An Optimum Start/Stop Control Algorithm for Heating and Cooling Systems in Buildings

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

May 1983

Sponsored by:
Office of Building and Community Systems
U.S. Department of Energy
U.S. Navy Civil Engineering Laboratory
U.S. Department of Defense
AN OPTIMUM START/STOP CONTROL ALGORITHM FOR HEATING AND COOLING SYSTEMS IN BUILDINGS

Cheol Park

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

May 1983

Sponsored by:
Office of Building and Community Systems
U.S. Department of Energy
U.S. Navy Civil Engineering Laboratory
U.S. Department of Defense
When a building structure is occupied intermittently, energy savings can be realized from the optimal start-up and shut-down of the heating or cooling system. This strategy, known as optimum start/stop control, reduces energy consumption by delaying the start-up of the space conditioning system until the last moment and then initiating shut-down as early as possible, while maintaining a preset level of comfort during the period of building occupancy.

Based on the bang-bang control theory, a simple optimum start/stop control algorithm is developed for computerized control systems in buildings. The optimum start time is obtained by finding the intersection of cool-down and heat-up curves that are approximated by exponential fitting of the previous and current day's data.

Information is presented in this report on the input and output variables, logic flow, and methodology employed in developing the algorithm. A computer program listing of the optimum start/stop control algorithm written in FORTRAN 77 and sample input and output data are included in the appendices.

Key words: digital control systems; energy conservation; energy management and control systems; heating and cooling systems; optimum start/stop time; preheat time.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. OPTIMUM START/STOP ALGORITHM</td>
<td>4</td>
</tr>
<tr>
<td>2.1 OVERVIEW</td>
<td>4</td>
</tr>
<tr>
<td>2.2 INPUT AND OUTPUT DATA</td>
<td>6</td>
</tr>
<tr>
<td>2.3 ASSUMPTIONS AND LIMITATIONS</td>
<td>8</td>
</tr>
<tr>
<td>2.4 METHODOLOGY</td>
<td>9</td>
</tr>
<tr>
<td>2.5 APPLICATION NOTES</td>
<td>15</td>
</tr>
<tr>
<td>3. CONCLUSIONS</td>
<td>24</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>25</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>26</td>
</tr>
<tr>
<td>APPENDIX A. DETERMINATION OF OPTIMUM START TIME FOR HEATING</td>
<td>27</td>
</tr>
<tr>
<td>APPENDIX B. FLOW CHARTS OF THE COMPUTER PROGRAMS</td>
<td>34</td>
</tr>
<tr>
<td>APPENDIX C. COMPUTER PROGRAM LISTING</td>
<td>41</td>
</tr>
<tr>
<td>APPENDIX D. SAMPLE INPUT AND OUTPUT OF THE PROGRAM</td>
<td>53</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1. Room air temperature with respect to time of day under an ideal situation ........................................... 5
Figure 2. Room air temperature with respect of time of day under a realistic situation ................................. 5
Figure 3. A case with the on-off control operation ................. 12
Figure 4. A typical temperature history during the initial cycle ................................................................. 12
Figure 5. Relationships of subprograms .............................. 14
Figure 6. Flow chart of the main algorithm, OPTSS ............. 16

LIST OF TABLES

Table 1. Cross reference table of notation ....................... 17
1. INTRODUCTION

When a building is occupied intermittently, energy savings can be realized by minimizing the time the heating or cooling system is operated. The interior building temperature is maintained at a comfortable level only during occupancy. For example, during the heating season, the heating system is turned off shortly before the end of an occupied period and the space temperature decays until the heating equipment is reactivated. This reactivation occurs either because a new occupied period is approaching or because the indoor temperature has reached a predetermined minimum temperature which must be maintained to prevent freezing and condensation problems. Building control algorithms that try to determine the start and stop times for the heating and cooling equipment such that start-up is delayed until the last moment and shut-down takes place as early as possible before the end of occupancy, are commonly referred to as "optimum start/stop" algorithms [1,2]. One such algorithm is the subject of this report.

Due to thermal inertia of both the building structure and its heating and cooling equipment, a preheat or precool time is almost always required to raise or lower the space temperature to the desired level before the beginning of occupancy. This start-up time depends on the outdoor environment, the thermal response of the building envelope, and the thermal performance of space conditioning equipment [3-5]. The starting time of the equipment is the main value to be determined in optimum start control. Optimum stop control makes use of the dead time after the heating or cooling equipment is turned off when thermal inertia prevents the indoor temperature from dropping below
or rising above comfort levels. This allows the system to be turned off before the end of an occupied period.

Practical use of optimum start control was accomplished by Jackson (3,4) on a heating system using an analog control device. With an intuitively derived relationship between indoor and outdoor air temperatures, the start time of preheat period was determined. Jackson claimed substantial energy savings from the use of optimum start control. He also indicated that a nighttime setback technique was not economically justified in control of intermittently occupied buildings. A field study was made by Henderson [5] comparing optimum start control with nighttime setback. Bloomfield and Fisk [6] described the optimization of intermittent heating with a detailed mathematical presentation and made simulations using prior knowledge of the thermal response factors of building structures.

Using recursive least squares estimation, a self-tuning optimum start control algorithm for a heating plant was developed by Dexter [7]. The preheat start time is expressed in terms of bulk structure temperature and unknown parameters that are to be determined adaptively using daily data. Both analog and digital simulations were made. The estimate of bulk temperature was calculated using a first order difference equation with a bulk time constant representing the thermal behavior of the structure.

As microprocessors became available, the HVAC industry began to implement microcomputers to control building equipment. Although software developed by industry exists on the market, details of the algorithms are not generally available in the public domain. The purpose of this report is to introduce a
simple optimum start/stop algorithm which has been developed for digital control of heating systems. With minimal changes, the same algorithm can be used to optimally start and stop building cooling systems.

In the algorithm presented, the starting time for the heating system is determined by using both the temperature rise characteristics during the preheat period of the previous day and the temperature decay behavior during the current cool-down period. The stop time is determined from the delay in the temperature cool-down cycle. A provision for prevention of freezing and condensation problems is also incorporated. The nature of the algorithm used is adaptive, but the approach is much simpler than that used by Dexter [7]. Neither a time series analysis nor recursive least squares estimation is involved.
2. OPTIMUM START/STOP ALGORITHM

2.1 OVERVIEW

According to optimum control theory, minimization of energy use can be achieved if the control is of the "bang-bang" type [8]. This means that, in the heating mode, the heating system operates at full power during the preheat period and at zero power during the cool-down period. Similar operating procedures are applied in the cooling mode, but for simplicity only heating operation will be described in detail. In addition, it will be assumed that the minimum temperature reached during the off-period is greater than the space temperature which would result in freezing or condensation problem.

The bang-bang control scheme is applied only during the unoccupied period. If the outdoor environmental conditions remain constant during the unoccupied period, an ideal situation is illustrated as shown in figure 1. Room air temperature, \( T_{RA} \), responds immediately on the starting or stopping of the heating equipment. Thermal inertia of the building structure or of the heating system is not accounted for. This kind of ideal response is impossible in the real world. Figure 2 represents a more realistic response. The outdoor environment and thermal response characteristics of the building structure determine the length of the preheat period.

In the optimum start/stop algorithm presented in this report, the start time for heating is determined by using the temperature rise characteristics during the heat-up period of the previous day and the temperature decay characteristics during the current cool-down period. The stop time is determined from the delay in the temperature decay.
Figure 1. Room air temperature with respect to time of day under an ideal situation

Figure 2. Room air temperature with respect to time of day under a realistic situation
2.2 **INPUT AND OUTPUT DATA**

It is assumed that the optimum start/stop algorithm is not executed continuously, but at discrete time intervals. The time interval is called the sampling period. The sampling period used depends upon the building response characteristics. The sampling period assigned in this report is 15 minutes. At each sampling instant, the following data are sampled:

- \( t \): time of day in military time expressed in hours
- \( T_{RA} \): room air temperature
- \( T_{OA} \): outdoor air dry-bulb temperature

Units for temperature data can be either metric or English units. Instead of room air and outdoor air temperatures, interior and exterior surface temperatures of a building structure may be used. Surface temperature measurements usually contain less noisy and more stable signals.

As initial input data, the main algorithm (OPTSS) requires the following information:

- \( t_{occ} \): start time of occupancy (military time)
- \( t_{unoc} \): ending time of occupancy (military time)
- \( t_s \): initial guess of starting time for use in the learning cycle (military time)
- \( y_{set} \): set point temperature during the occupied period

In addition, the room air temperature must be maintained above a minimum temperature to prevent freezing and condensation problems during the heating season, and it should not be higher than a maximum temperature during the
cooling season. Because of this, the following additional input data are also needed:

**HEAT:** logical variable

For the heating mode, HEAT is true and for the cooling mode, HEAT is false.

\( y_{\text{min}} \): minimum temperature allowed during the heating season

\( y_{\text{max}} \): maximum temperature allowed during the cooling season

While the most important output is the start time, \( t_s \), the following logical outputs are also provided for the purpose of system control via supporting software and hardware:

**DAYCNT:** logical variable

If DAYCNT is true, the daytime controller is to be called, otherwise the daytime controller is not called. The daytime controller is referred as a controller to be used in maintaining \( y_{\text{set}} \) during the occupied period assuming that the occupied period is at daytime.

**FSYSON:** logical variable

If FSYSON is true, the heating (or cooling) system operates at full output. Otherwise the heating (or cooling) system operates at less than full output.

**MAINTN:** logical variable

If MAINTN is true, a controller is called to maintain a minimum requirement in heating (or cooling).
When a simple on-off controller is used to maintain the minimum unoccupied temperature during the heating mode (or the maximum permissible temperature level during the cooling mode). Information on the on-off temperature differential, $\Delta y$, will also be required.

2.3 ASSUMPTIONS AND LIMITATION

The following assumptions were made in the development of the optimum start/stop algorithm:

(a) Full output operation is carried out only by the heating equipment during the preheating period and by the cooling equipment during the precooling period.

(b) A daytime controller (e.g., PI-controller) is available during the occupied period and both the daytime control and the optimum start/stop control do not interfere with each other in their operations. If the occupancy period is at nighttime, the daytime controller should be considered as a nighttime controller.

(c) Execution of the algorithm is performed once every sampling period of 15 minutes (i.e., four samples per hour).

(d) Maintaining a minimum (maximum) temperature load in the heating (cooling) mode during the off-period is done by an on-off controller.

The use of the algorithm in an actual implementation is not limited as long as the computer used in the controls associated with the system to be controlled has enough capacity to store sampled data and the program.
2.4 **METHODOLOGY**

The optimum start time for heating is determined by using a measured temperature rise curve from the preheat period of the previous day and a measured temperature decay curve from the current cool-down period, and finding the intersecting point of the two curves before occupancy. Equations of the two curves are approximated by simple exponential fits based on actual data. Each equation contains a single time constant \((\tau)\), and one predetermined time \((x_i)\) with its corresponding measured temperature \((y_i)\). Each time constant is determined from the exponential fitted equation using two data points. The intersection of two curves are obtained using a method for finding a root of the function which is expressed as a difference of two fitted equations.

An x-y coordinate system is employed to express these equations for convenience. Time and temperature are denoted by \(x\) and \(y\), respectively, and the origin of the x-axis is chosen as a midpoint of the occupied period. When the occupancy schedule for the next cycle (e.g., next day) is changed (i.e., \(t_{occ}\) and \(t_{unoc}\) are varied) before the beginning of the occupied period, the origin of the x-axis is translated by the amount of the change made.

Although it is desirable that the space temperature reaches the target temperature (set point) at the beginning of occupancy, the desired temperature may not be reached on time due to approximation errors in curve fitting and/or changes in characteristics of heating (cooling) equipment and building thermal response from the previous day's state. The temperature will reach the set point a little earlier or later than the optimum time. The fitted temperature rise curve is thus corrected by the amount of time offset, \(x_o\).
When the building thermal response is slow and the heating or cooling system has a transport delay (dead time), then the space temperature does not rise immediately, but responds after a certain time period is passed. The time period without the response of temperature rise may be called the "flat response" period or simply system dead time, $d_{on}$. Under these circumstances, the start time obtained by finding two curves should be advanced by the amount of the system dead time. Details on how the start time, $x_s$, for heating mode is determined can be found in Appendix A, where mathematical expressions are provided.

At the beginning of the unoccupied period, the heating system is usually turned off. However, when the decay of indoor temperature is slowed by the thermal characteristics of the building structure, energy savings can be realized by advancing the turning-off of the heating system so that the "flat response" period is included in the occupied period. This advanced stop time will be referred to as the optimum stop time, even though its determination is not based on optimum control theory. This approach is simple, compared with the method developed by Bloomfield and Fisk [6].

When the outdoor air temperature is low enough, the indoor air temperature may fall below the desired minimum temperature, $y_{min}$, during the off-period. The indoor temperature must be maintained above the minimum temperature to prevent freezing and condensation problems. A simple on-off control may be utilized to maintain the minimum level of temperature. The heating system is turned on when $y < y_{min}$, and turned off when $y > y_{min} + \Delta y$. In this case, the full capacity operation of the heating system may not be necessary, and partial
load operation may be adequate. This is illustrated in figure 3, where the
dead time is assumed to be zero.

A typical temperature history during the initial cycle (learning cycle) is
illustrated in figure 4. Possible time delays and offset are included.

Assuming the program run starts at near a midpoint time of the occupied period
of a typical weekday in the heating season, the following is a simplified
description of the sequence of operations performed by the program:

(1) Get initial input data and set initial conditions.
(2) Start to take data of $t$, $T_{RA} (=y_4)$, and $T_{OA}$ every 15 minutes.
(3) Turn off the system at the beginning of the unoccupied period.
(4) Determine dead time during the off-period.
(5) Check if on-off control is necessary to maintain a minimum
space temperature ($y \leq y_{min}$ at any time during the off-period).
(6) Turn on the system at the given initial guess of the start time.
(7) Determine dead time during the on-period.
(8) Turn off the system at the beginning of occupancy and let a daytime
controller take over.
(9) Update constant values, $x_1$, $x_2$, $x_3$, $y_1$, $y_2$, and $y_3$ (see Appendix A for
definition).
(10) Determine the minimum outdoor temperature.
(11) Update the heat-up curve.
(12) Determine the interval where an intersecting point of the heat-up and
cool-down curves locates.
(13) Begin a new cycle at the midpoint of the following day's occupied period.
Figure 3. A case with the on-off control operation

Figure 4. A typical temperature history during the initial cycle
(14) Turn off the system before the beginning of the unoccupied period by the amount equal to the off-period dead time.

(15) Repeat steps (4) through (5).

(16) Find the intersection of the heat-up and cool-down temperature curves by using the regula falsi method (false position method) [9].

(17) Predict the new start time incorporating the on-period dead time determined previously.

(18) Turn on the system at the newly calculated start time.

(19) Go to step (7).

It is possible to generalize the optimum start/stop control algorithm from the heating mode to the cooling mode by relaxing some of the assumptions made in Appendix A. The same equations used for heating given in Appendix A can be used for cooling except that $y$ is taken to be the highest outdoor dry-bulb temperature during the unoccupied period, the value of $y_{gg}$ is approximated as $0.5 \, y_{set}$ and the maximum allowable space temperature, $y_{max}$, replaces $y_{min}$ whenever it appears.

Figure 5 shows a block diagram of the relationships between procedures in the main algorithm. The following are brief descriptions of each routine shown in this figure:

OPTSS: Primary routine for optimum start/stop control. Each event is controlled sequentially. Both heating and cooling season operations are included.

XLTRT: Left-most and right-most values of the time coordinate $(x)$ are computed to be used as upper and lower limits of the interval in
Figure 5. Relationships of subprograms
ROOT subroutine.

ROOT: This subroutine finds the real root of a function in a given interval.

MAXMIN: A subroutine to obtain the maximum and minimum values of a given array.

XCOORD: This subroutine converts military time into the modified time coordinate, \( x \), and vice versa.

FYDIF: A function that obtains the difference of two functional values.

YONNEW: A function to update the heat-up profile, \( y_{ON}(x) \).

(See Appendix A.)

YOFF: A function to describe the building cool-down profile, \( y_{OFF}(x) \).

(See Appendix A.)

The flow chart of the main algorithm, the subroutine OPTSS, is shown in figure 6. Further detailed flow charts of the OPTSS and the associate subprograms are given in Appendix B. Table 1 is a cross reference of the notation used in the computer program, flow charts, main text, and Appendix A. A complete listing of the computer program appears in Appendix C. The computer program was written in FORTRAN 77 for the UNIVAC 1100/82 computer.

2.5 APPLICATION NOTES

The subroutine OPTSS contains four COMMON blocks of shared storage space with other subroutines and the main program. The DATA statements in the OPTSS contain the following pre-assigned numerical data:

EPS: small positive real number specifying the accuracy required of the ROOT routine (\( \approx 0.005 \)).
Figure 6. Flow chart of the main algorithm, OPTSS
Table 1. Cross reference table of notation

<table>
<thead>
<tr>
<th>Notation in Programs</th>
<th>Descriptions</th>
<th>Notation in Flow Charts</th>
<th>Notation in the Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(I)</td>
<td>array values</td>
<td>A(I)</td>
<td></td>
</tr>
<tr>
<td>AMAX</td>
<td>maximum value of array values</td>
<td>A_{MAX}</td>
<td></td>
</tr>
<tr>
<td>AMIN</td>
<td>minimum value of array values</td>
<td>A_{MIN}</td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>date</td>
<td>DATE</td>
<td></td>
</tr>
<tr>
<td>DAY</td>
<td>0 for non-working day 1 for working day</td>
<td>DAY</td>
<td></td>
</tr>
<tr>
<td>DAYCNT</td>
<td>true if the daytime controller operates false if the daytime controller does not operate</td>
<td>DAYCNT</td>
<td>DAYCNT</td>
</tr>
<tr>
<td>DELY</td>
<td>temperature difference</td>
<td>ΔY</td>
<td>Δy</td>
</tr>
<tr>
<td>DX</td>
<td>time increment used in XLTRT</td>
<td>ΔX</td>
<td></td>
</tr>
<tr>
<td>EPS</td>
<td>positive small number for accuracy used in ROOT</td>
<td>ε</td>
<td></td>
</tr>
<tr>
<td>EPSON</td>
<td>positive small number</td>
<td></td>
<td>ε</td>
</tr>
<tr>
<td>EPSSET</td>
<td>positive small number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPSX</td>
<td>positive small number determined by sampling frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSYSON</td>
<td>true if the system operates at full power false if the system is off</td>
<td>FSYSON</td>
<td>FSYSON</td>
</tr>
<tr>
<td>FX</td>
<td>scalar function values</td>
<td>f(x)</td>
<td></td>
</tr>
<tr>
<td>FXL</td>
<td>functional value of FX with the argument of XL</td>
<td>f_L</td>
<td></td>
</tr>
<tr>
<td>FXR</td>
<td>functional value of FX with the argument of XR</td>
<td>f_R</td>
<td></td>
</tr>
<tr>
<td>FX2</td>
<td>intermediate value of FX</td>
<td>f'</td>
<td></td>
</tr>
<tr>
<td>Notation in Programs</td>
<td>Description</td>
<td>Notation in Flow Charts</td>
<td>Notation in the Text</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
<td>-------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>HEAT</td>
<td>true if heating mode</td>
<td>HEAT</td>
<td>HEAT</td>
</tr>
<tr>
<td></td>
<td>false if cooling mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICYCLE</td>
<td>number of cycles (e.g., one cycle per day)</td>
<td>ICYCLE</td>
<td></td>
</tr>
<tr>
<td>IEND</td>
<td>index number of ending of search</td>
<td>IEND</td>
<td></td>
</tr>
<tr>
<td>IFLAG</td>
<td>0 if finding a root is successful</td>
<td>IFLAG</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 if finding a root is not successful</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISTART</td>
<td>index number of beginning of search</td>
<td>ISTART</td>
<td></td>
</tr>
<tr>
<td>ITDOWN</td>
<td>index number where temperature decay begins</td>
<td>ITDOQN</td>
<td></td>
</tr>
<tr>
<td>ITER</td>
<td>number of iteration</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>ITIME</td>
<td>index number of modified time of day</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>ITMAX</td>
<td>maximum number of iteration to obtain a root</td>
<td>IMAX</td>
<td></td>
</tr>
<tr>
<td>ITOFF</td>
<td>index number where ( X = XOFF )</td>
<td>ITOFF</td>
<td></td>
</tr>
<tr>
<td>ITON</td>
<td>index number where ( X = XSTART )</td>
<td>ITON</td>
<td></td>
</tr>
<tr>
<td>ITSET</td>
<td>index number where temperature reaches at set point</td>
<td>ITSET</td>
<td></td>
</tr>
<tr>
<td>ITUNOC</td>
<td>index number where ( X = XUNOC )</td>
<td>ITUNOC</td>
<td></td>
</tr>
<tr>
<td>ITUP</td>
<td>index number where temperature rise begins</td>
<td>ITUP</td>
<td></td>
</tr>
<tr>
<td>IW</td>
<td>index to control printing out</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAINTN</td>
<td>true if the on-off control is needed</td>
<td>MAINTN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>false if the on-off control is not needed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1 (cont.)

<table>
<thead>
<tr>
<th>Notation in Programs</th>
<th>Description</th>
<th>Notation in Flow Charts</th>
<th>Notation in the Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>number of intervals used in XLTRT</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>NMAX</td>
<td>total number of samples a day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPTHHR</td>
<td>number of samples in one hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSKIP</td>
<td>number of records to be skipped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARTON</td>
<td>true if the system operates with a partial capacity</td>
<td>PARTON</td>
<td></td>
</tr>
<tr>
<td>false if the system is off</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSCHDL</td>
<td>time when the schedule file is read (military time)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWI</td>
<td>event control switches (I = 0,...,7)</td>
<td>SWI</td>
<td></td>
</tr>
<tr>
<td>TAUOFF</td>
<td>system time constant during off-period</td>
<td>T&lt;sub&gt;OFF&lt;/sub&gt;</td>
<td>T&lt;sub&gt;OFF&lt;/sub&gt;</td>
</tr>
<tr>
<td>TAUON</td>
<td>system time constant during on-period</td>
<td>T&lt;sub&gt;ON&lt;/sub&gt;</td>
<td>T&lt;sub&gt;ON&lt;/sub&gt;</td>
</tr>
<tr>
<td>TBEGIN</td>
<td>origin of x-axis (military time)</td>
<td>t&lt;sub&gt;B&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>TDED0F</td>
<td>dead time during off-period</td>
<td>d&lt;sub&gt;OFF&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>TDEDON</td>
<td>dead time during on-period</td>
<td>d&lt;sub&gt;ON&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>TEMP</td>
<td>indoor or internal surface temperature</td>
<td></td>
<td>T&lt;sub&gt;RA&lt;/sub&gt;</td>
</tr>
<tr>
<td>TIME</td>
<td>time of day (military time)</td>
<td>TIME</td>
<td>t</td>
</tr>
<tr>
<td>TIMEX</td>
<td>modified time of day in scalar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TITLE</td>
<td>title of input data set in two rows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOA(I)</td>
<td>outdoor temperature</td>
<td>T&lt;sub&gt;OA&lt;/sub&gt;(I)</td>
<td>T&lt;sub&gt;OA&lt;/sub&gt;</td>
</tr>
<tr>
<td>Notation in Programs</td>
<td>Description</td>
<td>Notation in Flow Charts</td>
<td>Notation in the Text</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------</td>
<td>-------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>TOCC</td>
<td>beginning time of occupancy (military time)</td>
<td>( t_{\text{occ}} )</td>
<td></td>
</tr>
<tr>
<td>TOFF</td>
<td>optimum stop time (military time)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOUT</td>
<td>dry-bulb outdoor temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSTART</td>
<td>optimum start time (military time)</td>
<td>( t_s )</td>
<td></td>
</tr>
<tr>
<td>TUNOC</td>
<td>beginning time of unoccupancy (military time)</td>
<td>( t_{\text{unoc}} )</td>
<td></td>
</tr>
<tr>
<td>XD</td>
<td>X-value where Y-value is equal to YSET</td>
<td>( x_o )</td>
<td></td>
</tr>
<tr>
<td>XDATA(I)</td>
<td>modified time of day (X-value)</td>
<td>( x(I) )</td>
<td></td>
</tr>
<tr>
<td>XL</td>
<td>left-most value of X</td>
<td>( x_L )</td>
<td></td>
</tr>
<tr>
<td>XOCC</td>
<td>beginning of occupancy</td>
<td>( x_{\text{OCC}} )</td>
<td></td>
</tr>
<tr>
<td>XOCC1</td>
<td>past value of XOCC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XOFF</td>
<td>optimum off time</td>
<td>( x_{\text{OFF}} )</td>
<td></td>
</tr>
<tr>
<td>XR</td>
<td>right-most value of X</td>
<td>( x_R )</td>
<td></td>
</tr>
<tr>
<td>XROOT</td>
<td>root</td>
<td>( x_{\text{ROOT}} )</td>
<td></td>
</tr>
<tr>
<td>XSTART</td>
<td>optimum start time</td>
<td>( x_S )</td>
<td></td>
</tr>
<tr>
<td>XUNOC</td>
<td>beginning of unoccupancy</td>
<td>( x_{\text{UNOC}} )</td>
<td></td>
</tr>
<tr>
<td>XUNOC1</td>
<td>past value of XUNOC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XX</td>
<td>intermediate value of X</td>
<td>( x_{\text{XX}} )</td>
<td></td>
</tr>
<tr>
<td>X(I)</td>
<td>specific time of day with its origin TBEGIN (I = 1,2,3,4)</td>
<td>( x_i )</td>
<td></td>
</tr>
<tr>
<td>Notation in Programs</td>
<td>Descriptions</td>
<td>Notation in Flow Charts</td>
<td>Notation in the Text</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td>-------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>X2</td>
<td>intermediate value used in ROOT</td>
<td>X'</td>
<td></td>
</tr>
<tr>
<td>YDATA(I)</td>
<td>temperature ((Y\text{-value}))</td>
<td>Y(I)</td>
<td>(y)</td>
</tr>
<tr>
<td>YINF</td>
<td>steady-state temperature as (X) goes to infinity during off-period</td>
<td>(Y_{\infty})</td>
<td>(y_{\infty})</td>
</tr>
<tr>
<td>YMAX</td>
<td>maximum temperature</td>
<td>(Y_{\text{MAX}})</td>
<td>(y_{\text{max}})</td>
</tr>
<tr>
<td>YMIN</td>
<td>minimum temperature</td>
<td>(Y_{\text{MIN}})</td>
<td>(y_{\text{min}})</td>
</tr>
<tr>
<td>YOFF</td>
<td>temperature curve during cool-down period</td>
<td>(Y_{\text{OFF}})</td>
<td>(y_{\text{OFF}}(X))</td>
</tr>
<tr>
<td>YONNEW</td>
<td>updated temperature curve during on-period</td>
<td>(Y_{\text{ON}})</td>
<td>(y_{\text{ON}}(X))</td>
</tr>
<tr>
<td>YSET</td>
<td>set point temperature (target temperature)</td>
<td>(Y_{\text{SET}})</td>
<td>(y_{\text{set}})</td>
</tr>
<tr>
<td>YSS</td>
<td>steady-state temperature as (X) goes to infinity during on-period</td>
<td>(Y_{\text{SS}})</td>
<td>(y_{\text{SS}})</td>
</tr>
<tr>
<td>Y(I)</td>
<td>temperature ((I = 1, 2, 3, 4))</td>
<td>(Y_{i})</td>
<td>(y_{i})</td>
</tr>
</tbody>
</table>
ITMAX: maximum number of iterations permitted in ROOT to obtain a root within the specified accuracy (=20)

EPSOFF: small positive real number for the temperature tolerance used in determining the dead time during the off-period (=0.25°C)

EPSON: small positive real number for the temperature tolerance used in determining the dead time during the on-period (=0.25°C)

EPSSET: small positive real number for the temperature tolerance used in reaching the daytime set point temperature (=0.25°C)

The above numerical values were assigned to be appropriate for the simulated system under control. Depending upon the characteristics of the building and the heating/cooling system, the values in the DATA statements may be changed accordingly.

For testing purposes, the main program, OPMAIN, can be used. This program, which is listed at the end of Appendix C, calls the main routine, OPTSS, and the on-off control routine, ONOFF. In the OPMAIN program, the on-off control routine is the only routine called during non-working days. The on-off controller may be replaced with another type controller if desired. If occupancy schedule changes are needed, new values of t_{occ} and t_{unocc} for the next cycle must be provided before the ending of the current cycle.

A simulation run of the program has been made using a predetermined temperature history of the outdoor air and the room air to demonstrate input-output operation. Input data and resulting output data of this run are presented in Appendix D, and may be used for test purposes.
If the sampling frequency is to be changed, the integer number NPTH in the PARAMETER statement of the OPTSS and OPMAIN routines must be changed. For example, if the sampling interval is 10 minutes, the sampling frequency (NPTH) will be 6 (samples per hour).

Implementation of the optimum start/stop control algorithm on an actual building control computer requires that the main program, OPMAIN, is to be converted into a subroutine which serves as an interface routine between the main routine, OPTSS, and a supervisory program. The supervisory program may govern data collection and transmission activity and perform high level operations; for example, choosing a proper algorithm for a given situation based on the level of priority.
8. CONCLUSIONS

An optimum start/stop control algorithm is described for use in on-line digital control of HVAC systems. The start time for a heating system is determined using the temperature rise profile from the previous day's heat-up period and the temperature decay profile from the current cool-down period, and finding the point (time before occupancy) at which they intersect. The profiles are approximated from actual data using a simple exponential fit. With minor modifications, the algorithm is also capable of finding the optimum start and stop times for a building cooling system. If this algorithm is applied to lightweight, intermittently occupied buildings with low thermal inertia, energy savings should be realized, although the exact magnitude of these savings has not yet been determined. Future research involves implementation, testing, and verification of this algorithm on an energy management and control system in an actual building.
ACKNOWLEDGEMENTS

The author is indebted to Dr. George E. Kelly and Mr. William B. May for their helpful suggestions.
REFERENCES


APPENDIX A. DETERMINATION OF OPTIMUM START TIME FOR HEATING

If measured data are available on the building interior space temperature with respect to time, approximate equations can be constructed to fit both the temperature decay and rise curves that result from turning the heating equipment off and on. Assuming that the structure is very light (fast thermal response) and that the heating equipment has no dead time (immediate response), a temperature history similar to the one shown in figure A-l may be assumed. The off- and on-periods are defined as the period when heating equipment is off and full on, respectively. For convenience, an x-y coordinate system described in section 2.4 is used. Time and temperature are denoted by x and y, respectively. Military time at the origin of the x-y coordinate system is taken as a midpoint time of the occupied period.

During the on-period, an approximate equation yields:

\[ y_{ON}(x) = y_{SS} - (y_{SS} - y_1) e^{-\frac{x-x_1}{\tau_{ON}}} \]  \hspace{1cm} (1)

where

- \( x_1 \) = an arbitrary point of x in the on-period (the chosen value of \( x_1 \) is one-third of the on-period plus x-value at the intersection),
- \( y_1 \) = measured temperature at \( x_1 \),
- \( y_{SS} \) = steady-state temperature as \( x \to \infty \), and
- \( \tau_{ON} \) = time constant during the on-period.
Figure A-l. Temperature history of a lightweight structure with immediate response of heating equipment.
Using two data points, \((x_1, y_1)\) and \((x_2, y_2)\), the time constant can be obtained from:

\[
ON = \frac{x_2 - x_1}{\ln\left(\frac{y_{SS} - y_1}{y_{SS} - y_2}\right)}
\]  

(2)

where

\(x_2 = \) an arbitrary point of \(x\) in the on-period which is greater than \(x_1\) (the chosen value of \(x_2\) is two-thirds of the on-period plus \(x\)-value at the intersection), and

\(y_2 = \) measured temperature at \(x_2\).

An expression for the off-period is:

\[
y_{OFF}(x) = y_\infty + (Y_3 - y_\infty)e^{-\frac{x-x_3}{\tau_{OFF}}}
\]

(3)

where

\(x_3 = \) an arbitrary point of \(x\) in the off-period (the chosen value of \(x_3\) is one-fourth of the off-period plus \(x\)-value at the beginning of the unoccupied period.),

\(y_3 = \) measured temperature at \(x_3\),

\(y_\infty = \) steady-state temperature as \(x \to \infty\), and

\(\tau_{OFF} = \) time constant during off-period.

The off-period time constant is given by

\[
\tau_{OFF} = \frac{x_4 - x_3}{\ln\left(\frac{y_3 - y_\infty}{y_4 - y_\infty}\right)}
\]

(4)
If \( y_\infty \) and \( y_{SS} \) are predetermined, the decay and rise temperature curves can be determined using the given data points \((x_1, y_1), (x_2, y_2), (x_3, y_3), \) and \((x_4, y_4)\). The value of \( y_\infty \) is taken to be the lowest allowable indoor dry-bulb temperature during the unoccupied period (heating mode) and \( y_{SS} \) is approximated as \( 1.5 \cdot y_{\text{set}} \), where \( y_{\text{set}} \) is the set point temperature for occupancy. Since the time domain of interest is finite, the effect on \( y_{ON}(x) \) and \( y_{OFF}(x) \) of errors in the estimated asymptotic values \( y_\infty \) and \( y_{SS} \) is small.

After the functions \( y_{ON}(x) \) and \( y_{OFF}(x) \) are determined, the point of their intersection can be obtained using a method for finding a root of a function \( f(x) \), where \( f(x) = y_{ON}(x) - y_{OFF}(x) \). The method used was the regula falsi method (false position method [9]). For this method, if a function is bounded and has only one root in a given interval, the solution converges within a given tolerance after a number of iterations. The time corresponding to their intersection is then considered to be the optimum start time.

Difficulties can arise in using the regula falsi method with \( y_{ON}(x) \) if the whole unoccupied period is taken as the interval of interest. As seen in figure A-1, \( y_{ON}(x) \) is not, in general, bounded in that interval. Thus, the left-most value, \( x_L \), of the interval should be selected so that \( y_{ON}(x) \) is bounded in that interval. The approach used in this algorithm for choosing \( x_L \) is to set \( x_L \) equal to the value of \( x \) which satisfies the condition:

\[
y_{ON}(x) = y_{\min}, \quad \text{where } y_{\min} \text{ is the minimum temperature to maintain.}
\]

The optimum start time is determined by finding an intersection of the current temperature decay curve and the temperature rise curve of the previous day. Any changes in the heating system characteristics and environment in the
current day could result in a change in the temperature rise curve during the current on-period.

It is desirable that the temperature rise curve reaches the target temperature (set point) at the beginning of occupancy. If the temperature rise curve changes during the on-period and there are errors due to approximation, the space temperature will reach the set point a little earlier or later than the optimum time. In order to correct this offset, the fitted temperature rise equation should be corrected by the amount of time offset.

Figure A-2 shows both the fitted curve (solid line) based on measurement and the updated curve (dotted line) during the on-period. The x-coordinate is shifted by the difference, \( x_{\text{occ}} - x_0 \). \( x_{\text{occ}} \) is the beginning of occupancy and \( x_0 \) is the point where \( y \) is equal to the set point, \( y_{\text{set}} \). The updated equation is then

\[
y_{\text{on}}(x) = y_{\text{SS}} - (y_{\text{SS}} - y_1)e^{-\frac{x-x^*}{\tau_{\text{ON}}}}
\]

(5)

where

\[
x^* - \text{the updated } x_1, \text{ given by} \]

\[
x^* = x_1 + (x_{\text{occ}} - x_0),
\]

(6)

and

\[
x_0 = x_1 - \tau_{\text{ON}} \ln \left( \frac{y_{\text{SS}} - y_{\text{set}}}{y_{\text{SS}} - y_1} \right)
\]

(7)
Figure A-2. The fitted curve (solid line) based on measurement and the updated curve (dotted line) during the on-period.

Figure A-3. The dead time during the on-period.
Consequently, equation 5 should be used instead of equation 1 to determine the optimum start time in conjunction with equation 3.

When the building structure has slow thermal response and the heating system has a transport delay time (dead time), the assumption made earlier about dead time is not correct. Therefore, it is necessary to take account of the duration of any "flat response" during the on-period. This "flat response" period can be defined as the time period that \( |y - y_S| < \epsilon \), where \( y_S \) is the temperature at the beginning of the on-period and \( \epsilon \) is a small positive number. The dead time is then defined as the duration of the "flat response" period (see figure A-3). The calculated start time must then be adjusted by the amount of dead time, \( d_{ON} \). For example, if the calculated start time is \( x_S \) under the assumptions of light structure and no dead time, the correct start time for a system with high thermal mass and a heating system with transport delay will be

\[
x_S^* = x_S - d_{ON}.
\]

Since the magnitude of \( \epsilon \) strongly affects the dead time, the better the selection of \( \epsilon \), the better the estimate of the optimum start time. A value for \( \epsilon \) of 0.25°C was used in the computer program presented in Appendix C.
Flow charts of the optimum start/stop control algorithm are shown in figures B-1 through B-9. The most important subroutine is the OPTSS subroutine. For detailed information, this subroutine is divided into five blocks, which are given in subsequent figures (figures B-1 through B-3). Descriptions of principal variables can be found in table 1.
Figure B-1. Flow charts of the block 1 and 2 of the subroutine, OPTSS
Figure B-2. Flow charts of the block 3 and 4 of the subroutine, OPTSS.
Figure B-3. Flow chart of the block 5 of the subroutine, OPTSS

Figure B-4. Flow chart of the subroutine, XCOORD
Figure B-5. Flow charts of the functions: YONNEW, YOFF, and FYDIF

Figure B-6. Flow charts of the subroutine: MAXMIN
Figure B-7. Flow charts of the subroutines, ROOT and XLTRT
Figure B-9. Flow chart of the on-off program, OPMAIN

Figure B-8. Flow chart of the on-off subroutine, ONOFF
APPENDIX C. COMPUTER PROGRAM LISTING

Q$Q$Q$*OPT(1).OPTALL(O)

1 C
2 C
3 C  OPTSS : OPTIMUM START AND STOP CONTROL ALGORITHM
4 C
5 C  MAR. 3, 1983 C.P.
6 C
7 C
8 C
9 C  DAYCNT  TRUE IF THE DAYTIME CONTROLLER OPERATES
10 C  FALSE IF THE DAYTIME CONTROLLER DOES NOT OPERATE
11 C  DELY  TEMPERATURE DIFFERENCE
12 C  EPS  POSITIVE SMALL NUMBER FOR ACCURACY USED IN ROOT
13 C  EPSOFF  POSITIVE SMALL NUMBER
14 C  EPSON  POSITIVE SMALL NUMBER
15 C  EPSSET  POSITIVE SMALL NUMBER
16 C  EPSX  TOLERANCE DETERMINED BY SAMPLING FREQUENCY
17 C  FSYSNO  TRUE IF THE SYSTEM OPERATES AT FULL POWER
18 C  FTOL  FALSE IF THE SYSTEM IS OFF
19 C  H  TRUE FOR HEATING MODE
20 C  FALSE FOR COOLING MODE
21 C  ICYC  NUMBER OF CYCLES (ONE CYCLE PER DAY)
22 C  ITDOWN  INDEX NUMBER WHERE TEMPERATURE DECAY BEGINS
23 C  ITIM  INDEX NUMBER OF MODIFIED TIME OF DAY
24 C  ITMAX  MAXIMUM NUMBER OF ITERATION TO OBTAIN A ROOT USED IN ROOT
25 C  ITOFF  INDEX NUMBER WHERE X=OFF
26 C  ITON  INDEX NUMBER WHERE X=ON
27 C  ITSET  INDEX NUMBER WHERE TEMPERATURE REACHES AT THE SET POINT
28 C  ITUNC  INDEX NUMBER WHERE X=UNOC
29 C  ITUP  INDEX NUMBER WHERE TEMPERATURE RISE BEGINS
30 C  MAINTN  TRUE IF THE ON-OFF CONTROL IS NEEDED
31 C  FALSE IF THE ON-OFF CONTROL IS NOT NEEDED
32 C  NMAX  TOTAL NUMBER OF SAMPLES A DAY
33 C  NPTHR  NUMBER OF SAMPLES IN ONE HOUR
34 C  PARTON  TRUE IF THE SYSTEM OPERATES WITH A PARTIAL CAPACITY
35 C  FALSE IF THE SYSTEM IS OFF
36 C  SWI  EVENT CONTROL SWITCHES (I=0,...,7)
37 C  TAUFF  SYSTEM TIME CONSTANT DURING THE OFF-PERIOD
38 C  TAUN  SYSTEM TIME CONSTANT DURING THE ON-PERIOD
39 C  TBEGIN  ORIGIN OF X-COORDINATE (MILITARY TIME)
40 C  TDEDOD  DEAD TIME DURING THE OFF-PERIOD
41 C  TDEDON  DEAD TIME DURING THE ON-PERIOD
42 C  TEMP  INDOOR OR INTERIOR SURFACE TEMPERATURE
43 C  TIME  TIME OF DAY (MILITARY TIME)
44 C  TIMEX  MODIFIED TIME OF DAY IN SCALAR
45 C  TOA(1)  OUTDOOR TEMPERATURE
46 C  TOCC  BEGINNING TIME OF OCCUPANCY (MILITARY TIME)
47 C  TOFF  OPTIMUM STOP TIME (MILITARY TIME)
48 C  TOUT  DRY-BULB OUTDOOR TEMPERATURE
49 C  TSTART  OPTIMUM START TIME (MILITARY TIME)
50 C  TXNSCC  BEGINNING TIME OF UNOCCUPANCY (MILITARY TIME)
51 C  X(I)  MODIFIED TIME OF DAY WITH ITS ORIGIN AT TBEGIN
52 C  XD  X-VALUE WHERE Y-VALUE IS EQUAL TO YSET
53 C  XDATA(*)  MODIFIED TIME OF DAY (X-VALUE)
54 C  XOC  BEGINNING TIME OF OCCUPANCY IN X-COORDINATE
55 C  XOC1  PAST VALUE OF XOC
56 C  XOFF  OPTIMUM STOP TIME IN X-COORDINATE
57 C  XSTART  OPTIMUM START TIME IN X-COORDINATE

41
C XUNOC  BEGINNING TIME OF UNOCCUPANCY IN X-COORDINATE
C XUNOC1 PAST VALUE OF XOCC
C Y(I)  TEMPERATURE
C YDATA(*) TEMPERATURE (Y-VALUE)
C YINF  STEADY-STATE TEMPERATURE AS X GOES TO INFINITY DURING
C THE OFF-PERIOD
C YMAX  MAXIMUM TEMPERATURE
C YMIN  MINIMUM TEMPERATURE
C YSET  SET POINT TEMPERATURE (TARGET TEMPERATURE)
C YSS   STEADY-STATE TEMPERATURE AS X GOES TO INFINITY DURING
C THE ON-PERIOD

******************************************************************************

C SUBROUTINE OPTSS(TIME,TEMP,TOUT)
C LOGICAL SW0,SW1,SW2,SW3,SW4,SW5,SW6,SW7,HEAT,MAINTN,PARTON,
C & FSYSON,DAYCNT
C EXTERNAL FYDIF
C PARAMETER (NPTHR=4,NMAX=NPTHR*24)
C DIMENSION XDATA(0:NMAX),YDATA(0:NMAX),TOA(0:NMAX)
C COMMON /XY/ X(4),Y(4),XOCC,XUNOC,YSET
C & /CNST/ TAUON,TAUOFF,YINF,YSS,XD
C & /LIMIT/ YMIN,YMAX,HEAT,MAINTN,FSYSON,DAYCNT,XSTART
C & /TSET/ TSTART,TOFF,TOCC,TUNOC,TBEGIN
C & NAMELIST /RESULT/X,Y,XOCC,XUNOC,YSET
C & YSS,YINF,ICYCLE,ITIME,ITOFF,ITUNOC,ITDOWN,ITON,ITUP,ITSET,
C & TBEGIN,TOFF,TUNOC,TSTART,TOCC
C DATA EPS,ITMAX/0.005,20/
C DATA SW0/.TRUE.,/EPSOFF,EPSON,EPSSSET/3*0.25/

C INITIAL CONDITIONS

C EPSX=0.5/NPTHR
C IF(SWO) THEN
C ICYCLE=0
C SW1=.FALSE.
C SW2=.FALSE.
C SW3=.FALSE.
C SW4=.FALSE.
C SW5=.FALSE.
C SW6=.FALSE.
C SW7=.FALSE.
C MAINTN=.FALSE.
C PARTON=.FALSE.
C FSYSON=.FALSE.
C DAYCNT=.TRUE.

C CHANGE TIME COORDINATES

C CALL XCOORD(XSTART,TSTART,1)
C CALL XCOORD(XOCC,TOCC,1)
C CALL XCOORD(XUNOC,TUNOC,1)
C ENDIF

C STORE INPUT DATA AS ARRAYS IN TERMS OF INDEX TIME

C CALL XCOORD(TIMEX,TIME,1)
C ITIME=TIMEX*NPTHR
TOA(ITIME)=TOUT
XDATA(ITIME)=TIMEX
YDATA(ITIME)=TEMP
X(4)=XDATA(ITIME)
Y(4)=YDATA(ITIME)

TURN OFF THE SYSTEM AT THE BEGINNING OF UNOCCUPANCY OF INITIAL CYCLE

IF(SWO.AND.ABS(XDATA(ITIME)-XUNOC).LT.EPSX) THEN
  DAYCNT=.FALSE.
  ITOFF=ITIME
  ITUNOC=ITIME
  SWO=.FALSE.
  SW2=.TRUE.
  PRINT 100
ENDIF

TURN OFF THE SYSTEM AT THE BEGINNING OF UNOCCUPANCY AFTER INITIAL CYCLE

IF(SW1.AND.XDATA(ITIME).GE.XOFF) THEN
  DAYCNT=.FALSE.
  ITOFF=ITIME
  SW1=.FALSE.
  SW2=.TRUE.
  PRINT 200
ENDIF

DETERMINE DEAD TIME DURING THE OFF-PERIOD

IF(SW2.AND.ABS(YDATA(ITIME)-YDATA(ITOFF)).GE.EPSOFF) THEN
  TDEDOF=XDATA(ITIME)-XDATA(ITOFF)
  XOFF=XUNOC-TDEDOF
  ITDOWN=ITIME
  SW2=.FALSE.
  SW3=.TRUE.
  SW4=.TRUE.
  PRINT 300
ENDIF

MAINTAIN MINIMUM LEVEL OF OPERATION

IF(SW3) THEN
  IF((HEAT.AND.(Y(4).LE.YMIN)).OR.((.NOT.(HEAT)).AND.
& Y(4).GT.YMAX)) THEN
    IF(ICYCLE.GE.1) XSTART=XLEFT-TDEDON
    MAINTN=.TRUE.
    SW3=.FALSE.
    PRINT 400
  ENDIF
ENDIF

FIND THE INTERSECTION OF ON- AND OFF-TEMPERATURE CURVES

IF(ICYCLE.GE.1) THEN
  IF(ABS(XDATA(ITIME)-X(3)).LT.EPSX) THEN
    Y(3)=YDATA(ITIME)
174 C ENDIF
175 C IF(.NOT.MAINTN).AND.(XDATA(ITIME).GT.X(3).AND.XDATA(ITIME) & .LT.XSTART).AND.(ABS(Y(3)-Y(4)).GT.EPSSET)) THEN
176 C IF(HEAT) THEN
177 IF(Y(4).GE.Y(3)) THEN
178 YINF=TOAMAX
179 ELSE
180 YINF=TOAMIN
181 ENDIF
182 ELSE
183 IF(Y(4).LE.Y(3)) THEN
184 YINF=TOAMIN
185 ELSE
186 YINF=TOAMAX
187 ENDIF
188 ENDIF
189 C
190 C
191 C
192 C
193 X=x0.2FE
194 X=x0.24
195 CALL ROOT(XL,XR,eps,ITMAX,FYDIF,XROOT,IFLAG)
196 IF(IFLAG.EQ.0) THEN
197 XSTART=XROOT-TDEDON
198 ELSE
199 XSTART=x0.24-TDEDON
200 ENDIF
201 ENDIF
202 CALL XCOORD(XSTART,TSTART,TBEGIN,2)
203 ENDIF
204 C
205 C TRUN ON THE SYSTEM AT OPTIMUM START TIME
206 C
207 C
208 IF(SW4.AND.XDATA(ITIME).GE.XSTART) THEN
209 FSYSON=.TRUE.
210 ITON=ITIME
211 MAINTN=.FALSE.
212 SW4=.FALSE.
213 SW5=.TRUE.
214 PRINT 500
215 ENDIF
216 C
217 C DETERMINE DEAD TIME DURING THE ON-PERIOD
218 C
219 C
220 IF(SW5.AND.ABS(YDATA(ITIME)-YDATA(ITON)).GE.EPSON) THEN
221 TDEDON=XDATA(ITIME)-XSTART
222 ITUP=ITIME
223 SW5=.FALSE.
224 SW6=.TRUE.
225 PRINT 600
226 ENDIF
227 C
228 C TURN OFF THE SYSTEM NEAR THE BEGINNING OF OCCUPANCY AND CALL
229 C THE DAYTIME CONTROLLER
230 C
231 C
FSYSON* .FALSE.
DAYCNT* .TRUE.
ITSET=ITIME
SW6* .FALSE.
SW7* .TRUE.
PRINT 700
ENDIF

COMPUTE X- AND Y-VALUES BASED ON PREVIOUS OBSERVATION
AND UPDATE THEM USING NEW TOCC AND TUNOC

IF(SW7) THEN
CALL XCOORD(XOFF,TOFF,TBEGIN,2)
PRINT 900
PRINT RESULT
PRINT 900
XOCC1=XOCC
XUNOC1=XUNOC
IF(TUNOC.GT.TOCC) THEN
TBEGIN=0.5*(TUNOC+TOCC)
ELSE
TBEGIN=0.5*(TUNOC+24.+TOCC)
IF(TBEGIN.GE.24.) TBEGIN=TBEGIN-24.
ENDIF
CALL XCOORD(XOCC,TOCC,TBEGIN,1)
CALL XCOORD(XUNOC,TUNOC,TBEGIN,1)
K1=(ITSET-ITUP)/3+ITUP
K2=(ITSET-ITUP)*2/3+ITUP
IF(ICYCLE.EQ.0) THEN
K3=(ITON-ITUNOC)/4+ITUNOC
ELSE
K3=(ITON-ITDOWN)/4+ITDOWN
ENDIF
X(1)=XDATA(K1)+XOCC-XOCC1
X(2)=XDATA(K2)+XOCC-XOCC1
X(3)=XDATA(K3)+XUNOC-XUNOC1
Y(1)=YDATA(K1)
Y(2)=YDATA(K2)
Y(3)=YDATA(K3)
XSTART=XSTART+XOCC-XOCC1
XOFF=XOFF+XUNOC-XUNOC1
CALL XCOORD(XSTART,TSTART,TBEGIN,2)
CALL XCOORD(XOFF,TOFF,TBEGIN,2)

DETERMINE MAXIMUM AND MINIMUM OUTDOOR TEMPERATURES
CALL MAXMIN(TOA,TOAIN,TOAMAX,NMAX)

COMPUTE CONSTANTS FOR ON- AND OFF-PERIOD TEMPERATURE EQUATIONS

IF(HEAT) THEN
YSS=1.5*YSET
YINF=TOAMIN
ELSE
YSS=0.5*YSET
YINF=TOAMAX
ENDIF
DETERMINE XLEFT AND XRIGHT

CALL XLTRT(XLEFT,XRIGHT)

ICYCLE=ICYCLE+1

SW7=.FALSE.

PRINT 800

PRINT 900

PRINT RESULT

PRINT 900

ENDIF

RESET SWITCH SW1 AT THE BEGINNING OF NEXT CYCLE

IF(ICYCLE.GE.1.AND.ABS(TIME-TBEGIN).LT.EPSX) SW1=.TRUE.

FORMAT STATEMENTS

100 FORMAT(SX,'---SW0---SYSTEM OFF AT THE FIRST CYCLE')

200 FORMAT(SX,'---SW1---SYSTEM OFF')

300 FORMAT(SX,'---SW2---DECAY/RISE RESPONSE OCCURS')

400 FORMAT(SX,'---SW3---ON-OFF CONTROLLER TAKES OVER')

500 FORMAT(SX,'---SW4---SYSTEM ON AT FULL POWER')

600 FORMAT(SX,'---SW5---UPRISE/DECAY RESPONSE OCCURS')

700 FORMAT(SX,'---SW6---DAYTIME CONTROLLER TAKES OVER')

800 FORMAT(SX,'---SW7---CALCULATIONS FOR NEXT CYCLE ARE DONE')

RETURN

END

**************************************************************

FYDIF : TEMPERATURE DIFFERENCE

**************************************************************

YONNEW UPDATED TEMPERATURE DURING THE HEAT-UP PERIOD

YOFF TEMPERATURE DURING THE COOL-DOWN PERIOD

FUNCTION FYDIF(XX)

TEMPERATURE DIFFERENCE BETWEEN YONNEW AND YOFF

TO BE USED IN DETERMINATION OF INTERSECTION. XROOT

FYDIF=YONNEW(XX)-YOFF(XX)

RETURN

END

**************************************************************

YONNEW, YOFF : THE ON- AND OFF-PERIOD TEMPERATURES

FUNCTION YONNEW(XX)

COMMON /XY/ X(4),Y(4),XOCC,XUNOC,YSET

& /CNST/ TAUON,TAUOFF,YINF,YSS, XD
THE ON-PERIOD TEMPERATURE WITH ADJUSTMENT

\[ T_{\text{ON}} = \frac{(X(2) - X(1))}{\ln\left(\frac{Y_{\text{SS}} - Y(1)}{Y_{\text{SS}} - Y(2)}\right)} \]

\[ X_D = X(1) - T_{\text{ON}} \ln\left(\frac{Y_{\text{SS}} - Y(1)}{Y_{\text{SS}} - Y(1)}\right) \]

\[ X_{\text{IP}} = X(1) + X_{\text{OCC}} - X_D \]

\[ Y_{\text{ONNEW}} = Y_{\text{SS}} - (Y_{\text{SS}} - Y(1)) \times \exp((X_{\text{IP}} - X)/T_{\text{ON}}) \]

RETURN

ENTRY YOFF(XX)

THE OFF-PERIOD TEMPERATURE

\[ T_{\text{OFF}} = \frac{(X(4) - X(3))}{\ln\left(\frac{Y(3) - Y_{\infty}}{Y(4) - Y_{\infty}}\right)} \]

\[ Y_{\text{OFF}} = (Y(3) - Y_{\infty}) \times \exp((X(3) - X)/T_{\text{OFF}}) + Y_{\infty} \]

RETURN

END

ROOT: FIND A ROOT OF A FUNCTION \( F(X) = 0 \) IN A GIVEN INTERVAL BY THE REGULA-FALSI METHOD

REFERENCE:
Carnahan, Luther, and Wilkes

THE ORIGINAL PROGRAM WAS MODIFIED IN FORTRAN77.

---

EPS A POSITIVE SMALL NUMBER FOR ACCURACY
FX SCALAR FUNCTION VALUE
IFLAG 0 IF FINDING A ROOT IS SUCCESSFUL
       1 IF FINDING A ROOT IS NOT SUCCESSFUL
ITMAX MAXIMUM NUMBER OF ITERATIONS
XL LEFT-MOST X-VALUE
XR RIGHT-MOST X-VALUE
XROOT A REAL ROOT

---

SUBROUTINE ROOT(XL,XR,EPS,ITMAX,FX,XROOT,IFLAG)

PRINT 100,XL,XR,EPS,ITMAX
100 FORMAT(3F10.5,15)

SET LEFTMOST AND RIGHTMOST FUNCTION VALUES

FXL=FX(XL)
FXR=FX(XR)

CHECK FOR PRESENCE OF A ROOT

IF(FXL*FXR.LT.0.) THEN

BEGIN REGULA FALSI ITERATION

DO 10 I=1,ITMAX

---
X2=(XL*FXR-XR*FXL)/(FXR-FXL)
FX2=FX(X2)
C CHECK FOR CONVERGENCE
C IF(ABS(FX2).LE.EPS) GOTO 20
C KEEP RIGHT OR LEFT SUBINTERVAL
C IF(FX2*FXL.LT.0.) THEN
XR=X2
FXR=FX2
ELSE
XL=X2
FXL=FX2
ENDIF
10 CONTINUE
PRINT 200,ITMAX
200 FORMAT(5X,'NO CONVERGENCE AFTER',I5,2X,'ITERATIONS')
ELSEIF (FXL*FXR.EQ.0.) THEN
ITER=1
IF(FXL.EQ.0.) THEN
X2=XL
FX2=0.
ELSE
X2=XR
FX2=0.
ENDIF
ELSE
IFLAG=1
PRINT 300
300 FORMAT(5X,'POSSIBLY NO ROOT ')
RETURN
ENDIF
20 XROOT=X2
IFLAG=0
C* PRINT 400,ITER,XROOT,FX2
400 FORMAT(5X,'ITER = ',5X,'XROOT = ',F10.6/5X,'FX2 = ',F10.6)
C RETURN
END
C**********************************************************************
C XLTRT : LEFTMOST AND RIGHTMOST X-VALUES FOR THE SUBROUTINE. ROOT
C**********************************************************************
C
C DX TIME INCREMENT
C N NUMBER OF INTERVALS
C XL LEFT-MOST VALUE OF X
C XR RIGHT-MOST VALUE OF X
C**********************************************************************
C
SUBROUTINE XLTRT(XL,XR)
LOGICAL HEAT
COMMON /XY/ X(4),Y(4),XUNOC,YSET
& /LIMIT/ YMIN,YMAX,HEAT,MAINTN,FSYSON,DAYCNT,XSTART
C TIME BASIS IS HOUR, AND TIME INCREMENT IS 5 MIN.

DX=5./60.
N=(XOCC-XUNOC)/DX
XX=X(2)
DO 10 I=1,N
IF(HEAT) THEN
  IF(YONNEW(XX).LE.YMIN) GOTO 20
ELSEIF(YONNEW(XX).GE.YMAX) THEN
  GOTO 20
ENDIF
XX=XX-DX
10 CONTINUE
XL=XX
XR=XOCC
PRINT 100.XL.XR
100 FORMAT(5X,'XLEFT=',F10.4,5X,'XRIGHT=',F10.4/)
C SUBROUTINE XCOORD(X, TIME, TBEGIN, IFLAG)
  IF(FLAG.EQ.1) THEN
    IF(TIME.GE.TBEGIN .AND. TIME.LE.24.) THEN
      X=TIME-TBEGIN
    ELSE
      X=TIME+(24.-TBEGIN)
    ENDIF
  ELSE
    TIME=X+TBEGIN
  ENDIF
  RETURN
END

C ONOFF : THE ON-OFF CONTROL ALGORITHM

C SUBROUTINE ONOFF(TEMP)
  LOGICAL HEAT, MAINTN, FSYSON, DAYCNT, PARTON
  COMMON /LIMIT/ YMIN, YMAX, HEAT, MAINTN, FSYSON, DAYCNT, XSTART
& /ONOFFC/ PARTON, DELY
  IF(HEAT) THEN
    IF(TEMP.LE.YMIN) PARTON=.TRUE.
    IF(TEMP.GE.YMIN+DELY) PARTON=.FALSE.
    ELSEIF(TEMP.GE.YMAX) THEN
      PARTON=.TRUE.
    ELSEIF(TEMP.LE.YMAX-DELY) THEN
      PARTON=.FALSE.
    ENDIF
  ELSEIF(TEMP.GE.YMAX) THEN
    PARTON=.TRUE.
  ELSEIF(TEMP.LE.YMIN) THEN
    PARTON=.FALSE.
  ENDIF
  RETURN
END

C OPMAIN : MAIN PROGRAM OF OPTIMUM START/STOP CONTROL
FOR BOTH HEATING AND COOLING SEASONS

C DATE DATE OF YEAR
C DAY =0 FOR NON-WORKING DAY
C =1 FOR WORKING DAY
C NSKIP NUMBER OF RECORDS TO BE SKIPPED IN PRINTING OUT
C RSCHDL TIMES WHEN THE SCHEDULE FILE IS READ (MILITARY TIME)
C TITLE TITLE OF INPUT DATA SET IN TWO ROWS
C
C PROGRAM OPMAIN
LOGICAL HEAT, MAINTN, FSYSON, DAYCNT, PARTON
INTEGER DATE, DAY
CHARACTER TITLE(2)*80
PARAMETER (NPTH=4)
DIMENSION RSCHDL(2)
COMMON /XY/ X(4),Y(4),XOCC,XUNOC,YSET
& /CNST/ TAUON,TAUOFF,YINF,YSS,XD
& /LIMIT/ YMIN,YMAX,HEAT,MAINTN,FSYSON,DAYCNT,XSTART
& /ONOFFC/ PARTON,DELY
& /TSET/ TSTART,TOFF,TOCC,TUNOC,TBEGIN
NAMELIST /INIT/ DATE,DAY,TOCC,TUNOC,TSTART,
& YSET,YMIN,YMAX,DELY,HEAT,NSKIP
& /DAYOCC/ DATE,DAY,TOCC,TUNOC
& /OUTPUT/ TIME,MAINTN,PARTON,FSYSON,DAYCNT,
& TSTART,TOFF,TOCC,TUNOC,TBEGIN
DATA RSCHDL/6.0,18.0/
OPEN FILE 7 FOR INITIAL AND SCHEDULE INFORMATION
OPEN FILE 8 FOR SIMULATED DATA OF MEASURED VALUES
READ INITIAL INPUT DATA
READ(7,1000) TITLE
READ(7,INIT)
PRINT 1000, TITLE
IW=0
I=0
READ SIMULATED MEASURED DATA AND SCHEDULE INFORMATION
READ(8.*,EN=999) TIME,TEMP,TOUT
IF(I.EQ.0) TBEGIN=TIME
IF((ABS(TIME-RSCHDL(1)).LT.0.5/NPTH).OR.
& (ABS(TIME-RSCHDL(2)).LT.0.5/NPTH)) THEN
READ(7,DAYOCC)
PRINT DAYOCC
ENDIF
MAINTAIN MINIMUM REQUIREMENT DURING NOT-WORKING DAYS
IF(DAY.EQ.0) THEN
MAINTN=.TRUE.
ELSE
CALL OPTSS(TIME,TEMP,TOUT)
ENDIF
IF(MAINTN) CALL ONOFF(TEMP)
IF(IW.EQ.NSKIP+1) THEN
PRINT *,TIME,TEMP,TOUT
PRINT OUTPUT
IW=0
ENDIF
IW=IW+1
I=1
GOTO 10
C FORMAT STATEMENTS
C 1000 FORMAT(A80/A80)
C 999 STOP
END
<table>
<thead>
<tr>
<th>TIME</th>
<th>TEMP</th>
<th>TOUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.000</td>
<td>18.300</td>
</tr>
<tr>
<td>2</td>
<td>12.250</td>
<td>18.300</td>
</tr>
<tr>
<td>3</td>
<td>12.500</td>
<td>18.300</td>
</tr>
<tr>
<td>4</td>
<td>12.750</td>
<td>18.300</td>
</tr>
<tr>
<td>5</td>
<td>13.000</td>
<td>18.300</td>
</tr>
<tr>
<td>6</td>
<td>13.250</td>
<td>18.300</td>
</tr>
<tr>
<td>7</td>
<td>13.500</td>
<td>18.300</td>
</tr>
<tr>
<td>8</td>
<td>13.750</td>
<td>18.300</td>
</tr>
<tr>
<td>9</td>
<td>14.000</td>
<td>18.300</td>
</tr>
<tr>
<td>10</td>
<td>14.250</td>
<td>18.300</td>
</tr>
<tr>
<td>11</td>
<td>14.500</td>
<td>18.300</td>
</tr>
<tr>
<td>12</td>
<td>14.750</td>
<td>18.300</td>
</tr>
<tr>
<td>13</td>
<td>15.000</td>
<td>18.300</td>
</tr>
<tr>
<td>14</td>
<td>15.250</td>
<td>18.300</td>
</tr>
<tr>
<td>15</td>
<td>15.500</td>
<td>18.300</td>
</tr>
<tr>
<td>16</td>
<td>15.750</td>
<td>18.300</td>
</tr>
<tr>
<td>17</td>
<td>16.000</td>
<td>18.300</td>
</tr>
<tr>
<td>18</td>
<td>16.250</td>
<td>18.300</td>
</tr>
<tr>
<td>19</td>
<td>16.500</td>
<td>18.300</td>
</tr>
<tr>
<td>20</td>
<td>16.750</td>
<td>18.300</td>
</tr>
<tr>
<td>21</td>
<td>17.000</td>
<td>18.300</td>
</tr>
<tr>
<td>22</td>
<td>17.250</td>
<td>18.300</td>
</tr>
<tr>
<td>23</td>
<td>17.500</td>
<td>18.300</td>
</tr>
<tr>
<td>24</td>
<td>17.750</td>
<td>18.300</td>
</tr>
<tr>
<td>25</td>
<td>18.000</td>
<td>18.300</td>
</tr>
<tr>
<td>26</td>
<td>18.250</td>
<td>18.300</td>
</tr>
<tr>
<td>27</td>
<td>18.500</td>
<td>17.900</td>
</tr>
<tr>
<td>28</td>
<td>18.750</td>
<td>17.700</td>
</tr>
<tr>
<td>29</td>
<td>19.000</td>
<td>17.500</td>
</tr>
<tr>
<td>30</td>
<td>19.250</td>
<td>17.300</td>
</tr>
<tr>
<td>31</td>
<td>19.500</td>
<td>17.100</td>
</tr>
<tr>
<td>32</td>
<td>19.750</td>
<td>16.900</td>
</tr>
<tr>
<td>33</td>
<td>20.000</td>
<td>16.700</td>
</tr>
<tr>
<td>34</td>
<td>20.250</td>
<td>16.500</td>
</tr>
<tr>
<td>35</td>
<td>20.500</td>
<td>16.300</td>
</tr>
<tr>
<td>36</td>
<td>20.750</td>
<td>16.100</td>
</tr>
<tr>
<td>37</td>
<td>21.000</td>
<td>15.900</td>
</tr>
<tr>
<td>38</td>
<td>21.250</td>
<td>15.700</td>
</tr>
<tr>
<td>39</td>
<td>21.500</td>
<td>15.500</td>
</tr>
<tr>
<td>40</td>
<td>21.750</td>
<td>15.300</td>
</tr>
<tr>
<td>41</td>
<td>22.000</td>
<td>15.100</td>
</tr>
<tr>
<td>42</td>
<td>22.250</td>
<td>14.900</td>
</tr>
<tr>
<td>43</td>
<td>22.500</td>
<td>14.700</td>
</tr>
<tr>
<td>44</td>
<td>22.750</td>
<td>14.500</td>
</tr>
<tr>
<td>45</td>
<td>23.000</td>
<td>14.300</td>
</tr>
<tr>
<td>46</td>
<td>23.250</td>
<td>14.100</td>
</tr>
<tr>
<td>47</td>
<td>23.500</td>
<td>13.900</td>
</tr>
<tr>
<td>48</td>
<td>23.750</td>
<td>13.700</td>
</tr>
<tr>
<td>49</td>
<td>24.000</td>
<td>13.500</td>
</tr>
<tr>
<td>50</td>
<td>24.250</td>
<td>13.300</td>
</tr>
<tr>
<td>51</td>
<td>24.500</td>
<td>13.100</td>
</tr>
<tr>
<td>52</td>
<td>24.750</td>
<td>12.900</td>
</tr>
<tr>
<td>53</td>
<td>25.000</td>
<td>12.700</td>
</tr>
<tr>
<td>54</td>
<td>1.250</td>
<td>9.5750</td>
</tr>
<tr>
<td>55</td>
<td>1.500</td>
<td>9.4500</td>
</tr>
<tr>
<td>56</td>
<td>1.750</td>
<td>9.3250</td>
</tr>
<tr>
<td>57</td>
<td>2.000</td>
<td>9.2000</td>
</tr>
<tr>
<td>TIME</td>
<td>TEMP</td>
<td>TOUT</td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>116</td>
<td>16.750</td>
<td>3.4000</td>
</tr>
<tr>
<td>117</td>
<td>17.000</td>
<td>3.2000</td>
</tr>
<tr>
<td>118</td>
<td>17.250</td>
<td>2.9750</td>
</tr>
<tr>
<td>119</td>
<td>17.500</td>
<td>2.7500</td>
</tr>
<tr>
<td>120</td>
<td>17.750</td>
<td>2.5250</td>
</tr>
<tr>
<td>121</td>
<td>18.000</td>
<td>2.3000</td>
</tr>
<tr>
<td>122</td>
<td>18.250</td>
<td>2.0250</td>
</tr>
<tr>
<td>123</td>
<td>18.500</td>
<td>1.7500</td>
</tr>
<tr>
<td>124</td>
<td>18.750</td>
<td>1.4750</td>
</tr>
<tr>
<td>125</td>
<td>19.000</td>
<td>1.2000</td>
</tr>
<tr>
<td>126</td>
<td>19.250</td>
<td>1.0000</td>
</tr>
<tr>
<td>127</td>
<td>19.500</td>
<td>0.8000</td>
</tr>
<tr>
<td>128</td>
<td>19.750</td>
<td>0.6000</td>
</tr>
<tr>
<td>129</td>
<td>20.000</td>
<td>0.4000</td>
</tr>
<tr>
<td>130</td>
<td>20.250</td>
<td>0.2250</td>
</tr>
<tr>
<td>131</td>
<td>20.500</td>
<td>0.0500</td>
</tr>
<tr>
<td>132</td>
<td>20.750</td>
<td>-0.1250</td>
</tr>
<tr>
<td>133</td>
<td>21.000</td>
<td>-0.3000</td>
</tr>
<tr>
<td>134</td>
<td>21.250</td>
<td>-0.4750</td>
</tr>
<tr>
<td>135</td>
<td>21.500</td>
<td>-0.6500</td>
</tr>
<tr>
<td>136</td>
<td>21.750</td>
<td>-0.8250</td>
</tr>
<tr>
<td>137</td>
<td>22.000</td>
<td>-1.0000</td>
</tr>
<tr>
<td>138</td>
<td>22.250</td>
<td>-1.1500</td>
</tr>
<tr>
<td>139</td>
<td>22.500</td>
<td>-1.3000</td>
</tr>
<tr>
<td>140</td>
<td>22.750</td>
<td>-1.4500</td>
</tr>
<tr>
<td>141</td>
<td>23.000</td>
<td>-1.6000</td>
</tr>
<tr>
<td>142</td>
<td>23.250</td>
<td>-1.7250</td>
</tr>
<tr>
<td>143</td>
<td>23.500</td>
<td>-1.8500</td>
</tr>
<tr>
<td>144</td>
<td>23.750</td>
<td>-1.9750</td>
</tr>
<tr>
<td>145</td>
<td>24.000</td>
<td>-2.1000</td>
</tr>
<tr>
<td>146</td>
<td>24.250</td>
<td>-2.2500</td>
</tr>
<tr>
<td>147</td>
<td>24.500</td>
<td>-2.4000</td>
</tr>
<tr>
<td>148</td>
<td>24.750</td>
<td>-2.5500</td>
</tr>
<tr>
<td>149</td>
<td>25.000</td>
<td>-2.7000</td>
</tr>
<tr>
<td>150</td>
<td>1.250</td>
<td>9.5750</td>
</tr>
<tr>
<td>151</td>
<td>1.500</td>
<td>9.4500</td>
</tr>
<tr>
<td>152</td>
<td>1.750</td>
<td>9.3250</td>
</tr>
<tr>
<td>154</td>
<td>2.250</td>
<td>9.1000</td>
</tr>
<tr>
<td>155</td>
<td>2.500</td>
<td>9.0000</td>
</tr>
<tr>
<td>156</td>
<td>2.750</td>
<td>8.9000</td>
</tr>
<tr>
<td>157</td>
<td>3.000</td>
<td>8.8000</td>
</tr>
<tr>
<td>158</td>
<td>3.250</td>
<td>8.7500</td>
</tr>
<tr>
<td>159</td>
<td>3.500</td>
<td>8.7000</td>
</tr>
<tr>
<td>160</td>
<td>3.750</td>
<td>8.6500</td>
</tr>
<tr>
<td>161</td>
<td>4.000</td>
<td>8.6000</td>
</tr>
<tr>
<td>162</td>
<td>4.250</td>
<td>8.7000</td>
</tr>
<tr>
<td>163</td>
<td>4.500</td>
<td>8.8000</td>
</tr>
<tr>
<td>164</td>
<td>4.750</td>
<td>8.9000</td>
</tr>
<tr>
<td>165</td>
<td>5.000</td>
<td>9.0000</td>
</tr>
<tr>
<td>166</td>
<td>5.250</td>
<td>9.3750</td>
</tr>
<tr>
<td>167</td>
<td>5.500</td>
<td>9.7500</td>
</tr>
<tr>
<td>168</td>
<td>5.750</td>
<td>10.1250</td>
</tr>
<tr>
<td>169</td>
<td>6.000</td>
<td>10.5000</td>
</tr>
<tr>
<td>170</td>
<td>6.250</td>
<td>11.2500</td>
</tr>
<tr>
<td>171</td>
<td>6.500</td>
<td>12.0000</td>
</tr>
<tr>
<td>172</td>
<td>6.750</td>
<td>12.7500</td>
</tr>
<tr>
<td>173</td>
<td>7.000</td>
<td>13.5000</td>
</tr>
<tr>
<td>175</td>
<td>7.500</td>
<td>15.1000</td>
</tr>
<tr>
<td>176</td>
<td>7.750</td>
<td>15.9000</td>
</tr>
<tr>
<td>177</td>
<td>8.000</td>
<td>16.7000</td>
</tr>
<tr>
<td>178</td>
<td>8.250</td>
<td>17.1000</td>
</tr>
<tr>
<td>179</td>
<td>8.500</td>
<td>17.5000</td>
</tr>
<tr>
<td>180</td>
<td>8.750</td>
<td>17.9000</td>
</tr>
<tr>
<td>181</td>
<td>9.000</td>
<td>18.3000</td>
</tr>
<tr>
<td>182</td>
<td>9.250</td>
<td>18.3000</td>
</tr>
<tr>
<td>183</td>
<td>9.500</td>
<td>18.3000</td>
</tr>
<tr>
<td>184</td>
<td>10.000</td>
<td>18.3000</td>
</tr>
<tr>
<td>185</td>
<td>10.250</td>
<td>18.3000</td>
</tr>
<tr>
<td>186</td>
<td>10.500</td>
<td>18.3000</td>
</tr>
<tr>
<td>187</td>
<td>10.750</td>
<td>18.3000</td>
</tr>
<tr>
<td>188</td>
<td>11.000</td>
<td>18.3000</td>
</tr>
<tr>
<td>189</td>
<td>11.250</td>
<td>18.3000</td>
</tr>
<tr>
<td>190</td>
<td>11.500</td>
<td>18.3000</td>
</tr>
<tr>
<td>191</td>
<td>11.750</td>
<td>18.3000</td>
</tr>
<tr>
<td>192</td>
<td>12.000</td>
<td>18.3000</td>
</tr>
<tr>
<td>193</td>
<td>12.250</td>
<td>18.3000</td>
</tr>
<tr>
<td>194</td>
<td>12.250</td>
<td>18.3000</td>
</tr>
<tr>
<td>195</td>
<td>12.500</td>
<td>18.3000</td>
</tr>
<tr>
<td>196</td>
<td>12.750</td>
<td>18.3000</td>
</tr>
<tr>
<td>197</td>
<td>13.000</td>
<td>18.3000</td>
</tr>
<tr>
<td>198</td>
<td>13.250</td>
<td>18.3000</td>
</tr>
</tbody>
</table>
INPUT DATA

OPTIN

1  OPTIN:  INPUT DATA FOR OPMAIN
2    HEATING MODE
3 $INIT DATE = 61,DAY = 1,TOCC = 9.0,TUNOC = 17.0,TSTART = 4.0,
4      YSET = 18.3,YMIN = 1.0,YMAX = 27.0,DELY = 1.0,HEAT = T,NSkip = 5,$END
5 $DAYOCC DATE = 61,DAY = 1,TOCC = 9.0,TUNOC = 17.0,$END
6 $DAYOCC DATE = 62,DAY = 1,TOCC = 9.0,TUNOC = 17.0,$END
7 $DAYOCC DATE = 62,DAY = 1,TOCC = 9.0,TUNOC = 17.0,$END
8 $DAYOCC DATE = 63,DAY = 1,TOCC = 9.0,TUNOC = 17.0,$END

END PR

OUTPUT

$PRINT OBJ_NAME$,

OPTIN:  INPUT DATA FOR OPMAIN

HEATING MODE

$INIT

DATE = 61,DAY = 1,TOCC = .90000000+001,TUNOC = .17000000+002,TSTART = .40000000+001,YSET = .18300000+002,
YMIN = .10000000+001,YMAX = .27000000+002,DELY = .10000000+001,HEAT = T,NSkip = 5
$END

13.500000  18.300000  4.750000

$OUTPUT

TIME = .13500000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

15.000000  18.300000  4.700000

$OUTPUT

TIME = .15000000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

16.500000  18.300000  3.600000

$OUTPUT

TIME = .16500000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

---SW0---SYSTEM OFF AT THE FIRST CYCLE

$DAYOCC

DATE = 61,DAY = 1,TOCC = .90000000+001,TUNOC = .17000000+002
$END

18.000000  18.300000  2.300000

$OUTPUT

TIME = .18000000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

---SW2---DECAY/RISE RESPONSE OCCURS

19.500000  16.700000  8.000000

$OUTPUT

TIME = .19500000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

21.000000  14.300000  1.300000

$OUTPUT

TIME = .21000000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END

22.500000  12.300000  1.300000

$OUTPUT

TIME = .22500000+002,MAINTN = F,PARTON = F,FSYSON = F,DAYCNT = T,TSTART = .40000000+001,TOFF = .00000000 ,TOCC = .90000000+001,
TUNOC = .17000000+002,TBEGIN = .12000000+002
$END
.00000000 10.500000 -2.100000
$OUTPUT
TIME = .00000000, MAINTN = F, PARTON = F, SYSY = F, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
1.5000000 9.4500000 -2.9500000
$OUTPUT
TIME = .15000000+001, MAINTN = F, PARTON = F, SYSY = F, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
3.0000000 8.8000000 -3.6000000
$OUTPUT
TIME = .30000000+001, MAINTN = F, PARTON = F, SYSY = F, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
---SW4--- SYSTEM ON AT FULL POWER
4.5000000 8.8000000 -3.9500000
$OUTPUT
TIME = .45000000+001, MAINTN = F, PARTON = F, SYSY = T, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
---SW5--- UPRISE/DECAY RESPONSE OCCURS
$DAYOCC
DATE = 62, DAY = 1, TOCC = .90000000+001, TUNOC = .17000000+002
$END
6.0000000 10.5000000 -3.9000000
$OUTPUT
TIME = .60000000+001, MAINTN = F, PARTON = F, SYSY = T, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
7.5000000 15.1000000 -3.0000000
$OUTPUT
TIME = .75000000+001, MAINTN = F, PARTON = F, SYSY = T, DAYCNT = F, TSTART = .40000000+001, TOFF = .00000000, TOCC = .90000000+001, TUNOC = .17000000+002, TBEGIN = .12000000+002
$END
---SW6--- DAYTIME CONTROLLER TAKES OVER
*******************************************************************************
$RESULT
X = .00000000 .00000000 .00000000 .21000000+02.
Y = .00000000 .00000000 .00000000 .18300000+02, XOFF = .35000000+01, XSTART = .16000000+02, TAUN = .00000000
TAUOFF = .00000000, TEDDN = .75000000+000, TEDD0F = .15000000+01, YSS = .00000000, YINF = .00000000, YCYCLE = 0.
ITIME = 84, ITOFF = 20, ITUNOC = 20, ITDOWN = 26, ITON = 64, ITUP = 67.
ITSET = 84, TBEGIN = .12000000+02, TOFF = .15500000+02, TUNOC = .17000000+02, TSTART = .40000000+01, TOCC = .90000000+01
$END
*******************************************************************************
XLEFT= 14.9167 XRIGHT= 20.0000
---SW7--- CALCULATIONS FOR NEXT CYCLE ARE DONE
*******************************************************************************
$RESULT
X = .17000000+02, .18500000+02, .67500000+01, .21000000+02.
Y = .10500000+02, .15100000+02, .16300000+02, .18300000+02, XOFF = .25000000+01, XSTART = .15000000+02, TAUN = .47376636+01
TAUOFF = .00000000, TEDDN = .75000000+000, TEDD0F = .15000000+01, YSS = .27450000+02, YINF = .40000000+01, YCYCLE = 1.
ITIME = 84, ITOFF = 20, ITUNOC = 20, ITDOWN = 26, ITON = 64, ITUP = 67.
ITSET = 84, TBEGIN = .13000000+02, TOFF = .15500000+02, TUNOC = .17000000+02, TSTART = .40000000+01, TOCC = .90000000+01
9.000000  18.300000  -1.700000

$OUTPUT
TIME = .90000000+001, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001,
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

10.500000  18.300000  1.000000

$OUTPUT
TIME = .10500000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

12.000000  18.300000  3.500000

$OUTPUT
TIME = .12000000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

13.500000  18.300000  4.750000

$OUTPUT
TIME = .13500000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

15.000000  18.300000  4.700000

$OUTPUT
TIME = .15000000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

---SW1--- SYSTEM OFF
16.500000  18.300000  3.600000

$OUTPUT
TIME = .16500000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

$DAYOC
DATE = 62. DAY = 1. TOCC = .90000000+001, TUNOC = .17000000+002
$END

18.000000  18.300000  2.300000

$OUTPUT
TIME = .18000000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

---SW2--- DECAY/RISE RESPONSE OCCURS
19.500000  16.700000  .8000000

$OUTPUT
TIME = .19500000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .40000000+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

21.000000  14.300000  -.3000000

$OUTPUT
TIME = .21000000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .41115713+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END

22.500000  12.300000  -1.300000

$OUTPUT
TIME = .22500000+002, MAINTN = F, PARTON = F, FSYSNO = F, DAYCNT = T, TSTART = .41635842+001, TOFF = .15500000+002, TOCC = .90000000+001
TUNOC = .17000000+002, TBEGIN = .13000000+002
$END
.00000000 10.500000 -2.1000000
$OUTPUT
TIME  =  .00000000, MAINTN  =  F, PARTON  =  F, FSYSNON  =  F, DAYCNT  =  F, TSTART  =  .41742094+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
1.5000000 9.4500000 -2.9500000
$OUTPUT
TIME  =  .15000000+001, MAINTN  =  F, PARTON  =  F, FSYSNON  =  F, DAYCNT  =  F, TSTART  =  .43090498+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
3.0000000 8.8000000 -3.6000000
$OUTPUT
TIME  =  .30000000+001, MAINTN  =  F, PARTON  =  F, FSYSNON  =  F, DAYCNT  =  F, TSTART  =  .44677372+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
4.5000000 8.8000000 -3.9500000
$OUTPUT
TIME  =  .45000000+001, MAINTN  =  F, PARTON  =  F, FSYSNON  =  F, DAYCNT  =  F, TSTART  =  .47176206+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
--- SW4--- SYSTEM ON AT FULL POWER
--- SW5--- UPRISE/DECAY RESPONSE OCCURS
$DATE
DATE  =  63, DAY  =  1, TOCC  =  .90000000+001, TUNOC  =  .17000000+002
$END
6.0000000 10.500000 -3.9000000
$OUTPUT
TIME  =  .60000000+001, MAINTN  =  F, PARTON  =  F, FSYSNON  =  T, DAYCNT  =  F, TSTART  =  .47176206+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
7.5000000 15.100000 -3.0000000
$OUTPUT
TIME  =  .75000000+001, MAINTN  =  F, PARTON  =  F, FSYSNON  =  T, DAYCNT  =  F, TSTART  =  .47176206+001, TOFF  =  .15500000+002, TOCC  =  .90000000+001, TUNOC  =  .17000000+002, TBEGIN  =  .13000000+002
$END
--- SW6--- DAYTIME CONTROLLER TAKES OVER
******************************************************************************

$RESULT
X  =  .17000000+002, .18500000+002, .67500000+001, .20000000+002,
Y  =  .10500000+002, .15100000+002, .16300000+002, .18300000+002, XOFF  =  .10000000+001, XSTART  =  .15717621+002, TAUON  =  .47376636+001,
TAUOFF  =  .18973245+002, TDEDON  =  .53237939+000, TDEDOF  =  .30000000+001, YSS  =  .27450000+002, YINF  =  .40000000+001, ICYCLE  =  1,
ITIME  =  80, ITOFF  =  10, ITDOWN  =  20, ITON  =  22, ITUP  =  63, ITUP  =  65,
ITSET  =  80, TBEGIN  =  .13000000+002, TOFF  =  .14000000+002, TUNOC  =  .17000000+002, TSTART  =  .47176206+001, TOCC  =  .90000000+001
$END
******************************************************************************

XLEFT= 15.4167 XRIGHT= 20.0000
--- SW7--- CALCULATIONS FOR NEXT CYCLE ARE DONE
******************************************************************************

$RESULT
X  =  .17500000+002, .18750000+002, .80000000+001, .20000000+002,
Y  =  .12000000+002, .15900000+002, .14300000+002, .18300000+002, XOFF  =  .10000000+001, XSTART  =  .15717620+002, TAUON  =  .42966613+001,
TAUOFF  =  .18973245+002, TDEDON  =  .53237939+000, TDEDOF  =  .30000000+001, YSS  =  .27450000+002, YINF  =  .40000000+001, ICYCLE  =  2,
ITIME  =  80, ITOFF  =  10, ITDOWN  =  20, ITON  =  22, ITUP  =  63, ITUP  =  65,
ITSET  =  80, TBEGIN  =  .13000000+002, TOFF  =  .14000000+002, TUNOC  =  .17000000+002, TSTART  =  .47176204+001, TOCC  =  .90000000+001
9.000000  18.300000  -1.700000

$OUTPUT
TIME = .9000000+001, MAINTN = F, PARTON = F, FSYSON = F, DAYCNT = T, TSTART = .47176204+001, TOFF = .14000000+002, TOCC = .90000000+01
TUNOC = .17000000+002, TBEGIN = .13000000+002

$END

10.500000  18.300000  1.000000

$OUTPUT
TIME = .10500000+002, MAINTN = F, PARTON = F, FSYSON = F, DAYCNT = T, TSTART = .47176204+001, TOFF = .14000000+002, TOCC = .90000000+01
TUNOC = .17000000+002, TBEGIN = .13000000+002

$END

12.000000  18.300000  3.500000

$OUTPUT
TIME = .12000000+002, MAINTN = F, PARTON = F, FSYSON = F, DAYCNT = T, TSTART = .47176204+001, TOFF = .14000000+002, TOCC = .90000000+01
TUNOC = .17000000+002, TBEGIN = .13000000+002

$END
OPTIN(1)

1 OPTIN: INPUT DATA FOR OPMAIN
2 HEATING MODE
3 $INIT DATE=61.DAY=1.TOCC=9.0.TUNOC=17.0.TSTART=4.0,
4 YMIN=1.000000+001,YMIN=1.000000+002,DELY=.100000+001,HEAT=T,NSKP=5;$END
5 $DAYOCC DATE=61.DAY=1.TOCC=9.0.TUNOC=17.0;$END
6 $DAYOCC DATE=62.DAY=1.TOCC=8.0.TUNOC=16.0;$END
7 $DAYOCC DATE=62.DAY=1.TOCC=8.0.TUNOC=16.0;$END
8 $DAYOCC DATE=63.DAY=1.TOCC=7.0.TUNOC=16.0;$END

END PRT

$INIT

OPTIN: INPUT DATA FOR OPMAIN
HEATING MODE

$END

$OUTPUT

TIME = .13500000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

$OUTPUT

TIME = .15000000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

$OUTPUT

TIME = .16500000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

$OUTPUT

---SWO---SYSTEM OFF AT THE FIRST CYCLE

$DAYOCC

DATE = 61.DAY = 1.TOCC = .90000000+001,TUNOC = .17000000+002
$END

$OUTPUT

TIME = .18000000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

---SW2---DECAY/RISE RESPONSE OCCURS

$OUTPUT

TIME = .19500000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

$OUTPUT

TIME = .21000000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END

$OUTPUT

TIME = .22500000+002,MAINTN = F,PART0N = F,FSYSON = F,TSTART = .40000000+001,TOFF = .00000000,TOCC = .90000000+001.
TUNOC = .17000000+001,TBEGIN = .12000000+002
$END
$OUTPUT
TIME = .00000000,Maintn = F,Parton = F,Fsyson = F,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .90000000+001,
Tunoc = .17000000+002,Tbegin = .12000000+002
$END
1.500000 9.4500000 -2.9500000
$OUTPUT
TIME = .15000000+001,Maintn = F,Parton = F,Fsyson = F,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .90000000+001,
Tunoc = .17000000+002,Tbegin = .12000000+002
$END
3.0000000 8.8000000 -3.6000000
$OUTPUT
TIME = .30000000+001,Maintn = F,Parton = F,Fsyson = F,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .90000000+001,
Tunoc = .17000000+002,Tbegin = .12000000+002
$END
---SW4---SYSTEM ON AT FULL POWER
4.5000000 8.8000000 -3.9500000
$OUTPUT
TIME = .45000000+001,Maintn = F,Parton = F,Fsyson = T,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .90000000+001,
Tunoc = .17000000+002,Tbegin = .12000000+002
$END
---SW5---UPRISE/DECAY RESPONSE OCCURS
$DATE
DATE = 62,DAY = 1,TOCC = .80000000+001,TUNOC = .16000000+002
$END
6.0000000 10.5000000 -3.9000000
$OUTPUT
TIME = .60000000+001,Maintn = F,Parton = F,Fsyson = T,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .80000000+001,
Tunoc = .16000000+002,Tbegin = .12000000+002
$END
7.5000000 15.1000000 -3.0000000
$OUTPUT
TIME = .75000000+001,Maintn = F,Parton = F,Fsyson = T,Daycnt = F,Tstart = .40000000+001,Toff = .00000000,Tocc = .80000000+001,
Tunoc = .16000000+002,Tbegin = .12000000+002
$END
---SW6---DAYTIME CONTROLLER TAKES OVER
***************************************************************************************************
$RESULT
X = .00000000 .00000000 .00000000 .02100000+002
Y = .00000000 .00000000 .00000000 .18300000+002,Toff = .35000000+001,XTSTART = .16000000+002,TAUON = .00000000,
TAUOFF = .00000000,TEDDON = .75000000+000,TEDDFS = .15000000+001,TS = .00000000,TSIF = .00000000,ICYCLE = 0,
ITIME = 84,ITOFF = 20,ITUNOC = 20,ITDOWN = 26,ITON = 64,ITUP = 67,
ITSET = 84,TBEGIN = .12000000+002,TOFF = .15500000+002,TUNOC = .16000000+002,TSTART = .80000000+001
$END
***************************************************************************************************
XLEFT = 14.9167 XRIGHT = 20.0000
---SW7---CALCULATIONS FOR NEXT CYCLE ARE DONE
***************************************************************************************************
$RESULT
X = .17000000+002 .18500000+002 .67500000+001 .21000000+002
Y = .10500000+002 .15100000+002 .16300000+002 .18300000+002,TOFF = .25000000+001,XTSTART = .15000000+002,TAUON = .47376636+001,
TAUOFF = .00000000,TEDDON = .75000000+000,TEDDFS = .15000000+001,TS = .27450000+002,TSIF = .40000000+001,ICYCLE = 1,
ITIME = 84,ITOFF = 20,ITUNOC = 20,ITDOWN = 26,ITON = 64,ITUP = 67,
ITSET = 84,TBEGIN = .12000000+002,TOFF = .14500000+002,TUNOC = .16000000+002,TSTART = .30000000+001,TOCC = .80000000+001
$END
****************************************************************************************************

9.0000000 18.300000 -1.700000
$OUTPUT
TIME = .9000000+01,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = T,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
10.500000 18.300000 1.000000
$OUTPUT
TIME = .1050000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = T,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
12.000000 18.300000 3.500000
$OUTPUT
TIME = .1200000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = T,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
13.500000 18.300000 4.750000
$OUTPUT
TIME = .1350000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = T,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
---SW1---SYSTEM OFF
15.000000 18.300000 4.700000
$OUTPUT
TIME = .1500000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
16.500000 18.300000 3.600000
$OUTPUT
TIME = .1650000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
$DAYOCC
DATE = 62.DAY = 1.TOCC = .80000000+01,TUNOC = .16000000+02
$END
18.000000 18.300000 2.300000
$OUTPUT
TIME = .1800000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .3000000+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
---SW2---DECAY/RISE RESPONSE OCCURS
19.500000 16.700000 .8000000
$OUTPUT
TIME = .1950000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .36375446+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
21.000000 14.300000 -.3000000
$OUTPUT
TIME = .2100000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .33659873+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
22.500000 12.300000 -1.300000
$OUTPUT
TIME = .2250000+02,MAINTN = F,PARTRAN = F,FSYSON = F,DAYCNT = F,TSTART = .33550849+01,TOFF = .14500000+02,TOCC = .80000000+01.
TUNOC = .1600000+02,TBEGIN = .12000000+02
$END
$OUTPUT
TIME = .00000000 , MAINT = F, PRACTON = F, FSYSON = F, DAYCNT = F, TSTART = .33457973+001, TOFF = .14500000+002, TOCC = .80000000+002
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
1.5000000 9.4500000 -2.9500000
$OUTPUT
TIME = .15000000+001, MAINT = F, PRACTON = F, FSYSON = F, DAYCNT = F, TSTART = .34633873+001, TOFF = .14500000+002, TOCC = .80000000+002
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
3.0000000 8.8000000 -3.6000000
$OUTPUT
TIME = .30000000+001, MAINT = F, PRACTON = F, FSYSON = F, DAYCNT = F, TSTART = .36125493+001, TOFF = .14500000+002, TOCC = .80000000+002
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
--- SW4--- SYSTEM ON AT FULL POWER
4.5000000 8.8000000 -3.9500000
$OUTPUT
TIME = .45000000+001, MAINT = F, PRACTON = F, FSYSON = T, DAYCNT = F, TSTART = .36773434+001, TOFF = .14500000+002, TOCC = .80000000+002
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
--- SW5--- UPRISE/DECAY RESPONSE OCCURS
$DAYOC
DATE = 63, DAY = 1, TOCC = .70000000+001, TUNOC = .16000000+002
$END
6.0000000 10.5000000 -3.9000000
$OUTPUT
TIME = .60000000+001, MAINT = F, PRACTON = F, FSYSON = T, DAYCNT = F, TSTART = .36773434+001, TOFF = .14500000+002, TOCC = .70000000+001
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
7.5000000 15.1000000 -3.0000000
$OUTPUT
TIME = .75000000+001, MAINT = F, PRACTON = F, FSYSON = T, DAYCNT = F, TSTART = .36773434+001, TOFF = .14500000+002, TOCC = .70000000+001
TUNOC = .16000000+002, TBEGIN = .12000000+002
$END
--- SW6--- DAYTIME CONTROLLER TAKES OVER
**************************************************************************************************
$RESULT
X = .17000000+002, .18500000+002, .67500000+001, .21000000+002,
Y = .10500000+002, .15100000+002, .17700000+002, .18300000+002, XOFF = .00000000, XSTART = .15677343+002, TAUNO = .47376636+001,
TAUOFF = .16333456+002, TEDON = .10726566+001, TDEDOF = .40000000+001, YSS = .27450000+002, YINF = .40000000+001, ICYCLE = 1,
ITIME = 84, ITOFF = 10, ITUNOC = 20, ITDOWN = 26, ITON = 63, ITUP = 67,
ITSET = 84, TBEGIN = .12000000+002, TOFF = .12000000+002, TUNOC = .16000000+002, TSTART = .36773434+001, TOCC = .70000000+001
$END
**************************************************************************************************
XLEFT = 14.4167 XRIGHT = 19.5000
**************************************************************************************************
$RESULT
X = .17500000+002, .19000000+002, .92500000+001, .21000000+002,
Y = .10500000+002, .15100000+002, .14700000+002, .18300000+002, XOFF = .50000000+000, XSTART = .15177343+002, TAUNO = .47376636+001,
TAUOFF = .16333456+002, TEDON = .10726566+001, TDEDOF = .40000000+001, YSS = .27450000+002, YINF = .40000000+001, ICYCLE = 2,
ITIME = 84, ITOFF = 10, ITUNOC = 20, ITDOWN = 26, ITON = 63, ITUP = 67,
ITSET = 84, TBEGIN = .11500000+002, TOFF = .12000000+002, TUNOC = .16000000+002, TSTART = .26773434+001, TOCC = .70000000+001
An Optimum Start/Stop Control Algorithm for Heating and Cooling Systems in Buildings

Cheol Park

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

Office of Buildings and Community Systems
U.S. Navy Civil Engineering Laboratory
U.S. Department of Energy
U.S. Department of Defense
1000 Independence Avenue, SW
Washington, DC 20585

When a building structure is occupied intermittently, energy savings can be realized from the optimal start-up and shut-down of the heating or cooling system. This strategy, known as optimum start/stop control, reduces energy consumption by delaying the start-up of the space conditioning system until the last moment and then initiating shut-down as early as possible, while maintaining a preset level of comfort during the period of building occupancy.

Based on the bang-bang control theory, a simple optimum start/stop control algorithm is developed for computerized control systems in buildings. The optimum start time is obtained by finding the intersection of cool-down and heat-up curves that are approximated by exponential fitting of the previous and current day's data.

Information is presented in this report on the input and output variables, logic flow, and methodology employed in developing the algorithm. A computer program listing of the optimum start/stop control algorithm written in FORTRAN 77 and sample input and output data are included in the appendices.

digital control systems; energy conservation; energy management and control systems; heating and cooling systems; optimum start/stop time; preheat time.

Order From National Technical Information Service (NTIS), Springfield, VA. 22161

$10.00