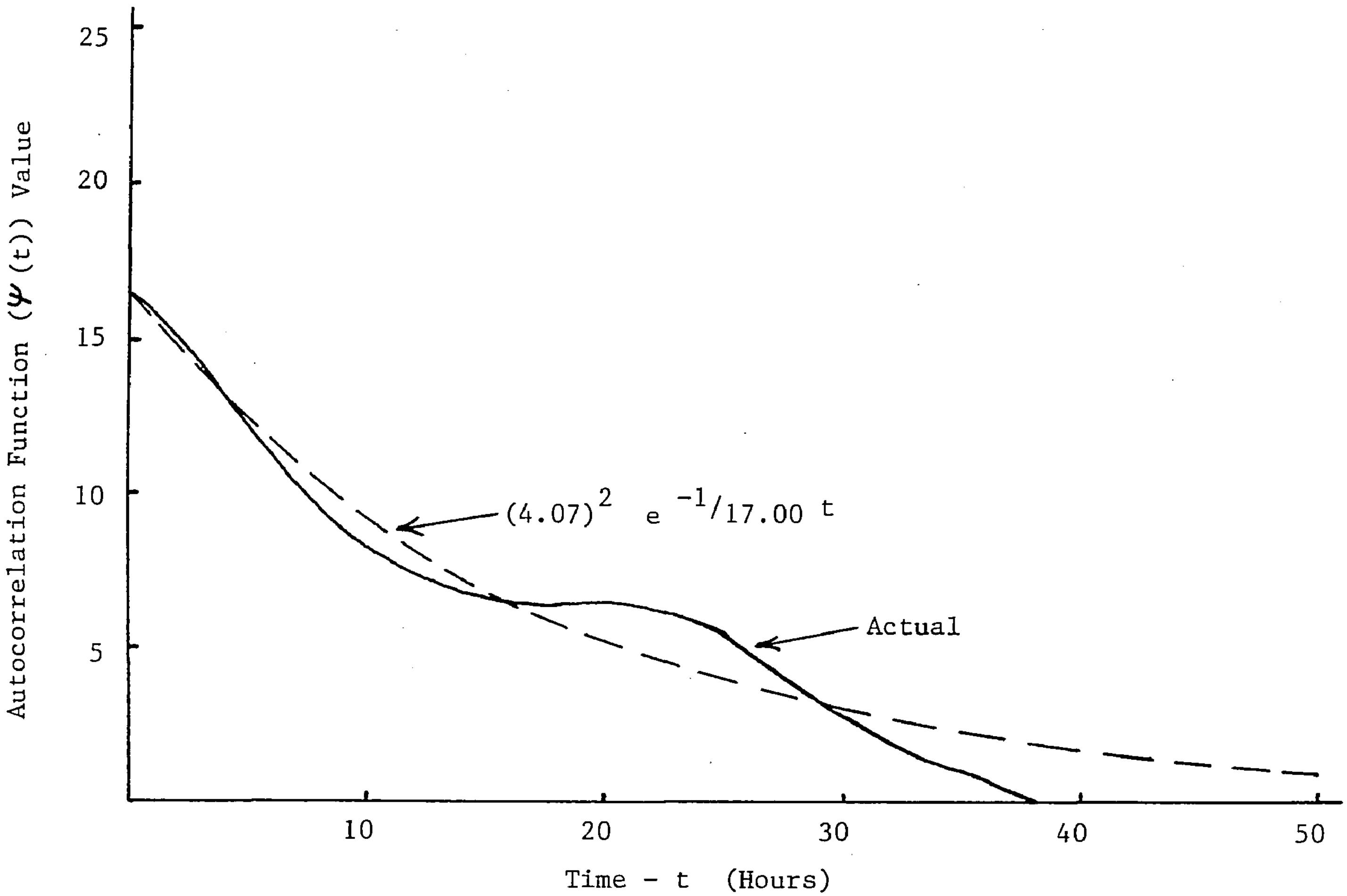


Figure 7. AUTOCORRELATION OF TEMPERATURE ERROR - OCTOBER 1978

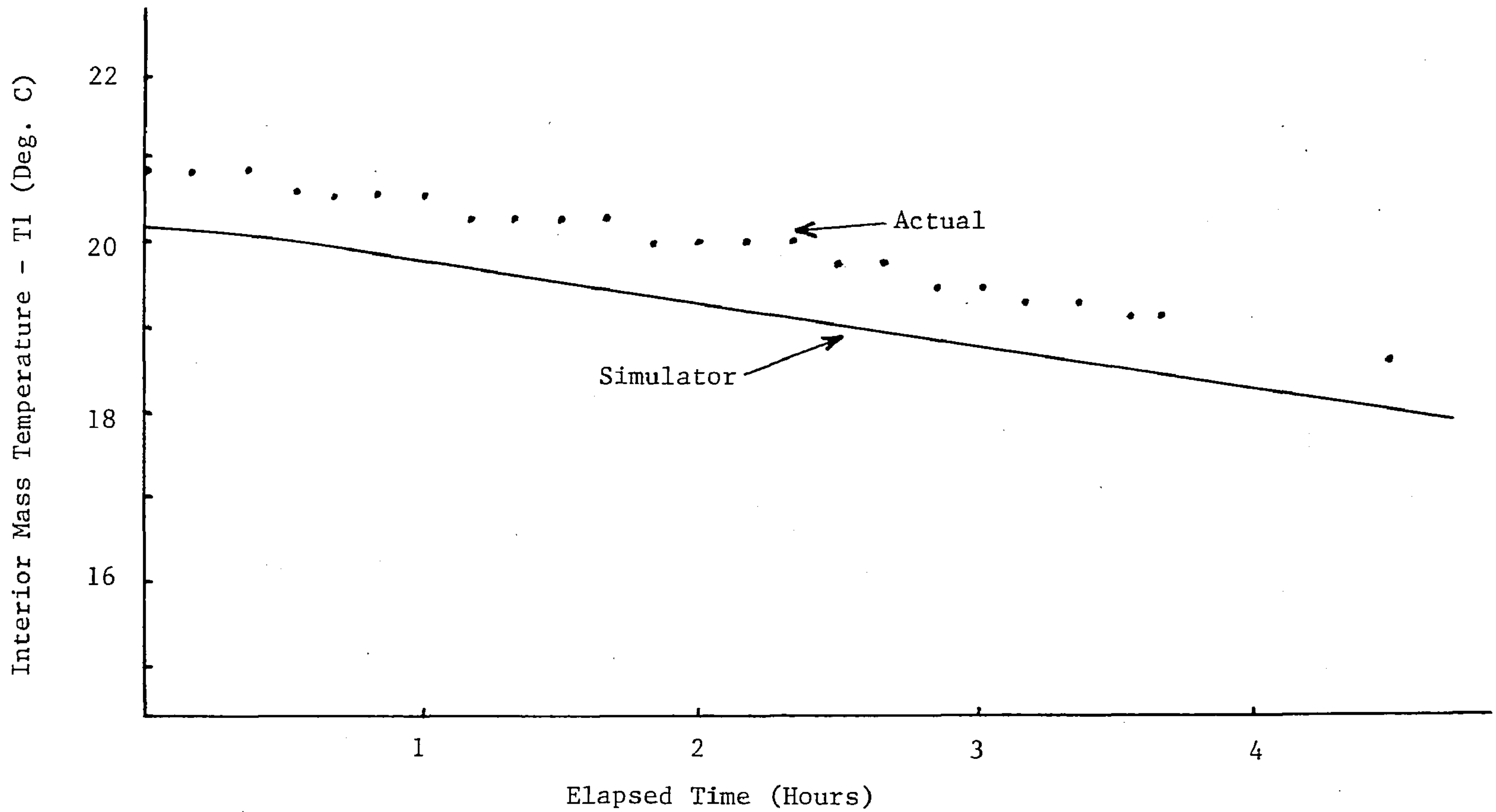


Figure 8. ACTUAL AND SIMULATOR TEMPERATURE DECAY - INTERIOR MASS TEMPERATURE

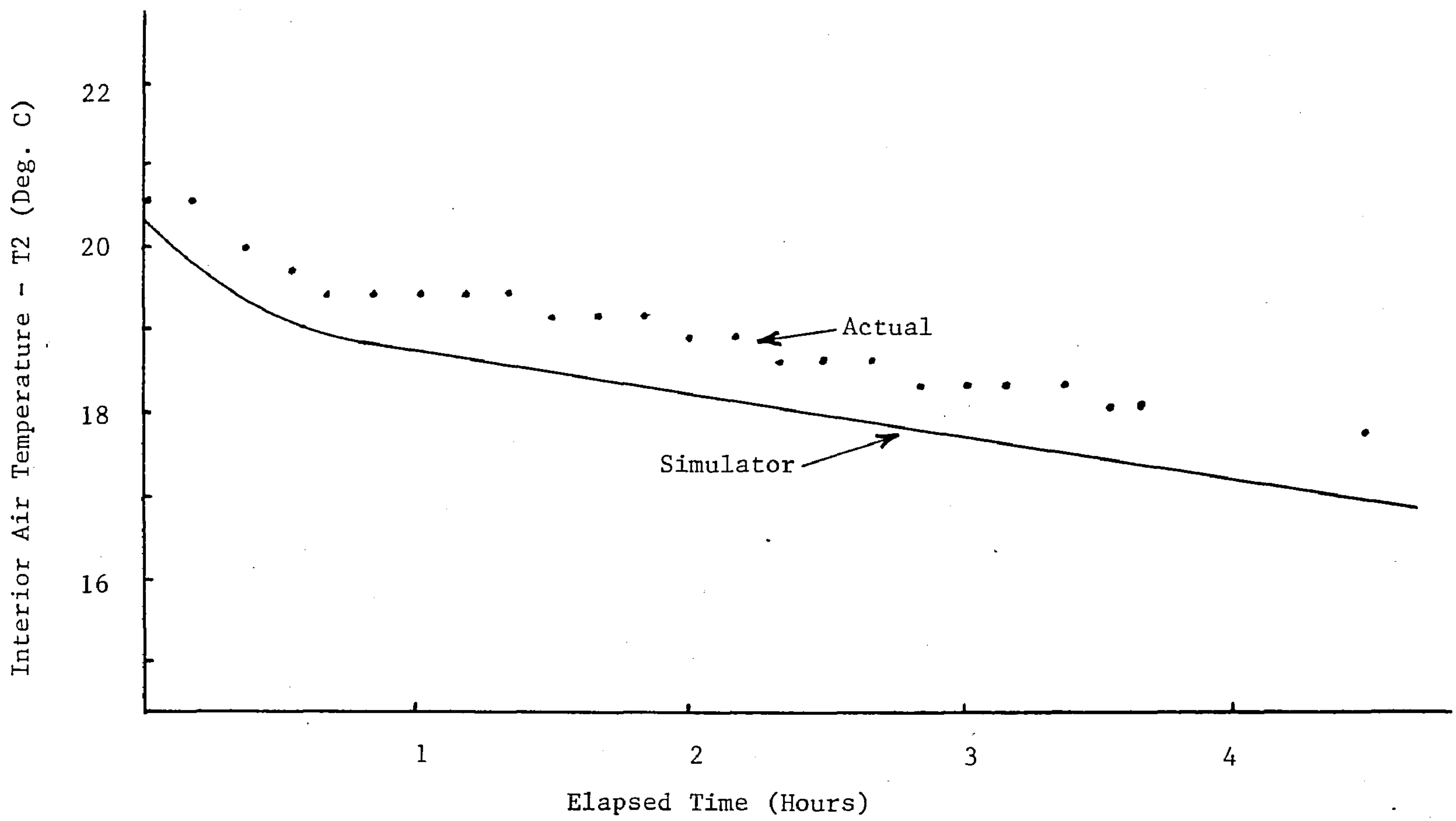


Figure 9. ACTUAL AND SIMULATOR TEMPERATURE DECAY - INTERIOR AIR TEMPERATURE

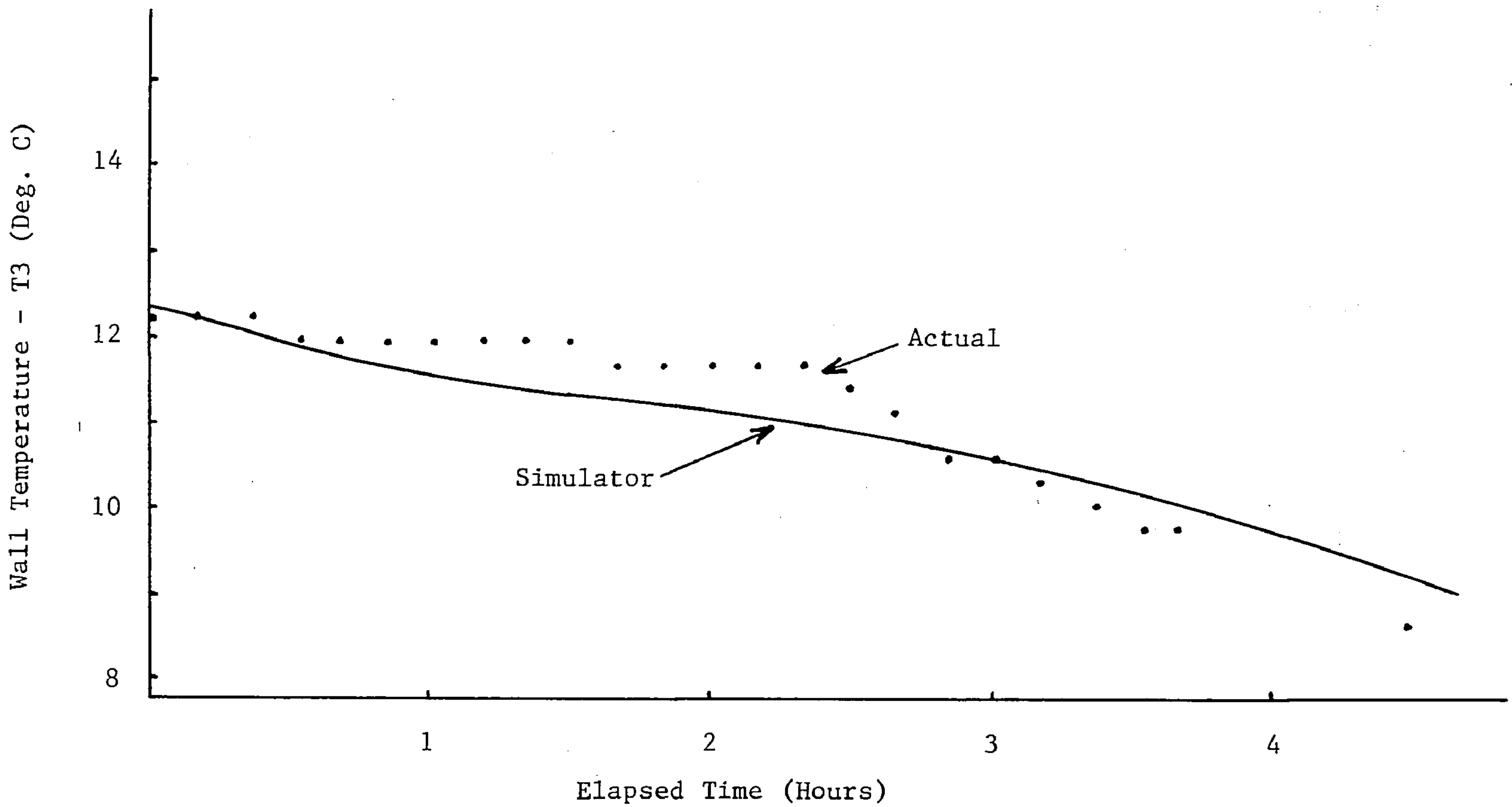


Figure 10. ACTUAL AND SIMULATOR TEMPERATURE DECAY - WALL TEMPERATURE

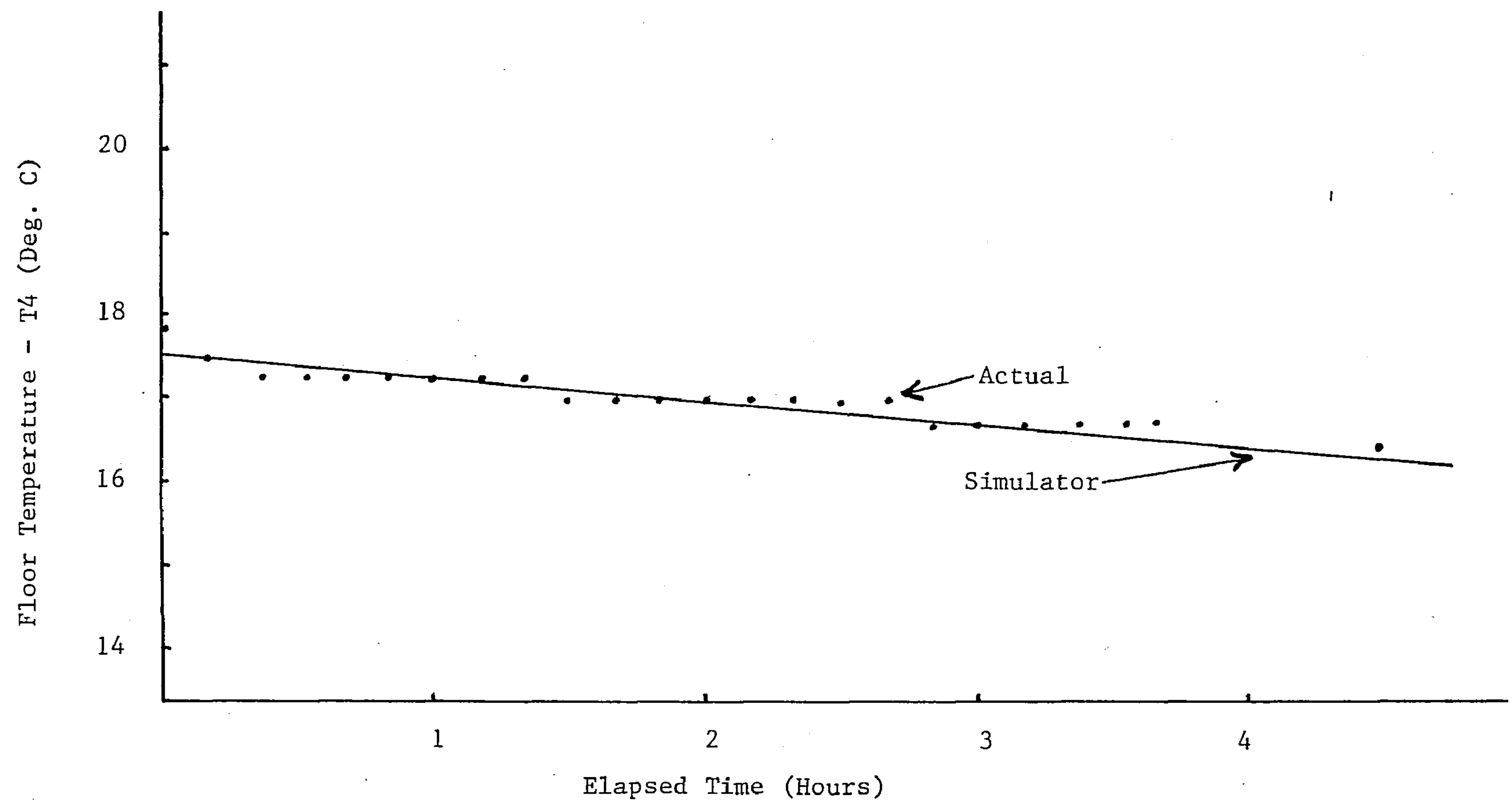


Figure 11. ACTUAL AND SIMULATOR TEMPERATURE DECAY - FLOOR TEMPERATURE

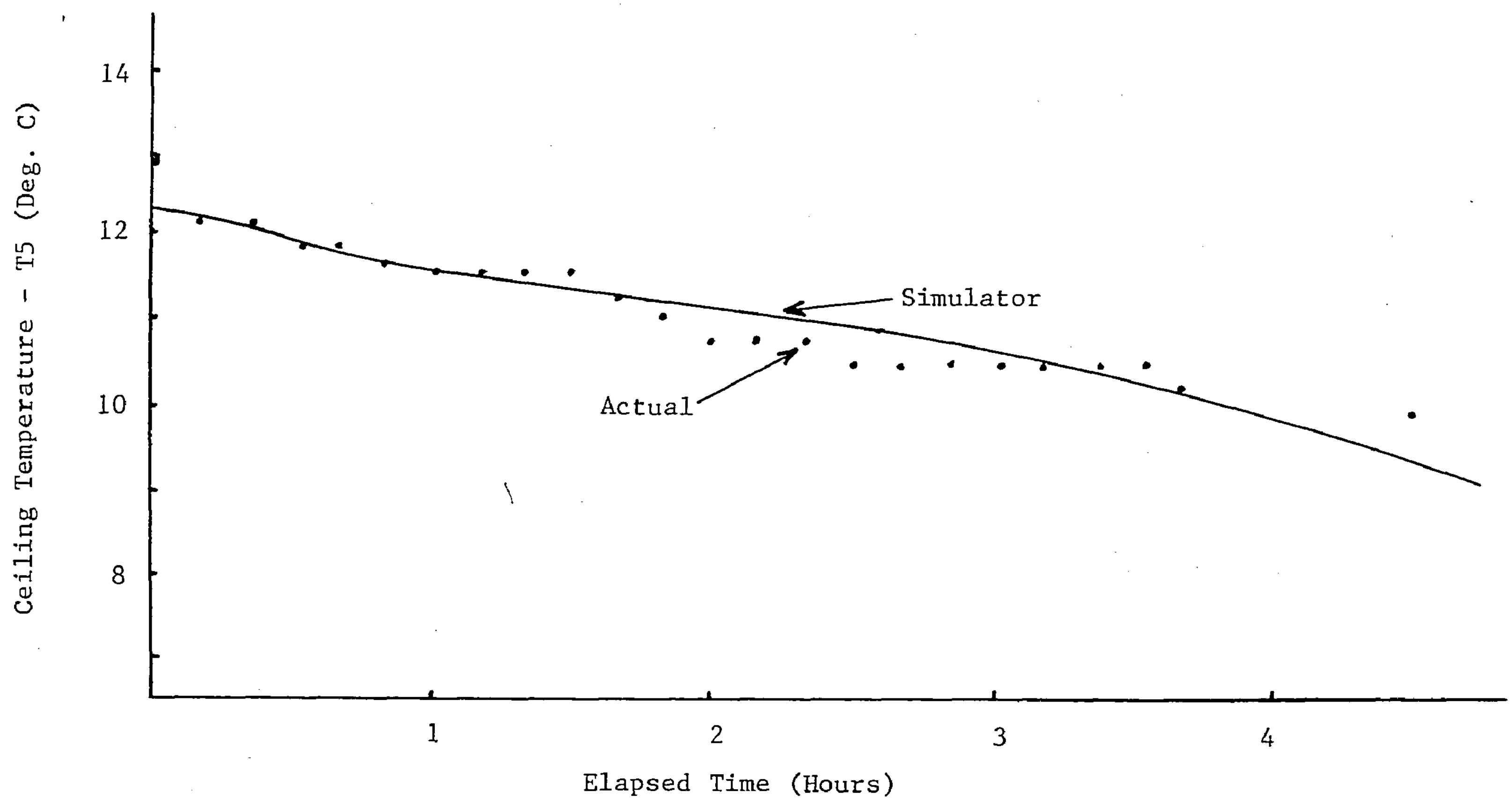


Figure 12. ACTUAL AND SIMULATOR TEMPERATURE DECAY - CEILING TEMPERATURE

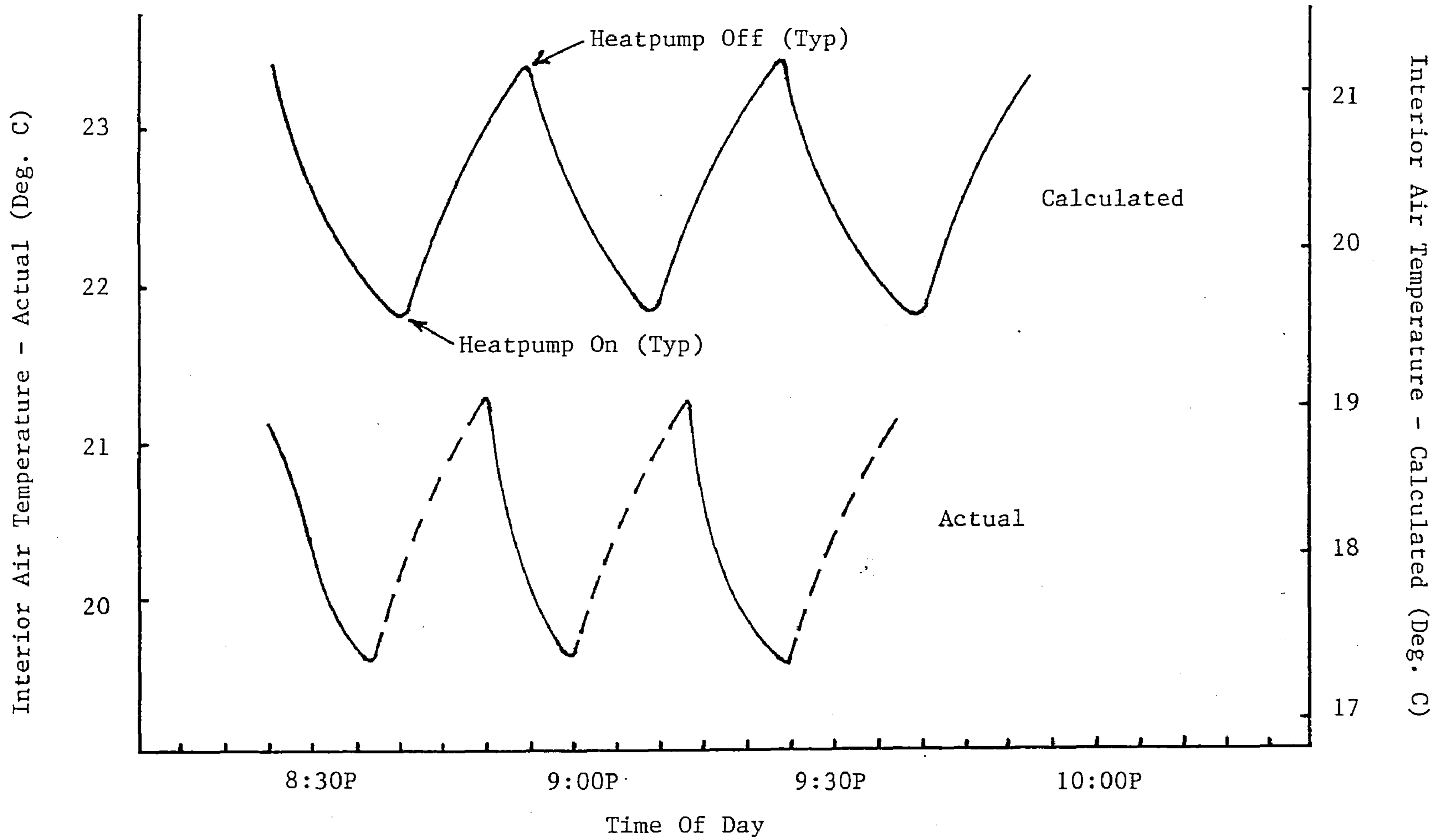


Figure 13. ACTUAL AND SIMULATOR HEATPUMP CYCLING - 3/30/80

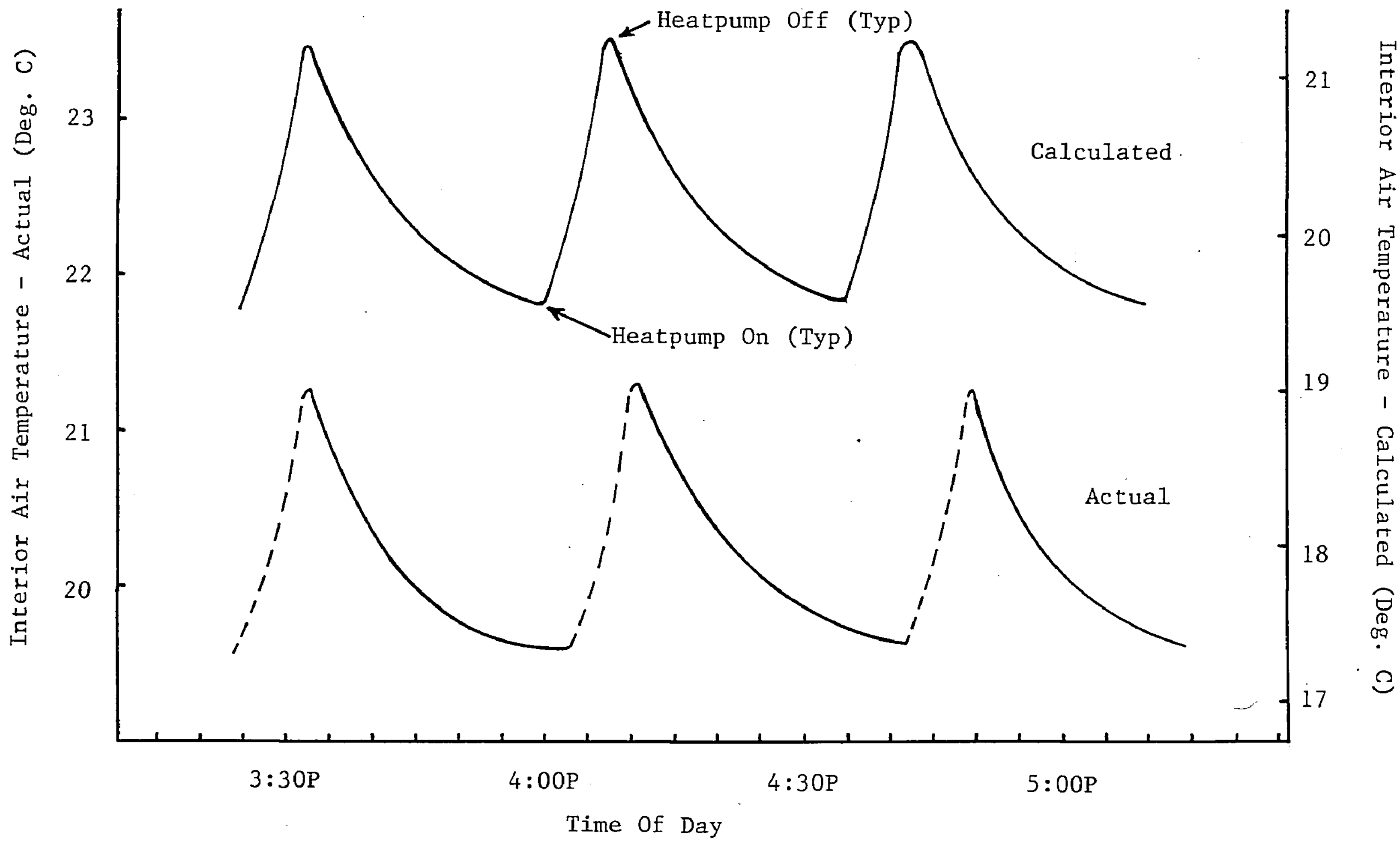


Figure 14. ACTUAL AND SIMULATOR HEATPUMP CYCLING - 3/22/80

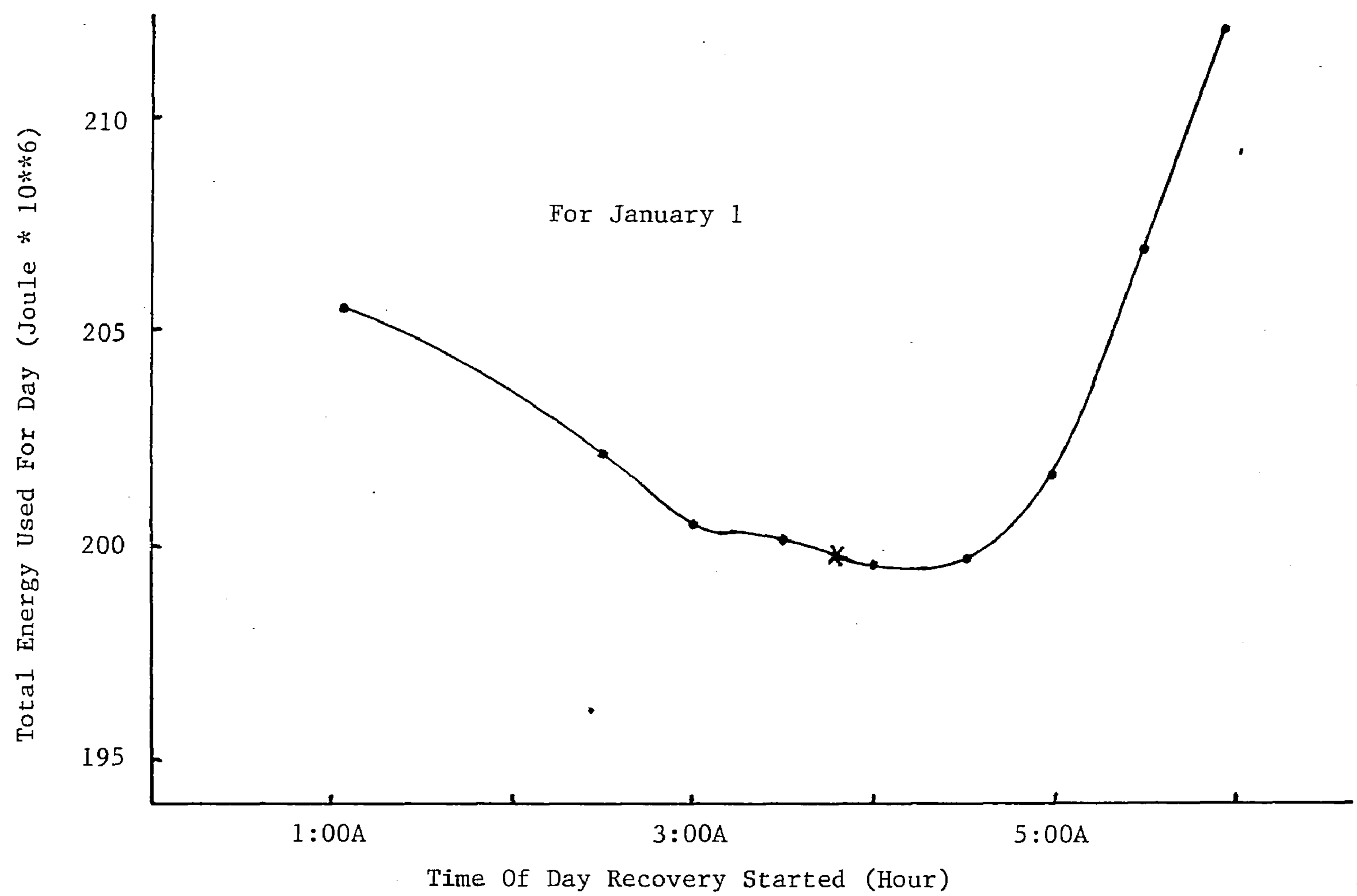


Figure 15. 24-HOUR ENERGY CONSUMPTION OF HEATPUMP SYSTEM WITH VARIOUS LENGTHS OF THERMOSTAT SETBACK DURATION - DETERMINISTIC OUTSIDE TEMPERATURE PROFILE

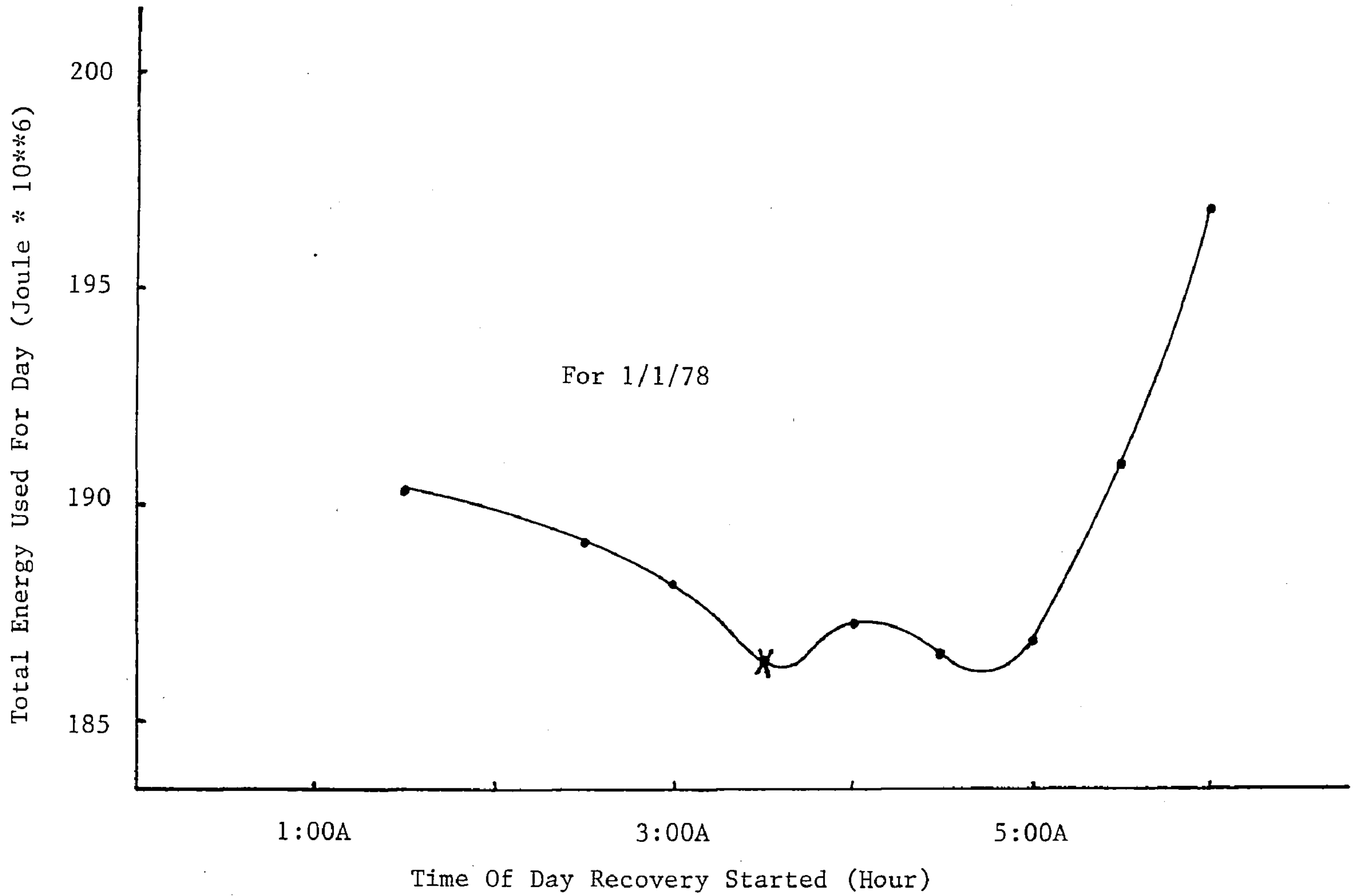


Figure 16. 24-HOUR ENERGY CONSUMPTION OF HEATPUMP SYSTEM WITH VARIOUS LENGTHS OF THERMOSTAT SETBACK DURATION - ACTUAL OUTSIDE TEMPERATURE PROFILE

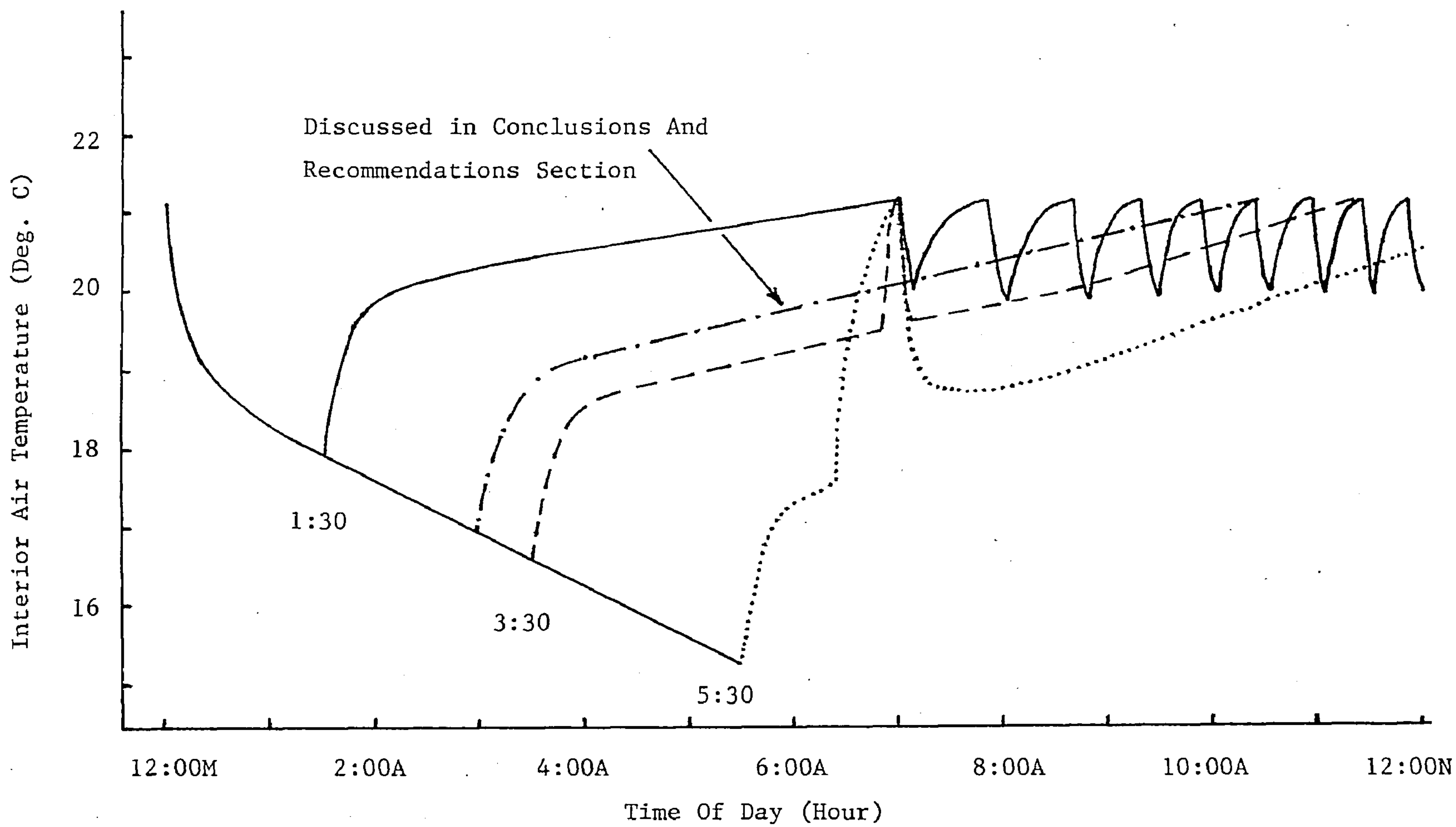


Figure 17. SIMULATED INTERIOR AIR TEMPERATURE PROFILES WITH SETBACK THERMOSTAT – ACTUAL OUTSIDE TEMPERATURE PROFILE – 1/1/78

Appendix A

Average Daily Temperatures November

1977 Through October 1978

AVERAGE DAILY TEMPERATURES (Deg. C)

Date	Nov. 77	Dec. 77	Jan. 78	Feb. 78	Mar. 78	Apr. 78
1	10.0	4.4	-3.3	-6.1	-3.9	17.7
2	15.0	3.9	-3.3	-6.1	-5.0	8.9
3	17.2	1.7	-6.7	-6.7	-5.0	0.6
4	21.1	1.7	-6.1	-8.9	-5.0	7.8
5	16.1	0.6	-2.2	-11.1	-7.2	10.0
6	11.1	0.6	3.3	-6.7	-5.6	7.8
7	11.1	-3.3	0.6	-5.0	-3.9	13.8
8	11.1	-3.9	8.3	-3.9	-3.9	8.3
9	13.8	-3.3	1.7	-8.9	0.0	6.7
10	12.2	-9.4	-10.6	-6.1	2.8	10.6
11	3.9	-10.0	-6.7	-7.8	2.8	12.8
12	1.7	-8.3	-5.6	-3.3	5.0	14.4
13	0.6	-0.6	-2.2	-3.3	2.8	15.0
14	0.0	3.9	-2.8	-2.2	7.8	10.6
15	5.6	5.6	-7.2	-6.1	5.6	7.2
16	9.4	3.3	-7.2	-6.1	1.7	7.8
17	10.6	0.6	-2.2	0.0	-1.1	7.8
18	6.1	0.0	-1.7	-3.3	-1.1	10.0
19	4.4	1.7	-5.6	-7.2	6.7	8.9
20	2.8	1.7	-3.3	-9.4	5.6	11.7
21	6.1	3.9	-6.1	-5.6	11.1	8.9
22	6.1	-0.6	-6.1	-7.8	9.4	10.0
23	3.3	0.6	-6.1	-4.4	13.8	10.6
24	6.1	2.2	-8.3	-2.8	5.6	11.7
25	2.2	2.8	-1.1	-4.4	1.1	11.7
26	0.0	-7.2	3.3	0.0	2.8	11.7
27	-1.7	-8.3	-6.1	-3.9	8.9	11.7
28	0.6	-8.3	-7.2	-6.1	10.0	12.2
29	-1.1	-6.1	-6.7		8.9	15.0
30	1.1	-1.1	-4.4		5.6	9.4
31		1.7	-7.8		8.3	

AVERAGE DAILY TEMPERATURES (Deg. C)

DATE	MAY 78	JUNE 78	JULY 78	AUG. 78	SEP. 78	OCT. 78
1	7.8	25.0	20.0	20.0	21.7	18.3
2	12.8	23.9	18.3	23.9	20.0	14.4
3	12.8	18.9	16.7	25.6	20.6	12.2
4	7.8	17.2	16.1	24.4	20.0	15.6
5	6.1	19.4	20.0	20.0	20.6	15.6
6	8.3	17.7	23.3	24.4	22.8	16.1
7	13.8	20.0	23.3	24.4	25.0	11.7
8	9.4	25.6	24.4	25.0	15.6	8.9
9	18.9	21.7	27.2	23.9	17.7	8.9
10	14.4	20.0	26.1	23.9	13.8	11.7
11	15.6	21.7	19.4	21.1	21.7	14.4
12	17.7	24.4	19.4	24.4	23.3	17.7
13	17.7	17.2	21.1	25.0	17.2	16.7
14	13.8	15.6	20.6	25.0	15.0	13.8
15	12.8	17.2	23.3	25.0	18.3	8.9
16	11.7	17.7	22.2	27.2	18.9	7.2
17	13.3	17.2	22.8	25.6	18.3	7.8
18	16.7	24.4	23.9	22.8	22.2	6.1
19	18.9	26.1	24.4	23.3	17.2	12.2
20	21.7	23.3	26.1	21.7	20.0	9.4
21	19.4	23.9	26.7	20.0	22.8	11.1
22	16.7	22.8	30.0	20.6	19.4	14.4
23	17.7	21.7	30.6	21.7	15.0	15.6
24	14.4	20.6	25.6	22.2	14.4	7.2
25	20.6	21.1	21.7	18.3	16.1	8.3
26	22.8	21.1	22.2	20.0	11.7	13.8
27	22.2	27.2	26.1	21.1	13.3	8.9
28	24.4	27.8	22.2	24.4	13.3	9.4
29	21.7	26.1	19.4	26.1	11.1	10.0
30	23.3	23.9	20.0	23.9	12.8	7.8
31	23.9		17.2	20.0		9.4

Appendix B

Hourly Temperatures January 1978

JANUARY 1978
OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 1	2	3	4	5	6	7	8
1	-3.9	-3.3	-5.0	-7.7	-4.4	0.6	1.7	1.7
2	-3.9	-3.3	-5.6	-9.4	-5.0	0.6	1.1	1.7
3	-5.0	-3.3	-6.7	-10.0	-6.7	-0.6	1.1	1.7
4	-4.4	-2.8	-7.8	-10.0	-7.2	-1.1	1.1	1.7
5	-5.0	-1.7	-8.3	-10.6	-7.8	-1.1	0.6	2.2
6	-5.0	-1.7	-9.4	-9.4	-7.2	-0.6	0.6	2.8
7	-5.0	-2.2	-8.9	-11.1	-6.7	0.0	0.0	3.3
8	-5.0	-3.3	-8.9	-10.6	-5.6	0.0	0.0	3.9
9	-5.0	-3.3	-7.2	-8.9	-4.4	0.6	-0.6	5.0
10	-4.4	-2.8	-6.1	-6.7	-3.3	1.7	-0.6	5.6
11	-3.3	-2.2	-5.6	-5.0	-2.2	3.9	0.0	5.6
12	-2.8	-2.2	-5.0	-3.9	-1.1	4.4	0.0	5.6
13	-1.7	-1.7	-4.4	-2.8	1.7	6.7	0.0	5.6
14	-1.7	-1.7	-3.9	-2.8	1.7	6.7	0.0	6.1
15	-1.7	-1.1	-3.9	-2.2	3.3	7.2	0.0	7.2
16	-1.7	-1.1	-4.4	-1.7	3.3	6.1	0.0	7.8
17	-2.8	-2.2	-4.4	-2.2	2.8	6.1	0.6	8.3
18	-3.3	-2.2	-5.6	-2.2	2.2	5.0	0.6	8.9
19	-3.3	-2.8	-6.1	-2.2	1.7	4.4	0.6	10.6
20	-3.3	-3.3	-7.2	-2.2	-0.6	3.9	1.1	11.7
21	-3.3	-4.4	-7.2	-2.2	-0.6	2.8	1.1	12.8
22	-3.3	-5.0	-6.7	-2.2	-0.6	2.8	1.7	13.8
23	-3.3	-5.6	-7.8	-3.3	-0.6	2.2	1.7	13.8
24	-3.3	-5.6	-8.3	-5.0	1.1	1.7	1.7	15.0

JANUARY 1978
OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 9	10	11	12	13	14	15	16
1	15.0	-12.2	-7.8	-7.8	-3.3	0.6	-6.7	-8.9
2	15.0	-12.2	-8.9	-8.3	-3.3	0.6	-7.2	-9.4
3	15.0	-13.3	-8.3	-8.3	-3.3	0.6	-7.2	-9.4
4	15.0	-13.3	-8.3	-8.3	-3.3	0.6	-7.8	-9.4
5	7.8	-13.3	-8.3	-8.9	-3.9	0.6	-8.9	-10.0
6	5.6	-12.8	-8.9	-9.4	-3.9	0.6	-9.4	-10.6
7	3.3	-13.3	-9.4	-9.4	-3.9	0.0	-9.4	-10.6
8	2.2	-12.8	-8.3	-9.4	-3.9	0.0	-9.4	-10.6
9	1.1	-12.2	-7.2	-8.3	-3.9	-0.6	-9.4	-8.3
10	0.6	-11.1	-6.1	-7.8	-3.9	-0.6	-8.9	-7.2
11	-0.6	-10.0	-5.6	-6.1	-3.3	-0.6	-7.8	-6.1
12	-2.2	-9.4	-5.0	-5.0	-2.8	-0.6	-7.2	-5.0
13	-5.0	-8.9	-5.0	-3.9	-2.2	-0.6	-6.1	-5.0
14	-5.6	-8.9	-4.4	-2.2	-1.7	-0.6	-5.6	-4.4
15	-6.7	-8.3	-4.4	-2.2	-1.7	-2.2	-5.6	-3.9
16	-7.2	-7.8	-3.9	-2.2	-1.7	-3.3	-5.0	-3.9
17	-8.3	-8.3	-4.4	-2.2	-1.7	-3.9	-5.6	-4.4
18	-7.8	-8.3	-5.0	-3.3	-1.7	-3.9	-6.7	-5.0
19	-8.3	-8.9	-6.1	-3.3	-1.1	-3.9	-7.2	-5.0
20	-8.9	-8.9	-6.1	-2.8	-1.1	-4.4	-7.2	-5.6
21	-9.4	-8.9	-7.2	-2.2	-1.1	-5.6	-6.7	-5.6
22	-11.1	-8.9	-7.8	-2.2	-0.6	-5.6	-7.2	-5.6
23	-11.7	-7.8	-7.8	-2.2	-0.6	-5.6	-7.8	-5.6
24	-11.7	-7.8	-7.8	-2.2	-0.6	-6.1	-8.3	-5.6

JANUARY 1978

OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 17	18	19	20	21	22	23	24
1	-5.6	1.1	-6.1	-4.4	-5.0	-6.1	-9.4	-12.2
2	-6.1	1.1	-6.7	-4.4	-5.6	-6.7	-10.0	-12.8
3	-6.1	1.1	-6.7	-5.0	-7.8	-6.7	-8.9	-12.8
4	-6.1	1.1	-6.7	-4.4	-8.9	-7.2	-8.9	-13.9
5	-6.1	1.1	-6.7	-4.4	-8.9	-8.3	-8.9	-14.4
6	-6.1	1.1	-8.3	-4.4	-8.3	-8.3	-9.4	-15.6
7	-6.1	1.1	-8.9	-4.4	-8.9	-7.8	-10.0	-16.1
8	-6.1	1.1	-8.9	-4.4	-7.8	-7.8	-10.0	-16.6
9	-6.1	0.6	-7.2	-4.4	-7.2	-7.2	-9.4	-15.0
10	-5.6	0.0	-5.6	-3.3	-6.1	-6.1	-7.2	-12.8
11	-5.6	-0.6	-5.6	-3.3	-5.0	-4.4	-5.6	-10.0
12	-5.0	-1.1	-4.4	-2.8	-4.4	-3.3	-4.4	-6.7
13	-5.0	-1.1	-4.4	-2.8	-4.4	-3.3	-3.3	-5.0
14	-5.0	-0.6	-2.8	-2.8	-4.4	-2.2	-3.3	-2.2
15	-4.4	-0.6	-3.3	-2.8	-4.4	-2.2	-2.8	-1.1
16	-4.4	-1.1	-3.3	-2.2	-4.4	-2.2	-2.8	-0.6
17	-4.4	-1.1	-2.8	-2.2	-4.4	-3.3	-3.9	-1.7
18	-4.4	-1.7	-2.8	-2.2	-5.0	-4.4	-5.6	-3.9
19	-4.4	-2.2	-3.3	-2.2	-5.0	-5.6	-6.1	-3.9
20	-2.8	-2.2	-3.9	-2.8	-5.0	-6.7	-6.1	-3.9
21	-2.2	-3.3	-3.9	-2.8	-5.0	-7.2	-6.7	-6.1
22	-0.6	-3.9	-4.4	-2.8	-5.0	-7.8	-8.3	-5.0
23	-0.6	-4.4	-4.4	-3.9	-5.6	-8.3	-9.4	-4.4
24	1.1	-5.0	-4.4	-3.9	-6.7	-10.0	-11.1	-5.0

JANUARY 1978
OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 25	26	27	28	29	30	31
1	-3.3	2.8	-7.8	-7.8	-8.3	-7.8	-6.7
2	-2.2	5.6	-7.8	-8.3	-7.8	-7.8	-6.7
3	-1.7	10.0	-7.8	-8.9	-7.8	-7.8	-7.2
4	-1.7	11.1	-7.8	-8.3	-7.8	-7.2	-7.8
5	-1.1	13.3	-7.8	-7.8	-7.8	-7.2	-8.9
6	-1.1	11.7	-7.2	-7.8	-7.8	-7.2	-10.0
7	-0.6	10.0	-7.2	-8.3	-7.8	-7.2	-10.6
8	0.6	8.9	-7.2	-8.3	-7.8	-7.2	-10.6
9	1.1	6.7	-6.7	-7.8	-7.8	-6.7	-9.4
10	0.6	4.4	-6.1	-7.8	-7.2	-5.6	-8.3
11	1.1	3.9	-5.0	-7.2	-6.1	-3.9	-7.8
12	1.1	3.3	-5.0	-7.2	-6.1	-3.9	-6.1
13	1.1	2.8	-5.0	-7.2	-5.6	-3.3	-5.6
14	1.1	2.2	-5.0	-7.2	-5.0	-2.8	-5.0
15	1.7	2.2	-5.6	-6.1	-5.0	-2.8	-5.0
16	2.2	1.7	-5.6	-5.6	-5.0	-2.2	-5.0
17	2.8	0.6	-5.6	-6.1	-5.0	-1.7	-5.0
18	2.8	-1.1	-6.1	-6.7	-5.0	-2.8	-5.6
19	2.8	-2.8	-6.1	-7.8	-6.1	-3.3	-6.1
20	2.2	-5.0	-6.7	-7.8	-7.2	-4.4	-6.7
21	2.2	-6.1	-6.7	-7.8	-8.3	-5.0	-7.2
22	2.8	-6.7	-7.2	-7.8	-8.3	-6.1	-7.2
23	2.8	-7.2	-7.8	-7.8	-8.3	-6.7	-7.8
24	2.8	-7.2	-7.8	-7.8	-7.2	-6.7	-7.8

Appendix C

Hourly Temperatures October 1978

OCTOBER 1978
OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 1	2	3	4	5	6	7	8
1	14.4	15.6	7.8	14.4	12.8	16.1	11.1	5.6
2	15.0	14.4	7.2	14.4	12.8	16.1	11.1	5.6
3	15.0	14.4	6.1	14.4	12.8	15.6	10.0	4.4
4	15.6	12.8	6.1	13.8	12.8	15.6	10.0	5.0
5	15.0	12.8	5.0	13.8	12.8	15.6	9.4	5.0
6	14.4	11.7	5.6	14.4	12.8	15.6	11.1	4.4
7	15.0	12.2	6.1	15.0	12.8	15.0	11.1	4.4
8	16.7	15.0	8.9	15.0	12.8	15.6	12.8	7.2
9	18.3	16.7	11.7	15.0	13.3	17.2	13.8	8.9
10	19.4	17.7	13.3	15.0	13.8	18.3	13.3	10.6
11	19.4	18.3	16.1	15.0	15.0	19.4	13.8	11.7
12	21.1	19.4	17.7	15.6	16.7	20.0	14.4	12.8
13	21.7	20.0	18.9	16.1	17.7	20.6	15.0	11.1
14	21.7	18.9	17.2	16.7	17.2	20.0	14.4	8.3
15	21.7	18.9	17.2	17.7	17.2	18.3	14.4	9.4
16	21.7	17.7	17.2	18.3	16.7	17.7	14.4	7.8
17	21.1	16.1	17.2	17.2	16.1	16.7	13.3	8.3
18	21.1	13.8	16.7	15.0	16.7	15.0	12.2	7.8
19	19.4	12.2	15.6	14.4	16.7	13.3	10.0	8.3
20	18.3	11.1	15.0	14.4	16.7	12.8	8.9	7.2
21	16.7	10.0	15.0	12.8	16.1	12.2	7.8	7.2
22	16.7	10.0	14.4	13.3	16.1	11.7	7.8	6.1
23	15.6	9.4	14.4	13.3	16.1	11.1	7.2	5.0
24	15.6	8.9	14.4	12.8	16.7	11.1	6.7	4.4

OCTOBER 1978
OUTSIDE AIR TEMPERATURES (Deg. C)

HOUR	DATE 9	10	11	12	13	14	15	16
1	3.3	3.9	8.3	13.8	13.3	16.7	7.8	3.3
2	3.3	2.8	7.8	13.8	12.2	16.1	7.2	2.8
3	4.4	3.3	6.7	13.3	11.7	15.6	7.2	1.1
4	4.4	2.8	7.8	14.4	12.8	17.2	5.6	1.1
5	3.3	1.7	6.1	13.8	12.2	17.7	5.6	2.2
6	2.8	2.8	6.1	13.8	11.7	18.3	5.0	1.1
7	2.8	3.3	6.7	14.4	10.6	18.3	5.0	1.7
8	6.1	7.2	10.0	14.4	14.4	18.9	6.1	4.4
9	8.3	11.7	13.3	15.6	16.7	18.9	7.2	6.1
10	10.0	13.8	16.7	16.1	18.9	18.9	7.2	8.9
11	11.7	16.1	20.0	17.2	20.6	19.4	7.8	10.6
12	12.8	17.7	21.7	20.0	21.7	17.2	8.9	11.7
13	13.8	19.4	22.2	20.6	22.2	13.3	11.7	12.2
14	14.4	21.1	22.8	21.1	22.2	13.8	13.3	12.8
15	15.0	21.7	21.7	22.8	22.2	12.8	13.3	9.4
16	14.4	20.6	21.7	22.8	22.8	12.2	11.7	8.9
17	13.8	18.9	21.1	22.2	21.1	11.7	10.6	8.9
18	10.6	16.1	20.6	20.6	20.6	10.6	8.3	8.3
19	10.0	15.6	18.3	19.4	20.0	9.4	6.7	8.3
20	9.4	14.4	16.1	18.3	18.3	9.4	5.0	8.3
21	7.8	11.7	15.0	17.2	18.3	8.9	5.0	8.3
22	6.1	11.7	13.8	15.6	18.3	8.3	3.9	8.3
23	5.0	11.7	15.0	15.0	17.7	7.8	4.4	7.8
24	4.4	10.6	14.4	13.8	17.2	7.8	3.9	7.8

OCTOBER 1978

OUTSIDE AIR TEMPERATURES (Deg. C)

	DATE							
HOUR	17	18	19	20	21	22	23	24
1	7.2	0.6	10.0	10.6	4.4	6.7	11.1	5.6
2	7.2	0.6	10.0	10.0	3.3	5.6	10.0	4.4
3	7.2	-0.6	9.4	10.0	3.9	5.6	8.3	3.9
4	6.7	-1.1	9.4	9.4	3.3	5.6	8.9	3.3
5	5.6	-1.7	8.9	8.9	2.8	5.0	9.4	2.8
6	5.0	-1.1	8.9	8.9	2.2	4.4	8.9	2.8
7	3.9	-0.6	9.4	9.4	2.8	5.0	8.9	2.2
8	4.4	1.1	10.0	10.0	5.6	6.7	14.4	4.4
9	6.1	4.4	11.1	11.7	10.0	11.1	16.7	5.6
10	7.8	7.8	12.8	11.7	13.3	14.4	20.6	7.2
11	9.4	10.0	13.8	11.7	16.1	18.9	22.8	8.9
12	11.1	12.8	15.0	12.2	17.7	21.7	23.9	10.0
13	12.2	13.3	15.0	12.8	18.9	22.8	23.9	11.7
14	12.8	12.8	15.0	13.3	19.4	23.3	23.9	12.2
15	13.3	13.3	15.0	14.4	20.0	23.3	23.3	12.2
16	13.8	13.3	14.4	13.3	20.0	23.9	22.2	11.7
17	11.7	13.3	14.4	12.2	17.2	21.1	20.6	10.0
18	8.3	12.2	13.3	10.6	16.1	19.4	15.6	8.3
19	6.1	11.7	13.3	8.9	14.4	18.3	11.1	8.3
20	5.6	10.6	12.8	8.3	12.8	14.4	10.0	7.2
21	6.7	10.6	12.8	6.7	12.2	13.8	9.4	6.1
22	5.0	10.6	12.8	5.6	10.0	13.3	7.8	6.1
23	3.9	10.6	11.1	4.4	8.3	11.7	7.2	6.1
24	1.7	10.6	10.6	3.9	8.3	12.2	6.1	4.4

OCTOBER 1978
OUTSIDE AIR TEMPERATURES (Deg. C)
DATE

HOUR	25	26	27	28	29	30	31
1	3.9	12.8	15.0	2.2	6.1	4.4	8.9
2	2.2	12.8	15.0	2.2	4.4	3.3	7.2
3	1.1	12.8	11.7	2.2	4.4	3.3	3.9
4	1.1	12.8	10.0	2.2	5.0	2.8	3.9
5	0.0	12.2	8.9	1.7	5.6	1.7	2.8
6	0.0	11.7	7.2	1.1	6.1	2.2	1.7
7	0.6	11.7	7.2	0.6	5.6	2.2	1.7
8	2.8	13.3	10.0	2.8	7.2	3.3	3.9
9	8.3	13.8	11.1	6.7	10.0	5.0	7.2
10	10.6	14.4	12.8	11.1	12.2	7.2	10.6
11	12.2	14.4	13.3	15.0	12.8	8.9	13.8
12	13.3	14.4	13.3	16.1	13.8	11.7	15.0
13	14.4	15.0	12.8	17.2	15.0	12.8	16.1
14	16.1	15.0	13.8	17.2	15.6	13.8	17.2
15	16.1	15.6	14.4	17.7	15.6	13.8	17.2
16	16.1	16.1	12.8	16.7	15.6	12.2	16.1
17	13.8	15.6	11.7	13.3	12.8	10.0	13.8
18	11.7	13.8	9.4	13.3	10.0	7.8	12.8
19	12.2	14.4	8.9	12.8	7.8	7.8	11.7
20	11.7	14.4	7.2	9.4	7.2	8.9	8.9
21	12.2	13.8	6.1	7.2	7.2	9.4	8.9
22	13.3	13.3	5.6	6.1	6.1	10.0	7.8
23	13.3	13.8	3.3	6.1	5.6	10.0	6.7
24	12.8	15.0	2.8	5.6	4.4	9.4	6.1

Appendix D

Differential Equations Of Modeled Residence

The differential equations which govern the flow of heat for the modeled residence are:

1. dT1/dt = A1 / R12 * (T2 - T1) / (R01 * C1 * V1)
2. dT2/dt = (QH + AW / R23 * (T3 - T2) + AF / R24 * (T4 - T2) + AC /R25 * (T5 - T2) + AG / R20 * (T0 - T2) + A1 / R12 * (T1 - T2)) / (R02 * C2 * V2)
3. dT3/dt = (AW / R23 * (T2 - T3) + AW / R30 * (T0 - T3)) / (R03 * C3 * V3)
4. dT4/dt = (AF / R24 * (T2 - T4) + AF / R4C * (TC - T4)) / (R04 * C4 * V4)
5. dT5/dt = (AC / R25 * (T2 - T5) + AC / R50 * (T0 - T5)) / (R05 * C5 * V5)

Terms are defined as follows:

A1 - surface area of interior mass

AW - surface area of outside walls exposed to interior space

AF - surface area of floors over cellar exposed to interior space

AC - surface area of outside ceilings exposed to interior space

AG - surface area of windows

C1 ... C5 - average specific heat of interior mass, interior air, walls, floors and ceilings respectively

QH - heat input from heating system

RO1 ... RO5 - average density of interior mass, interior air, walls, floors and ceilings respectively

R12 - inverse heat transfer coefficient between interior mass and interior air

R23 - inverse heat transfer coefficient between interior air and walls

R24 - inverse heat transfer coefficient between interior air and floors

R25 - inverse heat transfer coefficient between interior air and ceilings

R20 - inverse heat transfer coefficient between interior air and outside air through windows

R30 - inverse heat transfer coefficient between walls and outside air

R4C - inverse heat transfer coefficient between floors and cellar

R50 - inverse heat transfer coefficient between ceilings and outside air

t - time

T1 ... T5 - temperatures of interior mass, interior air, walls, floors and ceilings respectively

T0 - temperture of outside air

TC - temperature of cellar

V1 ... V5 - volumes of interior mass, interior air, walls, floors and ceilings respectively

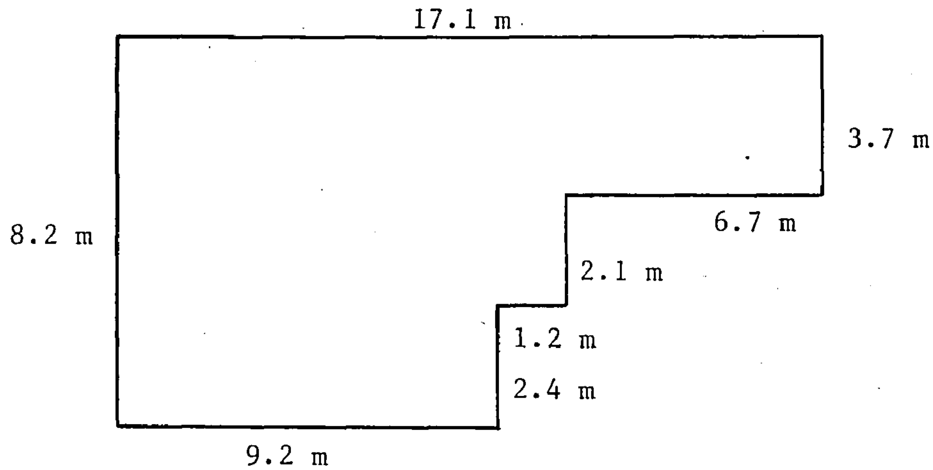
Appendix E

Calculation Of Parameters In Lumped-Heat-Capacity Model Of Residence

The residence is a 2-story colonial house of frame construction. Basement is located under the entire first floor area. Floors to basement are insulated with 8.89 cm. of fiberglass, as are all outside walls. Ceilings are insulated with 25.4 cm. of fiberglass insulation.

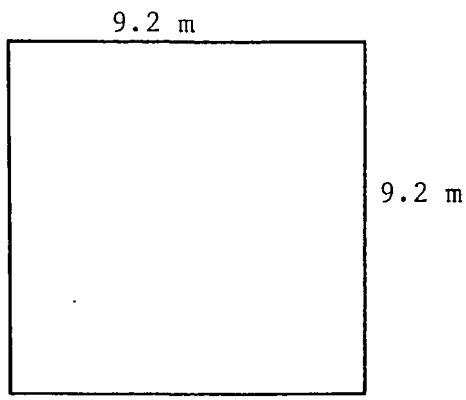
CALCULATION OF AREAS

Floors: First floor over basement



Measurements given above for the first floor are rounded to the nearest tenth of a meter. Actual calculated area is 106.8 square meters.

Walls: Second floor over first floor



The second floor overhangs the first floor in the front and back of the residence by a total of approximately one meter. The net area exposed to the outside was considered as wall area. Ceilings are all of nominal 2.4 meter height. The outside house area between floors was also considered as wall area. The total wall area calculated is 220.9 square meters (this excludes window and door area).

Ceilings:

Ceilings exposed to the outside total 115.2 square meters and include the entire second level and first level ceilings not under the second level.

Glass:

Windows, including glass and wood frames, and doors were included in the calculated area of 21.8 square meters.

Interior Mass:

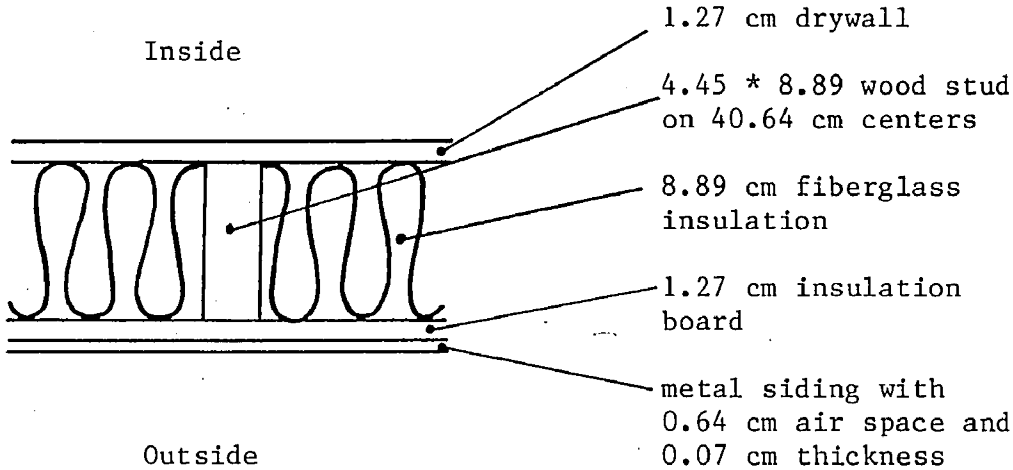
This area is estimated, with the largest contribution to the estimate being the calculated surface area of the interior walls and the floors and ceilings between residence levels. The total estimated surface area of all interior objects is 2136.7 square meters.

VOLUME, DENSITY, SPECIFIC HEAT AND INVERSE HEAT TRANSFER COEFFICIENT

Specific heat, density and the inverse heat transfer coefficient (R-value) were calculated based on a typical cross section of the walls, floors and ceilings. The parameters were calculated for the interior mass based on the cross section of an interior wall. Interior air parameters were selected from the available literature (Reference 3), as were the specific parameters for each of the materials used in the structures.

Following are the cross sections of the various structures and the calculated parameters based on the composite materials in each structure.

Walls:



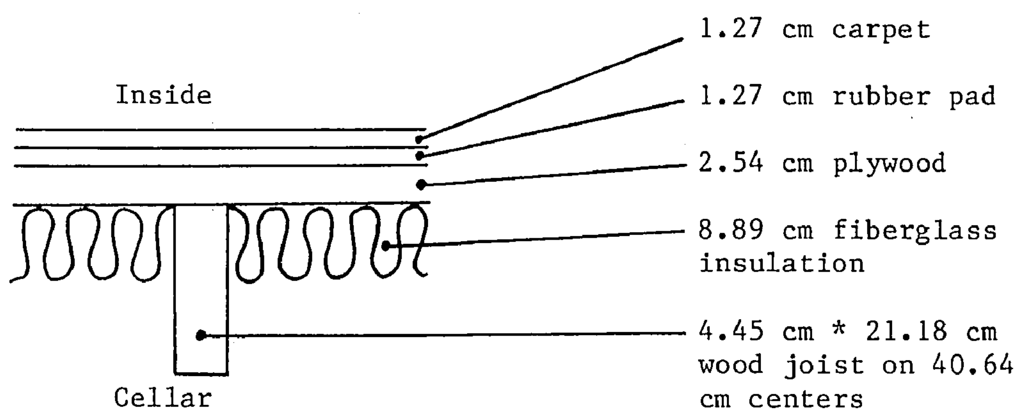
Volume was calculated to be 22.0 cubic meters total for the structure.

Density was calculated to be 294.3 kg / cubic meter.

Specific heat was calculated to be 958.1 joule / kg * deg K.

R-value was calculated based on that of each of the composite materials in the structure and assuming a surface resistance of 0.12 on the inside (still air) and 0.07 on the outside (an average 24.1 km/hr wind velocity). The composite R-value was 2.468 deg K * square meter / watt. For the Lumped-Heat-Capacity model it was assumed that half this R-value was located between the wall and the interior air, with the other half located between the wall and the outside air.

Floors:



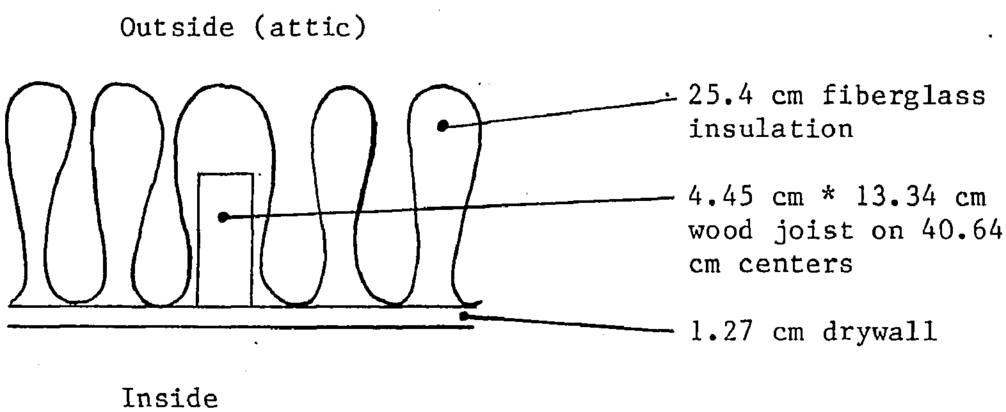
Volume was calculated to be 16.5 cubic meters total, not including the air space below the insulation and between floor joists.

Density was calculated to be 169.7 kg / cubic meter.

Specific heat was calculated to be 1188.3 joule / kg * deg K.

R-value was calculated based on that of the composite materials in the structure and assuming a surface resistance of 0.12 on both surfaces (still air). The composite R-value was 2.468 deg K * square meter / watt. For the Lumped-Heat-Capacity model it was assumed that half this R-value was located between the floor and the interior air with the other half located between the wall and the outside air.

Ceilings:



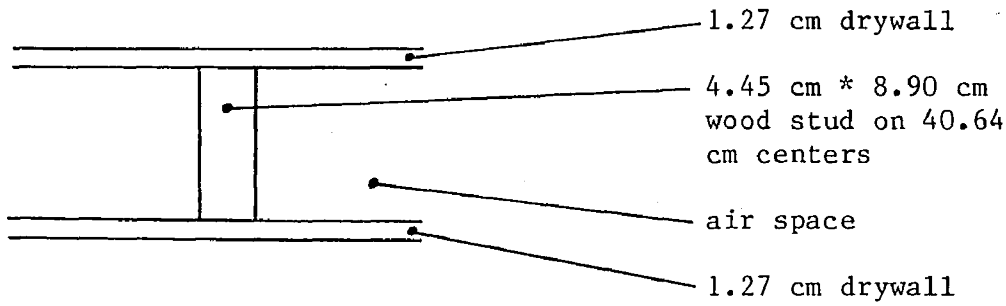
Volume was calculated to be 30.7 cubic meters total.

Density was calculated to be 231.5 kg / cubic meter.

Specific heat was calculated to be 857.7 joule / kg * deg K.

R-value was calculated based on that of the composite materials in the structure and assuming a surface resistance of 0.12 on both surfaces (still air). The composite R-value was 5.112 deg K * square meter / watt. For the Lumped-Heat-Capacity model it was assumed that half this R-value was located between the ceiling and the interior air with the other half located between the ceiling and the outside air.

Interior Mass:



Volume of all interior mass was estimated at 90.6 cubic meters. This includes interior walls, furnishings and floor between residence levels.

Density was calculated to be 125.3 kg / cubic meter.

Specific heat was calculated to be 719.6 joule / kg * deg K.

The R-value was selected to be one-half that for the entire interior wall thickness. The value estimated was 0.64 deg K * square meter / watt.

Interior Air:

Volume of the interior air was calculated as the difference in volume between the interior of the residence and the volume of the interior mass. This volume was 419.7 cubic meters.

Density was assumed that of air at 21.1 degrees Centigrade and equal to 1.2 kg / cubic meter.

Specific heat was also assumed as that of air at 21.1 degrees Centigrade. The value chosen was 1008.3 joule / kg * deg K.

An R-value equal to that published by the window manufacturers (Andersen Corporation) was chosen for the interface of interior air and outside air at the windows and doors. This R-value was 0.256 deg K * square meter / watt. Windows were not considered as separate construction entities in the Lumped-Heat-Capacity model of the residence; therefore, no specific heat, density and volume data were required.

Appendix F

Biography Of Author

The author was born in Norristown, Montgomery County, Pennsylvania on December 17, 1950 to Donald R. Yerkes and Henrietta G. Yerkes. He attended elementary, junior and senior high school in the Schwenksville Union School District, graduating in June, 1968. He attended Drexel University, Philadelphia, Pennsylvania from September, 1968 to June, 1973 where he graduated with a Bachelor of Science Degree in Mechanical Engineering, having majored in Control Theory. Upon graduation he began employment with Pennsylvania Power and Light Company at the Martins Creek Steam Electric Station, where he worked until April, 1974. Since April, 1974, the author has been employed as as engineer at the Homer Research Laboratories of Bethlehem Steel Corporation, Bethlehem, Pennsylvania.