Predictive Control of a Simple H.V.A.C. System in a Test Hut

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ABSTRACT

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As a preliminary step towards cost effective predictive control of H.V.A.C. systems in commercial and institutional buildings, a minimal microcomputer (Apple II+) based monitoring and control system was developed. It is used to predict hourly ambient and room temperatures for a test hut 24 hours in advance, and to control the operation of an air conditioner, a baseboard heater, and a fan used to blow outside air into the hut so as to precool or preheat the mass of the hut, within the comfort zone (18 °C to 24 °C) according to calculations designed to minimize the use of purchased energy. Preheating was done with a 150 W. light bulb, with the fan off. Only twelve hourly ambient and room temperature readings are required for the control calculations. For normal weather, the shape of the predicted ambient temperature curve is derived from a short Fourier series, with 3 constants derived from historical temperature records, changed every two weeks. The Fourier shape is
adjusted up or down to match the previous 24 hour average temperature. When measured ambient temperatures differ strongly from those previously predicted, the arrival of a weather front is indicated, and the H.V.A.C. control strategy is changed until a new normal ambient temperature pattern is established. Room temperatures were predicted with a simple one capacitor model for the thermal flows, using "as built" thermal parameters derived from measured room temperatures. During a six day trial in November 1984, the system worked well in every respect, preventing the use of the air conditioner altogether, despite the arrival of a weather front at an awkward time.
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<td>A</td>
<td>An integration constant for the capacitor.</td>
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<td>A_j</td>
<td>Area of jth glazing</td>
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<tr>
<td>B</td>
<td>( \sqrt{R_C^*C^*W} + I )</td>
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<tr>
<td>C</td>
<td>Storage capacitance</td>
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<td>C(1)</td>
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<td>C(2), C(2)</td>
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<td>IG</td>
<td>Internal heat gains + auxiliary heating</td>
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<td>R_{AL}</td>
<td>Resistance between living space and ambient temperature</td>
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<td>R_C</td>
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<td>t</td>
<td>Time</td>
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<tr>
<td>t_{sr}</td>
<td>Sunrise time</td>
</tr>
<tr>
<td>t_{ss}</td>
<td>Sunset time</td>
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<td>w</td>
<td>( 2 \times \pi/24 )</td>
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\[ \frac{\pi}{(tsr - tss)} \]

a
Inverse of time constant

\[ \theta \]
Curve-fitted phase angle from past weather data for Fourier series

\[ \theta_1 = \tan^{-1}(R_C \cdot C \cdot w) \]

\[ \theta_2 = \tan^{-1}\left(\frac{w}{a}\right) \]

\[ \theta_3 = \tan^{-1}\left(\frac{a}{w}\right) \]

\[ \theta_4 = \tan^{-1}\left(\frac{a}{2w}\right) \]

\[ \tau \]
Time constant = \( C \cdot (R_{AL} + R_{LS} + R_C) \)

\[ \tau_j \]
Transmission of jth glazing
CHAPTER 1

INTRODUCTION

Normally, commercial office building heating and cooling system capacities are designed for the worst cases liable to occur at a particular location. The worst cases occur at most only a few days a year. For the majority of the year, the system is overdesigned and therefore inefficient. If a constant temperature at the middle of the comfort zone is to be maintained with an oversized system, we must either operate it in short bursts, or dump either hot or cool air to the outside, to balance the rate of heat or cooling generation with the load. If, however we allow the building temperature to fluctuate within the comfort zone (i.e. over a range of 5 or 6 °C) during occupied hours, we can not only make better use of the heating system, but, for most of the year can utilize fan cooling and internal heat gains to replace chiller cooling and purchased heat. This is done with Predictive Control by utilizing the thermal storage capacity in the mass of the building components, which can only be done when the internal temperature is allowed to fluctuate. Except when a weather front is passing through the locality, it is relatively easy to predict the
fluctuations in ambient temperature for a 12 or 24 hour period. We know that the minimum ambient temperature will occur just before dawn, and the maximum at about 2 p.m. solar time. For each building, after a few months of observation, we can obtain two balance temperatures: BL, the ambient temperature below which heating is required to supplement internal heat gains when the building internal temperature, TR is at the centre of the comfort range, and BU, the ambient temperature where cooling is required when TR is at the centre of the comfort zone. Suppose at 10 a.m. one day we predict (with the aid of weather records in our computer and measurements of TA from midnight to 10 a.m.) that TA will rise above BU at 1 p.m., and remain above BU for two hours. Instead of maintaining TR constant, we turn on the fan at 10 a.m. and cool the building with outside air, say 2°C toward the bottom of the comfort zone. The fan is shut off at noon or 12:30. Thereafter the internal heat gains warm the building, let's say to the top of the comfort zone at 3 p.m. The stored internal heat gains then carry the building through to the next morning, without purchased heat on many days of the year.

Should the building be below the comfort range at 8 a.m., perhaps because of a night setback, a further savings can be made with Predictive Control. Heating is delayed to the last possible time before the occupants arrive. The
building air is then heated, at full power, to the middle of the comfort zone, as rapidly as possible. Because of its high thermal inertia, the building mass remains cool, and is heated by internal gains rather than purchased heat to reach the comfort zone over the next hour or two. The stored internal heat gains are recovered the next night, along with those used to heat the thermal mass to the top of the comfort zone in the afternoon. During much of the cooling season, the morning warm up can be done by circulating ambient air, rather than with the heating system, so the thermal mass can be cooled at night to be below the comfort range in the morning, ready to absorb internal heat gains, and prevent operation of the chiller for most or all of the day.

The essence of Predictive Control is then to predict up to 24 hours in advance when purchased heating or cooling will be required, and then if possible to store "free" heat or cool in advance to prevent the predicted purchase. The building temperature is varied over a 5 or 6 °C range (centered on a different temperature in winter than in summer) to minimize purchases of energy over the next 24 hours. In most climates it is not possible to operate without purchased energy every day of the year, but annual savings of 50 to 60% [11] should be possible for office buildings, because of the large internal gains available for
pre-heating.

The requirements for the Predictive Control system are some sensors and controls integrated with a computer having the appropriate software. The computer must control the heating, cooling and ventilation systems. The minimum required sensors are ambient temperature and indoor temperature. In large, zoned buildings, a temperature sensor for each zone will be required. Solarimeters, pressure, wind and humidity sensors would be useful, but are not crucial. The software falls into three general categories. (i) A real time ambient temperature prediction routine, with a historical file, and an analysis of recent temperature trends, capable of differentiating normal days from those when a weather front is passing through. (ii) A building thermal inertia evaluator capable of utilizing sensor data to correct the calculated thermal inertia for "as built" anomalies. (iii) An operating system, with different strategies for the various conditions desired throughout the year, capable of predicting the variation of room temperature for 24 hours in advance when the heating or cooling appliances are operated. The set point for room temperature varies almost continuously, but it does not float, as it would with a thermostat with a wide deadband. When neither pre-heating or pre-cooling are required, room temperature is adjusted to the middle of the comfort zone.
For many days in the intermediate seasons, with normal controls, heating will be applied during the morning when ambient temperatures are low, while cooling is required in the afternoon, when ambient has risen. Often, the afternoon heat gain is about equal to the morning losses, so if all systems were off, no energy would be required to keep the average indoor temperature close to the static thermostat setting during occupied hours. Predictive Control goes further than simple inaction on those days. The building is kept closer to the middle of the comfort zone in the afternoon by creating a longer but smaller temperature drop in the morning with controlled ventilation (if appropriate).

In the winter season, a large part of the solar and internal heat gains are utilized with Predictive Control, to reduce fuel consumption. Temperature setbacks to reduce night heating requirements are inherent in Predictive Control. An extra advantage is that the setback is variable from day to day, and from hour to hour, which often gives extra savings. The exceptions are some days when sudden weather changes are in the wrong direction, (a cold front) so the setback strategy based on a predicted normal ambient temperature pattern is too large, increasing the heating required the next day. However, these are only a few days in the winter and have only a minor effect on the overall savings.
In the summer season "free cooling" is utilized at night as well as during occupied hours, reducing cooling energy consumption and often demand load charges.

In contrast to many other conservation techniques, the absolute savings from Predictive Control are enhanced by most other conservation techniques. Reduction of infiltration increases the savings possible with controlled predictive ventilation, by lowering the minimum ventilation achievable when ventilation increases energy usage. Increased insulation or glazing resistance increases the thermal inertia time constant, and the separation between the cooling and heating balance temperatures, so more time is available to store heat or cold in the available thermal mass, and it can be utilized over a longer period. Delamping reduces the internal heat gains that can be utilized in winter, but has a greater impact on the summer cooling requirements because the indoor outdoor temperature differences are much smaller in summer, in most climates. Anything that reduces the temperature differences between different zones of a building will enhance the savings with Predictive Control because the effective temperature band of operation will be widened. Complaints from the colder rooms limit the amount of pre-cooling possible, and complaints from the warmer rooms limit the amounts of pre-heating possible. As an example, judicious amounts of phase change
storage in the corner and centre rooms can pay off handsomely with this extra leverage. Increasing the effective thermal inertia of a building by removing carpets or changing air flows to obtain some heat exchange with more of the structural mass of a building can help as well.

Predictive Control has already been used in a few large buildings [11]. However, the computers employed were very expensive minicomputers with large memory capacities. The programs used are proprietary, so we can only guess that their sophistication matches the computers used. The objective of this work was to develop and validate short programs and low cost monitoring and control systems suitable for Predictive Control with inexpensive microcomputers. When such systems are fully developed, they will allow the use of this technique in the majority of commercial buildings, with investments of only a few thousand dollars, rather than a few hundred thousand.

The development of a complete Predictive Control system suitable for use in large multizone buildings was not attempted in this initial effort. Rather, most of the crucial elements of the system were developed and validated in short experiments in a test hut. These include a subprogram to predict ambient temperature 24 hours in advance, on days when no weather front passes through, a program and
hardware to monitor 9 temperatures and control a rudimentary 3 element H.V.A.C. system in the test hut, and a separate procedure to evaluate the "as built" thermal resistances and thermal capacity necessary to obtain a thermal inertia time constant for the test hut. This time constant is necessary to evaluate an expected room temperature variation 24 hours in advance during operation of the on line control program, so that, for instance, pre-cooling is limited to amounts that cannot cause the use of purchased heat the next night. Some elements of a complete Predictive Control system were left for later development. These include methods for evaluating the maximum possible solar input for 24 hours in advance, and reconciling separate strategies for pre-cooling, etc., in the cases of full sun, no sun or partial sun. Another element left for later development is the prediction of latent cooling loads on humid summer days. Since there were no occupants in the test hut during the experiments, and the ventilating fan flow could not be varied, a routine for insuring minimum ventilation has yet to be developed. Thus far, only on-off controls have been used. Routines for the control of metering valves will be added later. A routine for fast morning warmup was not developed here. No insurmountable problems are foreseen for any of these future additions. The time and budget available simply did not allow their development at this stage.
In order to validate those elements of the control system chosen for development here as directly as possible, and avoid some mathematical complications that might confuse the issues at hand, the test hut experiment was deliberately kept simpler than an experiment in an occupied building. Direct solar gains were suppressed by making the test hut windowless. Minimum fan ventilation was not supplied. The heating and cooling appliances had no modulating controls. They were either on at full power or off. The internal gains (supplied by a 150 Watt incandescent bulb) were kept constant 24 hours a day. The cavity surrounding 3 of the test room walls, the ceiling and floor was kept at a constant 20°C 24 hours a day. (In fact this caused a slight complication, but one easily resolved). The test hut doors were never opened during the monitoring period. The goal was to show that the low cost methods adopted had practical potential, not to simulate fully the control of a real building. This task will be third stage of the overall research program.

The development and validation of a new, fast method to predict hourly ambient temperatures 24 hours in advance on days with normal weather is discussed in chapter 2. Three constants derived from historical weather records, and one derived from on site measurements of ambient temperature are substituted in a short Fourier series. The historical
weather constants are changed every two weeks. This technique is also used to signal the arrival and departure of weather fronts, so that the on line control strategy for the H.V.A.C. system can be changed as required. In chapter 3, a simple one capacitor model for the thermal flows in a building is adapted for use in this problem. A new method providing closed solutions to predict the hourly room temperature 24 hours in advance is developed. These are necessary for proper execution of the on line Predictive Control program. The same model was used in an off line calculation of the "as built" effective resistances and thermal capacity (in terms of the one capacitor model) for the test hut. Unfortunately, closed solutions for this problem are not yet available. Instead, a least squares best fit procedure was used to select the four thermal parameters (3 R's and the C) used in the on line control calculations. To reduce the time required for the least squares search, an iterative technique using measured temperatures during inversion of the model equations was used to select starting values for the least squares variation of the four thermal parameters. This method gave calculated room temperatures that matched those measured in an auxiliary experiment (described in chapter 5) to well within the accuracy of the low cost thermometers used. Thus, it is quite sufficient for the purpose at hand, even though somewhat lacking in mathematical elegance. Chapter 4 contains descriptions of
the test hut, of the hardware used for Data Acquisition and control of the H.V.A.C. system, and of the details of the on line Predictive Control program. The experimental results are presented and analyzed in chapter 5, which also contains conclusions and recommendations for further studies.
CHAPTER 2

TEMPERATURE PREDICTION ROUTINE

2.0 Introduction

Since the start of human civilization, weather prediction has been an important factor for men, particularly for farmers and sailors. The prediction process was crude, and sudden changes were not usually foreseen. Nowadays, with detailed weather records for several decades, and low cost micro-computers available, we can do better.

In this chapter we describe the development of a micro-computer program which is capable of forecasting hourly ambient temperatures 24 hours in advance for normal weather and of sensing the arrival of abnormal weather, using ambient temperatures measured on site for the 12 previous hours and three constants derived from historical weather data. In normal weather, the daily variation of ambient temperature is similar to the historical pattern, whatever the daily mean temperature. Abnormal weather occurs during a change of weather system—i.e. the daily mean temperature changes suddenly. A weather front is the boundary between a high pressure system and a low pressure system. When a high pressure system arrives the temperature will drop rapidly.
and remain below the historical average temperature for several days. On the arrival of a low pressure system, the temperature rises slowly and the weather remains warmer than average for several days. Because of the possibility of changes of weather systems, the program must be able to recognize both the arrival of a weather front and the establishment of a new normal pattern.

In the prediction routine, a distorted 24 hour sinusoid, based on a short Fourier series is used to match the 2 week average of the historical daily ambient temperature swing. The daily pattern obtained is then placed around a daily mean temperature derived from current measurements and used in the on line control program. When the measured temperatures deviate strongly from the predicted ones for several hours, the computer switches to the abnormal weather subroutine, and a different H.V.A.C. control strategy is used.

The strategy for abnormal weather is simply to oppose the weather front, if possible by maintaining room temperature near the middle of the comfort zone. For a cold front, we store internal gains by allowing room temperature to rise a few degrees. Should that heat be required later, it is available. If it is not required, no great expense has been incurred. For a hot front, we use fan cooling, if
possible, to evacuate more than the internal gains and cool the building a bit. There is a risk with each of these actions that overheating or overcooling will occur later, requiring extra expenditures with the H.V.A.C. system. Thus, the rate of heating or cooling should be modulated, both with the season and with the time of day. Since the weather front condition lasts only a few hours in most cases, "free" heating at 4 P.M. is unlikely to cause extra cooling expense, because we return to the normal weather strategy before midnight, with plenty of time to use free cooling. However, the use of "free" heat at 11 A.M. could lead to purchased cooling at 2 P.M., so a lower rate of heating is advisable in summer until the new average ambient temperature accompanying the colder system is available.

There are, of course, other ways to predict the weather. Cloud formation can be an advance indication of the weather for the next few days. In many ancient civilizations, people predicted weather by studying wind direction and by interpreting the form, the colour, and the composition of the clouds. This technique, passed on from generation to generation and from century to century, is reasonably reliable in many locations. Unfortunately, Montreal is not one of those locations.

Today, government weather bureau predictions are based on the global weather situation rather than local weather
formations. To establish the global structure of weather patterns, readings from many stations and satellite cloud pictures are fed to computers. Weather records from the past decade or more are stored in tapes and disks and are used in the weather forecasting process. This process can be carried out either with probabilistic or non-probabilistic models [12]. With the probabilistic models, the most likely paths for the pressure systems are estimated. In the non-probabilistic models, a suitable mathematical function is matched to the weather data.

A new computer, CRAY, purchased by Environment Canada in 1984, is the most powerful computer used in weather forecasting in Canada. Currently, it can predict weather up to 3 days in advance and theoretically, to 100 hours ahead. The various items predicted by this computer include the maximum and minimum temperature for each day, dew point temperature, barometric pressure, wind speed and wind direction, precipitation and cloudiness index. The rental and maintenance cost of hardware and software for this system is around 10 million dollars each year [8]. An additional 8 millions dollars [8] of annual operating cost is needed.

The accuracy of weather forecasts turned out by CRAY is high. It is, however, too sophisticated for online thermal
control of commercial buildings. Furthermore, expensive local measuring instruments would be required to utilize CRAY's capabilities since local temperatures and wind regimes can vary significantly from the regional values, especially in downtown locations. A simplified system, which can provide a reasonably accurate weather prediction with only local measurements, is a more practical solution. In addition, the CRAY system only predicts daily extreme temperatures. For optimal building H.V.A.C. control, we would like to update our control strategy hourly when abnormal weather occurs. With the present system, we can predict hourly ambient temperature changes using only a few low cost sensors and an Apple micro-computer, to within 1.5 degree Celsius, which is accurate enough for control purposes.

2.1 Calculation of the Historic Daily Temperature Variation

The daily temperature swing varies seasonally with the amount of sunshine available on the horizontal. In summer at Montreal, the mean daily range of temperature is about 15 degrees Celsius due to the longer days and high elevation of the sun. The shorter days and lower sun angle in December produce a lower mean range of about 5 degrees.

A summary of the monthly mean of the daily temperature variation for Montreal, using ten years of weather data is
shown in Fig. 2.1 [5][9]. The twenty-four hour cycle is separated into three regions. The ends of the white region are the times for the daily minimum and maximum temperatures. The numbers shown above the white region are temperature increases above the daily minimum, averaged over each one hour period, and rounded to 1 figure accuracy. The ends of the black region are the sunrise and sunset times. Here, the hourly numbers show the temperature decrease below the daily maximum. During the times shown as hatched regions, the sun is up, but low in the sky, so air temperatures are decreasing. This particular summary was obtained from Environment Canada [5][9], but a similar one could be calculated from weather tapes for any other location.

Although the table in Fig. 2.1 gives a good summary of temperature changes for an average day for each month, a functional equivalent was preferred, for ease of programming. Therefore, a Fourier series was fitted to the data for each month shown in Fig. 2.1. Since Environment Canada had rounded the data of Fig. 2.1, creating unrealistic plateaus of constant temperature for periods up to 4 hours, some of the temperatures were changed by fractional amounts (no more than ± 0.4 degree Celsius) to recreate smooth data curves. A curve-fit program, shown in Appendix A, was used to determine the coefficients of the
Figure 2.1 Daily temperature variation for Montreal
fundamental and the first and second overtones of the Fourier series. It was found that the second overtone did not improve the accuracy of the fit sufficiently to warrant its use. Thus, the equation used for the fits shown in Fig. 2.2 - 2.13 was the equivalent of:

\[ TA(t) = A(1) + A(2) \times \sin(w*t) + A(3) \times \cos(w*t) + A(4) \times \sin(2\times w*t) + A(5) \times \cos(2\times w*t) \]  \hspace{1cm} (2.1) 

Where \( TA(t) \) is the ambient temperature, and \( w \) is the angular frequency of the fundamental, \( w = 2 \times \pi / 24 \) (rad./hr.)

In order to speed up the calculation, the cosine functions were replaced by two phase angles, \( \theta_1 \) and \( \theta_2 \), in the sine terms. Therefore, equation (2.1) becomes:

\[ TA(t) = C(1) + C(2) \times \sin(w*t + \theta_1) + C(3) \times \sin(2\times w*t + \theta_2) \]  \hspace{1cm} (2.2) 

Where:

\[ C(1) = A(1) \]
\[ C(2) = \sqrt{A(2)^2 + A(3)^2} \]
\[ C(3) = \sqrt{A(4)^2 + A(5)^2} \]
\[ \theta_1 = \tan^{-1} \left[ A(3)/A(2) \right] \]
\[ \theta_2 = \tan^{-1} \left[ A(5)/A(4) \right] \]
\[ w = 2 \times \pi / 24 \]
\[ t = \text{Time} \]
An analysis of the results showed that a simple relationship existed between the two phase angles calculated: $\theta_1$ was always approximately 3 times $\theta_2$. The synthetic curves obtained with $\theta_1 = 3\theta_2$ were almost identical to the curves generated by fitting with equation (2.2). Thus equation (2.2) was further simplified to:

$$TA(t) = C(1) + C(2) \times \sin(w*\pi t + 3\theta) + C(3) \times \sin(2w*\pi t + \theta)$$  \hspace{1cm} (2.3)

Where: $\theta = \theta_2$

Different constants $C(1)$, $C(2)$, $C(3)$ and $\theta$ were determined for each month. The maximum absolute difference between the synthetic curves and the smoothed data (Figs. 2.2 - 2.13) derived from Fig. 2.1, and labelled Actual Y in Tables 2.1 - 2.12, is 1.1 degrees Celsius, which is well within recorded year to year weather differences. The prediction routine was checked against real temperatures recorded in 1983 to 1984, as will be discussed in section 2.3.

2.2 Data Acquisition System

Temperature data was collected with a system consisting of: a controllable switch to select any of 9 thermistor thermometers; a power supply for the thermistors; an amplifier; a voltmeter; and an Apple II+ computer equipped
Figure 2.2  Temperature variation with weather data for January
Figure 2.3  Temperature variation with weather data for February
Figure 2.4 Temperature variation with weather data for March
Figure 2.5. Temperature variation with weather data for April
Figure 2.6  Temperature variation with weather data for May
Figure 2.7  Temperature variation with weather data for June
Figure 2.8  Temperature variation with weather data for July
Figure 2.9  Temperature variation with weather data for August
Figure 2.10  Temperature variation with weather data for September
Figure 2.11 Temperature variation with weather data for October.
Figure 2.12 Temperature variation with weather data for November
Figure 2.13 Temperature variation with weather data for December
TEMPERATURE VARIATION CURVE FITTING FOR JANUARY

POWER REGRESSION:

\[ Y = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2w \cdot t + \theta) \]

where \( w = 2 \cdot \pi / 24 \)
\( \theta = 1.1963 \)

\( C(1) \) THROUGH \( C(M) \)

| \( C(1) \) | \( 0.3375E+01 \) |
| \( C(2) \) | \( 0.2797E+01 \) |
| \( C(3) \) | \( 0.8467E+00 \) |

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Table 2.1 Temperature variation curve fitting for January
TEMPERATURE VARIATION CURVE FITTING FOR FEBRUARY

POWER REGRESSION:

\[ Y = C(1) + C(2) \times \sin(wt + 3\theta) + C(3) \times \sin(2\times wt + \theta) \]

WHERE \[ w = \frac{2\pi}{24} \]
\[ \theta = 1.1910 \]

\[ C(1) \] THROUGH \[ C(M) \]
\[ C(1) = 0.4396E+01 \]
\[ C(2) = 0.3978E+01 \]
\[ C(3) = 0.1008E+01 \]

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Table 2.2 Temperature variation curve fitting for February
TEMPERATURE VARIATION CURVE FITTING FOR MARCH

POWER REGRESSION:

\[ Y = C(1) + C(2) \times \sin(w \times t + 3 \times \theta) + C(3) \times \sin(2 \times w \times t + \theta) \]

WHERE \( w = \frac{2 \times \pi}{24} \)
\( \theta = 1.2429 \)

\( C(1) \) THROUGH \( C(M) \)

\[ C(1) = 0.4963 \times 10^1 \]
\[ C(2) = 0.4462 \times 10^1 \]
\[ C(3) = 0.9012 \times 10^0 \]

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Table 2.3 Temperature variation curve fitting for March
TEMPERATURE VARIATION CURVE FITTING FOR APRIL

POWER REGRESSION:

\[ Y = C(1) + C(2) \times \sin(\omega t + 3\theta) + C(3) \times \sin(2\omega t + 2\theta) \]

WHERE \( \omega = \frac{2\pi}{24} \)
\( \theta = 1.2640 \)

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Table 2.4 Temperature variation curve fitting for April
TEMPERATURE VARIATION CURVE FITTING FOR MAY

POWER REGRESSION:

\[ Y = C(1) + C(2) \times \sin(\omega t + 3\theta) + C(3) \times \sin(2\omega t + \theta) \]

WHERE \( \omega = \frac{2\pi}{24} \)
\( \theta = 1.2668 \)

\( C(1) \) THROUGH \( C(3) \)

- \( C(1) = 0.8333E+01 \)
- \( C(2) = 0.7484E+01 \)
- \( C(3) = 0.5584E+00 \)

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Table 2.5 Temperature variation curve fitting for May
**TEMPERATURE VARIATION CURVE FITTING FOR JUNE**

**POWER REGRESSION:**

\[
Y = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \phi)
\]

WHERE

\[
\begin{align*}
   w &= 2 \cdot \frac{\pi}{24} \\
   \theta &= 1.2951
\end{align*}
\]

C(1) THROUGH C(M)

\[
\begin{align*}
   C(1) &= 0.7938E+01 \\
   C(2) &= 0.7115E+01 \\
   C(3) &= 0.5883E+00
\end{align*}
\]

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Table 2.6 Temperature variation curve fitting for June
TEMPERATURE VARIATION CURVE FITTING FOR JULY

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(wt+3\theta) + C(3) \sin(2wt+\theta) \]

WHERE \( w = \frac{2 \pi}{24} \)
\( \theta = 1.2798 \)

C(1) THROUGH C(M)

C(1) = 0.7729E+01
C(2) = 0.7225E+01
C(3) = 0.7075E+00

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Table 2.7 Temperature variation curve fitting for July
TEMPERATURE VARIATION CURVE FITTING FOR AUGUST

POWER REGRESSION:

\[ Y = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta) \]

WHERE \[ w = 2 \cdot \pi/24 \]
\[ \theta = 1.3084 \]

C(1) THROUGH C(3)

| \( C(1) \) | 0.8146E+01 |
| \( C(2) \) | 0.7628E+01 |
| \( C(3) \) | 0.1058E+01 |

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Table 2.8 Temperature variation curve fitting for August
TEMPERATURE VARIATION CURVE FITTING FOR SEPTEMBER

POWER REGRESSION:

\[ Y = C(1) + C(2) \times \sin(w \times t + 3 \times \theta) + C(3) \times \sin(2 \times w \times t + \theta) \]

WHERE \( w = 2 \times \pi / 24 \)
\( \theta = 1.2958 \)

**C(1) THROUGH C(M)**

\[ C(1) = 0.6429E+01 \]
\[ C(2) = 0.6574E+01 \]
\[ C(3) = 0.1155E+01 \]

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Table 2.9 Temperature variation curve fitting for September
TEMPERATURE VARIATION CURVE FITTING FOR OCTOBER

POWER REGRESSION:

\[ Y = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta) \]

WHERE \[ w = 2 \pi / 24 \]
\[ \theta = 1.2975 \]

C(1) THROUGH C(M)

C(1) = 0.5583E+01
C(2) = 0.5233E+01
C(3) = 0.1464E+01

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Table 2.10 Temperature variation curve fitting for October
TEMPERATURE VARIATION CURVE FITTING FOR NOVEMBER

POWER REGRESSION:

\[ Y = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta) \]

WHERE \[ w = \frac{2 \cdot \pi}{24} \]
\[ \theta = 1.2829 \]

\[ C(1) \text{ THROUGH } C(M) \]
\[ C(1) = 0.2992E+01 \]
\[ C(2) = 0.2909E+01 \]
\[ C(3) = 0.9465E+00 \]

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<th>ABSOLUTE DIFFERENCE</th>
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Table 2.11: Temperature variation curve fitting for November
TEMPERATURE VARIATION CURVE FITTING FOR DECEMBER

POWER REGRESSION:

\[ Y = C(1) + C(2) \cdot \sin(w \cdot t + \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta) \]

\[
\begin{align*}
w &= 2 \cdot \pi / 24 \\
\theta &= 1.2422 
\end{align*}
\]

\begin{tabular}{lcc}
\hline
\textbf{ACTUAL} & \textbf{ACTUAL} & \textbf{CALCULATED} & \textbf{ABSOLUTE} \\
\textbf{t} & \textbf{Y} & \textbf{Y} & \textbf{DIFFERENCE} \\
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1.00 & 1.3 & 1.4 & 0.1 \\
2.00 & 1.0 & 1.0 & 0.0 \\
3.00 & 0.7 & 0.5 & 0.2 \\
4.00 & 0.4 & 0.1 & 0.3 \\
5.00 & 0.1 & -0.1 & 0.2 \\
6.00 & 0.1 & -0.1 & 0.2 \\
7.00 & 0.4 & 0.2 & 0.2 \\
8.00 & 0.5 & 0.8 & 0.3 \\
9.00 & 1.0 & 1.6 & 0.6 \\
10.00 & 2.0 & 2.5 & 0.5 \\
11.00 & 3.0 & 3.3 & 0.3 \\
12.00 & 4.0 & 4.0 & 0.0 \\
13.00 & 5.0 & 4.4 & 0.6 \\
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15.00 & 4.5 & 4.4 & 0.1 \\
16.00 & 4.0 & 4.1 & 0.1 \\
17.00 & 3.4 & 3.6 & 0.2 \\
18.00 & 3.1 & 3.2 & 0.1 \\
19.00 & 2.8 & 2.8 & 0.0 \\
20.00 & 2.5 & 2.6 & 0.1 \\
21.00 & 2.4 & 2.4 & 0.0 \\
22.00 & 2.1 & 2.2 & 0.1 \\
23.00 & 1.8 & 2.1 & 0.3 \\
\hline
\end{tabular}

Table 2.12 Temperature variation curve fitting for December
with an Analogue/Digital converter card and a battery operated clock. Suitable filters to prevent signals induced by elevator switch sparks or T.V. stations from changing the switch channel were installed. The data collection is controlled through a program which will be discussed later.

Wires are used to connect the joystick socket (Fig. 2.14, Table 2.13) [5] of the computer to the switch control. Within the joystick socket, there are 4 annunciators, AN0, AN1, AN2 and AN3. When AN2 is triggered, the switch scanner is reset to the first sensor connection. The scanner is switched to the next sensor each time AN0 is triggered, to read the desired measurement.

The A/D converter [6] transforms the electric voltage received through the amplifier into Binary Coded Decimal numbers for storage by the Apple II+ computer.

The data acquisition program as well as the program to retrieve data are listed in Appendix B. The time interval between each reading is user selectable. The B.C.D. data is translated into simple binary code and sorted into separate files, periodically stored on disk. The retrieve data program is used to transfer data from disk for calculation or display.
Figure 2.14 Game Input/Output connector pinout

Table 2.13 Game I/O connector signal Descriptions

<table>
<thead>
<tr>
<th>Pin</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+5v</td>
<td>+5 volt power supply. Total current drain on this pin must be less than 100mA</td>
</tr>
<tr>
<td>2-4</td>
<td>PB0-PB2</td>
<td>Single-bit (pushbutton) inputs. These are standard 74LS series TTL inputs</td>
</tr>
<tr>
<td>5</td>
<td>C040 STROBE</td>
<td>A general-purpose strobe. This line, usually high, goes low during RC of a read or write cycle to any address from $8040$ through $804F$. This is a standard 74LS TTL output.</td>
</tr>
<tr>
<td>6,7,10,11</td>
<td>GCO-GC3</td>
<td>Game controller inputs. These should each be connected through a 150k Ohm variable resistor to +5v.</td>
</tr>
<tr>
<td>8</td>
<td>GND</td>
<td>System electrical ground</td>
</tr>
<tr>
<td>12-15</td>
<td>AND-AN5</td>
<td>Annunciation outputs. These are standard 74LS series TTL outputs and must be buffered if used to drive other than TTL inputs.</td>
</tr>
<tr>
<td>9,16</td>
<td>NC</td>
<td>No internal connection</td>
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2.3 **Comparison Between the Theoretical and Experimental Curves**

Using monitored temperatures for 24 hours, an experimental curve was generated with the curve-fit program by a least squares fit to equation (2.3) when the parameters $C(2)$, $C(3)$ and $\theta$ were varied systematically. This was compared to the monthly average Historic curve, placed to have the same 24 hour average temperature, $C(1)$ as the experimental curve. The experimental temperatures, curves and absolute differences are shown in Fig. 2.15 - Fig. 2.20 and Table 2.14 - Table 2.19. Two observations drawn from these graphs are:

1. The curves are very similar for normal weather conditions, and are inconsistent when weather fronts (Fig. 2.18) pass through.

2. Larger differences between the two curves are observed mainly at the beginning of the month. (e.g. Fig. 2.17).

It seems that a month is too long a period for calculating the constants in equation (2.3). Therefore the constants used were changed twice a month. On the last seven or eight days of each month, and the first eight days of the next month, the averages of the 2 sets of monthly constants determined above were used. The better fits obtained in this way for Nov. 7 and Nov. 29 are shown in Fig. 2.21 and Fig. 2.22.
Figure 2.15  Comparison of historic curve and experimental weather data for 19th October, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 19th October, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(w*t+3*\theta) + C(3) \sin(2*w*t+\theta) \]

WHERE \( w = 2*\pi/24 \)
\( \theta = 1.2360 \)

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Table 2.14 Temperature variation curve fitting for 19th October, 1983
Figure 2.16 Comparison of historic curve and experimental weather data for 20th October, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 20th October, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(w \cdot t + 3 \cdot \theta) + C(3) \sin(2 \cdot w \cdot t + \theta) \]

WHERE \( w = \frac{2\pi}{24} \)
\( \theta = 1.2462 \)

\[ C(1) \text{ THROUGH } C(M) \]
\[ C(1) = 0.5073E+01 \]
\[ C(2) = 0.5528E+01 \]
\[ C(3) = 0.2003E+01 \]

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Table 2.15 Temperature variation curve fitting for 20th October, 1983
Figure 2.17 Comparison of historic curve and experimental weather data for 7th November, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 7th November, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(w \cdot t + 3 \cdot e) + C(3) \sin(2 \cdot w \cdot t + e) \]

\[
\begin{align*}
\text{WHERE} & \quad w = \frac{2 \pi}{24} \\
& \quad e = 1.2651 \\
\end{align*}
\]

\[ C(1) \text{ THROUGH } C(M) \]

\[
\begin{align*}
C(1) &= 0.8077E+01 \\
C(2) &= 0.4391E+01 \\
C(3) &= 0.1224E+01 \\
\end{align*}
\]

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Table 2.16 Temperature variation curve fitting for 7th November, 1983
Figure 2.18 Comparison of historic curve and experimental weather data for 8th November, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 8th November, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta) \]

WHERE \( w = \frac{2 \pi}{24} \)
\[ \theta = 0.9261 \]

C(1) THROUGH C(M)

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Table 2.17 Temperature variation curve fitting for 8th November, 1983
Figure 2.19 Comparison of historic curve and experimental weather data for 9th November, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 9th November, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2)\sin(w*t + 3*\theta) + C(3)\sin(2*w*t + \theta) \]

\[ \text{WHERE} \quad w = \frac{2\pi}{24} \]
\[ \theta = 1.3884 \]

\[ C(1) \text{ THROUGH } C(M) \]
\[ C(1) = 0.8408E+01 \]
\[ C(2) = 0.3287E+01 \]
\[ C(3) = 0.1808E+01 \]

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Table 2.18 Temperature variation curve fitting for 9th November, 1983
Figure 2.20 Comparison of historic curve and experimental weather data for 29th November, 1983.
TEMPERATURE VARIATION CURVE FITTING FOR 29th November, 1983

POWER REGRESSION:

\[ Y = C(1) + C(2) \sin(w \cdot t + 3 \cdot \theta) + C(3) \sin(2 \cdot w \cdot t + \theta) \]

WHERE \( w = 2 \cdot \pi / 24 \)
\( \theta = 1.2760 \)

C(1) THROUGH C(M)

| C(1) = 0.3718E+01 |
| C(2) = 0.2558E+01 |
| C(3) = 0.7006E+00 |

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Table 2.19  Temperature variation curve fitting for 29th November, 1983
Figure 2.21 Comparison of improved historic curve and experimental weather data for 7th November.
Figure 2.22 Comparison of improved historic curve and experimental weather data for 29th November.
2.4 Prediction Process

Before predicting the purchased energy requirements for the next day, we must decide whether or not we are in a normal weather regime. If a weather front is passing through when the prediction is made, the consequent change in average daily temperature will usually invalidate the prediction. We want to change our control strategy as soon as possible after the arrival of the weather front. On the other hand, we want to avoid changing strategy for a short term fluctuation in ambient temperature caused by a variation in wind direction or a cloud covering the sun, etc. A compromise must be made for the number of observations used to calculate the experimental ambient temperature curve. The more observations used, the less impact of fluctuations lasting only an hour or two on the curve obtained, but the longer the wait to be sure that a weather front has occurred. After a number of trials with the observed weather fronts, the following procedure was adopted. At each hour during normal weather an experimental curve is calculated, by varying $C(1)$, $C(2)$, $C(3)$ and $\theta$ to minimize the sum of the squares of the deviations, using observations for the previous 11 hours, plus the current observation. This provides a reasonably accurate normal weather prediction for all of the data so far analyzed, but
responds too slowly to fast moving weather fronts, which are typically of 3 to 4 hours duration in Montreal. To sense the weather front, we generate a 24 hour experimental curve from the first six of the twelve observations, and shift the historic curve to match the average of that experimental curve. The last six observations are then compared statistically to the shifted historic curve. The boundary between normal and abnormal weather is taken at a standard deviation of 1.6. This corresponds to an error of 1.5 °C for each of the 6 points. For higher standard deviations, we switch to the weather front strategy subroutine. For standard deviations less than 1.6, we shift the historic curve to a mean derived from all 12 observations and proceed with the predictions for purchased energy. The results of this process for a slowly moving weather front are shown in Fig. 2.23 to 2.25. The arrival of the weather front is sensed at time 20:00 in Fig. 2.24, 4 hours after it began.

The weather front strategy subroutine contains a section to check at each hour whether or not normal temperature patterns have been reestablished. This is done in two different ways consecutively. First, it may happen that the new normal temperature pattern has the same 24 hour average temperature as the pattern before the arrival of the weather front. To examine this possibility, we compare the last six observations statistically with the extension in time of the
Figure 2.23 Temperature curves predicted from 21:00 Nov. 7 to 12:00 Nov. 8, 1983

- Temperature observed before the calculation
- Temperature observed after the calculation
- Experimental curve derived from 12 observations previous to the calculation
Figure 2.24 Temperature curves predicted from 19:00 Nov. 8 to 6:00 Nov. 9, 1983

- Temperature observed before the calculation
+ Temperature observed after the calculation
—— Experimental curve derived from 12 observations previous to the calculation
Figure 2.25 Temperature curves predicted from 11:00 to 20:00 Nov. 9, 1983

- Temperature observed before the calculation
- Temperature observed after the calculation
- Experimental curve derived from 12 observations previous to the calculation
shifted historic curve used before the weather front. Again, the boundary between abnormal and normal weather is taken at a standard deviation of 1.6. If $\sigma < 1.6$, we return to the normal weather routine, using the same historic curve. If $\sigma > 1.6$ we must check for a return to a normal temperature pattern at a different 24 hour average temperature. For this calculation, we calculate an experimental 24 hour curve from the previous 12 observations, (i.e. during the weather front) using least squares regression to obtain new values for $C(1), C(2), C(3)$ and $\theta$. The historic curve is then shifted to the average of this experimental curve. A statistical analysis then follows, but in this case for 12 previous observations. The use of only 6 observations here could lead to a premature strategy change, since the temperatures during the passage of a weather front generally change slowly either up or down, and could match the slope of the historic curve during a 6 hour period. We need a nearly sinusoidal variation of the slope to be sure that normal weather has returned. The criterion for normal weather is again $\sigma < 1.6$. If that occurs, we resume the normal weather routine with the historic curve shifted to the new 24 hour average temperature. In the example shown in Figs. 2.24 and 2.25, the passage of the weather front lasted 21 hours. The return to the normal weather routine was by the first method at the same average temperature, only 3
hours after the exit of the weather front. For a case with a shift of the average temperature, the return could be slower, up to a maximum of 12 hours. However, there is not as much urgency to shift strategy at the end of a weather front as at the beginning, since the weather front strategy will match the new normal weather strategy reasonably well in most cases.

The prediction subroutine is listed in Appendix C. It includes a section to display the results graphically on the monitor, which was used to generate Figs. 2.23 to 2.25. It was checked experimentally for a total of 3 months, discontinuously, between September and December 1983 and between August and November 1984. In most cases, the passage of a weather front was detected with 4 or 5 abnormal observations.
CHAPTER 3

MODEL FOR THERMAL FLOWS

IN A BUILDING

3.0 Introduction

To carry out predictive control properly, we need to calculate the delayed response to any heating or cooling action available to the computer: viz.; increasing or reducing the ventilation rate; turning the heater on or off (or changing the heater power); and turning the chiller on or off. Each of these actions may change the room temperature expected at the critical times on the next day when the purchase of heat or cooling is expected. To calculate the delayed response, we need information about the thermal inertia and the thermal losses of the building (or zone for a multiple zone building). This must be accurate enough to predict the future room temperature to within 1 degree Celsius. The intentions of the designer, as read from drawings will not be accurate enough for the thermal losses, since few buildings are finished as designed, and settling and repairs can change the thermal resistance of walls and windows. The thermal inertia of the building will depend in part on the mass of the furnishings.
installed, which will change periodically. Thus we need a model for the losses and inertia of the building which can be updated according to measurements of the actual situation, as built and as operated. We prefer a model where the update can be handled automatically by the computer, with low cost sensors. This led us to investigate models where the inertia and loss parameters can be inferred from the periodic temperature measurements required in any case for the control function of the computer program, i.e. from a series of measurements of room and ambient temperatures.

The method chosen also helps to alleviate another problem. For simple buildings, we would like to use only one indoor thermometer, to minimize calculation time and computer memory requirements, as well as sensor costs. In general, it will be impossible to locate that thermometer so that it reads the average temperature for the indoor air in contact with every exterior wall of the building. In most buildings, both vertical and horizontal temperature gradients are larger than 5 degree Celsius on many days of the year. The thermometer cannot be placed where it will interfere with occupant traffic. In addition, that thermometer may be poorly calibrated. However, if all of the control decisions are taken in terms of the actual temperatures read, wherever the indoor and outdoor thermometers are placed, we can adjust the inertia and loss.
constants of the model to compensate for the difference between those readings and the average temperature that would be used in a priori calculations of the heat losses. In any case, we can only check the calculations against the recorded temperatures. Thus we need to predict the temperatures at the position of the sensors used, not at some arbitrary spot corresponding to average room or ambient temperature over all the walls and roof of the building. The inertia and loss constants derived from the temperature measurements and our model will not be "accurate" in terms of the average room temperature. That is of little consequence here, because the control decisions are to be made according to measurements by the actual thermometers as set in place. There is no need to predict average room temperature at all: we need only to ensure that our predicted temperatures match later measurements, by varying parameters in the model until they do. After a few weeks of monitoring, parameters accurate enough for the control program are obtained.

The model used is a simplified version of the one used by Kerr [13], [14], [15] and by Shapiro [22] to analyse the measurements taken at the La Macaza solar house and the B.P. greenhouse. The analogy between Ohm's Law, $\Delta V = IR$, and the linear heat flow equation $\Delta T = QR$, which forms the basis for the definition of "thermal resistance" is shown in Table
3.1. We use an electric circuit analogy to the heat flows, rather than the thermal differential equations, in order to utilize electric circuit theorems, and to have a standard graphical representation of the thermal circuits. The solution should find applications in the design of solar buildings as well as in the predictive control of office buildings. Therefore, we include the solar input in this description of the model, even though there was none in the preliminary experiments done for this thesis.

3.1 Calculation Model

Solar radiation enters a building through windows and is absorbed on various surfaces (e.g. furniture and walls etc.) after passing through the air layer. Part of the energy is absorbed in the surface, and the rest reflects. Most of the reflected energy is absorbed by other surfaces. The heat transmission between the room and the outside air depends on the U value of the wall. Fig. 3.1. shows a typical heat flow diagram for an office. The analogous electrical circuit model is shown in Fig. 3.2., with the following assumptions:

1. 1-dimensional, linear and steady state heat flow in each component.

\[ q = U \times A \times \Delta T \]
\[ R_{\text{Elect}} = \frac{V_1 - V_2}{I} \quad \leftrightarrow \quad R_{\text{Thermal}} = \frac{T_1 - T_2}{q} \]

With \( I = \text{Charge/Time} \) \quad \quad \quad \quad q = \text{Heat/Time}

\[ C = \text{Charge/V} \quad \leftrightarrow \quad C = \text{Energy/T} \]

(store charge in C) \quad \quad \quad \quad (Store heat in C)

Thus stored energy

Not analogous

\[ E_C = 0.5 \cdot C \cdot V_C^2 \quad \quad \quad \quad E_C = \int q_C \, dt \]

\[ = C \Delta T_C \]

<table>
<thead>
<tr>
<th>Electric</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>R \ Resistance</td>
</tr>
<tr>
<td>C</td>
<td>C \ Capacity</td>
</tr>
<tr>
<td>V</td>
<td>T \ Temperature</td>
</tr>
<tr>
<td>I</td>
<td>q \ Heat flow</td>
</tr>
</tbody>
</table>

Table 3.1  Electric circuit analogy to the thermal flows
Figure 3.1 Thermal flow diagram for an office
Figure 3.2 Electric circuit model for thermal flows in an office
Where: \( q = \text{Heat flow through wall or ceiling, etc. (Watt)} \)
\( U = \text{Effective heat transfer coefficient of wall, etc. (W/m}^2\text{-K)} \)
\( A = \text{Surface area of wall or ceiling, etc. (m}^2\) \)
\( \Delta T = \text{Temperature difference (°K)} \)

2. The storage capacity and \( U \) values are not functions of temperature.

3. The ground potential (i.e. zero for arbitrary ambient temperature scale) is taken below the coldest temperature ever observed at this particular location.

4. Internal gains and space heating are constant for each hour of the calculation.

5. The calculation is only for normal weather.

Part of the solar energy in Fig. 3.2., penetrates the thermal storage \( C \) by conduction through the bulk resistance of the storage \( R_C \). After absorption and conversion to heat, another part of the solar energy reaches the living space by conduction, convection and radiation through the resistance \( R_{LS} \) of the storage surface and the air film beyond it. Simultaneously, heat is lost from the living space to the outside through the glazing \( (R_G) \), walls \( R_W \) and roof \( R_R \). \( R_{AL} \) is the summation of \( R_G, R_W \) and \( R_R \) in parallel. Shapiro [21] modelled the solar input as a square wave constant current source using switch SW1 to turn the solar source on at dawn and off at dusk and to change from the daytime
average ambient temperature to the nighttime average temperature. In addition, a program (S.U.N.N.Y.) was developed to calculate the extreme dawn and dusk temperatures for clear day. That program requires the orientation and area of the glazing for input, to calculate the solar intensity. By using this square wave input to predict the extreme temperatures for clear-design days, designers can quickly decide whether overheating will occur, and change their glazing or storage design as required, since the solutions for the temperatures are simple single exponential buildups or decays. The main disadvantages for the present task are that the times when maximum and minimum temperatures occur are shifted by several hours, and that several iterations are required before a stationary solution is reached.

In order to predict room temperature accurately as a function of time, realistic solar intensities and ambient temperatures must be used. Square wave approximations are not useful for predictive control.

The time dependent ambient temperature is expressed in the Fourier series form which was discussed in Chapter 2.

\[
TA(t) = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta)
\]

Where: \( TA(t) \) = Ambient temperature at time \( t \).
C(1) = Average temperature of previous day.
C(2), C(3), \theta = Curve fitted coefficients from past weather data.

w = \frac{2 \pi}{24}

For a vertical window facing due south the solar input is assumed to be a half-sine wave in Ref [16] and [17] placed between sunrise and sunset for each day.

\[ S(t) = \begin{cases} 
  S_1 \sin(w_1(t - tsr)) & \text{daytime} \\
  0 & \text{night time}
\end{cases} \]

where:

- \( w_1 = \frac{\pi}{(tsr - tss)} \)
- tsr = Sunrise Time, in hours.
- tss = Sunset Time, in hours.

For a clear day, for solar noon,

\[ S_1 = \sum_{j} i_j A_j \]

where:

- I = Solar Intensity (0.9 kW/m²)
- \( i_j = \text{Incident angle between the direct beam solar radiation and the normal to the glazing } j \).
- \( \tau_j = \text{Transmission factor for glazing } j \).
- \( A_j = \text{Area of glazing } j \).

In order to simulate the effect of internal heat sources added to the room, a heat source is included in the circuit (Fig. 3.2). The modified circuit, as shown in Fig. 3.3,
Figure 3.3 Revised thermal circuit model for an office
\[ I_2 = A \cdot e^{-at} + a \cdot S_1 \cdot B \cdot \left( \frac{\sin[w_1(t - tsr) + \phi_1 - \phi_2]}{\sqrt{a^2 + w_1^2}} \right) \]

\[ - w \cdot a \cdot C \cdot \left( \frac{C(2) \cdot \sin(w*t + 3*\theta + \phi_3)}{\sqrt{a^2 + w^2}} \right) + \]

\[ 2 \cdot C(3) \cdot \sin(2*w*t + \theta + \phi_4) \cdot \frac{1}{\sqrt{a^2 + (2*w)^2}} \]  \hspace{1cm} (3.2)

Where:

- \( A \) is obtained essentially as a boundary condition, by substituting equation 3.1 in the constraint equation, and eliminating \( I_2 \) and \( I_3 \) with the current measurements for \( TR \) and \( TA \), as shown in Appendix D.

\[ \alpha = \frac{1}{(R_C + R_{LS} + R_{AL}) \cdot C} = \frac{1}{\text{Time constant}} \]

\[ B = \sqrt{(R_C^2 \cdot \omega_1^2 + 1} \]

\( C(2), C(3), \theta \) = Curve fitted coefficients from past weather data

\[ \phi_1 = \tan^{-1}(R_C \cdot \omega_1) \]

\[ \phi_2 = \tan^{-1}\left(\frac{\omega_1}{a}\right) \]

\[ \phi_3 = \tan^{-1}\left(\frac{a}{w}\right) \]
also includes switch SW1 and SW2. SW1 closes between sunrise and sunset, when solar radiation is an input source; hence SW1 remains open at night time. SW2, on the other hand, closes whenever the internal sources are on.

Three operating modes are easily deduced from the circuits:

3.1.1 Charging mode (Mode 1)

With SW1 and SW2 both closed, the circuit is in the charging mode. The period of solar charging is between sunrise and sunset. Room temperature can be determined by the following expression:

For loop ABDE \( I_V = 0 \)

\[
\frac{1}{C} \int (I_2' - I_1) \, dt + R_C \cdot (I_2 - I_1) + R_{LS} \cdot I_2 + R_{AL} \cdot I_3 + T_A(t) = 0 \quad (3.1)
\]

Constraints

\[ I_1(t) = S_1 \cdot \sin(w_1(t-t_{sr})) \]

\[ I_3(t) = I_G + I_2(t) \]

By solving these equations, as explained in Appendix D, the heat flow through the walls & roof can be expressed in terms of the capacitor output current:
\[
\phi_w = \tan^{-1}\left(\frac{a}{2 \cdot w}\right)
\]
\[
w_1 = \pi/(tsr - tss)
\]
\[
w = 2 \cdot \pi/24
\]

IG = Internal heat gains + auxiliary heating.
I2 = Heat flow through the room.

The Heat flow equation can be expressed in terms of a response function [9], [10] by:

\[
I2(t) = CA(t) + SI(t) + TT(t)
\]
or

\[
I3(t) = IG + CA(t) + SI(t) + TT(t)
\]

Where:

CA(t) = time response function due to thermal mass of building.
SI(t) = Time response function due to solar input.
TT(t) = Time response function due to ambient temperature.

Room temperature is calculated by:

\[
TR(t) = (I2(t) + IG) \cdot R_{AL} + TA(t)
\]  \hspace{1cm} (3.3)

3.1.2 Discharging or Charging (Mode 2)

With SW2 closed and no solar input (SW1 open), the capacitor (thermal mass) is either discharging, charging or in an equilibrium mode. If the internal source generates an equal amount of heat to the heat loss through the wall and C is at room temperature, an equilibrium state is obtained and
room temperature remaining constant. If the internal source is larger than the heat loss, charging will occur. Otherwise, the capacitor will discharge, keeping room temperature higher than ambient temperature. All these states are represented by the following equations:

For loop ABDE, \( IV = 0 \)

\[
1 - \int I_2 \, dt + R_C \cdot I_2 + R_{LS} \cdot I_2 + R_{AL} \cdot I_3 \\
\frac{C}{C} = 0
\]  

(3.4)

Constraint:

\[ I_3(t) = I_G + I_2(t) \]

With \( I_2 \) negative when the capacitor is being charged by part of \( I_G \), and \( I_2 = 0 \) when \( I_G = I_3 \), at equilibrium.

The heat flow out of the capacitor with no solar input is found to be:

\[
I_2 = A \cdot e^{-\alpha t} - w \cdot a \cdot C \cdot \left\{ \frac{C(2) \cdot \sin(w \cdot t + 3\theta + \phi_3)}{\sqrt{(a^2 + w^2)}} \right. + \\
\left. \frac{2 \cdot C(3) \cdot \sin(2 \cdot w \cdot t + \theta + \phi_4)}{\sqrt{(a^2 + (2 \cdot w)^2)}} \right\} \]

(3.5)

Room temperature is expressed as:

\[
TR(t) = (I_2(t) + I_G) \cdot R_{AL} + TA(t)
\]

(3.6)
3.1.3 Discharging mode (Mode 3)

With both SW1 and SW2 open, the thermal storage is in the discharging mode. The discharge current is obtained from the following equations:

Consider loop ABDE, \( \Sigma V = 0 \).

\[
\frac{1}{C} \int I_2 \, dt + R_C \cdot I_2 + R_{LS} \cdot I_2 + R_{AL} \cdot I_3 + T_A(t) = 0
\]  
(3.7)

Constraint:

\[ I_3(t) = I_2(t) \]

As shown in Appendix E, the heat flow \( I_2(t) \) can be expressed as:

\[
I_2 = A \cdot e^{-at} - w \cdot a \cdot C \cdot \left\{ \frac{C(2) \cdot \sin(w \cdot t + 3 \theta + \phi_3)}{(a^2 + w^2)} + \frac{2 \cdot C(3) \cdot \sin(2w \cdot t + \theta + \phi_4)}{(a^2 + (2w)^2)} \right\}
\]  
(3.8)

and

\[
T_R(t) = I_2(t) \cdot R_{AL} + T_A(t)
\]  
(3.9)

With these equations we can calculate room temperature for the different operating conditions, on a clear day with
normal weather. Since the internal source can change from hour to hour, we must do an hour by hour calculation. When the operating mode changes, we must calculate a new A for the capacitor discharge term for each hour. A least squares comparison with the measured hourly temperatures can give values for A and C and then A and B. The resistances and capacitance thus obtained can be used on partly cloudy days, but the solar input for the calculation must be changed each hour to correspond to the measured value. To avoid this complication, the preliminary measurements done for this thesis were obtained with a windowless test hut. For on line predictive control, some assumptions must be made about internal gains during the prediction period. In office buildings, these are reasonably well known, or else one could use those that occurred during the last recorded day. The internal gains should be changed seasonally, since, in this model, fan cooling for ventilation amounts to a negative internal gain. For simplicity, in the validation experiment on Nov. 8 discussed in chapter 5, the fan was kept off.
CHAPTER 4

EXPERIMENTAL APPARATUS

AND THE PREDICTIVE CONTROL PROGRAM

4.0 Introduction

Low cost predictive control requires both simple models for the building thermal inertia and for the ambient temperature prediction, to enable the use of microcomputers, and inexpensive, reliable hardware for temperature sensing and control of the H.V.A.C. system. In order to determine the feasibility of a full scale system, and to develop and validate most of the elements of a predictive control program, a partial experiment was carried out in a test hut on the roof of the Centre for Building Studies. A baseboard heater, a window type air conditioner and a site fabricated fan ventilator were controlled with a predictive program written for an Apple II+ computer. Internal gains were simulated with light bulbs. To avoid the complications of large fluctuations in the solar input on partially cloudy days, the test hut was set up with no windows. Thus, a simpler thermal inertia model than that of Chapter 3 could be validated with better certainty, allowing a more reliable comparison to a calculation for the energy that would have
been consumed with normal, non-predictive controls during the same time period. Budget restrictions did not allow building a second test hut for a side by side comparison.

4.1 Experimental Equipment

The test hut (Fig. 4.1, 4.2 and 4.3) had been constructed on the roof of the Centre for Building Studies for a previous study of the effects of window to wall area ratio on energy consumption, in 1980 [6]. The intent was to simulate an outside office with one wall exposed to the weather and the other five sides contained in a thermostatically controlled cavity, to simulate the thermal environment of the neighbouring rooms in an office building. With no circulation of air, all the heat losses from the test room are through a single wall, easy to measure and to calculate. For this experiment, 293 Kg (645 lb.) of concrete blocks were also located inside the test chamber, to increase the thermal storage capacity to correspond to concrete construction, and allow a reasonable amount of preheating or precooling, necessary for predictive control.

Temperatures were measured with YSI Series 400 thermistor probes manufactured by Yellow Spring-Instrument Co. Inc. A total of 9 probes were used to measure temperature at different locations. The first two probes were used to measure ambient temperature, one with a tubular
Figure 4.1  Horizontal section through the test hut
Figure 4.2 Vertical section through the test hut
Figure 4.3 Vertical section through the external wall panel
radiation and wind shield, and one without a shield. Three other probes were placed diagonally across the room, to measure air temperature at different heights and depths. The cavity, concrete block storage surface, and outside and inside wall surface temperatures were also measured, to allow separate checks of the components of the thermal inertia model.

The probes were connected to a modified Gulton chart recorder, shown schematically in Fig. 4.4. An ice point instrument (NAR/E Ice Point Reference) was used to check the zero point of the probes and amplifier.

The monitoring and control circuit in Fig. 4.4 contains three main parts: a Remote Control; a Chart Recorder with an electronic selector for the thermistors; and the heating and cooling Equipment Controller. The Remote Control, located in the Apple II+, was used to send signals to select different channels for either recording temperatures or controlling the heating and cooling equipment. The actual switches were located in the test hut.

To record a temperature, a reset signal (+5V) is sent from the amplifier (741) to the chart recorder to reset the selector to the first channel. Successive signals through the channel select line step the chart recorder output through the thermistors in order. When the desired channel
is reached, the analog digital converter is cleared and the thermistor voltage is digitized and routed to the proper memory file in the Apple.

A similar procedure was used to control the heating and cooling appliances. An initialize signal (-5V) from the 741 amplifier turns all three appliances off. Seven pulses through the control appliance line turns on the heater. Fourteen pulses are used to turn on the air conditioner, and 21 pulses for the fan and damper.

A Rotron model MU2A1 fan was installed at the top right corner of the exposed outside wall, as shown in Fig. 4.5, with a precipitation shield on the outside, and a spring loaded damper to reduce infiltration when the fan is off. With the fan on, exhaust air was expelled through the electro-mechanical controlled damper shown in Fig. 4.6, located at the lower left corner of the exposed wall. The flow rate of the fan was measured in situ with a Datametrics Model 810L-M-DAX flowmeter. The measured flow rate was 19 l/s (40 CFM) ± 10% for different outside wind speeds.

The cavity between the inner and outer wall was kept at 20 °C by a Honeywell thermostat. It was heated by three 100 ft long heating cables suspended in loops from the ceiling to the floor. The 0.5 KW cables were manufactured by Heron Cable Industries Limited (Model ADkS-500-C1). The cooling
was supplied by a 1465 Watt (5000 BTU/hr) window air conditioner. The model used was a Mastercraft-5000, manufactured by Canadian Tire Limited.

The heater for the test room was a 1500 Watt Mastercraft baseboard heater. The cooling equipment was an air-conditioner identical to that placed in the cavity, previously calibrated by El Diasty [6].

4.2 The On Line Control Program

Because of the RAM memory limitations of the Apple II+ computer, the Predictive Control Program is organized as five separate programs on a disk, written to RAM sequentially as required, and linked by common memory files, kept on the same disk. Files of all the monitored temperatures and the changes in the modes of operation of the H.V.A.C. system were kept on a second disk, to be used for analysis. The five major programs are: (a) The Initialization routine, used to reserve space for the common memory files on the disk, and to collect values for ambient temperature for the first 12 hours, for use in the first prediction (c.f. flow charts and program listings in Appendix E); (b) The Prediction routine, used to calculate the coefficient $C(1)$ from the 12 hours of recorded ambient temperature, and to decide if the recent temperatures are
Figure 4.5 Cross section of fan

Figure 4.6 Cross section of mechanical controlled damper
normal or abnormal; (c) The Normal Control routine used to request operation of the baseboard heater or air conditioner, should room temperature be outside the comfort zone, to calculate the amount of advance free heating or cooling required to prevent use of the baseboard heater or air conditioner in the 24 hour period previewed, to check if the use of free heating will entail the purchase of cooling later and vice versa, and revise the calculated amount of free heat or cool to be used accordingly, and to request action to move room temperature to the middle of the comfort zone with free heat or cool if none of the above actions were chosen; (d) The Abnormal Control routine, used to request action to move room temperature to the middle of the comfort zone with free heat or cool until a normal ambient temperature pattern reappears; (e) The Time Control routine, used to take the nine temperatures every 5 minutes, and store 15 minute averages, to exit to the Prediction routine every hour, to check every 5 minutes if the actions chosen in the Normal or Abnormal Control routines are feasible at that time, or should be delayed five minutes (e.g., if ambient temperature > room temperature, fan cooling is impossible), and to operate the baseboard heater or air conditioner if room temperature is outside the comfort zone at any 5 minute check.
4.2.1 Initialization

This routine is only used once, upon commencing on line predictive control, for a period between 11 and 12 hours long. Three files on disk 1 must have measured values before the Prediction and Normal Control routines can be used. These are: DATA1, which contains the last ambient temperature read and the time at which it was read; DATA2, which contains the 11 previous hourly ambient temperatures; and VARB, which contains the last room temperature read, the time at which it was read, C(1), the daily average temperature corresponding to the last 12 hourly ambient temperatures recorded, and C(2), C(3) and 6, taken from a list embedded in the code for the Prediction routine, in this case appropriate for each 2 week period at Montreal. For the first TA in DATA2, a single reading taken at startup is used. The other ten values are each an average of 4 measured ambient temperatures taken at the 45, 50, 55 and 60 minute marks for each hour. When DATA1 is filled at the end of Initialization, room temperature is also stored in VARB.

In addition, a fourth file is opened on disk 1 during Initialization. This is OPER, which will soon contain a code number for the mode of operation chosen for the H.V.A.C. system during the Normal or Abnormal Control routines, and the time required for operation in that mode, in the case of
pre-cooling or pre-heating. The codes are: 0, which means take no action; 1, which means pre-cool; and 4, which means move room temperature to the middle of the comfort zone (i.e. the abnormal control path is in effect).

Ten files are reserved on disk 2, during Initialization. Each of the nine temperatures measured is stored in a separate file at 15 minute intervals, during the operation of the Time Control routine. The tenth file contains a coded history of the H.V.A.C. system operation. Whenever the mode of operation is changed, the time and the new mode of operation are stored. The codes are: 0, which means all H.V.A.C. components are off (i.e. heating with internal gains); 1, which means the fan was turned on; 2, which means the baseboard heater was turned on; and 3, which means the air conditioner was turned on.

The Initialization program is eliminated from RAM when it loads the Prediction routine from disk 1.

4.2.2 Prediction

The first task done in this routine is the calculation of C(1) from the twelve ambient temperatures stored in DATA1 and DATA2. This is done as described in chapter 2, by fitting the historical average curve to the 12 TA, and then taking the smoothed 24 hour average TA as C(1). Next, the
last six TA are used to decide whether the temperature pattern is normal or abnormal, using \( \sigma = 1.6 \) as the criterion, as described in chapter 2. For normal weather, C(l) is stored in VARB, and the Normal Control routine is written to RAM from disk l. For abnormal weather, the Abnormal Control routine is run.

4.2.3 Normal Control

The first step in this routine is to calculate the ambient temperature for 24 hours in advance using the Fourier series approximation. If the predicted TA will neither exceed BU, the balance point for cooling nor fall below BL, the balance point for heating during the next 24 hours, we calculate a predicted room temperature for that period, using the circuit analogy and the best fit Resistances and Capacitor, embedded in the code at line 120. If the average predicted room temperature will be above CM, the temperature at the middle of the comfort zone, we apply fan cooling if possible until the future average reaches CM.

If cooling will be required in the next 24 hours, the amount required is calculated from the hourly temperature difference across the building envelope and \( R_{AL} \), the "as built" thermal resistance of the envelope, assuming that the air conditioner would operate as required by the load. Next the time required for fan pre-cooling to supply the same
amount of cooling starting as soon as possible and using ambient air at the hourly predicted temperatures is calculated. If pre-cooling will cause a demand for baseboard heating in the next 24 hours, the amount of pre-cooling is reduced to avoid the heating expense. The reason for using a prediction for 24 hours is to ensure that both the highest and the lowest ambient temperatures are included, so that this check and the converse one for pre-heating are meaningful. The pre-cooling operation mode code and the adjusted time for pre-cooling are stored in OPER.

If heating will be required in the next 24 hours, the fan is turned off, to allow internal gains to heat the room for the current hour. If this amount of pre-heating exceeds the amount required later, fan cooling will be applied after the next hourly prediction. The operation mode code 0 is stored in OPER. At exit from each of the branches of Normal Control, the Time Control program is called from disk 1.

4.2.4 Abnormal Control

The control strategy chosen for the period of time when a weather front is passing through is quite simple. Room temperature is kept close to the middle of the comfort zone with fan cooling or internal gains (if possible) until the ambient temperature pattern returns to normal. Then Normal
control is resumed with a new C(l) corresponding to ambient temperature after the weather front. In most cases, this Abnormal Control strategy will amount to opposing the change induced by the weather front with free heat or cool: i.e. we heat during a cold front and cool during a warm front. The compensation (if any) at the restart of Normal Control will also usually be done with free heat or cool. Occasionally, however, this Abnormal Control strategy will not be optimal and will result in some purchased heat or cool. However, this cannot be predicted in advance, because we don't know in advance what the 24 hour average ambient temperature after the weather front will be. More complex control strategies would also miss the optimal action occasionally, so a simple strategy was chosen. The steps taken in Abnormal Control are correspondingly simple. Code 4 is stored in OPER, and the Time Control program is called from disk 1 to create the appropriate signals to turn the fan on and off.

4.2.5 Time Control

Signals to operate the data acquisition system and to turn the appliances on and off are generated in this routine, at five minute intervals. The first step is to read the OPER file, which contains the operation codes and durations selected during the Normal and Abnormal Control routines. Next the nine temperatures are read from the
D.A.S. and the time is taken from the Apple Clock board in the Apple. Every 15 minutes, the temperatures are averaged and stored on disk 2, and the prediction routine is called at the end of each hour.

If room temperature is outside the comfort range, either the baseboard heater or the air conditioner is turned on for five minutes, and either Code 2 or Code 3, plus the time are files on disk 2. This action has first priority, and continues until either room temperature reaches the comfort zone or the hour is up. With room temperature in the comfort zone, and Code 0 (fan, baseboard heater, and air conditioner off, internal gains on), the appliances are turned off, Code 0 and the time are filed on disk 2. If room temperature is still within the comfort zone at the next five minute check, this process is repeated for another five minutes, unless the hour is up. For Code 1 (fan precooling) the fan is turned on for 5 minutes, if TR > TA, Code 1 and the time are filed on disk 2, and the duration in RAM is reduced by five minutes. If ambient temperature is too high for pre-cooling, no action is taken until the next five minute readings for TA and TR. For simplicity, the escapes from (10) and (12) to (8) when the requested duration for pre-cool has been met are not shown on the flow chart. For Code 4, (neither heat nor pre-cool required) the fan is turned on or off to move room temperature to within a degree of the middle of
the comfort zone.
CHAPTER 5

RESULTS AND DISCUSSION

5.0 Introduction

In order to validate the thermal inertia model of chapter 3, and to obtain the "as built" capacitance and resistors required to use the on line predictive control program, a preliminary experiment was run on Nov, 8, 1984. To obtain the simplest possible thermal inputs for the electric circuit analogy, all of the appliances except the internal gains (a 150 watt light bulb) were disabled. The light bulb was run continuously at constant power for 20 hours to heat the test hut slowly. Nov 8 was chosen retroactively because it was cool enough to keep room temperature within the comfort limits for a time as long as the RC time constant (13 hours) of the test hut, and because the ambient temperature pattern was very close to the pattern predicted from the Fourier series formula (c.f. Fig. 5.1)

Proper operation of the on line predictive control program described in chapter 4 was verified by using it to control all of the test hut appliances for a period of six days beginning on Nov 20, 1984. To obtain some feeling for
the savings available with this technique, a calculation using the same electric circuit model, and the same thermal parameters, obtained from the preliminary experiment of Nov 8, but without any pre-cooling, pre-heating, baseboard heating or air conditioner cooling was done for the weather of the same six day period. Whenever the calculated room temperature went above the comfort zone, i.e. over 24°C (as it happened, calculated room temperatures never went below the comfort zone; c.f. Fig. 5.4), losses through the front panel were calculated for a room temperature of 24°C. This is close to what would occur if the air conditioner were turned on by a normal thermostat set with its upper dead band limit at 24°C. Thus, the area above the comfort zone for this calculated room temperature, multiplied by the thermal capacity of the test hut is a rough measure of the purchased cooling prevented by the use of predictive control during those six days.

The measure is only rough because: (a) the model is too simple, even for the test hut; and (b) a cavity controlled to be at a fixed temperature does not reflect what would happen in neighbouring rooms in a real building. With predictive control, the neighbouring rooms would vary in temperature through the comfort zone, pretty well in step with the control room. In our experiment, the measured temperatures are slightly effected by heat gains or losses
from or to the cavity whenever the test room temperature is not 20 °C. In other words, the loss resistor, $R_{AL}$ from the test room should either change with temperature, or be calculated with an extra loop containing the cavity temperature. To avoid these complications, $R_{AL}$, $R_{LS}$, $R_C$ and $C$ were kept independent of temperature, but were adjusted with a least squares fit to measured test room temperatures over a range of 19 °C to 25 °C. During the six day calculation, the maximum measured temperature difference to ambient cross the front panel was 27 °C, and the minimum was 10 °C. The maximum temperature difference between the cavity and the test room was 4 °C. Since the area between the cavity and the test room is more than 5 times the area of the front panel, this is not a minor effect. However, any savings estimated here would not be entirely valid for a real building in any case. Moreover, six days of data, while enough to show that the on line predictive control system operates as desired, is not enough to extrapolate to an annual savings. Thus, a rough estimate of the savings is sufficient to show that some savings exist, and that they could be large enough to justify refining the program and extending the experiments.
5.1 Preliminary Experiment to Establish "As Built" Thermal Parameters for the Test Hut

For the experiment on Nov. 8, 1984, a modified version of the Time Control program was used to read all 9 temperatures every 15 minutes. None of the appliances were controlled by the program. The internal gain light bulb was switched on manually to provide a constant power heat source. Before the readings shown in Fig. 5.1, the 2 doors to the cavity and test room were left partly open for 3 hours to allow both room temperature and the storage surface temperature to stabilize at 19 °C. Then the doors were closed, and the experiment began at 5 p.m., yielding 20 hourly temperatures for each of the thermometers. The observed room, storage surface and ambient temperatures are shown in Figs 5.1, 5.2, and 5.3.

As derived in Appendix F, the 3 resistors and C were first obtained by inversion of the electric circuit equations, using the measured TA, TR and TS (equations F:9 - F.14) iterated until the solutions were stable. Seventeen different values were obtained for each component, using a set of 4 hourly measurements of TR, TA and TS for each inversion; i.e. one set of C and the 3 resistances was obtained for readings from 17 to 20 hours, another for readings from 18 to 21 hours, etc. The seventeen values so obtained were then averaged to yield:
Figure 5.1 Preliminary comparison between measured and predicted room temperatures
Figure 5.2 Comparison between measured and predicted room temperatures with adjusted $R_{AL}$, $R_{LS}$, $R_C$ and $C$
Figure 5.3 Comparison between measured and predicted storage surface temperatures with adjusted $R_{AL}$, $R_{LS}$, $R_C$ and $C$.
\[ R_{AL} = 200 \pm 30 \quad (^{\circ}C/kW) \]
\[ R_{LS} = 17 \pm 1 \quad (^{\circ}C/kW) \]
\[ R_{C} = 12.5 \pm 0.7 \quad (^{\circ}C/kW) \]
\[ C = 0.059 \pm 0.01 \quad (kW \, hr/^{\circ}C) \]

The errors quoted are standard deviations for each set of 17 values.

With this procedure the averages are influenced less by the first and last few readings than by the others. The first and last readings are only used in one inversion; the second and second last readings are each used in two inversions; while the fourth to sixteenth readings are each used in 4 inversions. This is useful because the time lag between storage and air temperature is not established until a few hours into the experiment, and because the last few room temperatures are well above the cavity temperature (20 \(^{\circ}C\)), so the simple \( R_{AL} \) model used is least appropriate there.

To show the reliability of the circuit model as it is used for online control, a predicted hourly room temperature was calculated using the above four experimental circuit parameters, plus the Fourier coefficients derived from the smoothed TA for Nov. 8 (i.e. equations F9 - F14). The result is shown in Fig. 5.1.
This kind of iteration procedure is very sensitive to errors in the thermometer readings, as was made clear by a partial sensitivity test. Shifting five of the measured room temperatures by 0.5 °C caused the results for $C$, $R_C$, and $R_{LS}$ to change by as much as 100%. Therefore, a least squares fitting procedure was adopted to adjust the above circuit parameters to final values for use in the on line control program.

In the least squares procedure, each of the circuit parameters was changed manually in steps of 1% or less, above and below the values obtained in the inversion iteration technique. For each change of a single parameter, a new predicted hourly room temperature curve was calculated for Nov. 8. The last 3 points, above 25 °C were excluded from the sum of the squares of the differences between the predicted and measured hourly temperatures. In each case, least square minima were found within 10% of the circuit parameters found by the inversion iteration technique. The order for variation of the circuit parameters was: first $R_{AL}$; then $R_{LS}$; then $C$; and then $R_C$. $R_{AL}$ is the largest of the parameters, and was not very sensitive to changes in room temperature in the iteration technique, so it was used to minimize the squares of the differences first. The results for this variation gave:
\[ R_{AL} = 212 \quad (\degree C/kW) \]
\[ R_{LS} = 15 \quad (\degree C/kW) \]
\[ R_C = 13 \quad (\degree C/kW) \]
\[ C = 0.055 \quad (kW \text{ hr}/\degree C) \]

This gives a time constant \( \tau = \frac{1}{a} = C (R_{AL} + R_C + R_{LS}) \)

\[ \tau = 13 \text{ hours} \]

The room temperature curve calculated with these adjusted parameters gave a better fit to experiment than that of Fig. 5.1, as shown in Fig. 5.2. Since we are dealing with a four dimensional space, there is some possibility that a lower least squares minimum exists outside of the range searched. The main validation for the circuit parameters obtained is the fact that the on line control worked properly. However, an extra check was obtained by calculating the temperature at the storage surface, with the same circuit and Fourier constants, and comparing it to the measured values, as shown in Fig. 5.3. The maximum difference between predicted and measured temperatures for both Figs. 5.2 and 5.3 is 2 \degree C. This is nearly within the experimental difference obtained when all nine thermistors were placed simultaneously in a thermos bottle containing water at about 40 \degree C. The maximum and minimum readings differed by 2 \degree C. When all 9 thermistors were placed in an accurate electronic ice point device, the difference obtained was only 0.1 \degree C.
\( R_{AL} = 212 \, ^\circ C/kW \) corresponds to an R value in British Units of 7.5 (hr-ft\(^2\).F/Btu). An A.S.H.R.A.E. [1] calculation using constants for the materials quoted in El Diasty's thesis gave R11. Since the fan and exit damper openings provide extra infiltration and the test hut materials and seals have had four years of deterioration exposed on the roof, and since the effective R value should be reduced by losses to the cavity, R7.5 is a reasonable value.

To check the magnitude of the losses to the cavity when room temperature was above 25 °C on Nov. 8, a subsidiary calculation was done with \( R_{AL} \) reduced by a factor of 4/9 for the last six points of the predicted hourly room temperature curve. The value 4/9 was obtained from A.S.H.R.A.E. calculations for the heat losses through the front panel and the cavity walls at hour 33, with room temperature at 27 °C, ambient at 5 °C, and the cavity at 20 °C. As shown in Fig. 5.2, the fit is better than the thermometer errors. For on line predictive control in real buildings there is no need to change \( R_{AL} \) as a function of room temperature, since the neighbouring rooms will generally be at the same temperatures as the control room. A single \( R_{AL} \) was used for this experiment as well, because the appliances were controlled to keep room temperature between 18 °C and 24 °C.
5.2 The On Line Predictive Control Experiment

The Data Acquisition and Control systems were operated as outlined in chapter 4, using the thermal parameters as adjusted from the least squares procedure, for a continuous period of 6 3/4 days, beginning at 7 p.m. on Nov. 19, 1984. Thus, the initialization TA file was complete at 7 a.m. Nov. 20, and computer control began then. To create a neutral starting point for the experiment, the test hut doors were partly opened between 11 a.m. and 2 p.m. Nov. 20, until both room temperature and the storage surface temperature stabilized at the middle of the comfort zone, 21 °C. The upper balance temperature for cooling with the air conditioner, BU had been determined in several previous short experiments. BU = -3 °C was used in the control program. Since ambient temperature had never been cold enough during the previous experiments to determine the lower balance point for baseboard heating, BL, an arbitrary value of -10 °C (2 degrees below the lowest ambient previously measured) was used.

Measured results for ambient and room temperature, beginning at 2 p.m. Nov. 20 are shown in Fig. 5.4. The series of F's shown on the figure indicate hours when the fan was on for at least 5 minutes. Neither the baseboard heater nor the air conditioner were used during this period.
Figure 5.4 Results from on line Predictive Control experiment and calculated curve for estimation of savings.
The ambient curve shows the passage of a warm front near 3 p.m. (hour 87) on day 4. In terms of the prevention of purchased cooling, this is the most inconvenient time for a warm front. The previous strategy selected under normal control had been calculated with the assumption of cooler ambient temperatures than those that actually occurred on the afternoon of day 4. The need for a switch to the abnormal control routine cannot be definitely determined until 3 or 4 hours after the beginning of the warm front period. Nevertheless, the pre-cooling obtained in the early morning of day 4, plus the priority given to fan cooling under normal control prevented (just barely) the use of the air conditioner on that afternoon. Room temperature at hour 89 (5 p.m.) just reached 24 °C, but did not exceed it. Soon after the warm front was recognized, at hour 90 or 91, the abnormal control routine operated properly to move room temperature near the middle of the comfort zone, and to keep it within 2 °C of 21 °C for about 15 hours until the return to normal control at hour 105 or 106.

Except during the warm front, precooling was obtained in the early morning each day. Room temperature reached the bottom of the comfort zone several hours before dawn on days 2, 3 and 4, before midnight on day 5, and near dawn on day 7. On day 6, room temperature was kept near the bottom of the comfort zone for a longer period than for days 2, 3 and
4, in anticipation of the higher afternoon ambient temperatures predicted for day 6. Pre-heating was also achieved each evening, except during the warm front, with room temperature reaching the top of the comfort zone after working hours each day except day 5. At noon, room temperature was within 1 °C of the middle of the comfort zone each day except for day 7, so good comfort was maintained during working hours. During the periods of normal control, all the minima of the room temperature curve were nearly coincident with the minima of the ambient temperature curve, so heat losses at night were reduced compared to what would have occurred with control by a regular thermostat without a night setback. Thus, during this six day period, the mass of the test hut was utilized as a thermal storage for "free" heat and cool, even though room temperature never left the comfort zone, good comfort near the centre of the zone was maintained during working hours, no energy was purchased except to run the fan, and night losses were reduced.

The upper curve in Fig. 5.4 shows room temperatures calculated with the same model, ambient temperature and parameter values used in the on line control program, but assuming no fan cooling. Whenever the curve rose above 24 °C, heat losses through the front panel were calculated as though room temperature were 24 °C, so the calculated losses
are close to those that would have occurred if the air conditioner went on above 24 °C, and off below 24 °C, with no deadband. The internal gains were kept constant at 150 W for the calculation. No ventilation or cavity losses were assumed beyond those implied in the adjustment of $R_{AL}$ by the least squares fitting procedure. On days 2, 3 and 4, when this curve passes above the comfort zone after a period of at least ten hours below the upper comfort limit, the ambient temperature is about -3 °C, the BU used in the control program. This is an indication that this portion of the software is internally consistent. Little meaning can be derived from the other crossings of the upper comfort limit because they are too close to periods when the curve is above the limit and the calculated room temperature does not match the temperature (24 °C) used for the heat loss calculations. A rough estimate of the cooling energy saved can be obtained by multiplying the area of this curve above the upper comfort limit (105 °C-hr) by the thermal capacity of the test hut (55 W/°C), to give about 6 kWhr of thermal energy savings. With inefficient stop start operation of the air conditioner, this might correspond to a savings of 10 kWhr of electricity. This particular fan uses a power of only 15 watts. It was on for a total of 8.4 hours over the six days, using only 0.1 kWhr, which can be neglected. For a building with 100 offices, and a six day work week, this amounts to a rough savings on cooling of $30 for that week.
However, warmer weeks, with a weekly average ambient temperature near 10 °C would show much larger savings. If we assume an average savings on cooling of $50 per week for 35 weeks, plus equal savings for heating, a rough estimate for the yearly total savings is something over $3000. When the fast morning warmup routine is added to the control program, further large savings will result. For buildings with demand load charges, prevention of chiller or heater operation at peak load times during most billing periods would likely triple the cash savings. The capital cost of such a system produced in reasonable quantities should not exceed $6000.

Three room air temperatures measured in the vertical midplane of the test room are shown for the first four days of the experiment in Fig. 5.5. One thermometer was close to floor level, just behind the front panel, another was at the centre of the room, and the third was close to the ceiling at the back of the room. Evidently, in this temperature range, the relative error between these particular three thermistor thermometers is much less than the absolute difference of 2 °C found for all 9 thermometers at 40 °C. The temperature gradient observed is always in the expected direction, with the back ceiling warmer than the front floor, even though the maximum apparent temperature difference is only 2 °C (hour 41). A small temperature gradient was expect, for two reasons: the cavity had a very
Figure 5.5 Measured air temperatures at three different interior locations
small temperature gradient during heating periods because the heating wires were hung from ceiling to floor at about one foot intervals; also, any heat derived from the concrete block storage was emitted at a low height, since the top of the storage was only 80 cm above the floor.

Whatever the accuracy of the thermometers, these results do show that the average room temperature moves up and down through the horizontal midplane containing the centre thermometer. For instance, at hours 25, 30, 55 and 57 the centre temperature is closer to the front bottom than the back ceiling air temperature. Nearby, at hours 28, 31, and 56 the centre temperature is closer to the ceiling air temperature than the floor air temperature. Thus, the point of adjusting the model thermal parameters is not only to correct for construction errors and changes with settling and weathering, but to find parameters appropriate to a thermometer at a fixed location. Such parameters can differ from those appropriate for a heat loss calculation using average room temperature, especially, as would be the case in an occupied room, if the monitoring thermometer is not placed at the centre of the room.

As expected, portions of the room air did go outside the comfort zone at times, even though the centre temperature did not. Eight of the recorded ceiling air temperatures are
above 24 °C, and six of the floor air temperatures are below 18 °C. No temperature inversions were recorded, even though the fan cooling was applied near the ceiling level.

5.3 Conclusions

1. The ambient temperature prediction system developed here, using a short Fourier series, with 3 constants derived from weather records and one from recent on site temperature measurements read into an Apple microcomputer, predicts normal ambient temperatures 24 hours in advance closely enough for use in building control systems. The Apple program developed is fast enough for use in on line H.V.A.C. control systems. This system can be used to sense the arrival or departure of a weather front within 3 or 4 hours of the event, allowing microcomputer controlled changes of H.V.A.C. control strategy in time to prevent energy waste, for most weather fronts.

2. The room temperature prediction system developed here, using closed solutions for the simple one capacitor model of the thermal flows, plus the predicted ambient temperatures, one measured room temperature, and appropriate "as built" thermal parameters for the test hut, predicts the centre temperature of the test room air closely enough for use in the test hut H.V.A.C.
control system. It is likely, but not yet proven, that this system will also work well enough in more complex buildings.

3. The preliminary Apple microcomputer based Predictive Control system developed here worked well in a short 6 day trial with the simple 3 element H.V.A.C. system of the test hut. More software must be developed before the system can be used in an occupied building, and longer trials must be done, but the essential elements of the system are in place. Low cost hardware has been used to monitor the temperatures required and to switch the H.V.A.C. subsystems on and off. Apple software has been developed to predict both ambient and room temperature 24 hours in advance, to change control strategies when unusual weather occurs, to calculate the optimal amount of pre-heating or pre-cooling required 24 hours in advance, with revisions each hour as indoor or outdoor conditions change, and to take action to obtain the calculated amounts of internal gain heating or fan cooling. During the six day trial, enough savings through prevention of use of the air conditioner were obtained to allow the hope that the fully developed system will be cost effective.

4. More development of the system is warranted.
5.4 **Recommendations for Further Studies**

1. More on line control experiments should be done, at all seasons of the year, with the present program and test hut configuration. This will provide estimates for the energy savings expected during each season, and for how often the passage of a weather front induces operation of the air conditioner or baseboard heater with the present software.

2. More complex strategies for the abnormal weather routine should be tested and compared with the present one. For example, one might move room temperature to the bottom of the comfort zone for warm fronts occurring after midnight, or for warm fronts with recorded temperatures well above those that had been predicted for normal weather.

3. More experiments should be done to check the present ambient temperature prediction and weather front recognition system at different seasons of the year. This will provide estimates for the worst case longest time before recognition of a weather front with the present software, and for the worst error expected in the ambient temperature prediction for normal weather.

4. A computerized method for evaluating "as built" thermal parameters for the electric circuit model should be
developed and validated. This will allow automatic seasonal variation of these parameters with the on line control program.

5. The room temperature prediction system should be validation for more complex buildings than the test hut. This will help clarify the limitations of the simple one capacitor model used for the thermal flows.

6. To move towards using this system for predictive control in occupied buildings, several software routines should be added to the system, and validated by experiments:

(a) Minimum ventilation air should be maintained during occupied hours. This involves either proportional control of the fan or control of a multiple fan system, plus control of the mixing and outside air dampers, for large buildings.

(b) Night temperature set backs or set ups outside the comfort zone should be added. This could be combined with a routine for moving the comfort zone seasonally. The extra set back or set up should only be used when pre-cooling or pre-heating within the comfort zone is not enough to prevent the predicted use of purchased energy the next day. (i.e. it would not be used often)

(c) A fast morning warm up or cool down of room air
temperature to the centre of the comfort zone should be added. This will involve a comparison both of energy usage and of comfort attained in the two cases of fast or normal warm up.

(d) For summer use, calculation of dehumidification strategies should be added. This will involve the addition of ambient and indoor humidity sensors. Extra savings will sometimes be available from ventilation beyond that required for pre-cooling, to keep the moisture content of the indoor building materials as low as possible.

(e) A prediction of maximum and minimum solar gains 24 hours in advance should be added. On many days, a single pre-heating or pre-cooling strategy will cover both cases, with predicted room temperatures never outside the comfort zone for either extreme of solar gains. On the other days, however, what amounts to a prediction of solar gains will have to be made. One possibility is simply to use the historical average solar gains. Another is to install a solarimeter to monitor, say, sunlight on a horizontal plane, and extract probabilities for strings of sunny and cloudy days in a row for each week from the weather records. In November in Montreal, one can predict with good certainty that after 3 sunny days in a row, the fourth day will be
cloudy.

(f) The on line program should be extended to handle buildings with several zones, each with a different set of internal gains, thermal loss and inertia parameters, and controls for the H.V.A.C. system.

7. A research program should be initiated to test whether methods to predict the arrival of weather fronts in advance, using only on site measurements and historical weather records, are possible. Small ambient pressure and temperature variations, or changes in the pattern of wind variations during normal weather might provide advance clues. Most probable intervals between weather fronts for the various seasons could be extracted from the weather records. With such predictions, action could be taken during normal weather periods to prevent the use of purchased energy during passage of the next weather front.
REFERENCES


Techniques", Notes for Short Courses held on May 15-16, 1980, Centre for Building Studies, Concordia University, Ch. 4 & Ch. 8.


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PROGRAM MAIN

This is a curve fitting program, with adoption of least square method, to generate a Fourier series curve.

Symbol:

\[
\begin{align*}
X &= X \text{ values of data points.} \\
Y &= Y \text{ values of data points.} \\
F &= \text{Function matrix.} \\
FT &= \text{Transpose of function matrix.} \\
A &= \text{Product of matrix FT and F.} \\
B &= \text{Product of matrix FT and Y.} \\
C &= \text{Coefficient of Fourier Series.} \\
YY &= \text{Values of Y at X by the curve.} \\
OM &= \text{Frequency (2*PI/24)} \\
theta &= \text{Phase angle.} \\
N &= \text{Number of point.} \\
M &= \text{Number of degree.} \\
CHE &= \text{Title of curve.}
\end{align*}
\]

DIMENSION X(50), Y(50), FT(750), A(7,8), B(7), C(7), YY(50)

COMMON C, OM
CHARACTER*25 CHE
CHARACTER*1 TEM
OM=2*3.1415927/24

Read in the title of the curve.

READ (5, ' (C25) ' ) CHE
WRITE (6, 100) CHE

Read in the number of constant's C and number of data points.

READ(5,*) M, N

Read X-Y values of data points and generate a F matrix.

DO 2 I=1, N
READ (5,*) X(I), Y(I)
F(I,1)=1.
F(I,2) = COS(OM*X(I))
F(I,3) = SIN(OM*X(I))
F(I,4) = COS(2*OM*X(I))
F(I,5) = SIN(2*OM*X(I))
2 CONTINUE

Generate the transpose of the F matrix.

DO 3 I=1, N
DO 3 J=1, M
FT(J, I)=F(I, J)
3 CONTINUE
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Determine the coefficients of a simultaneous equation system, matrix A.

CALL MATMPY(FT,F,A,M,N,M)

Determine the column of constants of the simultaneous equation system.

CALL MATMPY(FT,Y,B,M,N,1)

DO 4 I=1,M
   A(I,M+1)=B(I)

4

Determine C values by solving simultaneous equation using Cholesky Method.

MP1=M+1

CALL CHLSKY(A,M,MP1,C)

Determine the phase angle.

THETA=(ATAN(C(2)/C(3))+3.1415927)/3

Curvefit the data again using only one phase angle and 1 overtone Fourier series.

M=M-2

Generate the F matrix.

DO 5 I=1,N
   F(I,1)=1.
   F(I,2)=SIN(QM*X(I)+THETA)
   F(I,3)=SIN(2*QM*X(I)+THETA)

5

CONTINUE

Generate the transpose of the F matrix.

DO 6 I=1,N
   DO 6 J=1,M
   FT(J,I)=F(I,J)

6

CONTINUE

Determine the coefficients of matrix A.

CALL MATMPY(FT,F,A,M,N,M)

Determine the column of constants of the simultaneous equation system.

CALL MATMPY(FT,Y,B,M,N,1)

DO 7 I=1,M
   A(I,M+1)=B(I)

7

Determine C values by solving simultaneous equation using Cholesky Method.

MP1=M+1
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CALL CHLSKY(A,M,MP1,C)
  C 0115

  Calculate the value of Y at point X of the curve.  C 0116

DO 8 I=1,N
  8 Y(I)=C(1)*C(2)*SIN(OM*X(I)+3*THETA)+C(3)*SIN(2*OM*X(I)+
      $\theta$)
    WRITE(6,200) THETA
    WRITE(6,300) (I,C(I),I=1,N)
    WRITE(6,400)
  C 0118

  Calculate the absolute different and print the data.  C 0119

DO 9 I=1,N
  9 DF=ABS(Y(I)-YY(I))
    WRITE(6,500) X(I),Y(I),YY(I),DF
  C 0120

  Check whether there is another set of data.  C 0121

READ(5,'(C1)') TEM
  C 0122

IF (TEM .EQ. 'Y') GOTO 1
  C 0123
100 FORMAT('10,'TEMPERATURE VARIATION CURVE FITTING FOR ',
     $C(\theta)$)
  C 0124

$9$ 'T10,'POWER REGRESSION: -\theta, /
    $T15,'Y = C(1)+C(2)';$
    $SIN(OM*X+3*THETA)+C(3)*SIN(2*OM*X-THETA)';$ /
    'T44,'WHERE OM = 2\pi/24';$
200 FORMAT('10,'T50,'THETA = \theta',F8.2,/'$
     $T95,'C(1) THROUGH C(M)';$
300 FORMAT('1H,26X,'C(','I1,') = ',E14.7)
400 FORMAT(1H,12,'ACTUAL',T27,'ACTUAL',T41,'CALCULATED',
     $T56,'ABSOLUTE ' /
      $T15,'X',T30,'Y',T45,'Y',T56,'DIFFERENCE')
500 FORMAT(7X,3(2X,F8.2,5X),5X,F6.2)
  C 0125

STOP
END

NO ERRORS:FTD.R04-00  MAINPROG  MAIN  TABLE SPACE: 4 KB
STATEMENT BUFFER: 20 LINES/1321 BYTES  STACK SPACE: 178 WORDS
SINGLE PRECISION FLOATING PT SUPPORT REQUIRED FOR EXECUTION
SUBROUTINE MATMPY(A,B,C,M,N,L)

Subroutine to perform matrix multiplication.

DIMENSION A(7,50),B(50,7),C(7,8)

Determine matrix C as product of A and B matrix.

DO 1 I=1,M
  DO 1 J=1,L
    C(I,J)=0
  1     DO 1 K=1,N
    C(I,J)=C(I,J)+A(I,K)*B(K,J)

RETURN
END

NO ERRORS: F7D R04-00 SUBROUTINE MATMPY TABLE SPACE: 1 KB
STATEMENT BUFFER: 20 LINES/1321 BYTES STACK SPACE: 172 WORDS
SINGLE PRECISION FLOATING PT SUPPORT REQUIRED FOR EXECUTION
SUBROUTINE CHLSKY(A,N,M,X)**

Subroutine using Cholesky's method to generate solutions for the simultaneous linear algebraic equation

DIMENSION A(7,8),X(7)

Calculate first row of upper unit triangular matrix.

DO 1 J=2,N
1 A(1,J)=A(1,J)/A(1,1)

Calculate other elements of Upper and Lower matrices.

DO 6 I=2,N
J=I
DO 5 II=J,N
1 SUM=0.
JMM=J-1
DO 2 K=1,JMM

2 SUM=SUM+A(II,K)*A(K,J)
3 A(II,J)=A(II,J)-SUM

4 IP1=I+1
DO 5 JJ=IP1,M
SUM=0.
IMM=I-1
DO 3 K=1,IMM

5 SUM=SUM+A(I,K)*A(K,JJ)
6 A(I,JJ)=(A(I,JJ)-SUM)/A(I,I)
CONTINUE

Solve for X(I) by back substitution.

X(N)=A(N,N+1)
L=N-1
DO 7 NN=1,L
SUM=0.
I=N-NN
IP1=I+1
DO 8 J=IP1,N
7 SUM=SUM+A(I,J)*X(J)
8 X(I)=A(I,H)-SUM
RETURN
END

APPENDIX B
00010 REM THIS IS A DATA ACQUISITION PROGRAM WHICH IS USED
00020 REM FOR DATA COLLECTION OF AN INTERVAL OF TIME. THIS
00030 REM DATA WILL STORE IN DISK B.
00040 REM
00050 REM
00060 REM"RDS SUBROUTINE"
00070 REM TO ACCESS DISK WITHOUT THE USE OF DISK OPERATING SYSTEM
00080 REM (DOS).
00090 REM
0110 FOR X = 896 TO 927
0120 READ P
0130 POKE X, P
0140 NEXT
0150 DATA 169,3,160,138,32,217,3,96,0,0,1,96,2,0,0,0,155,3,0,96,0,0,2,
0,96,170,1,299,236,118
0160 DIR AD(12),1T$(10,40)
0170 REM
0180 REM SYMBOLS
0190 REM AD = NUMBER OF DAY OF EACH MONTH.
0200 REM TT = TEMPORARY STORAGE OF DATA BEFORE ACCESS TO DISK.
0210 REM ST = SECTOR NUMBER.
0220 REM TR = TRACK NUMBER.
0230 REM IN = NUMBER OF TRACK PER CHANNEL.
0240 REM SC = TIME INTERVAL BETWEEN EACH READING IN SECOND.
0250 REM
0260 REM
0270 REM INITIAL VARIABLES
0280 REM
0290 DS = CHR$(4)
0300 LL = 1
0310 LD = 0
0320 ST = 0
0330 FOR I = 1 TO 12
0340 READ AD(I)
0350 NEXT
0360 DATA 31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31
0370 DATA VIB(10)
0380 INPUT "INPUT NUMBER OF CHANNEL(S)" ; NC
0390 INPUT "TIME INTERVAL BETWEEN EACH READING (SEC) " ; SC
0400 IN = INT (35 / NC)
0410 REM STORE NUMBER OF CHANNELS AND READING'S INTERVAL BETWEEN
0420 REM EACH CHANNEL IN MEMORY. CALL SUBROUTINE TO STORE THIS
0430 REM INFORMATION AS WELL AS TITLE, UNIT, AND FACTOR IN LAST
0440 REM TRACK OF DISK B.
0450 REM
0460 POKE 24576, NC
0470 TP = INT (SC / 10000)
0480 POKE 24584, TP
0490 POKE 24585, TP
0500 TP = INT ((SC - TP * 10000) / 100)
0510 POKE 24586, TP
0520 TP = INT (SC - INT (SC / 100) * 100)
0530 POKE 24587, TP
0540 GOSUB 2130
0550 TP = 0
0560 ST = 0
0570 REM LOAD ASSEMBLY LANGUAGE AA/DD IN MEMORY. THIS
0580 REM PROGRAM ACCEPT AND TERMINATE ONLY ONE SET OF DATA
0590 REM IN MEMORY AT A TIME.
APPLESOFT BASIC

0610 REM
0620 PRINT D$; "LOAD AA/DD"
0630 REM
0640 REM  RESET TO FIRST CHANNEL.
0650 REM
0660 HOME
0670 POKE 49245, 1
0680 GOSUB 2050
0690 POKE 49244, 0
0700 REM  GET THE INITIAL TIME OF THE FIRST READING.
0710 REM
0720 REM
0730 GOSUB 1440
0740 GOTO 1030
0750 REM  PRINT D$; "IN#4"
0760 REM  PRINT D$; "PR#4"
0770 REM  INPUT "",; TIS
0780 REM  PRINT D$; "INFO"
0790 REM  PRINT D$; "PR#0"
0800 REM
0810 REM  CONVERT THE TIME INTO NUMERICAL NUMBER AND PRINT
0820 REM  THE TIME IN SCREEN.
0830 REM
0840 M1 = VAL (MID$(T1$, 1, 2))
0850 D1 = VAL (MID$(T1$, 4, 2))
0860 H1 = VAL (MID$(T1$, 7, 2))
0870 M2 = VAL (MID$(T1$, 10, 2))
0880 S1 = VAL (MID$(T1$, 13, 2))
0890 VTAIL (8); HTAB (15)
0900 PRINT LEFT$(T1$, 14)
0910 REM
0920 REM  CHECK WHETHER THE RIGHT TIME FOR ANOTHER READINGS.
0930 REM
0940 IF (M1 < MJ) GOTO 750
0950 IF (D1 < DJ) GOTO 750
0960 IF (H1 < HJ) GOTO 750
0970 IF (M2 < MJ) GOTO 750
0980 IF (S1 < SJ) GOTO 750
0990 REM
1000 REM  TRANSFER SENSOR'S DATA TO MEMORY AND PRINT
1010 REM  THE DATA IN SCREEN.
1020 REM
1030 VTAIL (10 + LL); HTAB (16)
1040 PRINT LL; " ";
1050 TPS = " "
1060 FOR X = 0 TO 5
1070 SE = PEEK (49856 + X)
1080 TPS = TPS + CHR$(SE)
1090 NEXT
1100 PRINT TPS
1110 TPS(1, LL, LD) = TPS
1120 LL = LL + 1
1130 REM
1140 REM  CHECK WHETHER ALL CHANNELS HAVE BEEN PROCESSED.
1150 REM  IF NOT, ADVANCE ONE CHANNEL TO CONVERT DATA AGAIN.
1160 REM  IF ALL CHANNELS ARE PROCESSED RESET THE SENSORS
1170 REM  BACK TO FIRST CHANNEL.
1180 REM
1190 IF (LL > NC) GOTO 1270
1200 POKE 49241, 1
1210 GOSUB 2050
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1220  POKE 49240.0
1230  FOR I = 1 TO 400
1240  CALL 49664
1250  NEXT
1260  GOTO 1030
1270  LL = 1
1280  POKE 49245,1
1290  GOSUB 2050
1300  POKE 49244.0
1310  LD = LD + 1
1320  REM
1330  REM CHECK WHETHER ALL THE MEMORY IS OCCUPIED. IF YES
1340  REM GOTO SUBPROGRAM STORAGE
1350  REM
1360  IF (LD > 39) THEN GOTO 1710
1370  TS = TS
1380  GOSUB 1510
1390  GOTO 750
1400  REM
1410  REM GET THE TIME FROM THE CLOCK AND CONVERT THE TIME INTO
1420  REM NUMERICAL VALUE AND CALCULATE THE NEXT READING TIME.
1430  REM
1440  PRINT D:="IN4"
1450  PRINT D:="PH4"
1460  INPUT "";TS
1470  PRINT D:="IN00"
1480  PRINT D:="PR00"
1490  TS$ = TS
1500  MT = VAL (MID$(TS$,1,2))
1510  D$ = VAL (MID$(TS$,4,2))
1520  H$ = VAL (MID$(TS$,1,1))
1530  M$ = VAL (MID$(TS$,3,1))
1540  S$ = VAL (MID$(TS$,5,1))
1550  M = M + SC
1560  S = S + 60
1570  H = H + INT (S / 60) * 60
1580  M = M - INT (H / 60) * 60
1590  D = D + INT (H / 24) * 24
1600  H = H - INT (H / 24) * 24
1610  MT = MT + INT (D / AD(MT))
1620  D = D - INT (D / AD(MT)) * AD(MT)
1630  IF (MT > 12) THEN MT = MT - 12
1640  RETURN
1650  REM
1660  REM SUBPROGRAM STORAGE
1670  REM THIS SUBPROGRAM STORE READINGS IN DISK E.
1680  REM
1690  REM
1700  REM POKE 911,ST
1710  FOR II = 1 TO 14
1720  TP = ASC (MID$(TS$,(II),1))
1730  POKE (24576 + II),TP
1740  NEXT
1750  FOR KK = 1 TO NC
1760  POKE 910,(KK - 1) * IN + TR
1770  FOR JJ = 0 TO 29
1780  FOR II = 1 TO 6
1790  TP = ASC (MID$(TT$(KK,JJ),(II),1))
1800  POKE (24591 + JJ * 6 + II),TP
1810  NEXT JI
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1830 NEXT JJ
1840 CALL 896
1850 NEXT KK
1860 REM GET THE TIME FROM CLOCK AND CHECK WHETHER THE DISK IS FULL. IF YES, THE PROGRAM IS COMPLETED.
1870 REM
1880 REM
1890 REM PRINT "IN#4"
1891 PRINT D$"PR#4"
1900 INPUT "T:116"
1910 PRINT D$"IN#0"
1920 PRINT D$"PR#0"
1930 TR  = TR + 1
1940 LD  = LD + 0
1950 ST  = ST + 1
1960 IF (ST > 16) GOTO 1030
1970 ST = 0
1980 TR = TR + 1
1990 IF (TR > = IN) END
2000 REM DELAY SUBROUTINE
2010 REM FOR I = 1 TO 300
2020 NEXT I
2030 RETURN
2040 REM READ IN CHANNEL TITLE, UNIT AND THE MULTIPLICATION FACTOR OF EACH CHANNEL. STORE THESE DATA IN THE LAST TRACK OF THE DISK.
2050 REM
2060 REM
2070 REM I = 1
2080 FOR II = 1 TO NC
2090 PRINT "INPUT TITLE OF CHANNEL ";II
2100 INPUT TP$
2110 FOR J = 1 TO 32
2120 IF (MID$ (TP$ , J , 1) = "") THEN TP = 0: GOTO 2200
2130 TP = ASC (MID$ (TP$ , J , 1))
2140 POKE (24591 + (I - 1) * 64 + J), TP
2150 NEXT J
2160 PRINT "INPUT THE UNIT OF THIS CHANNEL"
2170 INPUT TP$
2180 FOR J = 1 TO 16
2190 IF (MID$ (TP$ , J , 1) = "") THEN TP = 0: GOTO 2270
2200 TP = ASC (MID$ (TP$ , J , 1))
2210 POKE (24623 + (I - 1) * 64 + J), TP
2220 NEXT J
2230 PRINT "INPUT THE FACTOR OF THIS CHANNEL"
2240 INPUT FA
2250 TP = INT (FA / 100)
2260 FA = FA - TP * 100
2270 POKE (24639 + (I - 1) * 64 + 1), TP
2280 POKE (24639 + (I - 1) * 64 + 2), FA
2290 IF (II = NC) THEN GOTO 2370
2300 IF INT (II / 3) * 3 <> II THEN I = I + 1: GOTO 2430
2310 POKE 910, 34
2320 POKE 911, ST
2330 ST = ST + 1
2340 CALL 896
2350 POKE 911, ST
2360 I = 1
2370 NEXT
APPLeSofT BASIC

0010 REM * THIS PROGRAM IS FOR RETRIEVICNG DATA FROM DISK B,
0020 REM STORED BY DATA ACQUISITION PROGRAM.
0030 REM
0040 REM
0050 DIM B(10,40),E$(10),C(10),C$(10),AD(12),D(10)
0060 REM
0070 REM SYMBOLS
0080 REM B = DATA FROM MEMORY OF ONE TRACK
0090 REM E$ = TITLE NAME OF CHANNELS
0100 REM C$ = UNIT OF CHANNEL
0110 REM C = MULTIPLICATION FACTORS
0120 REM AD = NUMBER OF DAY OF EACH MONTH
0130 REM D = ARRAY TO STORE MONTH, DAY, HOUR, MINUTE AND SECOND
0140 REM ST = SECTOR NUMBER
0150 REM TR = TRACK NUMBER
0160 REM AL = NUMBER OF TRACK PER CHANNEL
0170 REM SC = TIME INTERVAL BETWEEN EACH READING IN second.
0180 REM
0190 FOR X = 896 TO 927
0200 READ P
0210 POKE X,P
0220 NEXT
0230 DATA 169,3,160,38,32,217,3,96,0,0,1,96,2,0,0,0,155,3,0,96,0,
0240 DATA 0,1,0,0,96,1,0,1,239,216,118
0250 REM INITIAL VARIABLE
0260 REM
0270 I = 910
0280 S = 811
0290 FOR I = 1 TO 12
0300 READ AD(I)
0310 NEXT
0320 DATA 31,28,31,30,31,30,31,31,30,31,30,31
0330 REM CALL SUBROUTINE TO CHECK NUMBER OF CHANNEL IN THE
0340 REM DISK AND CHECK WHETHER IT IS A DATA DISK.
0350 REM
0360 REM
0370 GOSUB 1320
0380 PRINT "PLEASE TURN THE PRINTER ON AND WAIT "
0390 IF ST = 34 THEN PRINT "AGAIN"
0400 ST = 0
0410 EN = IN * 16 - 1
0420 REM LOAD FORMAT ROUTINE IN MEMORY
0430 REM PRINT CHR$(4) "BRSY PRINTUSR,A$94A0"
0440 REM RETRIEVE ALL THE POSSIBLE DATA STORED IN THE DISK
0450 REM
0460 REM
0470 FOR II = 0 TO EN
0480 IF (ST = 16) THEN ST = 0:TR = TR + 1
0490 PRINT CHR$(4) "PR#1"
0500 FOR K = 1 TO HC
0510 POKE 7,TR + (K - 1) * IN
0520 POKE S,ST
0530 CALL 895
0540 REM READ THE TIME OF THE FIRST READING AND CONVERT THE
0550 REM TIME INTO NUMERICAL VALUE
0560 REM
0570 REM
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0610 IF (PEEK(24576) = 0 AND PEEK(24577) = 0) THEN END
0620 FOR I = 1 TO 14
0630 A$ = CHR$(PEEK(24575 + I))
0640 IF (I = 2 OR I = 12) THEN A$ = ""
0650 T2$ = T2$ + A$
0660 NEXT
0670 D(1) = VAL (LEFT$(T2$, 2))
0680 D(2) = VAL (MID$(T2$, 4, 2))
0690 D(3) = VAL (MID$(T2$, 7, 2))
0700 D(4) = VAL (MID$(T2$, 10, 2))
0710 D(5) = VAL (MID$(T2$, 13, 2))
0720 REM: READ IN ALL THE DATA IN THE TRACK
0730 REM: FOR I = 0 TO 35
0740 D(K,I) = 0
0750 TP = 0
0760 JJ = 10
0770 FOR J = 2 TO 6
0780 A = PEEK(24591 + I * 6 + J)
0790 IF (J = 3) THEN NEXT J
0800 JJ = JJ / 10
0810 B(K,I) = B(K,I) + A * JJ
0820 NEXT J
0830 B(K,I) = B(K,I) * C(K)
0840 NEXT I
0850 NEXT K
0860 REM: PRINT THE TITLE, THE TIME AND ALL THE DATA RECORDED
0870 REM: IN EACH CHANNEL.
0880 REM: PRINT 
0890 PRINT "FIRST READING'S TIME ": ;T2$
0900 PRINT TAB(3) "TIME BETWEEN EACH READING ": ;SC;" SEC."
0910 PRINT 
0920 PRINT "TITLE OF CHANNEL "; USR(K)'2,0';": 
0930 PRINT "B(K,I); ";USR(K)'C$(K)';"
0940 NEXT K
0950 PRINT "TIME ":
0960 PRINT "TIME ":
0970 PRINT TAB(4): PRINT USR(K)'4,0';
0980 NEXT K
0990 PRINT 
1000 FOR I = 0 TO 35
1010 PRINT USR(D(4))'2,0'; "; USR(D(4));
1020 FOR K = 1 TO NC
1030 PRINT USR(B(K,I))'7,1';
1040 NEXT K
1050 REM: DETERMINE THE NEXT READING TIME OF THE DATA.
1060 D(5) = L(5) + SC
1070 IF (L(5) + 60) THEN D(L) = D(4) + INT(D(5)/60):
1080 L(5) = D(5) - INT(L(5)/60) * 60
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1200 IF (D(4) >= 60) THEN D(3) = D(3) + INT (D(4) / 60):
1210 IF (D(3) >= 24) THEN D(2) = D(2) + INT (D(3) / 24):
1220 IF (D(2) >= 10) THEN D(2) = 1:
1230 IF (D(1) = 13) THEN D(1) = 1
1240 PRINT
1250 NEXT
1260 ST = ST + 1
1270 NEXT
1280 END

1290 REM: READ IN NUMBER OF CHANNEL AND CHECK WHETHER THE DISK
1300 REM: IS FOR DATA ACQUISITION STORAGE.
1310 I = 1
1320 ST = 0
1330 POKE I; 34
1340 POKE ST; ST
1350 CALL 896
1360 NC = PEEK (24576) * 10000 + PEEK (24585) * 100 + PEEK (24586)
1370 SC = 0
1380 IF (NC < 10 OR NC > 10) THEN PRINT "WRONG DISK"; END
1390 FOR II = 1 TO NC
1400 FOR J = 1 TO 32
1410 TPS = CHR$ (PEEK (24591 + (I - 1) * 64 + J))
1420 IF (TPS = \$) THEN GOTO 1480
1430 C$(II) = II$(II) + TPS
1440 NEXT
1450 NEXT
1460 FOR J = 1 TO 16
1470 FOR J = 1 TO 16
1480 C$(II) = PEEK (24639 + (I - 1) * 64 + J) * 100 + PEEK (24639 + (I - 1) * 64 + J)
1490 IF (INT (II / 3) * 3 < II) THEN I = I + 1: GOTO 1590
1500 ST = ST + 1
1510 POKE 911, ST
1520 CALL 096, ST
1530 PRINT "NUMBER OF CHANNEL "; NC
1540 RETURN
APPENDIX C
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APPLESOFT BASIC

0010 REM
0020 REM THIS PROGRAM PREDICT AMBIENT TEMPERATURE AND
0030 REM DETERMINE WHETHER NORMAL OR ABNORMAL WEATHER.
0040 REM
0050 DIM XG(12),YG(12),XB(12),YB(12),X(48),Y(48)
0060 REM
0070 REM SYMBOLS
0080 REM XG = TIME OF NORMAL WEATHER DATA.
0090 REM YB = AMBIENT TEMPERATURE OF NORMAL WEATHER DATA.
0100 REM XB = TIME OF WEATHER FRONT DATA.
0110 REM YB = AMBIENT TEMPERATURE OF WEATHER FRONT DATA.
0120 REM
0130 REM INITIAL VARIABLE
0140 REM
0150 REM OM = 0.26179392
0160 D$ = CHR$(4)
0170 REM
0180 REM DEFINE FUNCTION EA AND EB TO CALCULATE AMBIENT
0190 REM TEMPERATURE.
0200 REM
0210 DEF FN EA(W) = C1 + C2 * SIN (OM * W + 3 * TH) + C3 * SIN (2 *
0220 OM * W + TH)
0230 DEF FN EB(W) = C4 + C2 * SIN (OM * W + 3 * TH) + C3 * SIN (2 *
0240 OM * W + TH)
0250 REM
0260 REM READ NORMAL WEATHER DATA FROM FILE DATA2.
0270 PRINT D$;"OPEN DATA2"; PRINT D$;"READ DATA2"; INPUT BD;
0280 FOR I = 1 TO 11; INPUT XB(I),YB(I); NEXT;
0290 PRINT D$;"CLOSE DATA2"
0300 REM
0310 REM READ IN NEW WEATHER DATA FROM FILE DATA1.
0320 PRINT D$;"OPEN DATA1"; PRINT D$;"READ DATA1"; INPUT T$;
0330 PRINT D$;"CLOSE DATA1"
0340 REM
0350 REM WHICH MONTH THE NEW DATA IS NOW AND DETERMINE
0360 REM THE COEFFICIENT OF THE THEORETICAL CURVE.
0370 REM NN = VAL (LEFT$(T$,.2))
0380 RESTORE
0390 FOR I = 1 TO NN
0400 READ C1,C2,C3,TH
0410 NEXT
0420 REM
0430 REM ADJUST THE COEFFICIENT OF THE VARIABLE IF THE DATE
0440 REM IS AT THE FIRST AND LAST FEW DAYS OF THE MONTH.
0450 REM
0460 IF (VAL("MIDS$(T$;4,2)) < = 8) THEN NN = VAL (LEFT$(T$,.2))
0470 IF (-NN = 0) THEN NN = 12
0480 IF (VAL("MIDS$(T$;4,2)) > .25) THEN NN = VAL (LEFT$(T$,.2))
0490 RESTORE
0500 IF (NN < > VAL (LEFT$(T$,.2)) THEN FOR I = 1 TO NN;
0510 READ T1,T2,T3,T4; NEXT; C1 = (C1 + T1) / 2; C2 = (C2 + T2) / 2;
0520 C3 = (C3 + T3) / 2; TH = (TH + T4) / 2
0530 REM
0540 REM CALCULATE THE MEAN TEMPERATURE OF THE FIRST SET OF DATA.
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0510 REM
0520 SM = 0
0530 FOR I = 1 TO 6
0540 SM = SM + (YB(I) - "FN EA(XB(I))")
0550 NEXT
0560 C4 = C1 + SM / 6
0570 REM
0580 REM "DETERMINE THE STANDARD DEVIATION OF THE SECOND SET DATA"
0590 REM "WITH RESPECT TO THE FIRST SET DATA'S CURVE."
0600 REM
0610 SM = 0
0620 FOR I = 7 TO 12
0630 TP = (YB(I) - "FN EB(XB(I))")
0640 SM = SM + TP ^ 2
0650 NEXT
0660 TP = "SQR(SM / 5)
0670 REM
0680 REM "IF THE DEVIATION IS GREATER THAN 1.6 THEN ABNORMAL"
0690 REM "WEATHER, ENCOUNTER." 
0700 REM
0710 IF (TP > 1.6) THEN GOTO 940
0720 REM
0730 REM "NORMAL WEATHER"
0740 REM "DETERMINE THE MEAN TEMPERATURE OF ALL THE PAST DATA."
0750 REM "UPDATE THE DATA AND STORE BACK IN THE FILE."
0760 REM
0770 SM = 0
0780 FOR I = 1 TO 12
0790 SM = SM + (YB(I) - "FN EA(XB(I))")
0800 NEXT
0810 C4 = C1 + SM / 12
0820 IF ((YB(7) - "FN EB(XB(7))") < 1.5) THEN FOR I = 1 TO 6:
0830 XB(I) = XB(I + 1): YB(I) = YB(I + 1): NEXT
0840 FOR I = 7 TO 11
0850 YB(I) = YB(I + 1)
0860 NEXT: GOSUB 1250: PRINT TAB(15): PRINT "(NORMAL WEATHER)"
0870 PRINT D$: "OPEN DAT2": PRINT D$: "DELETE DAT2",
0880 PRINT D$: "OPEN DAT2": PRINT D$: "WRITE DAT2": PRINT BD:
FOR I = 1 TO 11: PRINT XB(I)="YB(I)"
0890 PRINT D$: "CLOSE DAT2"
0900 PRINT D$: "RUN INCREASE": END
0910 REM
0920 REM "ABNORMAL WEATHER"
0930 REM "STORE THE ABNORMAL DATA IN FILE DATAB AND CHECK"
0940 REM "WHETHER THE WEATHER RETURN TO NORMAL WEATHER."
0950 REM
0960 IF (BD < 0) THEN PRINT D$: "OPEN DATB": PRINT D$: "READ DATB"
FOR I = 1 TO BD: INPUT XB(I), YB(I): NEXT: PRINT D$: "CLOSE DATB"
0970 TE = C1
0980 IF (BD < 12 AND BD < 0) THEN SM = 0: FOR I = 1 TO BD:
SM = SM + (YB(I) - "FN EA(XB(I))") : NEXT: C4 = C1 + SM / BD
0990 IF (BD = 0) THEN FOR I = 7 TO 11: XB(I) = XB(I - 6) = XG(I)
1000 YB(I - 6) = YB(I): NEXT: BD = 6
1010 IF (BD = 12) THEN SM = 0: FOR I = 1 TO 12:
SM = SM + (YB(I) - "FN EA(XB(I))") : NEXT: C4 = C1 + SM / BD
SM = 0: FOR I = 1 TO 12: TP = YB(I) - "FN EB(XB(I))"
SM = SM + TP ^ 2: NEXT: TP = "SQR(SM / 12"
1020 IF (BD = 12 AND TP < 0.16) THEN FOR I = 1 TO 6: XB(I) = XB(I)
YB(I) = YB(I): NEXT: GOTO 460
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1000 IF (BD = 12 AND TP > 0.16) THEN FOR I = 1 TO 11;
   XB(I) = XB(I + 1); YB(I) = YB(I + 1); NEXT; BD = 11
1100 XD = TD
1200 BD = BD + 1; XB(BD) = XB(12); YB(BD) = YG(12); GOSUB 1250;
   PRINT TAB(15); PRINT "\(\text{WEATHER FRONT}\)"; PRINT \(\text{PRINT} \text{PRINT} \)
1300 REM UPDATE THE ABNORMAL WEATHER DATA AND NORMAL WEATHER
1400 REM DATA IN FILES.
1500 REM
1600 REM PRINT DS="\"OPEN DATAB\"1; PRINT DS="\"DELETE DATAB\"1;
1700 PRINT DS="\"OPEN DATAB\"2; PRINT DS="\"DELETE DATAB\"2;
1800 PRINT DS="\"OPEN DATAB\"3; PRINT DS="\"WRITE DATAB\"3; FOR I = 1 TO BD;
   PRINT XB(I);"; YB(I); NEXT; PRINT DS="\"CLOSE DATAB\"3"
1900 FOR I = 7 TO 11
2000 XG(I) = XG(I + 1)
2100 YG(I) = YG(I + 1)
2200 NEXT
2300 PRINT DS="\"OPEN DATAB\"2; PRINT DS="\"DELETE DATAB\"2;
2400 PRINT DS="\"OPEN DATAB\"2; PRINT DS="\"WRITE DATAB\"2; PRINT BD;
   FOR I = 1 TO 11; PRINT XG(I);"; YG(I); NEXT;
2500 PRINT DS="\"CLOSE DATAB\"2"
2600 PRINT DS="\"RUN INCREASE\"1; END"
2700 PRINT DS="\"PREDICTION COEFFICIENT OF EACH MONTH."
2800 PRINT DS="\"TIME SERIES DATA\""
2900 DATA 3.3752.79650.84673.119634.39583.97761.00811.19104.96254.46169.91241.2429
3000 DATA 6.58335.92011.67013.12640.63333.74836.55940.126887.93757.11475.68291.2951
3100 DATA 7.72927.22857.07491.37988.14589.62781.05801.30858.642
3200 DATA 9.657381.15541.2958
3300 DATA 5.58335.25271.46421.29752.99172.90898.96491.22801.222
3400 DATA 1671.97951.718581.2422
3500 PRINT "\(\text{DISPLAY THE PREDICTION CURVE AS WELL AS} \)
3600 PRINT "\(\text{THE ACTUAL DATA ON THE SCREEN.} \)
3700 PRINT DS="\"VTAB (7)\"; PRINT "\"20\"; VTAB (13); PRINT "\"10\"; VTAB (19); PRINT "\"0\"
3800 PRINT DS="\"VTAB (21); HTAB (4); FOR I = 1 TO 48 STEP 6;
3900 IF (X(I) < 10) THEN PRINT \"0\";
4000 PRINT DS="\"X(I); X(I); NEXT; I IF (X(I) < 10) THEN PRINT \"0\";
4100 PRINT DS="\"VTAB (23); HTAB (5); PRINT \"TEMPERATURE PREDICTION AT \" X(I); \"12; \" TOP\"
4200 FOR I = 10 TO 140 STEP 10; HPLLOT 27; I TO 33; I NEXT
4300 FOR I = X(I) TO X(I) + 48; STEP 1111 = 30 + (I - X(I)) * 4.5;
4400 II = INT (1111); J = FN EB(I); J = 150 - J - 5
4500 IF (1 = X(I)) THEN HPLLOT 11; JG
4600 IF (I < X(I)) THEN HPLLOT TO 11; JJ
4700 NEXT
4800 FOR I = 1 TO 12; TX = 30 + (X(I) - X(I)) * 4.5; TX = INT (TX);
4900 IF TX < 30 THEN TX = TX + 24 + 4.5
5000 FOR I = 13 TO 24; TX = 30 + (X(I) - X(I)) * 4.5; TX = INT (TX);
5100 IF TX < 30 THEN TX = TX + 24 + 4.5
5200 FOR I = 25 TO 48; TX = 30 + (X(I) - X(I)) * 4.5; TX = INT (TX);
5300 IF TX < 30 THEN TX = TX + 24 + 4.5
5400 FOR I = 51 TO 143; TX = 30 + (X(I) - X(I)) * 4.5; TX = INT (TX);
5500 IF TX < 30 THEN TX = TX + 24 + 4.5
1410 PRINT DS: "PRIS"; PRINT CHR$(17); RETURN
1420 HPLOT TX, TY; FOR II = -1 TO 1; FOR JJ = -1 TO 1;
  HPLOT TO TX - II, TY - JJ; NEXT J; NEXT II; RETURN
1430 HPLOT TX - 1, TY TO TX + 1, TY; HPLOT TX, TY - 1 TO TX, TY + 1
1440 RETURN
Mode 1 (SW1, SW2 closed)

Between sunrise and sunset time \( t_{sr} < t < t_{ss} \)

\[
I_1 = S_1 \sin[w_1(t-t_{sr})]
\]  
\( \text{(D.1)} \)

\[
I_3 - I_2 = IG
\]  
\( \text{(D.2)} \)

where \( IG = \) Hourly recalculated internal gain and assume to be constant within that hour.

Consider loop ABDE \( E_V = 0 \)

\[
1 = \int (I_2 - I_1)dt + R_C(I_2 - I_1) + R_{LS}I_2 + C
\]  
\( R_{AL}I_3 + TA(t) = 0 \) 
\( \text{(D.3)} \)

From eq. D.2 \( I_3 = IG + I_2 \)  
\( \text{(D.4)} \)

Substitute eq. D.1 & eq. D.4 into eq. D.3

\[
1 = \int \{I_2 - S_1\sin[w_1(t-t_{sr})]\}dt + R_C\{I_2 - C \}
\]
\[
S_1\sin[w_1(t-t_{sr})]\} + R_{LS}I_2 +
\]  
\( R_{AL}I_3 + TA(t) = 0 \)  
\( \text{(D.5)} \)
Differential w.r.t. time for eq. D.5

\[
\frac{dI_2}{dt} - \frac{1}{C} \left[ I_2 - Sl \cdot \text{SIN}[wl \cdot (t-tsr)] \right] + R_C \frac{dI_2}{dt} - R_L \frac{dI_2}{dt} + R_{AL} \frac{dI_2}{dt} + \frac{dTA(t)}{dt} = 0
\]

\[
\frac{dI_2}{dt} = \frac{1}{C} \left[ \text{SIN}[wl \cdot (t-tsr)] + \frac{R_C \cdot Sl \cdot \text{COS}[wl \cdot (t-tsr)] - \frac{dTA(t)}{dt}}{C} \right]
\]

\[
\frac{dI_2}{dt} + \frac{1}{C \cdot (R_L + R_{AL} + R_C)} \left[ I_2 = \frac{1}{C \cdot (R_L + R_{AL} + R_C)} \left[ \text{SIN}[wl \cdot (t-tsr)] + \frac{R_C \cdot C \cdot Sl \cdot \text{COS}[wl \cdot (t-tsr)] - \frac{dTA(t)}{dt}}{C} \right] \right]
\]
Let \( a = \frac{1}{C \cdot (R_C + R_{LS} + R_{AL})} \)

\[
\frac{dI_2}{dt} + a \cdot I_2 = a \cdot \{ S_1 \cdot B \cdot \sin(w_1 \cdot (t - tsr) + \phi_1) \} - C \cdot \frac{dT_A(t)}{dt}
\]

(D.7)

Where:

\[
B = \frac{1}{\sqrt{(R_C \cdot C \cdot w_1)^2 + 1}}
\]

\[
\phi_1 = \tan^{-1}(R_C \cdot C \cdot w_1)
\]

The complementary solution of eq. D.7

\[
I_{2C} = A \cdot e^{-\alpha t}
\]

Where:

\[
\alpha = \frac{1}{(R) \cdot C} = \text{1/time constant}
\]

To find particular solution

First find

\[
\frac{dT_A(t)}{dt}
\]

Given from chapter 2

\[
T_A(t) = C(1) + C(2) \cdot \sin(w \cdot t + 3 \cdot \theta) + C(3) \cdot \sin(2 \cdot w \cdot t + \theta)
\]
\[
\frac{dIA(t)}{dt} = C(2) \cdot w \cdot \cos(w \cdot t + 3 \cdot \theta) + 2 \cdot w \cdot C(3) \cdot \cos(2 \cdot w \cdot t + \theta)
\]

Therefore eq. D.7 becomes

\[
\frac{dI2}{dt} + a \cdot I2 = a \cdot \left[ S1 \cdot B \cdot \sin(w \cdot (t - tsr) + \phi_1) \right] - C \cdot w \left[ C(2) \cdot \cos(w \cdot t + 3 \cdot \theta) + 2 \cdot C(3) \cdot \cos(w \cdot t + \theta) \right]
\]

From mathematics table [2], the particular solution

\[
I2_p = a \cdot S1 \cdot B \left\{ \frac{\sin(w \cdot (t - tsr) + \phi_1) - \cos(w \cdot (t - tsr) + \phi_1)}{(a^2 + w^2)} \right\} - a \cdot C \left\{ \frac{\cos(w \cdot t + 3 \cdot \theta) + \sin(w \cdot t + 3 \cdot \theta)}{(a^2 + w^2)} \right\} + C(3) \left\{ \frac{\cos(2 \cdot w \cdot t + \theta) + 2 \cdot w \cdot \sin(2 \cdot w \cdot t + \theta)}{(a^2 + (2w)^2)} \right\}
\]

\[
I2_p = a \cdot S1 \cdot B \left\{ \frac{\sin[w \cdot (t - tsr) + \phi_1 - \phi_2]}{(a^2 + w^2)} \right\} - a \cdot C \left\{ \frac{C(2) \cdot \sin[w \cdot t + 3 \cdot \theta + \phi_2]}{(a^2 + w^2)} \right\} + 2 \cdot C(3) \cdot \sin[2 \cdot w \cdot t + \theta + \phi_3] \left\{ \frac{\sin[w \cdot t + 3 \cdot \theta]}{(a^2 + (2w)^2)} \right\}
\]
The general solution

\[ I_2 = I_{2c} + I_{2p} \]

\[ I_2 = A e^{-t} + a S1 \cdot B \left( \frac{\sin(wl*(t+tsr)+\phi_1 - \phi_2)}{\sqrt{a^2 + wl^2}} \right) - \]

\[ w^2 \cdot a \cdot C \left\{ \frac{C(2) \cdot \sin(w^2 t + 3 \theta + \phi_3)}{\sqrt{a^2 + w^2}} + \right. \]

\[ \left. \frac{2 \cdot C(3) \cdot \sin(2 \cdot w^2 t + \theta + \phi_4)}{\sqrt{a^2 + (2 \cdot w)^2}} \right\} \quad (D.8) \]

Where:

- \( A \) is obtained essentially as a boundary condition, by substituting eq. D.8 in D.2, and eliminating \( I_2, I_3 \) and \( S1 \) with the current measurements for \( TR, TA \) and \( S1 \), as shown below.

\[ a = \frac{1}{(IR) \cdot C} = \frac{1}{\text{Time constant}} \]

\[ B = \sqrt{(RC \cdot C \cdot wl)^2 + 1} \]

- \( C(2), C(3), \theta \) = Curvefitted coefficient from past weather data

\[ \phi_1 = \tan^{-1}(RC \cdot C \cdot wl) \]
\[ \phi_2 = \tan^{-1}\left[ \frac{w_1}{a} \right] \]

\[ \phi_3 = \tan^{-1}\left[ \frac{a}{w} \right] \]

\[ \phi_4 = \tan^{-1}\left[ \frac{a}{2 \cdot w} \right] \]

\[ w_1 = \pi/(tsr - tss) \]

\[ w = 2 \cdot \pi / 24 \]

**IG** = Heat gains or losses from other sources

**I2** = Heat flow through the room.

A is obtained by substituting equation D.8 in D.2 and I3 can be expressed as:

\[
I_3 = IG + A e^{-at} + a^*S1*B \left[ \frac{\sin(w_1(t-tsr)+\phi_1 - \phi_2)}{\sqrt{a^2 + w_1^2}} \right] - \\
\left[ C(2) * \frac{\sin(w*t+3*e + \phi_3)}{\sqrt{a^2 + w^2}} \right] + \\
\left[ 2*C(3) * \frac{\sin(2*w*t + \theta + \phi_4)}{\sqrt{a^2 + (2*w)^2}} \right] 
\]

From figure 3.3

\[
I_3 = \frac{TR - TA}{RAL} 
\]
Then

$$A e^{-bt} = \frac{TR - TA}{R_{AL}} - IG - \alpha S_1 B \left[ \frac{\text{SIN}[wl*(t-tsr)+\phi_1 - \phi_2]}{\sqrt{\alpha^2 + w^2}} \right] + w \alpha C \left\{ \frac{C(2)*\text{SIN}[w*t+3*\theta + \phi_3]}{\left[\alpha^2 + w^2\right]} \right\} + \frac{2*C(3)*\text{SIN}[2*w*t+\theta + \phi_4]}{\left[\alpha^2 + (2*w)^2\right]}$$  \hspace{1cm} (D.9)

With the current measurements for TR, TA and S1 (S1 = 0 for no solar input)\(^1\) then A can be calculated.
Mode 2 (SW1 opened & SW2 closed)

A similar solution, as shown below, is obtained either performing the above calculation for mode 1 or substituting $S_1 = 0$.

$$ I_2 = A e^{-at} \left\{ \frac{C(2) \sin[w*t+3*\theta + \phi_3]}{\sqrt{\alpha^2 + w^2}} + \frac{2C(3) \sin[2w*t + \phi_4]}{\sqrt{\alpha^2 + (2w)^2}} \right\} $$

(D.10)

and $I_3 = I_2 + I_G$
Mode 3 (SW1, SW2 opened)

A similar solution, as shown below, is obtained either performing the above calculation for mode 1 or substituting \( S1 = 0 \) and \( IG = 0 \).

\[
I2 = A e^{-at} - \frac{w \cdot c \cdot C}{(\alpha^2 + w^2)} \frac{C(2) \cdot \sin[w \cdot t + 3 \cdot \theta + \phi_3]}{\sqrt{\alpha^2 + w^2}} + \frac{2 \cdot c \cdot C(3) \cdot \sin[2 \cdot w \cdot t + \theta + \phi_4]}{\sqrt{\alpha^2 + (2w)^2}} \]

(D.11)

and \( I3 = I2 \)
On Line Predictive Control program flowchart
START

Initialize 14 data file

Read TA

Store TA and time in DATA1 & DATA2

NO

IS DATA2 full?

YES

Read ambient temperature

Run Prediction

Initialization program
1. Input past ambient temperatures TA(12)

2. Calculate the average temperature for the past 24 hours

3. Do the last six ambient temperatures fit the historical curve?

   NO: Store C(1) in VARB

   YES: Normal weather. Update C(1) in the common data file

4. Run Normal Control

5. Run Abnormal Control

.Prediction program
Predict next 24 hour amb. temperature & calculate next 24 hour room temperature

Is ambient temperature between the heating & cooling balance points all day tomorrow?

Will ambient temp. exceed the cooling balance temperature?

Calculate extra heat gain to be offset by pre-cool

Calculate the time required for pre-cooling

Is pre-cooling creates a demand for heating at night decrease the amount of pre-cooling

Store operation code and length of operation in OPER file
0 all off
1 pre-cool
4 move to centre of comfort zone
Run Time Control

Normal Control program (1/3)
Normal Control program (8/3)
4

Calculate $E(T_R - T_M)$

Decrease room temperature with fan cooling

YES

Will $E(T_R - T_M)$ decrease?

NO

Decrease fan cooling time

5

Calculate the sum of the temperature excursions away from the middle of comfort zone

Calculate the decrease in room temperature for adding 5 minutes of fan cooling

Will the average room temperature be closer to the middle of the comfort zone?

Remove the last 5 minutes of fan cooling

Normal Control program (3/3)
Store Code 4 in OPER

- Store mode code in OPER file
- 0 all system off
- 1 pre-cooling
- 4 abnormal weather

Run Time Control

Abnormal Control program
Read the chosen operation code & time period from OPER (0, 1 or 4)

Read time from the clock & 9 temperatures from data acquisition

File average temperatures every 15 mins

Branch to Prediction every hour

Normal thermostat action: If room temperature is outside the comfort zone, turn on heater or air-conditioner for 5 mins.

For Code 0, heat with internal gains for 5 minutes

For Code 1, cool with fan, if possible for 5 minutes

Time Control program (1/5)
For Code 1, turn on fan for 5 minutes unless ambient temperature is too high.

File fan operation Code on disk 2 & reduce duration in OPER and RAM.

Time Control program (2/5)
Is room temperature below the comfort zone?

Turn air-conditioner on for 5 minutes

File Code 3 on disk 2

Turn heater on for 5 minutes

File Code 2 on disk 2

Time Control program (3/5)
File 0 operation code on disk 2 & turn all systems off

File Code 0 & turn all systems off

Wait for 5 minutes

Time Control program (4/5)
Is room temperature higher than the middle of comfort zone?

Turn fan off

Wait for 5 minutes

Time Control program (5/5)
BASIC
APPLESOFT BASIC

0010 REM
0020 REM   :INITIALIZATION PROGRAM
0030 REM
0040 REM THIS PROGRAM CREATES COMMON DATA FILE BEFORE RETRIEVING
0050 REM 12 HOURS' WEATHER DATA
0060 REM
0070 DS = CHR$(4); DIM TP(15), AD(12), A(12), T(15), SU(15)
0080 PRINT D$:"BRUN AA/DD.D1"
0090 Z = 1
0100 REM
0110 REM   GET TIME FROM INTERNAL CLOCK
0120 REM   CALL SUBROUTINE TO READ TIME DATA
0130 REM   TIME DATA IS IN 12 HOUR FORMAT AND CHARACTER FORM
0140 REM
0150 PRINT D$:"IN4"; PRINT D$:"PR4"; INPUT ""; T$; PRINT D$:"IN20";
0160 PRINT D$:"PR0"
0170 NC = 9
0180 FOR I = 0 TO NC - 1: PRINT D$:"OPEN CHAO": I1
0190 PRINT D$:"DELETE CHAO": II: PRINT D$:"WRITE CHAO": III: PRINT D$:"CLOSE CHAO": I1: NEXT I
0200 BDSUB 410
0210 NS = I$C = 300
0220 T(N3) = VAL ( MIDS ( T$,7,2) ) + A(N3) = TP(0)
0230 N3 = N3 + 1
0240 REM
0250 REM   CHECK FOR END OF DATA
0260 REM   IF END OF DATA THEN:
0270 REM ELSE:
0280 REM   CALL SUBROUTINE TO STORE TIME AND WEATHER
0290 REM WHEN CONVERSION COMPLETE CHECK FOR VALID TIME
0300 REM
0310 IF (N3) = 13 THEN GOTO 350
0320 PRINT D$:"IN4"; PRINT D$:"PR4"; INPUT ""; T$; PRINT D$:"IN20";
0330 PRINT D$:"PR0"; VTAB (S) HTAB (17) PRINT LEFT$ (T$,14)
0340 M1 = VAL ( MIDS ( T$,1,2) )
0350 D1 = VAL ( MIDS ( T$,4,2) )
0360 H1 = VAL ( MIDS ( T$,7,2) )
0370 M2 = VAL ( MIDS ( T$,10,2) )
0380 S1 = VAL ( MIDS ( T$,13,2) )
0390 IF (M > N1) THEN IF (D > D1) THEN IF (H > H1) THEN I1
0400 IF (M = N1) THEN IF (D = D1) THEN IF (S = S1) THEN I1
0410 BMOSUB 620: GOTO 320
0420 REM
0430 REM   READ IN DATA FROM DATA ACQUISITION
0440 REM
0450 POKE 49245,0: FOR K = 1 TO 800: NEXT K: POKE 49244,0:
0460 FOR K = 1 TO 500: NEXT K: FOR I = 0 TO NC - 1:
0470 FOR I = 1 TO 300: CALL 49684: NEXT II: PRINT I
0480 TP(I) = 0: FOR II = 3 TO 5:
0490 IF (PEEK (49856) + II) - 176) / 10 ^ (II - 2) + TP(I):
0500 NEXT II: TP(I) = TP(I) + (PEEK (49857) - 176)
0510 IF (PEEK 49856) = 173 THEN TP(I) = TP(I) + 1.
0520 TP(I) = (TP(I) - 1.8) * 1.8: POKE 49241,0: FOR K = 1 TO 700:
0530 NEXT K: POKE 49240,0: FOR K = 1 TO 300: NEXT K: NEXT II: RETURN
0540 IF I < Z THEN FOR I = 0 TO NC - 1: SU(I) = SU(I) + TP(I):
0550 NEXT ZZ = Z + 1: GOTO 190
0560 FOR I = 1 TO NC - 1: TP(I) = SU(I) / 4: NEXT I
0570 FOR I = 0 TO NC - 11: PRINT D$:"APPEND CHAO": I1:", D2";
0580 PRINT D$:"WRITE CHAO"; I1
CHANGE THE CLOCK TIME FROM CHARACTERS TO NUMBERS.

MT = VAL (MID$ (TS, 1, 2))
D = VAL (MID$ (TS, 4, 2))
H = VAL (MID$ (TS, 7, 2))
S = VAL (MID$ (TS, 13, 2))

S = S - INT (S / 60) * 60
H = H + INT (M / 60) - 12
D = D + INT (H / 24) * 24
MT = IF (MT > 12) THEN MT = MT - 12

CREATE COMMON DATA FILES
STORE PAST 12 HOUR WEATHER INTO THE DATA FILES

PRINT D$: "CLOSE DATA"
BASIC
APPLESOFT BASIC

0010 REM  PREDICTION PROGRAM
0020 REM
0030 REM THIS PROGRAM DETERMINES WHETHER NORMAL OR ABNORMAL WEATHER WILL OCCUR FOR THE NEXT 24 HOURS
0040 REM FOR NORMAL WEATHER, CALCULATE THE AVERAGE TEMPERATURE AND THE COEFFICIENT OF THE HISTORIC CURVE
0050 REM FOR ABNORMAL WEATHER, TEMPERATURE WILL BE CHECKED TO DETERMINE WHETHER THE WEATHER HAS RETURNED TO NORMAL OR IT REMAINS A WEATHER FRONT

0140 REM
0150 DIM X(12), Y(12), XBAR, YBAR, XBAR, YBAR
0160 OM = 0.261799392
0170 DEF FN EA(N) = C1 + C2 * SIN (OM * N + 3 * TH) + C3 * SIN (2 * OM * N + TH)
0180 DEF FN EB(N) = C4 + C2 * SIN (OM * N + 3 * TH) + C3 * SIN (2 * OM * N + TH)

0230 PRINT D$ "READ IN WEATHER DATA AND STORE THEM IN DATA FILES"
0240 PRINT D$ "OPEN VARA,D1$"; PRINT D$ "CLOSE VARA"
0250 PRINT D$ "OPEN DATA2"; PRINT D$ "READ DATA2"; FOR I = 1 TO 12; INPUT XBAR, YBAR; NEXT; PRINT D$ "CLOSE DATA2"
0260 PRINT D$ "OPEN DATA1"; PRINT D$ "READ DATA1"; INPUT T$: INPUT XBAR, YBAR; PRINT D$ "CLOSE DATA1"
0270 NN = VAL (LEFT$ (T$, 2)); RESTORE I = 1 TO NN; READ C1, C2, C3, TH; NEXT

0280 REM CHECK WHETHER THE PAST 12 HOUR WEATHERS HAVE FOLLOWED HISTORIC TREND
0290 REM
0300 IF (VAL (LEFT$ (T$, 4, 2)) < = 7) THEN NN = VAL (LEFT$ (T$, 2))
0310 IF (VAL (LEFT$ (T$, 4, 2)) > = 23) THEN NN = VAL (LEFT$ (T$, 2))

0320 RESTORE IF (NN (LEFT$ (T$, 2))) THEN FOR I = 1 TO NN;
0330 NEXT C1 = (C1 + T) / 2; C2 = (C2 + T) / 2; C3 = (C3 + T) / 2; TH = (TH + T) / 2

0340 SM = 0; FOR I = 1 TO 12; TP = (YBAR - FN EA(XBAR)); SM = SM + TP^2; NEXT; TP = SQRT(SM / 5)

0350 IF (TP > 1.6) THEN Goto 360

0360 REM NORMAL WEATHER ROUTINE
0370 REM
0380 REM CALCULATE THE AVERAGE TEMPERATURE FOR THE PAST 12 HOUR A
0390 REM THE HISTORIC COEFFICIENT
0400 REM
0410 REM
0420 SM = 0; FOR I = 1 TO 12; SM = SM + (YBAR - FN EA(XBAR)); NEXT C4 = C1 + SM / 12
0430 IF (Y7 - FN EB(X7)) < 1.5) THEN FOR I = 1 TO 6;
APPLESOFT BASIC

0440 FOR I = 7 TO 11: XG(I) = XG(I-1) + 1: YG(I) = YG(I-1) + 1: NEXT I
0450 PRINT D$:"OPEN DATA2": PRINT D$:"DELETE DATA2": PRINT D$:"WRITE DATA2": FOR I = 1 TO 11: PRINT IG(I): 1: YB(I): NEXT I: PRINT D$:"CLOSE DATA2":

0470 REM RUN NORMAL CONTROL PROGRAM
0480 REM
0500 PRINT D$:"RUN NORMCONTROL.D1": REM NORMAL DAY OPERATION
0510 REM
0520 REM ABNORMAL WEATHER
0530 REM CHECK IF THE WEATHER HAS RETURNED TO NORMAL
0540 REM
0550 REM
0560 IF (BD < 0) THEN PRINT D$: "OPEN DATAB": PRINT D$: "READ DATAB": FOR I = 1 TO BD: INPUT XB(I), YB(I): NEXT I: PRINT D$: "CLOSE DATAB"
0570 IF (BD = 0) THEN FOR I = 7 TO 11: XB(I-6) = XB(I): YB(I-6) = YB(I): NEXT I: BD = 5
0580 IF (BD < 12) THEN SM = 1: FOR I = 1 TO BD: SM = SM + (YB(I) - FN EA(XB(I))): NEXT I: C4 = SM + BD
0590 IF (BD = 12) THEN SM = 1: FOR I = 1 TO 12: SM = SM + (YB(I) - FN EA(XB(I))): NEXT I: C4 = SM + BD
0600 IF (BD = 12 AND TP < 0.16) THEN FOR I = 1 TO 6: XB(I) = XB(I): YB(I) = YB(I): NEXT I: BD = 12
0610 IF (BD = 12 AND TP > 0.16) THEN FOR I = 1 TO 11: XB(I) = XB(I-1): YB(I) = YB(I-1): NEXT I: BD = 11
0620 BD = BD + 1: XB(BD) = XB(12): YB(BD) = YB(12)
0630 REM STORE ALL THE COEFFICIENTS IN DATA FILES
0640 REM
0680 T1 = 0: T1 = 0
0690 PRINT D$:"OPEN CONTROL.D1": PRINT D$: "DELETE CONTROL": PRINT D$: "OPEN CONTROL": PRINT D$: "WRITE CONTROL": PRINT T1: 1: T1: PRINT D$: "CLOSE CONTROL"
0700 REM RUN ABNORMAL CONTROL PROGRAM
0710 REM
0730 PRINT D$: "RUN ABCONTROL.D1"
0740 REM
0750 REM ******** DATA BLOCK ********
0770 DATA 3.375, 2.7965, 0.84673, 1.1963, 4.3958, 3.9776, 1.0081, 1.1910, 4.9625, 4.416, 90124, 1.2429
0780 DATA 8.5833, 5.9201, 67012, 1.2640, 8.3333, 7.4836, 35840, 1.2668, 7.9
0790 DATA 379, 1.147, 38829, 1.2951
0800 DATA 7.7292, 7.2251, 70749, 1.2798, 8.1548, 7.6278, 1.0580, 1.3085, 6.42
0810 DATA 92.6, 3738, 1.1584, 1.2959
0820 DATA 5.3833, 5.2327, 1.4642, 1.2975, 2.9917, 2.9089, 94649, 1.2820, 2.2
0010 REM BASIC
0020 REM --- NORMAL CONTROL PROGRAM
0030 REM THIS PROGRAM PERFORMS THE OPERATIONS FOR A NORMAL DAY
0040 REM IT DETERMINES WHETHER ADVANCE HEATING OR ADVANCE COOLING IS REQUIRED
0050 REM IT DETERMINES WHETHER SUCH OPERATIONS IS POSSIBLE
0060 REM
0080 DEF FN ASI(W) = ATN (W / SQRT (1 - W * W))
0090 DEF FN ACD(W) = ATN (W / SQRT (1 - W * W)) + 1.5708
DEF FN EGT(W) = 0.1256 * SIN (W) - 0.0043 * COS (W) + 0.1538
+ SIN (2 * W) + 0.0698 * COS (2 * W)
0100 DIM A(20),DM(2),SM(2),SD(24),SQ(24),TA(24),TP(24),TR(24),TT(24),TM(24)
0110 PRINT D1:"OPEN VARB.D1: PRINT D1:"READ VARB:"
0120 PRINT D1:"INPUT BD,A(2),A(3),A(4),A(5),TT(0),TA(0),TR(0):"
PRINT D1:"CLOSE VARB:"
0130 BU = - 3: BL = - 10: CU = 24: CL = 18: CH = 21: CC = 0,055: R1 = 15
R2 = 210: RC = 13: OM(1) = 0,261793972;OM(2) = 1: B1 = 0
0140 FOR I = 1 TO 24: TT(I) = TT(0) + I: SQ(I) = 0,15
IF (TT(I) > 23) THEN TT(I) = TT(I) - 24
0150 IF (TT(I) > 6 OR TT(I) < 18) THEN SQ(I) = 0,15
0160 NEXT I
0170 IF I = 0 OR I = 24: SQ(I) = SQ(I)
0180 NEXT I
0190 PRINT D1:"BODR 800"
0200 PRINT D1:"PRB:"
0210 FOR I = 1 TO 24: PRINT TT(I),TR(I),TA(I): NEXT I
0230 NEXT I
0240 BOD0 700
0250 FOR JJ = 1 TO 24
0260 IF (TR(JJ) < CU) THEN BOD0 440
0270 NEXT JJ
0280 FOR JJ = 1 TO 24: BOD0 590
0300 NEXT JJ
0310 REM SUBROUTINE:
0320 REM
0330 REM THIS SUBROUTINE DETERMINES THE FOLLOWINGS:
0340 REM SUNRISE AND SUNSET TIME
0350 REM SOLAR TIME TO LOCAL TIME
0360 REM INCIDENT ANGLE
0370 REM
0380 DIM AD(12): FOR I = 1 TO 12: READ AD(I): NEXT I
0390 DATA 31, 28, 31, 30, 31, 30, 31, 30, 31, 30, 31, 30
0400 N = 0: J = VAL (LEFTS (TS, 2)) - 1
IF (J < 0) THEN FOR I = 1 TO J: N = N + AD(I): NEXT I
0410 DE = 0,99795 * COS (0,0172028 * (N - 173)) * DE = FN ABD(DE)
0420 BR = FN ACD( TAN LA) + TAN (DE)) * BS = 12 + BR / PI
0430 IF IC = FN ACI( - SIN (DE) + COS (LA)) THEN RETURN
0440 REM THIS ROUTINE CALCULATES THE AMOUNT OF ADVANCE COOLING NEE
0430 REM IT DETERMINES THE POSSIBILITY FOR ADVANCE COOLING AND THE
0440 REM TIME IT WILL BE REQUIRED
0450 REM
0460 REM SM(I) = 0: FOR I = II TO JJ:
0470 NEXT
0480 IF (TR(I) > CU) THEN SM(I) = SM(I) + (TR(I) - CU) / R2
0490 REM
0500 VD = 0.02 * SM(2) = 0: FOR TI = 1 TO II STEP 0.5: I = INT (TI):
0510 TP(I) = FN EA(TI + TI(0) * I)
0520 IF (TP(I) < TR(I)) THEN SM(2) = SM(2) + 0.5 * 1.2 * VD * (TR(I) - TP(I))
0530 IF (SM(2) > SM(I)) GOTO 530
0540 REM
0550 NEXT TI: TI = 1: TI = 60: GOTO 1290
0560 FOR I = 1 TO 24: BD(I) = SQ(I): NEXT: FOR I = 1 TO TI Step 0.5:
0570 J = INT (I): TP(I) = FN EA(I)
0580 IF (TP(I) < TR(J)) THEN SQ(J) = SQ(J) - 0.5 * 1.20 * VD * (TR(I) - TP(I)): NEXT
0590 BDUB 840
0600 FOR I = 1 TO JJ: IF (TR(I) < CL) THEN TI = TI - 0.5: GOTO 530
0610 REM
0620 IF (TI < 1) THEN TI = TI + 60
0630 IF (TI > 1) THEN TI = 1: GOTO 1230
0640 REM
0650 REM THIS ROUTINE CALCULATES THE AMOUNT OF ADVANCE HEATING NEEDED
0660 REM IT DETERMINES THE POSSIBILITY OF HAVING ADVANCE HEATING
0670 REM IT DETERMINES THE TIME FOR ADVANCE HEATING
0680 REM
0690 SM(I) = 0: FOR I = II TO JJ:
0700 IF (TR(I) < CL) THEN SM(I) = SM(I) + (TR(I) - CL) / R2
0710 REM
0720 FOR I = 1 TO 24: BD(I) = SQ(I) + 5: NEXT
0730 BDUB 840
0740 FOR I = 1 TO JJ: IF (TR(I) > CU) THEN TI = 0: GOTO 1230
0750 REM
0760 REM THIS ROUTINE CHECKS IF THE ROOM TEMPERATURE CAN
0770 REM REMAIN IN THE MIDDLE OF THE COMFORT ZONE
0780 REM
0790 SM(I) = 0: FOR I = 1 TO 24: SM(I) = SM(I) + (TR(I) - CM) * 2: NEXT
0800 IF (TR(O) = CM) THEN TI = 0: GOTO 1290
0810 IF (TR(O) < CM) THEN GOTO 1310
0820 IF (TR(O) > TA(O)) THEN GOTO 1310
0830 VD = 0.02: FOR I = 1 TO 24: BD(I) = SQ(I): NEXT:
0840 IF (BD(I) = SQ(I)) THEN 80(I) = 80(I) - 0.5 * 1.2 * VD * (TR(I) - TA): GOTO 1050:
0850 IF (I = 1 TO 24: IF (TR(I) < CL OR TR(I) > CU) THEN GOTO 1310
0860 TZ = 1: GOTO 1230
0800 REM THIS ROUTINE CALCULATES THE ROOM TEMPERATURE ACCORDING TO:
0810 REM ROOM STORAGE
0820 REM
0830 REM
0840 A(6) = SQRT((RC * CC + OM(2) * 2 + 1)
0850 A(7) = 1 / ((RC + R2 + RC) * CC)
0860 A(8) = ATN((RC * CC + OM(2))
0870 A(9) = ATN(OM(2) / A(7))
0880 A(10) = ATN(A(7) / (OM(1))
0890 A(11) = ATN(A(7) / (2 * OM(1))
0900 A(12) = A(7) * SU / A(6) / SQRT(A(7) * 2 + OM(2))
0910 A(13) = OM(1) * A(7) / CC + A(3) / SQRT(A(7) * 2 + (OM(1) * 2)
0920 A(14) = 2 + OM(1) / A(7) / CC + A(4) / SQRT(A(7) * 2 + (OM(1) * 2)
0930 FOR I = 1 TO 24
0940 IF (TM(I - 1) = 0) THEN TP(1) = A(12) * SIN((OM(2) * TT(I - 1) -
0950 IF (TM(I - 1) = 1) THEN A(I) = (TR(I - 1) - TA(I - 1)) / R2 + TP(I)
0960 IF (TR(I - 1) = 2 OR TM(I - 1) = 3) THEN TP(I) = A(13) * SIN(OM(1)
0970 IF (TR(I - 1) = 2 OR TM(I - 1) = 3) THEN A(I) = (((TR(I - 1) - TA(I - 1)) * EXP(A(7) * TT(I - 1))
0980 REM RECALCULATE THE CAPACITOR TERM FOR DIFFERENT MODE
0990 IF (TT(I) = 0) THEN A(1) = A(1) * EXP( - (A(7) * 24)
1000 IF (TM(I) = 1 AND TM(I - 1) = 1) THEN BOSUB = 110
1010 IF (TM(I) = 1 AND TM(I - 1) = 2) THEN BOSUB = 1170
1020 IF (TM(I) = 1 AND TM(I - 1) = 3) THEN BOSUB = 1170
1030 IF (TM(I) = 1 AND TM(I - 1) = 4) THEN BOSUB = 1190
1040 IF (TM(I) = 2 AND TM(I - 1) = 1) THEN BOSUB = 1190
1050 IF (TM(I) = 2 AND TM(I - 1) = 2) THEN BOSUB = 1180
1060 IF (TM(I) = 2 AND TM(I - 1) = 3) THEN BOSUB = 1180
1070 IF (TM(I) = 2 AND TM(I - 1) = 4) THEN BOSUB = 1180
1080 IF (TM(I) = 3 AND TM(I - 1) = 1) THEN BOSUB = 1180
1090 IF (TM(I) = 3 AND TM(I - 1) = 2) THEN BOSUB = 1180
1090 NEXT I: RETURN
1100 A(1) = A(I) + A(11) * SIN((OM(2) * (TT(I) - BR)) + A(B) - A(9))
1110 A(I) = A(I) * EXP( - (A(7) * (TT(I - 1) - TT(I))) / BO(I - 1)
1120 TP(1) = A(I) * EXP( - (A(7)))
1130 TP(2) = A(12) * SIN((OM(1) * (TT(I) - BR)) + A(B) - A(9))
1140 TP(3) = A(13) * SIN((OM(1) + TT(I) + A(10)) + 3 * A(5))
1150 TP(4) = A(14) * SIN((OM(1) * TT(I) + A(11) + A(5))
1160 TP(5) = TP(1) + TP(2) - TP(3) - TP(4) * TP(5) = BO(I) + TP(5)
1170 A(I) = A(I) - A(11) * SIN((OM(2) * (TT(I) - BR)) + A(B) - A(9))
1180 A(I) = A(I) * EXP( - (A(7) * (TT(I - 1) - TT(I))) / BO(I - 1)
1190 TP(1) = A(I) * EXP( - (A(7) * TT(I)))
1200 TP(2) = A(13) * SIN((OM(1) * TT(I) + A(10)) + 3 * A(5))
1210 TP(3) = A(14) * SIN((OM(1) * TT(I) + A(11) + A(5))
1220 TP(4) = TP(1) + TP(2) - TP(3) * TP(4) = BO(I) + TP(4)
1230 REM THIS ROUTINE SENDS MESSAGE TO THE CONTROL SYSTEM
1240 REM
1250 REM
1260 IF (TR(0) > CL AND TR(0) < CU) THEN IF (TR(0) > TA(0)) THEN TI =
1270 IF (TR(0) > CL AND TR(0) < CU) THEN IF (TR(0) < TA(0)) THEN TZ = 2: GOTO 1290
1290 TZ = 0
1290 FOR J = 1 TO 5: POKE 49243,0: FOR K = 1 TO 140: NEXT K: POKE 49242,0: FOR K = 1 TO 100: NEXT K: NEXT J
1300 IF (TZ = 0) THEN GOTO 1340
1310 FOR I = 1 TO TZ: FOR J = 1 TO 5: POKE 49245,0: FOR K = 1 TO 400: NEXT K: NEXT J: POKE 49244,0: FOR K = 1 TO 200: NEXT K: NEXT J
1320 FOR J = 1 TO 15: POKE 49241,0: FOR K = 1 TO 800: NEXT K: POKE 49240,0: FOR K = 1 TO 500: NEXT K: PRINT J: PRINT J: NEXT J
1330 NEXT I
1340 PRINT D$: "IN04": PRINT D$: "PR04": INPUT T$: PRINT D$: "IN00": PRINT D$: "PR00": PRINT D$: "APPEND OPER.D2": PRINT D$: "WRITE OPER": PRINT T$: PRINT D$: "CLOSE OPER": PRINT D$: "OPEN CONTROL.D1": PRINT D$: "DELETE CONTROL": PRINT D$: "OPEN CONTROL": PRINT D$: "WRITE CONTROL": PRINT D$: "CLOSE CONTROL": PRINT D$: "RUN TIME CONTROL PROGRAM"
1370 REM
1380 REM
1390 PRINT D$: "RUN TIMEC"
BASIC
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0010 REM
0020 REM ABNORMAL CONTROL PROGRAM
0030 REM
0040 REM THIS PROGRAM ACTIVATES THE NEEDED DEVICES WHICH CONTR
0050 REM OL THE ROOM TEMPERATURE WITH THE MIDDLE OF THE COMFORT IO
0060 REM
0070 DIM A(20), D(2), M(2), T(24), TA(24), TP(24), TR(24), TT(24), T
0080 PRINT D$="OPEN VARD.D1" PRINT D$="READ VARB";
0090 PRINT D$="CLOSE VARB";
0100 REM
0110 REM CHECK ROOM TEMPERATURE
0120 REM STORE THE CONTROL MODE INTO A FILE
0130 REM
0140 IF (TR(0) > 1) THEN IF (TR(0) > TA(0)) THEN T1 = 1: BOTO 170
0150 IF (TR(0) < 1) THEN T1 = 0: BOTO 170
0160 T1 = 0
0170 FOR J = 1 TO 5: POKE 49243, 0: FOR K = 1 TO 140: NEXT K;
0180 IF (T1 = 0) THEN BOTO 220
0190 FOR J = 1 TO 5: POKE 49243, 0: FOR K = 1 TO 200: NEXT K;
0200 FOR J = 1 TO 5: POKE 49241, 0: FOR K = 1 TO 800: NEXT K;
0210 NEXT I
0220 PRINT D$="CIN8"; PRINT D$="PR8"; INPUT T8; PRINT D$="IN80";
0230 PRINT D$="PR80"
0240 PRINT D$="APEND OPER.D2"; PRINT D$="WRITE OPER"; PRINT T8;
0250 PRINT T1: PRINT D$="CLODE OPER"
0260 REM
0270 REM RUN TIME CONTROL PROGRAM
0280 REM
0290 PRINT D$="RUN TIME"
BASIC
APPLESOFT.BASIC.

0010 REM
0020 REM
TIME CONTROL PROGRAM
0030 REM
0040 REM
THIS PROGRAM CONTROLS THE OPERATION TIME AND STORING WEATHERS IN A DATA FILE
0050 REM
0060 REM
0070 REM
0080 CLEAR 12 = 1
0090 DE = CHR$(4) ; DIM TP(15), AD(12); FOR I = 1 TO 12: READ AD(I): NEXT I : DATA
0100 PRINT DE: "BRUN AA/DD.D":
0110 PRINT DE: "OPEN DATA1.DI": PRINT DE: "READ DATA1": INPUT TE:
0120 PRINT DE: "OPEN CONTROL": PRINT DE: "READ CONTROL": INPUT NE, SC:
0130 REM
0140 REM
CHECK FOR VALID TIME
0150 REM
READ IN WEATHER DATA FROM DATA ACQUISITION
0160 REM
0170 I = 1
0180 SC = SC = 160
0190 BDSUB 840; MS = M; JS = J; D; DI = DI; ME = MT; N = 10
0200 SC = 900: BDSUB 840; HOME
0210 VTab (5); HTAB (2); PRINT "TIME"
0220 PRINT DE: "IN$:" : PRINT DE: "PROC": INPUT "": TI;: PRINT DE: "IN$0":
0230 M1 = VAL (MID$(TI,1,2)) ; M1 = VAL (MID$(TI,4,2)) ; M2 = VAL (MID$(TI,14,2)) ; S1 = VAL (MID$(TI,13,2))
0240 BDSUB 670
0250 REM
0260 REM
CHECK WHETHER INPUT DATA IS REASONABLE
0270 REM
0280 IF (TP(0) - TP(6)) = 2 THEN BDSUB 220
0290 IF (M2 = 0 OR M2 = 5 OR M2 = 10 OR M2 = 15 OR M2 = 20 OR M2 = 25 OR M2 = 30) THEN BDSUB 710: BDSUB 910
0300 IF (N3 > 0) THEN IF (M2 > N3) THEN IF (M1 > M2) THEN IF (J = 1 TO 5) POKE 49243, 0: FOR K = 1 TO 140: NEXT K: POKE 49242, 0: FOR K = 1 TO 100: NEXT K: NEXT J = N3 = 0
0310 REM
0320 REM
CHECK FOR VALID ROOM TEMPERATURE FOR PERCENT OPERATION M OD
0330 REM
0340 IF (N3 = 4 AND TP(4) > 21) THEN N2 = 1: BDSUB 490
0350 IF (N3 = 4 AND TP(4) < 19) THEN N2 = 0: BDSUB 490
0360 IF (N2 = 2 AND TP(4) > 18,3) THEN N2 = 0: BDSUB 490
0370 IF (N2 = 3 AND TP(4) > 23,5) THEN N2 = 0: BDSUB 490
0380 IF (N3 = 0 AND TP(4) < 24) THEN N2 = 0: BDSUB 490
0390 IF (TP(0) = TP(4) > TP(0)) THEN N2 = 1: BDSUB 490
0400 IF (N3 = 1 AND TP(4) > 17,5) THEN N2 = 2: BDSUB 490
0410 IF (N3 = 1 AND TP(4) = 18) THEN N2 = 0: BDSUB 490
0420 IF (N3 = 1 AND TP(4) = 19) THEN N2 = 0: BDSUB 490
0430 IF (N3 = 1 AND TP(4) = TP(0)) THEN N2 = 1: BDSUB 490
0440 IF (N3 = 2 AND TP(4) < 24 AND TP(4) < TP(0)) THEN N2 = 0: BDSUB 490
0450 IF (N3 = 2 AND TP(4) > 18) THEN N2 = 0: BDSUB 490
0460 IF (N3 = 3 AND TP(4) > 24) THEN N2 = 0: BDSUB 490
0470 IF (TP(4) < 18) THEN N2 = 2: BDSUB 490
0480 IF (TP(4) = 24) THEN N2 = 0: BDSUB 490
0490 IF (N2 = 0) THEN FOR J = 1 TO 5: POKE 49243, 0: FOR K = 1 TO 140: NEXT K: POKE 49242, 0: FOR K = 1 TO 100: NEXT K: NEXT J:
BASIC
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0500 REM
0510 REM ACTIVATE CONTROL SYSTEM
0520 REM DOUBLE CHECK THAT THE CORRECT FUNCTION HAS BEEN ACTIVAT
0530 REM ED
0540 REM 0 = NO OPERATION
0550 REM 1 = FAN
0560 REM 2 = HEATER
0570 REM 3 = CHILLER
0580 IF (N2 < > 0 AND PDL (N2) = 0) THEN GOTO 220
0590 REM READ WEATHER DATA FROM DATA ACQUISITION
0600 REM
0610 REM
0620 FOR J = 1 TO 5: POKE 49243.0: FOR K = 1 TO 1401: NEXT K: POKE 49242.0: FOR K = 1 TO 1001: NEXT K: NEXT J
0630 FOR I = 1 TO N2: FOR J = 1 TO 5: POKE 49245.0: FOR K = 1 TO 400: NEXT K: NEXT J: NEXT I
0640 FOR J = 1 TO 13: POKE 49241.0: FOR K = 1 TO 800: NEXT K: POKE 49240.0: FOR K = 1 TO 300: NEXT K: NEXT J
0650 NEXT I
0660 GOSUB 890: GOTO 220
0670 POKE 49245.0: FOR K = 1 TO 800: NEXT K: POKE 49244.0: FOR K = 1 TO 500: NEXT K: FOR I = 0 TO NC - 1: FOR II = 1 TO 300: CALL 49644: NEXT II
0680 TP(I) = 0: FOR II = 3 TO 5: TP(I) = (PEEK (49856 + II) - 176) / 10 ^ (II - 2) + TP(I): NEXT II: TP(I) = TP(I) - 1.893 * 14.8
0690 POKE 49241.0: FOR K = 1 TO 1000: NEXT K: POKE 49240.0: FOR K = 1 TO 700: NEXT K: NEXT I: RETURN
0700 REM STORE DATA IN COMMON DATA FILES.
0710 REM
0720 REM
0730 PRINT D$;"OPEN VARB.D1": PRINT D$;"READ VARB": INPUT BD,A(2),A(3),A(4),A(5),TA,TR: PRINT D$;"CLOSE VARB";
0740 TT = VAL (MID$ (T#;7,2)) + TA = TP(0); TR = TP(4)
0750 PRINT D$;"OPEN VARB.D1": PRINT D$;"DELETE VARB": PRINT D$;"OPEN VARB": PRINT D$;"WRITE VARB"
0760 PRINT BD;",A(2),","A(3),","A(4),","A(5),",",TA",","TR"
0770 REM RUN PREDICTION PROGRAM
0780 REM
0790 REM
0800 PRINT D$;"RUN PREDICTION"
0810 REM
0820 REM CHANGE INPUT TIME FROM CHARACTER TO NUMBER
0830 REM
0840 MT = VAL (MID$ (T#;1,2)): ID = VAL (MID$ (T#;4,2))
H = VAL (MID$ (T#;7,2)): M = VAL (MID$ (T#;10,2))
S = VAL (MID$ (T#;13,2)): B = SCM: M = INT (S / 60)
0850 S = B - INT (S / 60) + 60: H = H + INT (M / 60): M = M - INT (M / 60) + 60: D = D + INT (H / 24): H = H - INT (H / 24) * 24
0860 MT = MT + INT (D / AD(MT)): ID = D - INT (D / AD(MT)) + AD(MT): IF (MT > 12) THEN MT = MT - 12
0870 RETURN
0880 REM RECORD ANY SYSTEM THAT WAS TURN ON AND LATER ANALYSIS
0890 REM
0900 PRINT D$;"APPEND OPER,D2": PRINT D$;"WRITE OPER": PRINT T1$;
PRINT N2: PRINT D$; "CLOSE QPER": N4 = N2: RETURN
0910 IF (ZI < > 0) THEN FOR I = 1 TO NC - 1; S(I) = S(I) + TP(I); NEXT I; ZI = I + 1: RETURN
0920 FOR I = 1 TO NC - 1; TP(I) = S(I) / F; S(I) = 0; NEXT I; ZI = 1
0930 FOR I = 0 TO NC - 1; PRINT D$; "APPEND CHAND": I; "," D$;
0940 PRINT D$; "WRITE CHAND": I;
0950 PRINT LEFT$ (TP$, 14); TP$ = STR$ (TP(I)); PRINT LEFT$ (TP$, 5)
0960 PRINT D$; "CLOSE CHAND": I: NEXT I
0970 FOR I = 0 TO NC - 1
0980 PRINT = "; I; PRINT TP(I); " DES C"
0990 NEXT I: RETURN
APPENDIX F

Determination of $C$, $R_C$, $R_{LS}$ and $R_{AL}$ from four measurements of each of $TA$, $TR$ and $TS$
At time $t$, $TA$, $TR$ & $TS$ are known from experiment.

From DE

\[
\frac{TR - TA}{R_{AL}} = I_3 \quad \text{(F.1)}
\]

and

\[
I_3 - I_2 = IG \quad \text{(F.2)}
\]

From eq. F.1 and Eq. F.2

\[
I_2 = \frac{TR - TA}{R_{AL}} \times IG \quad \text{(F.3)}
\]

Also $I_2$ can be express as:

\[
I_2 = A \times e^{-at} \quad \text{(F.4)}
\]
where:

\[
\alpha = \frac{1}{(R_{AL} + R_{LS} + R_C) \cdot C}
\]

From eq. F.2 & eq. F.4

\[
\frac{TR - TA}{RAL} = A \cdot e^{-\alpha t} + IG
\]  \hspace{1cm} (F.5)

also from circuit

\[
R_{LS} = \frac{TS - TR}{A \cdot e^{-\alpha t}}
\]  \hspace{1cm} (F.6)

From F.5 with 2 data points \( t_1, t_2 \)

\[
\frac{(TR_1 - TA_1) - IG \cdot R_{AL}}{(TR_2 - TA_2) - IG \cdot R_{AL}} = e^{-\alpha (t_1 - t_2)}
\]  \hspace{1cm} (F.7)

From F.5 with another 2 data points \( t_3, t_4 \)

\[
\frac{(TR_3 - TA_3) - IG \cdot R_{AL}}{(TR_4 - TA_4) - IG \cdot R_{AL}} = e^{-\alpha (t_3 - t_4)}
\]  \hspace{1cm} (F.8)
If the interval between two readings is constant

\[ t_1 - t_2 = \text{constant} = 1 \text{ hr.} \]

and let \( F(a) = e^{-a} \)

From eq. F.7

\[ F(a) = \frac{(TR_1 - TA_1) - IG \ast R_{AL}}{(TR_2 - TA_2) - IG \ast R_{AL}} \quad (F.9) \]

From eq. F.8

\[ R_{AL} = \frac{[(TR_3 - TA_3) - F(a)(TR_4 - TA_4)]}{IG \ast [1 - F(a)]} \quad (F.10) \]

from \( F(a) \)

\[ a = -\frac{1}{\ln[F(a)]} \quad (F.11) \]

From eq. F.5

\[ R_{LS} = \frac{TS - TR}{A \ast e^{-at}} \quad (F.12) \]

and \[ R_C = \frac{(TS + a \ast A \ast e^{-at})}{[(TR - TA)/R_{AL} - IG]} \quad (F.13) \]
\[ C = \frac{a}{(R_{AL} + R_{C} + R_{LS})} \]