Measuring Thermostat and Air Conditioner Performance in Florida Homes

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1.0 SUMMARY

This report summarizes the experimental results from 30 field tests in 23 Central Florida homes during the Summer of 1990. Detailed thermostat measurements were made at each site for a one to three day period. The purpose of this study was to determine how thermostats operate in actual buildings. This knowledge is necessary to understand the part load performance of air conditioners (ACs).

1.1 Background

While a great deal is known about how ACs and buildings perform separately, very little is known about how they perform together. The interactions between the building and AC are typically controlled by a thermostat. The thermostat senses the space temperature and turns the AC ON and OFF to maintain the required setpoint. Thermostat operation is complex because it depends on thermostat characteristics (e.g., switch deadband, sensing element time constants, anticipator) as well as building characteristics (thermal mass, etc.).

The purpose of this study was to measure thermostat/AC/building performance in several residences. This measured data provided insight into how thermostats really operate. Understanding thermostat performance is necessary to quantify the part load performance of AC systems.

1.2 Experimental Approach

A portable apparatus was developed which could be temporarily installed in a home. The apparatus included a Campbell 21XL datalogger, temperature and humidity sensors, and a thermostat status sensor. The datalogger sensed and recorded time, temperature and humidity each time the thermostat turned ON or OFF. Measured quantities were averaged and summed as required.

For each test site, the experimental apparatus was placed near (and connected to) the thermostat. It remained at each site for one to three days collecting and storing data. The test was repeated a total of 30 times at 23 different sites.

1.3 Results and Discussion

General Characteristics of the Homes

In addition to detailed thermostat data, average temperatures and humidities were recorded for each test period along with general information about each site. Table 1-1 lists some general information about the tested homes.

<table>
<thead>
<tr>
<th>General Characteristics of the Test Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Space Temperature</td>
</tr>
<tr>
<td>Average Space Relative Humidity</td>
</tr>
<tr>
<td>Average Floor Area</td>
</tr>
<tr>
<td>AC Relative Sizing</td>
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<tr>
<td>Home Age</td>
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</tbody>
</table>

*Some houses were included multiple times in the sample.
Generally, the characteristics of the test sites were typical of the results measured or assumed in other studies (Cummings 1990).

**Cycling Rates**

One of the primary interests of this study was to measure the cycling rate. The cycling rate (N) is defined as one over the time required to complete an ON and OFF cycle. While the concept of runtime fraction, or duty cycle, is widely understood, cycling rate is a more difficult concept. If AC unit is running 50% of the time, this indicates nothing about how often the AC unit turns ON and OFF. The AC unit could be ON for 60 minutes and OFF for 60 minutes (0.5 cycles/hour), or it could be ON for 10 minutes and OFF for 10 minutes (3 cycles/hour). Cycling rate is important because it indicates how often the AC unit starts and stops. Since losses occur each time an AC starts, part load performance depends on the cycling rate.

Cycling rate (N) is related to the runtime fraction (X) by the following equation:

\[ N = 4N_{\max}X(1-X) \]  

(1-1)

The development and basis of this equation is discussed in Section 3 and Appendix A. The constant \( N_{\max} \) is defined as the maximum cycle rate, which occurs when the runtime fraction is 50% (X=0.5). The constant \( N_{\max} \) fully defines cyclic behavior of a system at all conditions.

Equation (1-1) was curve-fit to the measured data for each test site to determine the constant \( N_{\max} \). Figure 1-1 is a histogram of the values of \( N_{\max} \) determined for each site. The average value was 2.5 cycles/hour with a minimum and maximum of 0.15 and 4.07, respectively. The average is lower than the nominal value of 3.125 cycles/hour implicitly assumed in the SEER rating procedure.

There was a fair amount of variation in \( N_{\max} \) from site to site. One of the goals of this study was to statistically analyze the dependence of \( N_{\max} \) on other system parameters. Several factors were analyzed including: temperature droop, thermostat deadband, AC sizing, house age, average runtime, and temperature setpoint. Only two of the parameters were correlated to \( N_{\max} \), at statistically significant levels (i.e., with T-ratios greater than 2): temperature droop and thermostat deadband. While these parameters were statistically significant, they explained only 41% of the variability of \( N_{\max} \).

Another goal of this study was to determine if building construction (frame vs. block) had any impact on cycling rate. It was postulated that block houses would have more thermal mass, which would decrease cycling rate. Of the 23 test sites, only six were frame construction; therefore, a statistical analysis was not feasible. However, a qualitative evaluation of the houses indicated no discernable differences between frame and block construction.

\*See Section 3.0 for definitions of droop and deadband.\*
Figure 1-1 Histogram of Maximum Cycle Rate \( (N_{max}) \) Measured at All Sites

Temperature Variation
The variation of temperature with runtime fraction \( (X) \), commonly referred to as droop, was also of interest in this study. Temperature droop is a commonly recognized occurrence in thermostats with anticipators. The average slope of temperature versus runtime \( (X) \) measured in this study was 2.1°F/X. The three electronic thermostats included in this study were observed to have negative droop; this was expected since electronic thermostats have no anticipating circuit.

Humidity Variation
The variation of relative humidity \( (RH) \) with \( X \) was also analyzed. Since RH is not directly controlled by the thermostat, the variation of RH with \( X \) was not highly correlated. Weather effects and other factors tended to overwhelm the impact of the thermostat on RH. The only consistent trend was that RH was always lower when the AC turned OFF than when it turned ON.

1.4 Application of Results
The results of this study improve our understanding of part load losses, which depend on \( N_{max} \). Using the part load function developed in this study, part load losses increase by 4.2% per each unit increase in \( N_{max} \) (assuming a time constant of 80 seconds for the AC unit). Based on the measured values of \( N_{max} \), the energy use attributable to part load losses ranged from 0% to 18%, with an average of 11%, in the tested houses.
1.5 Conclusions and Recommendations

The following conclusions and recommendations are made from this study:

- The commonly assumed maximum cycling rate (3 cycles/hour) is slightly higher than the average value of 2.5 measured in this study.

- As suggested in previous simulation studies (Henderson 1991), anticipator size and thermostat switch deadband were found to have the largest impact on $N_{\text{max}}$ in this study. However, these two factors explained only 41% of the measured variation in $N_{\text{max}}$, leaving more than half of the variation unexplained.

- Temperature droop is a common characteristic of the conventional thermostats with anticipators. The average value of droop was measured to be 2.1°F/X. This value of droop could be included in building simulation models to account for the time-of-day variation of space temperature due to thermostat dynamics.

- Humidity is only weakly dependent on thermostat operation; this was expected since the AC and thermostat do not directly control humidity.

- With $N_{\text{max}}$ equal to 2.5, cycling losses represent 11% of energy use on a seasonal basis (Using the part load function developed in this report with an AC time constant of 80 s).
2.0 INTRODUCTION

This report summarizes the experimental results from 30 field tests conducted in 23 homes during the Summer of 1990. For each test, detailed measurements of thermostat performance as well as indoor temperatures and humidities were measured over a one to three day period. The purpose of this study was to quantify how thermostats perform in actual buildings. This knowledge is necessary to understand the interactions of the building and air conditioner (AC) under part load conditions.

2.1 Background

While a great deal is known about the performance of ACs and buildings separately, very little is known about how they perform together. The interaction between the building and the AC is typically controlled by a thermostat. The thermostat senses air (and wall) temperature to determine when the AC unit should cycle ON and OFF to maintain the required setpoint. The thermostat itself is a complex device which includes a sensing element, a switch and an "anticipating" circuit. Building and furniture mass as well as transient characteristics of the AC system further increase system complexity.

Thermostat performance is important because it affects the part load performance of an AC. Generally, the fraction of time an AC unit operates (i.e., the runtime fraction) is directly proportional to the load. While the runtime fraction gives an indication of the amount of time an AC unit runs, it does not indicate how often the AC system cycles ON and OFF. For instance, if an AC system runs 50% of the time at a certain load condition, what is the cycling rate? The AC could be ON for 1 hour and OFF for 1 hour, or it could be ON for 10 minutes and OFF for 10 minutes. The cycling rate is what determines the part load performance since losses occur each time an AC system starts up. In summary, the cycling rate of the overall building/thermostat/AC system is important in determining part load performance of an AC.

2.2 Previous Studies

Several studies have modeled thermostat, building, and AC system performance including Henderson (1991), Nguyen and Goldschmidt (1983), Lamb and Tree (1981), McBride (1979) and Nelson (1974). These studies have generally shown that the thermostat is the most important factor in determining cycling rate. The anticipator size and deadband of the thermostat are the dominant factors, though the thermal mass of the building and the furniture also play an important role.

While a great deal of effort has gone into simulating thermostat performance, only a few studies have measured the actual performance of thermostats in the field (see Appendix D). Parken et al. (1985) measured cycling rates at three sites as part of the verification process for DOE's Seasonal Energy Efficiency Ratio (SEER) test procedure. Miller and Jaster (1985) measured the cycling rate of a several heat pumps in the heating mode. Goldschmidt et al. (1980) measured the cycling rates of an AC in a mobile home with and without furniture and showed how the cycling rate changed.

Generally, these limited studies all found the maximum cycling rates to vary widely in the 1 to 3 cycles/hour range. This contrasts with the value of 3.125 cycles/hour implicitly assumed in the SEER test procedure (ARI 1984).
2.3 Purpose of Study

The purpose of the current study was to measure thermostat performance in several Florida homes. This experimental data was necessary to verify the findings and assumptions of previous simulation and experimental studies. The approach used was to develop a portable data logger system to accurately and quickly measure the performance at multiple sites. With data available from multiple sites, a statistical approach to analyzing thermostat performance could be taken.

Additionally, temperature and humidity were measured for each site to determine the average values, as well as their variation with AC operation.

2.4 Overview of This Report

This report is organized into the following sections: Section 1 is a summary, Section 2 is an introduction, Section 3 discusses the theory and operation of thermostats, Section 4 discusses the experimental procedure and equipment used, Section 5 presents and discusses the experimental results, Section 6 presents an application of this cycling rate data, and section 7 lists the references. The Appendices include a derivation of the commonly used thermostat cycling equation (Appendix A), a listing of the datalogger program (Appendix B), a complete listing of the experimental results for each site (Appendix C), a listing of measured parameters from previous studies (Appendix D), and a derivation of a part load equation (Appendix E).
3.0 THERMOSTATS: THEORY AND OPERATION

This section discusses the theory and operation of thermostats in cooling applications. First, basic thermostat operation is discussed, along with the different types and configurations of thermostats which are available. Next, the mathematical theory and concepts necessary to quantify thermostat performance are developed. These concepts are used to quantify system performance in the following sections.

3.1 Basic Thermostat Operation

The basic function of the thermostat is to sense space temperature and switch the air conditioner (AC) ON and OFF to maintain the desired temperature setpoint. In this process, the thermostat interacts with the building and AC system. The dynamic characteristics of the building, AC system, and the thermostat all affect how the combined system reacts.

There are two primary types of thermostats used in cooling (and heating) applications today: 1) the conventional, bimetallic thermostat, and 2) the electronic, or programmable, thermostat. While both of these perform same basic function -- controlling the AC system to maintain a temperature setpoint -- their dynamic response differs. The characteristics of each thermostat is discussed below.

A Conventional Thermostat consists of a liquid mercury switch attached to a helical bimetal element. The air temperature is sensed by a bimetallic element which rotates as temperature increases (or decreases). The mercury switch, which is attached to the bimetal element, also rotates and switches the AC system ON and OFF. Another component common to this type of thermostat is the anticipator. The anticipator is a resistive heating element (e.g., a resistor) which artificially heats the bimetal element when the AC unit is OFF (for cooling). This forces the AC system to turn ON sooner than if the anticipator were not present. In effect, it "anticipates" when the turn-on temperature is about to be reached. The purpose of the anticipator is to improve comfort by reducing temperature swings in the space.

With an anticipator present, comfort is improved, but at the cost of increasing cycle rate of the AC system. The increased cycle rate increases the number of time the equipment starts, which decreases the overall efficiency of an AC system.

Conventional bimetallic thermostats are the most common type of thermostat used today.

An Electronic Thermostat consists of a temperature sensor interfaced to electronic logic which activates a relay. This type of thermostat differs form conventional thermostats in a couple of ways. First, the response of the temperature sensor in an electronic thermostat is much faster than the bimetal element in a conventional thermostat. This affects how the thermostat reacts to changes in space conditions. Second, electronic thermostats typically do not have an anticipator. Therefore, the only means to control the cycling rate is to change the deadband. Typically, the deadband (the difference between the turn-ON and turn-OFF temperature) is field adjustable. The deadband must be large enough to minimize AC system cycling, yet not so large as to cause excessive swings in air temperature.
3.2 Thermostat Theory and Performance: Cycling

To understand how thermostats perform, a few terms must first be defined. Figure 3-1 shows how the space temperature varies as the thermostat turns the AC ON and OFF for one complete cycle.

Figure 3-1 The Impact of AC Status on Space Temperature

A common feature of all thermostats is a deadband ($\Delta T_{spt}$), or temperature difference, between the temperature at which the AC unit cycles ON ($T_{on}$) and OFF ($T_{off}$). Typically the setpoint ($T_{spt}$) is taken as the mid-point between these temperatures.

The time to complete one cycle of operation is defined as:

$$t_{cycle} = t_{on} + t_{off}$$  \hspace{1cm} (3-1)

$t_{on}$ is the time the AC unit was ON and $t_{off}$ is the time the AC unit was OFF, as shown in Figure 3-1.
The runtime fraction ($X$), which indicates the fraction of time the AC unit runs, is defined as:

$$X = \frac{t_{on}}{t_{cycle}} = \frac{t_{on}}{(t_{on} + t_{off})}$$  \hspace{1cm} (3-2)

Another useful term useful for describing system performance is the cycle rate ($N$), which is defined as:

$$N = \frac{1}{t_{cycle}} = \frac{1}{(t_{on} + t_{off})}$$  \hspace{1cm} (3-3)

The performance of a thermostat in a building is commonly thought to be described by:

$$N = 4N_{max}X(1-X)$$  \hspace{1cm} (3-4)

This equation is used in the NEMA standard (1990) to quantify performance of wall-mounted, low voltage thermostats. The advantage of equation (3-4) is that the cyclic behavior of a thermostat is quantified by one constant ($N_{max}$). $N_{max}$ is physically defined as the maximum cycling rate, which occurs when the AC unit runs 50% of the time ($X=0.5$).

Equation (3-4) has also been used by others (Parken et al. 1985) to describe system cycling performance. They found that their field data conformed to this model very well. A discussion of the physical basis for equation (3-4) is given in Appendix A.

An algebraically equivalent form of equation (3-4) is:

$$t_{on} = \frac{t_{on, min}}{(1-X)}$$  \hspace{1cm} (3-5)

Equation (3-5) comes from algebraically recombing equations (3-1) through (3-4).

This equation has been used by Goldschmidt et. al. (1980) and Miller and Jaster (1985) to model field data. The constant in this equation ($t_{on, min}$) is physically defined as the minimum ON time -- which occurs when the runtime fraction ($X$) is zero.

Since equations (3-4) and (3-5) are algebraically equivalent, their constants can be related:

$$t_{on, min} = \frac{60}{4N_{max}}$$  \hspace{1cm} (3-6)

The factor of 60 is included in the numerator of equation (3-6) assuming units are minutes for $t_{on, min}$ and cycles/hour for $N_{max}$. This equation is useful for relating data from different researchers who may have used either equation (3-4) or (3-5).
Miller and Jaster (1985) developed an alternate form of equation (3-5) that they suggested for heat pumps and air conditioners:

\[ t_{on} = \gamma (1 + \alpha X) \frac{(1 - \alpha X)}{(1 - X)} \]  

(3-7)

They stated that the extra constant (\( \alpha \)) was added to account for the dependence of cooling (or heating) capacity on outdoor temperature. Since runtime fraction (\( X \)) also depends on outdoor temperature, the cooling (or heating) capacity is a function of \( X \); thus, the constant (\( \alpha \)) is required. Their data from field tests of three heat pumps in the heating mode confirmed the need for this extra term.

3.3 Thermostat Theory and Performance: Droop

Another important aspect of thermostat performance is droop: the variation of space temperature with runtime fraction (\( X \)). Droop typically occurs because of the anticipator. The artificial heating from the anticipator causes the AC unit to turn ON sooner than if it were not present. The anticipator's effect is only realized when the AC unit is OFF, therefore the average temperature depends on \( X \).

Simulation studies by Henderson (1991), Lamb and Tree (1981) and Nguyen and Goldschmidt (1983) have all demonstrated how the anticipator effects droop. For cooling, the net result is an increase in space temperature with increasing runtime fraction (\( X \)). When no anticipator is present, the opposite trend was observed: space temperature decreased with increasing runtime fraction.

In the NEMA Standard (1990), droop is defined as the change in average air temperature from \( X=0.2 \) to \( X=0.8 \). In this study, droop is defined as the slope of temperature versus runtime.

\[ T_{avg} = c_0 + d_0 X \]  

(3-8)

Or, as the constant \( d_0 \) in equation (3-8), where \( T_{avg} \) and \( X \) are defined over the same interval. In this study, \( T_{avg} \) and \( X \) are determined over each ON/OFF cycle (\( t_{cycle} \)).
4.0 EXPERIMENTAL SETUP

This section describes the experimental method used to collect the data presented in this report. First, the apparatus used to collect the data is described. Next, the techniques used to reduce and analyze data are presented. Finally, the experimental protocol used for each house is explained.

4.1 Experimental Apparatus

The goal of this study was to collect detailed cycling, temperature, and humidity data in several houses in an efficient manner. To meet these goals an apparatus was developed which: 1) was portable and easy to install and 2) could collect and store the required data.

A Campbell 21XL was selected as the datalogger in this study because it could be programmed to log data on an event (such as a switch closure). The datalogger was installed in a covered box with a 5 ft. pole attached to it's side. Temperature and humidity sensors were mounted at the top of this pole to sense space conditions. In addition, two wires extended from the top of the pole, which were attached to the thermostat terminals to sense thermostat status (i.e., ON or OFF). The AC status signal was input to the Campbell to determine when the thermostat turned ON and OFF. The apparatus was placed near the thermostat in each house as shown in Figure 4-1.

![Diagram of experimental apparatus](image)

**Figure 4-1 Placement of Experimental Apparatus Near Thermostat**
**Instrumentation**

The datalogger and instrumentation are shown schematically in Figure 4-2. The measured quantities for this study were temperature, relative humidity, and AC runtime status.

![Schematic of Datalogger and Instrumentation](image)

**Figure 4-2 Schematic of Datalogger and Instrumentation**

*Temperature* was measured with an unshielded type-T thermocouple (TC). The TC was mounted at the top of the pole as shown in Figure 4-1. The top of the pole, which was approximately 5 ft. above the floor, could typically be located within 1 to 2 feet of the thermostat location.

*Relative Humidity* was measured with a TCS 1200-HB humidity sensor (±1% accuracy). The humidity sensor was also mounted at the top of the pole as shown in Figure 4-1. The 4-20mA output of this sensor was converted to a voltage at the datalogger, where it was read.

*AC Status* was determined by measuring the voltage between the R and Y terminals on the thermostat. Two wires from the experimental apparatus were attached to these thermostat terminals in each house. When the AC unit is OFF, the voltage between R and Y is approximately 24 VAC, since the switch (e.g., either a liquid mercury bulb or a relay) is open. When the AC unit is ON, the switch closes and the voltage between these terminals is nearly zero.

A DC power supply was used to convert 24 VAC at the thermostat to 1 VDC as shown in Figure 4-2. The 1 VDC output signal was easily measured by the datalogger as a status signal. The DC power supply was designed to have a high input impedance (100,000 ohms) so that it would not impact the low impedance anticipator circuit (approximately 0.5 ohms).
Since thermostat switches often have a finite resistance, the voltage drop across the switch did not always go to zero. In electronic thermostats, this voltage drop across the switch was sometimes found to be as high as 1.5 VAC with the AC ON. Therefore, the threshold between ON and OFF was selected to be 0.1 VDC at the datalogger (or 2.4 VAC at the thermostat).

Programming the Campbell for the Required Data

Because detailed thermostat data were required, the data collection requirements for this study were slightly different than for other studies. Instead of collecting and storing data on a regular interval (e.g., 5 minutes), data had to be collected every time the AC unit switched ON and OFF. Therefore, the Campbell had to be programmed to collect and store times, temperatures, and humidities each time the AC status changed. It also had to average data over periods of indefinite length.

The datalogger monitored the status of the AC unit every ten seconds. If the AC status changed the required data was collected, averaged if necessary, and stored. Table 4-1 shows the data which was logged each time the AC status changed. The Campbell program used to collect this data is listed in Appendix B.

<table>
<thead>
<tr>
<th>Campbell Output Channel</th>
<th>Data Description</th>
<th>Units and/or Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Current Time: Year (YYYY)</td>
<td>1990</td>
</tr>
<tr>
<td>3</td>
<td>Current Time: Julian Day (DDD)</td>
<td>201</td>
</tr>
<tr>
<td>4</td>
<td>Current Time: Hours &amp; Minutes (hhmm)</td>
<td>2027</td>
</tr>
<tr>
<td>5</td>
<td>Current Time: Seconds (sss.s)</td>
<td>30.1</td>
</tr>
<tr>
<td>6</td>
<td>Temperature at the Current Time</td>
<td>78.0°F</td>
</tr>
<tr>
<td>7</td>
<td>Relative Humidity at the Current Time</td>
<td>55.22%</td>
</tr>
<tr>
<td>8</td>
<td>Average Temperature Since the Last Data was Stored</td>
<td>77.8°F</td>
</tr>
<tr>
<td>9</td>
<td>Average Relative Humidity Since the Last Data was Stored</td>
<td>54.10%</td>
</tr>
<tr>
<td>10</td>
<td>AC Unit Status at Current Time (1 = turned ON; 0 = turned OFF)</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

Data collected and stored whenever AC turns ON or OFF

TABLE 4-1
4.2 Data Collection and Reduction

After each house was tested, the apparatus was taken to FSEC where the stored data was downloaded for analysis. The raw data listed in Table 4-1 was reduced to final form by a FORTRAN program. The AC status flag was used to determine whether the data in each scan was for an ON or an OFF cycle. Then for each complete ON/OFF cycle, the data listed in Table 4-2 were calculated. See section 3 for definitions of the variables listed in Table 4-2.

<table>
<thead>
<tr>
<th>Calculated Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{on}$</td>
<td>AC ON time</td>
</tr>
<tr>
<td>$t_{off}$</td>
<td>AC OFF time</td>
</tr>
<tr>
<td>$t_{cycle}$</td>
<td>AC cycle time</td>
</tr>
<tr>
<td>$N$</td>
<td>Cycle Rate</td>
</tr>
<tr>
<td>$X$</td>
<td>Runtime Fraction</td>
</tr>
<tr>
<td>$T_{on}$</td>
<td>Temperature at which AC unit turned ON</td>
</tr>
<tr>
<td>$T_{off}$</td>
<td>Temperature at which AC unit turned OFF</td>
</tr>
<tr>
<td>$\Delta T_{dead}$</td>
<td>Deadband Temperature ($T_{on}$ - $T_{off}$)</td>
</tr>
<tr>
<td>$T_{avg}$</td>
<td>Average Temperature*</td>
</tr>
<tr>
<td>$RH_{on}$</td>
<td>Relative Humidity at which AC unit turned ON</td>
</tr>
<tr>
<td>$RH_{off}$</td>
<td>Relative Humidity at which the AC unit turned OFF</td>
</tr>
<tr>
<td>$\Delta RH_{dead}$</td>
<td>RH Deadband ($RH_{on}$ - $RH_{off}$)</td>
</tr>
<tr>
<td>$RH_{avg}$</td>
<td>Average Relative Humidity*</td>
</tr>
</tbody>
</table>

* Average $T$ and $RH$ calculated from weighted average of average ON and OFF averages: $T_{avg} = T_{on,avg}X + T_{off,avg}(1-X)$

Calculating Averages

In Table 4-2, the average $T$ and $RH$ over each complete ON/OFF cycle were calculated by time-weighing the average values for each scan (see note in Table 4-2). In the same fashion the averages over larger intervals were also calculated. This technique was used to determine the average $T$ and $RH$ for the entire test period in each house.

Hourly Runtime Profiles

The hourly runtime fraction was also calculated with an additional FORTRAN program. The average 24 hour profile for the house was also calculated. See Appendix C, plot 4.
4.3 Experimental Protocol

Each time a house was tested, the experimental protocol listed below was used:

1) The experimental apparatus was placed near the thermostat, the thermostat status wires were attached, and the unit was plugged into an AC outlet (to charge the Campbell's internal battery).

2) The occupants were asked questions about their house, including: floor area, number of occupants, house age, house type, etc. The name plate information was also taken off of the AC unit as well as the thermostat. Any abnormalities in the house, AC unit or thermostat were noted.

3) The experimental apparatus was left in the house for 1 to 3 days to log data automatically.

4) After 1 to 3 days, the apparatus was removed from the house and taken back to FSEC were the data was down loaded to an IBM-compatible PC. The apparatus was reset for the next test site.
5.0 RESULTS AND DISCUSSION

This section presents the experimental data measured in this study. First, a summary of the general characteristics for all the monitored houses is presented. Second, measured cycling rates, dead bands, and droop are presented. Finally, the interdependence of cycling rate with other system parameters is analyzed.

5.1 General Description of Monitored Houses

Several houses were monitored for this study using the experimental apparatus and protocol described in section 4. 30 separate tests were conducted in 23 different houses and apartments in Brevard County. The detailed results for all 30 of the tests are given in Appendix C, along with a summary table.

Table 5-1 summarizes the general characteristics of the monitored homes. Histograms of these values are also shown in Figures 5-1 through 5-5.

<table>
<thead>
<tr>
<th>General Characteristics of Monitored Homes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Average Temperature 78.3°F</td>
</tr>
<tr>
<td>Average RH</td>
</tr>
<tr>
<td>Floor Area²</td>
</tr>
<tr>
<td>AC Sizing² (ft²/ton)</td>
</tr>
<tr>
<td>House Age²</td>
</tr>
</tbody>
</table>

*Some houses were included multiple times in the sample

In general, the houses monitored in this study had characteristics typical of Florida homes. The temperature set point and the average relative humidity were both similar to results found in other studies in Central Florida (Cummings 1990). The size and age of the homes were also typical. It is interesting to note that the age of homes was either newer than 10 years, or older than 20 years -- a trend roughly corresponding to the activity level at Kennedy Space Center.

AC equipment sizing seems to follow the "one ton per 500 ft² of floor area" rule of thumb. New houses, which typically had higher insulation levels, tended towards the 600 to 700 ft²/ton range.

Several houses were tested multiple times. Typically the house was retested to determine the direct impact of a change (e.g. adding a new thermostat). These cases are discussed in section 5.8.

The tested homes are listed in Table 5-2. The type of construction (block, frame, apartment), type of thermostat (conventional or electronic) and date of test are listed, along with an ID letter. The ID letter is used to identify the houses on scatter plots presented later in this section.
<table>
<thead>
<tr>
<th></th>
<th>Description of Test Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Raustad1 A June 9 Block</td>
</tr>
<tr>
<td>2</td>
<td>Henderson B June 11 Block</td>
</tr>
<tr>
<td>3</td>
<td>Rudd C June 14 Block</td>
</tr>
<tr>
<td>4</td>
<td>Yerosh1 D June 25 Block</td>
</tr>
<tr>
<td>5</td>
<td>Holder E June 29 Block</td>
</tr>
<tr>
<td>6</td>
<td>Sherwin F July 11 Block</td>
</tr>
<tr>
<td>7</td>
<td>Parker G July 16 Block</td>
</tr>
<tr>
<td>8</td>
<td>Shirey H July 20 Apt</td>
</tr>
<tr>
<td>9</td>
<td>Redmonl I July 23 Block</td>
</tr>
<tr>
<td>10</td>
<td>Faireyl J July 27 Frame</td>
</tr>
<tr>
<td>11</td>
<td>Fairey2 K July 30 Frame</td>
</tr>
<tr>
<td>12</td>
<td>Kettles L Aug 4 Frame</td>
</tr>
<tr>
<td>13</td>
<td>Melody M Aug 8 Block</td>
</tr>
<tr>
<td>14</td>
<td>Dhere N Aug 14 Block</td>
</tr>
<tr>
<td>15</td>
<td>Dutton O Aug 18 Frame</td>
</tr>
<tr>
<td>16</td>
<td>Dernier P Aug 21 Block</td>
</tr>
<tr>
<td>17</td>
<td>Vieira1 Q Aug 24 Block</td>
</tr>
<tr>
<td>18</td>
<td>Vieira2 R Aug 27 Block</td>
</tr>
<tr>
<td>19</td>
<td>Dumner S Aug 31 Block</td>
</tr>
<tr>
<td>20</td>
<td>Raustad2 T Sept 5 Block</td>
</tr>
<tr>
<td>21</td>
<td>Goulet U Sept 8 Block</td>
</tr>
<tr>
<td>22</td>
<td>Cummings3 V Sept 14 Block</td>
</tr>
<tr>
<td>23</td>
<td>Cummings2 W Sept 13 Block</td>
</tr>
<tr>
<td>24</td>
<td>Cummings1 X Sept 12 Block</td>
</tr>
<tr>
<td>25</td>
<td>Mellor Y Sept 17 Frame</td>
</tr>
<tr>
<td>26</td>
<td>Walker Z Sept 21 Block</td>
</tr>
<tr>
<td>27</td>
<td>Kalaghchky 1 Oct 1 Frame</td>
</tr>
<tr>
<td>28</td>
<td>Shirey 2 Oct 4 Apt</td>
</tr>
<tr>
<td>29</td>
<td>Kanan 3 Oct 11 Apt</td>
</tr>
<tr>
<td>30</td>
<td>Yarosh2 4 Oct 20 Block</td>
</tr>
</tbody>
</table>

ID is used in Figures 5-8, 5-17 to 5-22 in this section.
All tests performed in 1990 Summer season.
Figure 5-1  Histogram of Average Space Temperature

Figure 5-2  Histogram of Average Space Relative Humidity

5-3
Figure 5-3  Histogram of Floor Area

Figure 5-4  Histogram of AC Sizing (Floor Area per AC Unit Size)
Figure 5-5  Histogram of House Age

5.2 Thermostat Cycling Rate: \( N_{\text{max}} \)

For each test, equation (5-1) (the same as eqn. (3-4)) was curve-fit to the measured data to determine the constant \( N_{\text{max}} \). Figure 5-6 shows the measured data from one test (Rudd, C) along with the resulting fit to the equation. Each measured point corresponded to the \( X \) and \( N \) calculated for one complete ON/OFF cycle (see section 4.3). The \( N_{\text{max}} \) which resulted in the best fit for this test was 1.75 and the standard deviation of the measured data from the curve was 0.14.

\[
N = 4N_{\text{max}}X(1-X) \quad (5-1)
\]

As discussed in section 3, the constant \( N_{\text{max}} \) corresponds to the maximum value of the cycling rate function. The curve-fit of measured data to determine \( N_{\text{max}} \) was repeated for each test. The measured data and resulting curve-fit are shown for each test in Appendix C (see Plot 1).

Figure 5-7 shows a histogram of the curve-fit values of \( N_{\text{max}} \) for all tests. The average \( N_{\text{max}} \) for all tests was 2.48 cycles/hour. The standard deviation, minimum and maximum were 0.96, 0.15 and 4.07 respectively. The ratio of the standard deviation of the curve-fit (\( \sigma \)) to \( N_{\text{max}} \) gives a good indication of how well equation (5-1) fits the measured data. Figure 5-8 is a histogram of this ratio (100\( \sigma / N_{\text{max}} \)) from all tests. Typically the ratio of the standard deviation of the measured data from the curve (\( \sigma \)) to \( N_{\text{max}} \) was smaller than 10%, indicating that equation (3-4) fits the measured data well and accurately represents cycling rate performance.
Figure 5-6  Thermostat Cycling Equation Fit to Measured Data (Rudd, C)

Figure 5-7  Histogram of Maximum Cycling Rate ($N_{\text{max}}$)
Figure 5-8 Relative Error of Curve-Fits for $N_{max}$.

5.3 Thermostat Cycling Rate: $t_{on,\min}$

Equation (5-2) (which is the same as equation (3-5)) is an alternate form of the cycling rate equation which finds the ON time ($t_{on}$) as a function of $X$.

$$t_{on} = \frac{t_{on,\min}}{1-X}$$  \hspace{1cm} (5-2)

As discussed in section 3, this equation is algebraically equivalent to (5-1) (and the constant $t_{on,\min}$ is related to $N_{max}$).

Miller and Jaster (1985) suggested adding the term $\alpha X$ to account for the dependence of AC capacity on outdoor temperature (see section 3 and Appendix A).

$$t_{on} = \frac{\gamma(1+\alpha X)}{1-X}$$  \hspace{1cm} (5-3)

Note when $\alpha$ is zero, the constants $t_{on,\min}$ and $\gamma$ are equivalent.

Figure 5-9 shows equations (5-2) and (5-3) curve-fit to the measured data for one test (Rudd, C). Since both functions go to infinity as $X$ approaches 1, only data points for $X$ less than 0.9 were used in the curve-fits. The standard deviation of the data points from the curve-fits were 0.96 and 0.85 for equations (5-2) and (5-3) respectively.
Figure 5-9 Curve-Fit of Equations (5-2) and (5-3) to Measured Data (Rudd, C)

Figure 5-10 Comparing Standard Deviation of Fits for eqns. (5-2) and (5-3)
This indicates that equation (5-3), which includes an extra parameter \( \alpha \), fits the measured data slightly better than equation (5-2). The curve-fit of equations (5-2) and (5-3) to the measured data was repeated for each test (see Appendix C, Plot 2). Figure 5-10 compares the standard deviations of the curve-fits of equations (5-2) and (5-3) for each test. Most data points fall on or below the dashed line representing equal error, indicating that equation (5-3) fits the data better than equation (5-2).

The average value for \( \alpha \) was 0.14, with the minimum and maximum ranging from -0.25 to 0.7. As discussed in Appendix A, positive values of \( \alpha \) skew the cycling equation (5-1) to the left while negative values skew it to the right.

In summary, the addition of the \( \alpha \) term in equation (5-3) improves the degree of fit, but at the cost of increased complexity. In many cases it is questionable if the increased complexity is warranted.

5.4 Temperature Deadband and Droop

Besides cycling rate, other important aspects of a thermostat’s performance are deadband and droop. The thermostat deadband (\( \Delta T_{\text{set}} \)) is the difference between the temperatures at which the thermostat turns ON and OFF (see section 3). Droop is the variation of the average temperature with the runtime fraction (\( X \)). More specifically, it is defined as the slope of average temperature with \( X \) (\( d_o \) in equation (3-8)).

Figure 5-11 shows the deadband (\( \Delta T_{\text{set}} \)) as well as \( T_{\text{on}} \), \( T_{\text{off}} \), and \( T_{\text{avg}} \) versus the runtime fraction (\( X \)) for one of the test cases (Rudd, C). The deadband, though slightly scattered, was not a function of \( X \). The average deadband (\( \Delta T_{\text{set}} \)) for this thermostat was higher than typical, at about 4°F.

The middle plot in Figure 5-11 shows the turn-ON and turn-OFF temperatures versus \( X \) (\( T_{\text{on}} \) and \( T_{\text{off}} \)). Both \( T_{\text{on}} \) and \( T_{\text{off}} \) were fit to a linear function. The slope for both of these lines was about 6°F, indicating that the anticipator in this thermostat had a strong effect.

The bottom plot in Figure 5-11 shows the average temperature versus \( X \) (for a complete ON/OFF cycle, as defined in section 4). The slope of the line curve-fit to the data is defined as droop in this study. For this test site the droop (\( d_o \)) was 2.9°F.

The analysis in Figure 5-11 was repeated for all the test sites (see Appendix C, plot 3). Figure 5-12 is the histogram of the temperature deadband (\( \Delta T_{\text{set}} \)) calculated for each test and Figure 5-13 is the histogram of the droop (\( d_o \)). The average, standard deviation, minimum and maximum for deadband and droop are also given in Table 5-3.

| TABLE 5-3 |
|------------------|------|------|------|------|
| Measured Temperature Deadband (\( \Delta T_{\text{set}} \)) and Droop (\( d_o \)) | Mean | Std. Dev. | Minimum | Maximum |
| Dead Band: \( \Delta T_{\text{set}} \) (°F) | 2.3 | 1.2 | 0.8 | 6.7 |
| Droop: \( d_o \) (°F) | 2.1 | 2.1 | -3.8 | 6.6 |
Figure 5-11  Deadband ($AT_{off}$) and $T_{on}$, $T_{off}$, and $T_{avg}$ versus Runtime Fraction ($X$) (Rudd, C)
Figure 5-12  Histogram of Measured Deadband ($\Delta T_{sp}$)

Figure 5-13  Histogram of Droop ($d_o$)
The measured deadbands varied substantially from 0.8°F to 6.7°F. However, most were in the 2°F to 3°F range which have typically been observed in other studies (see Appendix D). The size of the deadband has been shown to effect the cycling rate by Henderson (1991) as well as others. This impact of deadband on cycling rate is further analyzed in a following section.

Both positive and negative values of droop were measured in the 30 tests. The 4 negative values for droop corresponded to 3 electronic, programmable thermostats and as well as an older thermostat which apparently had no anticipator (or a very weak one). The simulation study by Henderson (1991) also observed "negative droop" when an anticipator was not used. Typical values of droop with an anticipator present were in the 2°F to 4°F range. Droop is the primary indicator of anticipator strength (i.e., heating rate). The relationship between droop and cycling rate is discussed further in a following section.

5.5 Relative Humidity Deadband and Droop

In addition to temperature, the variation of relative humidity with X was also measured. Figure 5-14 shows the RH deadband (ΔRHₜₚ), as well as RHₓₚ, RHₓₚ, RHₓₚ, versus X for one of the test sites (Rudd, C). For this particular site, the RH deadband was typically 3% RH, but with a fair degree of scatter. The average RH also decreased slightly with increased X, indicating that the space RH depended on how often the AC operated. This analysis was repeated for each test site (see Appendix C, plot 6).

Figure 5-15 is a histogram of the RH deadband (ΔRHₜₚ) for all the test sites. The RH deadband was positive for all the test sites, indicating that the RH was always lower after the AC unit turned OFF. In psychrometric terms, this implied that the SHR line of the cooling process was always steeper than the RH contours on the psychrometric chart.

One test site had a very large RH deadband of 7.3%. This test site (Dutton, O) was the only one which operated in the CONSTANT fan mode. The average humidity at this site was also the highest measured in this study, at 70% RH. This result reinforced the findings of Khattar et al. (1985) that the CONSTANT fan mode greatly reduces AC latent capacity and increases indoor humidity levels.

Figure 5-16 is a histogram of the slope of RH with runtime fraction (RH droop). In general, the RH droop was negative, indicating that the average RH was lower when the AC ran more often. However, several sites exhibited the opposite trend. The large variation of droop was largely attributed to weather effects. While temperature is being directly controlled, RH is only controlled indirectly. Therefore, the variation of outdoor humidity across the test period could impact the indoor humidity more than the runtime fraction.

In general, the RH trends with X showed a more scatter than the temperature trends. This was true because the thermostat/AC unit does directly control RH. Therefore, variations in weather during each test period tended to overwhelm the other measured effects.
Figure 5-14 RH Deadband and $\text{RH}_{\text{on}}$, $\text{RH}_{\text{off}}$, and $\text{RH}_{\text{avg}}$ versus Runtime Fraction ($X$) (Rudd, C)
Figure 5-15  Histogram of RH Deadband ($RH_{\alpha} - RH_{err}$)

Figure 5-16  Histogram of RH Droop (slope versus X)
5.6 Statistical Analysis of Cycling Rate \( N_{\text{max}} \)

One of the major purposes of this study was to determine which system parameters affect the maximum cycling rate \( N_{\text{max}} \). Figures 5-17 through 5-22 show how \( N_{\text{max}} \) varies with deadband \( (\Delta T_{\text{set}}) \), droop \( (d_o) \), average space temperature, average runtime fraction \( (X_{\text{avg}}) \), house age, and relative AC sizing \( (\text{ft}^2/\text{ton}) \) respectively. Each point on these scatter plots is identified by an ID letter/number, which corresponds to the IDs listed in Table 5-2. The correlations of the system parameters to \( N_{\text{max}} \) are summarized in Table 5-4.

<table>
<thead>
<tr>
<th>Table 5-4</th>
<th>Statistical Analysis of System Parameters Versus ( N_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>Figure</td>
</tr>
<tr>
<td>Deadband ( (\Delta T_{\text{set}}) )</td>
<td>5-17</td>
</tr>
<tr>
<td>Temperature Droop ( (d_o) )</td>
<td>5-18</td>
</tr>
<tr>
<td>Average Temperature ( (^\circ F) )</td>
<td>5-19</td>
</tr>
<tr>
<td>Average Runtime ( (X_{\text{avg}}) )</td>
<td>5-20</td>
</tr>
<tr>
<td>House Age ( (\text{yrs}) )</td>
<td>5-21</td>
</tr>
<tr>
<td>AC Sizing ( (\text{ft}^2/\text{ton}) )</td>
<td>5-22</td>
</tr>
</tbody>
</table>

* A T-ratio of 2 (or greater) indicates the a 95% (or higher) probability that the slope (i.e. correlation coefficient) is not equal to zero.

Figure 5-17 shows how \( N_{\text{max}} \) varies with deadband \( (\Delta T_{\text{set}}) \). As expected from theory (see Appendix A), cycle rate is inversely proportional to deadband. The house with the highest deadband \( (\text{Wieiral, Q}) \) was also the site with the lowest observed cycling rate. Even though there is a substantial amount of scatter, Table 5-4 shows that the correlation between \( N_{\text{max}} \) and \( \Delta T_{\text{set}} \) was significant (i.e., T-ratio much greater than 2).

Figure 5-18 shows how \( N_{\text{max}} \) varies with temperature droop \( (d_o) \). As discussed previously, the amount of droop is determined by the strength of the anticipator. Again, in spite of the scatter, the strength of the anticipator (or droop) was highly correlated to \( N_{\text{max}} \). The T-ratio relating droop \( (d_o) \) to \( N_{\text{max}} \) was 3.5, indicating high confidence level in the trend.

Figure 5-19 shows \( N_{\text{max}} \) versus the average space temperature. As expected, there was no measurable dependence of \( N_{\text{max}} \) on the average temperature set point (the T-ratio for space temperature is listed in Table 5-4).

Figure 5-20 shows \( N_{\text{max}} \) versus the average runtime fraction \( (X_{\text{avg}}) \) for each site. As for space temperature, no statistically significant trend of \( N_{\text{max}} \) with \( X_{\text{avg}} \) could be discerned. This implies that the measured value of \( N_{\text{max}} \) was not dependent on the load on the building or the size of the AC unit.
Figure 5-17 Scatter Plot of $N_{\text{max}}$ Versus Thermostat Deadband ($\Delta T_{\text{st}}$)

Figure 5-18 Scatter Plot of $N_{\text{max}}$ Versus Temperature Droop ($d_o$)
Figure 5-19 Scatter Plot of $N_{\text{max}}$ Versus Average Space Temperature

Figure 5-20 Scatter Plot of $N_{\text{max}}$ Versus Average Runtime Fraction ($X_{\text{avg}}$)
Figure 5-21 Scatter Plot of $N_{max}$ Versus House Age

Figure 5-22 Scatter Plot of $N_{max}$ Versus AC Unit Sizing (ft$^2$/ton)
Figure 5-21 shows $N_{\text{max}}$ versus house age. This trend was also not statistically significant. However, one interesting factor about this plot is the degree of scatter on $N_{\text{max}}$ for the newer versus the older houses. New houses, especially when a conventional thermostat is used, exhibit much less scatter than older houses. This seems to confirm the findings suggested by previous studies (McBride 1979) that modern thermostats with anticipators tend to dominate cycling rate and reduce the impact of other system parameters.

Figure 5-22 shows $N_{\text{max}}$ versus the relative sizing of the AC unit (ft$^2$ floor area per ton of AC). As expected, no statistical trend of $N_{\text{max}}$ with AC sizing could be discerned (see Table 5-4). The relative sizing of the AC, which is also related to the average runtime ($X_{\text{avg}}$), had no impact on the cycling characteristics of the thermostat/building/AC system. While AC sizing does effect the value of $X$, it does not change the constant $N_{\text{max}}$ in the cycling equation.

In summary, only two parameters, deadband ($\Delta T_{\text{start}}$) and droop ($d_{\text{r}}$) were statistically significant. While they were significant to a high level of confidence, the degree of fit was poor. A multi-variable, linear regression of $N_{\text{max}}$ to these two parameters resulted in:

$$N_{\text{max}} = 2.82 + 0.161(d_{\text{r}}) - 0.296(\Delta T_{\text{start}})$$

with $R^2 = 41.3\%$

The $R^2$ indicates that the curve-fit explains only 41% of the total variation in $N_{\text{max}}$, which leaves more than half of the variation of $N_{\text{max}}$ unexplained.

5.7 Other Factors Related to Thermostat Performance

It was suspected that several characteristics of the building, AC unit and thermostat would also qualitatively affect thermostat performance. Some of these are discussed below.

**Block vs. Frame.** Initially, one goal of this study was to determine if the type of building construction (frame versus block) could be determined to have an impact on cycling rate ($N_{\text{max}}$). The premise was that block houses have more thermal mass, which should decrease the cycling rate. Figure 5-23 shows the same data as Figure 5-18, except each point has been labeled to indicate the type of building construction (F - Frame, B - Block, or A - Apartment).
Figure 5-23  The Effect of Construction (Block, Frame or Apartment) on $N_{max}$

Only 6 of the 30 tests were frame construction, so a statistical analysis of the differences was not possible. However, qualitative examination of the data indicates that building construction has no noticeable impact on $N_{max}$; the frame houses (F) are equally distributed with the block houses (B). Similarly, Apartments (A) showed no specific trend.

Thermostat Location. Another important characteristic which affects thermostat performance is location. Thermostat manufacturers always recommend that thermostats be located on an inside wall where they are never exposed to direct sun. However, several houses had thermostats installed on both outdoor and garage walls, which are typically warmer than indoor walls. Figure 5-24 shows the same data as 5-18 but with each point labelled according to thermostat location (I - Indoor, O - Outdoor, or G - Garage). Again, no discernable trend was observed. Though the house with the highest cycle rate had the thermostat located on the garage wall (G), so did the house with the lowest cycling rate.
5.8 Multiple Tests in the Same House

At several of the sites, multiple tests were run to test the impact of a system characteristic. Some of these special cases are discussed below.

Changing Thermostats. At the Vieira residence, an electronic thermostat was installed for the first test conducted at the site (VIEIRA1, ID=Q). This thermostat had an extremely wide deadband (6.7°F) which resulted in a very low cycling rate (0.15 cycles/hr). After this test, the thermostat was replaced with a conventional unit and site was retested (VIEIRA2, ID=R). This conventional thermostat decreased the deadband and increased the cycle rate to the values shown in Table 5-5.

<table>
<thead>
<tr>
<th>TABLE 5-5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparing Electronic and Conventional Thermostats</strong></td>
</tr>
<tr>
<td>Description</td>
</tr>
<tr>
<td>VIEIRA1, Q electronic thermostat</td>
</tr>
<tr>
<td>VIEIRA2, R conventional thermostat</td>
</tr>
</tbody>
</table>
Thermostat Covers. All thermostats come with a decorative cover which hides the internal workings of the thermostat. In addition to being decorative, this cover also affects the rate of heat transfer to the bimetallic element. Table 5-6 compares the measured performance of thermostat with and without the cover at the Cummings residence. In this case, removing the cover increased the cycle rate \(N_{\text{max}}\) from 1.16 to 1.52.

**TABLE 5-6**

<table>
<thead>
<tr>
<th>Description</th>
<th>(N_{\text{max}})</th>
<th>(\Delta T_{\text{set}})</th>
<th>Droop ((d_c))</th>
<th>Avg. Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUMMINGSI, X, without cover</td>
<td>1.52</td>
<td>2.6°F</td>
<td>1.1°F</td>
<td>79.6°F</td>
</tr>
<tr>
<td>CUMMINGS2, W, with cover</td>
<td>1.16</td>
<td>2.6°F</td>
<td>1.2°F</td>
<td>79.5°F</td>
</tr>
</tbody>
</table>

Temperature Setpoint. The impact of temperature setpoint was also analyzed at the Cummings residence. Table 5-7 compares thermostat performance at two different setpoints in the same house. Note that for this specific site, lowering the setpoint increased the temperature swing (or deadband) and reduced the effective droop. Both of these effects can be explained by the time response (i.e., time constant) of the bimetallic sensing element. Consistent with the statistical analysis of all the tests in section 5.6, the temperature set point had only a small impact on \(N_{\text{max}}\).

**TABLE 5-7**

<table>
<thead>
<tr>
<th>Description</th>
<th>(N_{\text{max}})</th>
<th>(\Delta T_{\text{set}})</th>
<th>Droop ((d_c))</th>
<th>Avg. Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUMMINGS2, W, normal set</td>
<td>1.16</td>
<td>2.6°F</td>
<td>1.2°F</td>
<td>79.5°F</td>
</tr>
<tr>
<td>CUMMINGS3, W, lower set</td>
<td>1.23</td>
<td>2.8°F</td>
<td>0.9°F</td>
<td>77.0°F</td>
</tr>
</tbody>
</table>

Changing AC Units. At the Raustad residence, the test was repeated when the old AC unit was replaced with a new, high-efficiency AC system of approximately the same size. The same thermostat was used for both systems. Table 5-8 compares the thermostat performance at this site before and after the new AC was installed. Surprisingly, the deadband and droop on the thermostat change substantially which in turn increased the cycling rate for the new unit. Upon further investigation, it was determined that some of this difference may have been due to occupant behavior. For the first test (RAUSTAD1), the occupants were using an oscillating fan which may have affected the thermostat. This was not true for the second test (RAUSTAD2).

Another factor which may have played a role was the close proximity of the thermostat to a supply duct. The new AC may have delivered colder air which hit the thermostat and affected the cycling rate.

5-22
While it was not the case for the system tested here, in general changing the AC unit should have no impact on thermostat performance.

<table>
<thead>
<tr>
<th>Description</th>
<th>$N_{max}$</th>
<th>Deadband $\Delta T_{int}$</th>
<th>Droop (d)</th>
<th>Avg. Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAUSTAD1, A, old AC Unit</td>
<td>3.38</td>
<td>2.9°F</td>
<td>4.3°F</td>
<td>76.6°F</td>
</tr>
<tr>
<td>RAUSTAD2, T, new AC Unit</td>
<td>3.74</td>
<td>2.2°F</td>
<td>5.8°F</td>
<td>77.0°F</td>
</tr>
</tbody>
</table>

5.9 Daily Runtime Profiles

From the collected thermostat cycling information, it was possible to construct a profile of the average AC runtime for each hour over the test period. Figure 5-25 shows a typical runtime profile which was constructed from the measured cycling data. (Rudd, C) In the top plot, the profiles for each day of the test period are shown, labeled as A, B, C for the first, second and third day. In the bottom plot, the composite runtime profile is developed by averaging the runtimes for each hour over the test period. The runtime profiles developed for each test site are shown in Appendix C (plot 4).

These runtime profiles give an indication of the average hourly power demand profiles at each site.
Figure 5-25 Composite Hourly Runtime Profiles Constructed from Cycling Data (Rudd, C)
5.10 Summary of Results

Section 5 has presented the measured results for this study. The following conclusions can be drawn from these results:

- The homes tested in this study were typical of homes in Brevard County. The average temperatures and humidities were 78°F and 56% RH for the 30 tests, and the average home size was 1500 ft².

- The average cycling rate ($N_{max}$) for the 30 field tests was 2.5 cycles/hour, with a high and a low of 4.1 and 0.15 respectively. While the average was in line with the value of 3.125 cycles/hour implicitly assumed in the SEER test procedure, there was a great deal of scatter in the measured values of $N_{max}$. A statistical analysis of the test sites revealed that thermostat deadband ($ΔT_{max}$) and anticipator strength had the largest impact on $N_{max}$. While these two thermostat parameters were statistically significant, they explained less than half of the total variation of $N_{max}$. The source of this unexplained variation could not be determined from this study.

- A statistical analysis of alternative cycling equation (5-3) proposed by Miller and Jaster (1985) indicated that it fit the measured data slightly better than the conventional cycling equation (5-2). Because the alternate equation is only slightly better, it is recommended that the simpler, conventional equation (5-1 or 5-2) still be used.

- A positive value of thermostat droop was observed in almost all the conventional thermostats tested. Electronic thermostats were all observed to have negative droop. These findings were consistent with simulation results from Henderson (1991). The average slope of temperature with runtime was 2.1°F/X.

- A qualitative examination of building construction (block versus frame) and thermostat location (garage versus interior wall) indicated no discernable affect on cycling rate. However, the sample size was inadequate to draw definitive, statistically-based conclusions.

- A repeat test at one house (Vieira) indicated the dramatic impact the thermostat can have on cycling rate. For the first test, an electronic thermostat was used which had an extremely wide deadband of 6.7°F. The value of $N_{max}$ measured at this site was 0.15 cycles/hour. For the second test, the original thermostat was removed and replaced with a conventional thermostat. The cycle rate for this case increased dramatically to 1.74 cycles/hour.
6.0 APPLICATIONS

This section briefly describes how the data collected in this study can be used. A equation for determining part load performance as a function of $N_{\text{max}}$, is developed and used to estimate the impact of $N_{\text{max}}$ on cycling losses.

6.1 Developing a Part Load Function

The part load efficiency of an air conditioner (AC) is a function of several parameters: the amount of time the AC operates, the number of times the AC turns ON and OFF, and the transient characteristics of the AC.

Equation (6-1) determines the degradation of efficiency at part load for an AC considering all the factors listed above.

$$\text{PLF}_{i-1} = 1 - 4\tau N_{\text{max}} (1-\text{CLF/PLF}_i)[1 - e^{-\frac{1}{4\tau N_{\text{max}} (1-\text{CLF/PLF}_i)}}]$$

(6-1)

where

- PLF = Part Load Factor (EER/EER$_{\text{max}}$)
- CLF = Cooling Load Factor ($Q_{\text{c}}/Q_{\text{C}}$)
- $\tau$ = Time Constant of AC at Start-up (time)
- $N_{\text{max}}$ = Maximum Cycling Rate (1/time)

The derivation of this equation is given in Appendix E. Note that the only assumptions used to derive this equation were: 1) that capacity is first order at start-up (equation E-4), and 2) that the cycling rate equation (E-2 or 1-1) is representative of thermostat performance.

Iterations are required to solve equation (6-1) since PLF occurs on both sides of the equation. Initially, PLF$_0$ is assumed to be 1, which is used to find PLF$_i$. Iterations proceed until PLF$_i$ converges to PLF$_{i-1}$.

Figure 6-1 shows how PLF varies with CLF when $N_{\text{max}}$ equals 1 through 4 cycles/hr, with the AC time constant ($\tau$) equal to 80 seconds. Increasing $N_{\text{max}}$ decreases the part load factor (PLF) at a given value of CLF. The part load curve from the SEER test procedure, with the default $C_o=0.25$, has also been included in the on the plot as a reference (ARI 1984). Note that the $N_{\text{max}} = 3$ curve closely corresponds to this curve. This is not surprising since a value of 3.125 of $N_{\text{max}}$ is implicit in the conditions specified in the SEER cyclic test.
Figure 6-1  Equation (6-1) Plotted with $N_{\text{max}} = 1, 2, 3, 4$

6.2 The Impact of $N_{\text{max}}$ on Cycling Losses

Table 6-1 compares the part load performance with $N_{\text{max}}$ at 1, 2, 3, 4 at 50% load (CLF=0.5). 50% load is used as the seasonal average in the SEER procedure to find part load efficiency.

<table>
<thead>
<tr>
<th>Part Load Losses$^a$ Compared to Steady State</th>
<th>$N_{\text{max}}=1$</th>
<th>$N_{\text{max}}=2$</th>
<th>$N_{\text{max}}=3$</th>
<th>$N_{\text{max}}=4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease in Efficiency$^b$</td>
<td>-4.2%</td>
<td>-8.1%</td>
<td>-11.6%</td>
<td>-14.9%</td>
</tr>
<tr>
<td>Increase in Energy Use$^b$</td>
<td>+4.4%</td>
<td>+8.8%</td>
<td>+13.1%</td>
<td>+17.5%</td>
</tr>
</tbody>
</table>

$^a$Using curves in Figure 6-1 with CLF=0.5 as seasonal average.
$^b$Using curves in Figure 6-1 with CLF=0.5 as seasonal average.

$^c$Compared to the steady state case without cycling losses.

$N_{\text{max}}$ has a substantial impact on the part load performance. When $N_{\text{max}}$ is 2.5, the average value measured in this study, it is expected that cycling losses would account for approximately 11% of total energy use.
7.0 REFERENCES


APPENDIX A

Deriving The Thermostat Cycling Equation
Deriving the Thermostat Cycling Equation

This appendix discusses the physical basis for the thermostat cycling function (equation 3-4). The discussion is heavily based on an analysis from Parken et al. (1985).

Figure A-1 shows how the space air temperature varies as the air conditioning (AC) system turns ON and OFF.

![Diagram showing the relationship between temperature, time, and AC status.]

Figure A-1  Space Temperature and AC Status

Equation (A-1) relates the runtime fraction of the AC to the building load \( Q_{bl} \) and the AC cooling capacity \( Q_{ac} \).

\[
\frac{t_{on}}{t_{cycle}} = \frac{Q_{bl}}{Q_{ac}} \quad (A-1)
\]

Though \( Q_{ac} \) varies with outdoor temperature as well as other conditions, it is approximately constant compared to \( Q_{bl} \).
Equation (A-2) is based on the assumption that the building load \( Q_m \) increases proportionally to the rate of temperature increase in the space when the AC system is OFF.

\[
Q_m = C\left[\frac{\partial T}{\partial t}\right]_{av} = C \frac{\Delta T_{sp}}{t_{off}}
\]  \hspace{1cm} (A-2)

The ON/OFF temperature difference, or deadband \( \Delta T_{sp} \), is a function of the thermostat, and is therefore constant. The constant \( C \) depends on the thermal characteristics of the building and thermostat (thermal capacitance, anticipator, etc).

When equations (A-1) and (A-2) are combined to eliminate \( Q_m \), the result is equation (A-3).

\[
Q_{AC} \frac{t_{on}}{t_{cycle}} \frac{t_{off}}{t_{cycle}} = C \frac{\Delta T_{sp}}{t_{off}} \frac{t_{off}}{t_{cycle}}
\]  \hspace{1cm} (A-3)

The term in parentheses is added to both sides of the equation to aid in simplification. By using the following definitions:

\[
X = \frac{t_{on}}{t_{cycle}}
\]

\[
N = \frac{1}{t_{cycle}}
\]

\[
t_{cycle} = t_{on} + t_{off}
\]

equation (A-3) can be rearranged into:

\[
N = \frac{Q_{AC}}{C \Delta T_{sp}} X (1-X)
\]  \hspace{1cm} (A-4)

By combining \( Q_{AC}, C, \) and \( \Delta T_{sp} \) into one constant, equation (A-4) can be rewritten as:

\[
N = 4N_m X (1-X)
\]  \hspace{1cm} (A-5)

A-3
$N_{\text{max}}$ is the constant which quantifies cycling performance. The factor of 4 is included so that the constant ($N_{\text{max}}$) is the maximum value of the function, which occurs at $X=0.5$.

Equation (A-5) is plotted in Figure A-2.

![Figure A-2](image_url)

**Figure A-2  Thermostat Cycling Equation (A-5)**

Comparing equations (A-4) and (A-5), the following relation is found:

$$N_{\text{max}} = \frac{1}{4} \frac{Q_{\text{ac}}}{C \Delta T_{\text{spot}}}$$  \hspace{1cm} (A-6)

Note that the maximum cycle rate of the thermostat/building ($N_{\text{max}}$) is inversely proportional to the thermostat deadband ($\Delta T_{\text{spot}}$) and the building thermal capacitance ($C$). The relative sizing of the AC system ($Q_{\text{ac}}/C$) is also an important factor affecting $N_{\text{max}}$.  

---

A-4
Alternate Forms of the Cycling Equation

Miller and Jaster (1985) have proposed an alternate form of the cycling equation which takes into account the fact that $Q_a$ varies with outdoor temperature. Since the runtime fraction ($X$) is also proportional to outdoor temperature, it is implied that $Q_a$ will in effect depend on $X$. Equation (A-7) is the functional form of the cycling equation assuming $Q_a$ depends on $X$:

$$N = \frac{4\beta X (1-X)}{(1-\alpha X)}$$  \hspace{1cm} (A-7)

Note that when $\alpha$ is zero, $\beta$ is equivalent to $N_{\text{max}}$. When $\alpha$ is not zero, $\beta$ is no longer the peak value of the function. A positive value of $\alpha$ skews the peak towards to the left (lower runtimes), while a negative value skews it the right (higher runtimes). This function is plotted in Figure A-3.

![Graph](image)

**Figure A-3**  Alternate Form of the Cycling Equation (A-7)

This form of the equation demonstrates that the outdoor temperature dependence of $Q_a$ will tend to skew the data from the symmetric form of the function given by equation (A-5).
APPENDIX B

Datalogger Program for
Campbell 21X
Campbell Program for Thermostat Testing Study

Enter Table 1
5 sec. Execution Interval

P17 TC Reference temp.
1 location

P14 TC - differential ; check thermocouple
reps
5 mv, 250 usec
in chan
type T
ref. location
location
0 multiplier
0 offset

P2 VOLTS - differential ; check relative humidity
reps
5000 mv, 250 usec
in chan
location
multiplier
0 offset

P2 VOLTS - differential ; check thermostat voltage
reps
5000 mv, 250 usec
in chan
location
multiplier
0 offset

P33 Z = X + Y ; sum TC readings
9 location of X
6 location of Y
6 location of Z

P33 Z = X + Y ; sum RH readings
5 location of X
7 location of Y
7 location of Z

P32 Z = Z + 1 ; increment counter
3 location

P39 IF voltage is less than F ; check if unit is on
4
4

P39 THEN DO (needs endif)

P39 IF flag
21 if flag 1 is low
30 THEN DO (needs endif)

P38 Z = X / Y
6 location X
3 location Y
6 location Z
6

P37 Z = X * F
4 location X
4

P37 Z = X * F
6 location Z
6

P37 Z = X / Y
7 location X
7 location Y
7 location Z
6

P30 Z = F
1
6

P30 Z = F
6

P91 IF flag ; set flag 0 high and move to final storage
20 do if flag 0 is low
10 set flag 0 high (doesn't need endif)

P77 TIME
1111 YY;DD;HH;MM;SS

P70 SAMPLE
5 reps
4 start location
IF X LT F
location
X = F
F
set flag 1 high
Z = F ;reset totals
F
location
P80
F
P81
F
P82
location
P83
F
P84
THEN DO (needs endif)
F
THEN DO (needs endif)
P85
IF flag
if flag 1 is high
THEN DO (needs endif)
P86
Z = X / Y
location X
location Y
location Z
P87
Z = X * F
location X
P88
Z = X * F
location Z
P89
Z = X / Y
location X
location Y
location Z
P90
Z = F
F
location Z
P91
IF flag ;set flag 0 high and move to final storage
P92
do if flag 0 is low
P93
set flag 0 high (doesn't need endif)
P94
P95
TIME
P96
YYYY:DD:HH:MM
P97
SAMPLE
P98
reps
P99
start location
P100
IF X .GE. F
P101
location
X .GE. F
P102
F
P103
set flag 1 low
P104
Z = F ;reset totals
P105
F
location
P106
F
P107
location
P108
F
P109
location
P110
END
P111
END

Campbell Channel
(front panel)
1 TC
2 RH
3 Istet volts

Intermediate Storage
("6 mode")
1 Panel Temp
2 Istat volts
3 # of meas.
4 TC
5 RH
6 Ist. TC
7 Tot. RH
8 Counts

Final Storage
("7 mode")
1 21x ID
2 Year
3 Julian Day
4 HH:MM:
5 SS
6 TC
7 RH
8 Avg. TC
9 Avg. RH
10 Flag *

* Flag - 0 = unit turned off this scan
- 1 = unit turned on this scan
- Entering data ....... two tables are available (1 and 2) with a third table available for subroutines. Enter *1 for table 1.

- Compiling ........ after program has been entered, compile with "*O", "*6", "*B", and "*D".

- "*0", "*B", "*D"......compiles; output ports and flags are set low.

- "*6"......compiles; ports, flags, timer, and data are UNALTERED.

- Setting time ....... "*5A; enter year (A), Julian day (A), hour-min (A), and sec (A).

- Internal memory...."*A mode: displays memory allocation.

- To reset Final Storage without altering program, enter in same value and recompile with "*6" then "*0" (the compile function is only executed after a program change has been made (i.e. "*6 will compile then "*0 won't erase input or intermediate storage)).

- Final Storage...."*7 mode: use A (advance) or B (back-up) to check data.

- Data will be in final storage only when unit turns on or off.

- Intermediate St. ..."*6 mode: shows the data that is collected by the program. Only selected portions will be transferred to Final Storage.

---

Star (*) Mode Summary

<table>
<thead>
<tr>
<th>Key</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>*0</td>
<td>LOG data and indicate active tables</td>
</tr>
<tr>
<td>*1</td>
<td>Program Table 1</td>
</tr>
<tr>
<td>*2</td>
<td>Program Table 2</td>
</tr>
<tr>
<td>*3</td>
<td>Program Table 3</td>
</tr>
<tr>
<td>*4</td>
<td>Enable/disable tape and/or printer output</td>
</tr>
<tr>
<td>*5</td>
<td>Display/set real time clock</td>
</tr>
<tr>
<td>*6</td>
<td>Display/alter Input Storage data, toggle flags</td>
</tr>
<tr>
<td>*7</td>
<td>Display Final Storage data</td>
</tr>
<tr>
<td>*8</td>
<td>Final Storage data transfer to cassette tape</td>
</tr>
<tr>
<td>*9</td>
<td>Final Storage data transfer to printer</td>
</tr>
<tr>
<td>*A</td>
<td>Memory allocation/reset</td>
</tr>
<tr>
<td>*B</td>
<td>Signature test</td>
</tr>
<tr>
<td>*C</td>
<td>Security</td>
</tr>
<tr>
<td>*D</td>
<td>Save/load program</td>
</tr>
</tbody>
</table>

---

Key Description/Editing Functions

<table>
<thead>
<tr>
<th>Key</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>*G</td>
<td>Key numeric entries into display</td>
</tr>
<tr>
<td>A</td>
<td>Enter Mode (followed by Mode Number)</td>
</tr>
<tr>
<td>B</td>
<td>Enter/advance</td>
</tr>
<tr>
<td>C</td>
<td>Back up</td>
</tr>
<tr>
<td>D</td>
<td>Change the sign of a number or index an Input Location to loop counter</td>
</tr>
<tr>
<td>#</td>
<td>Enter the decimal point</td>
</tr>
<tr>
<td>#A</td>
<td>Clear the right most digit keyed into the display</td>
</tr>
<tr>
<td>#B</td>
<td>Advance to the next instruction in program table (&quot;*1&quot;, &quot;*2&quot;, &quot;*3&quot;) or to next Output Array in Final Storage (&quot;*7&quot;)</td>
</tr>
<tr>
<td>#C</td>
<td>Back up to previous instruction in program table or to previous Output Array in Final Storage</td>
</tr>
<tr>
<td>#D</td>
<td>Delete entire instruction</td>
</tr>
</tbody>
</table>
APPENDIX C
Measured Data From Each Test Site

Summary for all tests  
Detailed data for each site

page C-2  
page C-5
<table>
<thead>
<tr>
<th>House Name</th>
<th>Test Type</th>
<th>Duration</th>
<th>Avg Temp, F</th>
<th>Avg RH, %</th>
<th>Avg Run Time, %</th>
<th>Avg Temp</th>
<th>Avg RH</th>
<th>Nmax</th>
<th>Nmax X (1-X)</th>
<th>Tavg = a0 + alX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Raustad</td>
<td>Block</td>
<td>34.85</td>
<td>76.62</td>
<td>56.48</td>
<td>61.89%</td>
<td>2.93</td>
<td>1.17</td>
<td>3.38</td>
<td>0.1148</td>
<td>74.00</td>
</tr>
<tr>
<td>2 Henderson</td>
<td>Block</td>
<td>58.15</td>
<td>80.70</td>
<td>54.27</td>
<td>19.30%</td>
<td>3.18</td>
<td>3.32</td>
<td>0.99</td>
<td>0.0649</td>
<td>80.59</td>
</tr>
<tr>
<td>3 Rudd</td>
<td>Block</td>
<td>109.23</td>
<td>77.47</td>
<td>53.05</td>
<td>22.86%</td>
<td>4.02</td>
<td>3.10</td>
<td>1.75</td>
<td>0.1409</td>
<td>76.80</td>
</tr>
<tr>
<td>4 Marvin</td>
<td>Block</td>
<td>11.33</td>
<td>76.91</td>
<td>54.55</td>
<td>43.95%</td>
<td>1.66</td>
<td>1.19</td>
<td>4.07</td>
<td>0.2561</td>
<td>75.35</td>
</tr>
<tr>
<td>5 Holder</td>
<td>Block</td>
<td>13.17</td>
<td>82.14</td>
<td>49.60</td>
<td>31.35%</td>
<td>3.04</td>
<td>1.05</td>
<td>2.67</td>
<td>0.0451</td>
<td>81.81</td>
</tr>
<tr>
<td>6 Sherwin</td>
<td>Block</td>
<td>110.05</td>
<td>79.83</td>
<td>66.37</td>
<td>32.07%</td>
<td>0.76</td>
<td>1.34</td>
<td>3.33</td>
<td>0.3244</td>
<td>79.61</td>
</tr>
<tr>
<td>7 Parker</td>
<td>Block</td>
<td>91.37</td>
<td>79.94</td>
<td>60.65</td>
<td>27.08%</td>
<td>4.66</td>
<td>1.06</td>
<td>2.37</td>
<td>0.4341</td>
<td>80.44</td>
</tr>
<tr>
<td>8 Shirley A</td>
<td>Apt</td>
<td>45.20</td>
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<td>1.36</td>
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| Averages | 61.03 | 78.28 | 55.71 | 0.40 | 2.33 | 1.88 | 2.48 | 0.1947 | 77.34 | 2.13 | 0.415 |
| Std Dev  | 28.30 | 2.00  | 6.11  | 0.12 | 1.23 | 1.39 | 0.96 | 0.1245 | 2.41  | 2.14 | 0.312 |
| Minimum  | 11.33 | 73.59 | 41.36 | 0.193| 0.76 | 0.25 | 0.15 | 0.0451 | 70.97 | -3.82 | 0.050 |
| Maximum  | 125.3 | 82.14 | 70.03 | 0.6352| 6.71 | 7.29 | 4.07 | 0.5660 | 81.81 | 6.57 | 1.420 |
### TABLE C-1 (cont.)
Summary of Measured Data From Each Site

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**Averages**

|                  | 77.88  | 3.34   |
|                  | 4.75   | 5.48   |
|                  | 3.45   | 3.45   |
|                  | 0.50   | 56.39  |
|                  | 2.97   | 2.27   |
|                  | 1.58   | 10.51  |
|                  | 0.45   | 5.45   |
|                  | 11.72  | 11.72  |
|                  | 0.17   | 5.599  |
| Std Dev          | 2.38   | 1.89   |
|                  | 0.32   | 2.75   |
|                  | 2.02   | 2.02   |
|                  | 0.29   | 7.07   |
|                  | 0.82   | 5.34   |
|                  | 18.93  | 18.93  |
|                  | 21.93  | 21.93  |
|                  | 16.56  | 16.56  |
|                  | 0.38   | 21.602 |

**Minimum**

|                  | 71.12  | 0.14   |
|                  | 0.09   | 68.49  |
|                  | -0.58  | -0.58  |
|                  | 0.40   | 80.87  |
|                  | 0.45   | 3.40   |
|                  | 5.58   | 5.58   |
|                  | 0.19   | 0.19   |
|                  | 0.38   | 21.602 |

**Maximum**

|                  | 81.92  | 7.47   |
|                  | 1.53   | 80.23  |
|                  | 8.51   | 8.51   |
|                  | 3.79   | 3.79   |
|                  | 111.12 | 111.12 |
|                  | 17.0   | 17.0   |
|                  | 121.552 | 121.552 |
### TABLE C-1 (cont.)
Summary of Measured Data From Each Site

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<th>Avg Dewpoint</th>
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<p>| Averages | 1555.9 | 2.3 | 0.7 | 2.75 | 560.5 | 0.00 | 18.4 | 81.36 | 66.97 | 217.33 |
| Std Dev  | 516.5  | 0.8 | 1.1 | 0.66 | 85.6  | 0.00 | 12.4 | 1.73  | 3.10  | 85.66  |
| Minimum  | 616    | 2   | 0   | 1.5  | 400.0 | 0.00 | 1   | 77.62 | 61.23 | 6.54   |
| Maximum  | 2700   | 5   | 5   | 4    | 792.0 | 0.00 | 35  | 84.71 | 71.74 | 403.59 |</p>
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<tr>
<td>F</td>
<td>Sherwin</td>
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<td>G</td>
<td>Parker</td>
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<tr>
<td>H</td>
<td>Shirey</td>
<td>C-20</td>
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<tr>
<td>I</td>
<td>Redmond</td>
<td>C-22</td>
</tr>
<tr>
<td>J</td>
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<td>C-24</td>
</tr>
<tr>
<td>K</td>
<td>Fairey2</td>
<td>C-26</td>
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<td>L</td>
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<td>O</td>
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<tr>
<td>P</td>
<td>Dernier</td>
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<td>T</td>
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<td>U</td>
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<tr>
<td>V</td>
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<tr>
<td>3</td>
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<td>C-62</td>
</tr>
<tr>
<td>4</td>
<td>Yarosh2</td>
<td>C-64</td>
</tr>
</tbody>
</table>
PLOT 1: CYCLING

\[ N = 4 + 3.35 \times (X - (1 - X)) \]
\[ \sigma = 0.115768 \]

X (RUNTIME FRACTION)

N (Cycles/HR)

PLOT 2: \( t_m \)

\[ t_m = \frac{4.58}{(1 - x)} \]
\[ \sigma = 0.465964 \]
\[ t_m = \frac{4.03 + 0.81 - X}{(1 - X)} \]
\[ \sigma = 0.239249 \]
Curve fits for: \( X < 0.9 \)

X (RUNTIME FRACTION)

\( t_m \) (minutes)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 2.64 (ON-OFF)

DEAD BAND (°F)

TEMP (°F)

\[ T_m = 73.97 + 4.36 \times (X - \sigma = 0.28) \]

X (RUNTIME FRACTION)

TEMP (°F)

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: RAUSTAD
START DATE: 6/9 OR 160
END DATE: 6/10 OR 161
TIME: 8:35
JULIAN HR: 3824.01
JULIAN HR: 3857.93
TOTAL ELAPSED TIME: 33.93
OFF
ON
AVERAGE TEMP (DEG F) 76.61 76.69 76.49
AVERAGE RH (%) 56.52 56.86 55.96
HOURS 33.93 20.84 13.09
X HOURS 61.42 38.58

SELECTED DATA RANGE:
STARTING 160 8 (3824.000)
ENDING 161 14 (3854.000)

THERMOSTAT DATA: RAUSTAD
PLOT 4: RUN TIME PROFILES

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: RAUSTAD
PLOT 1: CYCLING

N = 4 + 0.99 \cdot (X \cdot (1 - X))

\sigma = 0.084557

PLOT 2: T_m

\begin{align*}
T_m & = \frac{15.66}{(1 - X)} \\
\sigma & = 3.182154 \\
st & = \frac{(14.07 + 3.44 \cdot X)}{(1 - X)} \\
\sigma & = 3.04734
\end{align*}

Curve fits for: X < 0.9

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 3.18 F (ON-OFF)

AVERAGE TEMP (DEG F) = 80.70

AVERAGE RH (%) = 54.27

HOURS = 58.15

TOTAL = 19.30

OFF = 80.70

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: HENDERSON

START DATE: 6/11 OR 162

TIME: 21:17:15

JULIAN HR: 3685.29

END DATE: 6/14 OR 165

TIME: 7:26:20

JULIAN HR: 3943.44

ELAPSED TIME: 58.15

TOTAL = 19.30

ON = 80.20

OFF = 80.81

TOTAL = 58.15

OFF = 46.93

THERMOSTAT DATA: HENDERSON
PLOT 1: CYCLING

\[ N = 4 \times 1.75 \times (X \times (1 - X)) \]
\[ \sigma = 0.140929 \]

N (CYCLES/HR) vs X (RUNTIME FRACTION)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND (F): 0.02 (ON-OFF)

DEAD BAND (F) vs X (RUNTIME FRACTION)

AVERAGE TEMP (DEG F): 75.31 + 0.89 \times X (r=0.34)

TEMP (F) vs X (RUNTIME FRACTION)

AVERAGE RH (%) = 53.05

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: RUDD
START DATE: 6/14 OR 185
END DATE: 6/19 OR 170
TIME: 10:57:40
TIME: 8:11:15
JULIAN HR: 3654.96
JULIAN HR: 4054.19
ELAPSED TIME: 109.23

TOTAL ON OFF

AVERAGE TEMP (DEG F) 77.47 76.67 77.71
AVERAGE RH (%) = 53.05 51.97 53.37
HOURS 109.23 24.97 84.25
K-HOURS 22.55 77.14

EOF
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EOF
EOF
EOF
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EOF

THERMOSTAT DATA: RUDD
**Plot 1: Cycling**

Graph showing cycling behavior with N (cycles/hr) on the y-axis and X (runtime fraction) on the x-axis.

Mathematical equation:

\[ N = 4.07 \times (X \times (1-X)) \]

\[ \sigma = 0.256077 \]

**Plot 2: t_m**

Graph showing t_m (minutes) on the y-axis and X (runtime fraction) on the x-axis.

Mathematical equations:

\[ t_m = 3.68 / (1 - X) \]

\[ \sigma = 0.497046 \]

\[ t_m = (4.02 + 0.69 \times X) / (1 - X) \]

\[ \sigma = 0.478525 \]

Curve fit for: X < 0.9

**Plot 3: Temperature**

Graph showing temperature behavior with dead band and runtime fraction.

Average dead band: 1.68 F (On-Off)

**Summary of Thermostat Performance Data**

- Location: YAROSHI
- Start Date: 6/25 or 176
- Start Time: 19:46:10
- Julean HR: 4219.80
- End Date: 6/26 or 177
- End Time: 7:7:40
- Julean HR: 4231.13
- Elapsed Time: 11:33

<table>
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<tr>
<th>Description</th>
<th>Total</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Temp (Deg F)</td>
<td>76.91</td>
<td>76.72</td>
<td>77.08</td>
</tr>
<tr>
<td>Average RH (%)</td>
<td>54.55</td>
<td>54.30</td>
<td>54.75</td>
</tr>
<tr>
<td>Hours</td>
<td>11.33</td>
<td>4.88</td>
<td>6.45</td>
</tr>
<tr>
<td>X Hours</td>
<td></td>
<td>43.95</td>
<td>56.05</td>
</tr>
</tbody>
</table>

**Thermostat Data: YAROSHI**
THERMOSTAT DATA: YAROSH1
**PLOT 1: CYCLING**

N (CYCLES/HR) vs. X (RUNTIME FRACTION)

N = 4.237 \times (X + (1 - X))

\sigma = 0.434117

**PLOT 2: L_X**

L_X = \frac{6.51}{1 - X}

\sigma = 2.710086

L_X = \frac{(6.88 + 0.12 \times X)}{1 - X}

\sigma = 2.719802

Curve fits for: X < 0.9

**PLOT 3: TEMPERATURE**

AVERAGE DEAD BAND = 4.68 \degree F (ON-OFF)

AVERAGE TEMP (\degree F) = 79.94

AVERAGE RH (%) = 80.65

HOURS = 91.37

\% HOURS = 27.08

**SUMMARY OF THERMOSTAT PERFORMANCE DATA**

LOCATION: PARKER

START DATE: 7/16 OR 197

END DATE: 7/20 OR 201

JULIAN HR: 4721.98

JULIAN HR: 4813.35

ELAPSED TIME: 91.37

TOTAL | ON | OFF
---|---|---
AVERAGE TEMP (\degree F) | 77.99 | 77.99 | 80.67
AVERAGE RH (%) | 59.85 | 59.85 | 80.64
HOURS | 24.75 | 24.75 | 88.63
\% HOURS | 72.92 | 72.92 | 72.92

**THERMOSTAT DATA: PARKER**
PLT 1: CYCLING

N (CYCLES/HR)

X (RUNTIME FRACTION)

N = 4 * 2.48 * (X = (1 - X))

\( \sigma = 0.239424 \)

PLT 2: \( \Gamma_{w} \)

\( \Gamma_{w} = \frac{6.4}{(1 - X)} \)

\( \sigma = 1.960527 \)

\( \Gamma_{w} = (3.98 + 5.77 * X)/(1 - X) \)

\( \sigma = 1.462816 \)

Curve fits for: \( X < 0.9 \)

PLT 3: TEMPERATURE

AVERAGE DEAD BAND = 0.88 F (ON-OFF)

DEAD BAND (F)

X (RUNTIME FRACTION)

AVERAGE TEMP (DEG F) = 81.95

AVERAGE RH (%) = 63.33

HOURS = 45.20

\( \sigma = 0.4 \)

\( \sigma = 0.58 \)

45.20 ON 20.76 OFF 24.44

TOTAL 81.95 81.90 81.98

TOTAL 63.33 63.26 63.36

TOTAL 45.20 15.76 29.44

TOTAL 37.08 62.92

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: SHIREY

START DATE: 7/20 OR 201

TIME: 20:27:30

JULIAN HR: 4620.48

END DATE: 7/22 OR 203

TIME: 17:39:35

JULIAN HR: 4665.66

ELAPSED TIME: 45.20

THERMOSTAT DATA: SHIREY
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.349)

PLOT 5: ERROR ANALYSIS

N = 4 + AO + (X - (1 - X))

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 0.35% (ON-OFF)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: SHIREY
PLOT 4: RUN TIME PROFILES

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: REDMOND
PLOT 1: CYCLING

N (CYCLES/HR)

N = 4 + 2.46 * (X * (1 - X))
σ = 0.100902

X (RUNTIME FRACTION)

PLOT 2: t_m

\[ t_m = \frac{8.25}{(1 - x)} \]
\[ σ = 0.042135 \]
\[ t_m = \frac{5.74 + 1.9 \times X}{(1 - x)} \]
\[ σ = 0.000787 \]

Curve fits for X < 0.9

X (RUNTIME FRACTION)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 1.84 °F (ON-OFF)

AVERAGE TEMP (°C F)

HOURS

EOF

X HOURS

EOF

TOTAL

ON

OFF

77.40

77.37

77.42

58.46

58.12

58.72

36.28

28.65

36.64

43.88

36.12

THERMOSTAT DATA: FAIREY1
PLT 1: CYCLING

\[ N = 4 \cdot 2.46 \cdot (x = 1 - x) \]
\[ \sigma = 0.124212 \]

PLT 2: \( T_m \)

\[ t_m = \frac{6.55}{(1 - x)} \]
\[ \sigma = 1.524039 \]
\[ t_m = \frac{(4.9 + 2.51 \cdot x)}{(1 - x)} \]
\[ \sigma = 0.982758 \]

Curve fit for: \( x < 0.9 \)

PLT 3: TEMPERATURE

AVERAGE DEAD BAND = 1.28 F (ON-OFF)

AVERAGE TEMP (OEG F) = 77.77
AVERAGE RH (%) = 54.85

HOURS = 89.49
X HOURS = 51.44

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: FAIREY2
START DATE: 7/30 OR 211
END DATE: 8/2 OR 214
JULIAN HR: 3060.26
JULIAN HR: 3129.77

TOTAL ON OFF
AVERAGE TEMP (OEG F) 77.77 77.85 77.69
AVERAGE RH (%) 54.85 55.35 55.35
HOURS 89.49 36.74 33.74
X HOURS 51.44 48.56

THERMOSTAT DATA: FAIREY2
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.508)

PLOT 5: ERROR ANALYSIS

N = 4 - AD = (X - (1 - X))

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 45.3% (ON-OFF)

DEAD BAND (3 RH)

RH (%)  

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

DAY 211

DAY 212

DAY 213

THERMOSTAT DATA: FAIREY2
### PLOT 1: CYCLING

- $N = 4 \times 2.81 \times (1 - x)$
- $\sigma = 0.08505$

### PLOT 2: $t_m$

- $t_m = 5.93 \div (1 - x)$
- $\sigma = 7.038695$
- $t_m = (4.83 + 1.59 \times x) / (1 - x)$
- $\sigma = 0.738915$

Curve fits for: $x < 0.9$

### PLOT 3: TEMPERATURE

- Average Dead Band = 3.23°F (On/Off)

### SUMMARY OF THERMOSTAT PERFORMANCE DATA

**Location:** KETTLES

- **Start Date:** 6/4 or 216
- **Time:** 9:19:55
- **Julean HR:** 5160.33

- **End Date:** 6/7 or 219
- **Time:** 7:32:55
- **Julean HR:** 5239.55

- **Elapsed Time:** 70.22

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<td>Average Temp</td>
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<td>73.29</td>
<td>74.10</td>
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<tr>
<td>Average RH</td>
<td>49.80</td>
<td>49.78</td>
<td>49.85</td>
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<tr>
<td>Hours</td>
<td>70.22</td>
<td>43.70</td>
<td>26.52</td>
</tr>
<tr>
<td>% Hours</td>
<td>62.23</td>
<td>37.77</td>
<td></td>
</tr>
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</table>

**EOF**

### THERMOSTAT DATA: KETTLES
THERMOSTAT DATA: KETTLES
THERMOSTAT DATA: MELODY
PLT 1: CYCLING

N (CYCLES/HR)

N = 4 + 3.33 * (X - (1 - X))
σ = 0.2776857

X (RUNTIME FRACTION)

PLT 2: t_w

- t_w = 4.76 / (1 - X)
- σ = 1.05615
- t_w = (3.49 + 2.17 - X) / (1 - X)
- σ = 0.770249

Curve fits for: X < 0.9

X (RUNTIME FRACTION)

PLT 3: TEMPERATURE

AVERAGE DEAD BAND = 0.8 F (ON-OFF)

DEAD BAND (F)

AVERAGE TEMP (DEG F) = 81.66
AVERAGE RH (%) = 59.69
HOURS = 48.23
X HOURS = 31.38
EOF
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EOF
PLOT 4: RUN TIME PROFILES

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: DHERE
PLOT 1: CYCLING

N (CYCLES/HR) vs X (RUNTIME FRACTION)

N = 4 + 2.2 \times (X \times (1 - X))

\sigma = 0.15876

PLOT 2: \( t_m \)

\( t_m = 7.3 / (1 - x) \)

\sigma = 2.188137

\( t_m = (5.18 + 1.76 \times x) / (1 - x) \)

\sigma = 2.003237

Curve fits for: \( x < 0.9 \)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 1.86 \text{ F (ON-OFF)}

DEAD BAND (F)

AVERAGE TEMP (DEG F)

\( x = 0.9 \)

\sigma = 0.032

TEMP (F) vs X (RUNTIME FRACTION)

AVERAGE RH (%) = 70.03

\sigma = 0.03

HOURS = 48.20

\sigma = 0.04

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: DUTTON

START DATE: 8/16 OR 230 TIME: 17:16:15 JULIAN HR: 5513.27

END DATE: 8/20 OR 232 TIME: 17:28:15 JULIAN HR: 5584.47

ELAPSED TIME: 48.20

TOTAL \hspace{1cm} ON \hspace{1cm} OFF

AVERAGE TEMP (DEG F) = 74.69 \hspace{1cm} 75.00 \hspace{1cm} 74.37

AVERAGE RH (%) = 70.03 \hspace{1cm} 67.00 \hspace{1cm} 73.19

HOURS = 48.20 \hspace{1cm} 24.63 \hspace{1cm} 23.57

EOF \hspace{1cm} EOFOF

EOF

THERMOSTAT DATA: DUTTON
PLOT 4: RUN TIME PROFILES

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: DUTTON
PLT 1: CYCLING

\[ N = 4 \times 2.58 \times \left( \frac{x}{(1 - x)} \right) \]
\[ \sigma = 0.130862 \]

PLT 2: \( t_m \)

\[ t_m = \frac{6.05}{(1 - x)} \]
\[ \sigma = 1.170529 \]
\[ t_m = \frac{(5.20 + 1.2 \times x)}{(1 - x)} \]
\[ \sigma = 1.042974 \]
Curve fits for: \( x < 0.9 \)

PLT 3: TEMPERATURE

AVG DEAD BAND = 2.38°F (ON-OFF)

AVG TEMPERATURE (°F): 78.92, 78.96, 78.88
AVG RH (%) 63.53, 63.13, 64.23
HOURS 45.27, 28.75, 16.52
EOH 63.52, 36.48

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: DERNIER
ELAPSED TIME: 45.27

TOTAL | ON | OFF
---|---|---
78.92 | 78.96 | 78.88
63.53 | 63.13 | 64.23
45.27 | 28.75 | 16.52
63.52 | 36.48

THERMOSTAT DATA: DERNIER
THERMOSTAT DATA: DERNIER
PLOT 1: CYCLING

\[ N = 4 + 0.15 \times (X - (1 - X)) \]
\[ \sigma = 0.050969 \]

\[ X \text{ (RUNTIME FRACTION)} \]

PLOT 2: \( t_m \)

\[ t_m = \frac{111.12}{(1 - X)} \]
\[ \sigma = 113.786 \]
\[ t_m = \frac{(161.36 + 90.87 \times X)}{(1 - X)} \]
\[ \sigma = 121.5519 \]

Curve fits for: \( X < 0.9 \)

\[ X \text{ (RUNTIME FRACTION)} \]

PLOT 3: TEMPERATURE

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: VIEIRA1
START DATE: 8/25 OR 237 TIME: 5:54:50 JULIAN HR: 5672.91
END DATE: 8/27 OR 239 TIME: 16:19:0 JULIAN HR: 5730.32
ELAPSED TIME: 57.40

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<tr>
<th>TOTAL</th>
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<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE TEMP (DEG F)</td>
<td>76.27</td>
<td>74.37</td>
</tr>
<tr>
<td>AVERAGE RH (%)</td>
<td>56.77</td>
<td>56.27</td>
</tr>
<tr>
<td>HOURS</td>
<td>57.40</td>
<td>27.81</td>
</tr>
<tr>
<td>X HOURS</td>
<td>48.45</td>
<td>51.85</td>
</tr>
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</table>

THEROSTAT DATA: VIEIRA1
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.489)

PLOT 5: ERROR ANALYSIS

\[ N = A_0 + A_1 (1 - e^{-kt}) \]

ERROR (N)

ERROR (P)

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 4.18 \% (ON-OFF)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: VIEIRA1
PLOT 1: CYCLING

\[ N = 4 \times 1.74 \cdot (X - (1 - X)) \]
\[ \sigma = 0.105475 \]

X (RUNTIME FRACTION)

PLOT 2: \( t_m \)

\[ t_m = 6.69 / (1 - X) \]
\[ \sigma = 1.127912 \]
\[ t_m = (8.93 + 0.84 - X) / (1 - X) \]
\[ \sigma = 1.118098 \]

Curve fit for: \( X < 0.9 \)

X (RUNTIME FRACTION)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 2.8°F (ON-OFF)

AVERAGE TEMP (DEG F) = 76.82

AVERAGE RH (%) = 55.43

HOURS = 71.33

EOF

EOF

EOF

EOF

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: VIEIRA2

START DATE: 6/27 OR 239

END DATE: 6/30 OR 242

TOTAL

ON

OFF

76.82

76.28

77.18

55.43

55.03

55.69

71.33

28.43

42.90

39.85

60.15

THERMOSTAT DATA: VIEIRA2
PLOT 4: RUN TIME PROFILES

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: VIEIRA2
PLOT 1: CYCLING

\[ N = 4 + 3.64 \times (X - (1 - X)) \]
\[ \sigma = 0.140833 \]

X (RUNTIME FRACTION)

PLOT 2: T_

\[ T_\text{on} = \frac{4.25}{(1 - x)} \]
\[ \sigma = 0.550628 \]
\[ T_\text{off} = \frac{(3.6 + 0.92 \times x)}{(1 - x)} \]
\[ \sigma = 0.36995 \]

Curve fits for: \( X < 0.9 \)

X (RUNTIME FRACTION)

PLOT 3: TEMPERATURE

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: DUMMER
START DATE: 9/0 OR 243
TIME: 20:53:15
JULIAN HR: 3628.68
END DATE: 9/3 OR 246
TIME: 19:15:35
JULIAN HR: 3699.20
ELAPSED TIME: 70.37

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<thead>
<tr>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
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<tbody>
<tr>
<td>AVERAGE TEMP (DEG F)</td>
<td>78.41</td>
<td>78.64</td>
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<tr>
<td>AVERAGE RH (%)</td>
<td>41.36</td>
<td>41.54</td>
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<tr>
<td>HOURS</td>
<td>70.37</td>
<td>43.73</td>
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<tr>
<td>% HOURS</td>
<td>62.14</td>
<td>37.86</td>
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</tbody>
</table>

THERMOSTAT DATA: DUMMER
THERMOSTAT DATA: DUMMER
PLOT 1: CYCLING

\[ N = 4 \times 3.74 \times (X \times (1 - X)) \]
\[ \sigma = 0.20008 \]

PLOT 2: \( t_m \)

\[ t_m = 4.2 / (1 - X) \]
\[ \sigma = 0.588915 \]
\[ t_m = (3.55 + 0.99 \times X) / (1 - X) \]
\[ \sigma = 0.344767 \]
Curve fits for: \( X < 0.9 \)

PLOT 3: TEMPERATURE

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: RAUSTAD2
START DATE: 9/5/245 TIME: 17:50:23 JULIAN HR: 5843.84
END DATE: 9/7/250 TIME: 16:34:50 JULIAN HR: 5992.58
ELAPSED TIME: 46.74

<table>
<thead>
<tr>
<th></th>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP (°F)</td>
<td>79.01</td>
<td>79.22</td>
<td>78.80</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>54.90</td>
<td>55.15</td>
<td>54.63</td>
</tr>
<tr>
<td>HOURS</td>
<td>46.74</td>
<td>23.32</td>
<td>23.42</td>
</tr>
<tr>
<td>% HOURS</td>
<td>49.89</td>
<td>50.11</td>
<td></td>
</tr>
</tbody>
</table>

THERMOSTAT DATA: RAUSTAD2
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.49)

PLOT 5: ERROR ANALYSIS

ERROR (m)

ERROR (m/s)

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 1.42 \times (ON-OFF)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

DAY 248

TEMP (°C)

DAY 249

TEMP (°C)

DAY 250

TEMP (°C)

THERMOSTAT DATA: RAUSTAD2
**Plot 1: Cycling**

- Equation: \( N = 4 - 2.94 \times (1 - x) \)
- \( \sigma = 0.180875 \)

**Plot 2: \( l_m \)**

- Equation: \( l_m = 5.26 \times (1 - x) \)
- \( \sigma = 0.180875 \)

**Plot 3: Temperature**

- Average dead band: 1.25°F (on-off)

**Summary of Thermostat Performance Data**

- Location: Goulet
- Start date: 9/8 or 251
- Time: 13:55:50
- Julian date: 8013.93
- End date: 9/11 or 254
- Time: 20:00:25
- Julian date: 8092.01
- Elapsed time: 78.08

<table>
<thead>
<tr>
<th></th>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average temp (deg F)</td>
<td>78.17</td>
<td>78.56</td>
<td>77.98</td>
</tr>
<tr>
<td>Average RH (%)</td>
<td>55.93</td>
<td>54.98</td>
<td>56.42</td>
</tr>
<tr>
<td>Hours</td>
<td>78.08</td>
<td>25.97</td>
<td>52.11</td>
</tr>
<tr>
<td>( x ) hours</td>
<td>33.26</td>
<td>68.74</td>
<td></td>
</tr>
</tbody>
</table>

**Thermostat Data: Goulet**
THERMOSTAT DATA: GOULET
**SUMMARY OF THERMOSTAT PERFORMANCE DATA**

**LOCATION:** CUMMINGS3

**START DATE:** 9/14 OR 257
**END DATE:** 9/17 OR 260

**TIME:** 22:45:30 JULEAN HR: 8166.0

**TIME:** 7:06:40 JULEAN HR: 8223.11

**TOTAL:**

| AVERAGE TEMP (DEG F) | 78.98 | 76.48 | 77.36 |
| AVERAGE RH (%)       | 50.13 | 49.50 | 50.62 |
| HOURS                | 56.95 | 24.57 | 32.38 |

**TOTAL ON:**

| AVERAGE TEMP (DEG F) | 78.98 | 76.48 | 77.36 |
| AVERAGE RH (%)       | 50.13 | 49.50 | 50.62 |

**TOTAL OFF:**

| AVERAGE TEMP (DEG F) | 78.98 | 76.48 | 77.36 |
| AVERAGE RH (%)       | 50.13 | 49.50 | 50.62 |

**ELAPSED TIME:** 56.95

**THERMOSTAT DATA: CUMMINGS3**
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.437)

PLOT 5: ERROR ANALYSIS

ERROR (n)

ERROR (m/s)

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 2.38% (ON-OFF)

RH (%) vs X (RUN TIME FRACTION)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

DAY 257

DAY 258

DAY 259

THERMOSTAT DATA: CUMMINGS3
Summary of Thermostat Performance Data

Location: Cummings2
Start Date: 9/13 or 256
End Date: 9/14 or 257
Julian HR: 8138.18
Julian HR: 8160.33
Elapsed Time: 22.16

<table>
<thead>
<tr>
<th>Total</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>79.45</td>
<td>79.01</td>
<td>79.73</td>
</tr>
<tr>
<td>49.56</td>
<td>48.70</td>
<td>50.14</td>
</tr>
<tr>
<td>22.16</td>
<td>8.71</td>
<td>13.45</td>
</tr>
<tr>
<td>39.29</td>
<td>60.71</td>
<td></td>
</tr>
</tbody>
</table>

Thermostat Data: Cummings2
### Summary of Thermostat Performance Data

**Location:** CUMMINGS 1

| Start Date: 9/12 | Time: 16:57:40 | JULEAN Hr: 6114.98 |
| End Date: 9/13 | Time: 17:28:40 | JULEAN Hr: 6137.48 |
| Elapsed Time: 22.52 |

#### Thermostat Data

**Average Dead Band:** 2.87 F (On-Off)

**Average Temp (°F):**
- **Total:** 79.58
- **On:** 79.09
- **Off:** 79.05

**Average RH (%):**
- **Total:** 50.30
- **On:** 49.49
- **Off:** 50.79

**Hours:**
- **Total:** 22.52
- **On:** 6.59
- **Off:** 13.93

- 20 Hours:
- E0F
- E0F
- E0F
- E0F
- E0F

**Thermostat Data:** CUMMINGS 1
THERMOSTAT DATA: CUMMINGS1
PLOT 1: CYCLING

\[ N = 4 \times 1.18 \times (X \times (1-X)) \]
\[ \sigma = 0.397164 \]

X (RUNTIME FRACTION)

N (CYCLES/HR)

PLOT 2: \( t_m \)

\[ t_m = \frac{13.84}{(1 - X)} \]
\[ \sigma = 6.756617 \]
\[ t_m = \frac{(13.87 + 0.08 \times X)}{(1 + X)} \]
\[ \sigma = 6.829825 \]

Curve fits for: \( X < 0.9 \)

X (RUNTIME FRACTION)

\( t_m \) (minutes)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 2.4° (ON-OFF)

X (RUNTIME FRACTION)

DEAD BAND (°)

TEMP (°F)

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: MELLOR

START DATE: 9/17 OR 260 TIME: 22:2:0 JULIAN HR: 8238.03
END DATE: 9/20 OR 263 TIME: 19:56:40 JULIAN HR: 8307.81
ELAPSED TIME: 69.58

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE TEMP (°F)</td>
<td>78.59</td>
<td>78.13</td>
</tr>
<tr>
<td>AVERAGE RH (%)</td>
<td>60.73</td>
<td>60.05</td>
</tr>
<tr>
<td>HOURS</td>
<td>69.58</td>
<td>17.86</td>
</tr>
<tr>
<td>% HOURS</td>
<td>25.67</td>
<td>74.33</td>
</tr>
</tbody>
</table>

THERMOSTAT DATA: MELLOR
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.252)

HOUR OF DAY (EDT)

PLOT 5: ERROR ANALYSIS

ERROR (N)

ERROR (%)

JULIAN HOURS

PLOT 5: HUMIDITY

AVERAGE DEAD BAND (RH) = 0.25 % (ON-OFF)

DEAD BAND (RH)

RH (%) (X)

RH (%) (Y)

X (RUN TIME FRACTION)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

DAY 260

DAY 261

DAY 262

JULIAN TIME (h)

TEMP (°F)

TEMP (°C)

THERMOSTAT DATA: MELLO
PLOT 1: CYCLING

N = 4 * 1.71 * (X = (1 - X))

\( \sigma = 0.122842 \)

X (RUNTIME FRACTION)

N (CYCLES/HR)

PLOT 2: \( t_m \)

\( t_m = 8.88 / (1 - X) \)

\( \sigma = 1.252607 \)

\( t_m = (8.35 + 1.12 \times X) / (1 - X) \)

\( \sigma = 1.270502 \)

Curve fit for: X < 0.9

X (RUNTIME FRACTION)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 1.95 F (ON-OFF)

TEMP (F)

AVERAGE TEMP (DEG F) 78.33 79.09 79.48

AVERAGE RH (%) 47.89 47.69 48.03

HOURS 28.79 11.60 17.19

X HOURS 40.31 59.69

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: WALKER

START DATE: 9/21 OR 264 TIME: 18:16:40 JULEAN HR: 6331.28

END DATE: 9/23 OR 266 TIME: 0:4:5 JULEAN HR: 6360.07

ELAPSED TIME: 28.79

TOTAL ON OFF

THERMOSTAT DATA: WALKER
**THERMOSTAT DATA: KALAGHCHY**

**Plot 1: Cycling**

- Equation: \( N = 4 + 3.36 \times (X - (1-x)) \)
- \( \sigma = 0.271263 \)

**Plot 2: \( t_m \)**

- Equation: \( t_m = \frac{4.56}{(1-x)} \times \frac{0.977853}{1} \)
- \( \sigma = 0.980098 \)
- Curve fits for: \( X < 0.9 \)

**Summary of Thermostat Performance Data**

- Location: KALAGHCHY
- Start Date: 10/1 OR 274 Time: 20:42:10 Julian HR: 8572.70
- End Date: 10/4 OR 277 Time: 26:43:15 Julian HR: 8630.75
- Elapsed Time: 58.05

<table>
<thead>
<tr>
<th>Metric</th>
<th>Total</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Temp (F)</td>
<td>78.94</td>
<td>78.63</td>
<td>77.11</td>
</tr>
<tr>
<td>Average RH (%)</td>
<td>50.76</td>
<td>50.36</td>
<td>51.02</td>
</tr>
<tr>
<td>Hours</td>
<td>58.05</td>
<td>21.04</td>
<td>37.01</td>
</tr>
<tr>
<td>EOH</td>
<td>36.25</td>
<td>63.75</td>
<td></td>
</tr>
</tbody>
</table>
PLOT 4: RUN TIME PROFILES

DAILY PROFILES: A, B, C...

COMPOSITE PROFILE (AVG: 0.364)

PLOT 5: ERROR ANALYSIS

PLOT 6: HUMIDITY

AVERAGE DEAD BAND (RH) = 1.72 % (ON-OFF)

PLOT 7: TEMPERATURE VS TIME (3 DAYS)

THERMOSTAT DATA: KALAGHCHY
PLOT 1: CYCLING

\[ N = 4 + 2.44 \times (X) \]  
\[ \sigma = 0.22995 \]

X (RUNTIME FRACTION)  
N (CYCLES/HR)

PLOT 2: \( \tau_m \)

\[ \tau_m = \frac{6.59}{(1 - X)} \]
\[ \sigma = 2.85769 \]

\[ \tau_m = \frac{(4.2 + 7.16 \times X) / (1 - X)}{2.410546} \]  
Curve fits for: X < 0.9

X (RUNTIME FRACTION)  
\( \tau_m \) (minutes)

PLOT 3: TEMPERATURE

AVERAGE DEAD BAND = 1.13 °F (ON-OFF)

X (RUNTIME FRACTION)  
DEAD BAND (°F)

AVERAGE TEMP (DEG F) = 80.17 ± 3.27 °F (\( \sigma = 0.41 \))

X (RUNTIME FRACTION)  
TEMP (°F)

AVERAGE RH (%) 55.48

X (RUNTIME FRACTION)  
TEMP (°F)

THERMOSTAT DATA: SHIREY2

SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: SHIREY2
START DATE: 10/4 OR 277  TIME: 21:44:45  JULEAN HR: 6845.75
END DATE: 10/8 OR 281  TIME: 5:43:40  JULEAN HR: 6728.73
ELAPSED TIME: 80.98

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.89</td>
<td>80.98</td>
<td>80.58</td>
</tr>
<tr>
<td>55.46</td>
<td>55.14</td>
<td>55.58</td>
</tr>
<tr>
<td>80.98</td>
<td>19.29</td>
<td>61.69</td>
</tr>
<tr>
<td>23.82</td>
<td>75.18</td>
<td></td>
</tr>
</tbody>
</table>

EOF  
EOF  
EOF  
EOF  
EOF
THERMOSTAT DATA: KANNAN
PLOT 1: CYCLING

\[ N = 4 \times 4.03 \times (1 - x)^2 \]
\[ \sigma = 0.38278 \]

PLOT 2: \( t_m \)

\[ t_m = 3.75 \times (1 - x) \]
\[ \sigma = 0.661722 \]
\[ t_m = (4 + 0.65 \times x) \times (1 - x) \]
\[ \sigma = 0.884432 \]

SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: YAROSH2
START DATE: 10/20 OR 203
END DATE: 10/22 OR 295
TIME: 18:13:55
JULIAN HR: 7028.23
TIME: 7:8:25
JULIAN HR: 7063.14
ELAPSED TIME: 39.91

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE TEMP (DEG F)</td>
<td>77.41</td>
<td>78.99</td>
</tr>
<tr>
<td>AVERAGE RH (%)</td>
<td>63.32</td>
<td>63.05</td>
</tr>
<tr>
<td>HOURS</td>
<td>39.91</td>
<td>11.50</td>
</tr>
<tr>
<td>X HOURS</td>
<td>31.16</td>
<td>68.84</td>
</tr>
</tbody>
</table>

SELECTED DATA RANGE:
STARTING 293
ENDING 295

THERMOSTAT DATA: YAROSH2
APPENDIX D

Cycling Rate and Thermostat Parameters From the Literature
### TABLE D-1

Cycling Rate Parameters From Literature

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{\text{max}}$ (cycles/hr)</th>
<th>$t_{\text{on, min}}$ (minutes)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murphy &amp; Goldschmidt (1979)</td>
<td>2.83</td>
<td>5.3</td>
<td>Cooling mode in mobile home</td>
</tr>
<tr>
<td>Goldschmidt et al. (1980)</td>
<td>2.8-3.3</td>
<td>4.6-5.3</td>
<td>Cooling, Mobile home with and without metal chairs</td>
</tr>
<tr>
<td>Parken et al. (1985)</td>
<td>2.00</td>
<td>7.5</td>
<td>Cooling, Brick house w/basement</td>
</tr>
<tr>
<td></td>
<td>2.28</td>
<td>6.6</td>
<td>Cooling, Frame house w/ walk-out basement</td>
</tr>
<tr>
<td></td>
<td>1.64</td>
<td>9.1</td>
<td>Cooling, Frame house w/ walk-out basement</td>
</tr>
<tr>
<td>Miller &amp; Jaster (1985)</td>
<td>0.6-2.1</td>
<td>7.1-25</td>
<td>Heating mode for 9 heat pumps</td>
</tr>
<tr>
<td>Hart &amp; Goldschmidt (1980)</td>
<td>3.1</td>
<td>4.8</td>
<td>Heating mode</td>
</tr>
<tr>
<td>ARI (1984)</td>
<td>3.125</td>
<td>4.8</td>
<td>Inferred from cyclic test 6 min ON, 24 min OFF</td>
</tr>
</tbody>
</table>

Given data is bold, other value calculated from equation (A-6) $N_{\text{max}} = 60/(4t_{\text{on, min}})$. See Appendix A for definition of $N_{\text{max}}$ and $t_{\text{on, min}}$.

### TABLE D-2

Measured Thermostat Deadbands ($\Delta T_{\text{set}}$) from the Literature

<table>
<thead>
<tr>
<th>Source</th>
<th>Switch Deadband ($\Delta T_{\text{set}}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>McBride (1979)</td>
<td>0.8°F</td>
<td>Measured in laboratory</td>
</tr>
<tr>
<td>Miller &amp; Jaster (1985)</td>
<td>2.5°F</td>
<td>Measured in field tests</td>
</tr>
</tbody>
</table>
APPENDIX E

Derivation of Part Load Efficiency Function

E-1
Derivation of Part Load Factor

The goal is to find \( PLF = F(\text{CLF}, N_{\text{max}}, \tau) \)

First, define:

\[
X = \frac{t_{\text{ON}}}{t_{\text{cycle}}} \quad (E-1)
\]

where: \( t_{\text{ON}} \) = time AC is ON
\( t_{\text{cycle}} \) = time for a complete ON & OFF cycle

The thermostat cycling equation (from Appendix A) is defined as:

\[
N = 4N_{\text{max}}X(1-X) \quad (E-2)
\]

where: \( N \) = \( 1/t_{\text{cycle}} \), the number of ON/OFF cycles per hour
\( N_{\text{max}} \) = Maximum cycle rate

Rearranging equation (E-2) results in:

\[
t_{\text{ON}} = \frac{1}{4N_{\text{max}}(1-X)} \quad (E-3)
\]

The response of the an AC system is approximately first-order and can be represented as:

\[
Q = Q_{ss}(1 - e^{-t/\tau}) \quad (E-4)
\]

where: \( \tau \) = Time constant of AC system (time)
\( Q, Q_{ss} \) = AC cooling capacity (energy/time)

Integrating \( Q \) over \( t_{\text{on}} \):

\[
q = \int_0^{t_{\text{on}}} Q \, dt \quad (E-5)
q = Q_{ss}(t_{\text{on}} - \tau(1 - e^{-t_{\text{on}}/\tau}))
\]

Then defining:

\[
Q_{\text{avg}} = \frac{q}{t_{\text{cycle}}} \quad (E-6)
\]
\[ \text{EER}_{\text{avg}} = \frac{q}{E_{ss} t_{ON}} \]  
(\text{E-7})

\[ \text{EER}_{ss} = \frac{Q_{ss}}{E_{ss}} \]  
(\text{E-8})

\[ \text{CLF} = \frac{Q_{avg}}{Q_{ss}} = \frac{\text{Load}}{\text{AC Capacity}} \]  
(\text{E-9})

\[ \text{PLF} = \frac{\text{EER}_{avg}}{\text{EER}_{ss}} = \frac{\text{Part Load EER}}{\text{Steady State EER}} \]  
(\text{E-10})

Combining (E-5) with (E-6) and (E-9) results in:

\[ \text{CLF} = \frac{t_{ON}}{t_{cycle}} - \frac{\tau}{t_{cycle}} (1 - e^{-\tau/\tau}) \]  
(\text{E-11})

Combining (E-5) with (E-7) and (E-10) results in:

\[ \text{PLF} = 1 - \frac{\tau}{t_{ON}} (1 - e^{-\tau/\tau}) \]  
(\text{E-12})

Comparing (E-11) and (E-12) results in:

\[ X = \frac{t_{ON}}{t_{cycle}} = \frac{\text{CLF}}{\text{PLF}} \]  
(\text{E-13})

Finally, by substituting (E-3) and (E-13) into (E-12) results in:

\[ \text{PLF}_{i+1} = 1 - 4\pi N_{\text{max}} (1 - \text{CLF/PLF}_{i}) [1 - e^{-1 - \frac{4\pi N_{\text{max}} (1 - \text{CLF/PLF}_{i})}}] \]  
(\text{E-14})

Since PLF occurs on both sides of equation (E-14), iterations are necessary to find PLF.
The part load curve from the SEER test procedure is:

\[ \text{PLF} = 1 - C_o(1-\text{CLF}) \]  \hspace{1cm} (E-15)

Where \( C_o \) is equal to 0.25 by default.

By setting \( \text{CLF}=0 \), and comparing equations (E-14) and (E-15):

\[ C_o \approx 4\tau N_{\text{max}} \left(1 - e^{-\frac{1}{4\tau N_{\text{max}}}}\right) \]  \hspace{1cm} (E-16)

From the default values used in the cyclic tests in the SEER procedure, \( \tau \) and \( N_{\text{max}} \) can be shown to be:

\[ \tau = 76 \text{ seconds (0.0212 hours)} \]
\[ N_{\text{max}} = 3.125 \text{ cycles/hour} \]

This results in:

\[ C_o = 0.258 \]

This is very close to the default value of 0.25 used in the SEER test procedure.