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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

<u>General Characteristics of the Homes</u>
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 1-1

General Characteristics of the Test Sites	
Average Space Temperature	78.4°F
Average Space Relative Humidity	55.7%
Average Floor Area[a]	1566 ft^2
AC Relative Sizing[a]	561 ft^2/ton
Home Age[a]	18.8 years

[a]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).

<u>Cycling Rates</u>

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:

$$N = 4N_{max}X(1-X) \qquad (1\text{-}1)$$

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[1], 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.

[1]See Section 3.0 for definitions of droop and deadband.

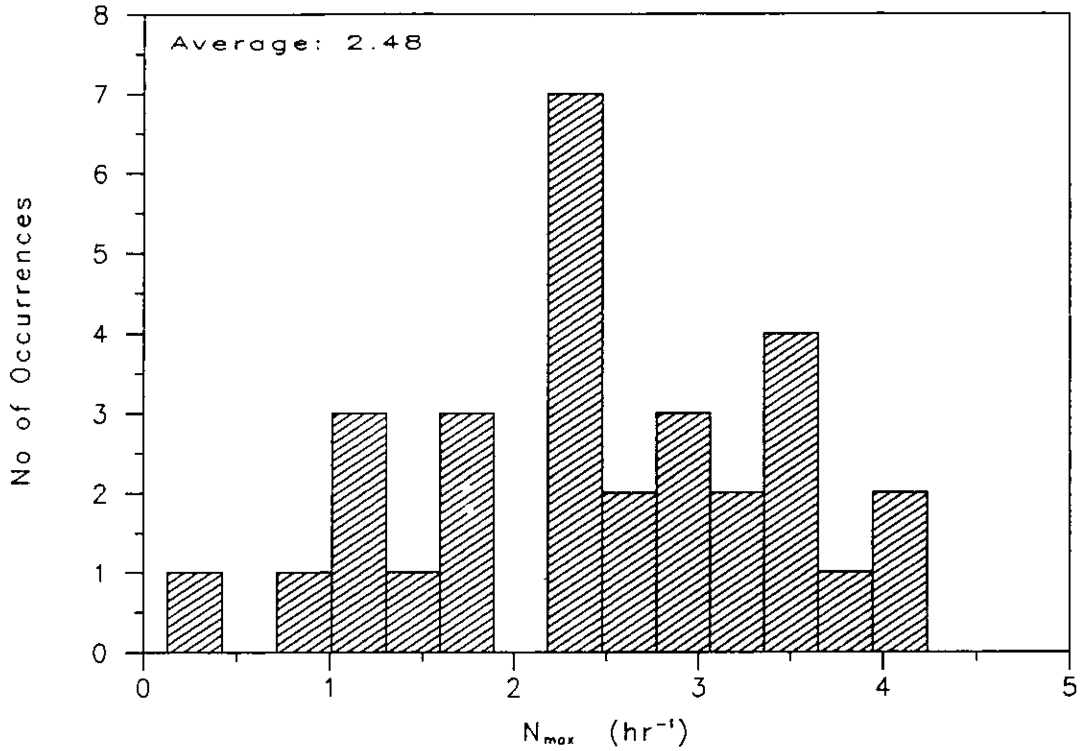

Figure 1-1 Histogram of Maximum Cycle Rate (N_{max}) Measured at All Sites

<u>Temperature Variation</u>
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.

<u>Humidity Variation</u>
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_{max} in this study. However, these two factors explained only 41% of the measured variation in N_{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_{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.

<u>A Conventional Thermostat</u> 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.

<u>An Electronic Thermostat</u> 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.

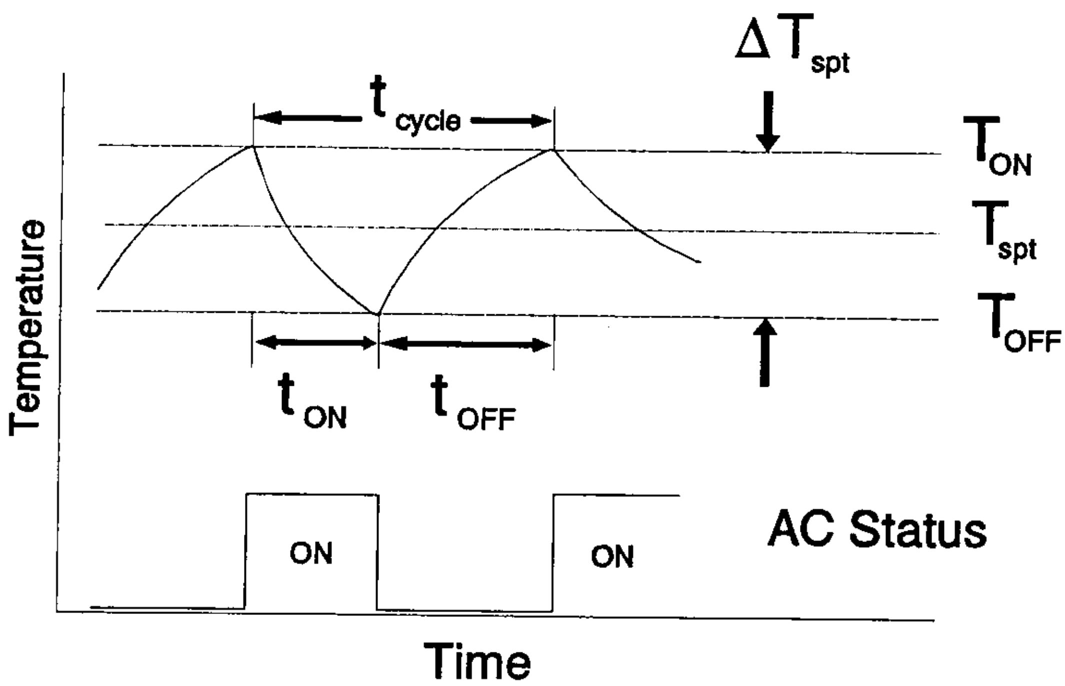

Figure 3-1 The Impact of AC Status on Space Temperature

A common feature of all thermostats is a deadband (ΔT_{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:

$$t_{cycle} = t_{ON} + t_{OFF} \tag{3-1}$$

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:

$$X = \frac{t_{ON}}{t_{cycle}} = \frac{t_{ON}}{(t_{ON} + t_{OFF})} \quad (3\text{-}2)$$

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

$$N = \frac{1}{t_{cycle}} = \frac{1}{(t_{ON} + t_{OFF})} \quad (3\text{-}3)$$

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

$$N = 4N_{max}X(1-X) \quad (3\text{-}4)$$

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:

$$t_{ON} = \frac{t_{ON,min}}{(1-X)} \quad (3\text{-}5)$$

Equation (3-5) comes from algebraically recombining 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:

$$t_{ON,min} = \frac{60}{4N_{max}} \quad (3\text{-}6)$$

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:

$$t_{ON} = \frac{\gamma(1+\alpha X)}{(1-X)} \qquad (3\text{-}7)$$

They stated that the extra constant (α) 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 (α) 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.

$$T_{avg} = c_o + d_o X \qquad (3\text{-}8)$$

Or, as the constant d_o 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.

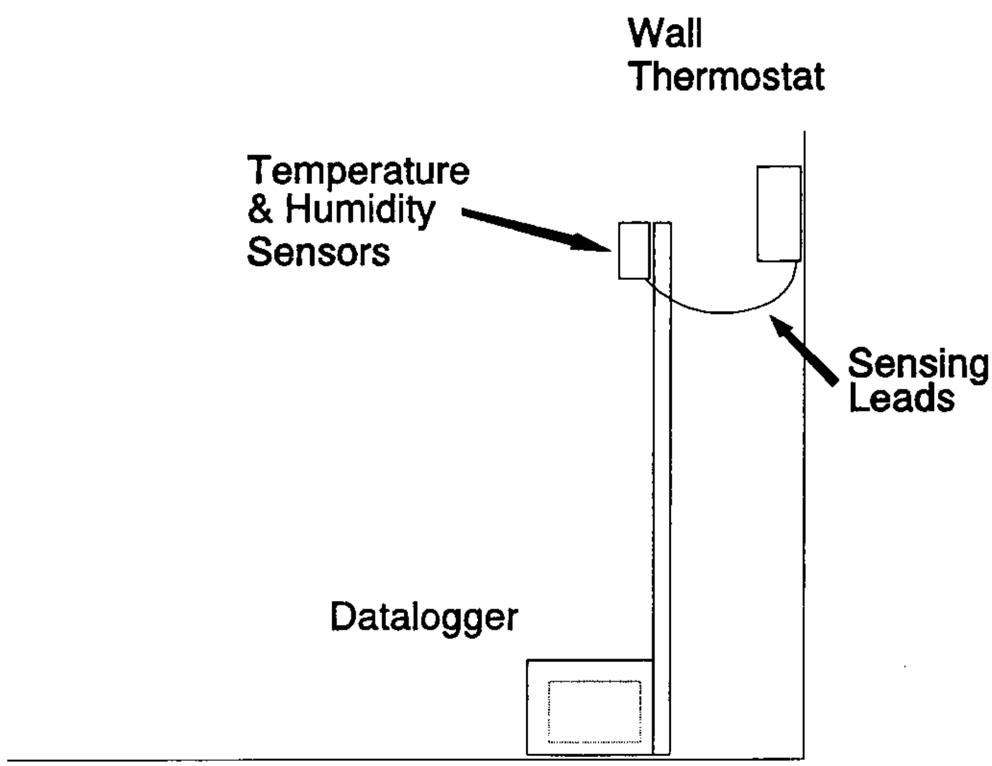

Figure 4-1 Placement of Experimental Apparatus Near Thermostat

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.

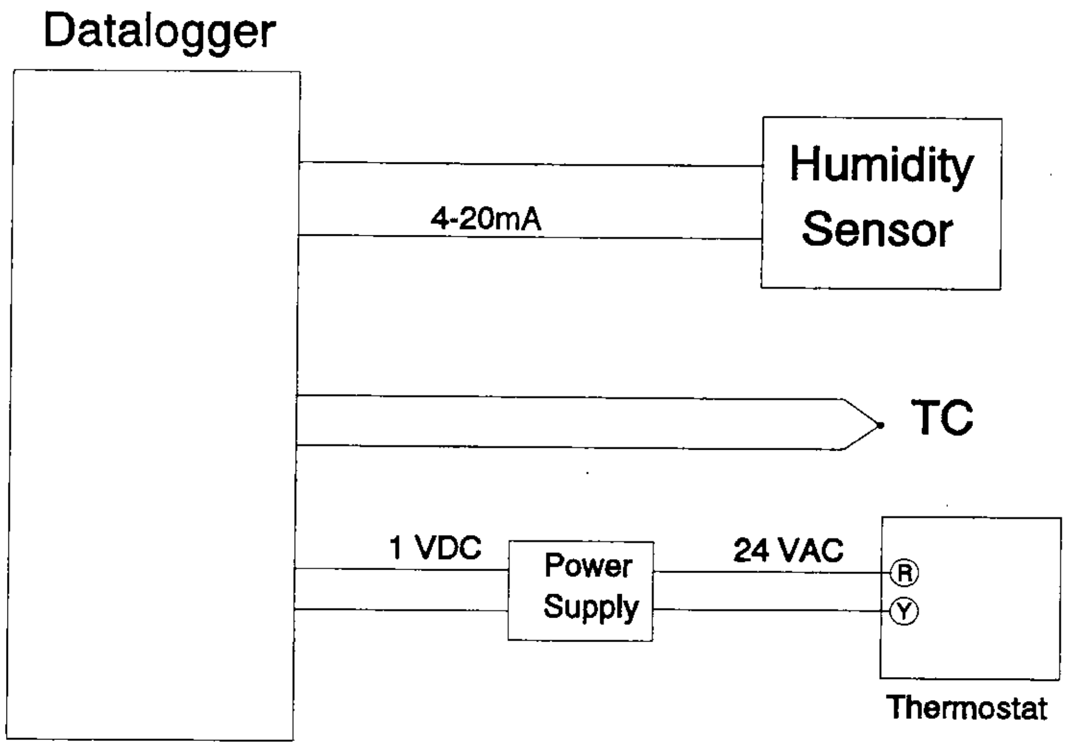

Figure 4-2 Schematic of Datalogger and Instrumentation

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 data logger, 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 4-1

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

4.2 Data Collection and Reduction

After each house was tested, the apparatus was taken to FSEC where the stored data was down-loaded 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 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 4-2

Calculated Data for Each Complete ON/OFF Cycle	
Calculated Variable	Description
t_{ON}	AC ON time
t_{OFF}	AC OFF time
t_{cycle}	AC cycle time
N	Cycle Rate
X	Runtime Fraction
T_{ON}	Temperature at which AC unit turned ON
T_{OFF}	Temperature at which AC unit turned OFF
ΔT_{spt}	Deadband Temperature (T_{ON} - T_{OFF})
T_{avg}	Average Temperature*
RH_{ON}	Relative Humidity at which AC unit turned ON
RH_{OFF}	Relative Humidity at which the AC unit turned OFF
ΔRH_{spt}	RH Deadband (RH_{ON} - RH_{OFF})
RH_{avg}	Average Relative Humidity*
* 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 5-1

General Characteristics of Monitored Homes

	Mean	Std. Dev.	Minimum	Maximum
Average Temperature	78.3°F	2.0°F	73.6°F	82.1°F
Average RH	55.7%	6.1%	41.4%	70.0%
Floor Area[a]	1566 ft^2	517 ft^2	616 ft^2	2700 ft^2
AC Sizing[a] (ft^2/ton)	561	86	400	792
House Age[a]	18.4 yr	12.4 yr	1 yr	35 yr

[a]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 ft^2 of floor area" rule of thumb. New houses, which typically had higher insulation levels, tended towards the 600 to 700 ft^2/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 5-2

Description of Test Sites					
1	Raustad1	A	June 9	Block	Conventional
2	Henderson	B	June 11	Block	Conventional
3	Rudd	C	June 14	Block	Conventional
4	Yarosh1	D	June 25	Block	Conventional
5	Holder	E	June 29	Block	Conventional
6	Sherwin	F	July 11	Block	Conventional
7	Parker	G	July 16	Block	Conventional
8	Shirey	H	July 20	Apt	Conventional
9	Redmond	I	July 23	Block	Conventional
10	Fairey1	J	July 27	Frame	Conventional
11	Fairey2	K	July 30	Frame	Conventional
12	Kettles	L	Aug 4	Frame	Conventional
13	Melody	M	Aug 8	Block	Conventional
14	Dhere	N	Aug 14	Block	Conventional
15	Dutton	O	Aug 18	Frame	Conventional
16	Dernier	P	Aug 21	Block	Conventional
17	Vieira1	Q	Aug 24	Block	Electronic
18	Vieira2	R	Aug 27	Block	Conventional
19	Dummer	S	Aug 31	Block	Conventional
20	Raustad2	T	Sept 5	Block	Conventional
21	Goulet	U	Sept 8	Block	Conventional
22	Cummings3	V	Sept 14	Block	Conventional
23	Cummings2	W	Sept 13	Block	Conventional
24	Cummings1	X	Sept 12	Block	Conventional
25	Mellor	Y	Sept 17	Frame	Electronic
26	Walker	Z	Sept 21	Block	Conventional
27	Kalaghchy	1	Oct 1	Frame	Electronic
28	Shirey	2	Oct 4	Apt	Conventional
29	Kannan	3	Oct 11	Apt	Conventional
30	Yarosh2	4	Oct 20	Block	Conventional

ID is used in Figures 5-8, 5-17 to 5-22 in this section.
All tests performed in 1990 Summer season.

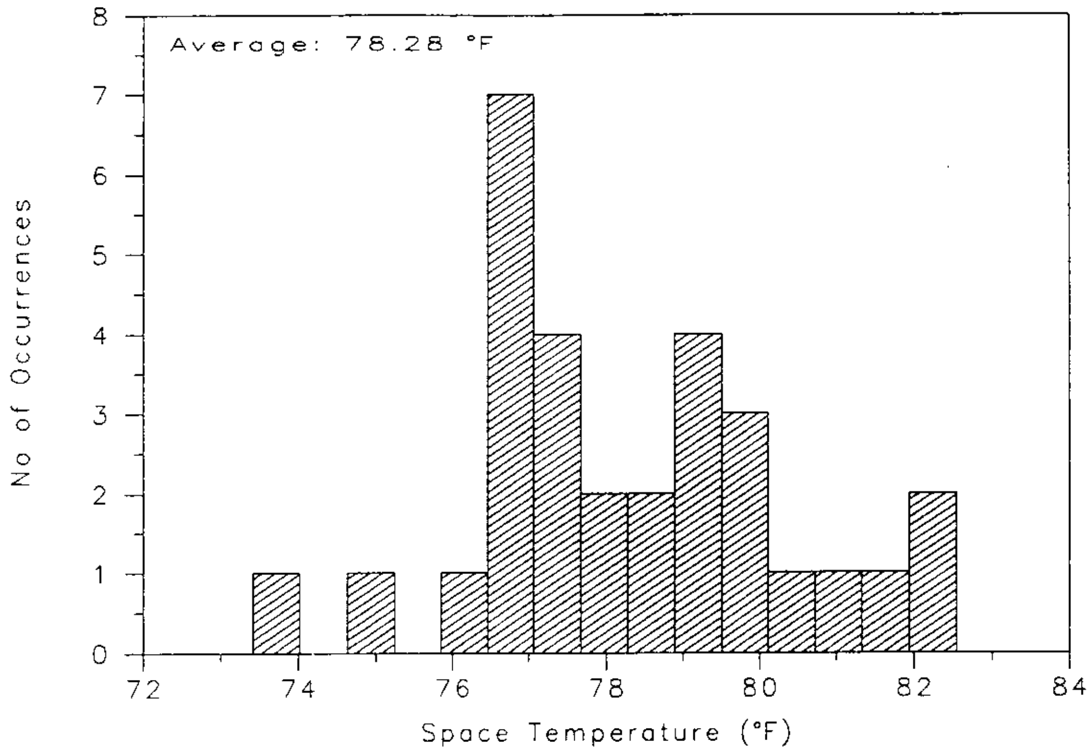

Figure 5-1 Histogram of Average Space Temperature

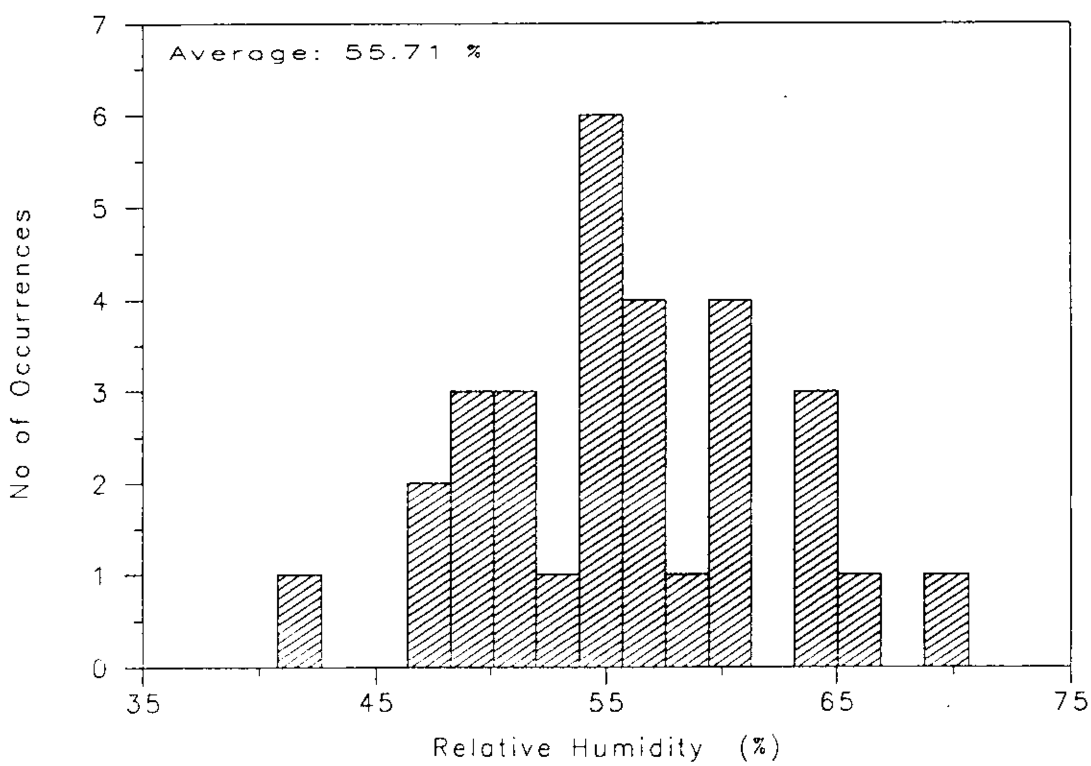

Figure 5-2 Histogram of Average Space Relative Humidity

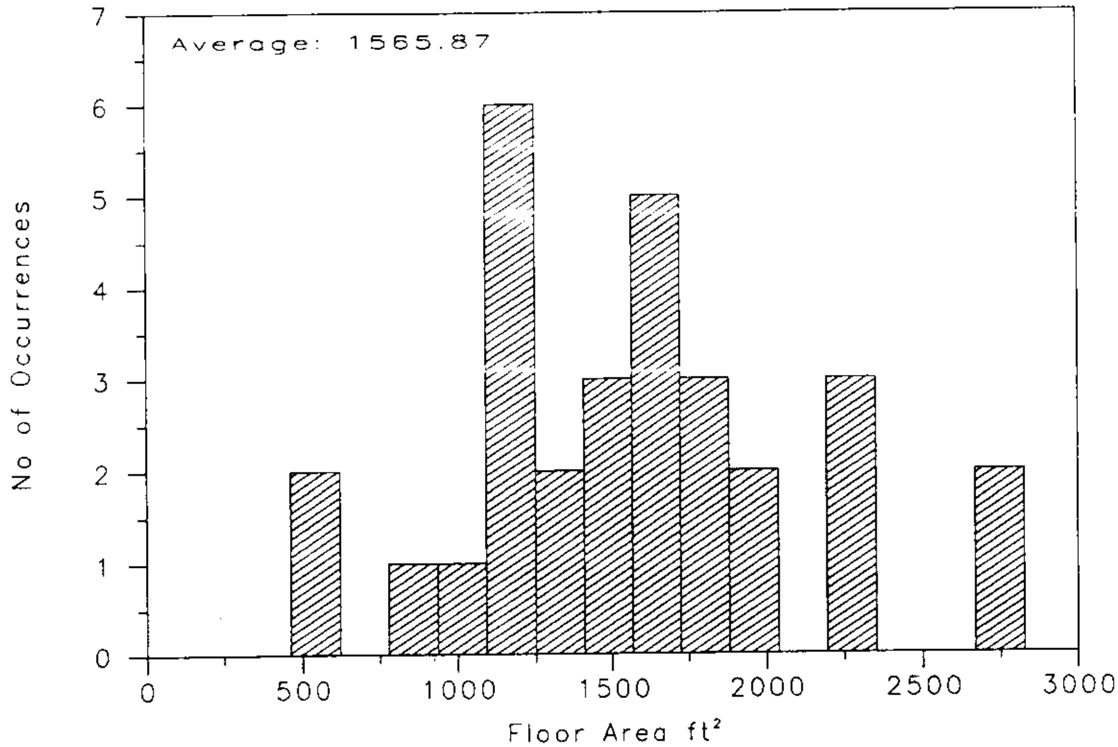

Figure 5-3 Histogram of Floor Area

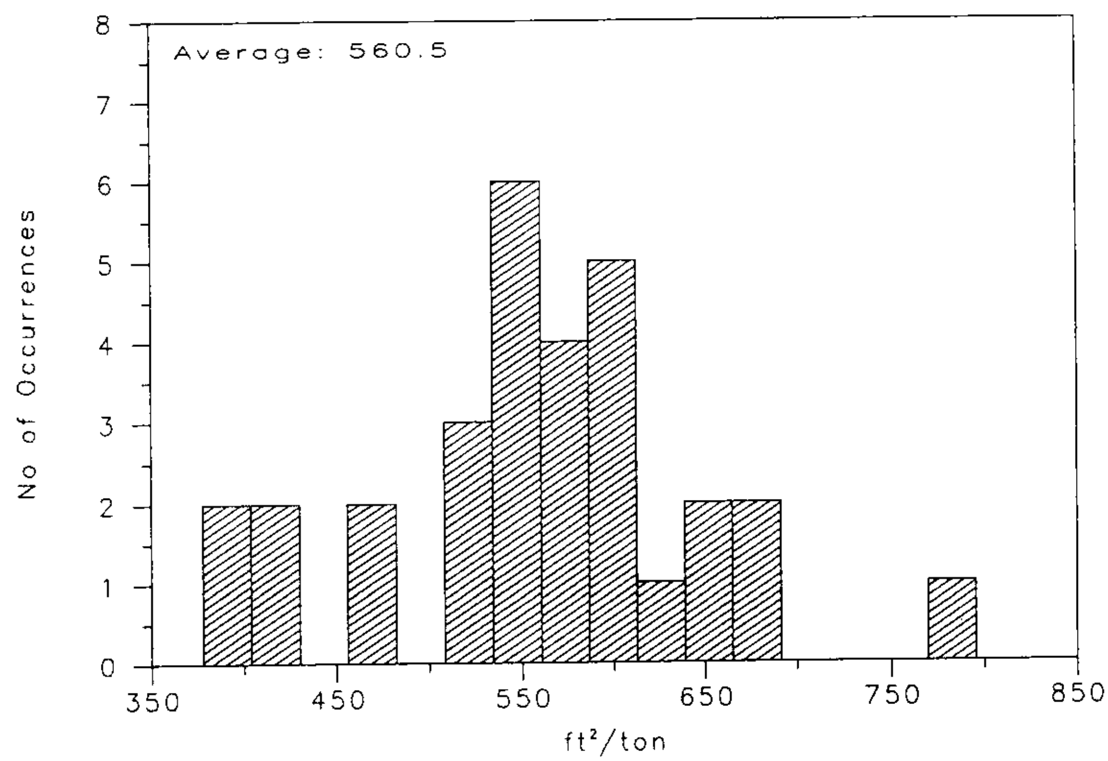

Figure 5-4 Histogram of AC Sizing (Floor Area per AC Unit Size)

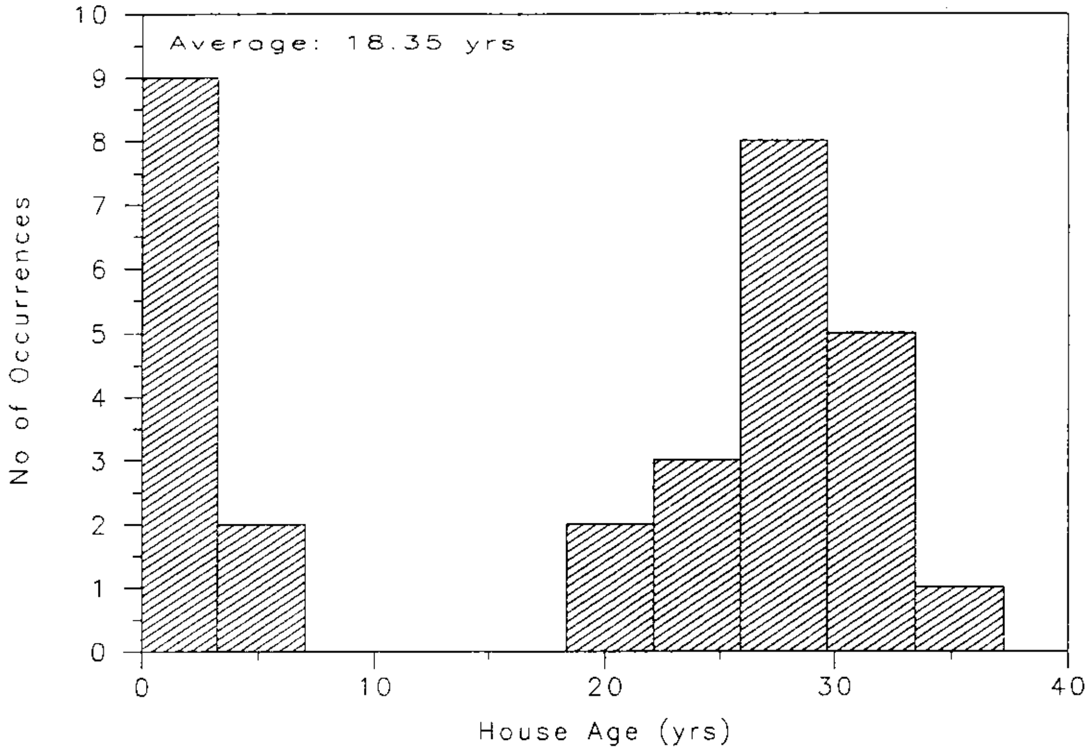

Figure 5-5 Histogram of House Age

5.2 Thermostat Cycling Rate: N_{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_{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_{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.

$$N = 4N_{max}X(1-X) \tag{5-1}$$

As discussed in section 3, the constant N_{max} corresponds to the maximum value of the cycling rate function. The curve-fit of measured data to determine N_{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_{max} for all tests. The average N_{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 (σ) to N_{max} gives a good indication of how well equation (5-1) fits the measured data. Figure 5-8 is a histogram of this ratio ($100\sigma/N_{max}$) from all tests. Typically the ratio of the standard deviation of the measured data from the curve (σ) to N_{max} was smaller than 10%, indicating that equation (3-4) fits the measured data well and accurately represents cycling rate performance.

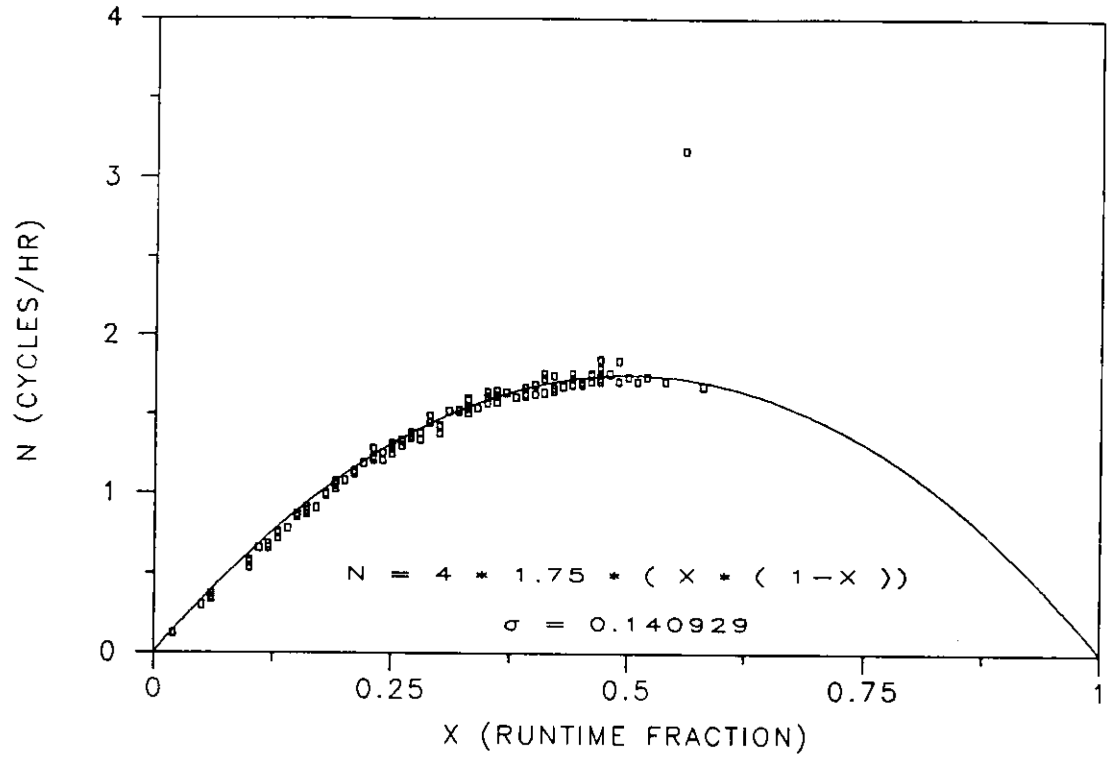

Figure 5-6 Thermostat Cycling Equation Fit to Measured Data (Rudd, C)

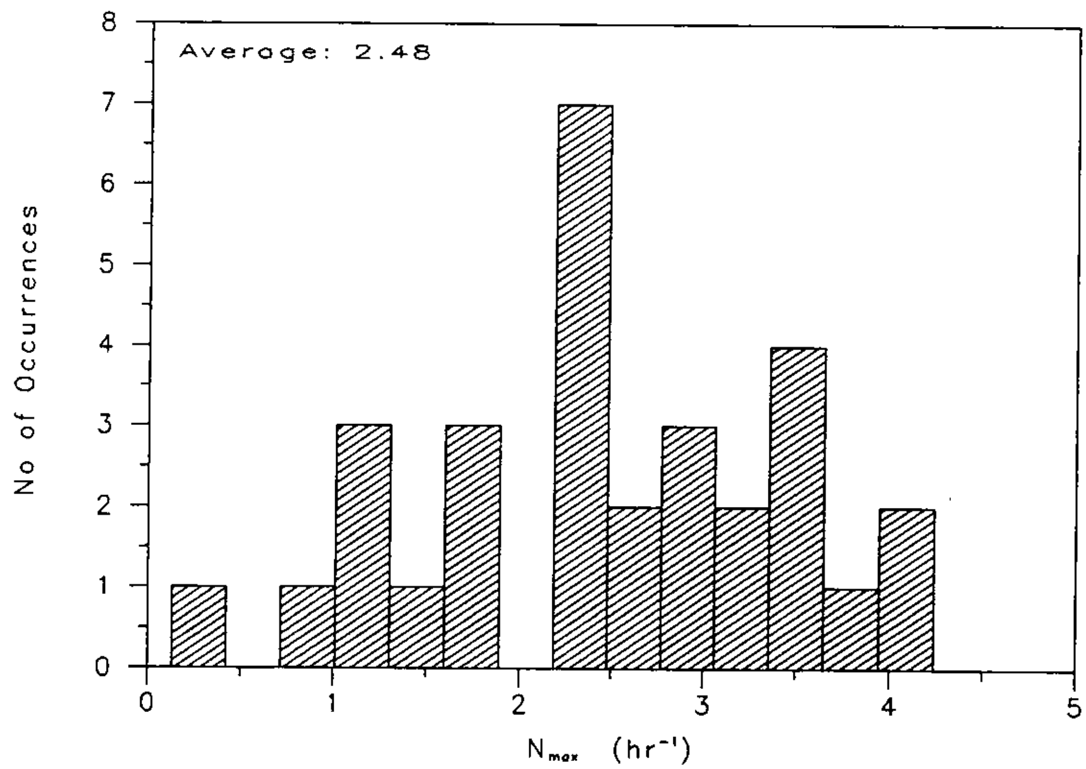

Figure 5-7 Histogram of Maximum Cycling Rate (N_{max})

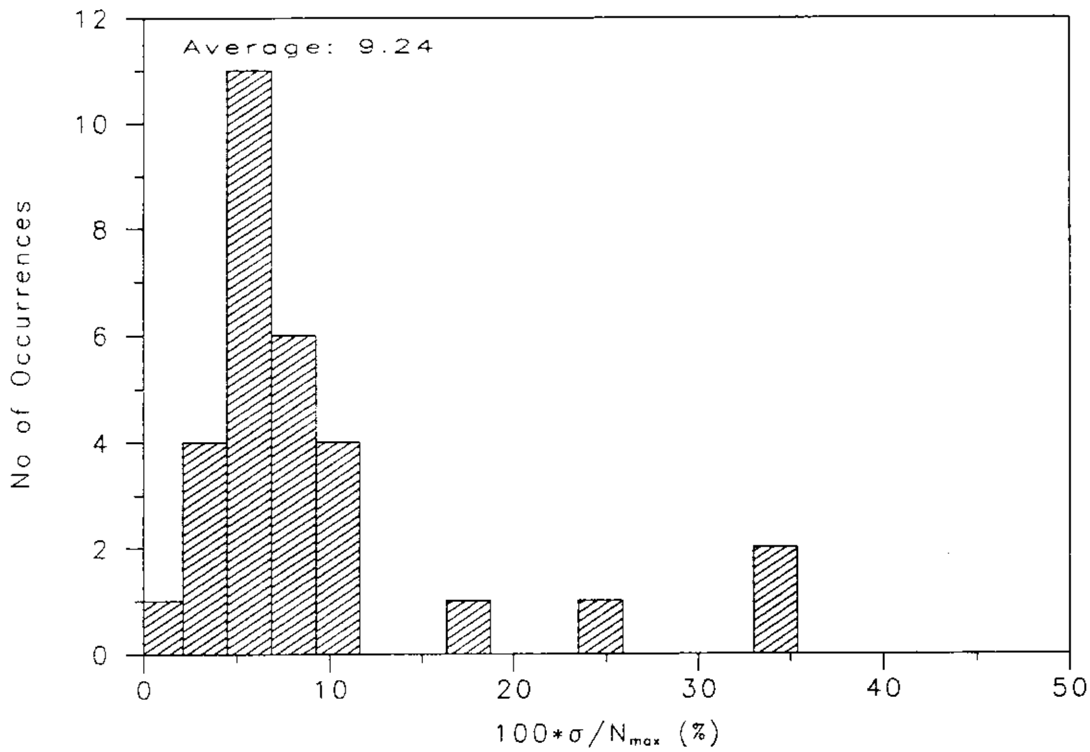

Figure 5-8 Relative Error of Curve-Fits for N_{max}

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.

$$t_{ON} = \frac{t_{ON,min}}{1-X} \tag{5-2}$$

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 αX to account for the dependence of AC capacity on outdoor temperature (see section 3 and Appendix A).

$$t_{ON} = \frac{\gamma(1+\alpha X)}{1-X} \tag{5-3}$$

Note when α is zero, the constants $t_{ON,min}$ and γ 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.

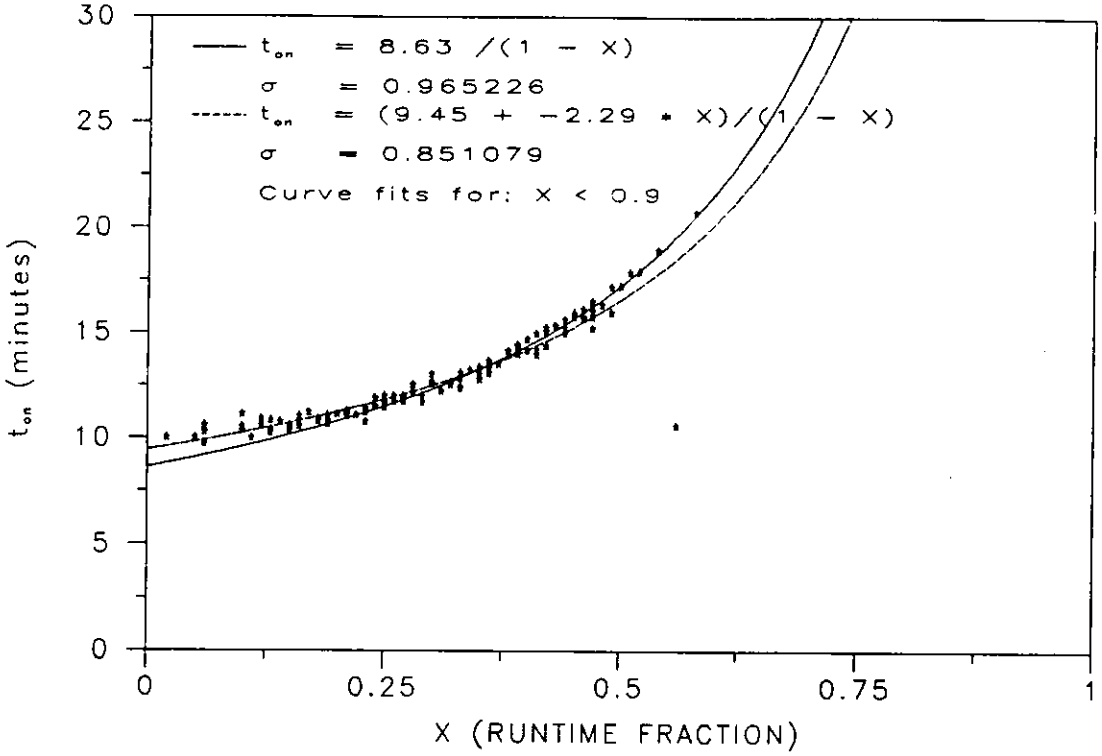

Figure 5-9 Curve-Fit of Equations (5-2) and (5-3) to Measured Data (Rudd, C)

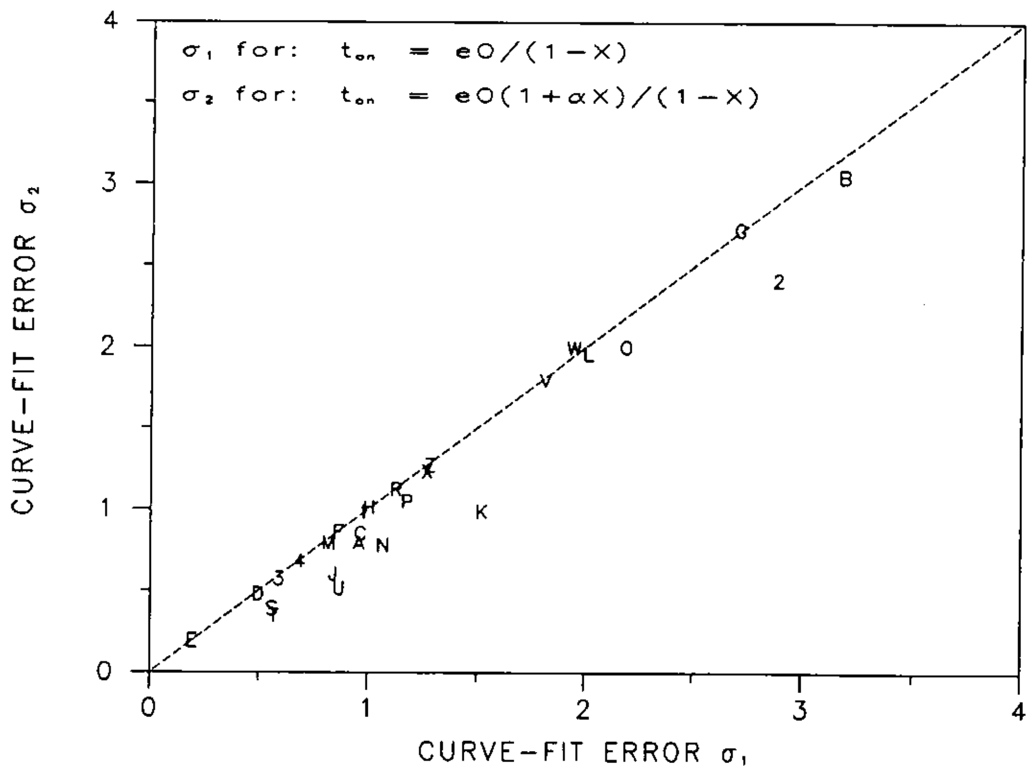

Figure 5-10 Comparing Standard Deviation of Fits for eqns. (5-2) and (5-3)

This indicates that equation (5-3), which includes an extra parameter α, 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 α was 0.14, with the minimum and maximum ranging from -0.25 to 0.7. As discussed in Appendix A, positive values of α skew the cycling equation (5-1) to the left while negative values skew it to the right.

In summary, the addition of the α 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 (ΔT_{spt}) 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 (ΔT_{spt}) as well as T_{ON}, T_{OFF} and T_{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 (ΔT_{spt}) 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_{ON} and T_{OFF}). Both T_{ON} and T_{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 (ΔT_{spt}) 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 (ΔT_{spt}) and Droop (d_o)

	Mean	Std. Dev.	Minimum	Maximum
Dead Band: ΔT_{spt} (°F)	2.3	1.2	0.8	6.7
Droop: d_o (°F)	2.1	2.1	-3.8	6.6

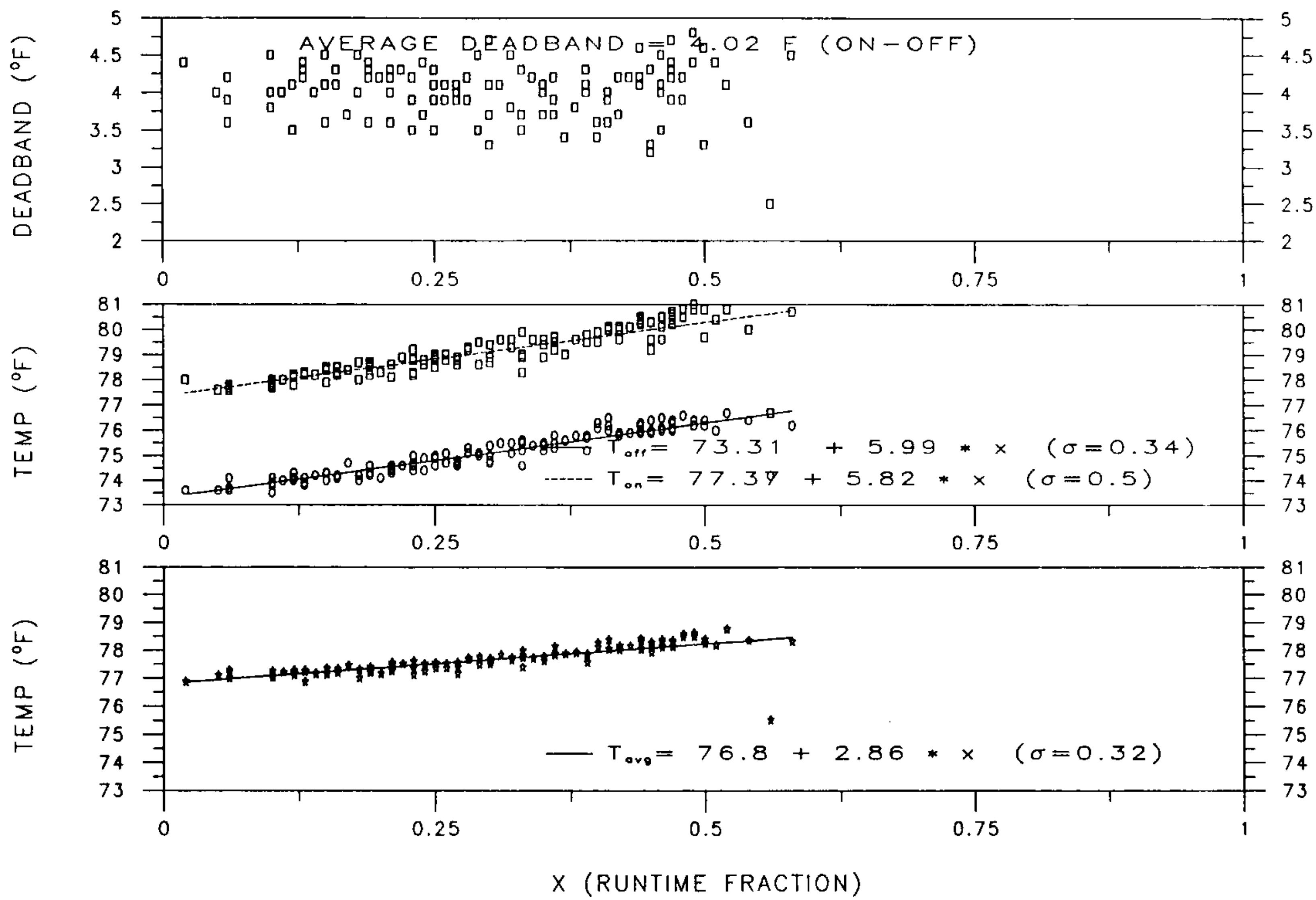

Figure 5-11 Deadband (ΔT_{spt}) and T_{ON}, T_{OFF}, and T_{avg} versus Runtime Fraction (X) (Rudd, C)

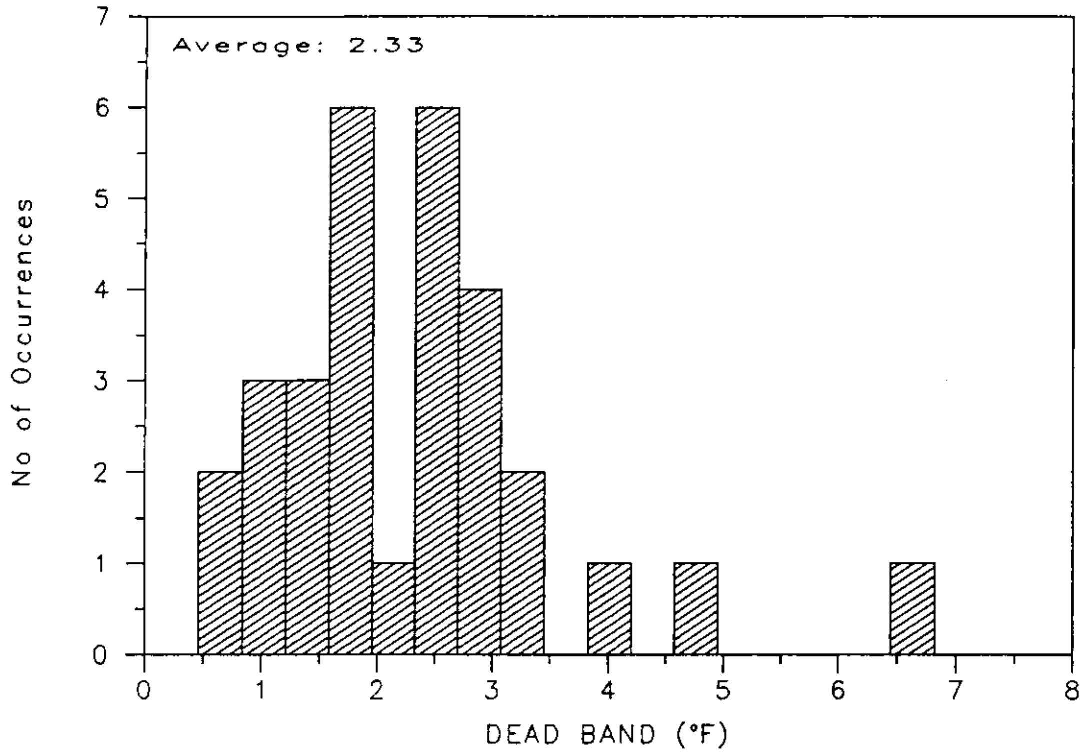

Figure 5-12 Histogram of Measured Deadband (ΔT_{spt})

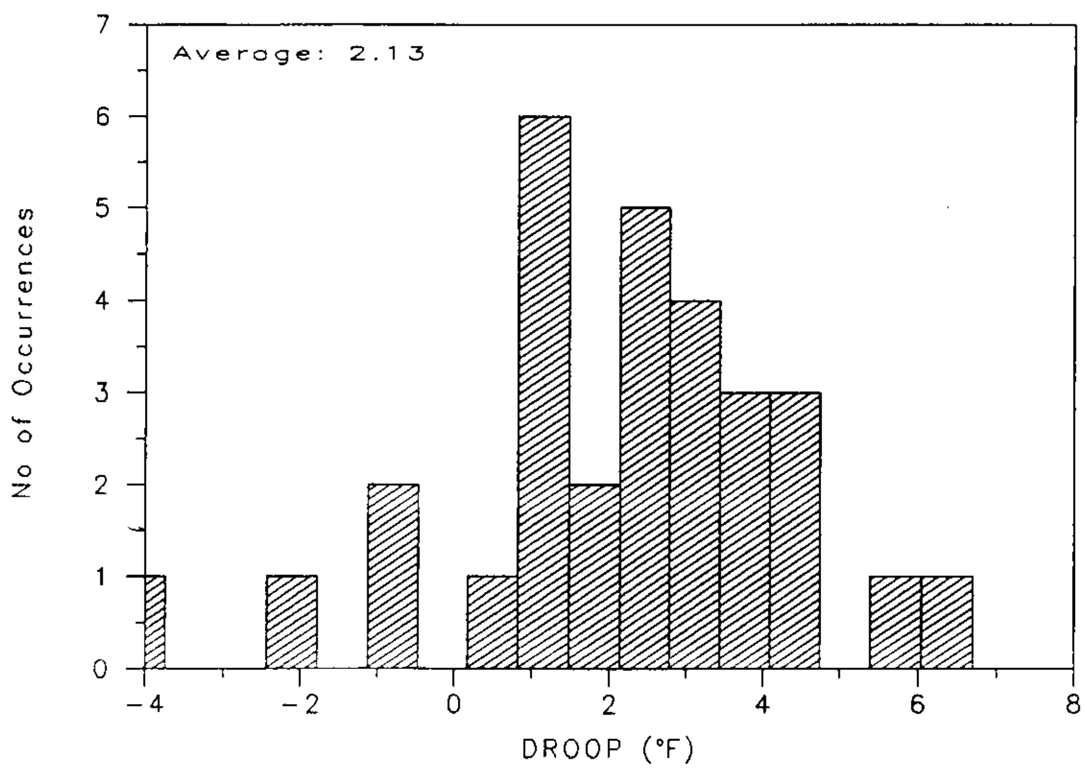

Figure 5-13 Histogram of Droop (d_o)

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 (ΔRH_{spt}), as well as RH_{ON}, RH_{OFF}, RH_{avg} 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 (ΔRH_{spt}) 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.

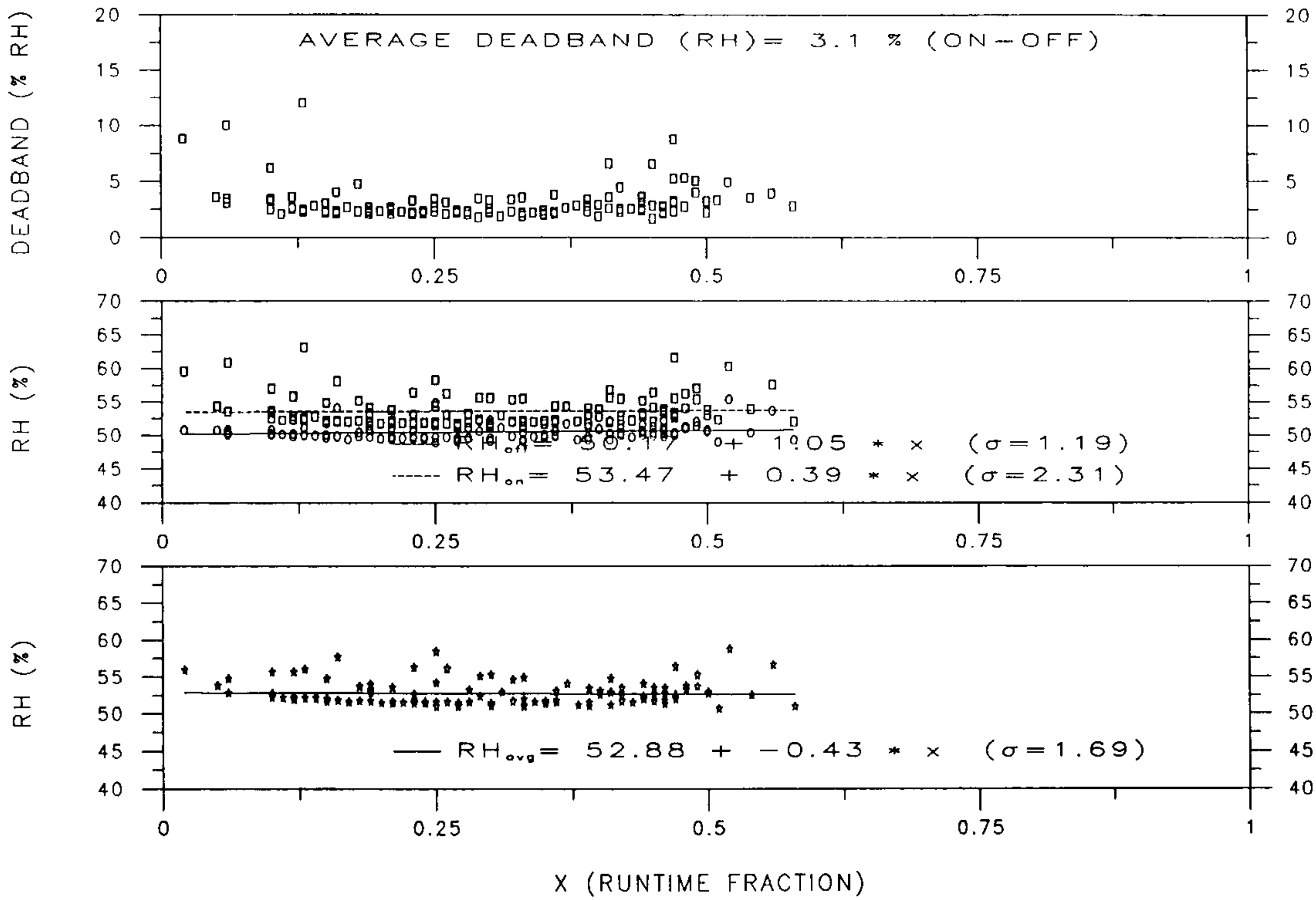

Figure 5-14 RH Deadband and RH_{ON}, RH_{OFF}, and RH_{avg} versus Runtime Fraction (X) (Rudd, C)

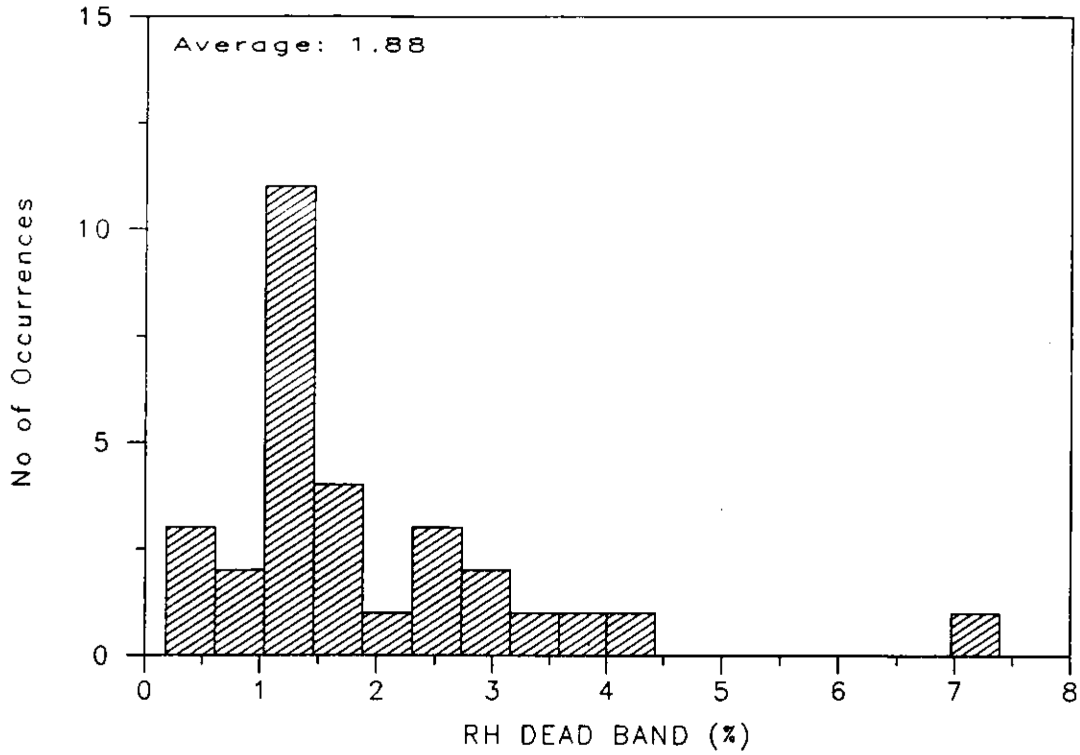

Figure 5-15 Histogram of RH Deadband (RH_{ON} - RH_{OFF})

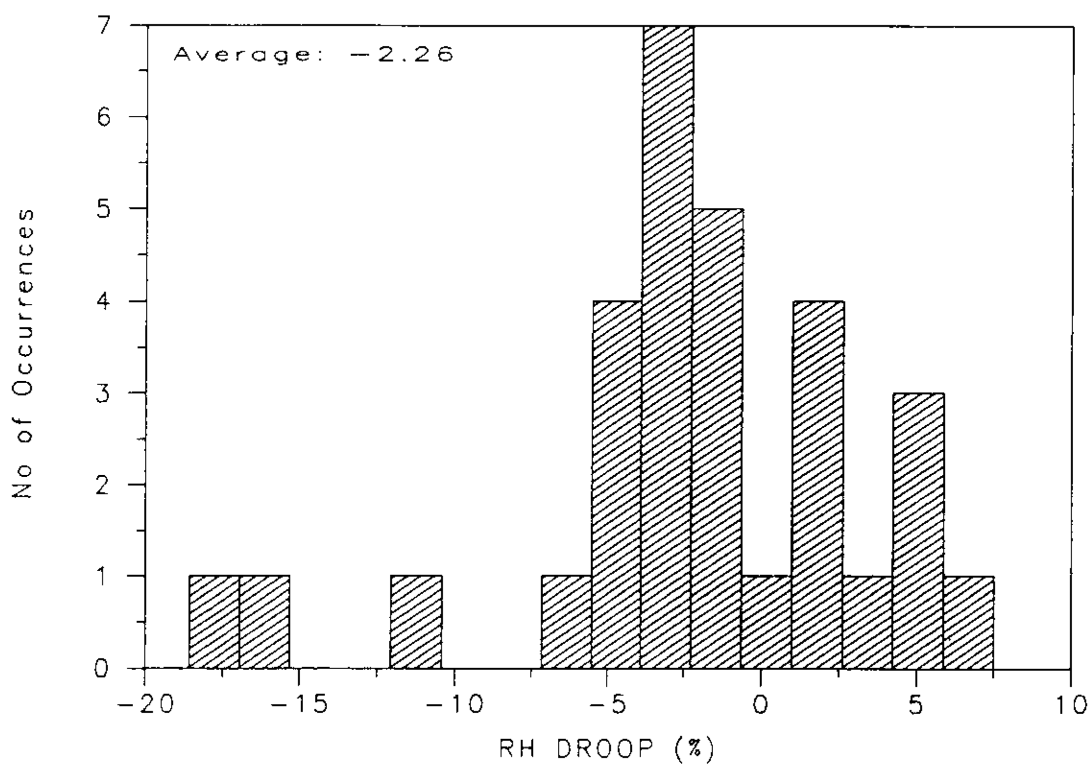

Figure 5-16 Histogram of RH Droop (slope versus X)

5.6 Statistical Analysis of Cycling Rate (N_{max})

One of the major purposes of this study was to determine which system parameters affect the maximum cycling rate N_{max}. Figures 5-17 through 5-22 show how N_{max} varies with deadband (ΔT_{spt}), droop (a_o), average space temperature, average runtime fraction (X_{avg}), house age, and relative AC sizing (ft^2/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_{max} are summarized in Table 5-4.

TABLE 5-4

Statistical Analysis of System Parameters Versus N_{max}

Variable	Figure	Slope	T-ratio[a]	Significant ?
Deadband (ΔT_{spt})	5-17	-0.444	-3.6	Yes
Temperature Droop (d_o)	5-18	0.250	3.5	Yes
Average Temperature (°F)	5-19	NA	-0.04	No
Average Runtime (X_{avg})	5-20	NA	0.96	No
House Age (yrs)	5-21	NA	-0.51	No
AC Sizing (ft^2/ton)	5-22	NA	0.27	No

[a]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_{max} varies with deadband (ΔT_{spt}). As expected from theory (see Appendix A), cycle rate is inversely proportional to deadband. The house with the highest deadband (Vieiral, 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_{max} and ΔT_{spt} was significant (i.e., T-ratio much greater than 2).

Figure 5-18 shows how N_{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_{max}. The T-ratio relating droop (d_o) to N_{max} was 3.5, indicating high confidence level in the trend.

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

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

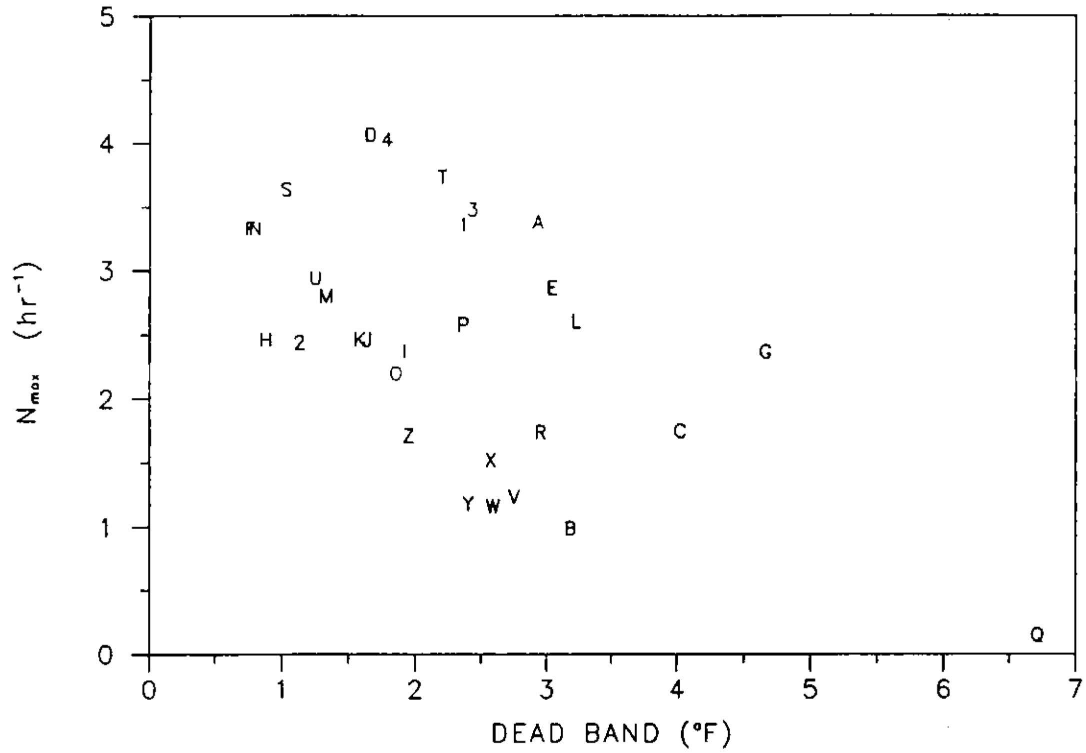

Figure 5-17 Scatter Plot of N_{max} Versus Thermostat Deadband (ΔT_{spt})

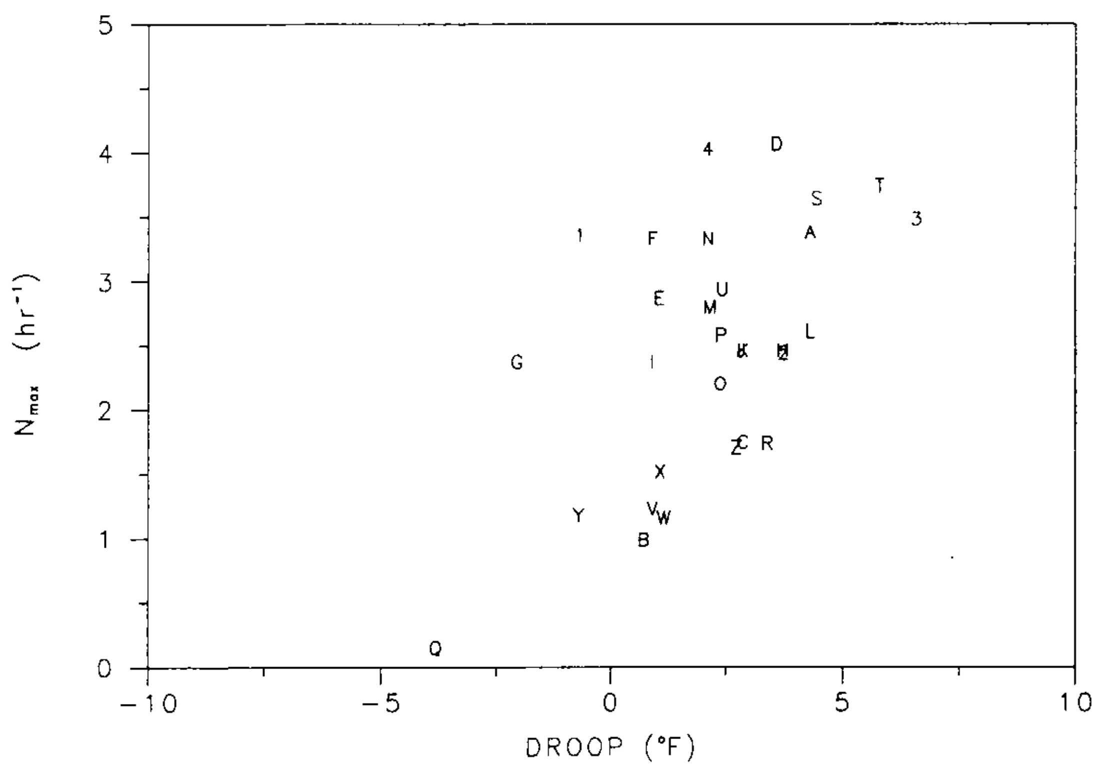

Figure 5-18 Scatter Plot of N_{max} Versus Temperature Droop (d_o)

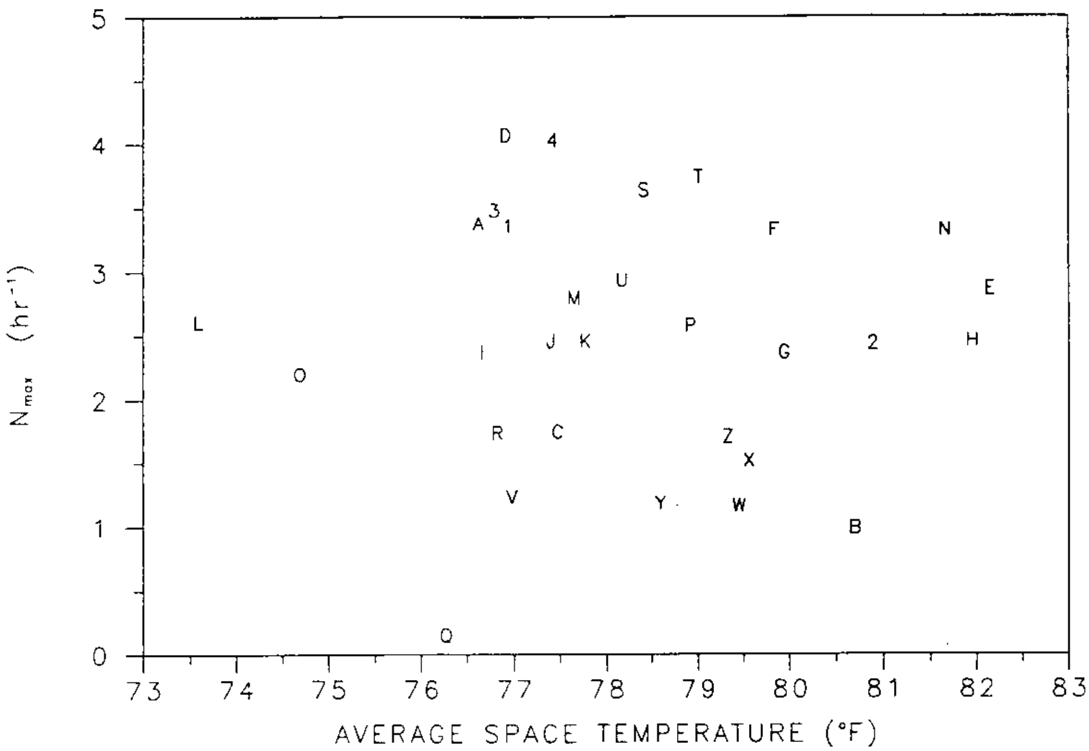

Figure 5-19 Scatter Plot of N_{max} Versus Average Space Temperature

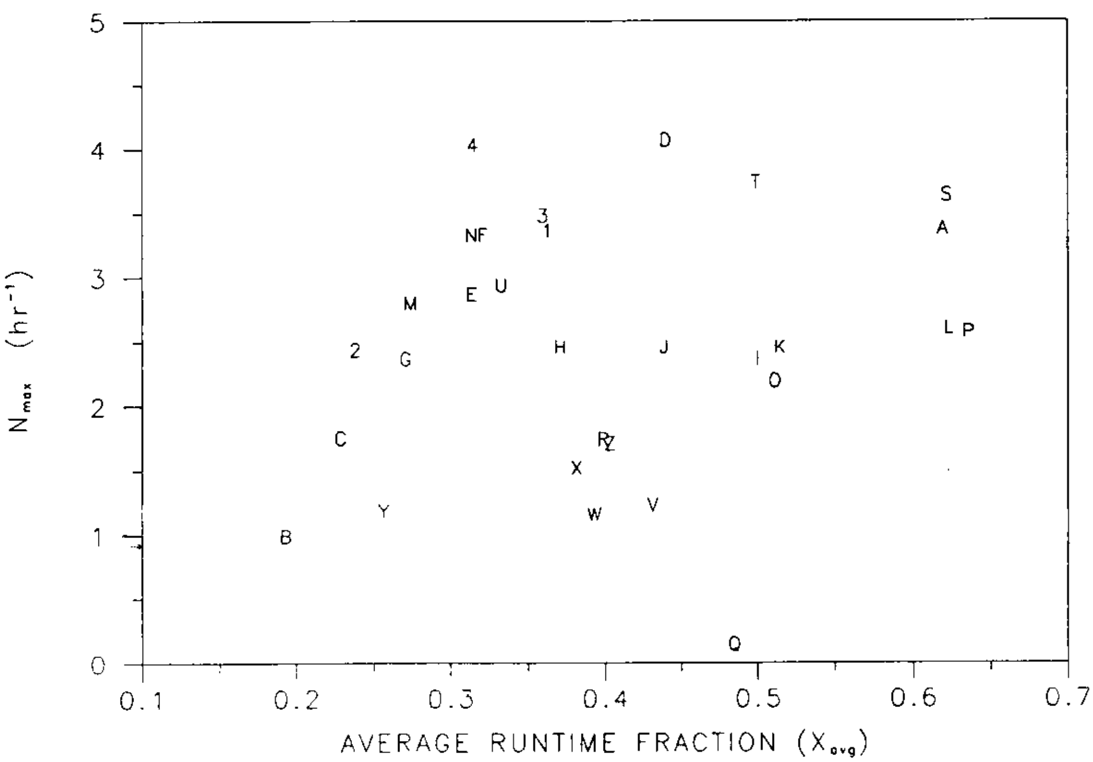

Figure 5-20 Scatter Plot of N_{max} Versus Average Runtime Fraction (X_{avg})

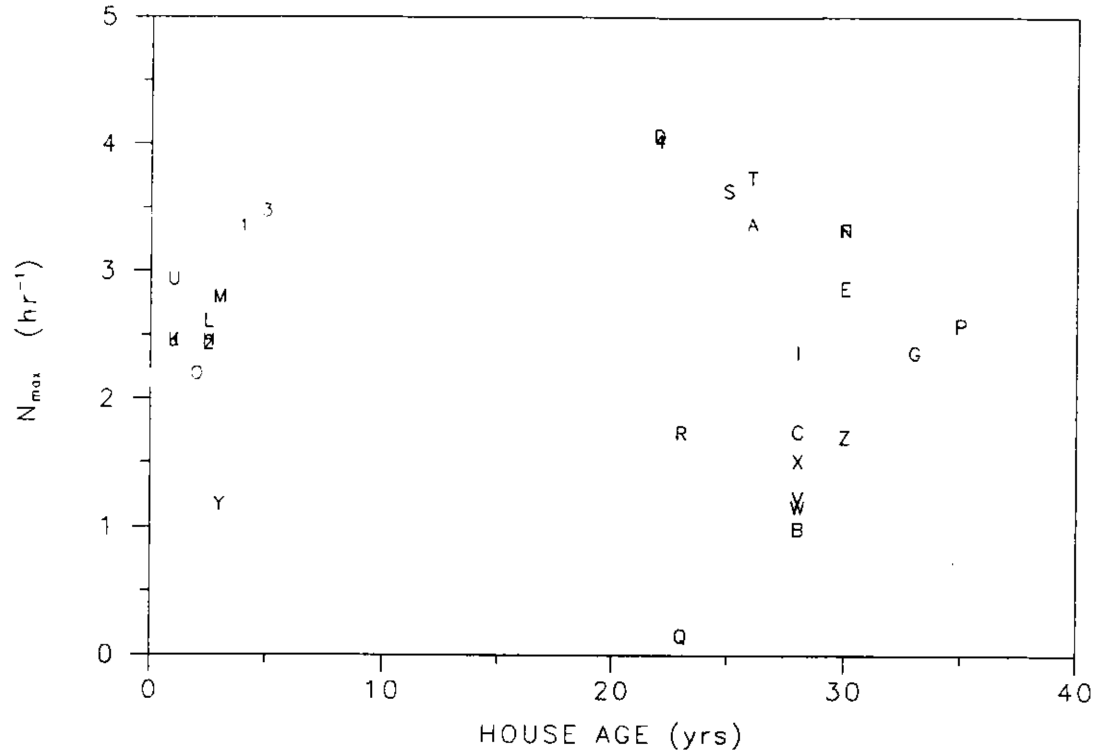

Figure 5-21 Scatter Plot of N_{max} Versus House Age

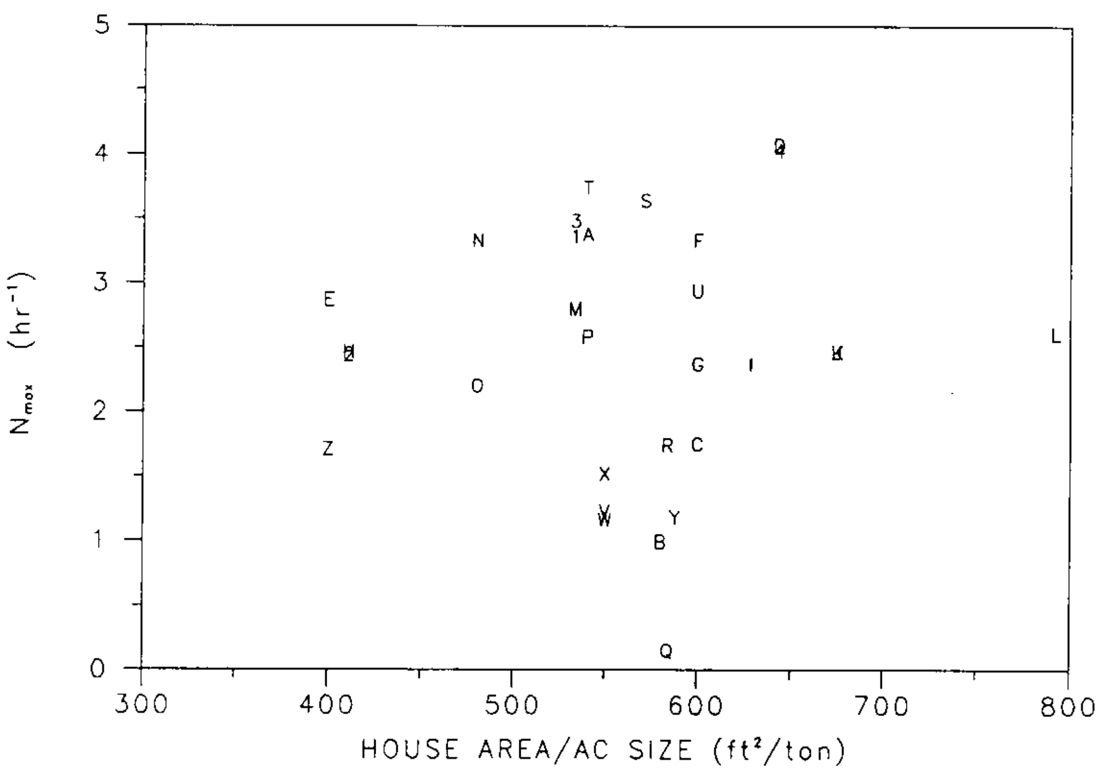

Figure 5-22 Scatter Plot of N_{max} Versus AC Unit Sizing (ft²/ton)

Figure 5-21 shows N_{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_{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_{max} versus the relative sizing of the AC unit (ft^2 floor area per ton of AC). As expected, no statistical trend of N_{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_{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_{max} in the cycling equation.

In summary, only two parameters, deadband (ΔT_{spt}) and droop (d_o) 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_{max} to these two parameters resulted in:

$$N_{max} = \underset{(6.3)}{2.82} + \underset{(2.1)}{0.161}(d_o) - \underset{(-2.2)}{0.296}(\Delta T_{spt}) \qquad \text{(T-ratios)}$$

with $R^2 = 41.3\%$

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

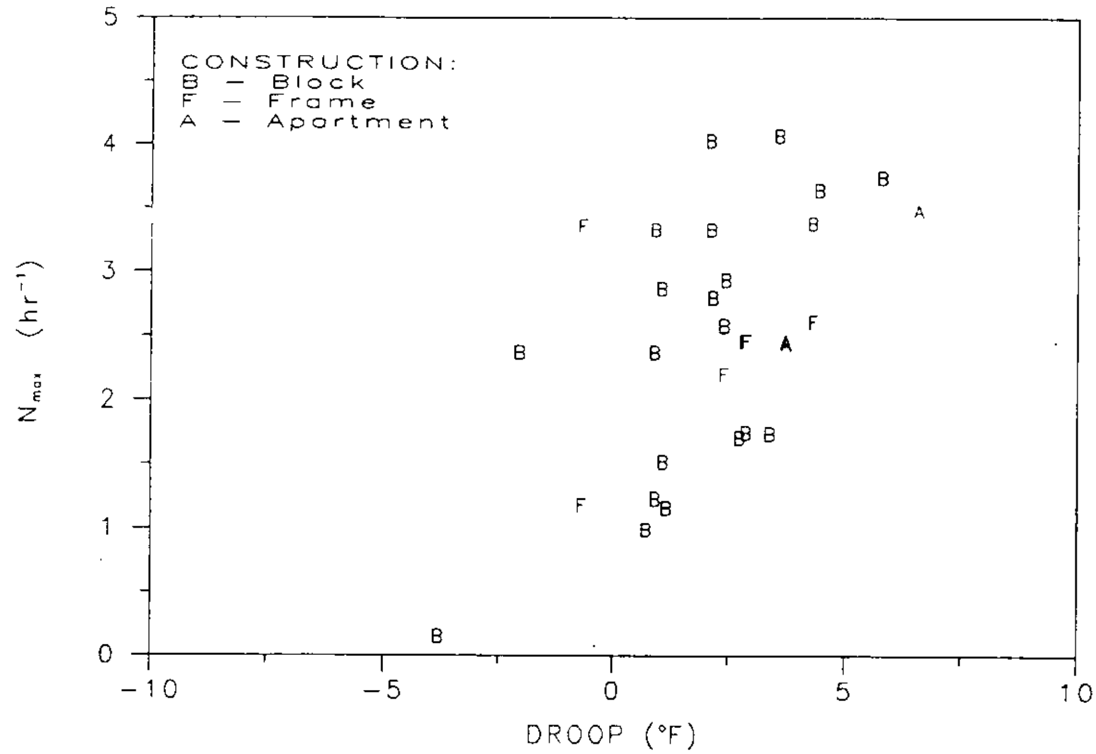

Figure 5-23 The Effect of Construction (Block, Frame or Apartment) on N_{max}

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 effects 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.

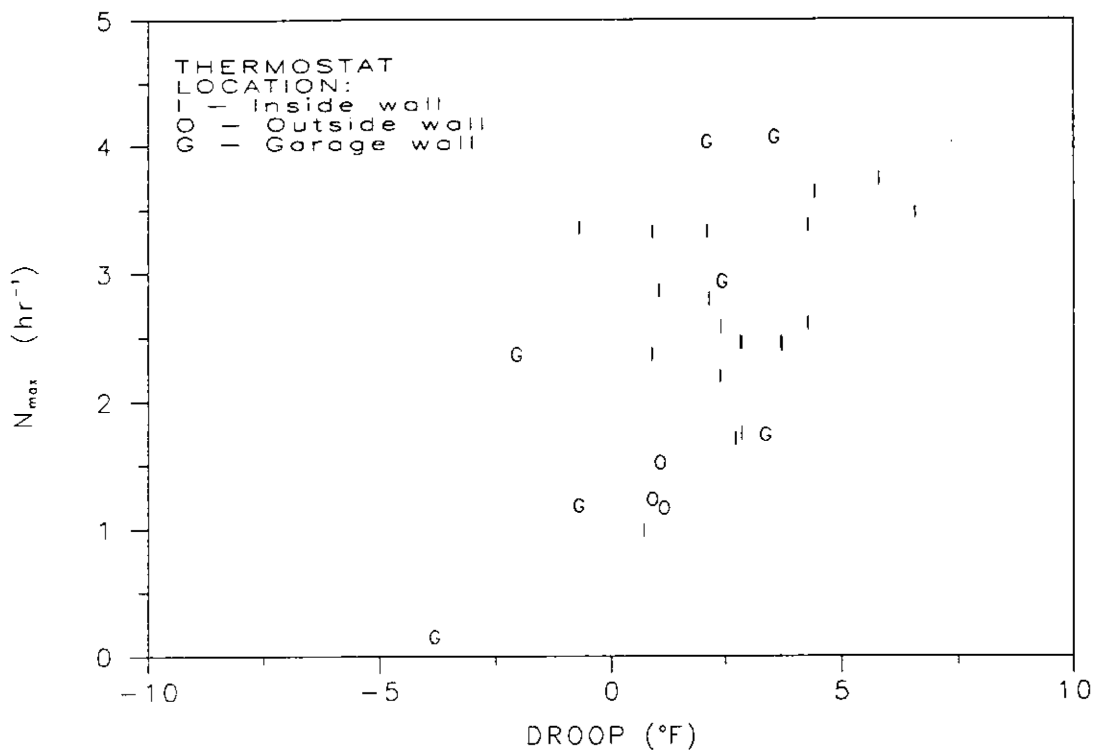

Figure 5-24 The Effect of Thermostat Location on N_{max}

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 5-5

Comparing Electronic and Conventional Thermostats

Description	N_{max}	Deadband ΔT_{spt}	Droop (d_o)	Avg. Space
VIEIRA1, **Q** electronic thermostat	0.15	6.7°F	-3.8°F	76.3°F
VIEIRA2, **R**, conventional thermostat	1.74	3.0°F	3.4°F	76.8°F

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 effects 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_{max}) from 1.16 to 1.52.

TABLE 5-6

Comparing Thermostat With and Without Cover				
Description	N_{max}	Deadband ΔT_{spt}	Droop (d_o)	Avg. Space
CUMMINGS1, X, without thermostat cover	1.52	2.6°F	1.1°F	79.6°F
CUMMINGS2, W, with thermostat cover	1.16	2.6°F	1.2°F	79.5°F

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_{max}.

TABLE 5-7

Comparing Thermostat Set Points				
Description	N_{max}	Deadband ΔT_{spt}	Droop (d_o)	Avg. Space
CUMMINGS2, W, normal set point	1.16	2.6°F	1.2°F	79.5°F
CUMMINGS3, V, lower set point	1.23	2.8°F	0.9°F	77.0°F

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.

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 5-8

Changing AC Units				
Description	N_{max}	Deadband ΔT_{spt}	Droop (d_o)	Avg. Space
RAUSTAD1, **A**, old AC Unit	3.38	2.9°F	4.3°F	76.6°F
RAUSTAD2, T, new AC Unit	3.74	2.2°F	5.8°F	77.0°F

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.

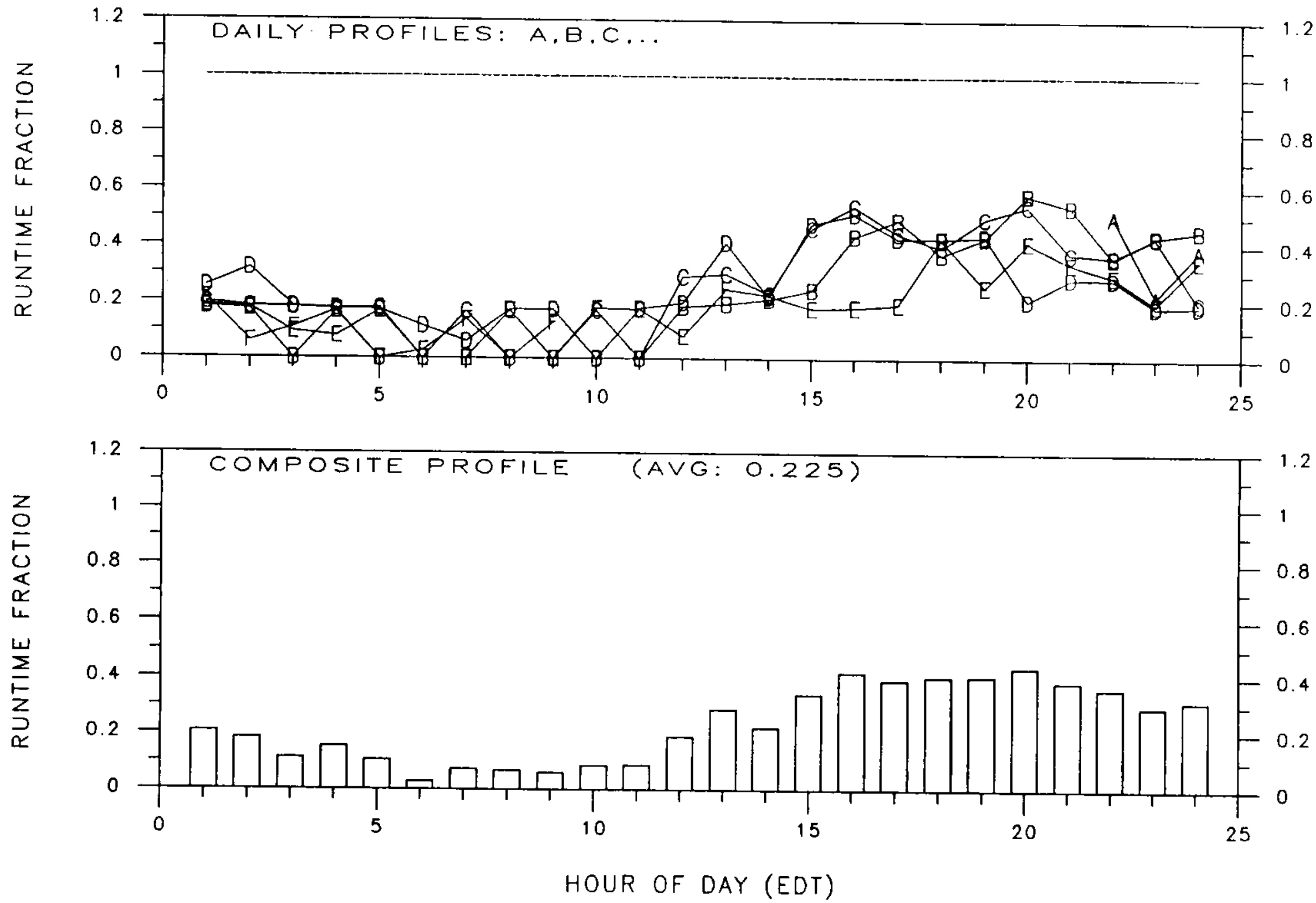

Figure 5-25 Composite Hourly Runtime Profiles Constructed from Cycling Data (Rudd, C)

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 ft^2.

- 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_{spt}) 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 the 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_{max} is developed and used to estimate the impact of N_{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.

$$PLF_{i+1} = 1 - 4\tau N_{max}(1-CLF/PLF_i)[1 - e^{\frac{-1}{4\tau N_{max}(1-CLF/PLF_i)}}] \qquad (6\text{-}1)$$

where
- PLF = Part Load Factor (EER/EER_{ss})
- CLF = Cooling Load Factor (Q_{BL}/Q_{AC})
- τ = Time Constant of AC at Start-up (time)
- N_{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_1. Iterations proceed until PLF_{i+1} converges to PLF_i.

Figure 6-1 shows how PLF varies with CLF when N_{max} equals 1 through 4 cycles/hr, with the AC time constant (τ) equal to 80 seconds. Increasing N_{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_D=0.25, has also been included in the on the plot as a reference (ARI 1984). Note that the N_{max} = 3 curve closely corresponds to this curve. This is not surprising since a value of 3.125 of N_{max} is implicit in the conditions specified in the SEER cyclic test.

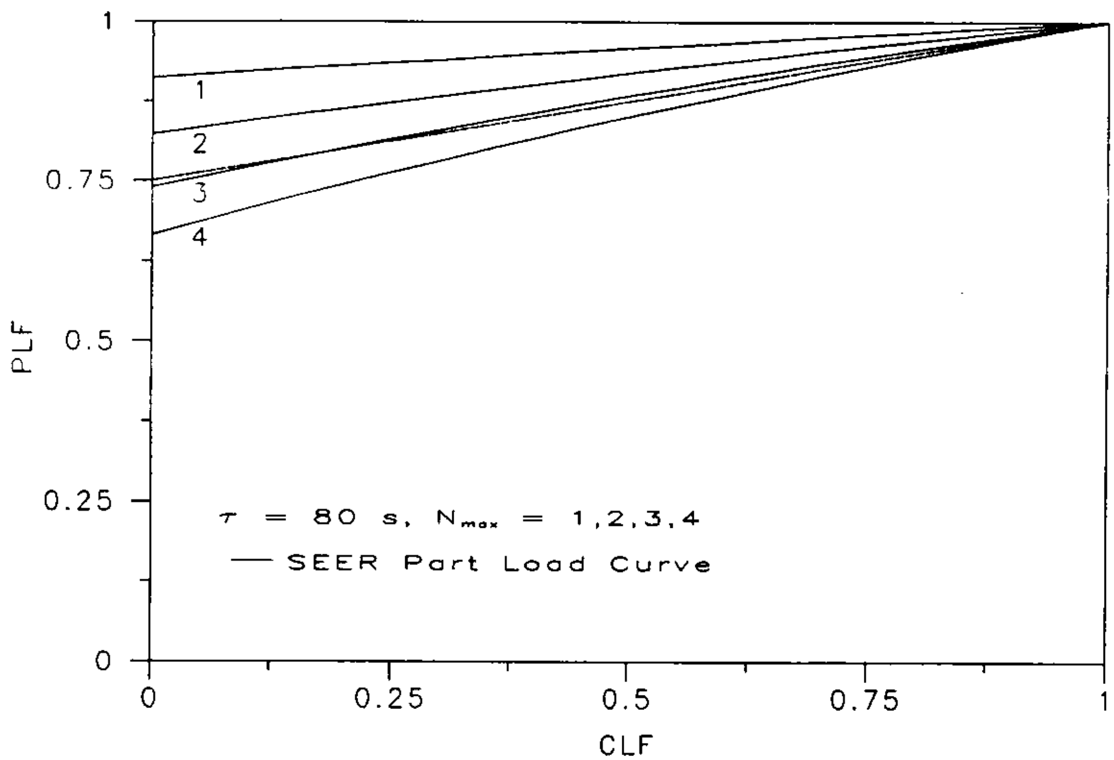

Figure 6-1 Equation (6-1) Plotted with N_{max} = 1,2,3,4

6.2 The Impact of N_{max} on Cycling Losses

Table 6-1 compares the part load performance with N_{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 6-1

Part Load Losses[a] Compared to Steady State

	N_{max}=1	N_{max}=2	N_{max}=3	N_{max}=4
Decrease in Efficiency[b]	-4.2%	-8.1%	-11.6%	-14.9%
Increase in Energy Use[b]	+4.4%	+8.8%	+13.1%	+17.5%

[a]Using curves in Figure 6-1 with CLF=0.5 as seasonal average. τ = 80 s.
[b]Compared to the steady state case without cycling losses.

N_{max} has a substantial impact on the part load performance. When N_{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.

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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.

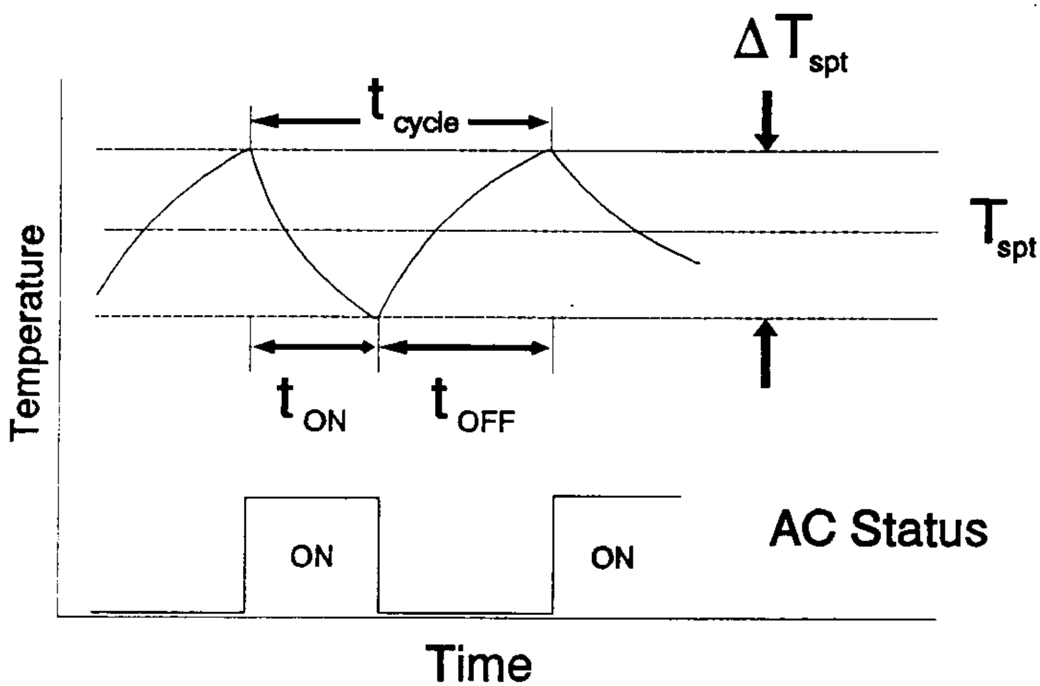


Figure A-1 Space Temperature and AC Status

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

$$\frac{t_{ON}}{t_{cycle}} = \frac{Q_{BL}}{Q_{AC}} \qquad \text{(A-1)}$$

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_{BL}) increases proportionally to the rate of temperature increase in the space when the AC system is OFF.

$$Q_{BL} = C\left[\frac{\partial T}{\partial t}\right]_{avg} \approx C\frac{\Delta T_{spt}}{t_{OFF}} \tag{A-2}$$

The ON/OFF temperature difference, or deadband (ΔT_{spt}), 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_{BL}, the result is equation (A-3).

$$Q_{AC}\frac{t_{ON}}{t_{cycle}}\left(\frac{t_{OFF}}{t_{cycle}}\right) = C\frac{\Delta T_{spt}}{t_{OFF}}\left(\frac{t_{OFF}}{t_{cycle}}\right) \tag{A-3}$$

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:

$$N = \frac{Q_{AC}}{C\Delta T_{spt}}X(1-X) \tag{A-4}$$

By combining Q_{AC}, C, and ΔT_{spt} into one constant, equation (A-4) can be rewritten as:

$$N = 4N_{max}X(1-X) \tag{A-5}$$

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

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

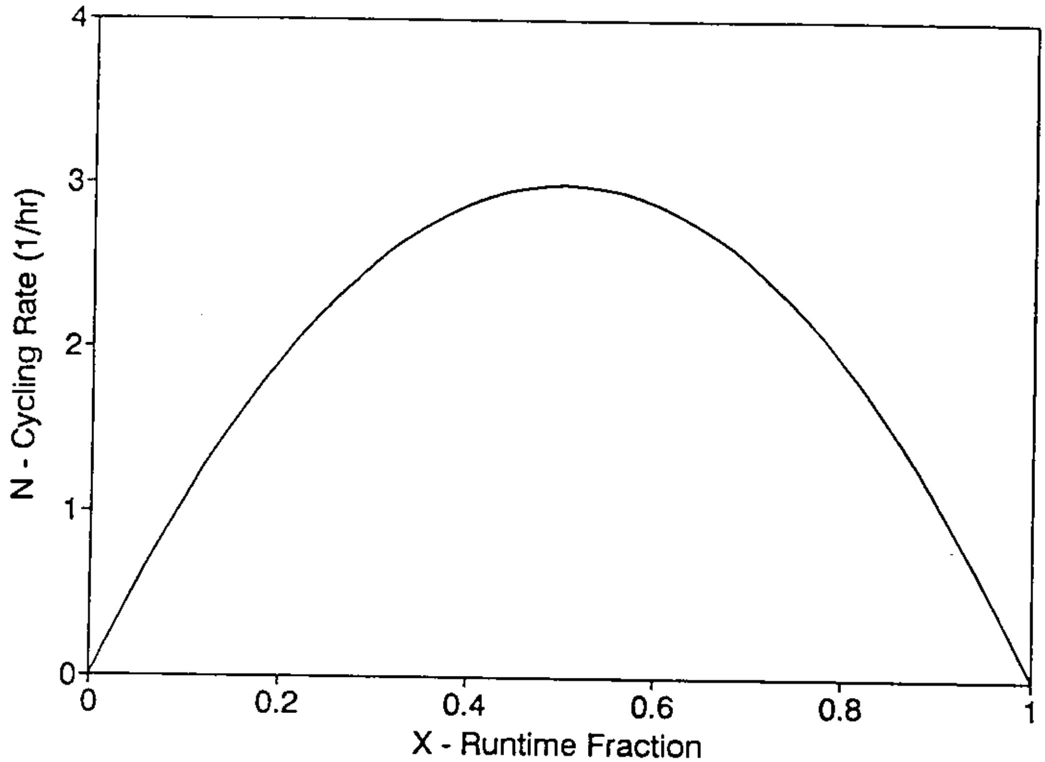


Figure A-2 Thermostat Cycling Equation (A-5)

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

$$N_{max} = \frac{1}{4}\frac{Q_{AC}}{C\Delta T_{spt}} \qquad \text{(A-6)}$$

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

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_{AC} varies with outdoor temperature. Since the runtime fraction (X) is also proportional to outdoor temperature, it is implied that Q_{AC} will in effect depend on X. Equation (A-7) is the functional form of the cycling equation assuming Q_{AC} depends on X:

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

Note that when α is zero, β is equivalent to N_{max}. When α is not zero, β is no longer the peak value of the function. A positive value of α 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.

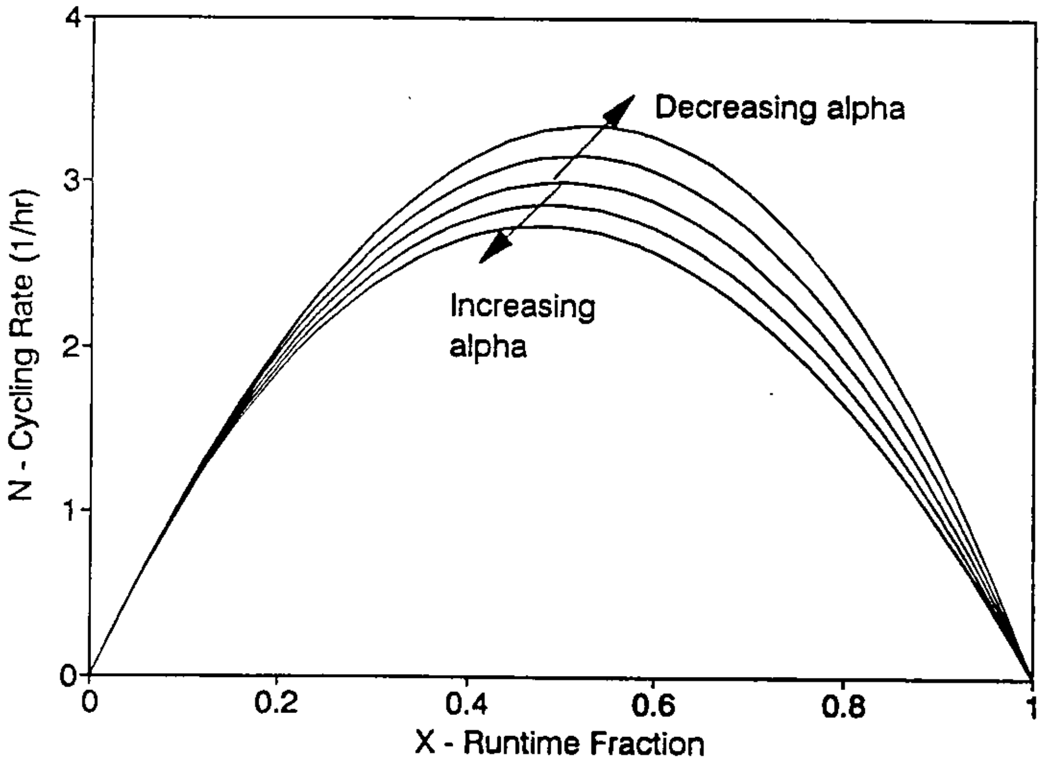


Figure A-3 Alternate Form of the Cycling Equation (A-7)

This form of the equation demonstrates that the outdoor temperature dependence of Q_{AC} 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 an "A" after each instruction)

INSTRUCTION	DESCRIPTION
*1	Enter Table 1
5	5 sec. Execution Interval
P17	TC Reference temp.
1	location
P14	TC - differential ;check thermocouple
1	reps
11	5 mv, 250 usec
1	in chan
1	type T
1	ref. location
4	location
.018	multiplier
.32	offset
P2	VOLTS - differential ;check relative humidity
1	reps
15	5000 mv, 250 usec
2	in chan
5	location
1	multiplier
0	offset
P2	VOLTS - differential ;check thermostat voltage
1	reps
15	5000 mv, 250 usec
3	in chan
2	location
1	multiplier
0	offset
P33	Z = X + Y ;sum TC readings
4	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
P89	IF voltage is less than F ;check if unit is on
2	location
4	X .lt. F
25	F
30	THEN DO (needs endif)
P91	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
P37	Z = X * F
4	location X
100	F
4	location Z
P37	Z = X * F
6	location X
100	F
6	location Z
P38	Z = X / Y
7	location X
3	location Y
7	location Z
P30	Z = F
1	F
8	location Z
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

```
 P89        IF X.lt.F
   2        location
   4        X.lt.F
  30        F
  11        set flag 1 high
 P30        Z = F   ;reset totals
   0        F
   3        location
 P30        Z = F
   0        F
   6        location
 P30        Z = F
   0        F
   7        location
 P95        END
 P95        END

 P89        IF voltage is greater than F ;check if unit is off
   2        location
   3        X .ge. F
  25        F
  30        THEN DO (needs endif)
 P91        IF flag
  11        if flag 1 is high
  30        THEN DO (needs endif)
 P38        Z = X / Y
   6        location X
   3        location Y
   6        location Z
 P37        Z = X * F
   4        location X
 100        F
   4        location Z
 P37        Z = X * F
   6        location X
 100        F
   6        location Z
 P38        Z = X / Y
   7        location X
   3        location Y
   7        location Z
 P30        Z = F
   0        F
   8        location Z

 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
 P70        SAMPLE
   5        reps
   4        start location
 P89        IF X.ge.F
   2        location
   3        X.ge.F
  30        F
  21        set flag 1 low
 P30        Z = F   ;reset totals
   0        F
   3        location
 P30        Z = F
   0        F
   6        location
 P30        Z = F
   0        F
   7        location
 P95        END
 P95        END
```

Campbell Channel (front panel)	Intermediate Storage (*6 mode)	Final Storage (*7 mode)
1 TC	1 Panel Temp	1 21x ID
2 RH	2 Tstat volts	2 Year
3 Tstat volts	3 # of meas.	3 Julian Day
	4 TC	4 HH:MM:
	5 RH	5 SS
	6 Tot. TC	6 TC
	7 Tot. RH	7 RH
	8 Counts	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 *0, *6, *B, and *D.
  *0, *B, *D.....compiles; output ports and flags are set low, the timer is reset, and data values in input and intermediate storage are RESET TO ZERO.
  *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 transfered to Final Storage.

Star (*) Mode Summary

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

Key Description/Editing Functions

Key	Action
0-9	Key numeric entries into display
*	Enter Mode (followed by Mode Number)
A	Enter/advance
B	Back up
C	Change the sign of a number or index an Input Location to loop counter
D	Enter the decimal point
#	Clear the right most digit keyed into the display
#A	Advance to the next instruction in program table (*1, *2, *3) or to next Output Array in Final Storage(*7)
#B	Back up to previous instruction in program table or to previous Output Array in Final Storage
#D	Delete entire instruction

APPENDIX C
Measured Data From Each Test Site

TABLE C-1
Summary of Measured Data From Each Site

C:\qpro\wql\tstat.wql Thermostat Cycling Data as of: 5/7/91 Range: a1..o44

	Name	House Type	Test Duration ,hrs	Avg Temp,F	Avg RH,%	Avg Run Time,%	Avg Temp Dbnd,F	Avg RH Dbnd,%	N=4*Nmax*X*(1-X) Nmax	Std Dev	Tavg = a0 + a1*X a0	a1	Std Dev
1	Raustad	Block	34.85	76.62	56.48	61.89%	2.93	1.17	3.38	0.1148	74.00	4.29	0.280
2	Henderson	Block	58.15	80.70	54.27	19.30%	3.18	3.32	0.99	0.0649	80.59	0.72	0.220
3	Rudd	Block	109.23	77.47	53.05	22.86%	4.02	3.10	1.75	0.1409	76.80	2.86	0.320
4	Marvin	Block	11.33	76.91	54.55	43.95%	1.66	1.19	4.07	0.2561	75.35	3.56	0.280
5	Holder	Block	13.17	82.14	49.60	31.35%	3.04	1.05	2.87	0.0451	81.81	1.05	0.050
6	Sherwin	Block	110.05	79.83	66.37	32.07%	0.76	1.34	3.33	0.3244	79.61	0.91	0.620
7	Parker	Block	91.37	79.94	60.65	27.08%	4.66	1.06	2.37	0.4341	80.44	-2.06	0.760
8	Shirey	Apt	45.20	81.95	63.33	37.08%	0.88	0.35	2.46	0.2394	80.58	3.71	0.400
9	Redmond	Block	89.27	76.66	47.97	50.00%	1.92	1.49	2.37	0.5660	76.19	0.9	1.420
10	Fairey1	Frame	65.28	77.40	58.46	43.88%	1.64	1.54	2.46	0.1010	76.16	2.82	0.660
11	Fairey2	Frame	69.49	77.77	54.85	51.44%	1.58	1.43	2.46	0.1240	76.33	2.86	0.390
12	Kettles	Frame	70.42	73.59	49.80	62.29%	3.22	0.91	2.61	0.0850	70.97	4.29	0.300
13	Melody	Block	125.30	77.65	56.45	27.41%	1.33	1.59	2.8	0.1860	77.03	2.15	1.040
14	Dhere	Block	48.23	81.66	59.89	31.36%	0.80	1.06	3.33	0.2770	80.64	2.11	0.630
15	Dutton	Frame	48.2	74.69	70.03	51.10%	1.85	7.29	2.20	0.1588	73.50	2.38	0.440
16	Dernier	Block	45.27	78.92	63.53	63.52%	2.36	1.16	2.58	0.1309	77.37	2.39	0.280
17	Vieira1	Block	57.40	76.27	56.77	48.45%	6.71	4.15	0.15	0.0510	78.02	-3.82	0.350
18	Vieira2	Block	71.33	76.82	55.43	39.85%	2.95	0.45	1.74	0.1065	75.47	3.37	0.160
19	Dummer	Block	70.37	78.41	41.36	62.14%	1.03	0.7	3.64	0.1408	75.70	4.43	0.140
20	Raustad2	Block	46.74	79.01	54.90	49.89%	2.20	1.42	3.74	0.2001	76.13	5.78	0.240
21	Goulet	Block	78.08	78.17	55.93	33.26%	1.25	2.88	2.94	0.1897	77.37	2.42	0.290
22	Cummings3	Block	56.95	76.98	50.13	43.14%	2.75	2.38	1.23	0.0806	76.57	0.91	0.270
23	Cummings2	Block	22.16	79.45	49.58	39.29%	2.59	2.14	1.16	0.0649	78.99	1.16	0.130
24	Cummings1	Block	22.52	79.56	50.30	38.14%	2.57	2.4	1.52	0.1037	79.13	1.08	0.260
25	Mellor	Frame	69.58	78.59	60.73	25.67%	2.4	0.25	1.18	0.3972	78.81	-0.71	0.150
26	Walker	Block	28.79	79.33	47.89	40.31%	1.95	3.61	1.71	0.1228	78.23	2.72	0.110
27	Kalaghchy	Frame	58.05	76.94	50.78	36.25%	2.36	1.72	3.36	0.2713	77.20	-0.69	0.160
28	Shirey2	Apt	80.98	80.89	55.46	23.82%	1.13	1.26	2.44	0.2300	80.00	3.72	0.500
29	Kannan	Apt	95.77	76.79	59.45	35.95%	2.43	2.71	3.48	0.2558	74.44	6.57	0.540
30	Yarosh2	Block	37.4	77.42	63.38	31.42%	1.78	1.38	4.03	0.3796	76.76	2.09	1.070
	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

C:\qpro\wq1\tstat.wq1   5/7/91   Range: p1..ae44

	Ton= b0+b1*X			Toff= c0+c1*X			RHavg = d0 + d1*X			T1on = e0/(1-x)		T2on=(f0+f1*x)/(1-x)			
	b0	b1	Std Dev	c0	c1	Std Dev	d0	d1	Std Dev	e0	Std Dev	f0	f1	alpha f1/f0	Std Dev
1 Raustad	75.05	5.25	0.37	71.47	6.43	0.40	53.51	5.06	1.15	4.52	0.959	3.70	1.26	0.34	0.790
2 Henderson	81.26	2.24	0.58	78.08	2.26	0.30	56.79	-15.90	2.57	15.66	3.182	14.07	3.44	0.24	3.047
3 Rudd	77.37	5.82	0.50	73.31	5.99	0.34	52.88	-0.43	1.69	8.63	0.965	9.45	-2.29	-0.24	0.851
4 Marvin	75.93	3.92	0.29	74.05	4.42	0.43	54.84	-0.71	0.88	3.68	0.497	4.02	-0.69	-0.17	0.479
5 Holder	81.92	4.24	0.09	79.60	2.22	0.21	52.97	-10.93	0.71	5.22	0.192	5.27	-0.10	-0.02	0.192
6 Sherwin	80.02	0.75	0.66	78.97	1.5	0.60	66.94	-1.39	2.77	4.54	0.864	4.68	-0.28	-0.06	0.861
7 Parker	81.29	0.83	0.69	76.10	2.39	0.31	59.92	1.00	1.84	6.61	2.710	6.68	-0.12	-0.02	2.720
8 Shirey	80.72	4.47	0.56	80.23	3.46	0.40	62.86	1.27	1.12	6.12	1.006	5.90	0.58	0.10	1.007
9 Redmond	76.81	1.46	1.53	74.72	1.83	1.36	49.32	-2.53	2.42	7.51	8.270	5.75	2.74	0.48	8.190
10 Fairey1	76.73	3.34	0.60	74.93	3.71	0.75	59.49	-2.18	1.48	6.25	0.842	5.24	1.90	0.36	0.601
11 Fairey2	76.73	3.66	0.34	75.00	3.96	0.50	56.92	-4.11	1.29	6.55	1.520	4.90	2.51	0.51	0.983
12 Kettles	71.12	7.16	0.48	68.49	6.15	0.29	47.96	2.94	0.50	5.84	2.010	5.10	1.07	0.21	1.960
13 Melody	77.55	2.31	1.04	76.13	2.6	1.10	56.94	-4.33	2.64	5.44	0.820	5.13	0.72	0.14	0.791
14 Dhere	80.96	2.04	0.63	79.97	2.44	0.70	58.85	1.31	2.18	4.76	1.070	3.49	2.17	0.62	0.778
15 Dutton	74.40	2.29	0.55	72.37	2.68	0.57	78.52	-17.11	3.79	7.30	2.186	6.18	1.76	0.28	2.000
16 Dernier	78.10	3.22	0.36	75.82	3.07	0.40	66.01	-3.66	2.65	6.05	1.180	5.28	1.20	0.23	1.043
17 Vieira1	79.54	0.14	0.36	71.69	2.47	0.35	58.17	-2.91	0.55	111.12	113.787	161.36	-90.87	-0.56	121.552
18 Vieira2	76.11	4.86	0.17	72.65	6.08	0.26	56.08	-1.77	0.98	8.69	1.128	8.30	0.84	0.10	1.118
19 Dummer	76.22	4.30	0.16	74.82	4.97	0.20	40.80	1.20	1.45	4.25	0.560	3.60	0.99	0.28	0.390
20 Raustad2	76.91	6.34	0.25	73.95	7.93	0.41	52.13	5.42	1.87	4.20	0.569	3.55	0.99	0.28	0.345
21 Goulet	77.81	2.66	0.32	76.73	2.19	0.30	57.74	-5.49	1.12	5.26	0.869	4.27	1.98	0.46	0.514
22 Cummings3	77.10	2.56	0.21	74.38	2.49	0.58	51.02	-2.09	0.86	12.2	1.811	12.75	-1.00	-0.08	1.791
23 Cummings2	79.49	2.62	0.09	76.93	2.55	0.35	51.44	-4.68	0.45	13	1.945	13.16	-0.28	-0.02	1.992
24 Cummings1	79.44	3.05	0.16	77.30	1.97	0.50	51.45	-2.94	0.67	9.89	1.270	10.57	-1.42	-0.13	1.231
25 Mellor	79.34	0.54	0.26	77.10	0.04	0.27	62.50	-6.13	1.11	13.84	6.757	13.87	-0.06	-0.00	6.830
26 Walker	78.51	4.14	0.18	76.99	3.09	0.21	45.56	5.84	1.66	8.88	1.283	8.35	1.12	0.13	1.271
27 Kalaghchy	77.59	0.59	0.21	75.51	-0.08	0.24	52.17	-3.82	1.10	4.58	0.978	4.66	-0.13	-0.03	0.980
28 Shirey2	80.26	4.52	0.62	79.47	3.27	0.41	55.99	-2.39	1.19	6.59	2.888	4.20	7.16	1.70	2.411
29 Kannan	75.09	7.47	0.61	72.28	8.51	0.60	57.72	6.01	2.89	4.36	0.591	4.05	0.70	0.17	0.570
30 Yarosh2	77.00	3.26	1.08	75.31	3.01	1.20	64.21	-2.77	1.77	3.75	0.686	4.00	-0.64	-0.16	0.679
Averages	77.88	3.34	0.47	75.48	3.45	0.50	56.39	-2.27	1.58	10.51	5.45	11.72	-2.16	0.17	5.599
Std Dev	2.36	1.89	0.32	2.75	2.02	0.29	7.07	5.34	0.82	18.93	20.19	27.97	16.56	0.38	21.602
Minimum	71.12	0.14	0.09	68.49	-0.08	0.2	40.8	-17.11	0.45	3.68	0.192	3.49	-90.87	-0.56	0.192
Maximum	81.92	7.47	1.53	80.23	8.51	1.36	78.52	6.01	3.79	111.12	113.787	161.36	7.16	1.70	121.552

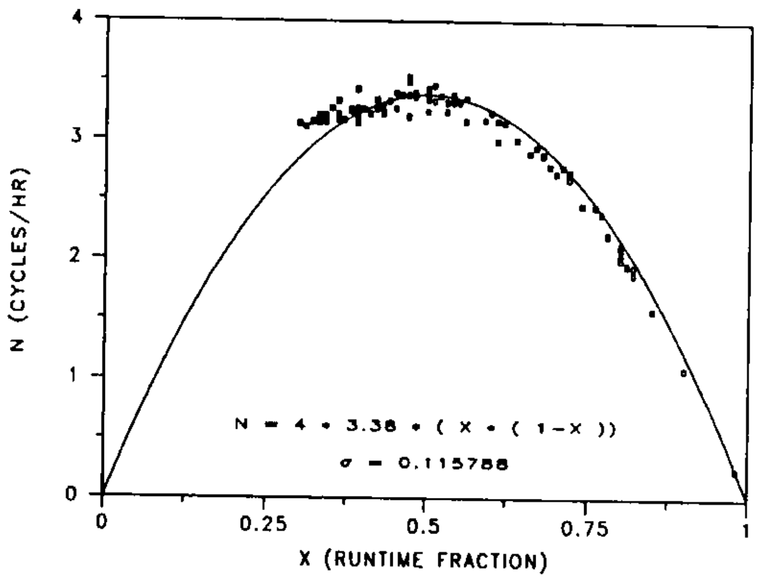
TABLE C-1 (cont.)
Summary of Measured Data From Each Site

C:\qpro\wq1\tstat.wq1 Thermostat Cycling Data as of: 5/7/91 Range: ag1..ar44

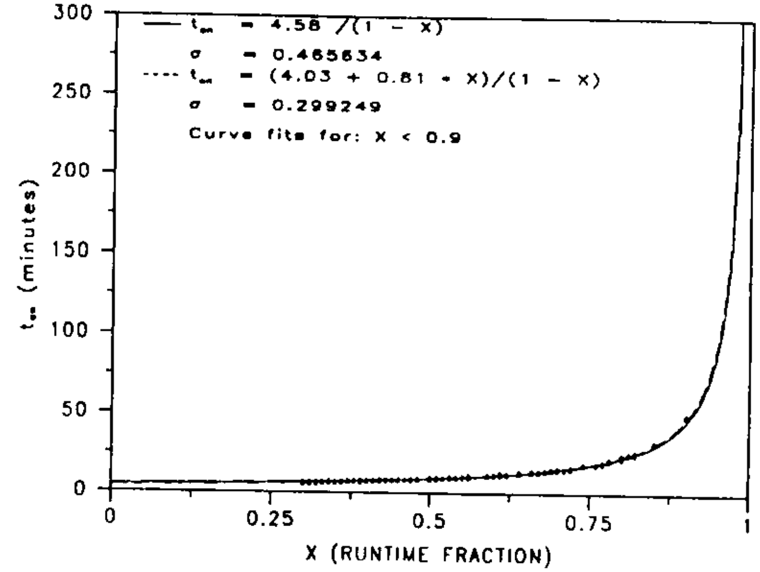
	Name	Floor Area Ft2	No of People A	No of People C	AC Size Tons	sqft/ tons	Wall: In, Out or Gar	Age of House Years	Avg Ambient Temp ,F	Avg Amb Dew-Point ,F	Solar radiation w/m2
1	Raustad	1350	2	0	2.5	540.0	I	26	83.13	71.74	403.58
2	Henderson	1450	2	0	2.5	580.0	I	28	77.62	61.47	256.79
3	Rudd	1200	2	0	2	600.0	I	28	80.16	66.73	234.46
4	Marvin	2250	2	0	3.5	642.9	G	22	78.28	69.40	6.54
5	Holder	1200	3	1	3	400.0	I	30	80.76	70.80	49.90
6	Sherwin	1800	4	0	3	600.0	I	30	79.32	67.94	175.10
7	Parker	1200	2	0	2	600.0	G	33	79.90	69.23	250.11
8	Shirey	616	2	0	1.5	410.7	I	2.5	82.18	70.52	277.54
9	Redmond	2200	2	0	3.5	628.6	I	28	82.11	69.33	220.98
10	Fairey1	2700	5	0	4	675.0	I	1	84.71	69.82	302.68
11	Fairey2	2700	5	0	4	675.0	I	1	81.74	69.62	218.92
12	Kettles	1980	2	2	2.5	792.0	I	2.5	83.25	69.04	286.13
13	Melody	1600	2	0	3	533.3	I	3	80.64	67.15	245.05
14	Dhere	1200	2	0	2.5	480.0	I	30	83.02	69.83	261.33
15	Dutton	1200	2	5	2.5	480.0	I	2	79.16	68.18	21.80
16	Dernier	1080	2	2	2	540.0	I	35	82.57	68.19	274.80
17	Vieira1	1460	2	1	2.5	584.0	G	23	82.40	68.72	306.10
18	Vieira2	1460	2	1	2.5	584.0	G	23	81.94	68.04	254.63
19	Dummer	2000	2	2	3.5	571.4	I	25	82.09	66.81	250.84
20	Raustad2	1350	2	0	2.5	540.0	I	26	81.38		203.75
21	Goulet	1800	2	0	3	600.0	G	1	83.44		307.58
22	Cummings3	1650	2	2	3	550.0	O	28	81.13	65.12	178.20
23	Cummings2	1650	2	2	3	550.0	O	28	82.37	64.61	263.13
24	Cummings1	1650	2	2	3	550.0	O	28	83.27	66.77	284.00
25	Mellor	1764	2	0	3	588.0	G	3	80.43	62.28	175.93
26	Walker	1200	2	1	3	400.0	I	30	83.88	66.43	178.70
27	Kalaghchy	1600	2	0	3	533.3	I	4	80.90	62.55	180.29
28	Shirey2	616	2	0	1.5	410.7	I	2.5	80.65	61.23	173.25
29	Kannan	800	3	0	1.5	533.3	I	5	79.70	62.05	176.54
30	Yarosh2	2250	2	0	3.5	642.9	G	22	78.63	61.60	101.20
	Averages	1565.9	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	85.68
	Minimum	616	2	0	1.5	400.0	0	1	77.62	61.23	6.54
	Maximum	2700	5	5	4	792.0	0	35	84.71	71.74	403.58

Detailed Data For Each Site

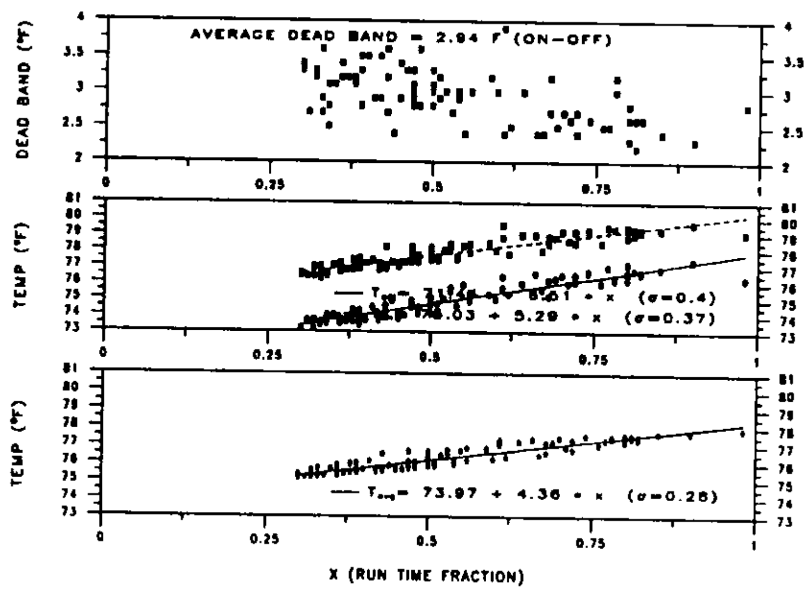
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



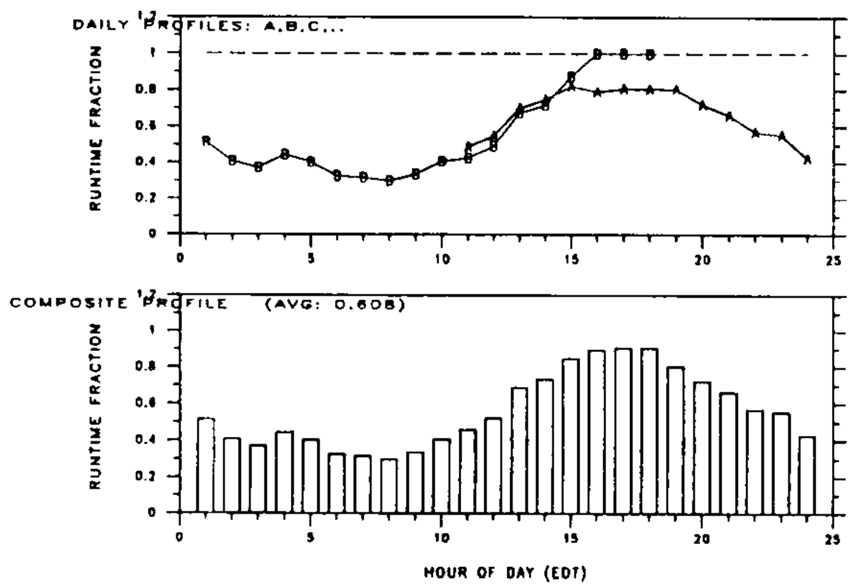
SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: RAUSTAD
START DATE: 6/ 9 OR 160 TIME: 8: 0:35 JULEAN HR: 3824.01
END DATE: 6/10 OR 161 TIME: 17:56: 5 JULEAN HR: 3857.93
ELAPSED TIME: 33.93

	TOTAL	ON	OFF
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
% HOURS		61.42	38.58

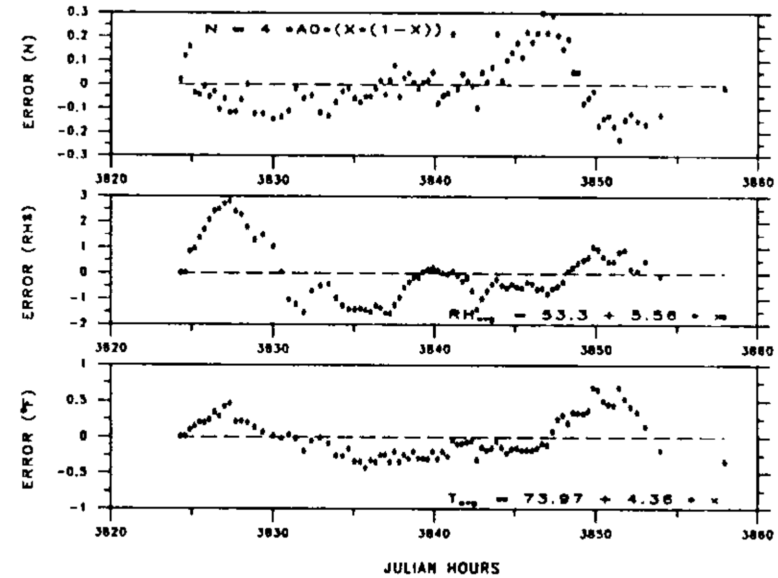
SELECTED DATA RANGE:
STARTING 160. , 8. (3824.000)
ENDING 161. , 14. (3854.000)

THERMOSTAT DATA: RAUSTAD

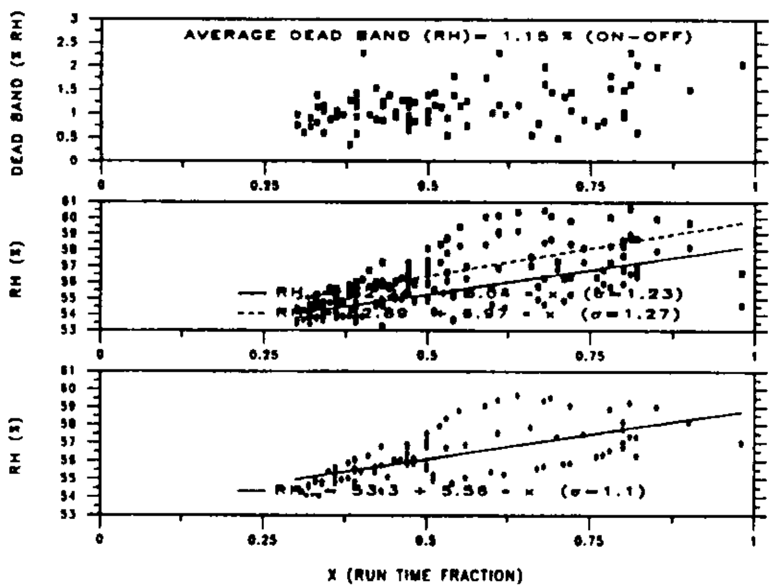
PLOT 4: RUN TIME PROFILES



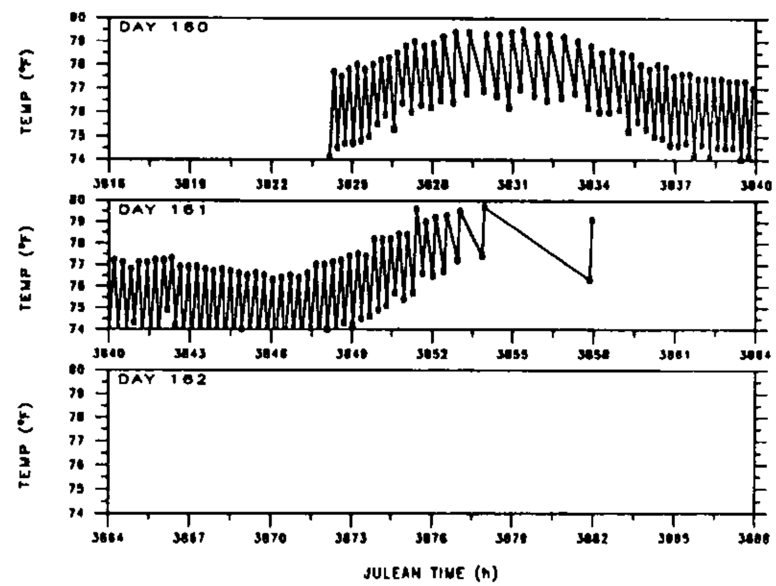
PLOT 5: ERROR ANALYSIS



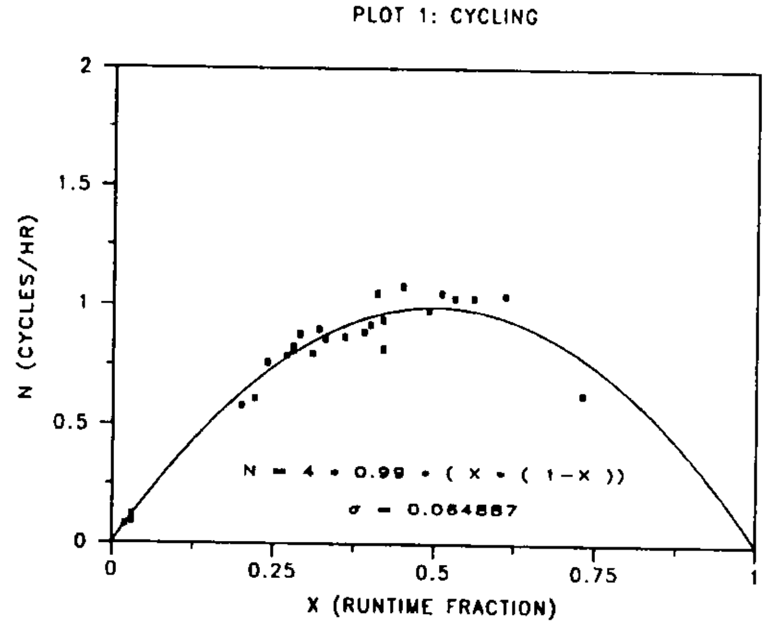
PLOT 6: HUMIDITY

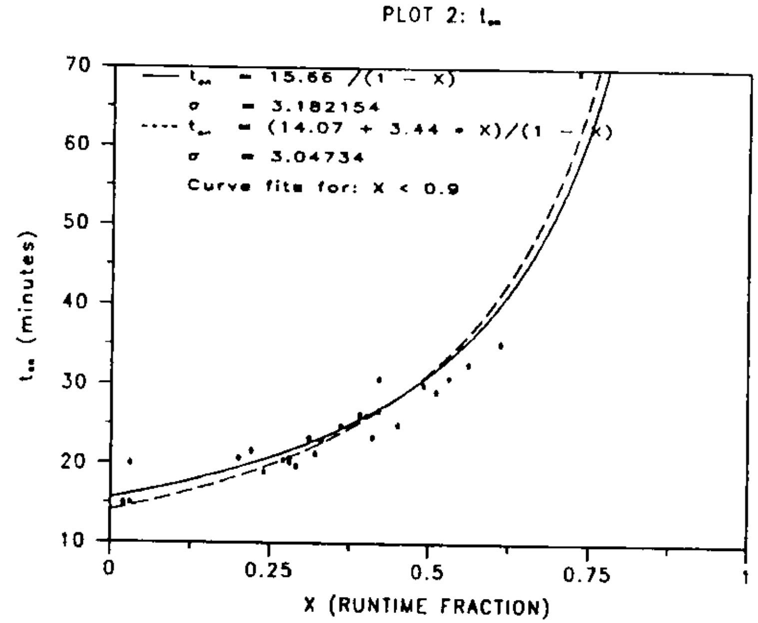


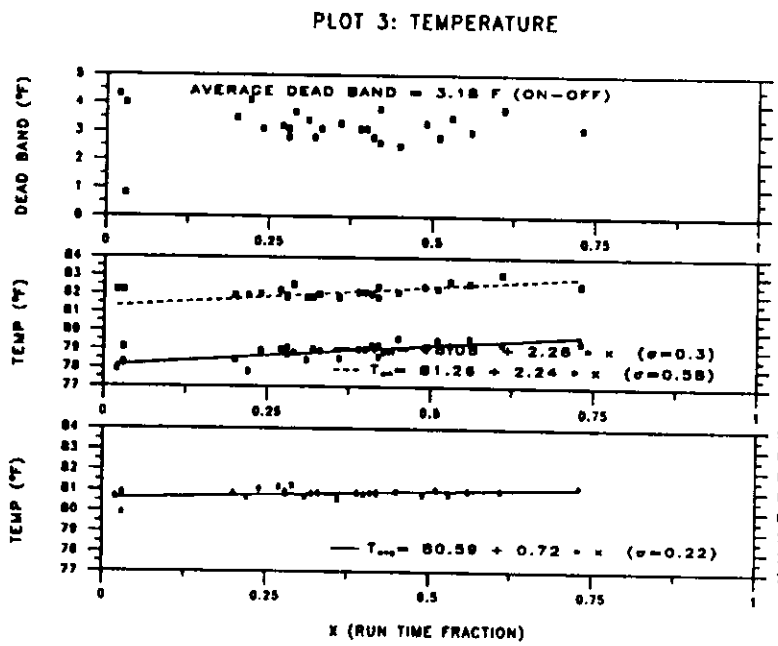
PLOT 7: TEMPERATURE VS TIME (3 DAYS)



THERMOSTAT DATA: RAUSTAD







SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION:	HENDERSON				
START	DATE: 6/11 OR 162	TIME:	21:17:15	JULEAN HR:	3885.29
END	DATE: 6/14 OR 165	TIME:	7:26:20	JULEAN HR:	3943.44
ELAPSED TIME:	58.15				

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	80.70	80.20	80.81
AVERAGE RH (%)	54.27	49.89	55.32
HOURS	58.15	11.22	46.93
% HOURS		19.30	80.70

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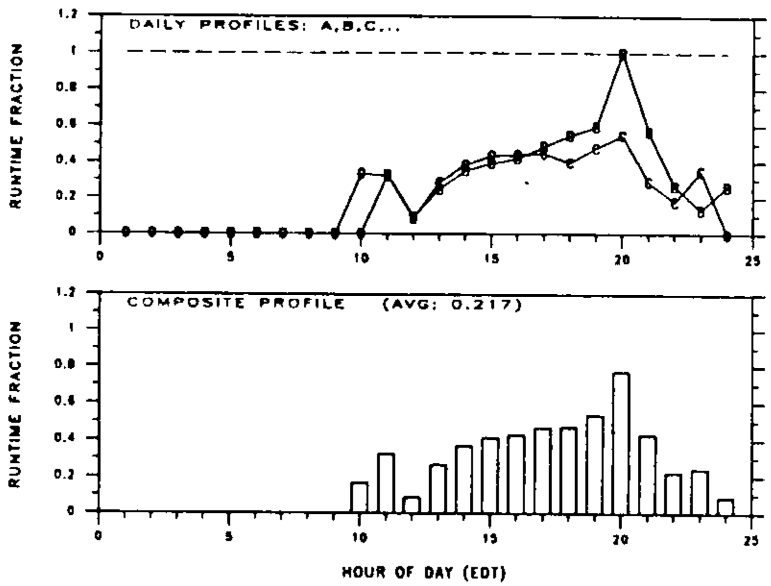
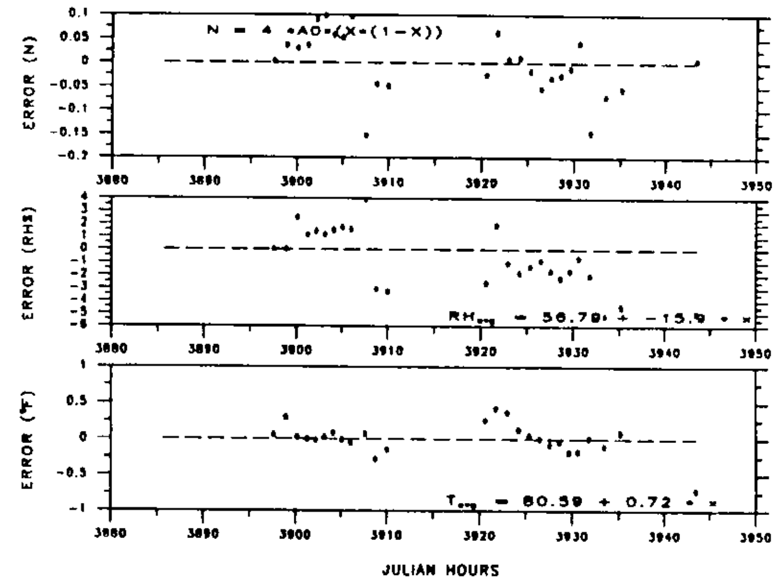
THERMOSTAT DATA: HENDERSON

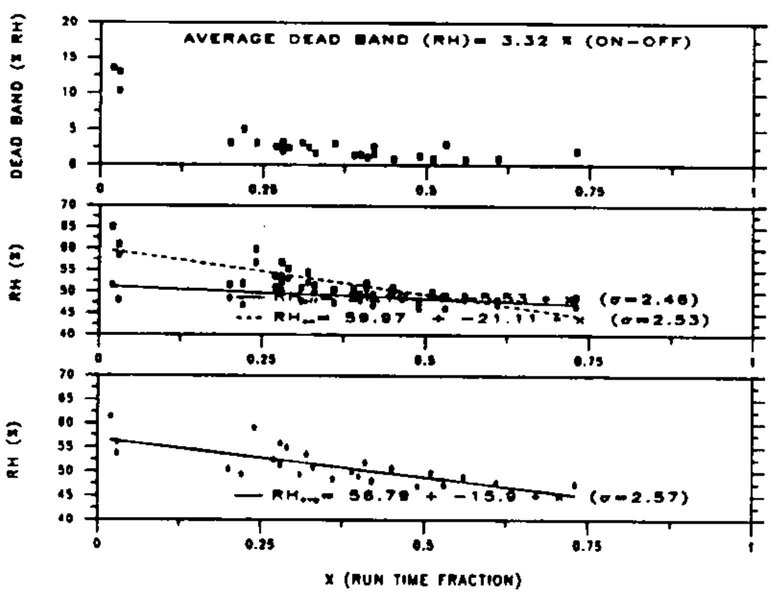
PLOT 4: RUN TIME PROFILES



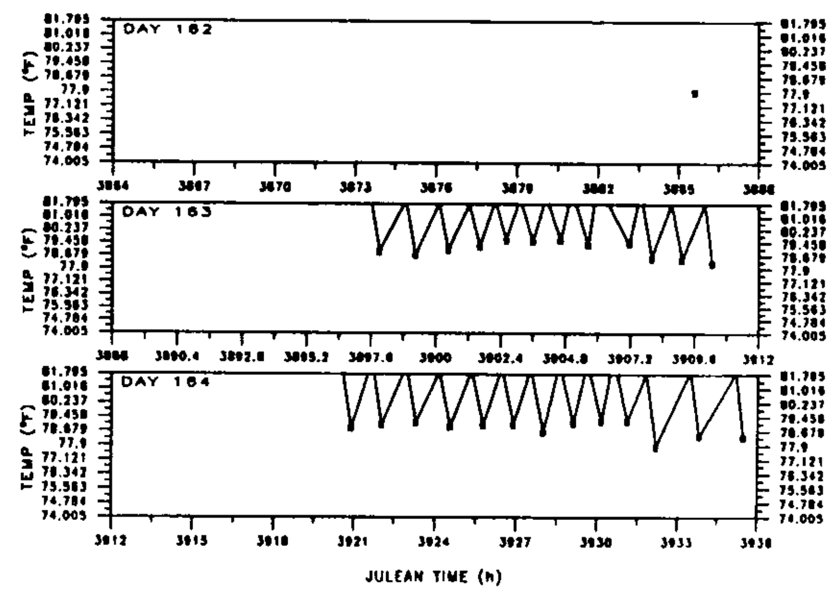
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

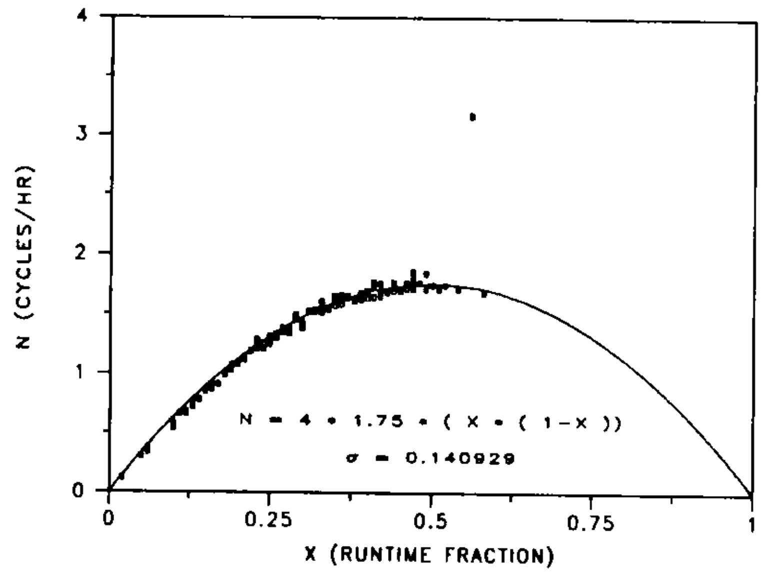


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

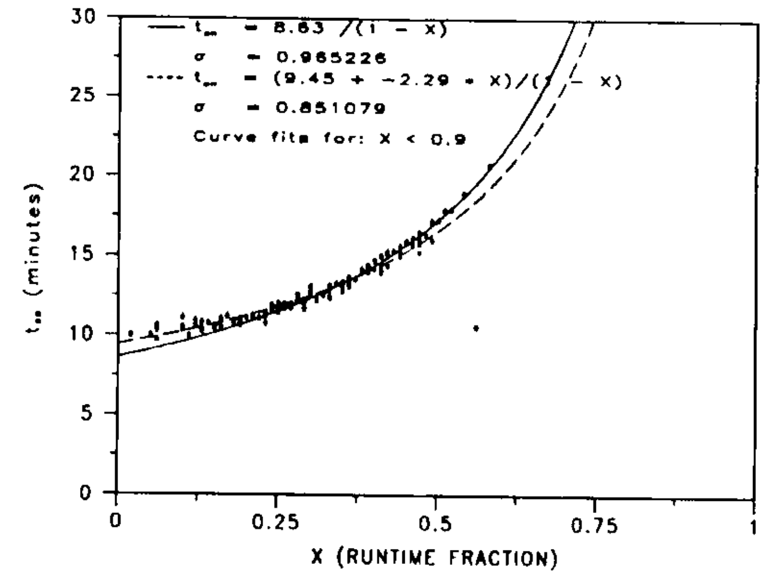


THERMOSTAT DATA: HENDERSON

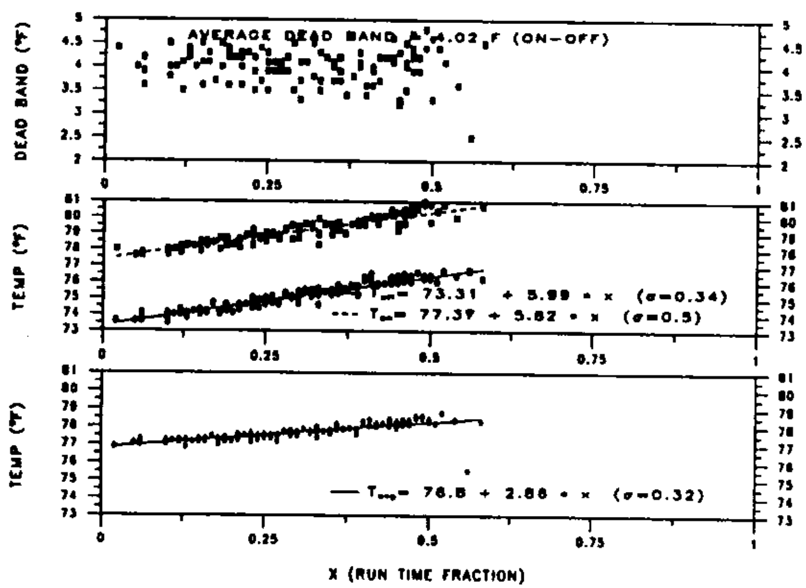
PLOT 1: CYCLING



PLOT 2: t



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: RUDD

START DATE: 6/14 OR 165 TIME: 18:57:40 JULEAN HR: 3954.96

END DATE: 6/19 OR 170 TIME: 8:11:15 JULEAN HR: 4064.19

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
% HOURS		22.86	77.14

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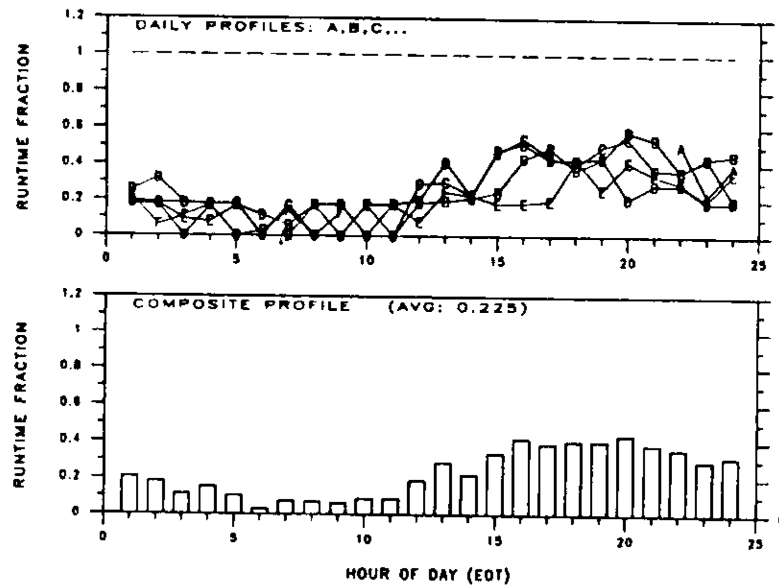
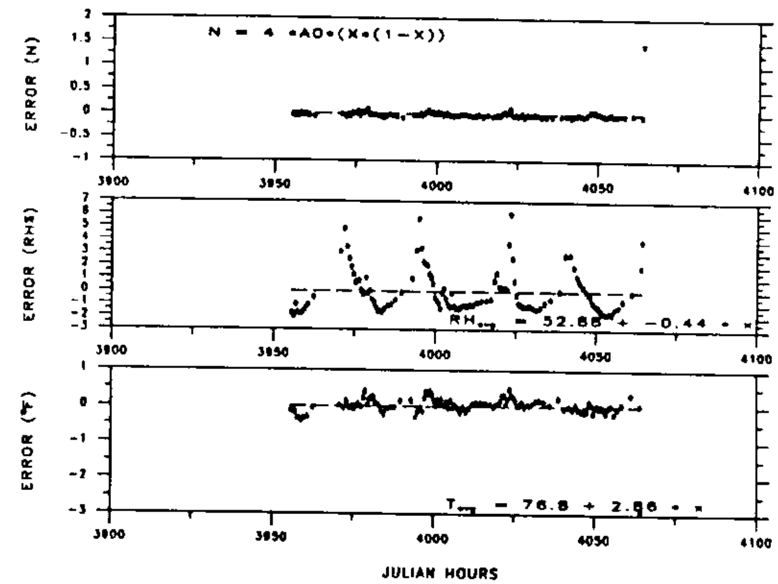
THERMOSTAT DATA: RUDD

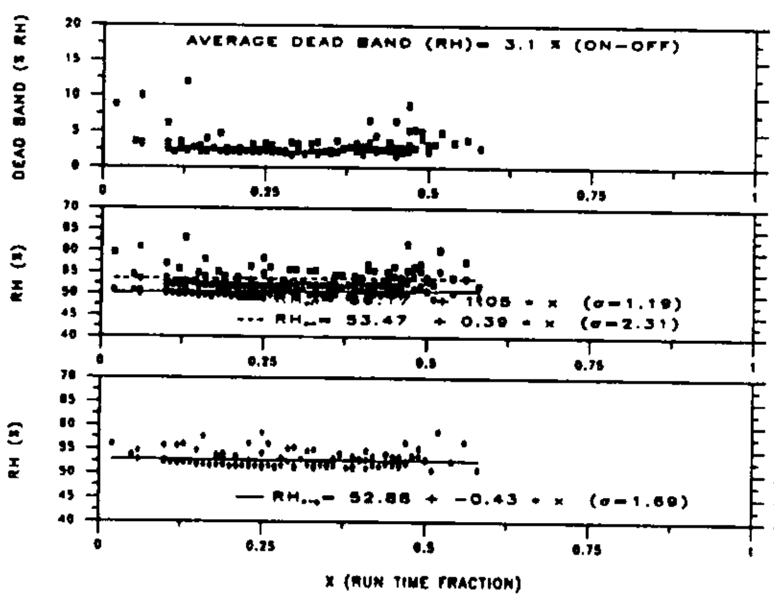
PLOT 4: RUN TIME PROFILES



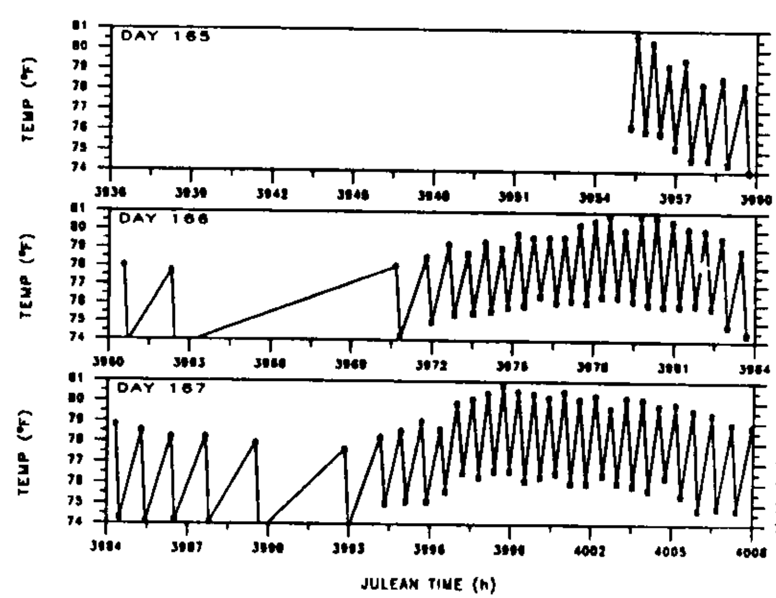
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

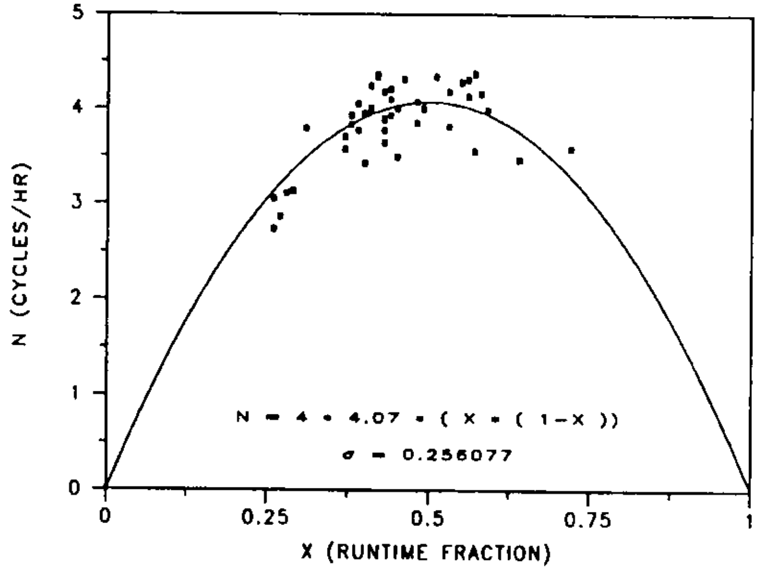


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

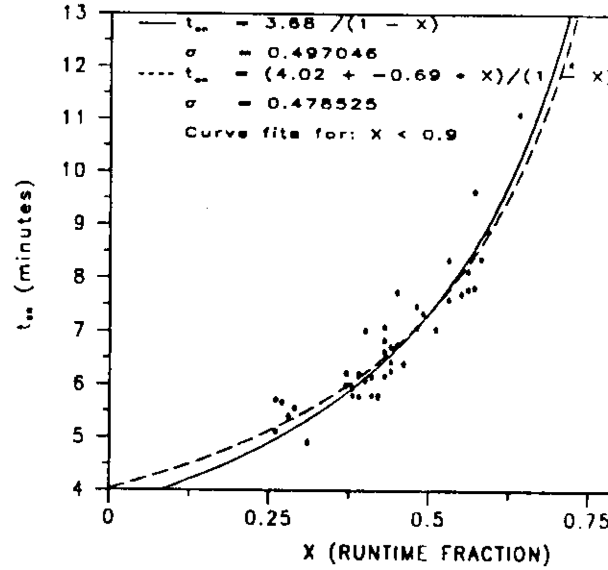


THERMOSTAT DATA: RUDD

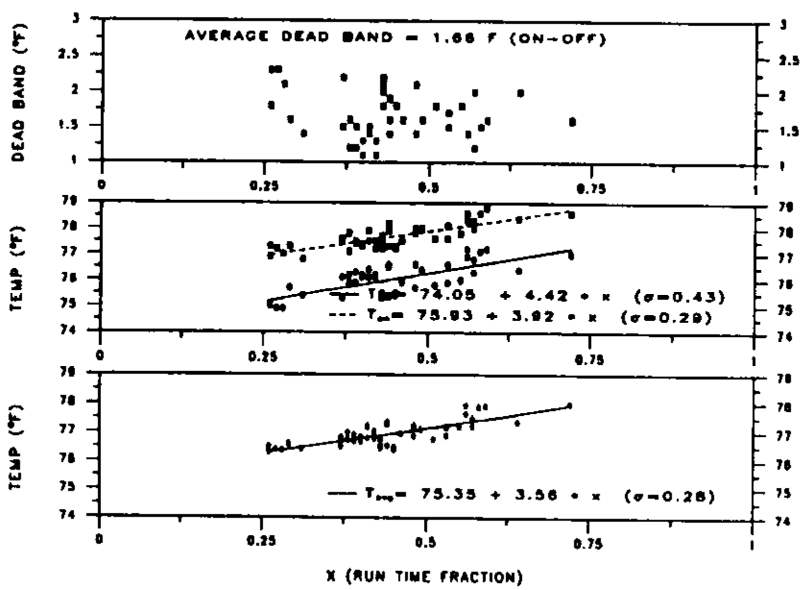
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: YAROSH1
START DATE: 6/25 OR 176 TIME: 19:48:10 JULEAN HR: 4219.80
END DATE: 6/26 OR 177 TIME: 7:7:40 JULEAN HR: 4231.13
ELAPSED TIME: 11.33

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.91	76.72	77.08
AVERAGE RH (%)	54.55	54.30	54.75
HOURS	11.33	4.98	6.35
% HOURS		43.95	56.05

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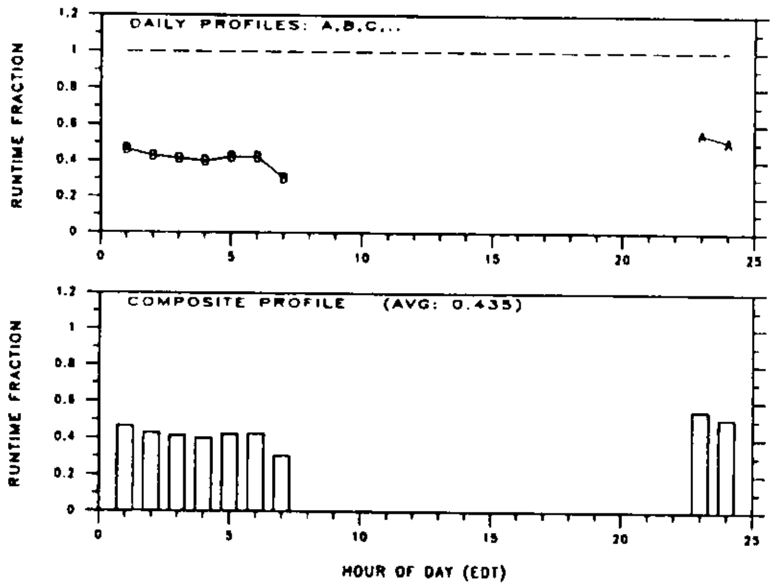
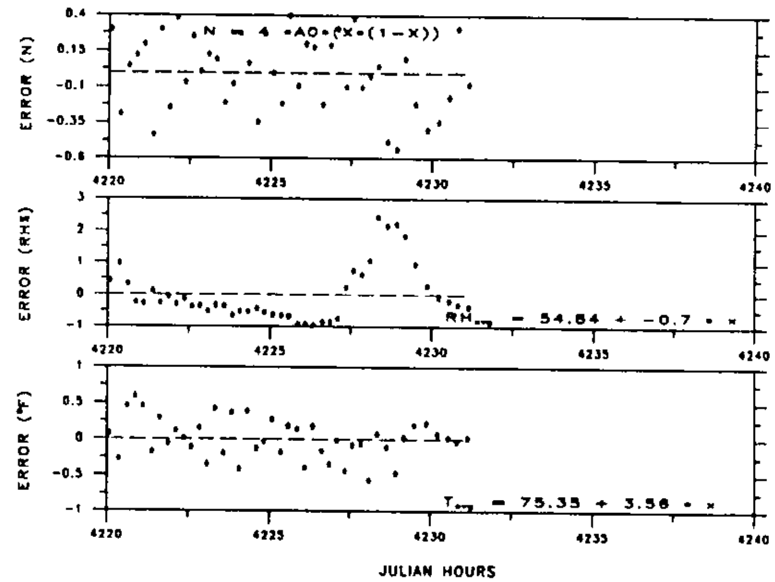
THERMOSTAT DATA: YAROSH1

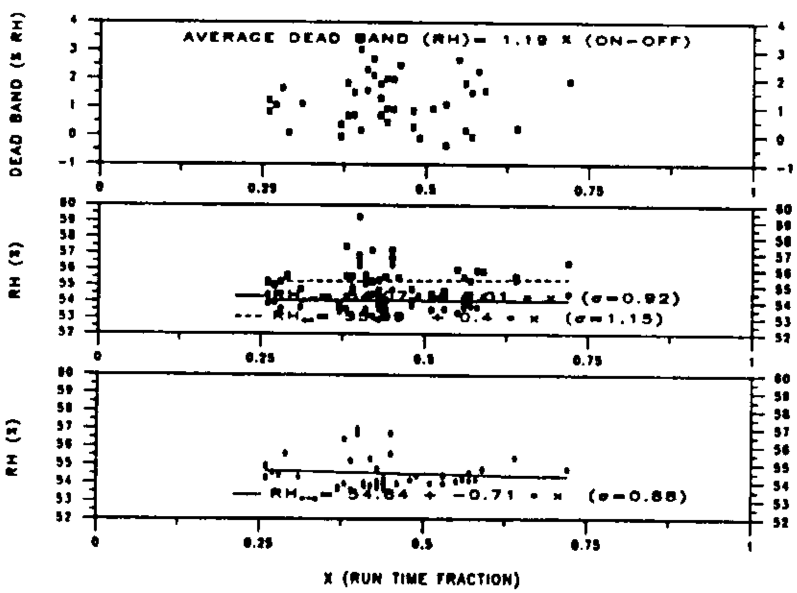
PLOT 4: RUN TIME PROFILES



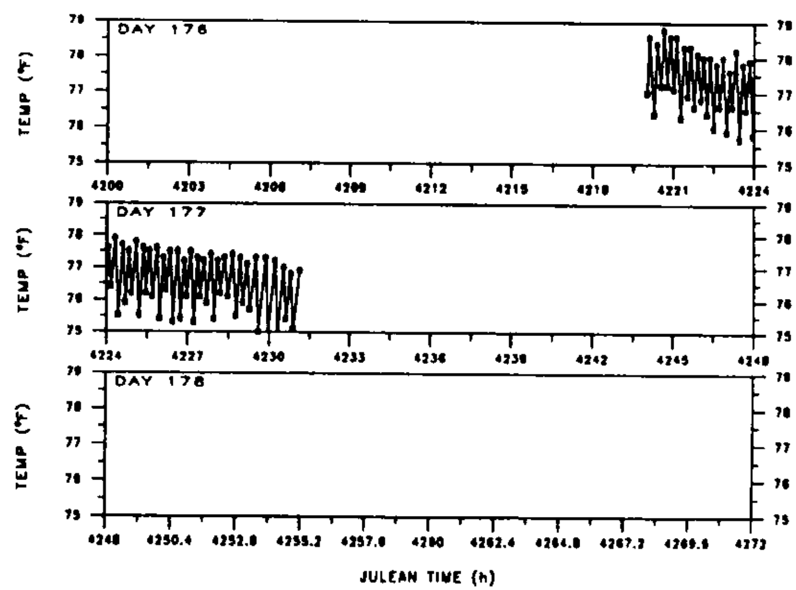
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

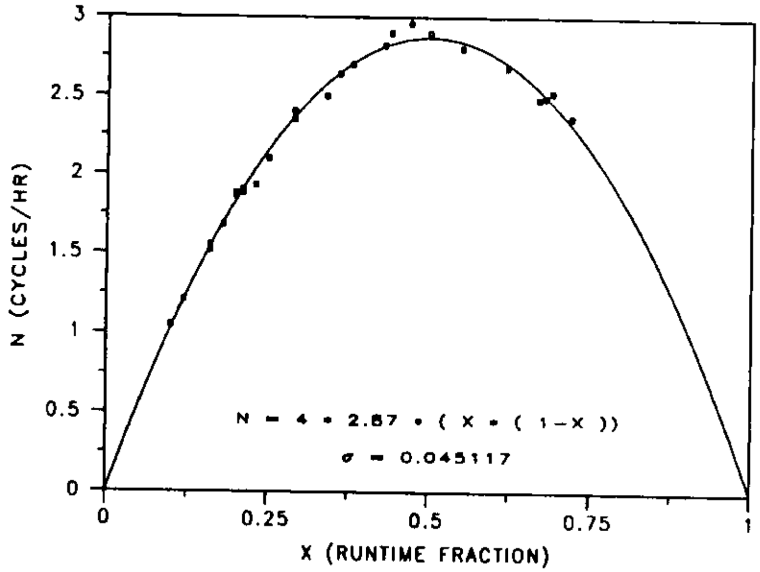


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

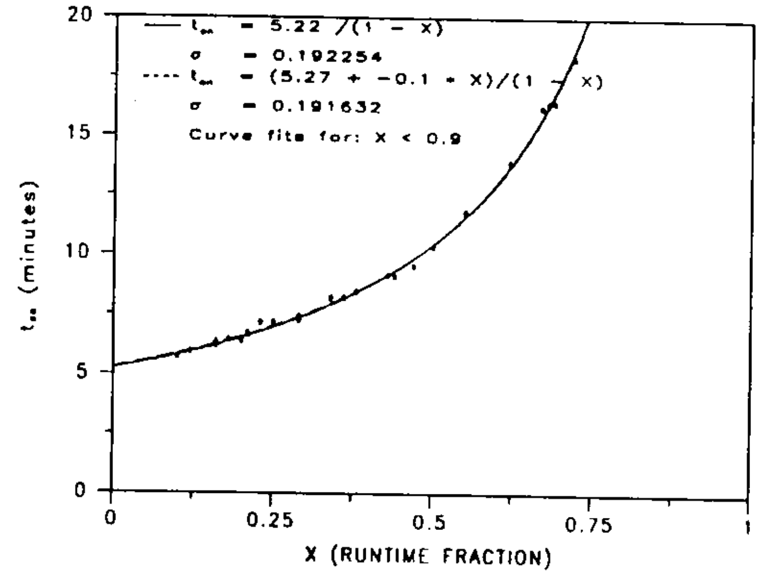


THERMOSTAT DATA: YAROSH1

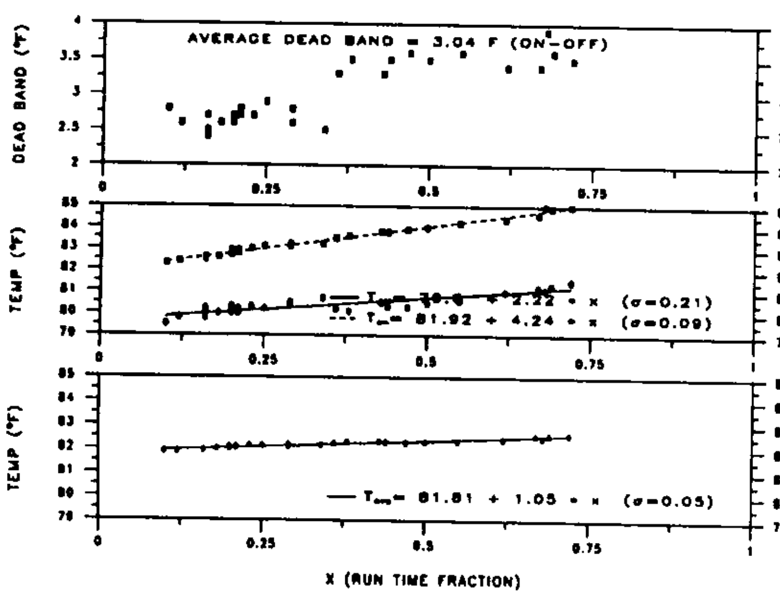
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: HOLDER

START	DATE: 6/29 OR 180	TIME: 17:13: 0	JULEAN HR:	4313.22
END	DATE: 7/ 0 OR 181	TIME: 6:23:30	JULEAN HR:	4326.39
ELAPSED TIME:	13.17			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	82.14	81.50	82.43
AVERAGE RH (%)	49.60	48.10	50.29
HOURS	13.17	4.13	9.04
% HOURS		31.35	68.65

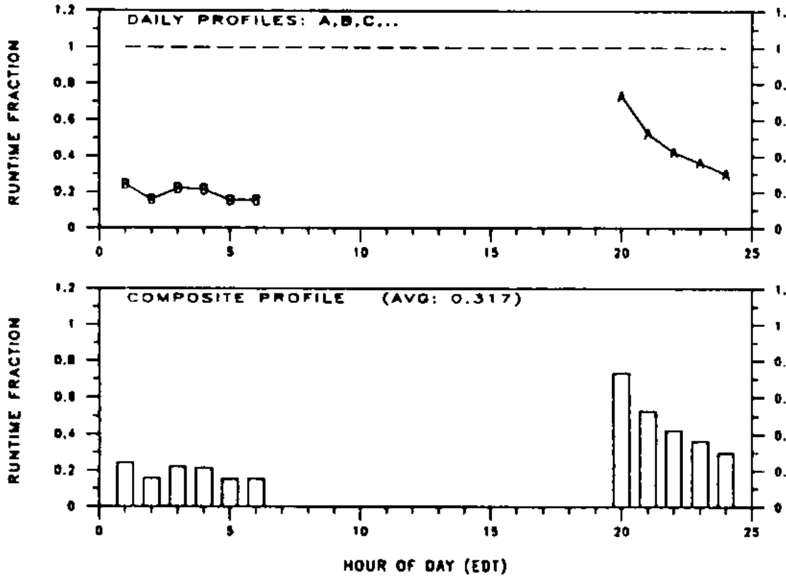
SELECTED DATA RANGE:

STARTING 180. , 12. (4308.000)

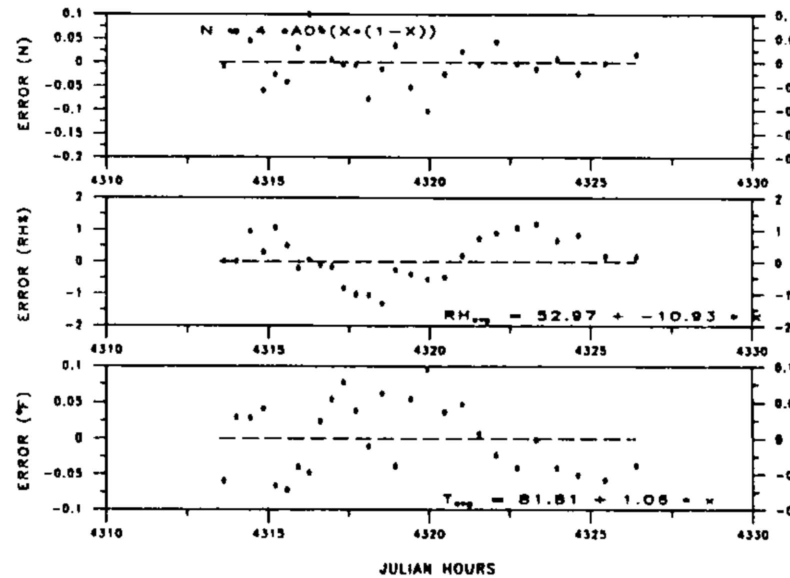
ENDING 181. , 6. (4326.000)

THERMOSTAT DATA: HOLDER

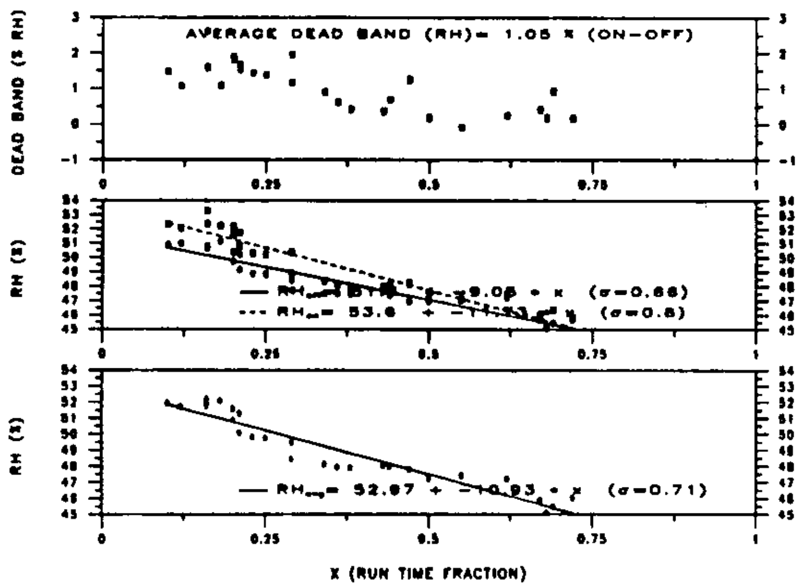
PLOT 4: RUN TIME PROFILES



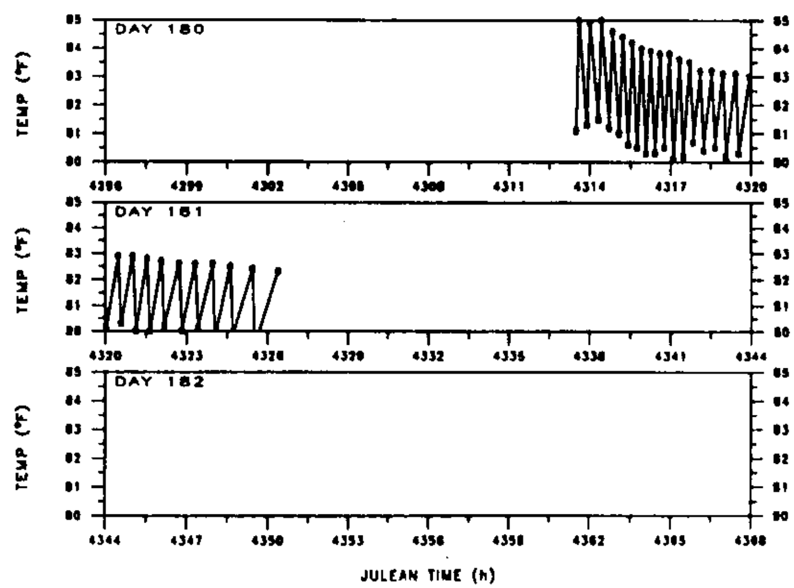
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

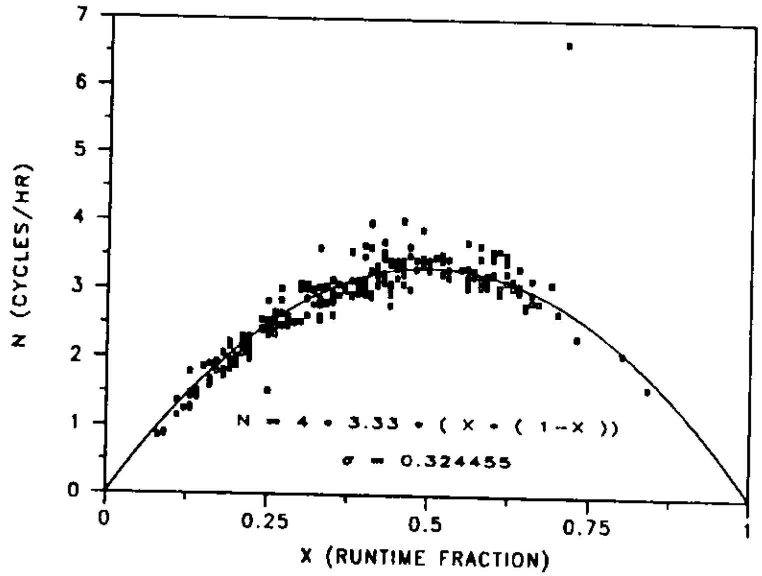


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

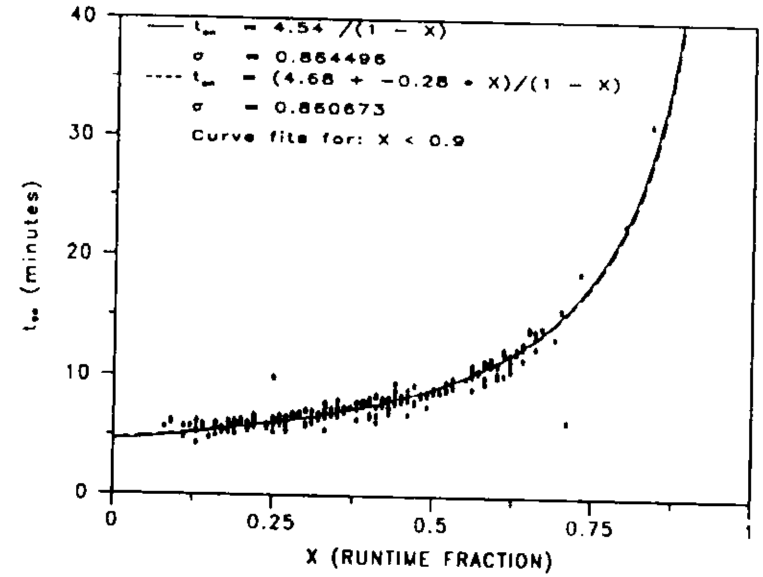


THERMOSTAT DATA: HOLDER

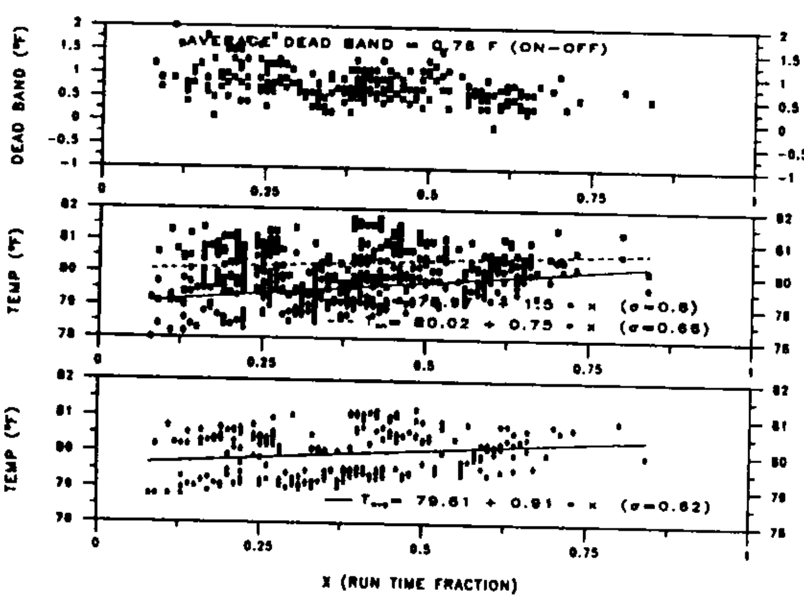
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: SHERWIN
START DATE: 7/11 OR 192 TIME: 17:58:35 JULEAN HR: 4601.98
END DATE: 7/16 OR 197 TIME: 8: 1:25 JULEAN HR: 4712.02
ELAPSED TIME: 110.05

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.83	79.98	79.77
AVERAGE RH (%)	86.37	86.31	86.40
HOURS	110.05	35.29	74.75
% HOURS		32.07	67.93

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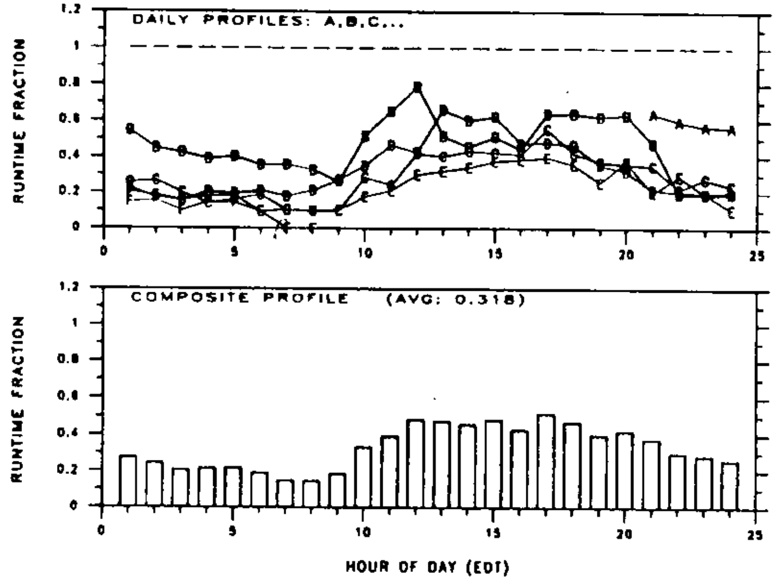
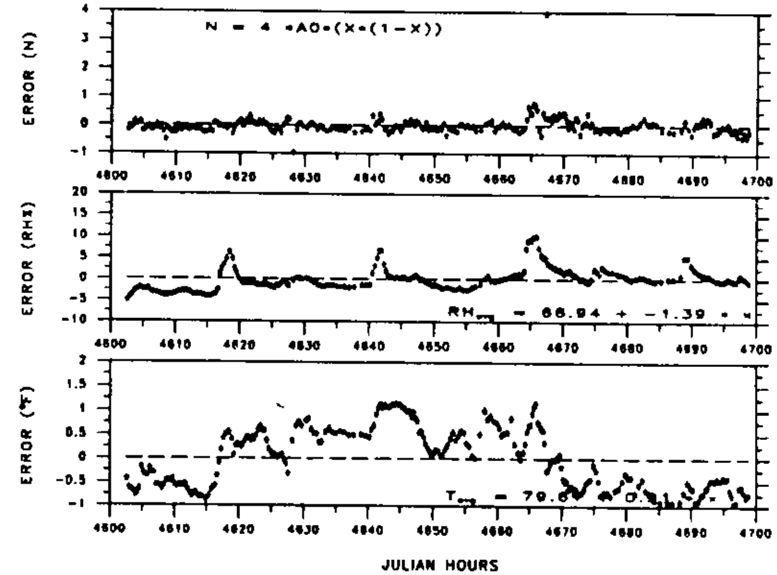
THERMOSTAT DATA: SHERWIN

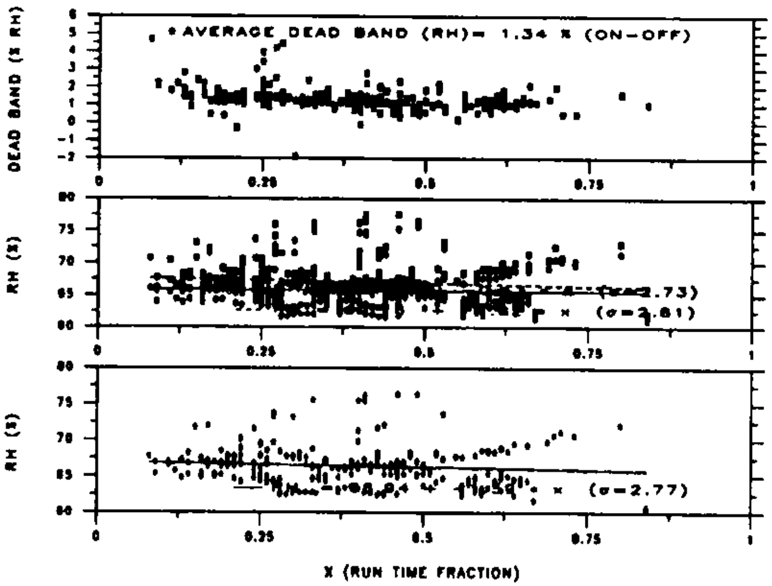
PLOT 4: RUN TIME PROFILES



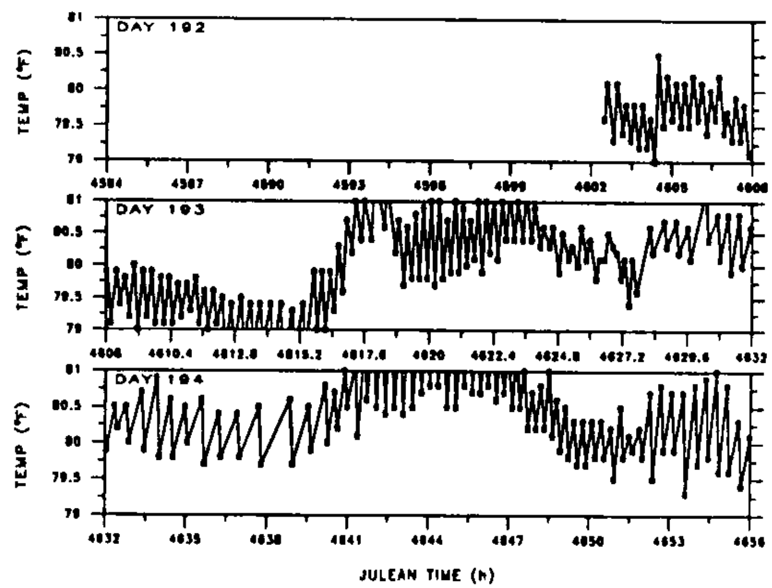
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

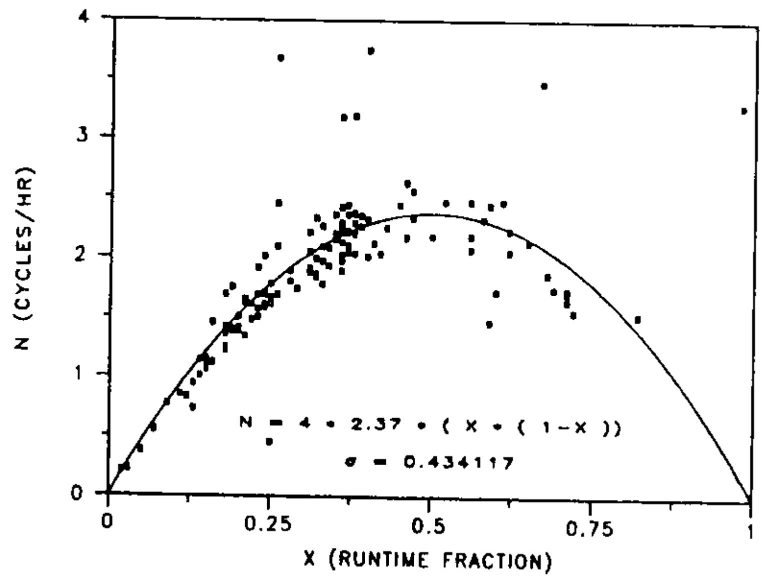


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

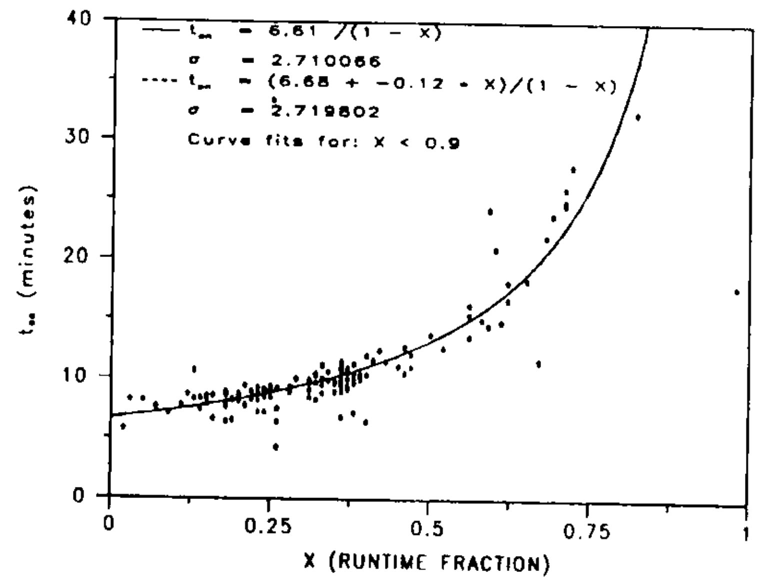


THERMOSTAT DATA: SHERWIN

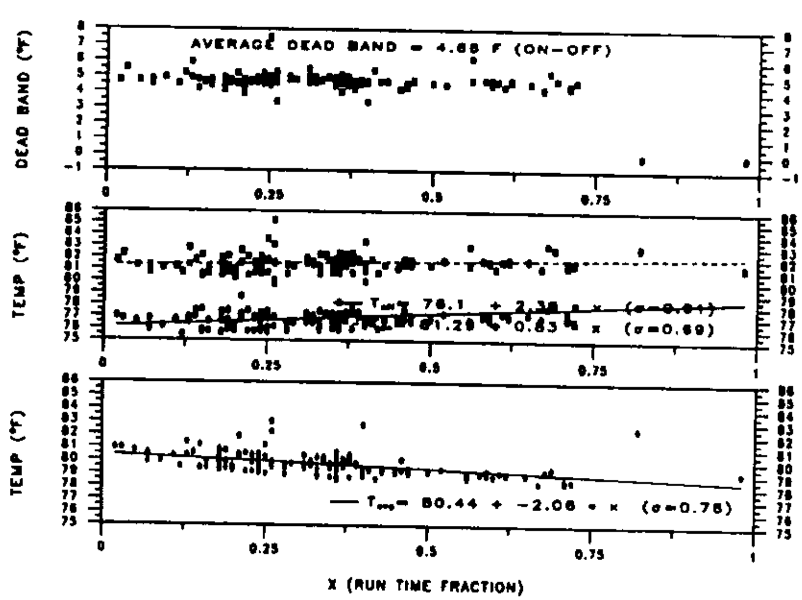
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: PARKER
START DATE: 7/16 OR 197 TIME: 17:58:35 JULEAN HR: 4721.98
END DATE: 7/20 OR 201 TIME: 13:20:50 JULEAN HR: 4813.35
ELAPSED TIME: 91.37

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.94	77.99	80.67
AVERAGE RH (%)	60.65	59.85	60.94
HOURS	91.37	24.75	66.63
% HOURS		27.08	72.92

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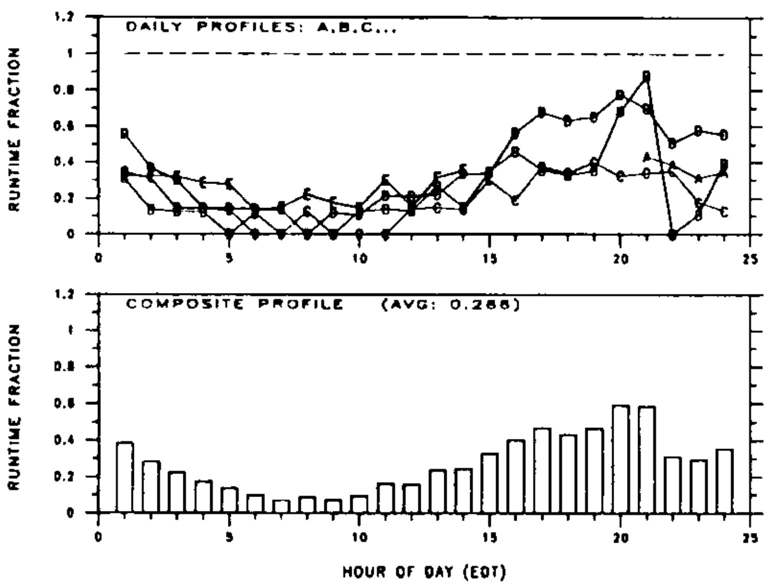
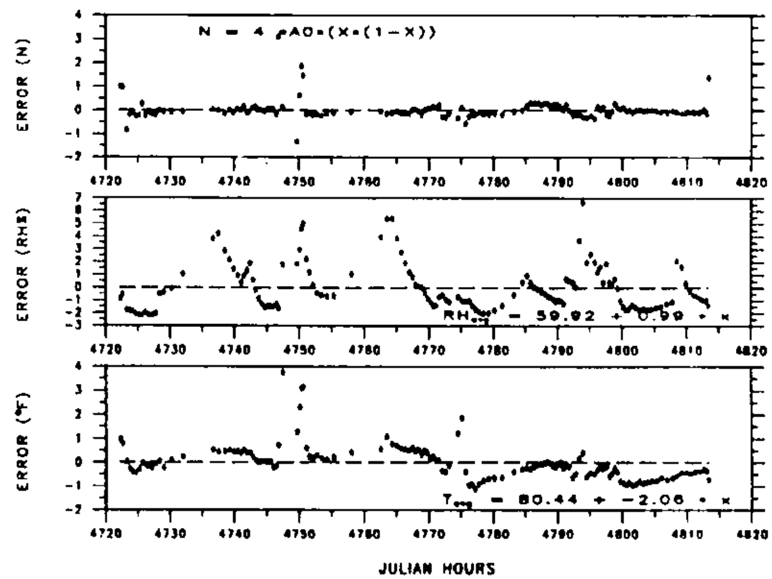
THERMOSTAT DATA: PARKER

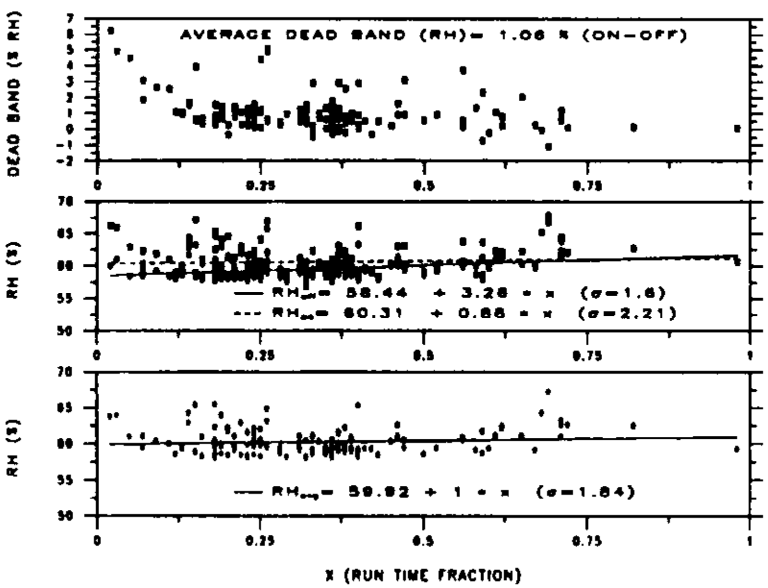
PLOT 4: RUN TIME PROFILES



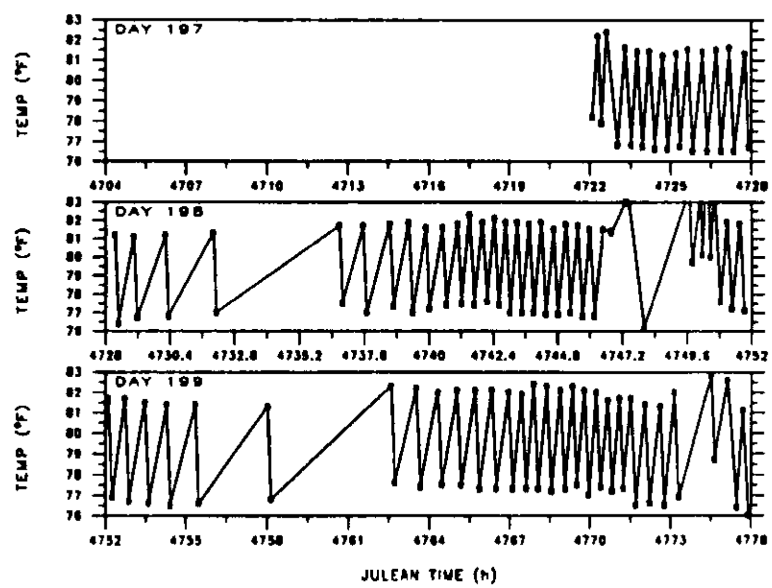
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

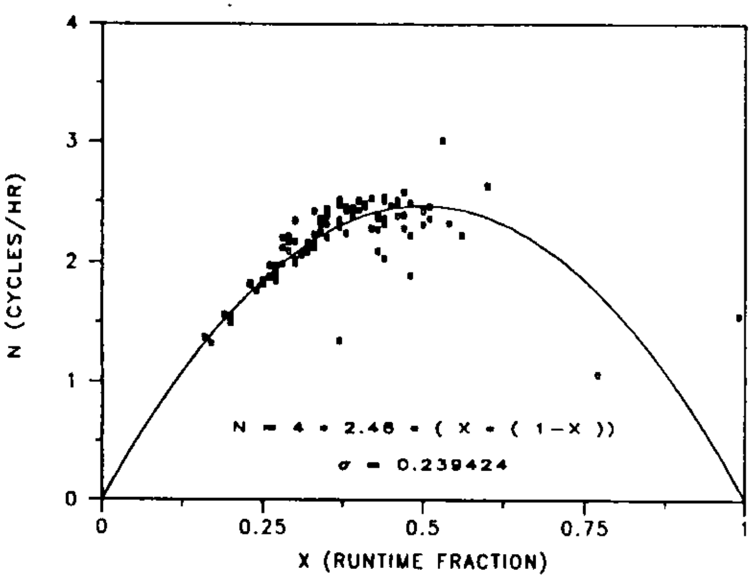


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

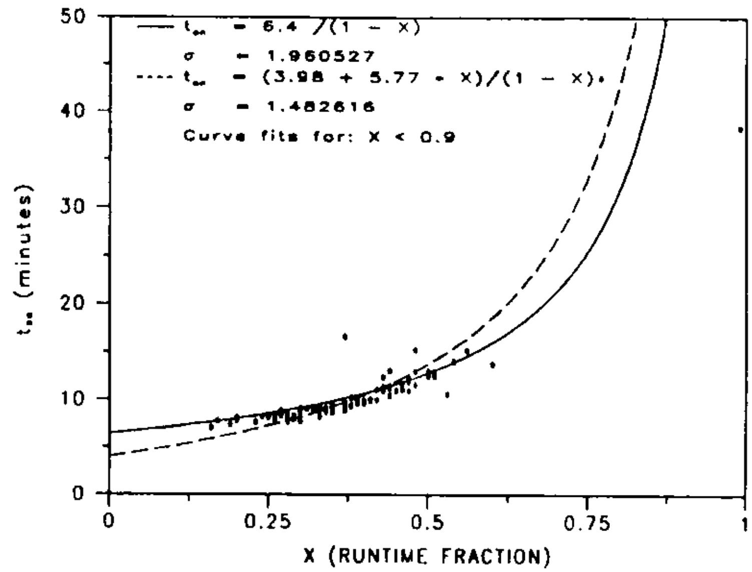


THERMOSTAT DATA: PARKER

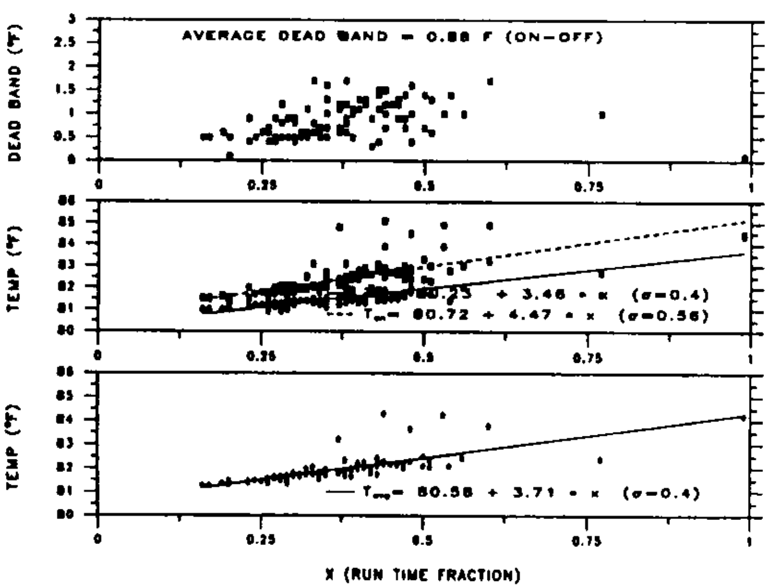
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: SHIREY
START DATE: 7/20 OR 201 TIME: 20:27:30 JULEAN HR: 4820.46
END DATE: 7/22 OR 203 TIME: 17:39:35 JULEAN HR: 4865.66
ELAPSED TIME: 45.20

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	81.95	81.90	81.98
AVERAGE RH (%)	63.33	63.26	63.36
HOURS	45.20	16.76	28.44
% HOURS		37.08	62.92

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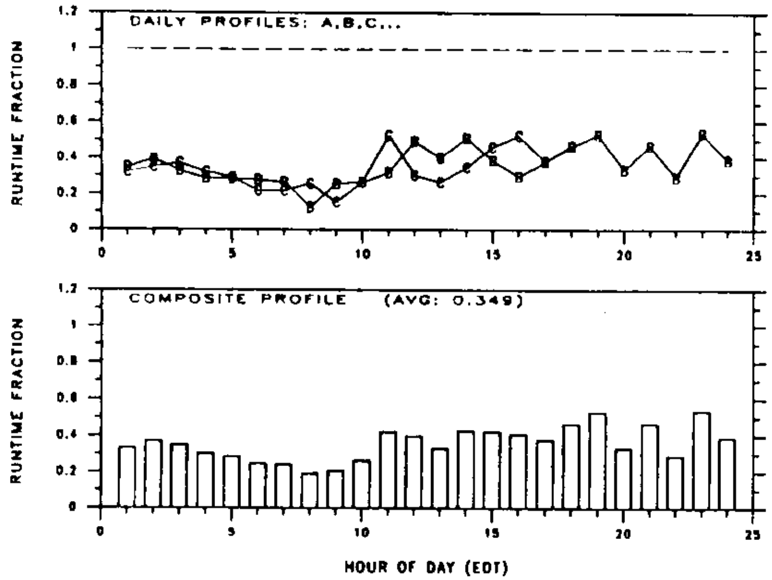
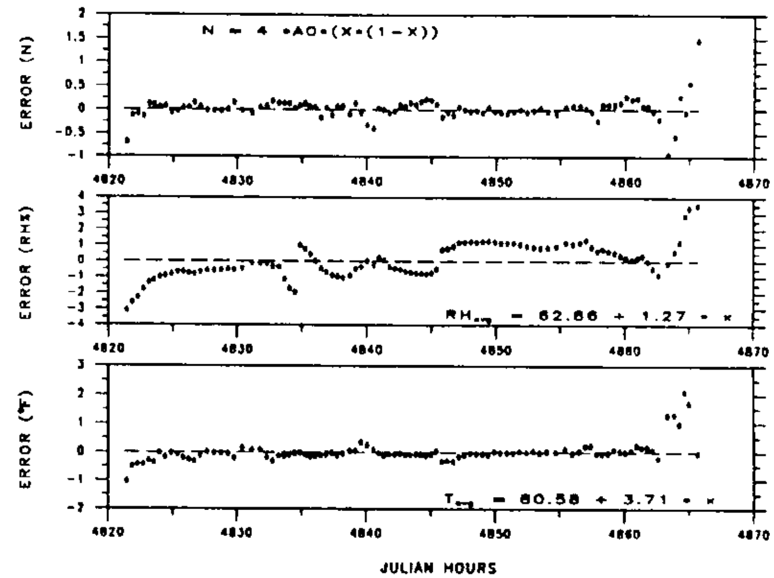
THERMOSTAT DATA: SHIREY

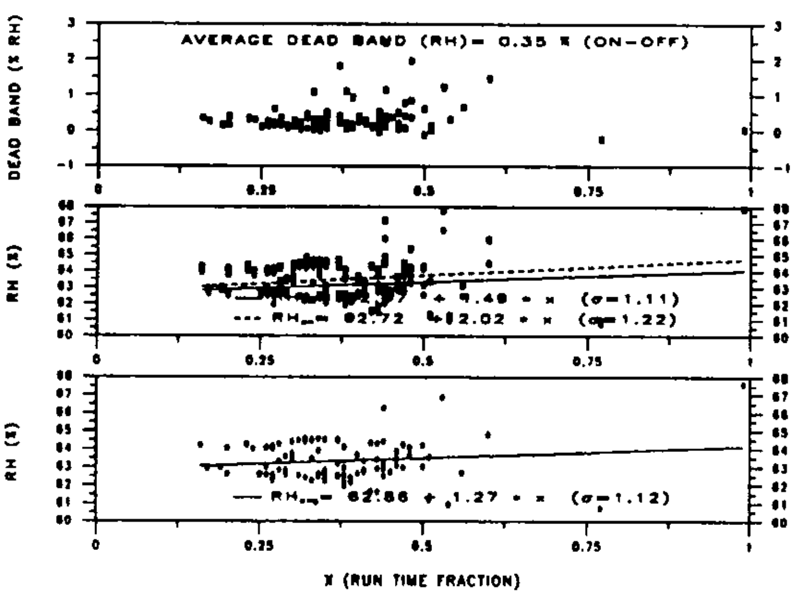
PLOT 4: RUN TIME PROFILES



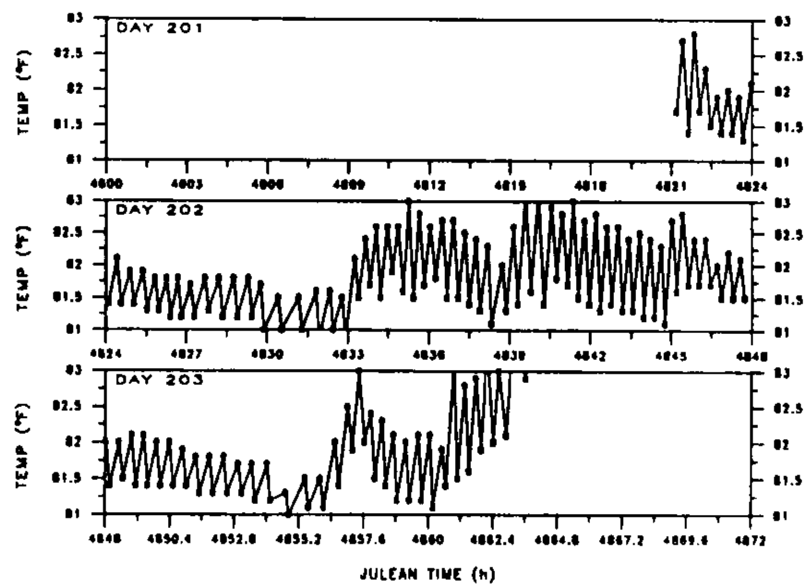
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

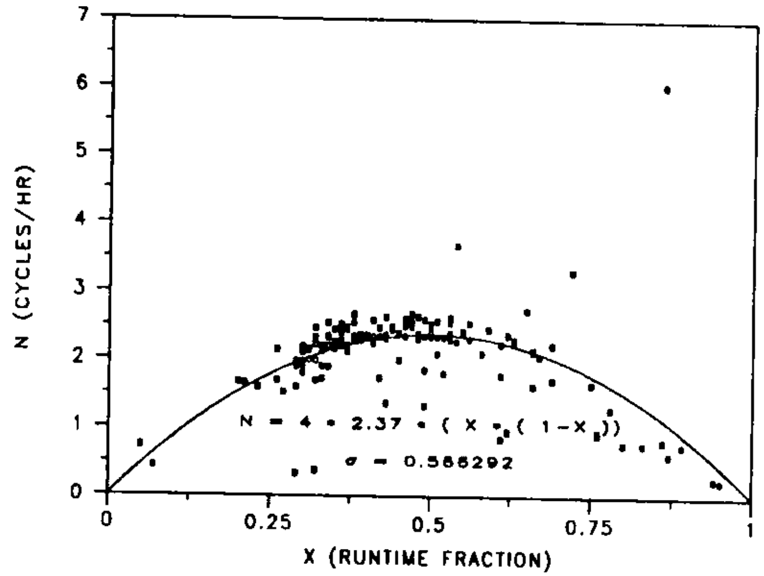


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

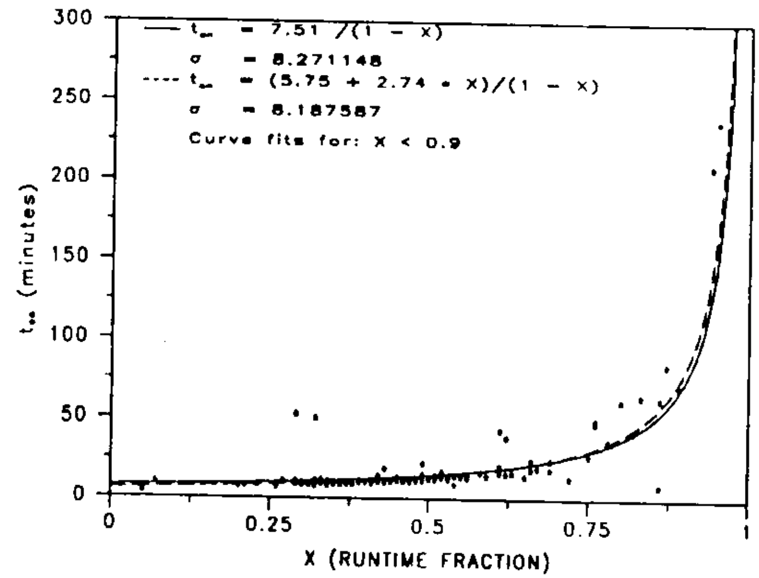


THERMOSTAT DATA: SHIREY

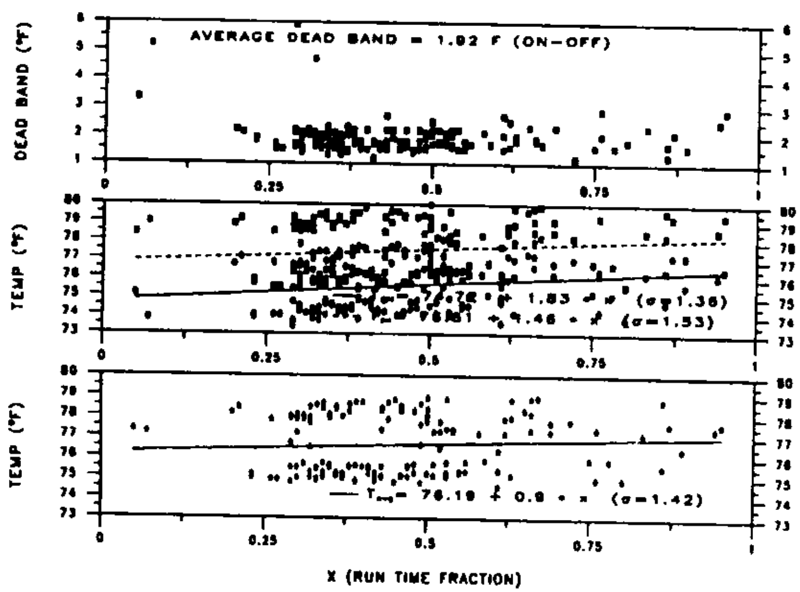
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: REDMOND

START DATE: 7/23 OR 204 TIME: 19: 9:45 JULEAN HR: 4891.16

END DATE: 7/27 OR 208 TIME: 12:25:50 JULEAN HR: 4980.43

ELAPSED TIME: 89.27

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.66	76.46	76.85
AVERAGE RH (%)	47.97	47.44	48.51
HOURS	89.27	44.64	44.63
% HOURS		50.01	49.99

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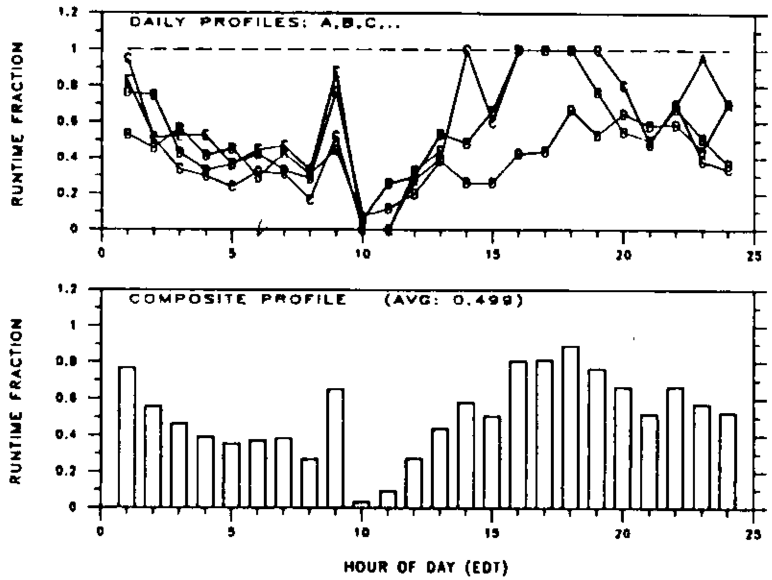
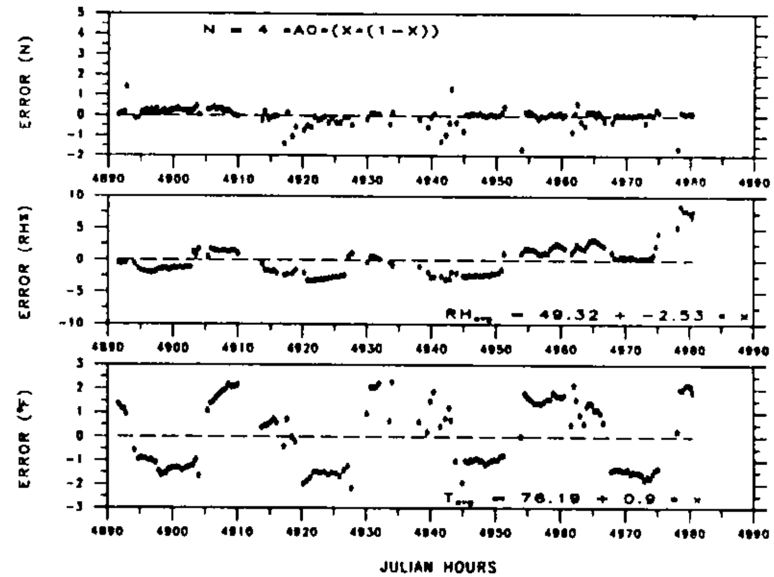
THERMOSTAT DATA: REDMOND

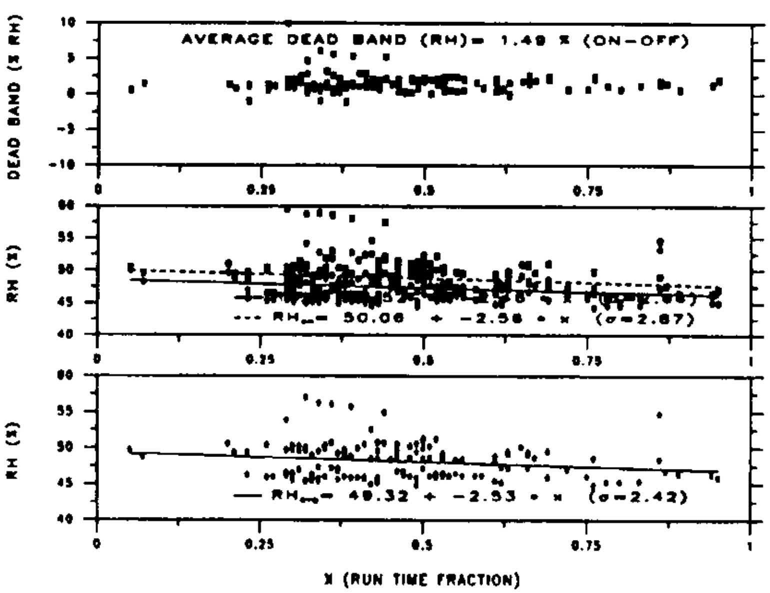
PLOT 4: RUN TIME PROFILES



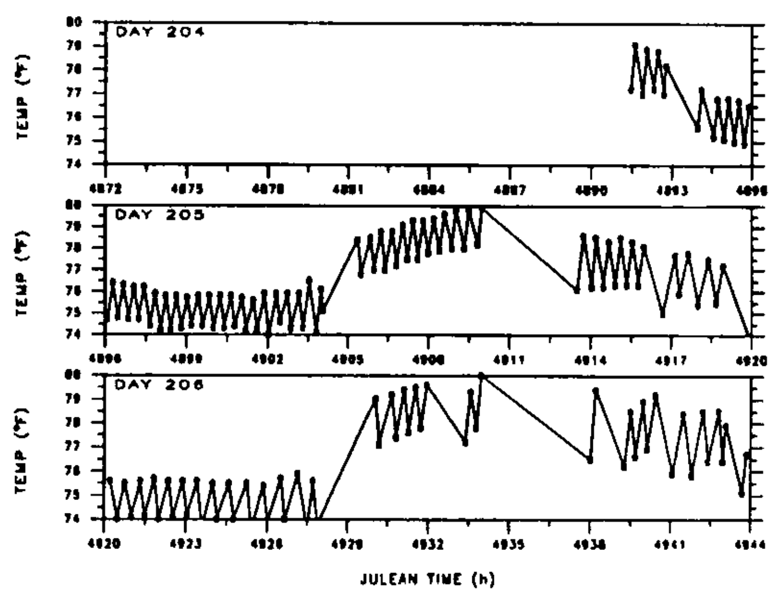
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

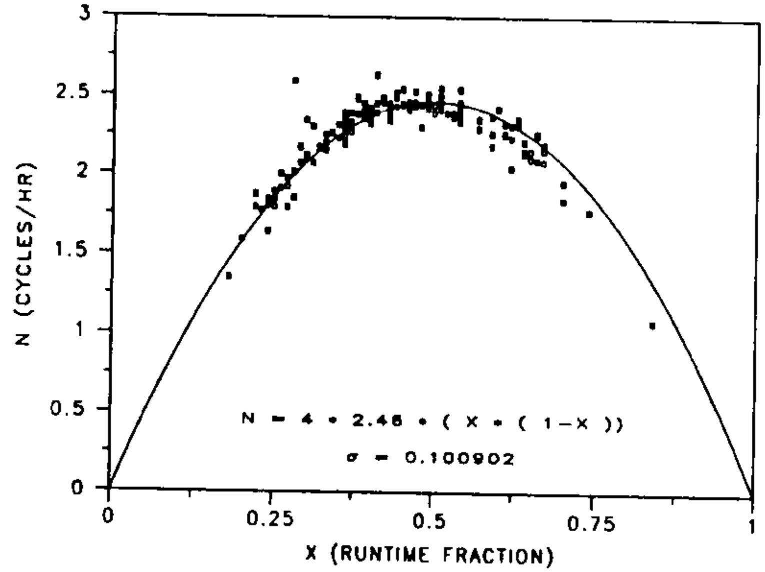


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

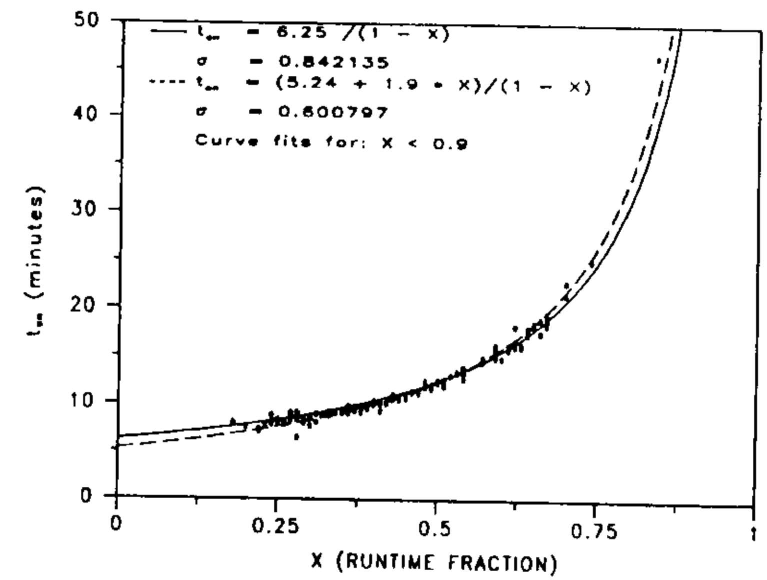


THERMOSTAT DATA: REDMOND

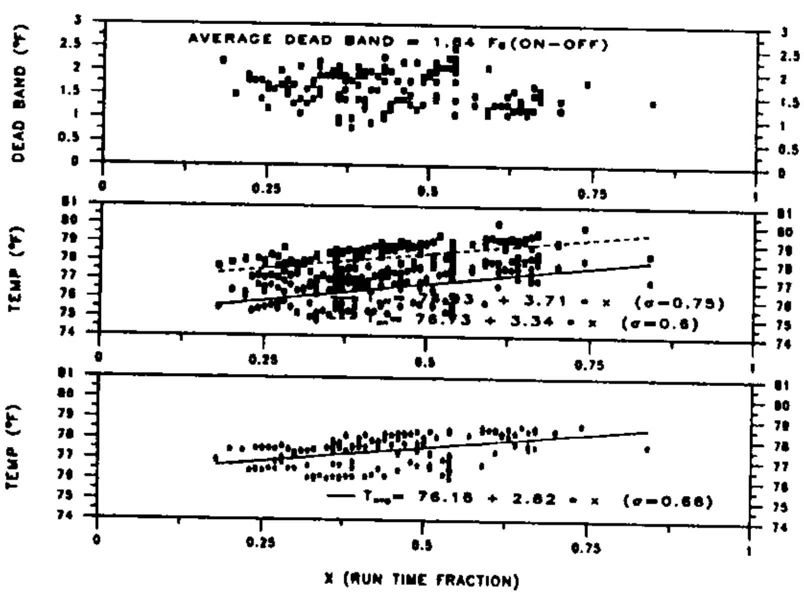
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION:	FAIREY1				
START	DATE: 7/27 OR 208	TIME:	16: 9:20	JULEAN HR:	4986.16
END	DATE: 7/30 OR 211	TIME:	11:26:25	JULEAN HR:	5051.44
ELAPSED TIME:	65.28				

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	77.40	77.37	77.42
AVERAGE RH (%)	58.46	58.12	58.72
HOURS	65.28	28.65	36.64
% HOURS		43.88	56.12

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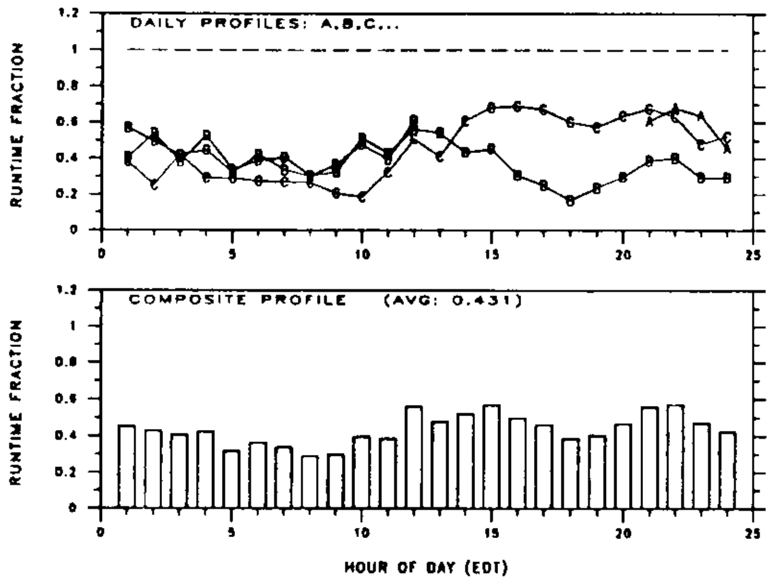
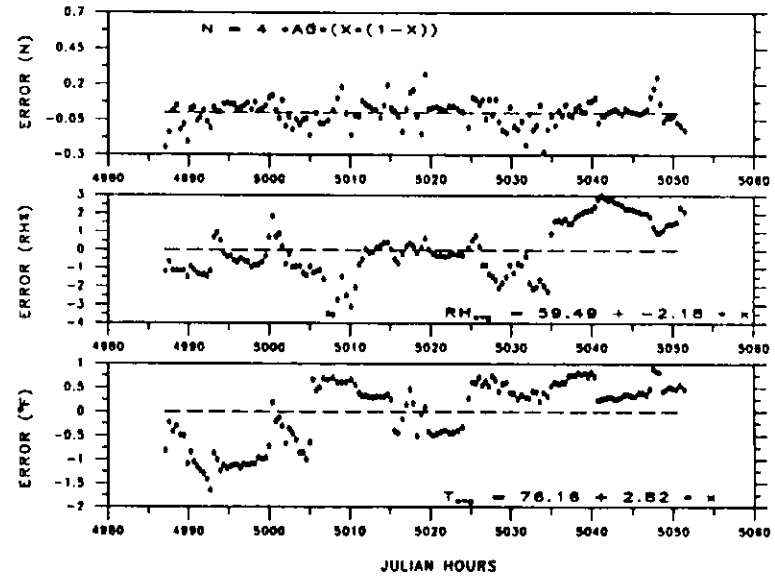
THERMOSTAT DATA: FAIREY1

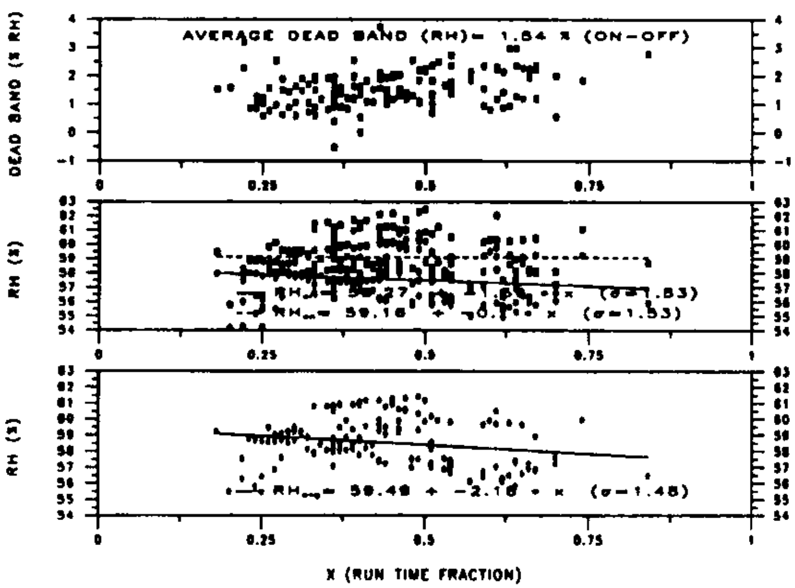
PLOT 4: RUN TIME PROFILES



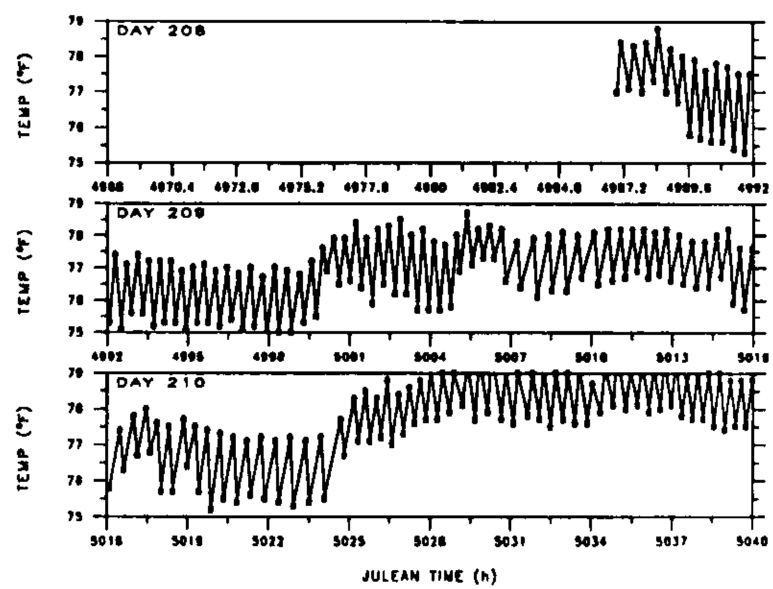
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

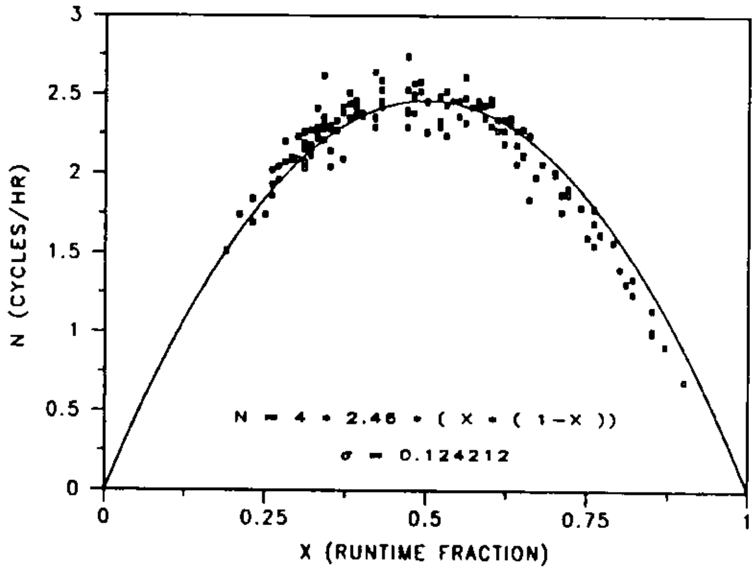


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

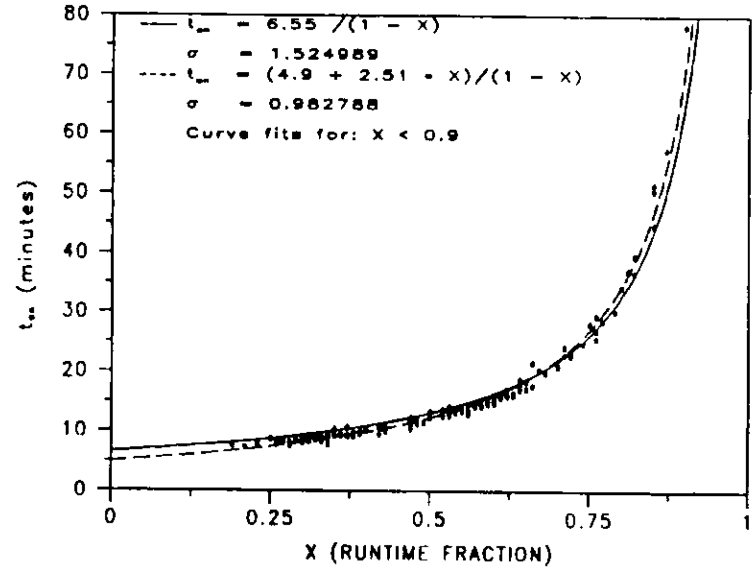


THERMOSTAT DATA: FAIREY1

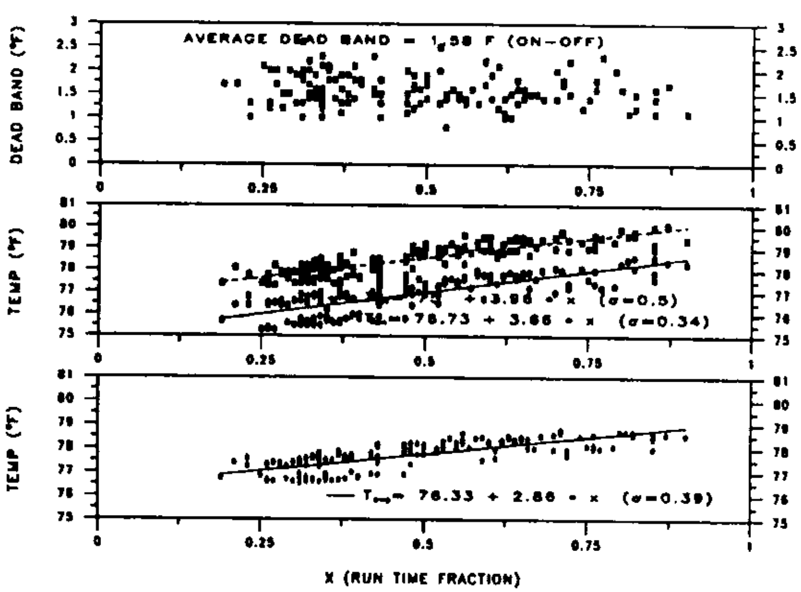
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: FAIREY2
START DATE: 7/30 OR 211 TIME: 20:16:55 JULEAN HR: 5060.28
END DATE: 8/ 2 OR 214 TIME: 17:46: 5 JULEAN HR: 5129.77
ELAPSED TIME: 69.49

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	77.77	77.85	77.69
AVERAGE RH (%)	54.85	54.35	55.38
HOURS	69.49	35.74	33.74
% HOURS		51.44	48.56

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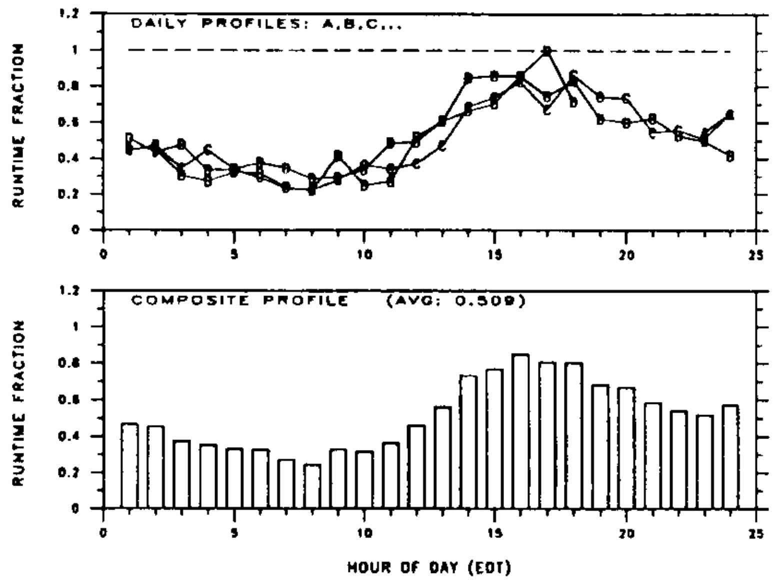
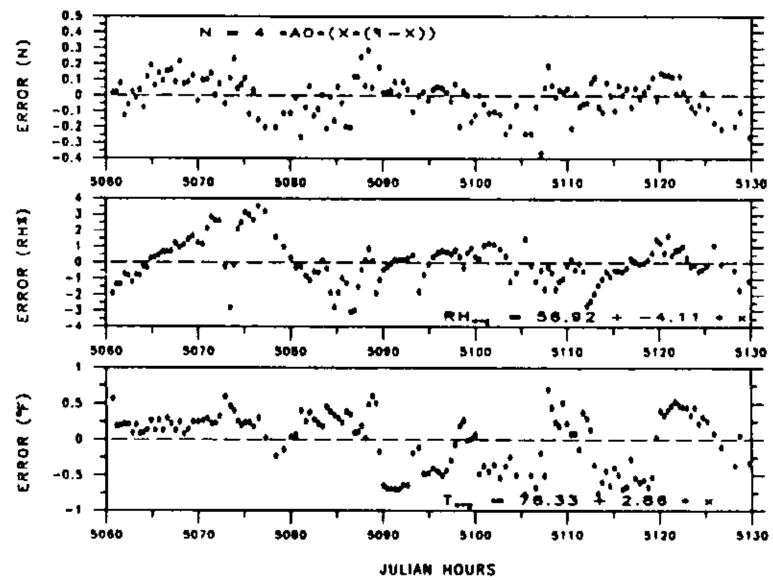
THERMOSTAT DATA: FAIREY2

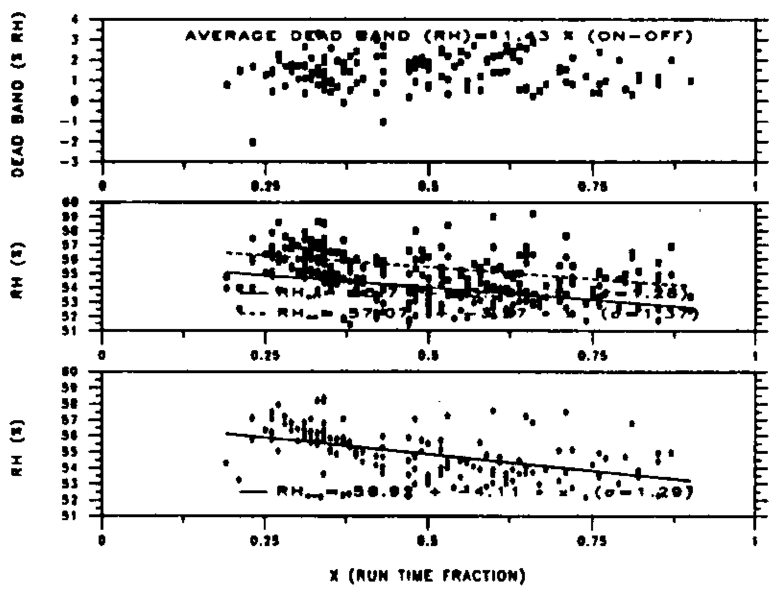
PLOT 4: RUN TIME PROFILES



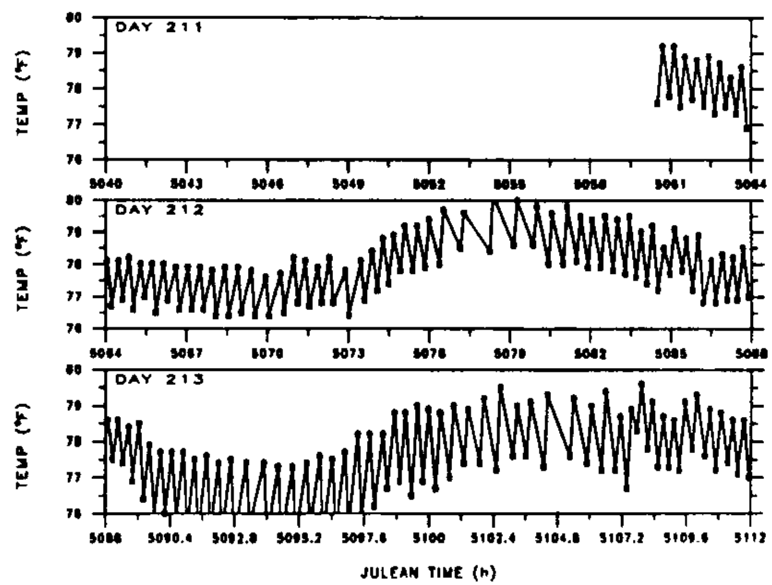
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

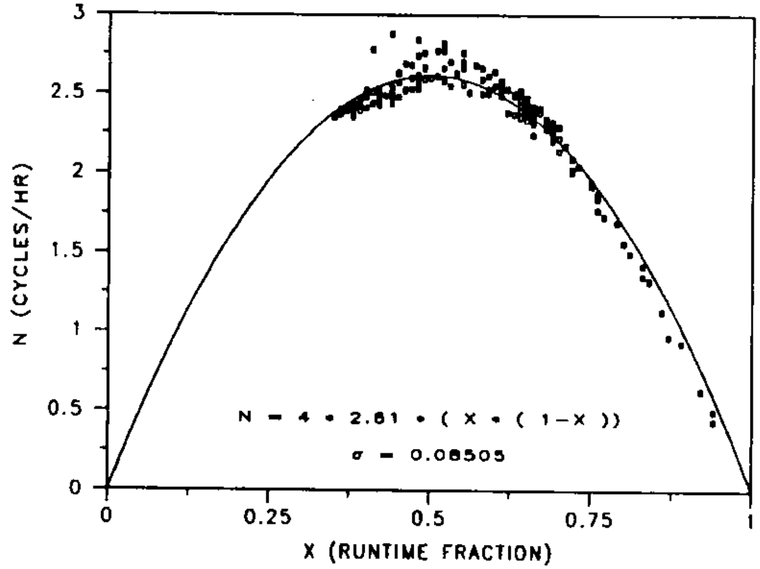


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

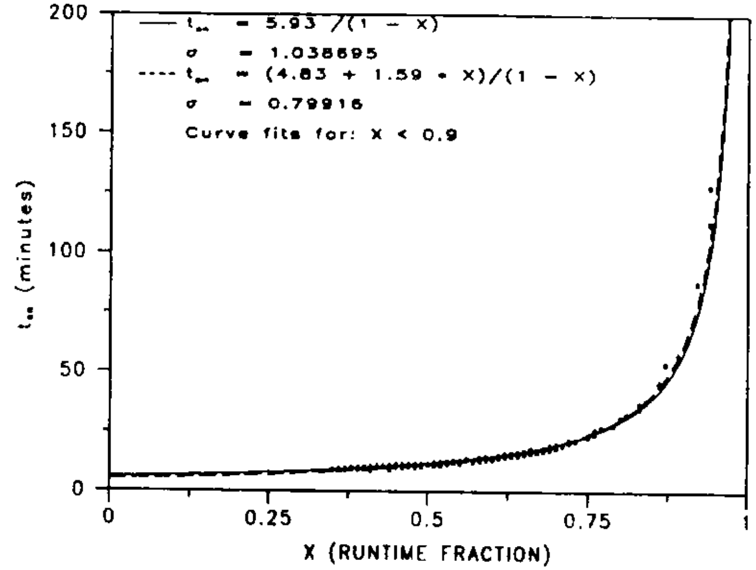


THERMOSTAT DATA: FAIREY2

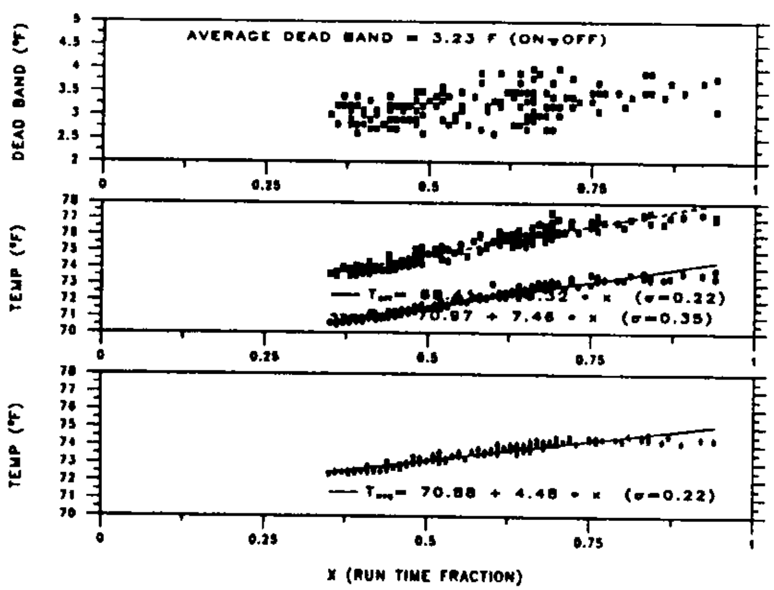
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: KETTLES

START	DATE: 8/ 4 OR 216	TIME:	9:19:55	JULEAN HR:	5169.33
END	DATE: 8/ 7 OR 219	TIME:	7:32:55	JULEAN HR:	5239.55
ELAPSED TIME:	70.22				

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	73.60	73.29	74.10
AVERAGE RH (%)	49.80	49.78	49.85
HOURS	70.22	43.70	26.52
% HOURS		62.23	37.77

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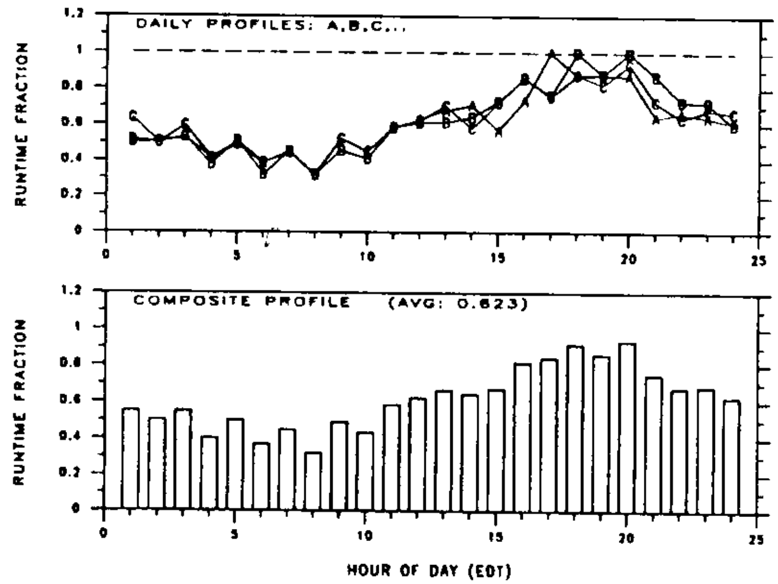
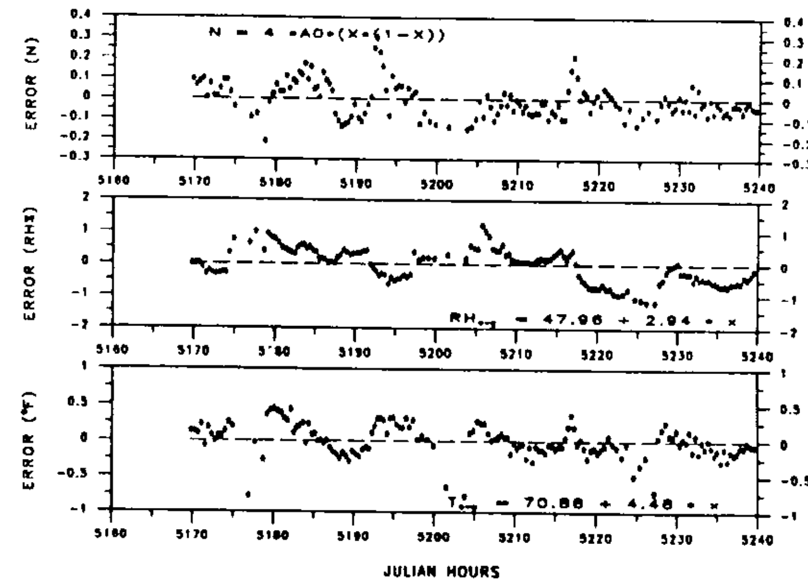
THERMOSTAT DATA: KETTLES

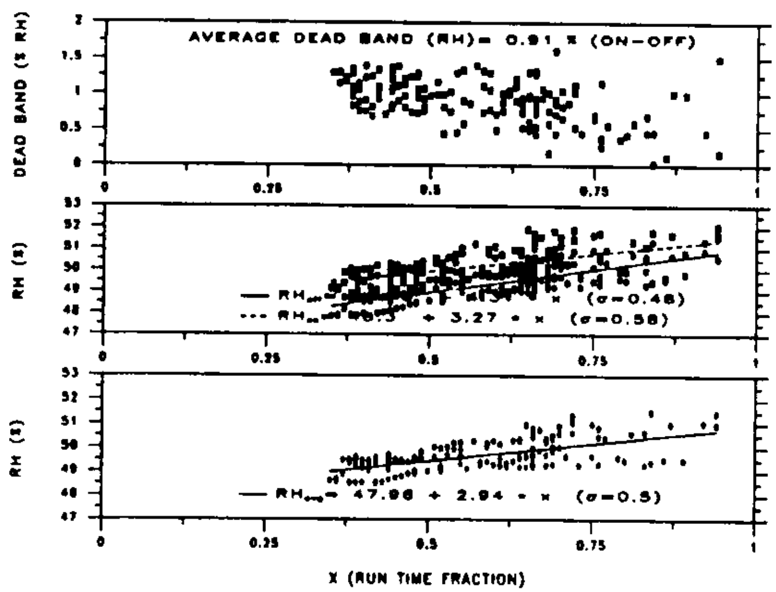
PLOT 4: RUN TIME PROFILES



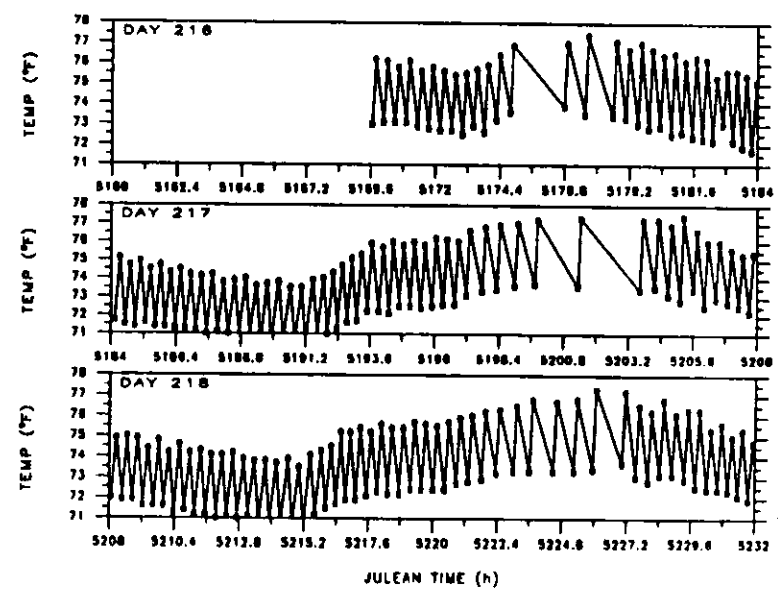
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

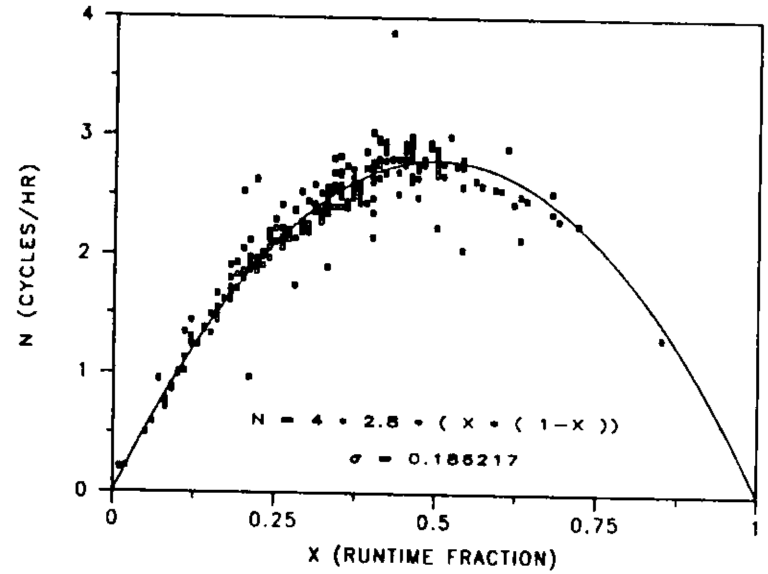


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

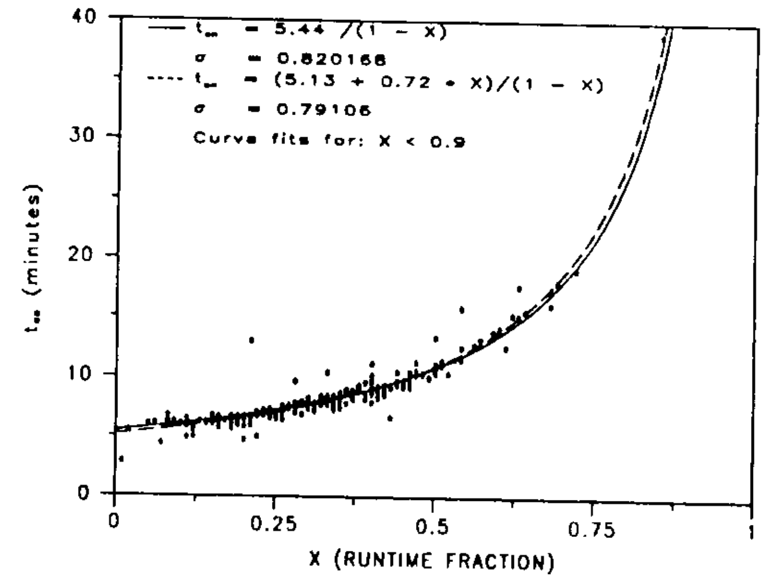


THERMOSTAT DATA: KETTLES

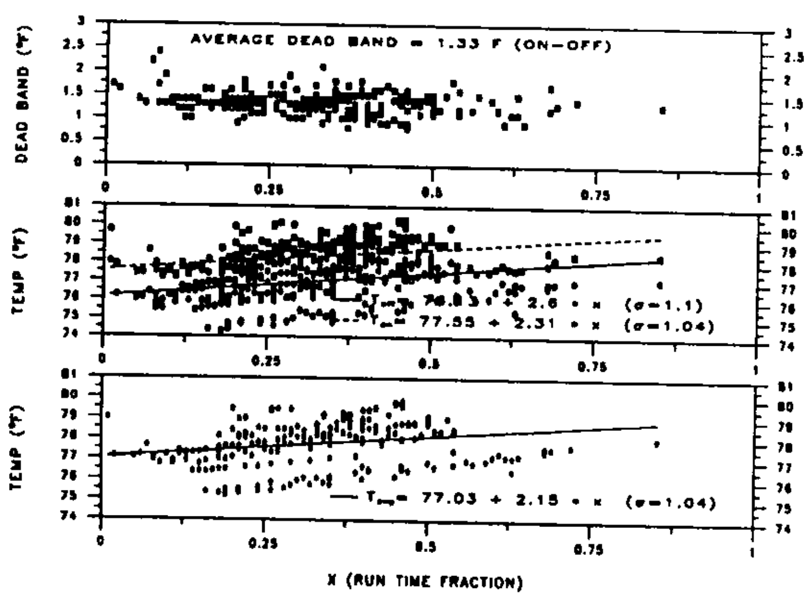
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: MELODY
START DATE: 8/ 8 OR 220 TIME: 18: 1:25 JULEAN HR: 5274.02
END DATE: 8/13 OR 225 TIME: 23:19:20 JULEAN HR: 5399.32
ELAPSED TIME: 125.30

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	77.65	77.85	77.57
AVERAGE RH (%)	56.45	55.30	56.89
HOURS	125.30	34.35	90.95
% HOURS		27.41	72.59

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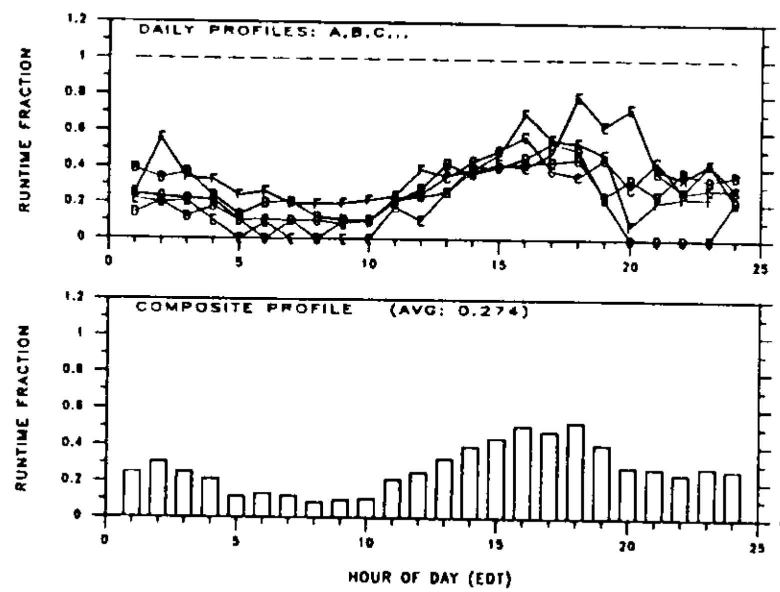
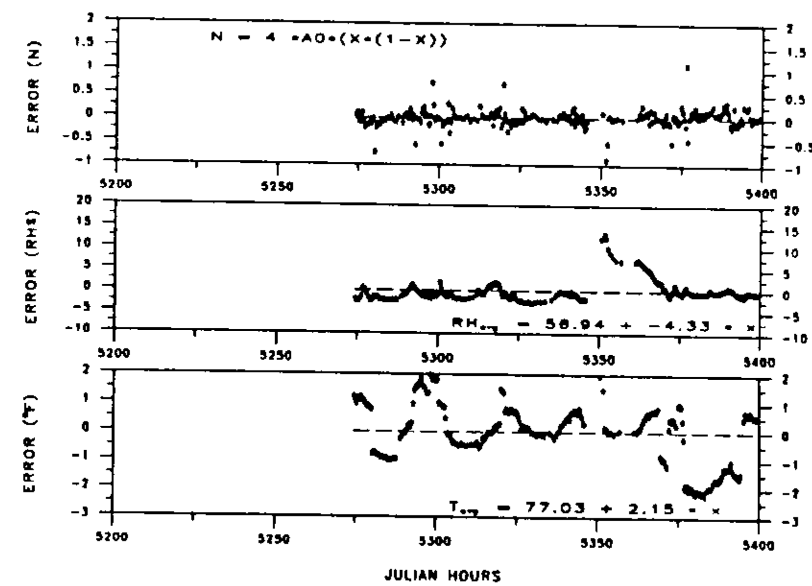
THERMOSTAT DATA: MELODY

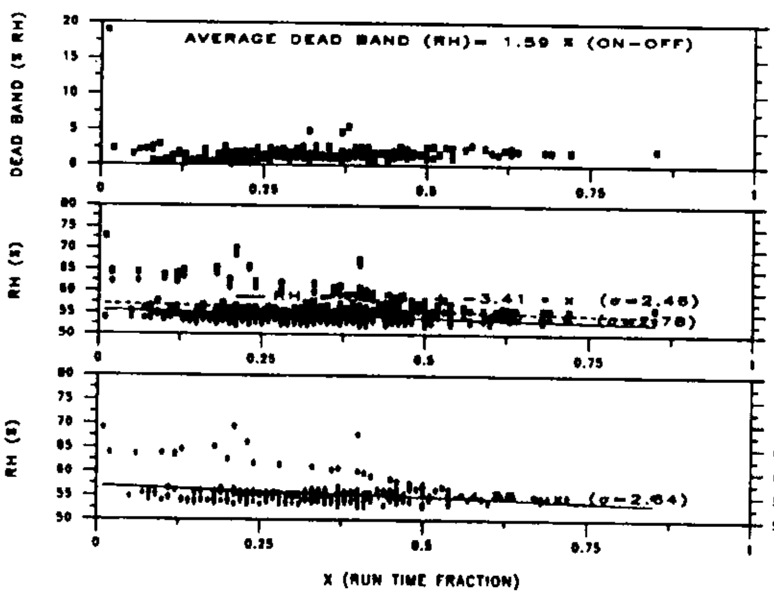
PLOT 4: RUN TIME PROFILES



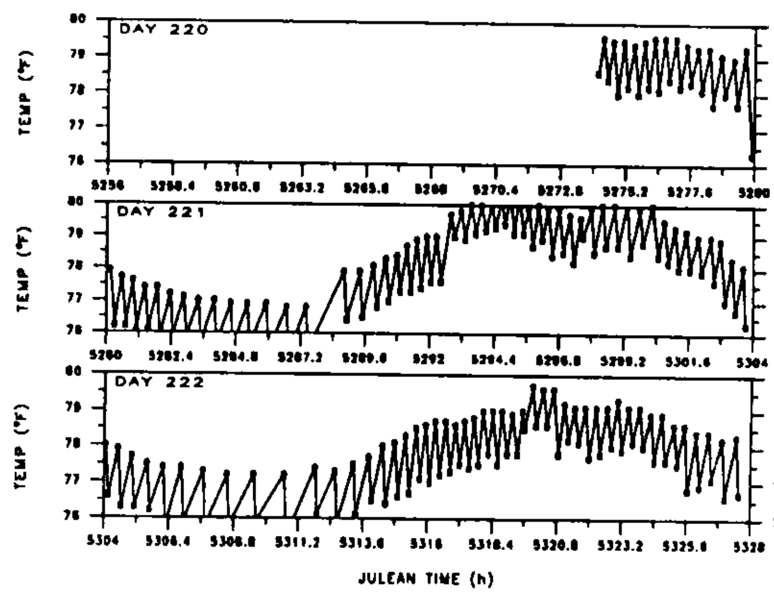
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

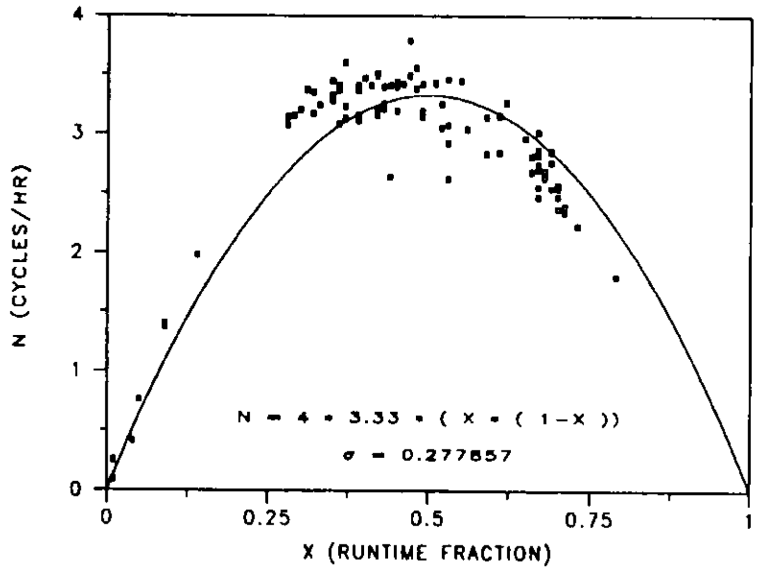


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

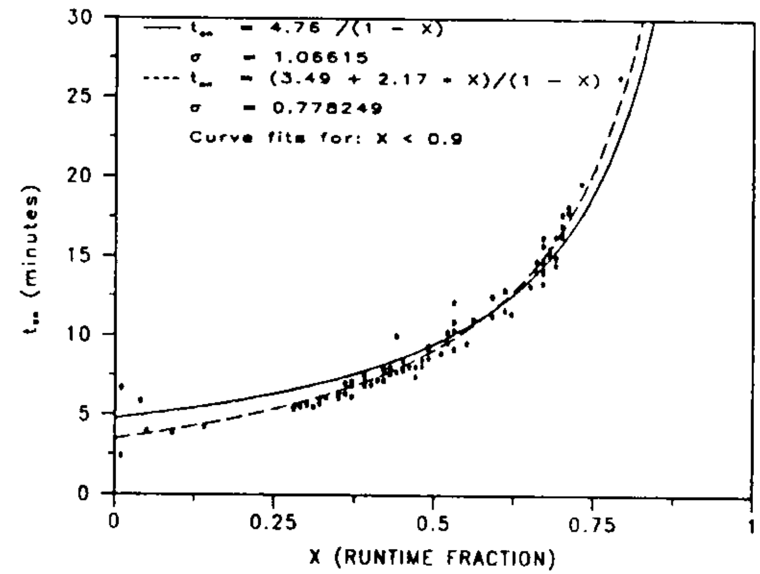


THERMOSTAT DATA: MELODY

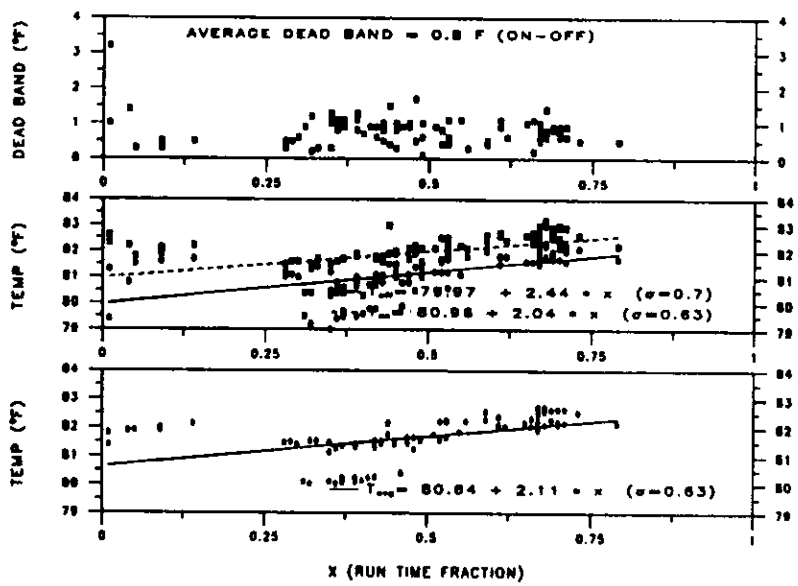
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: DHERE

START DATE: 8/14 OR 226 TIME: 17:58:50 JULEAN HR: 5417.98

END DATE: 8/16 OR 228 TIME: 18:12:55 JULEAN HR: 5466.22

ELAPSED TIME: 48.23

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	81.66	81.89	81.55
AVERAGE RH (%)	59.89	59.73	59.96
HOURS	48.23	15.13	33.11
% HOURS		31.36	68.64

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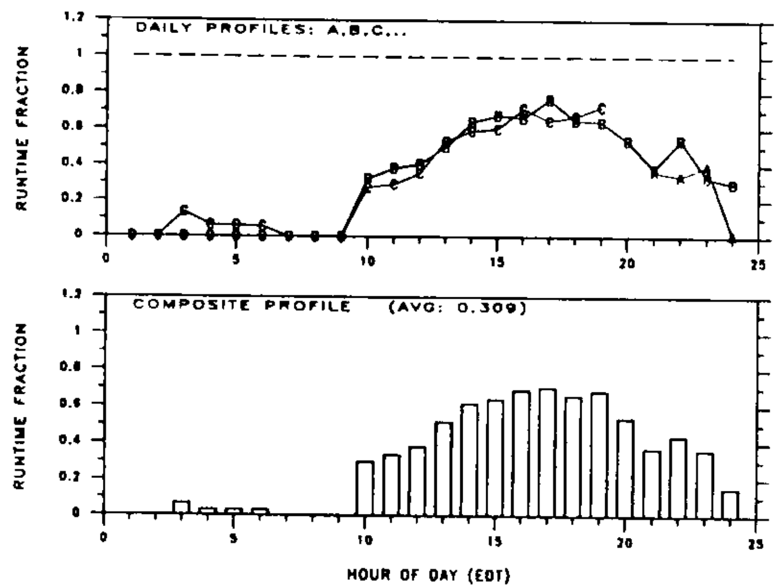
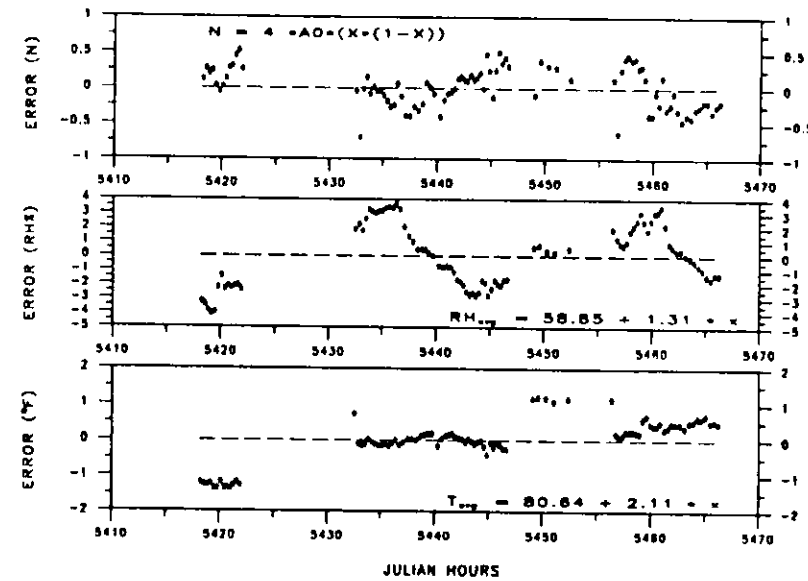
THERMOSTAT DATA: DHERE

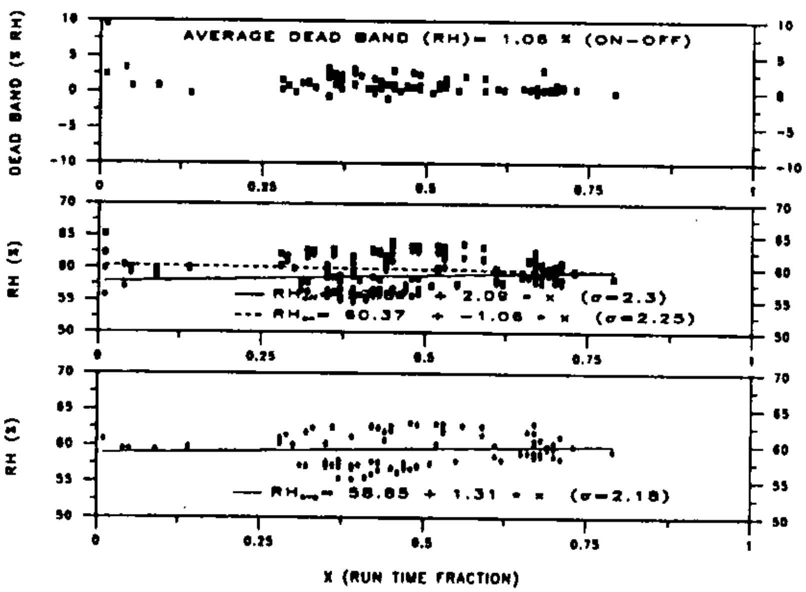
PLOT 4: RUN TIME PROFILES



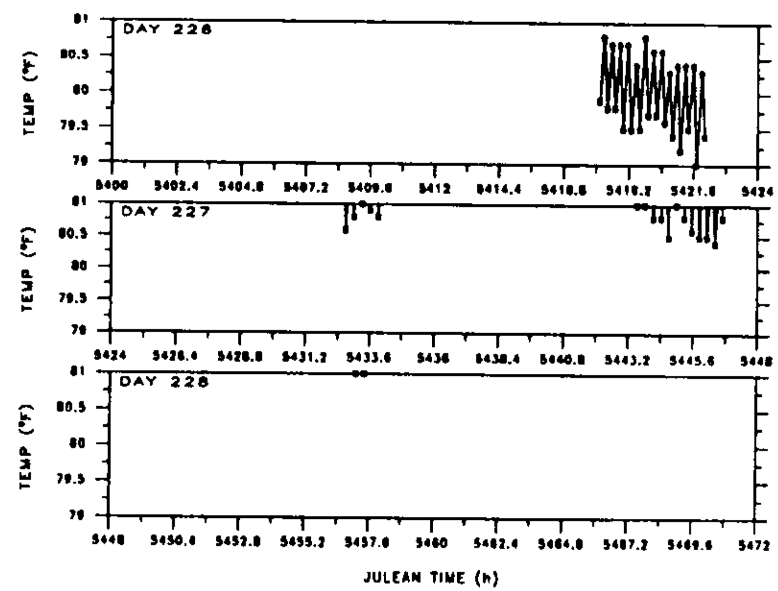
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

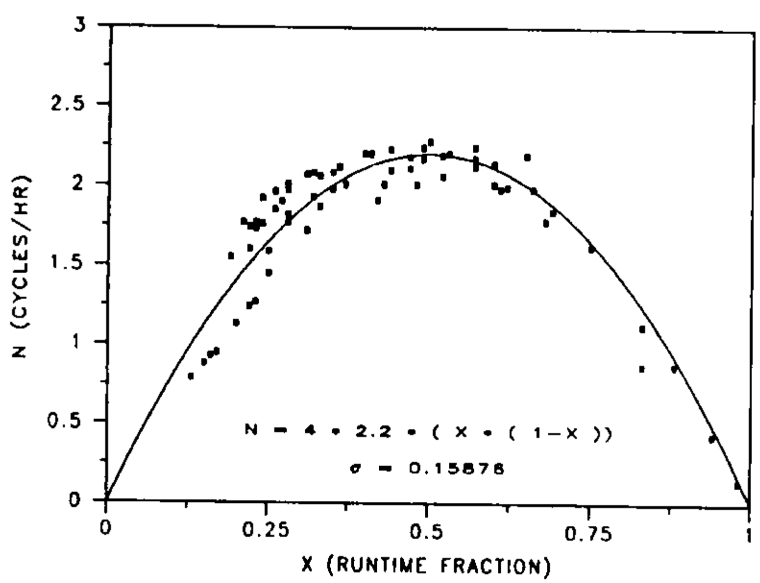


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

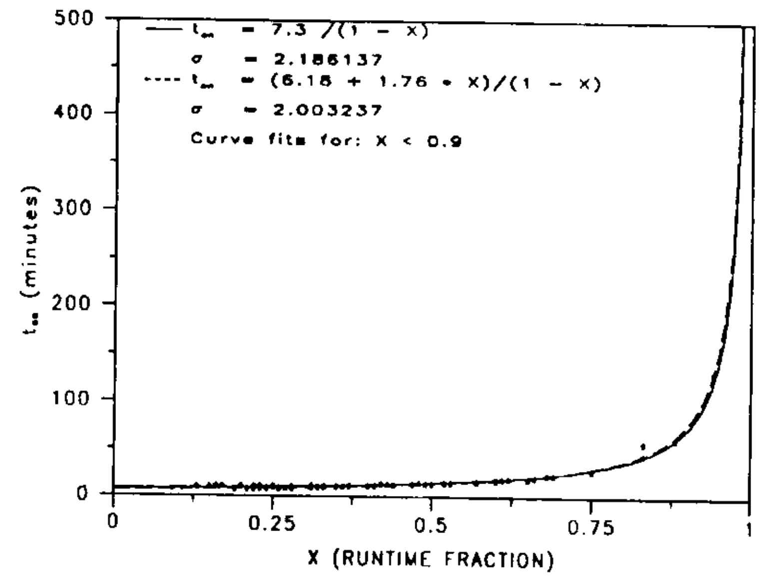


THERMOSTAT DATA: DHERE

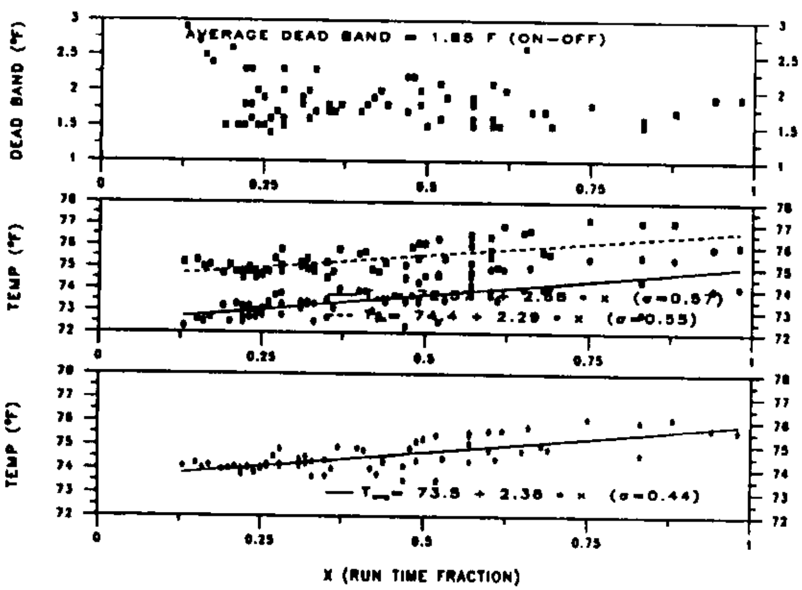
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: DUTTON

START	DATE: 8/18 OR 230	TIME: 17:16:15	JULEAN HR:	5513.27
END	DATE: 8/20 OR 232	TIME: 17:28:15	JULEAN HR:	5561.47
ELAPSED TIME:	48.20			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	74.69	75.00	74.37
AVERAGE RH (%)	70.03	67.00	73.19
HOURS	48.20	24.63	23.57
% HOURS		51.10	48.90

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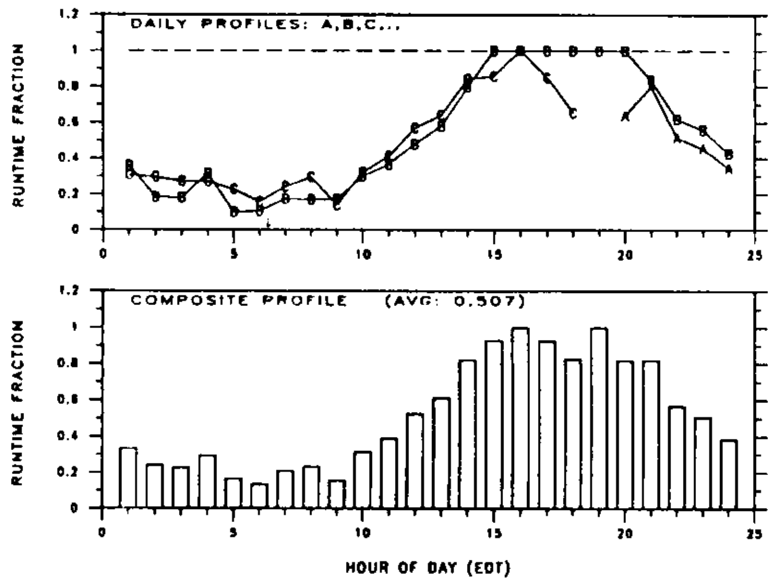
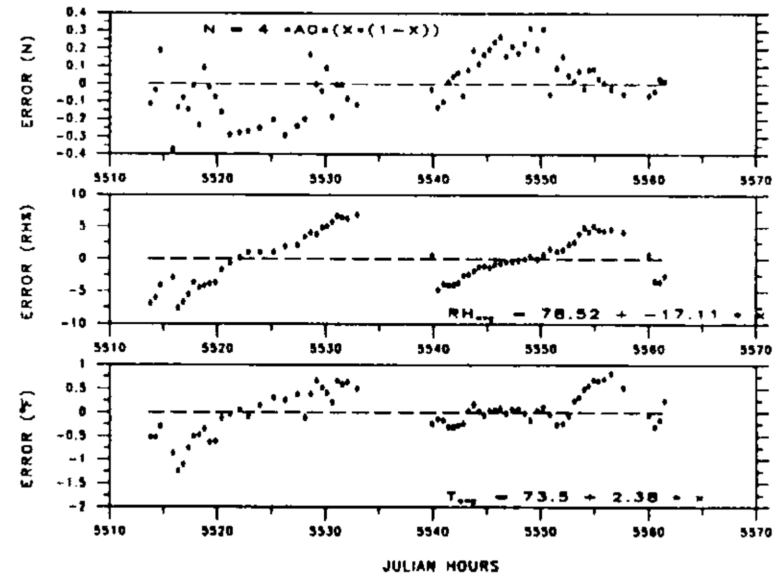
THERMOSTAT DATA: DUTTON

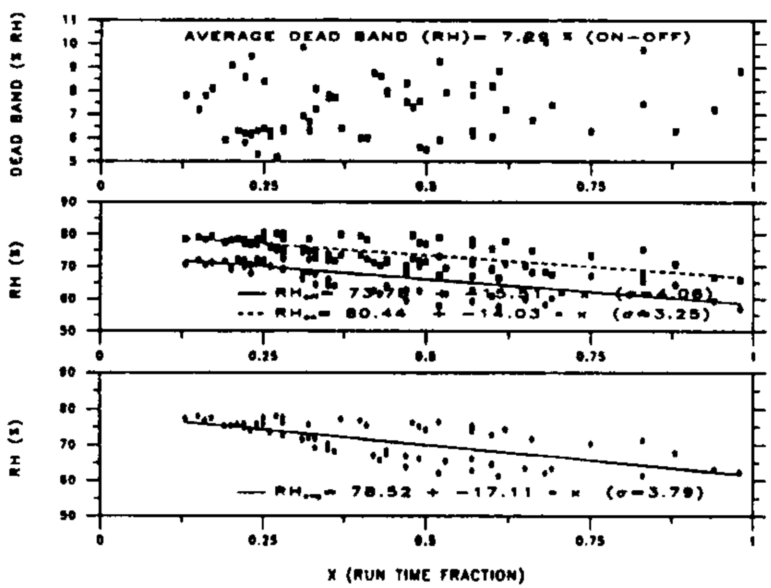
PLOT 4: RUN TIME PROFILES



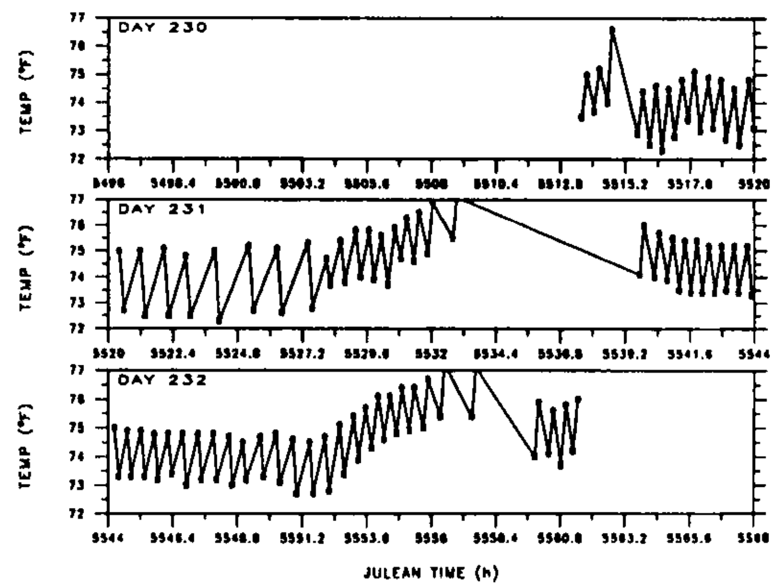
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

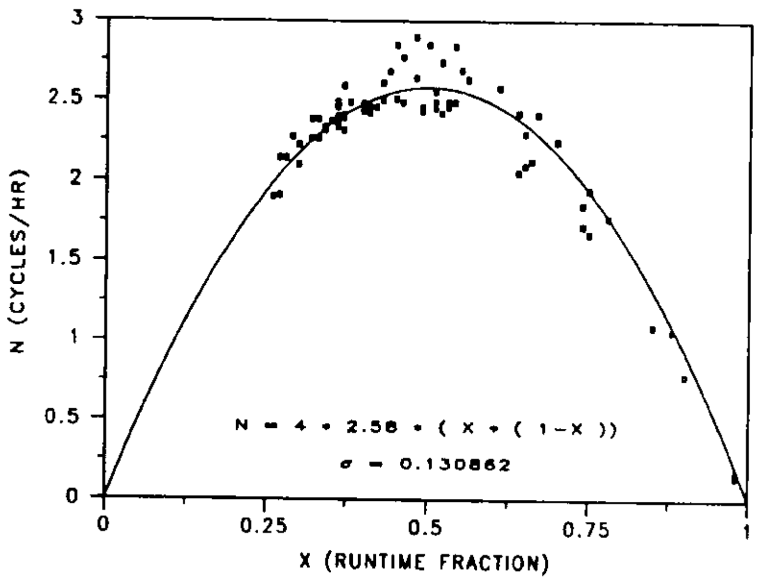


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

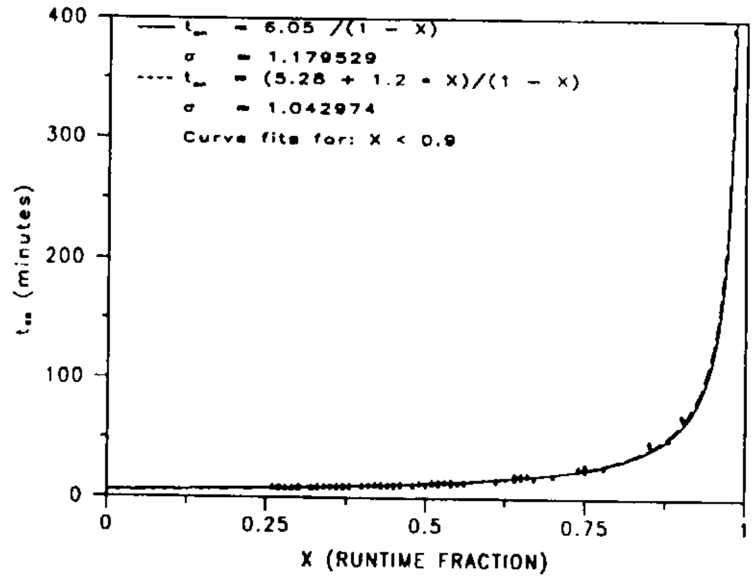


THERMOSTAT DATA: DUTTON

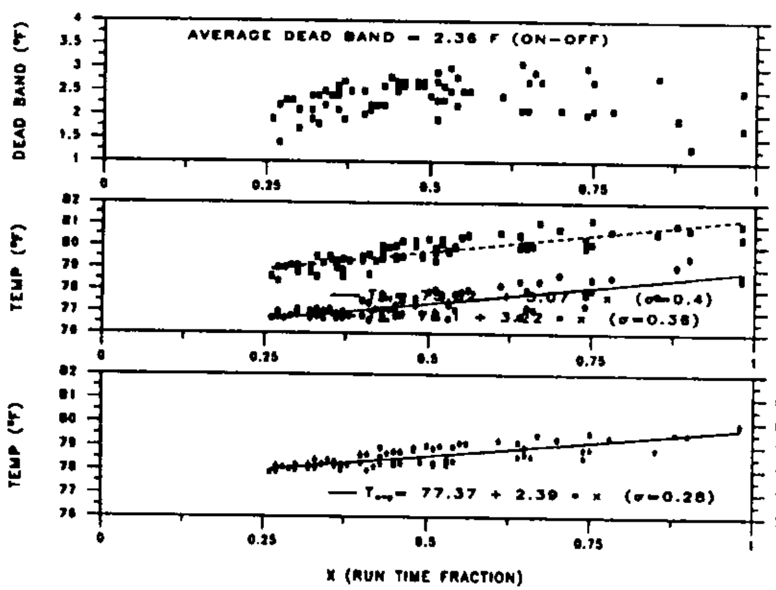
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: DERNIER

START	DATE: 8/21 OR 233	TIME: 22:39:20	JULEAN HR:	5590.66
END	DATE: 8/23 OR 235	TIME: 19:55:25	JULEAN HR:	5635.92
ELAPSED TIME:	45.27			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	78.92	78.98	78.86
AVERAGE RH (%)	63.53	63.13	64.23
HOURS	45.27	28.75	16.52
% HOURS		63.52	36.48

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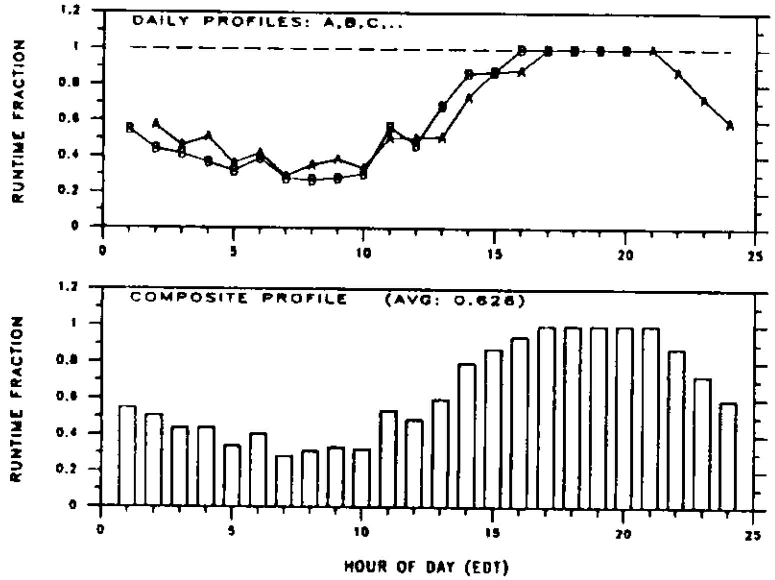
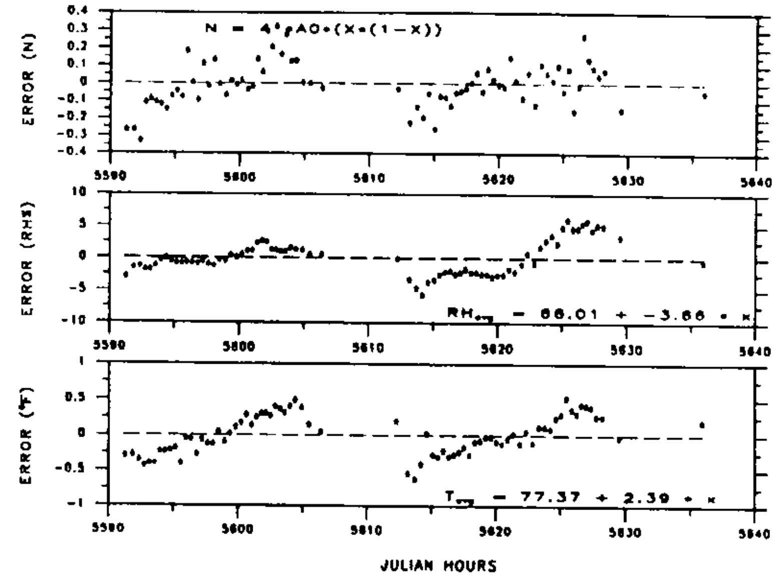
THERMOSTAT DATA: DERNIER

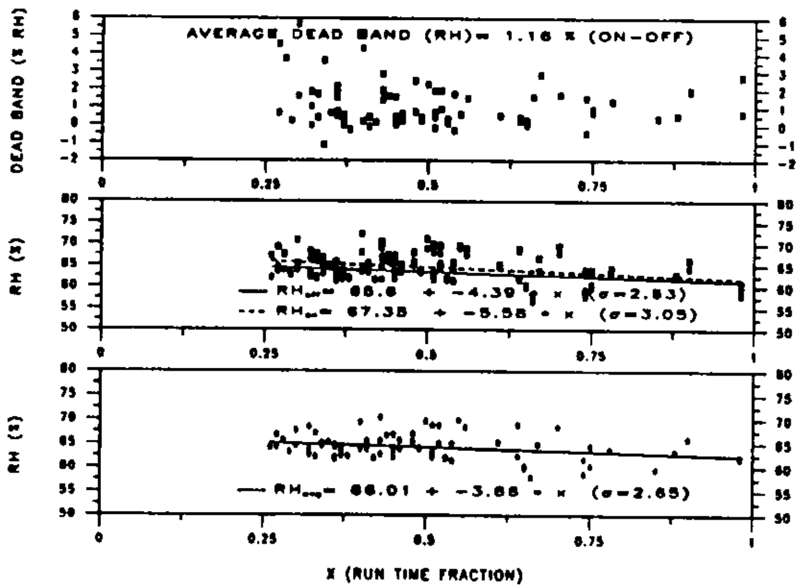
PLOT 4: RUN TIME PROFILES



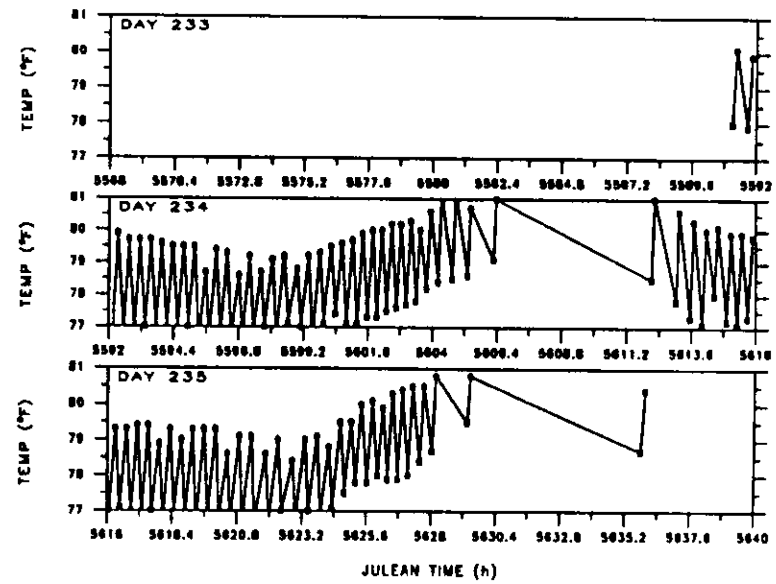
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

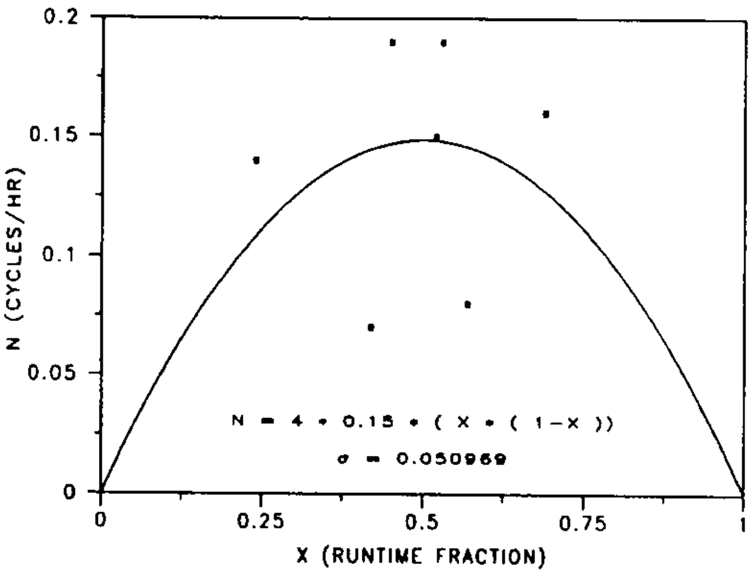


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

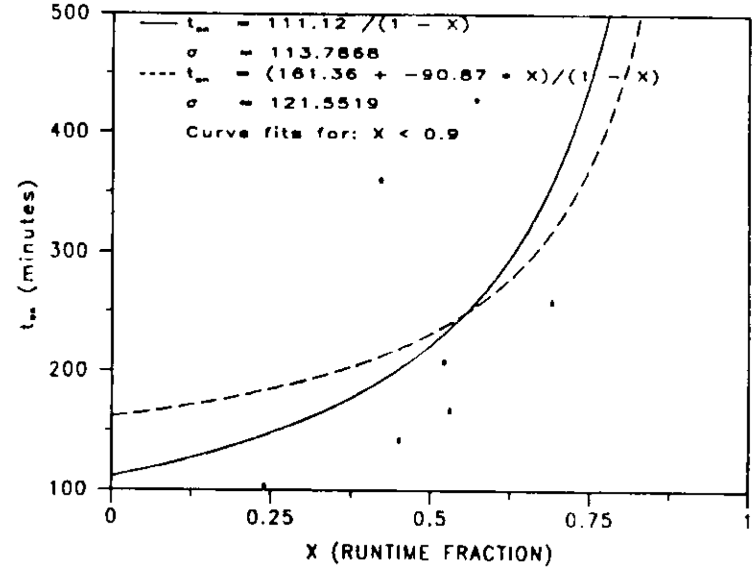


THERMOSTAT DATA: DERNIER

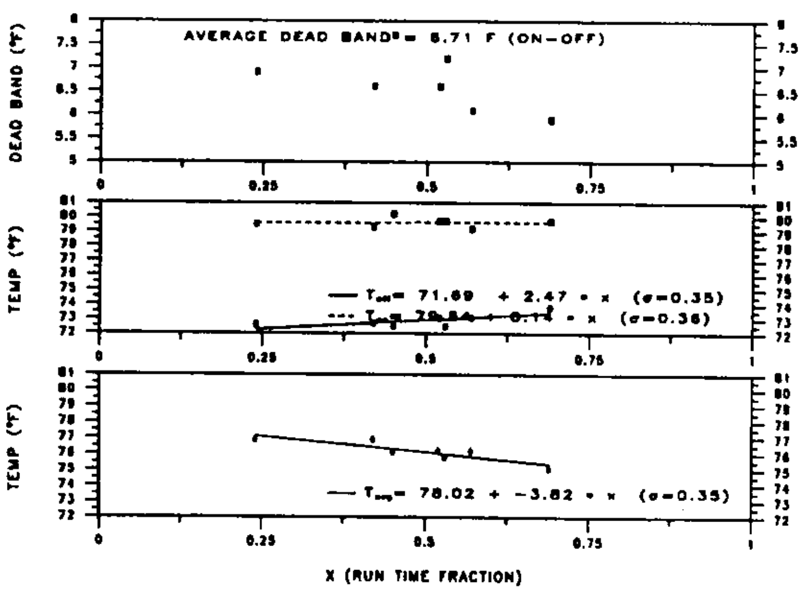
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: VIEIRA1
START DATE: 8/25 OR 237 TIME: 8:54:50 JULEAN HR: 5672.91
END DATE: 8/27 OR 239 TIME: 18:19: 0 JULEAN HR: 5730.32
ELAPSED TIME: 57.40

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.27	74.37	78.05
AVERAGE RH (%)	56.77	56.27	57.23
HOURS	57.40	27.81	29.59
% HOURS		48.45	51.55

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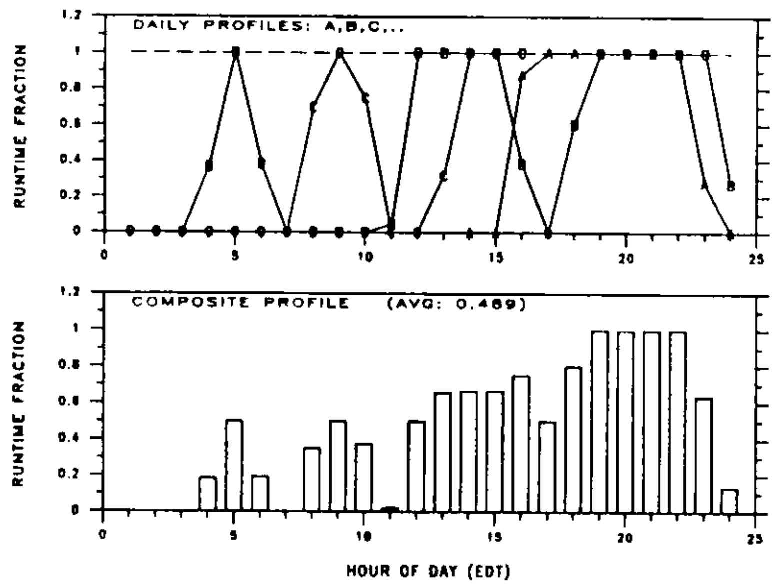
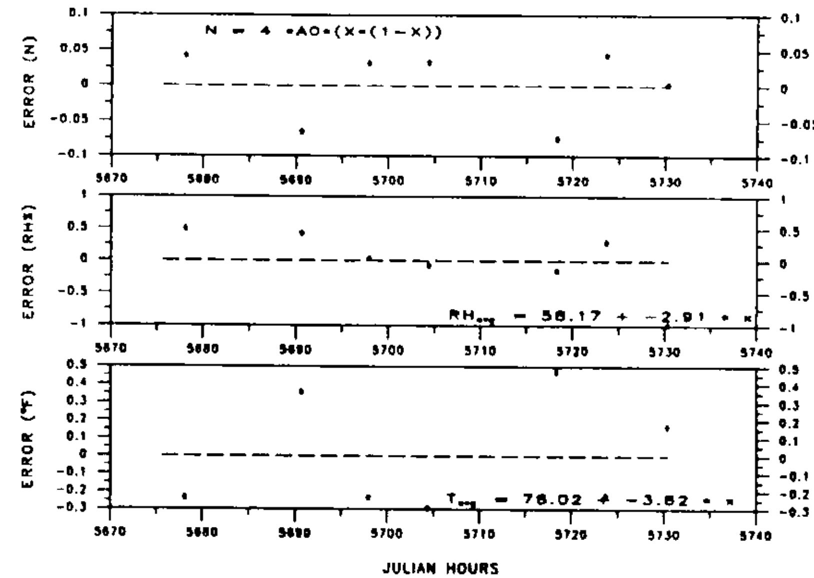
THERMOSTAT DATA: VIEIRA1

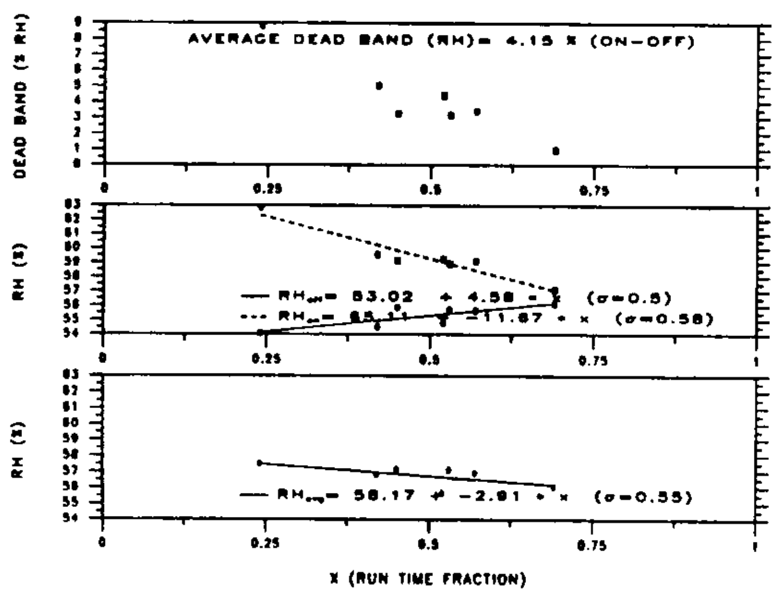
PLOT 4: RUN TIME PROFILES



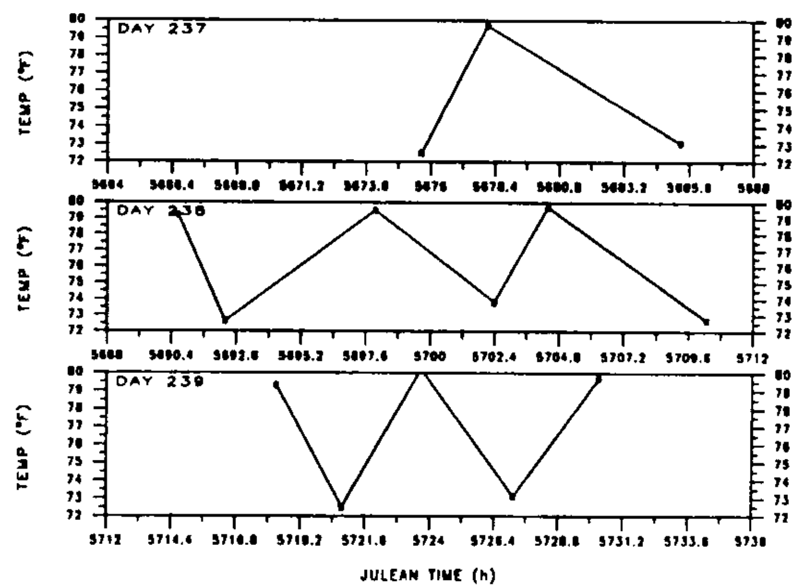
PLOT 5: ERROR ANALYSIS



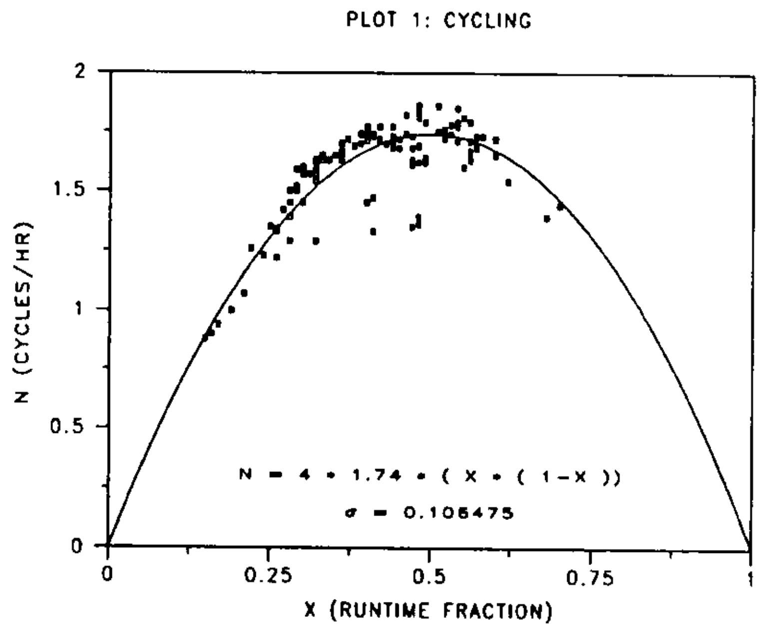
PLOT 6: HUMIDITY

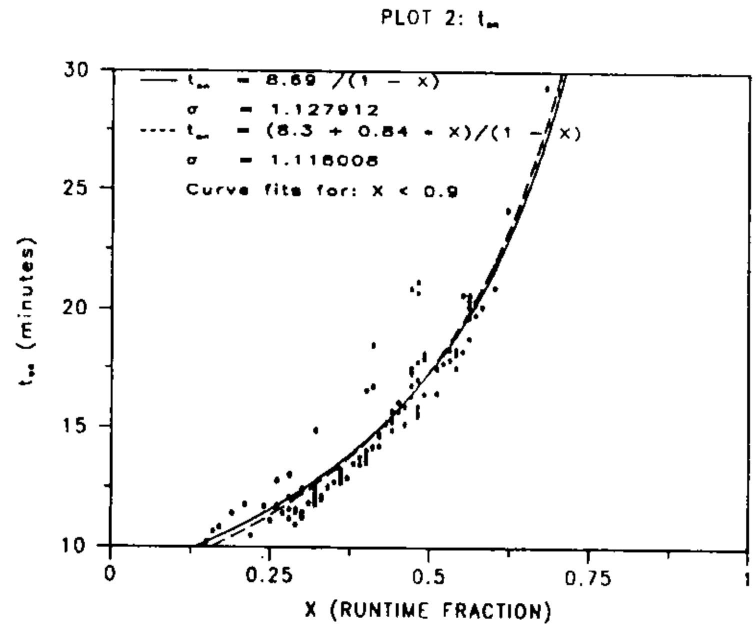


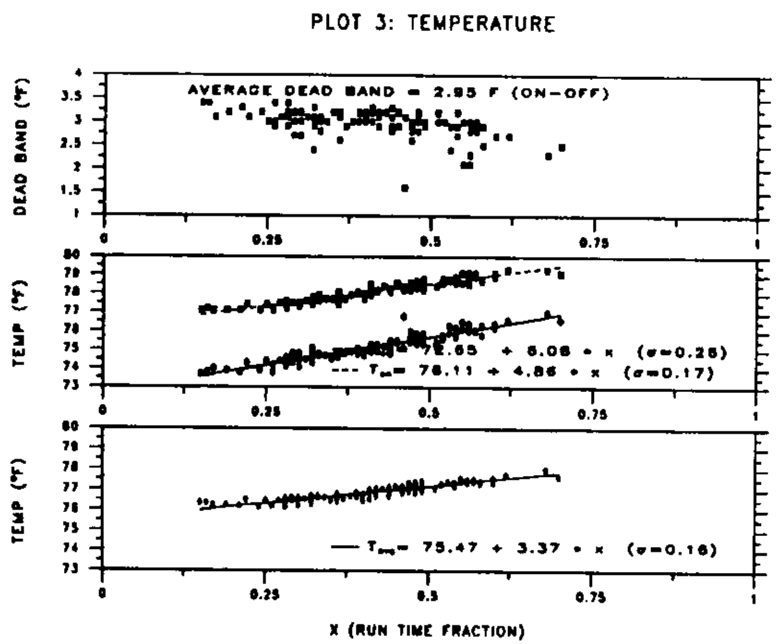
PLOT 7: TEMPERATURE VS TIME (3 DAYS)



THERMOSTAT DATA: VIEIRA1







SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: VIEIRA2

START	DATE: 8/27 OR 239	TIME: 22:52:45	JULEAN HR:	5734.88
END	DATE: 8/30 OR 242	TIME: 22:12:25	JULEAN HR:	5806.21
ELAPSED TIME:	71.33			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.82	76.28	77.18
AVERAGE RH (%)	55.43	55.03	55.69
HOURS	71.33	28.43	42.90
% HOURS		39.85	60.15

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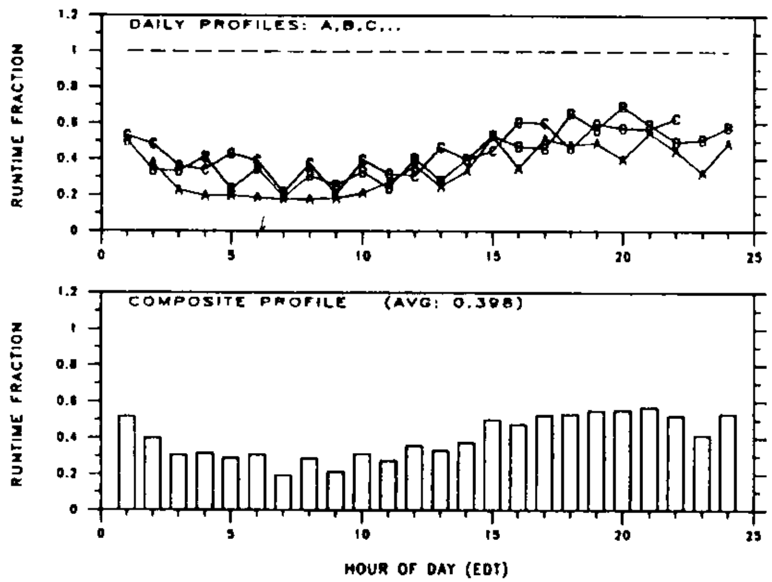
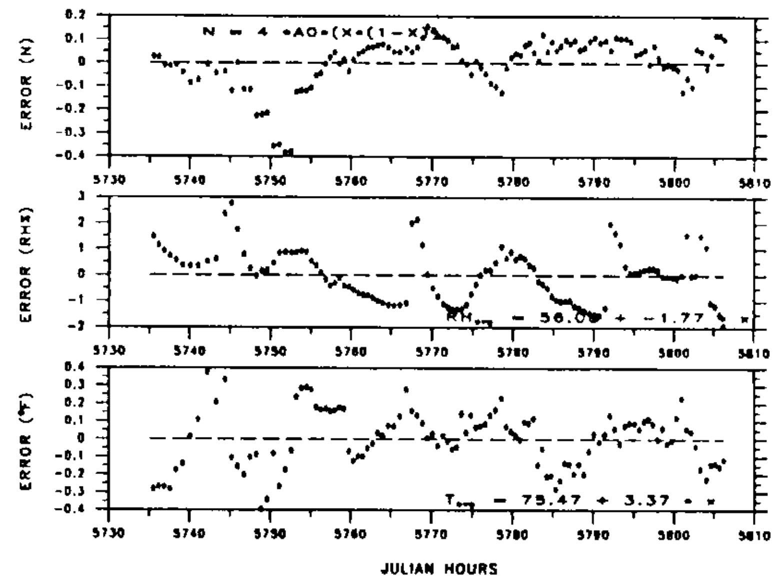
THERMOSTAT DATA: VIEIRA2

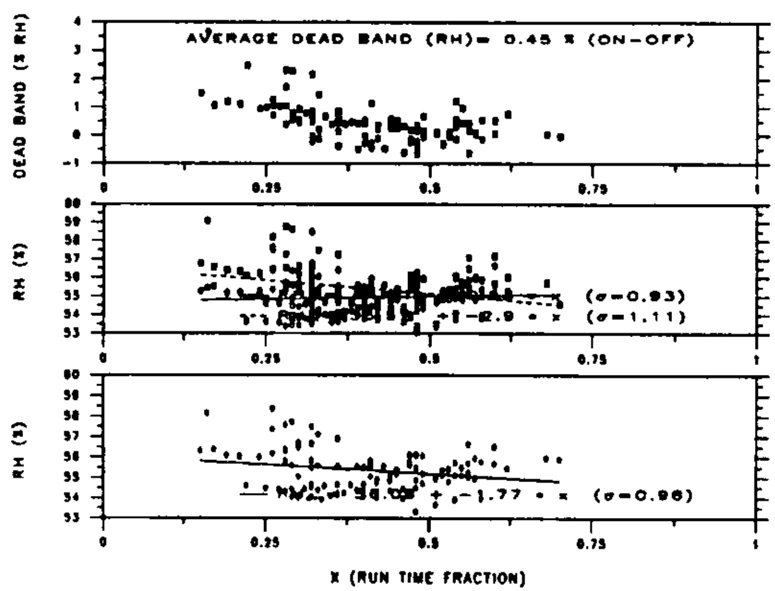
PLOT 4: RUN TIME PROFILES



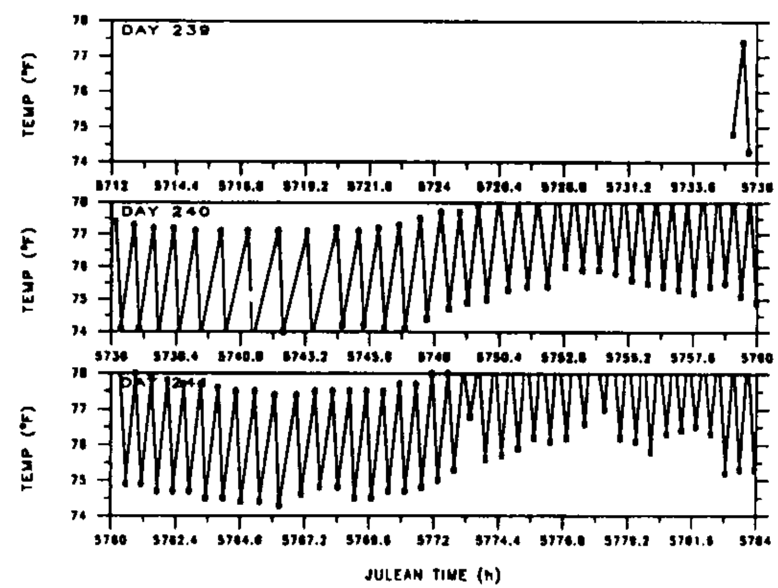
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

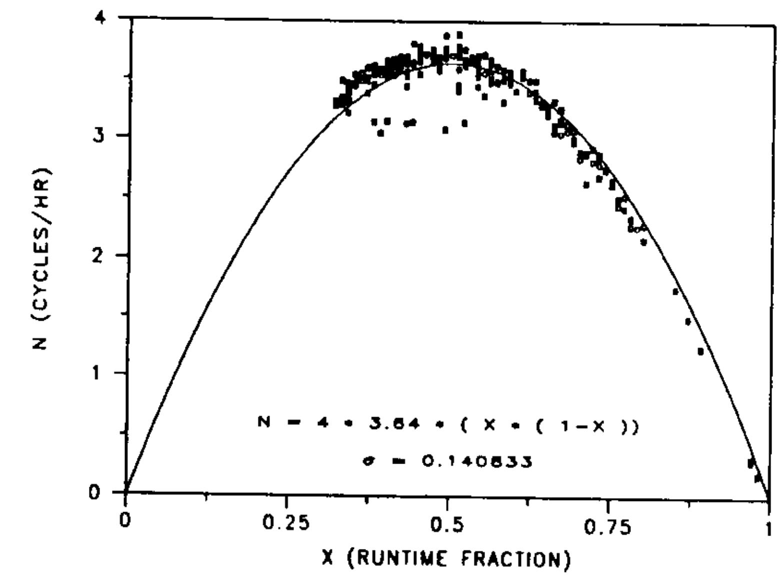


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

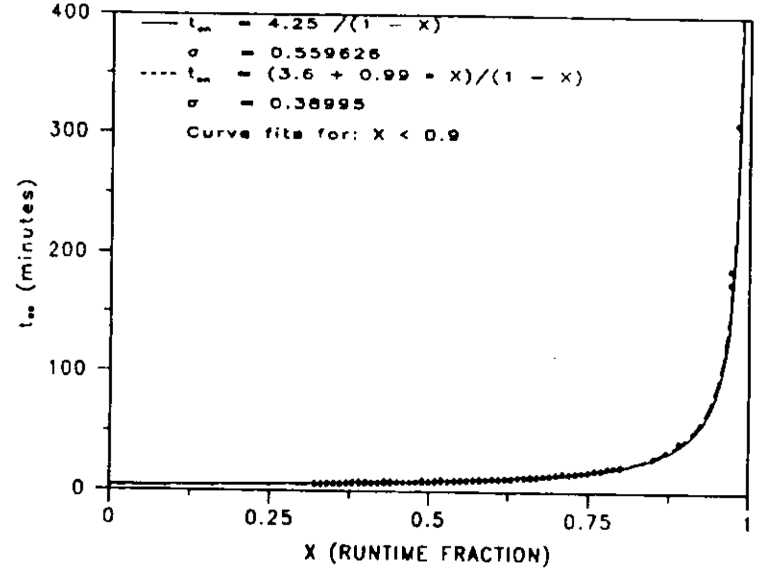


THERMOSTAT DATA: VIEIRA2

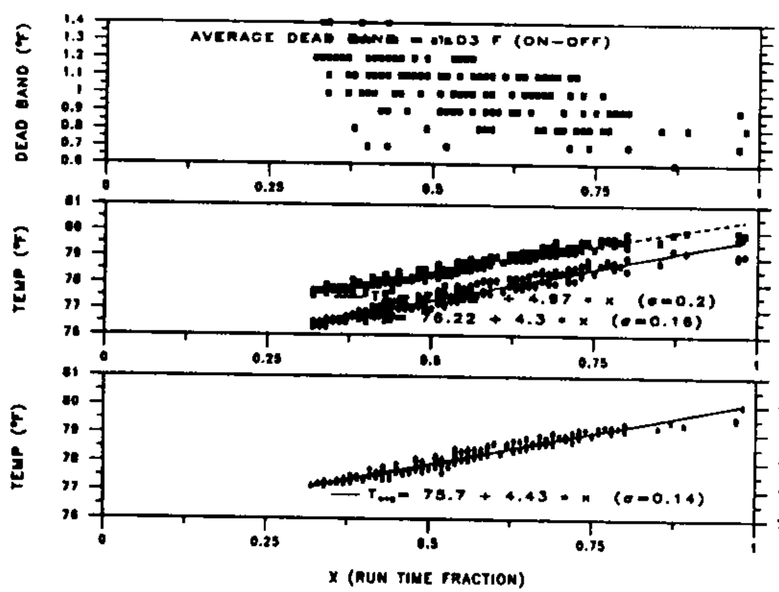
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: DUMMER
START DATE: 9/ 0 OR 243 TIME: 20:53:15 JULEAN HR: 5826.89
END DATE: 9/ 3 OR 246 TIME: 19:15:35 JULEAN HR: 5899.26
ELAPSED TIME: 70.37

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	78.41	78.64	78.02
AVERAGE RH (%)	41.36	41.34	41.38
HOURS	70.37	43.73	26.64
% HOURS		62.14	37.86

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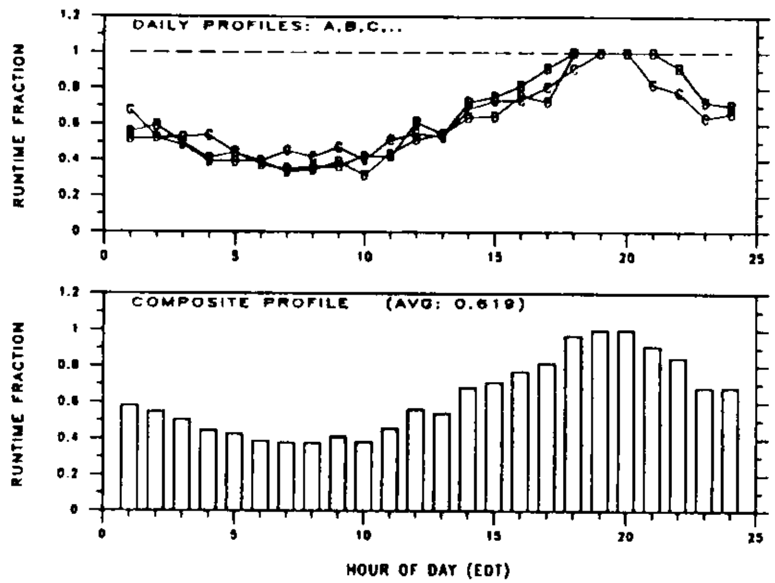
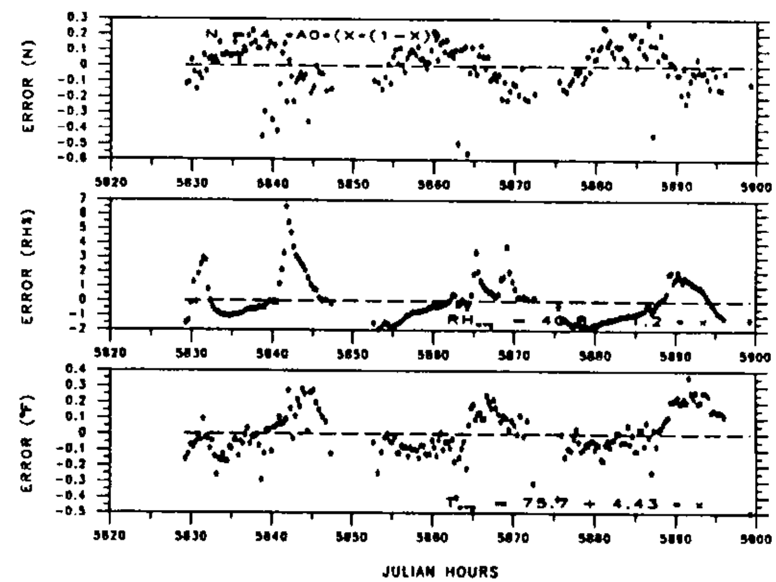
THERMOSTAT DATA: DUMMER

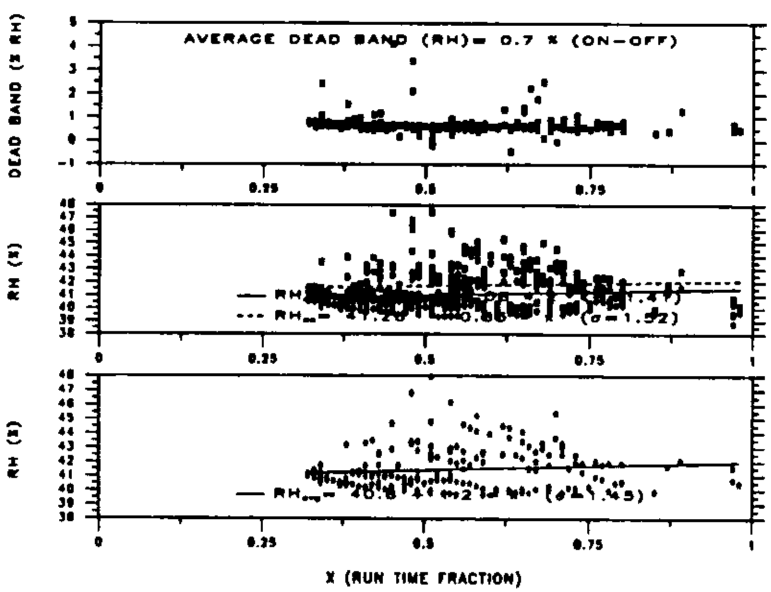
PLOT 4: RUN TIME PROFILES



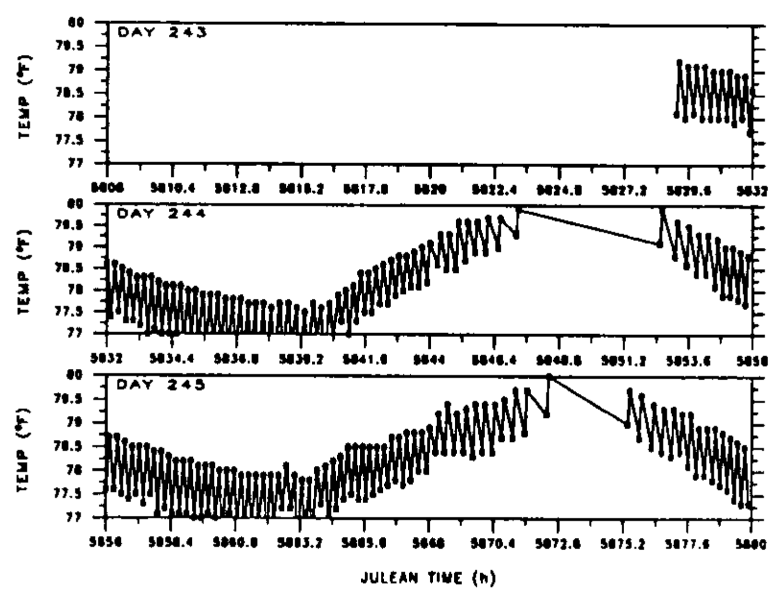
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

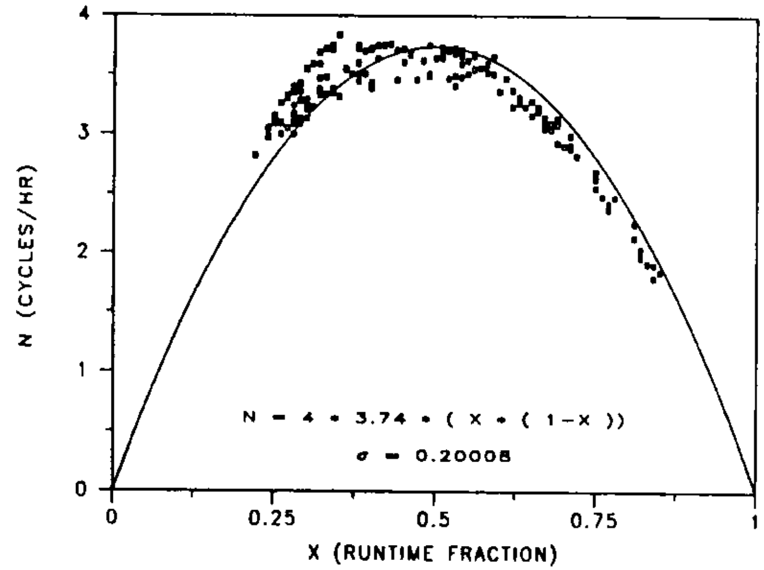


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

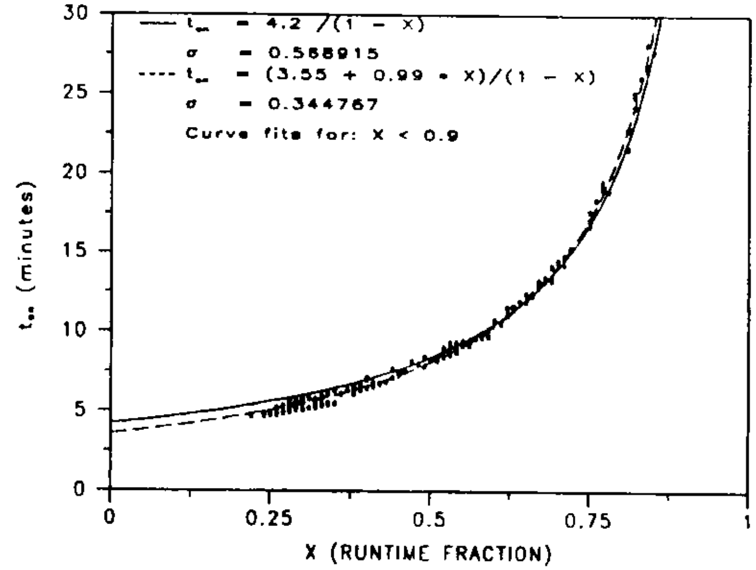


THERMOSTAT DATA: DUMMER

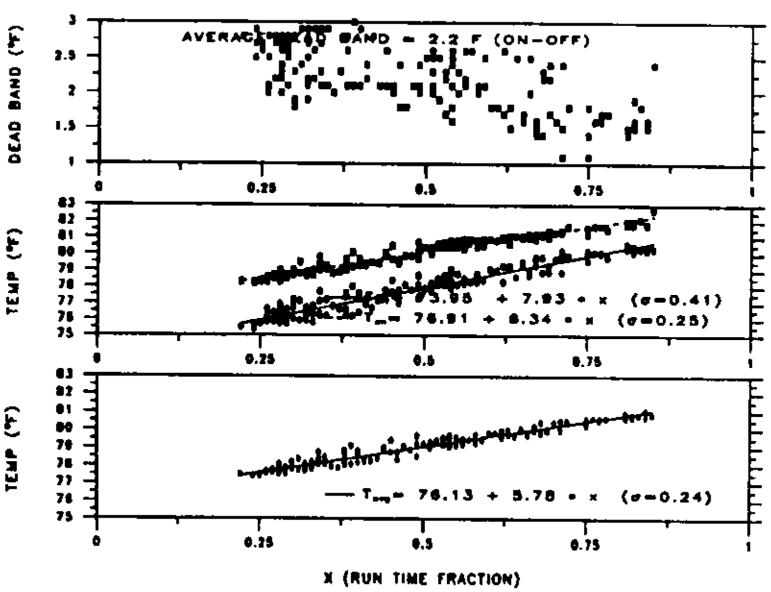
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: RAUSTAD2

START DATE: 9/ 5 OR 248 TIME: 17:50:25 JULEAN HR: 5945.84

END DATE: 9/ 7 OR 250 TIME: 16:34:50 JULEAN HR: 5992.58

ELAPSED TIME: 46.74

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.01	79.22	78.80
AVERAGE RH (%)	54.90	55.18	54.63
HOURS	46.74	23.32	23.42
% HOURS		49.89	50.11

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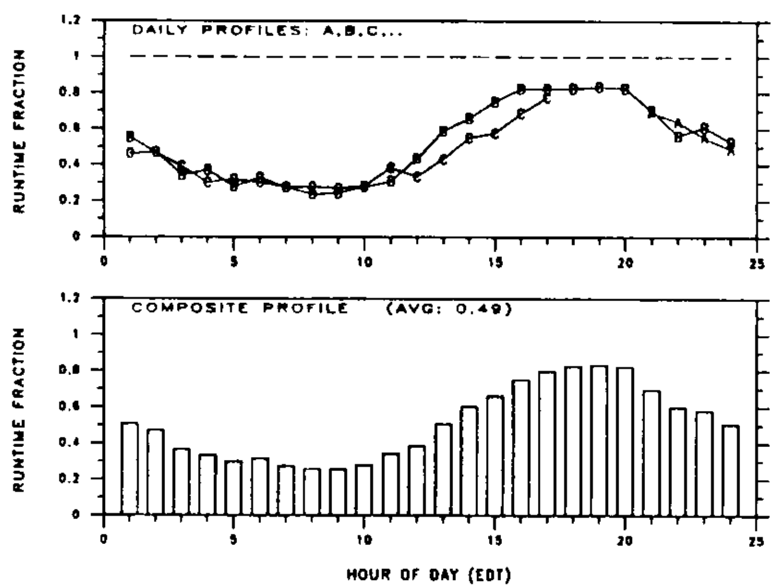
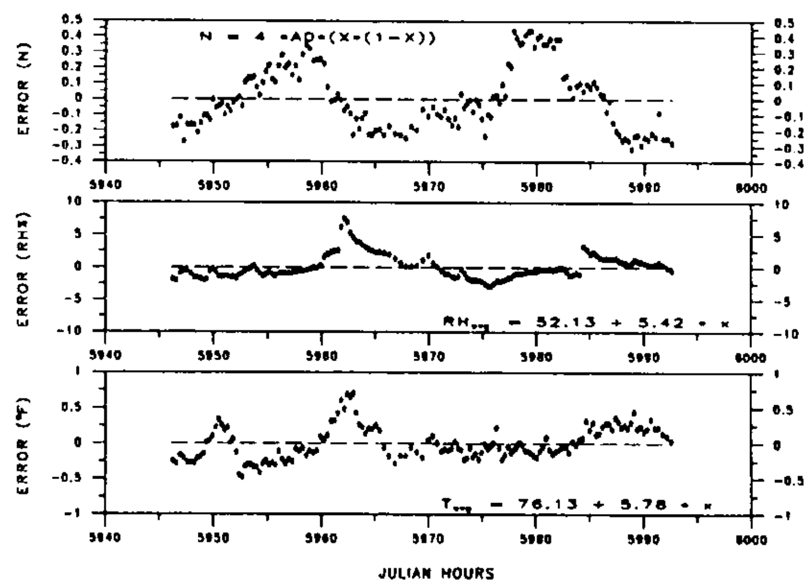
THERMOSTAT DATA: RAUSTAD2

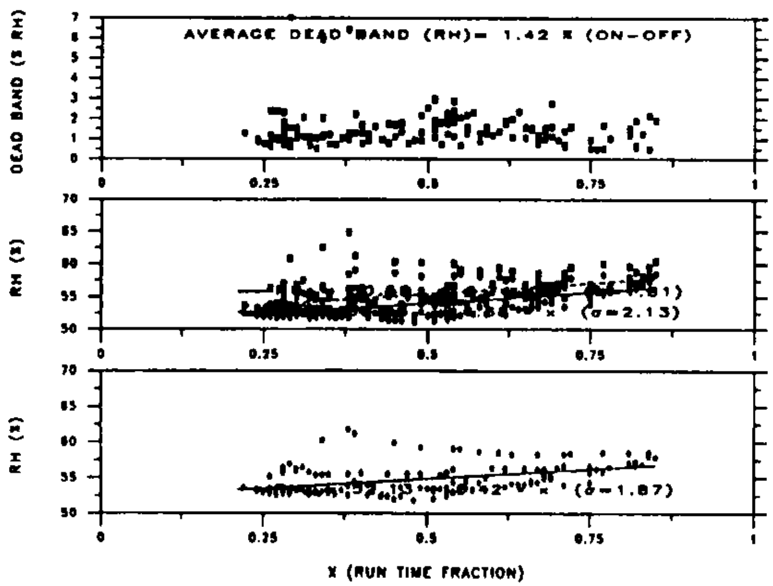
PLOT 4: RUN TIME PROFILES



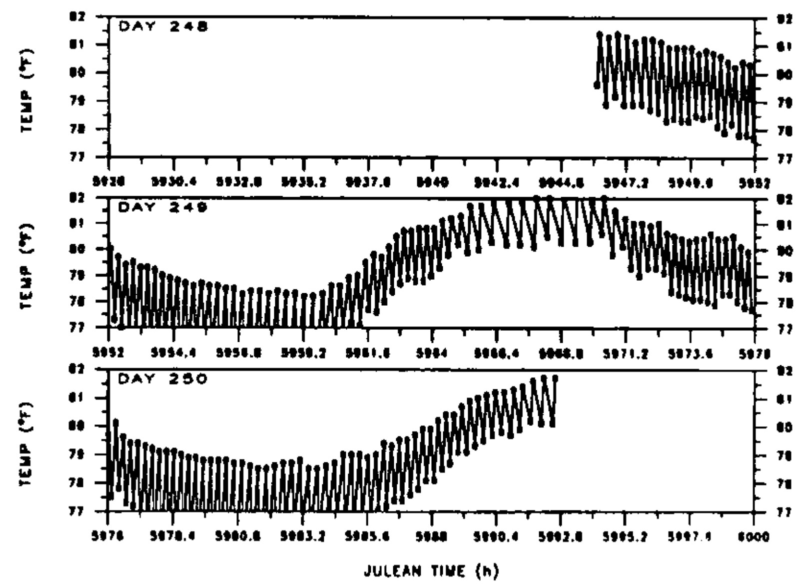
PLOT 5: ERROR ANALYSIS



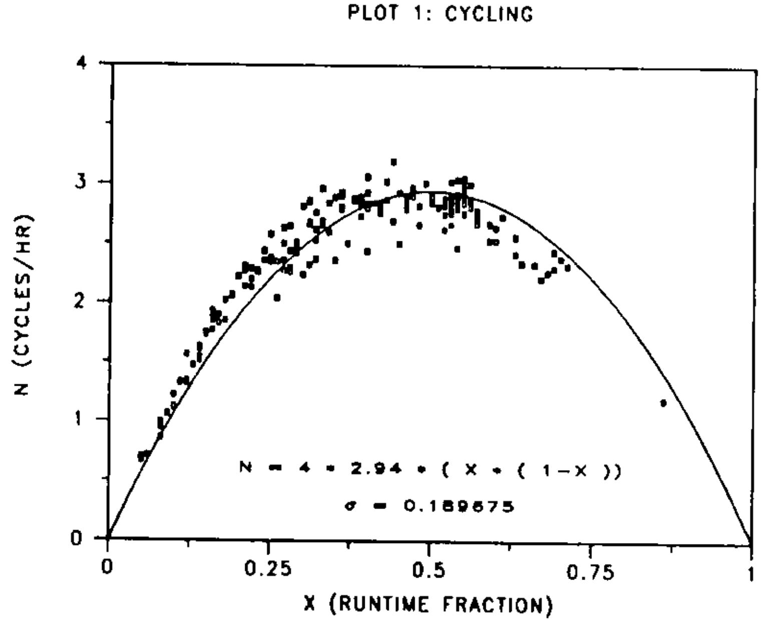
PLOT 6: HUMIDITY

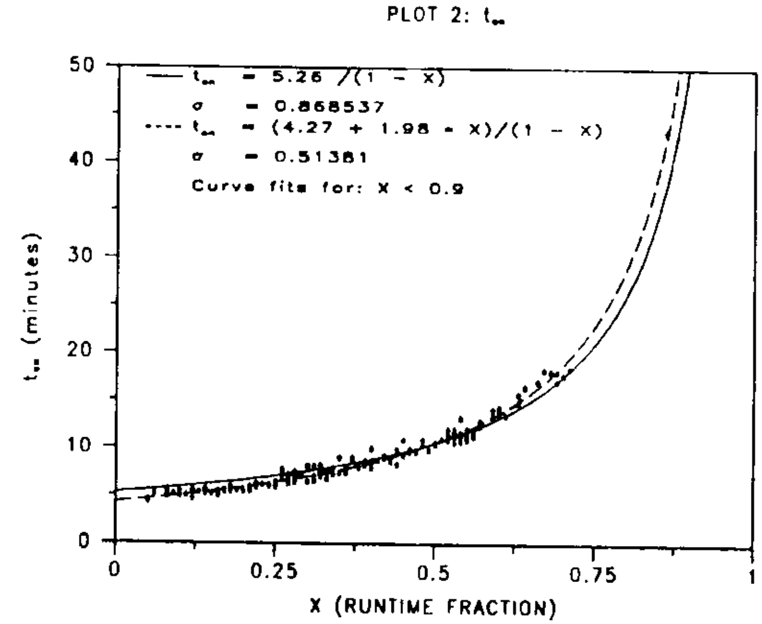


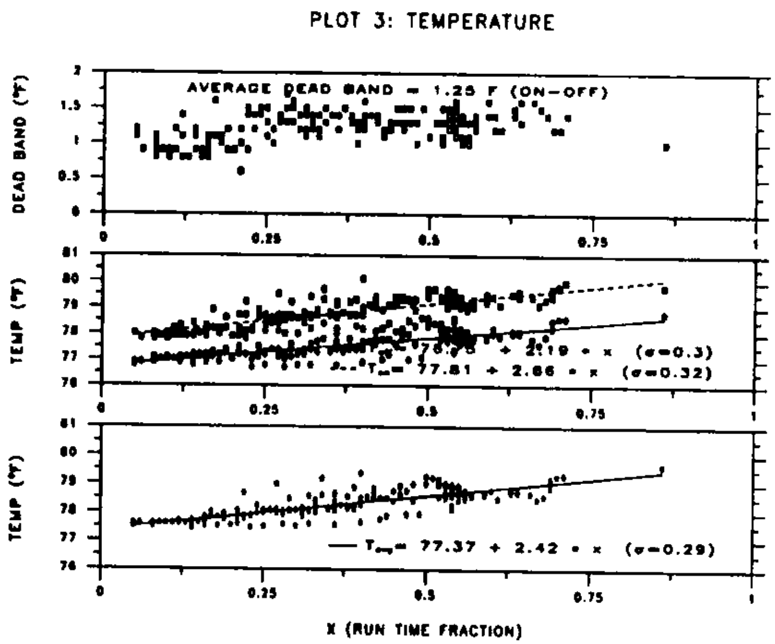
PLOT 7: TEMPERATURE VS TIME (3 DAYS)



THERMOSTAT DATA: RAUSTAD2







SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: GOULET
START DATE: 9/ 8 OR 251 TIME: 13:55:50 JULEAN HR: 6013.93
END DATE: 9/11 OR 254 TIME: 20: 0:25 JULEAN HR: 6092.01
ELAPSED TIME: 78.08

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	78.17	78.56	77.98
AVERAGE RH (%)	55.93	54.96	56.42
HOURS	78.08	25.97	52.11
% HOURS		33.26	66.74

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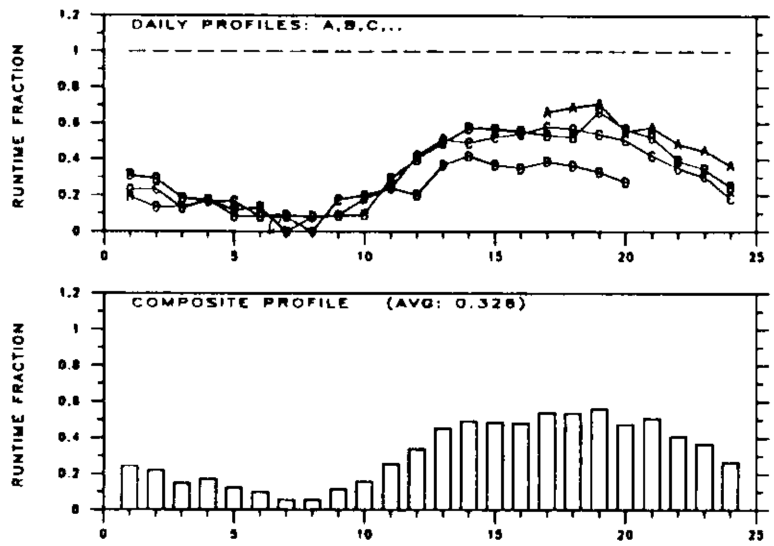
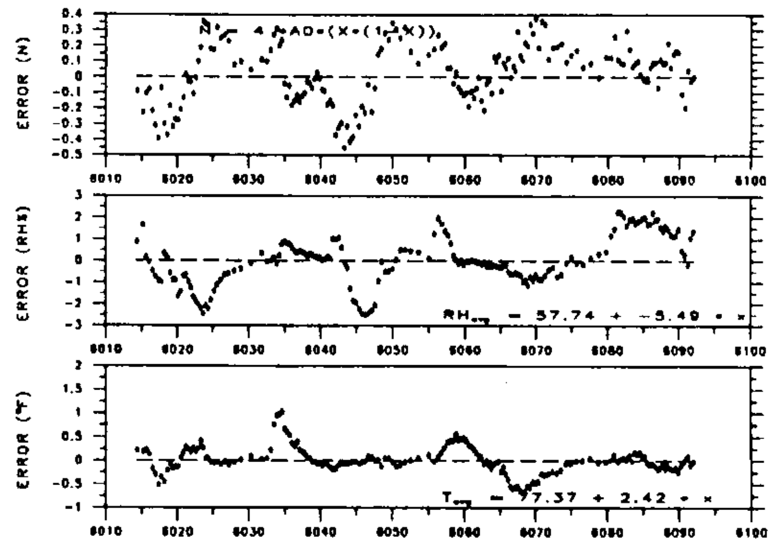
THERMOSTAT DATA: GOULET

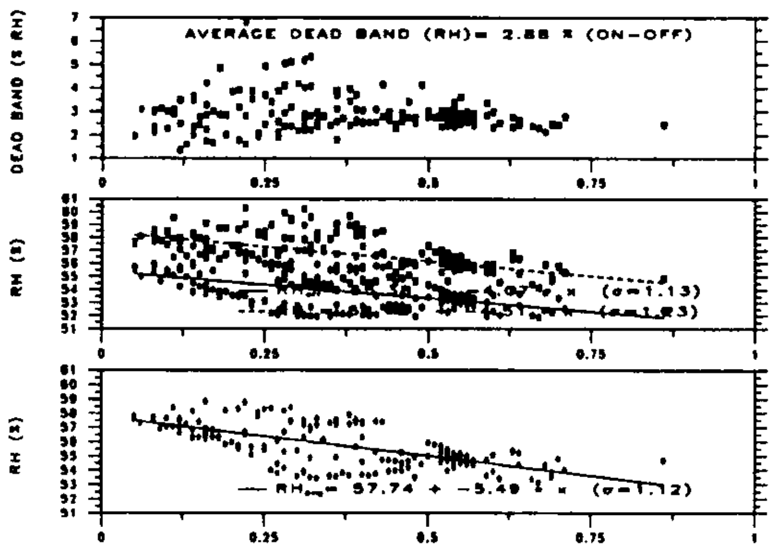
PLOT 4: RUN TIME PROFILES



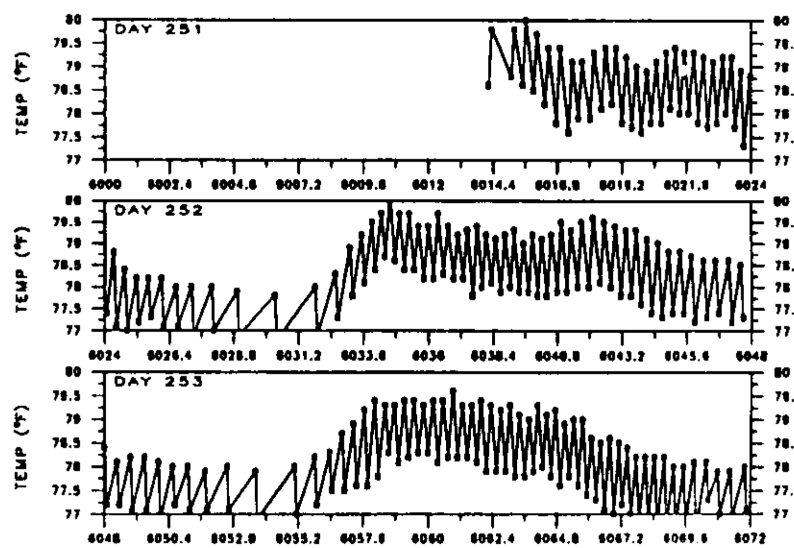
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

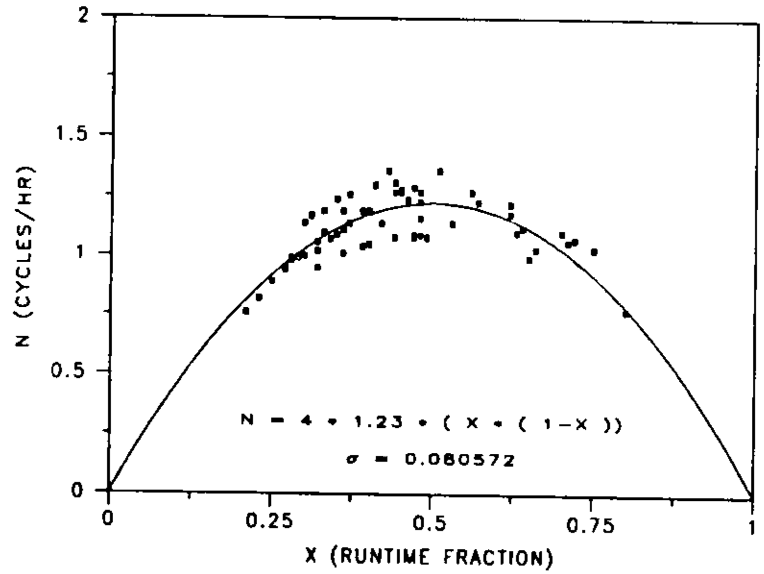


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

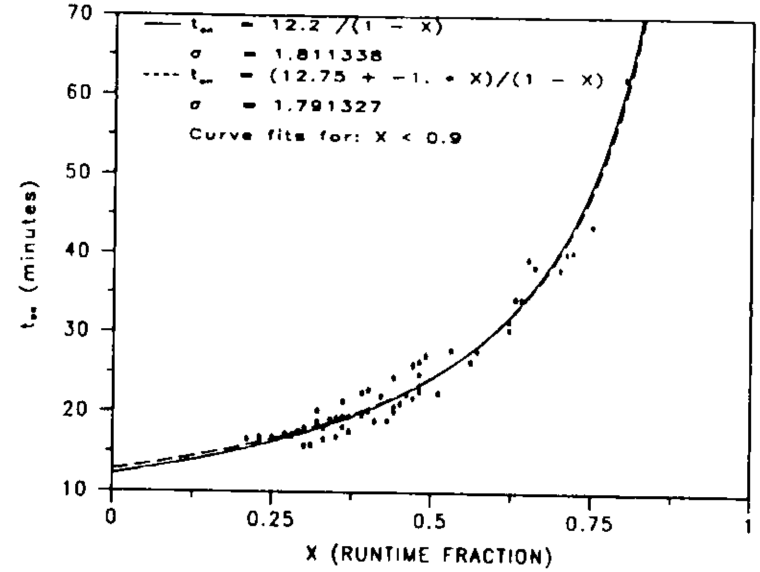


THERMOSTAT DATA: GOULET

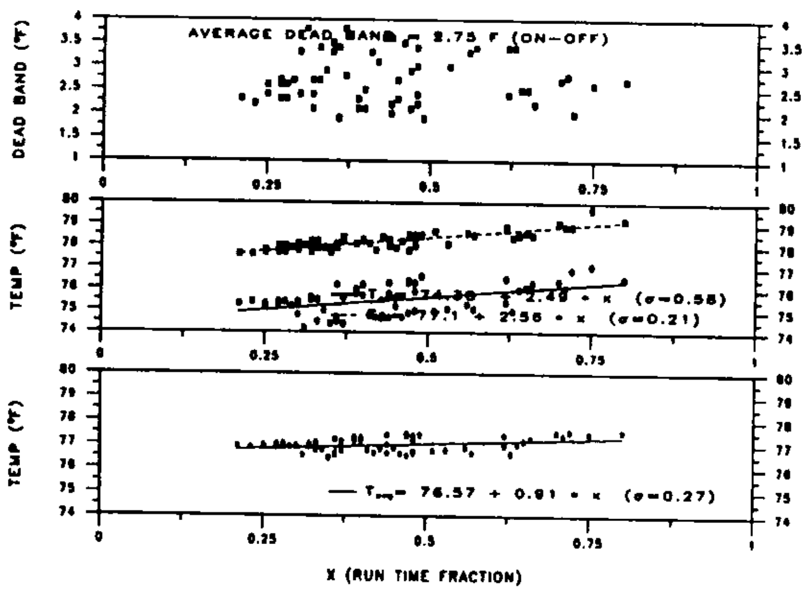
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: CUMMINGS3

START DATE: 9/14 OR 257 TIME: 22: 9:30 JULEAN HR: 6166.16

END DATE: 9/17 OR 260 TIME: 7: 6:40 JULEAN HR: 6223.11

ELAPSED TIME: 56.95

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.98	76.48	77.36
AVERAGE RH (%)	50.13	49.50	50.62
HOURS	56.95	24.57	32.38
% HOURS		43.14	56.86

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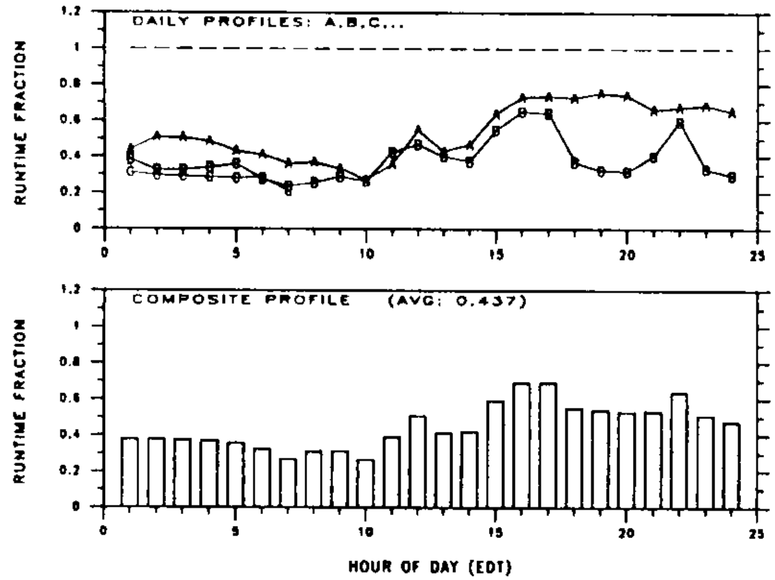
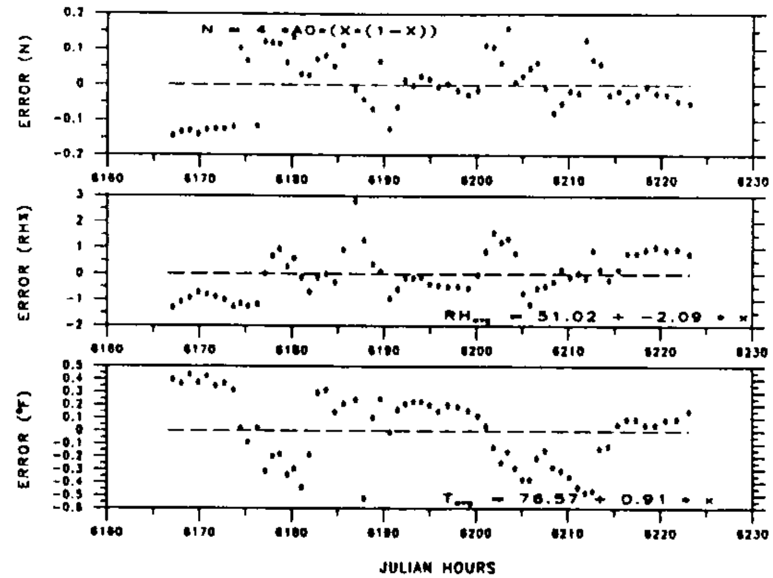
THERMOSTAT DATA: CUMMINGS3

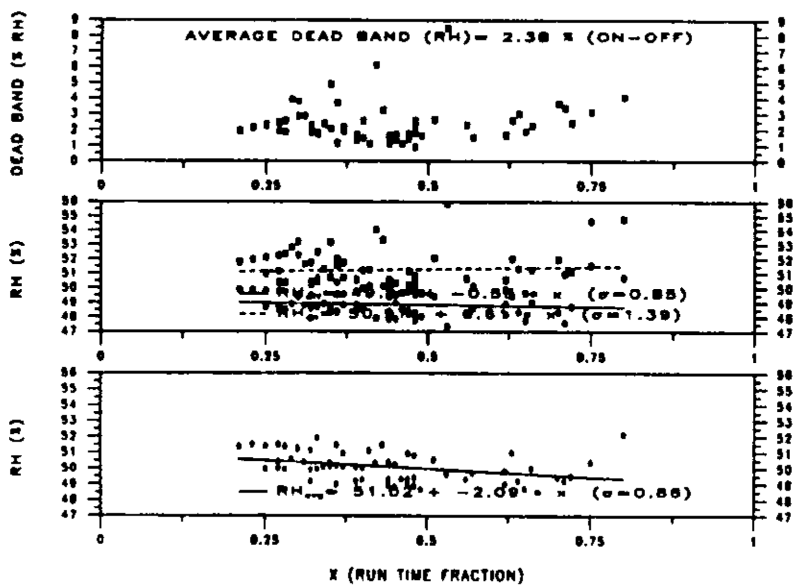
PLOT 4: RUN TIME PROFILES



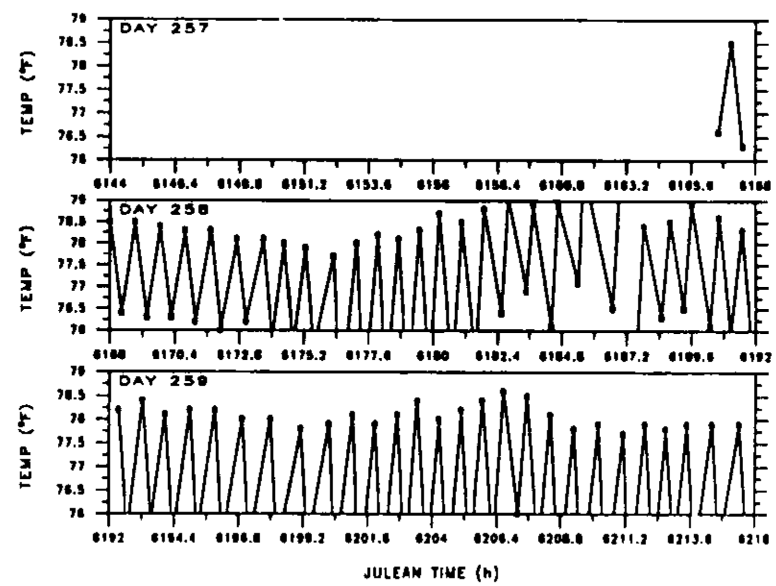
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

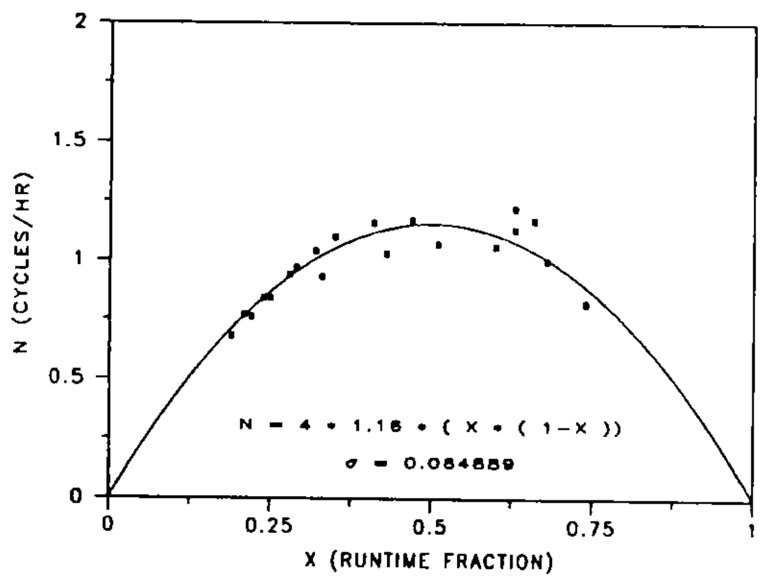


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

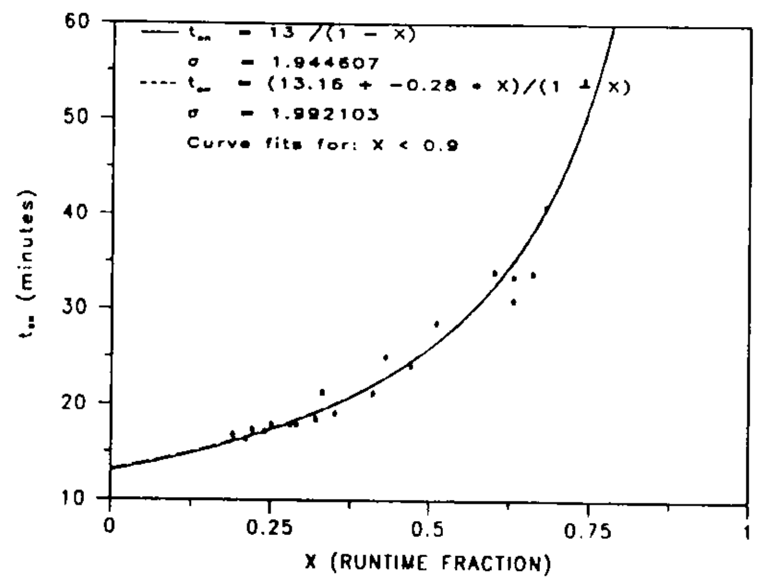


THERMOSTAT DATA: CUMMINGS3

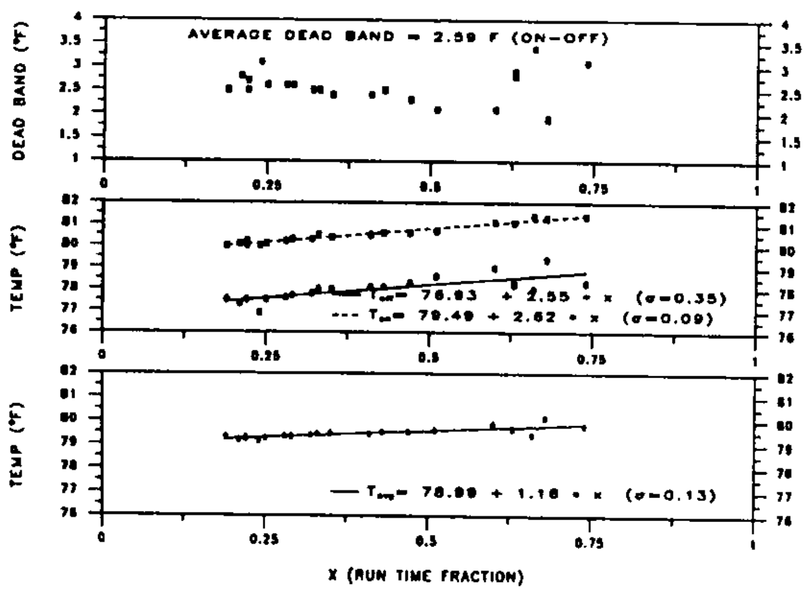
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: CUMMINGS2

START	DATE: 9/13 OR 256	TIME: 16:10:40	JULEAN HR:	6138.18
END	DATE: 9/14 OR 257	TIME: 16:20: 5	JULEAN HR:	6160.33
ELAPSED TIME:	22.16			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.45	79.01	79.73
AVERAGE RH (%)	49.58	48.70	50.14
HOURS	22.16	8.71	13.45
% HOURS		39.29	60.71

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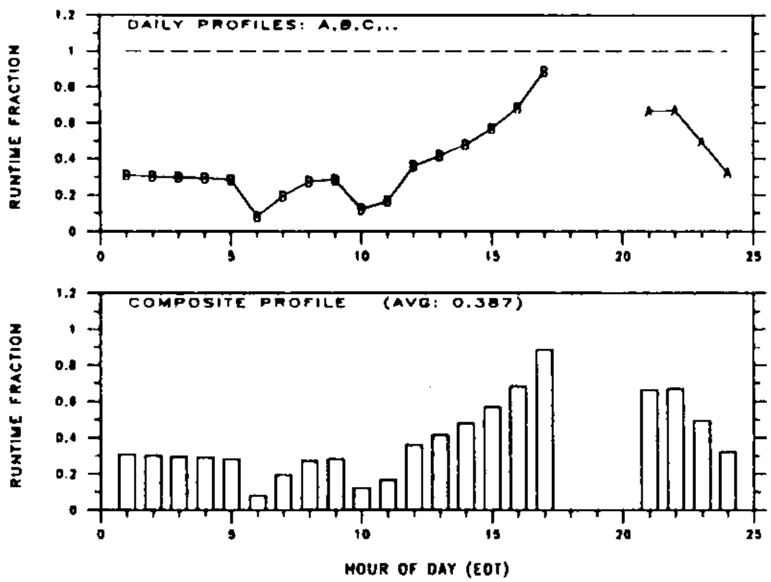
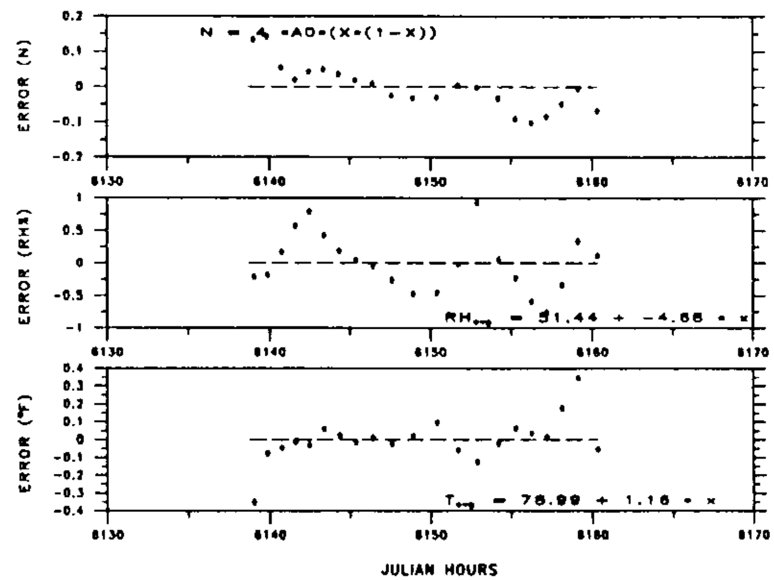
THERMOSTAT DATA: CUMMINGS2

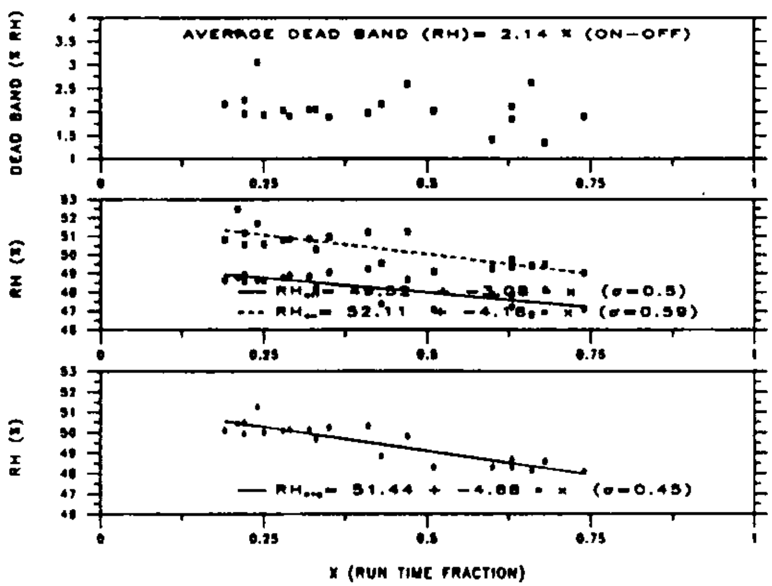
PLOT 4: RUN TIME PROFILES



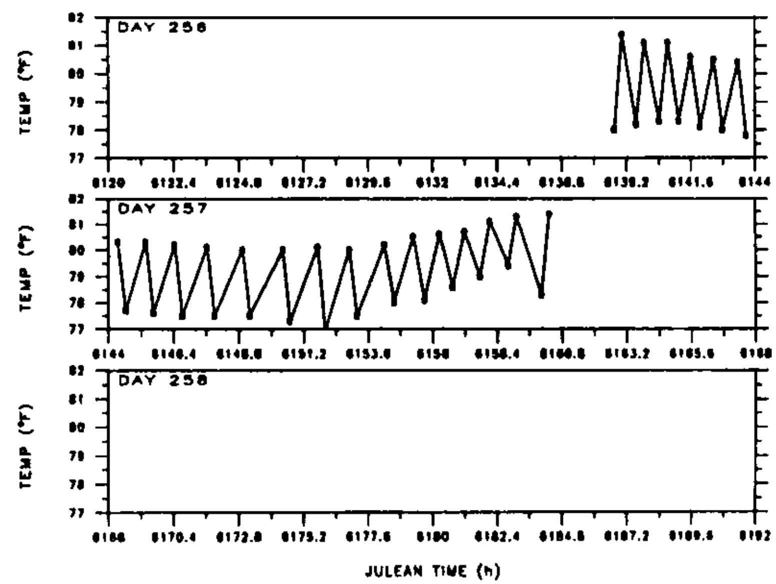
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

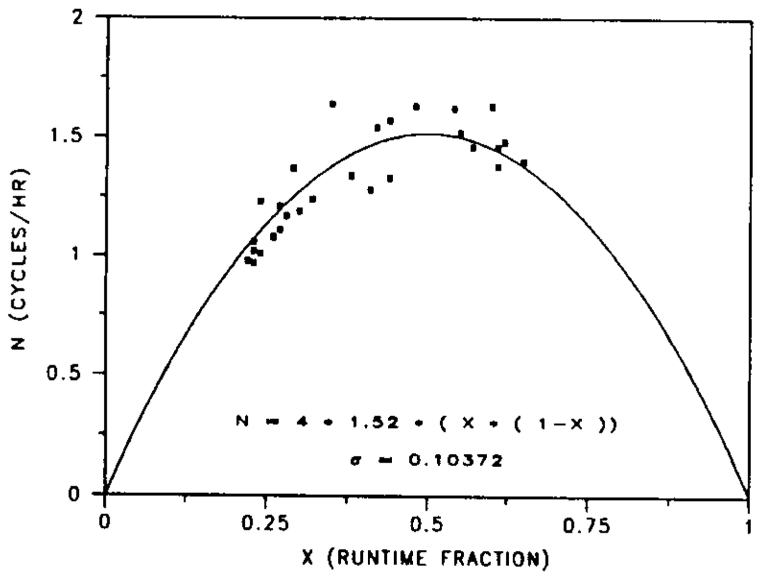


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

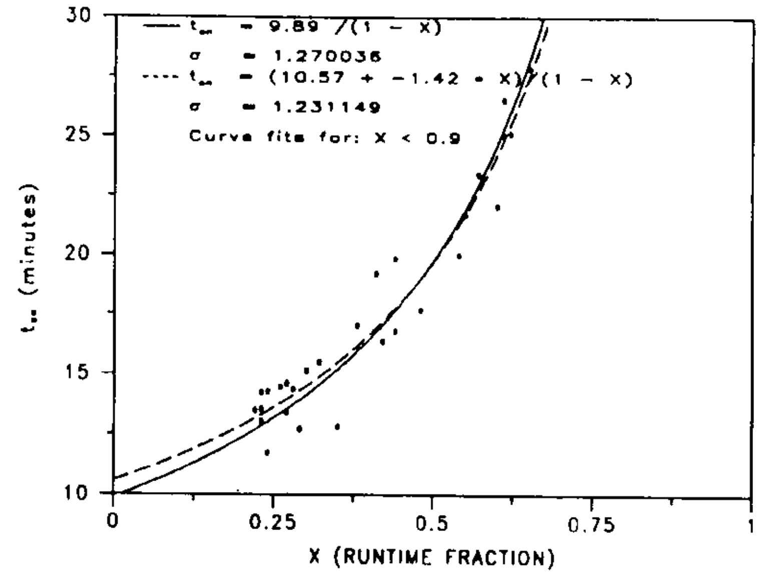


THERMOSTAT DATA: CUMMINGS2

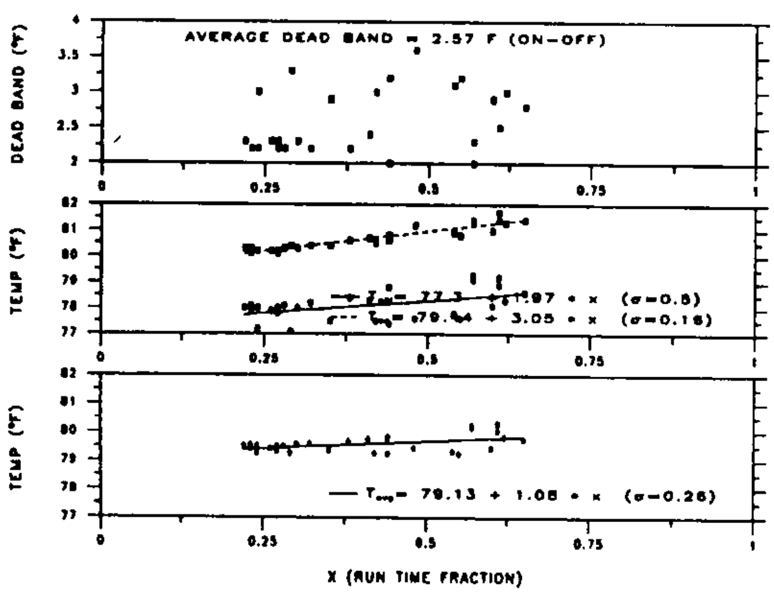
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: CUMMINGS1
START DATE: 9/12 OR 255 TIME: 16:57:40 JULEAN HR: 6114.96
END DATE: 9/13 OR 256 TIME: 17:28:40 JULEAN HR: 6137.48
ELAPSED TIME: 22.52

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.56	79.09	79.85
AVERAGE RH (%)	50.30	49.49	50.79
HOURS	22.52	8.59	13.93
% HOURS		38.14	61.86

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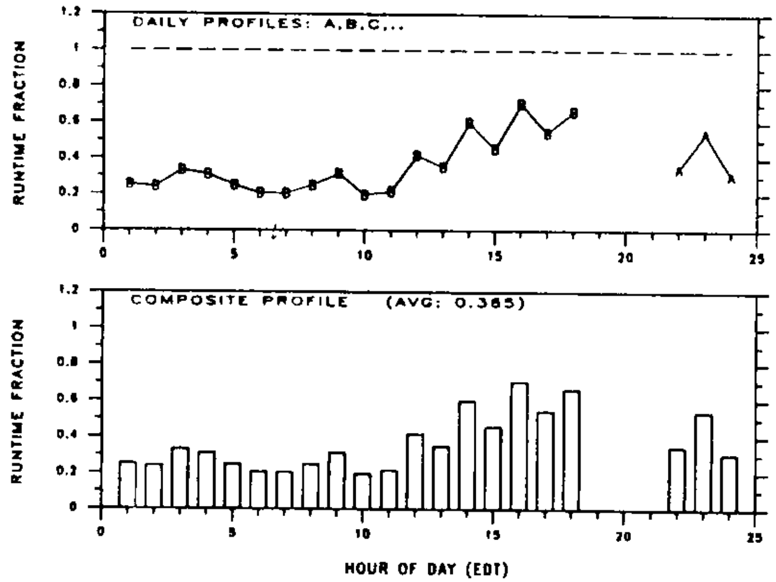
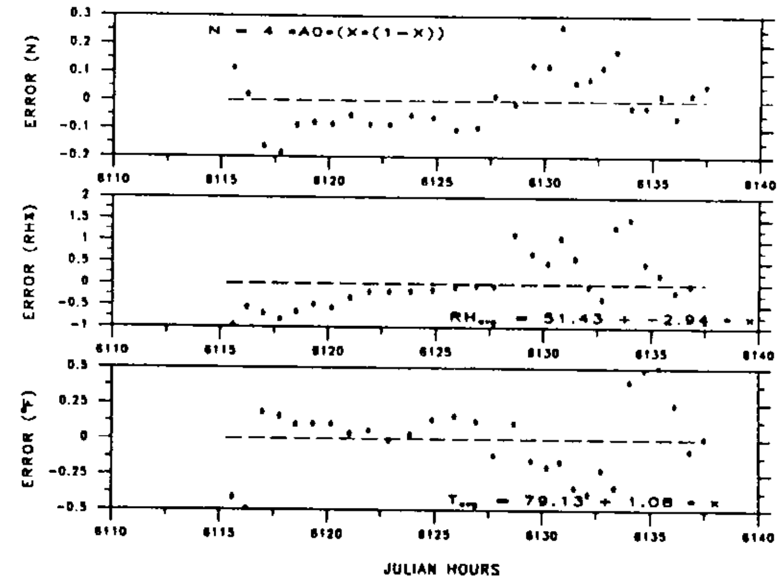
THERMOSTAT DATA: CUMMINGS1

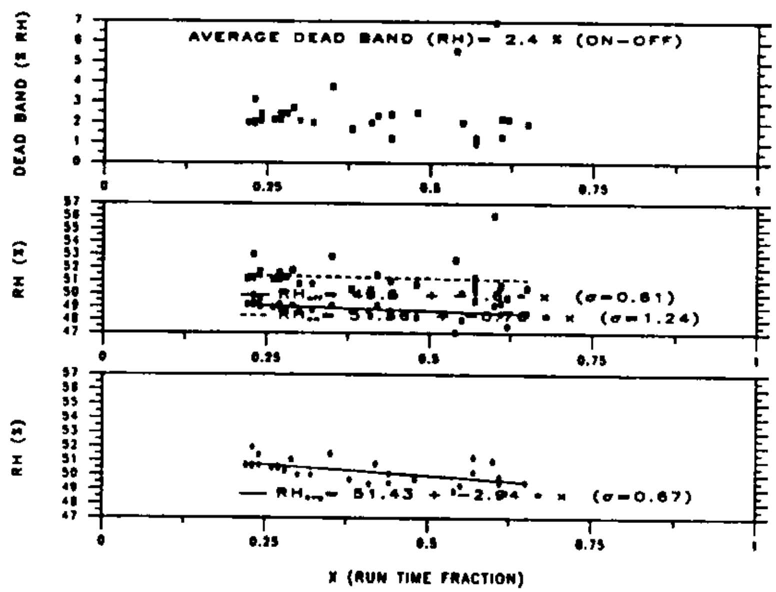
PLOT 4: RUN TIME PROFILES



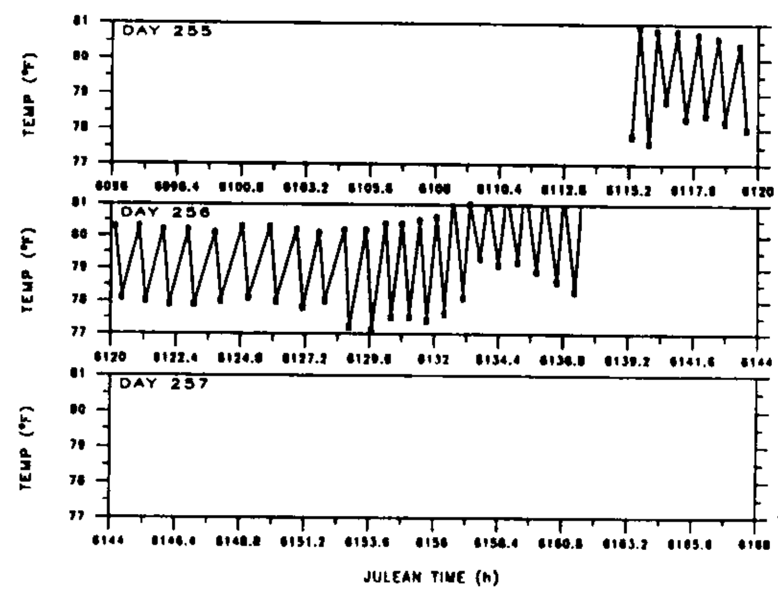
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

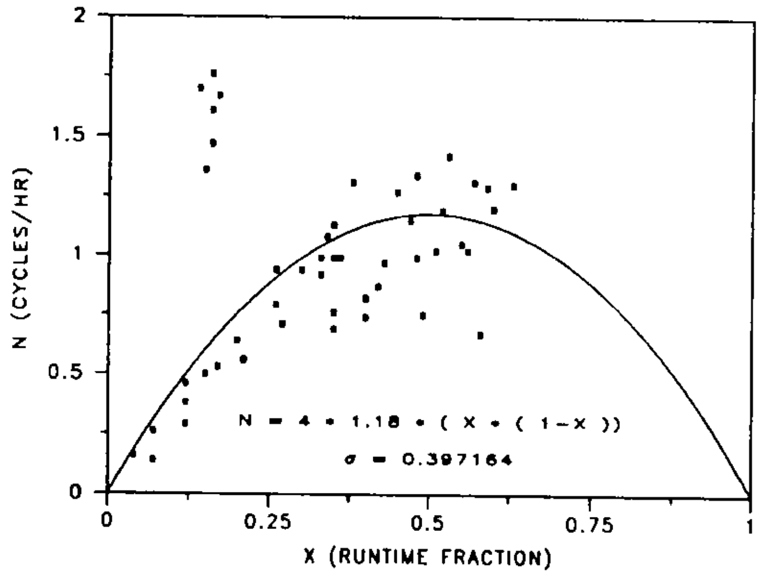


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

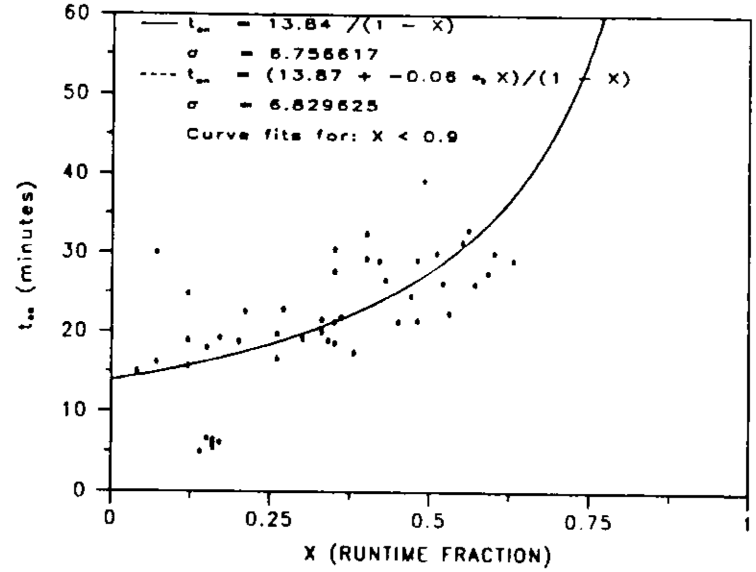


THERMOSTAT DATA: CUMMINGS1

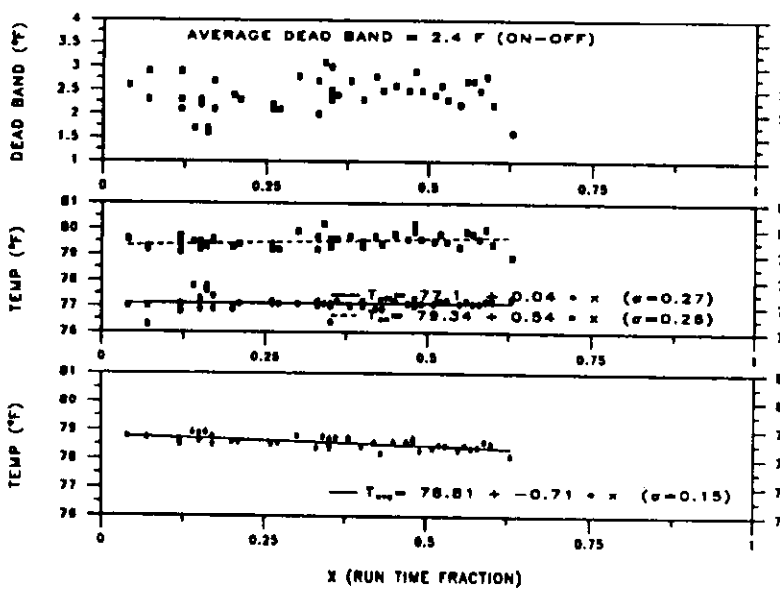
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: MELLOR

START	DATE:	9/17 OR 260	TIME: 22: 2: 0	JULEAN HR:	6238.03
END	DATE:	9/20 OR 263	TIME: 19: 36: 40	JULEAN HR:	6307.61
ELAPSED TIME:		69.58			

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	78.59	78.13	78.75
AVERAGE RH (%)	60.73	60.05	60.96
HOURS	69.58	17.86	51.71
% HOURS		25.67	74.33

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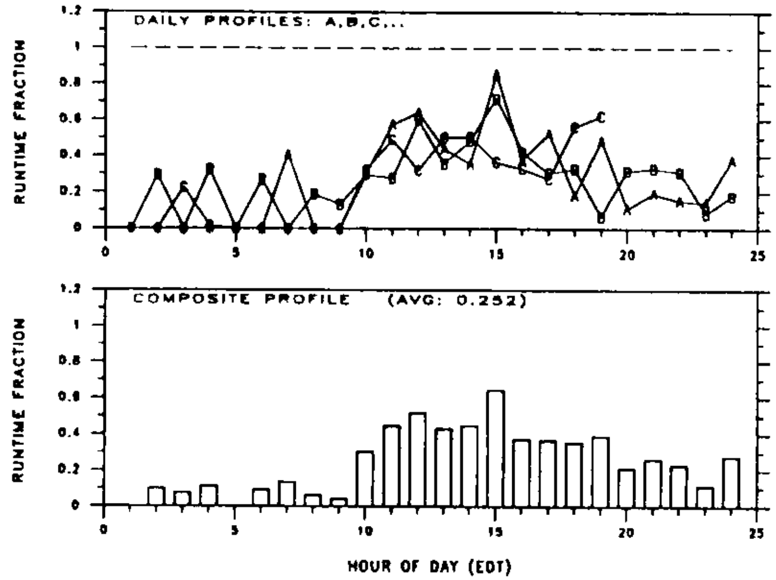
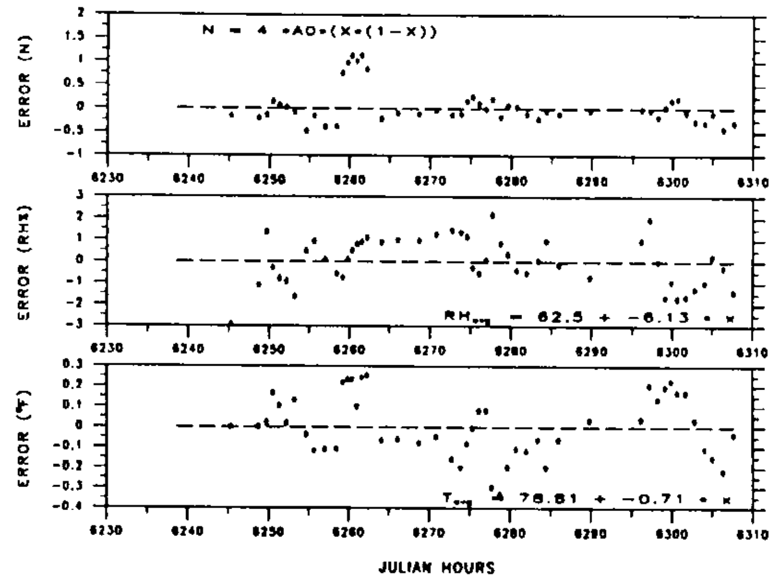
THERMOSTAT DATA: MELLOR

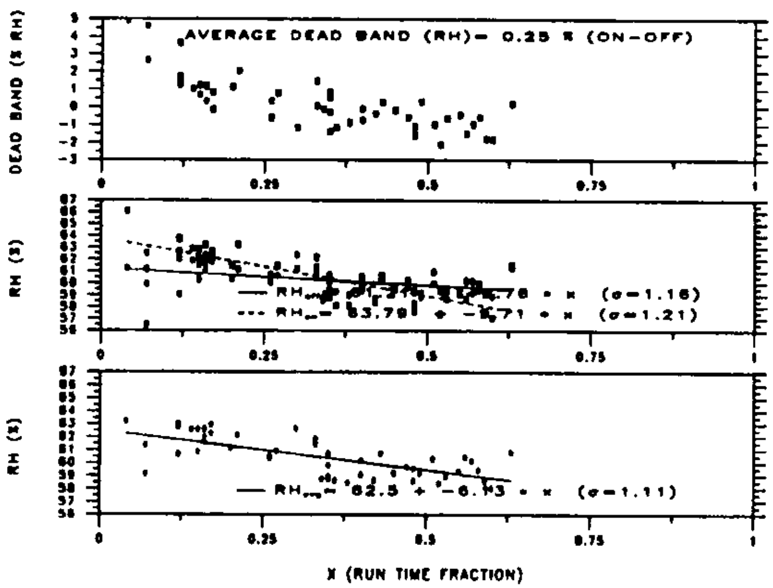
PLOT 4: RUN TIME PROFILES



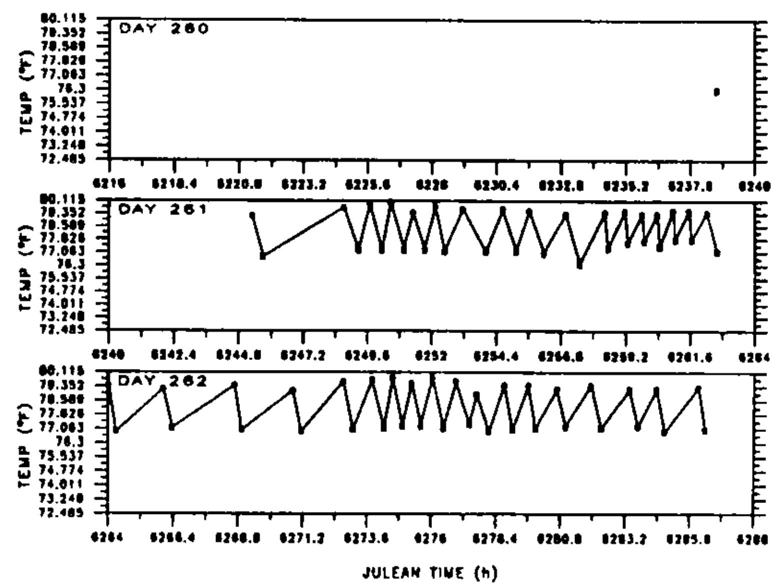
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

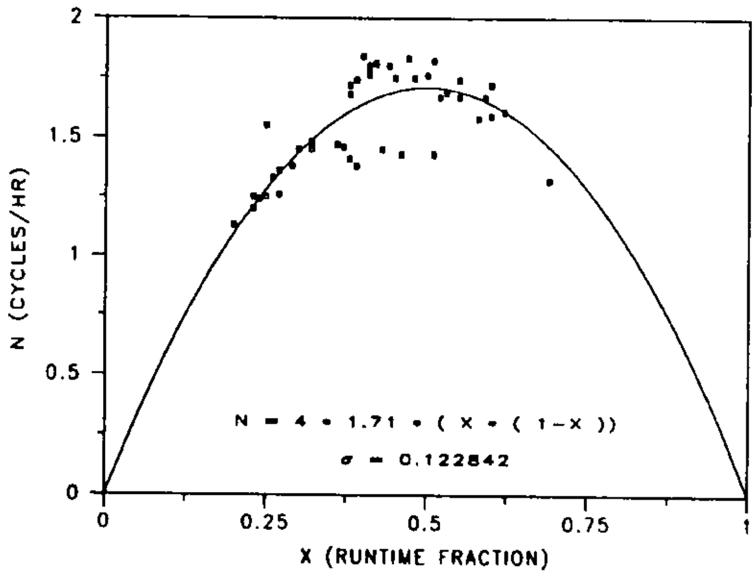


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

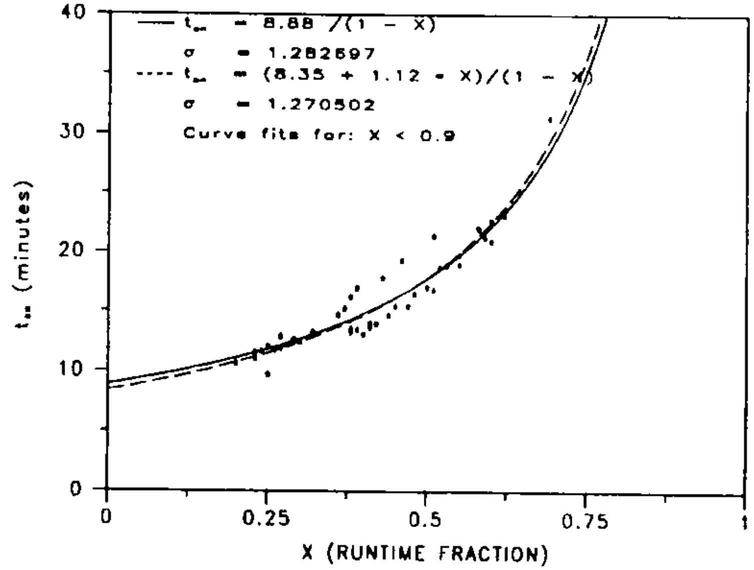


THERMOSTAT DATA: MELLOR

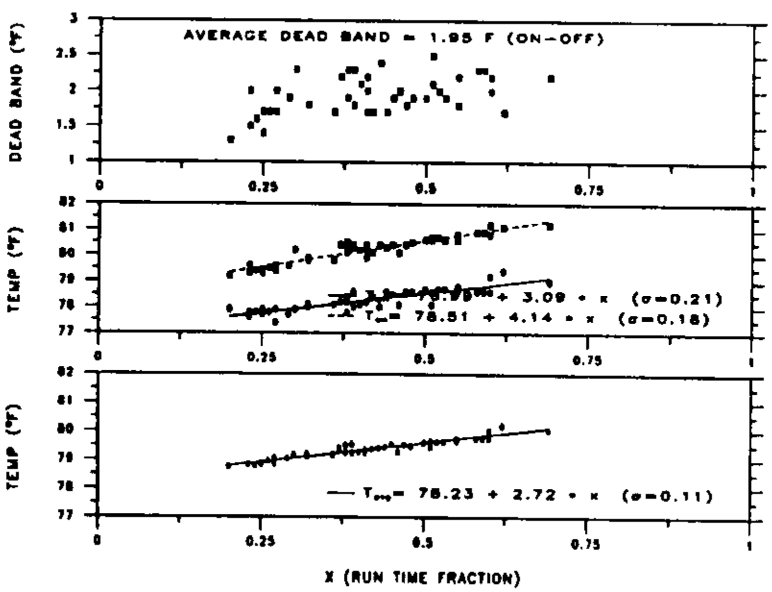
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



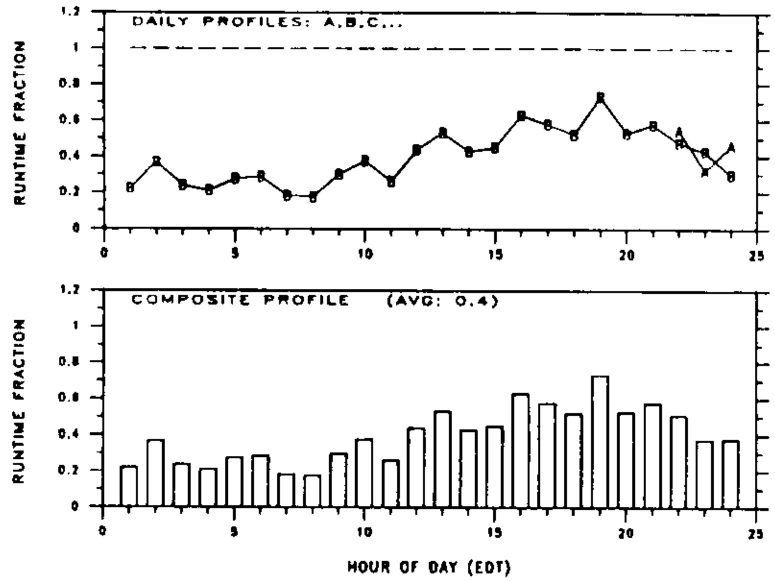
SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: WALKER
START DATE: 9/21 OR 264 TIME: 19: 16: 40 JULEAN HR: 6331.28
END DATE: 9/23 OR 266 TIME: 0: 4: 5 JULEAN HR: 6360.07
ELAPSED TIME: 28.79

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	79.33	79.09	79.48
AVERAGE RH (%)	47.89	47.69	48.03
HOURS	28.79	11.60	17.19
% HOURS		40.31	59.69

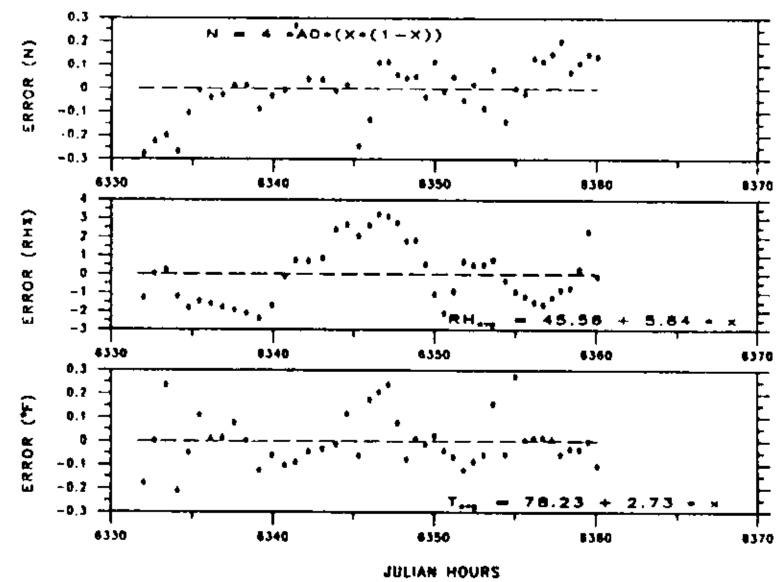
SELECTED DATA RANGE:
STARTING 264. , 19. (6331.000)
ENDING 266. , 0. (6360.000)

THERMOSTAT DATA: WALKER

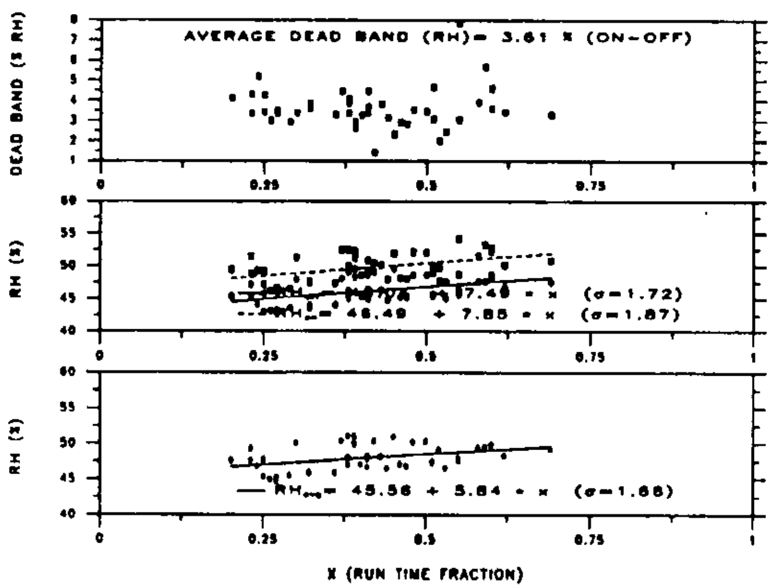
PLOT 4: RUN TIME PROFILES



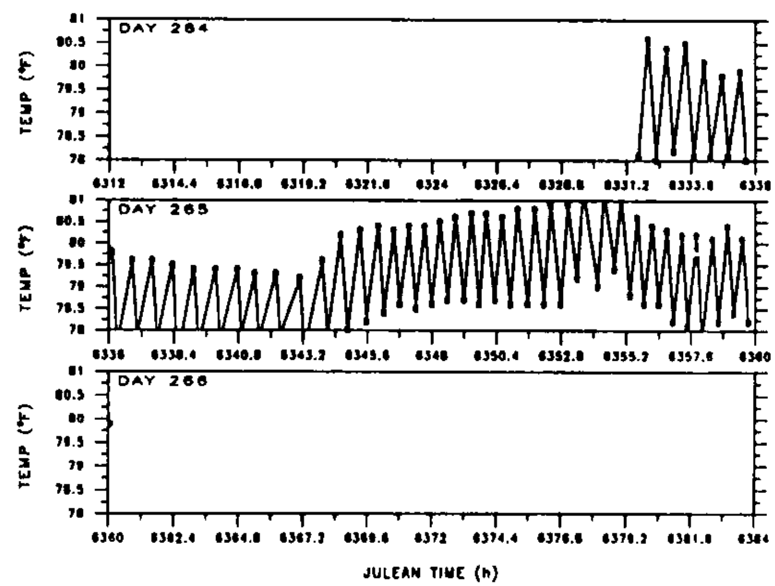
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

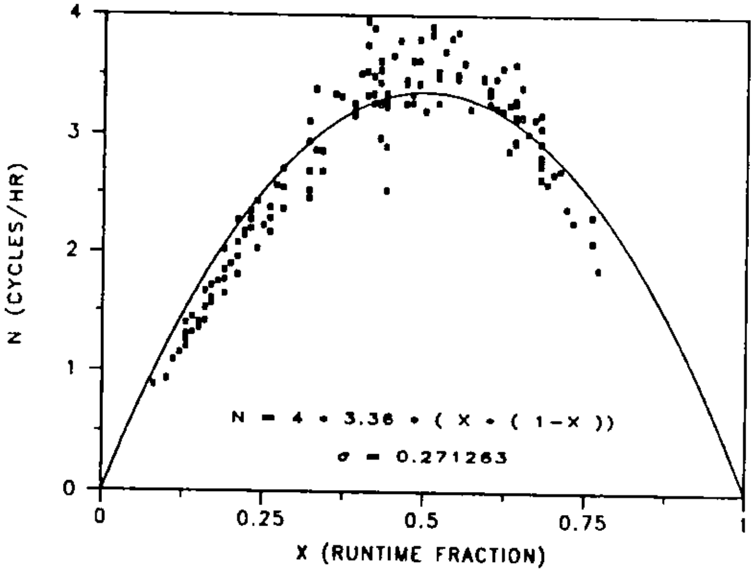


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

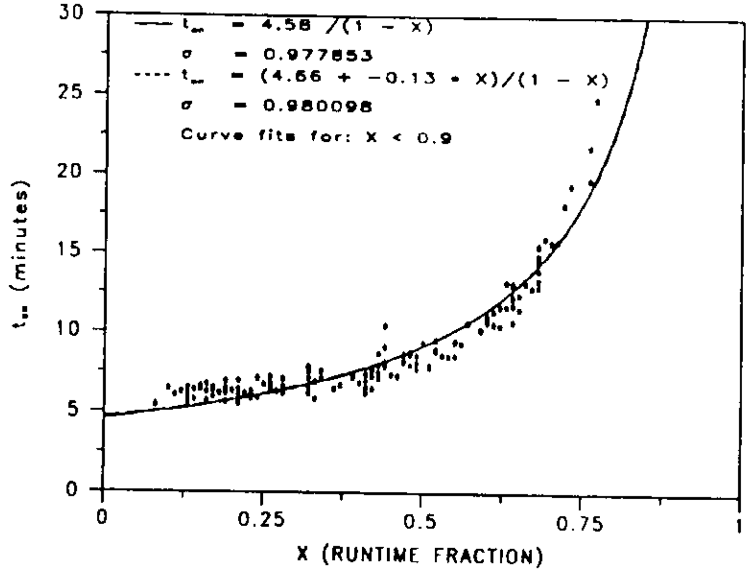


THERMOSTAT DATA: WALKER

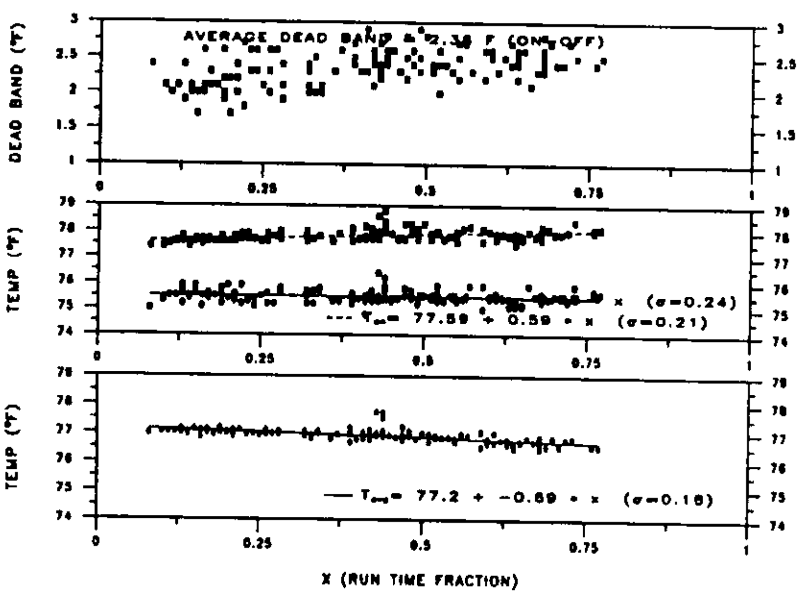
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: KALAGHCHY
START DATE: 10/ 1 OR 274 TIME: 20:42:10 JULEAN HR: 6572.70
END DATE: 10/ 4 OR 277 TIME: 6:45:15 JULEAN HR: 6630.75
ELAPSED TIME: 58.05

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.94	76.63	77.11
AVERAGE RH (%)	50.76	50.36	51.02
HOURS	58.05	21.04	37.01
% HOURS		36.25	63.75

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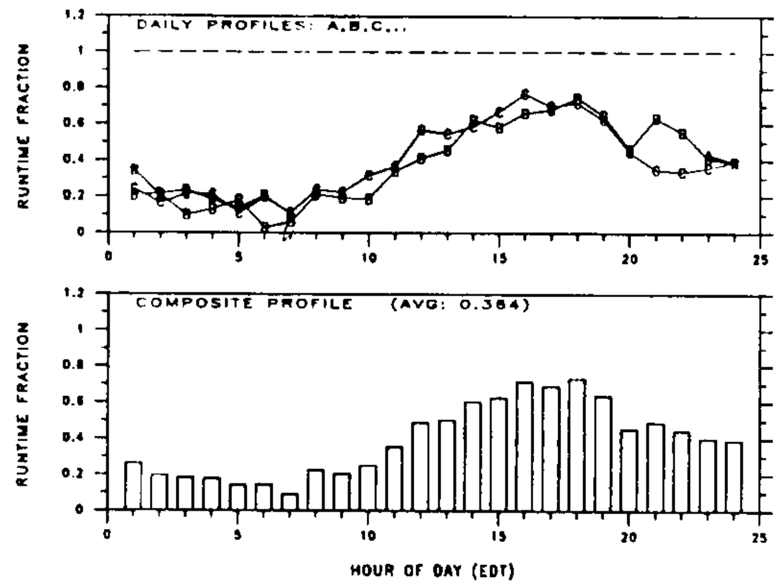
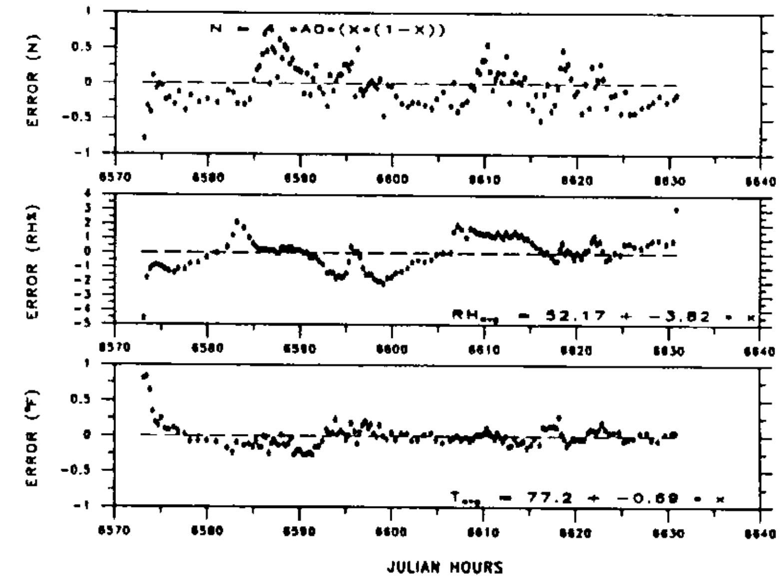
THERMOSTAT DATA: KALAGHCHY

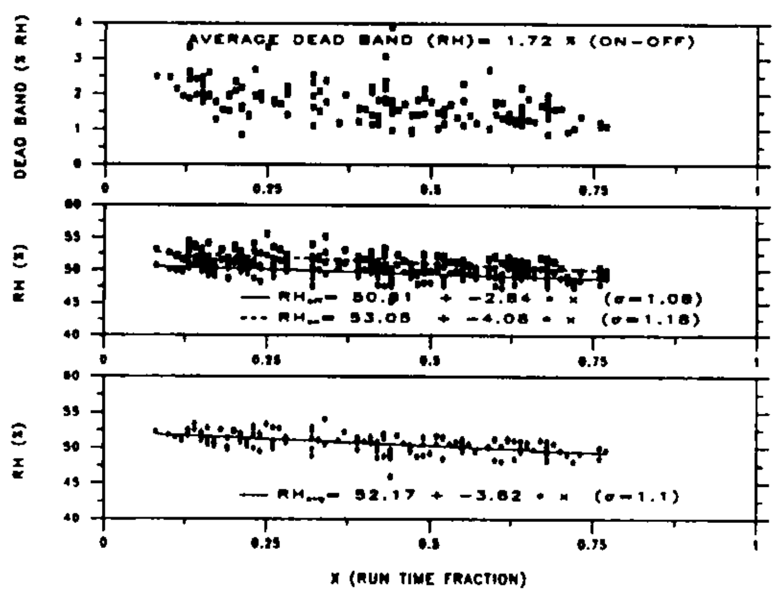
PLOT 4: RUN TIME PROFILES



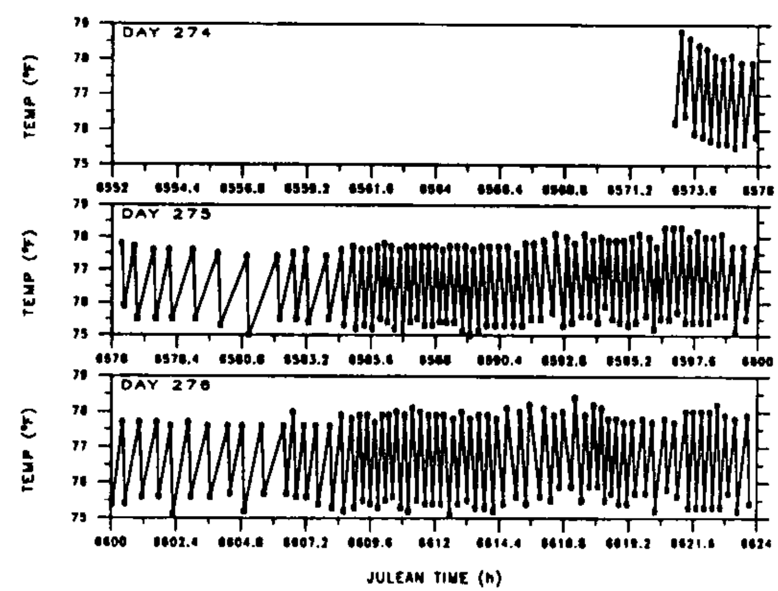
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

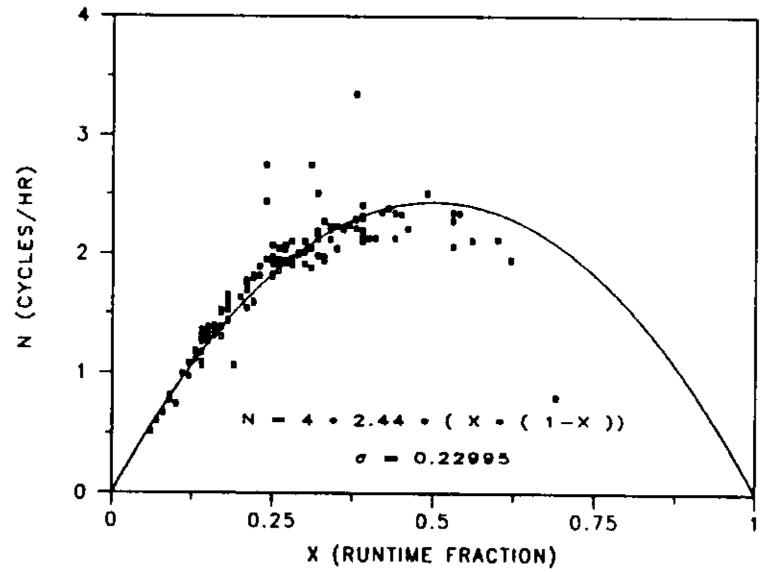


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

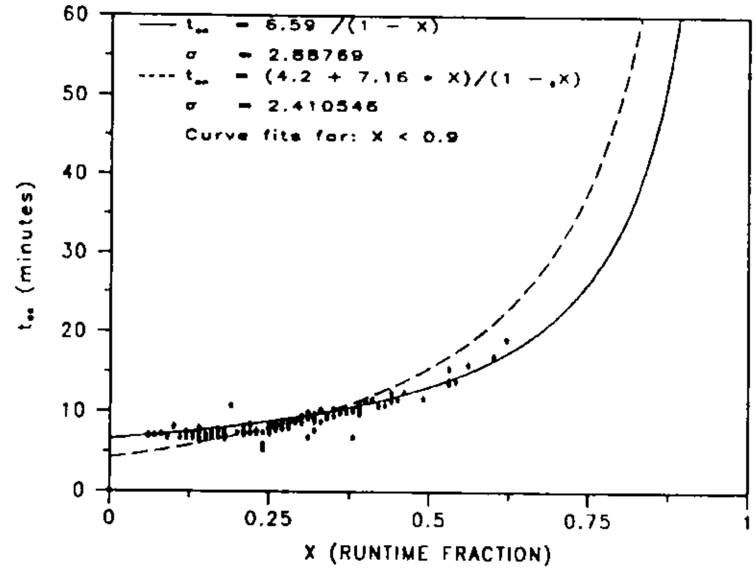


THERMOSTAT DATA: KALAGHCHY

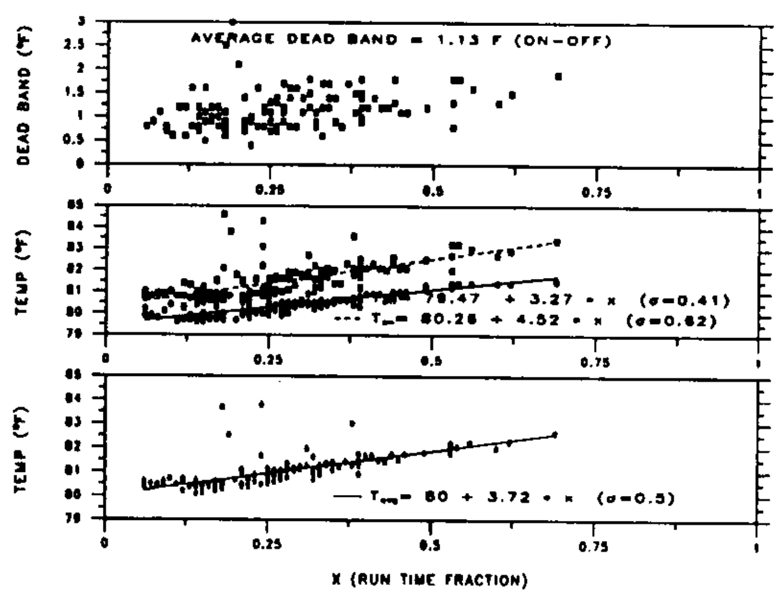
PLOT 1: CYCLING



PLOT 2: t_{on}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA
LOCATION: SHIREY2
START DATE: 10/ 4 OR 277 TIME: 21:44:45 JULEAN HR: 6645.75
END DATE: 10/ 8 OR 281 TIME: 6:43:40 JULEAN HR: 6726.73
ELAPSED TIME: 80.98

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	80.89	80.98	80.86
AVERAGE RH (%)	55.46	55.14	55.56
HOURS	80.98	19.29	61.69
% HOURS		23.82	76.18

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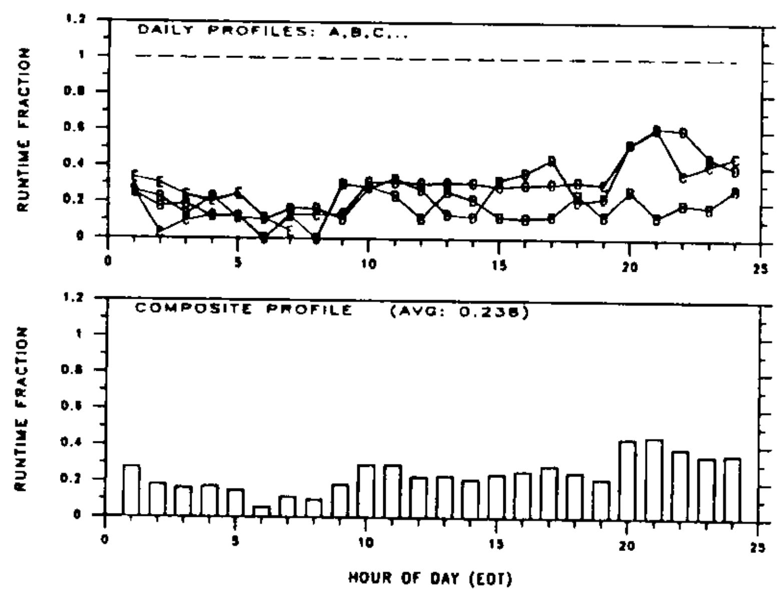
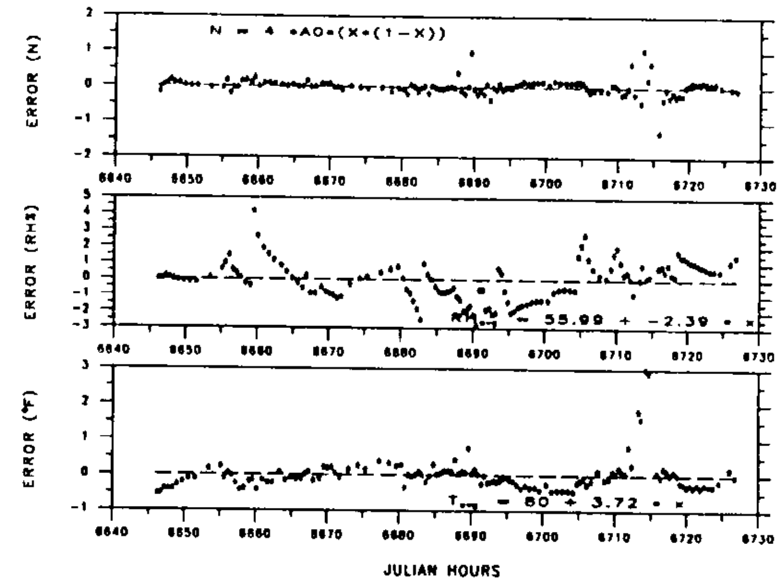
THERMOSTAT DATA: SHIREY2

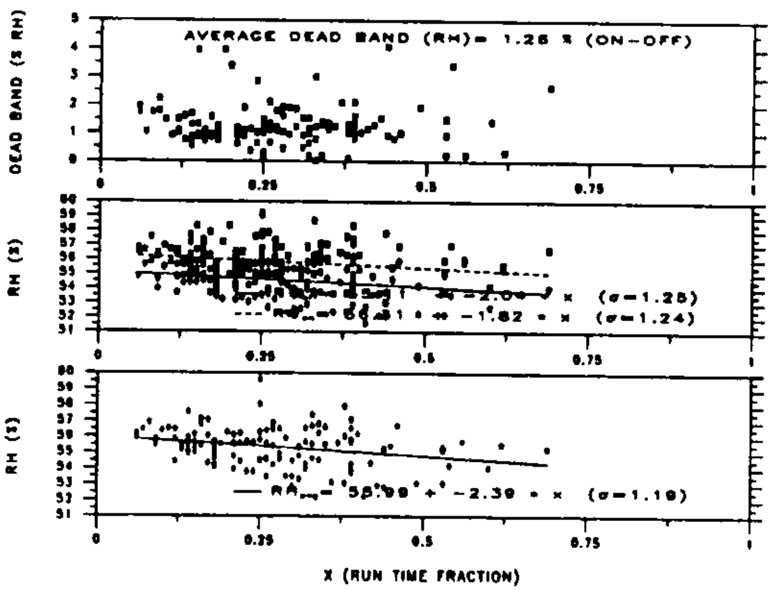
PLOT 4: RUN TIME PROFILES



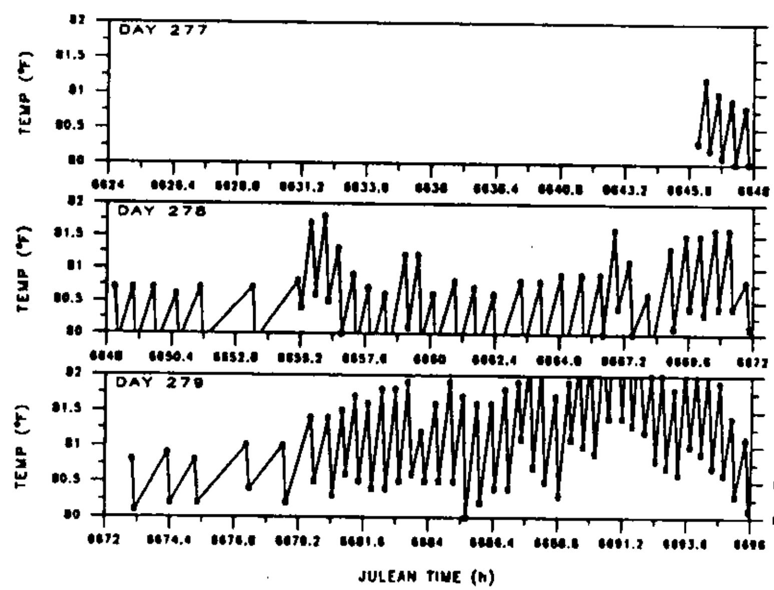
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY

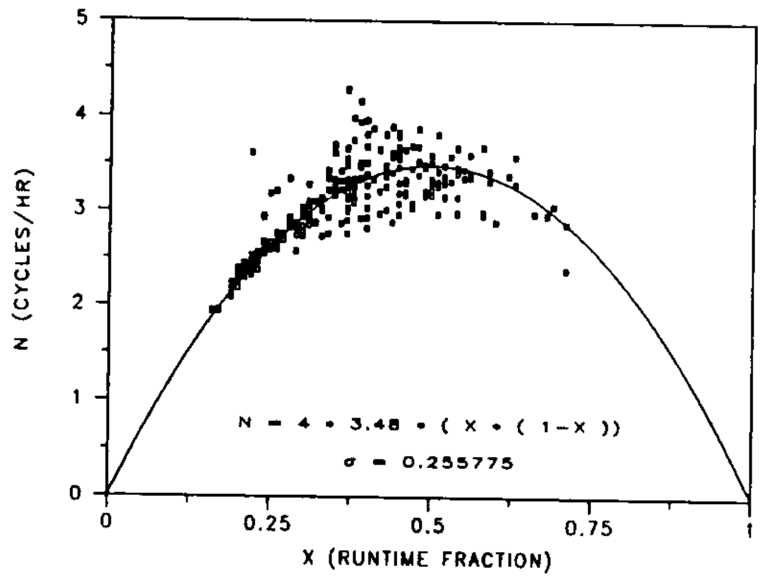


PLOT 7: TEMPERATURE VS TIME (3 DAYS)

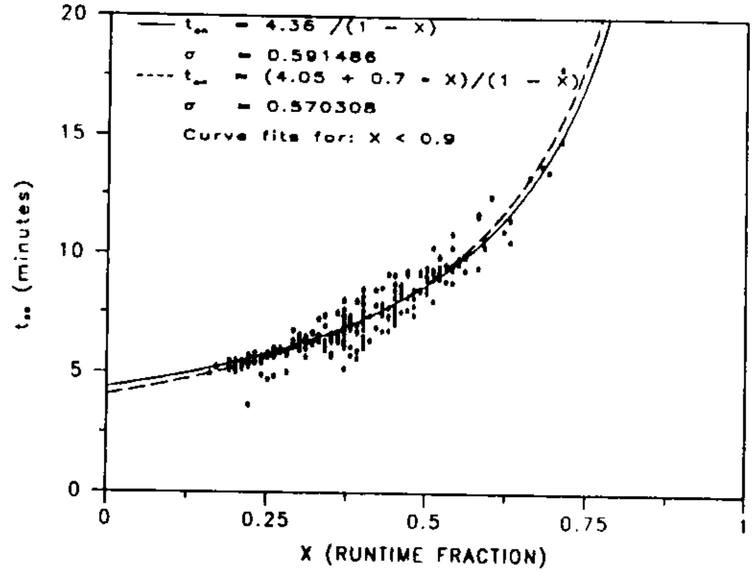


THERMOSTAT DATA: SHIREY2

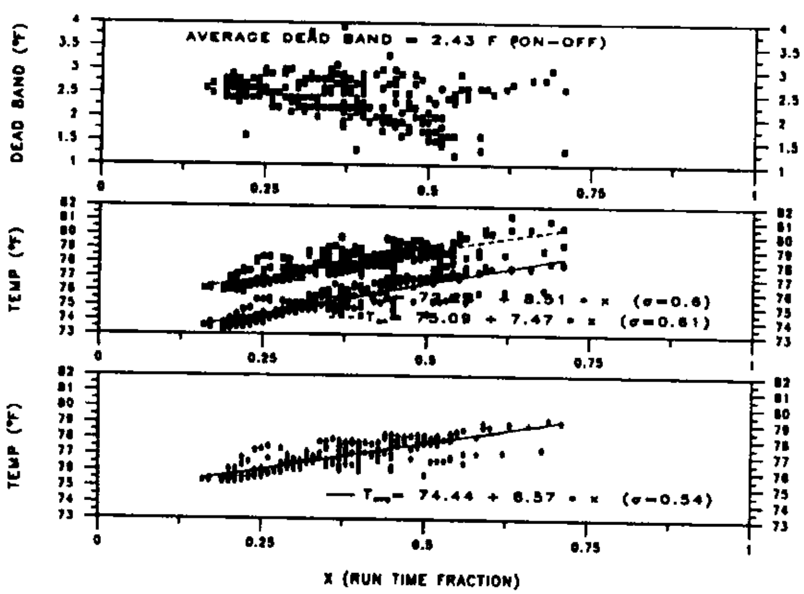
PLOT 1: CYCLING



PLOT 2: t_{∞}



PLOT 3: TEMPERATURE



SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: KANNAN

START DATE: 10/11 OR 284 TIME: 22: 7:40 JULEAN HR: 6814.13

END DATE: 10/15 OR 288 TIME: 21:53:55 JULEAN HR: 6909.90

ELAPSED TIME: 95.77

	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	76.79	76.70	76.83
AVERAGE RH (%)	59.45	59.28	59.55
HOURS	95.77	34.43	61.34
% HOURS		35.95	64.05

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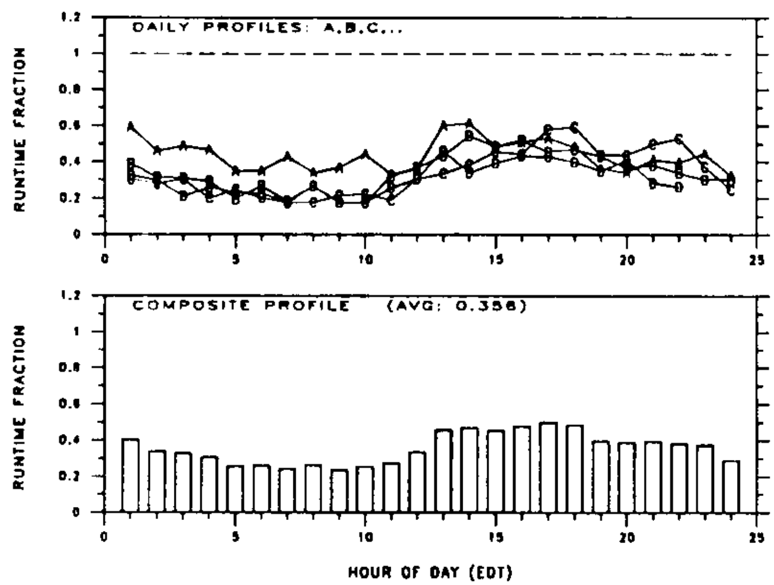
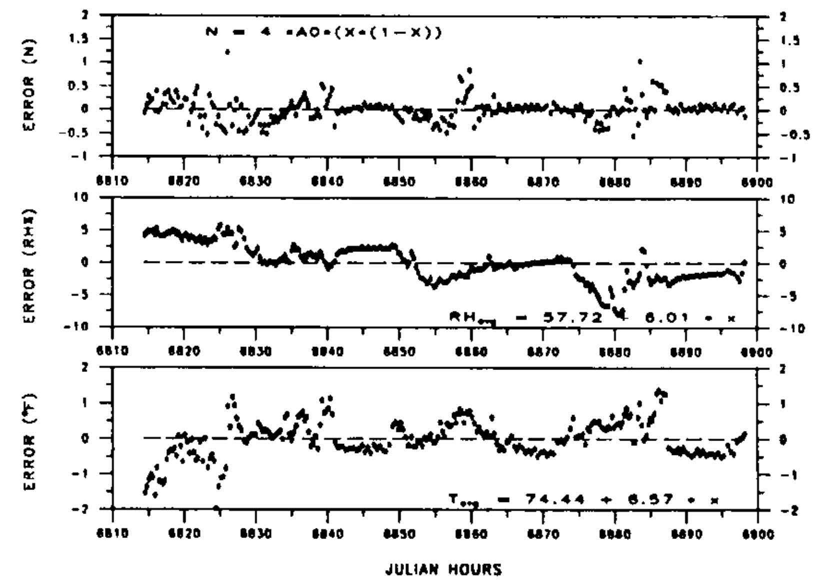
THERMOSTAT DATA: KANNAN

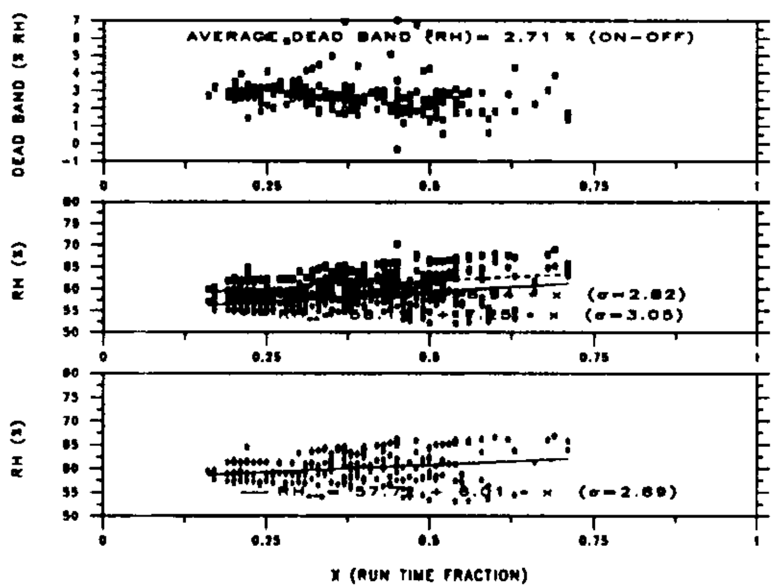
PLOT 4: RUN TIME PROFILES



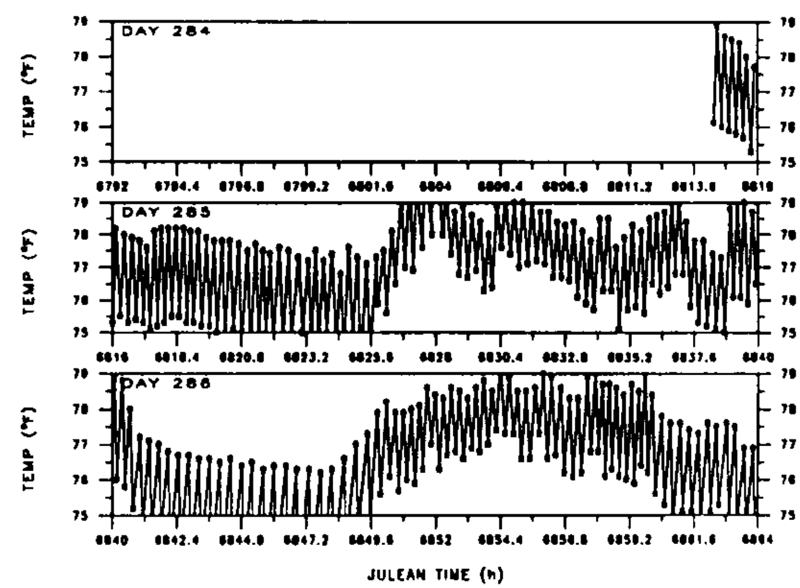
PLOT 5: ERROR ANALYSIS



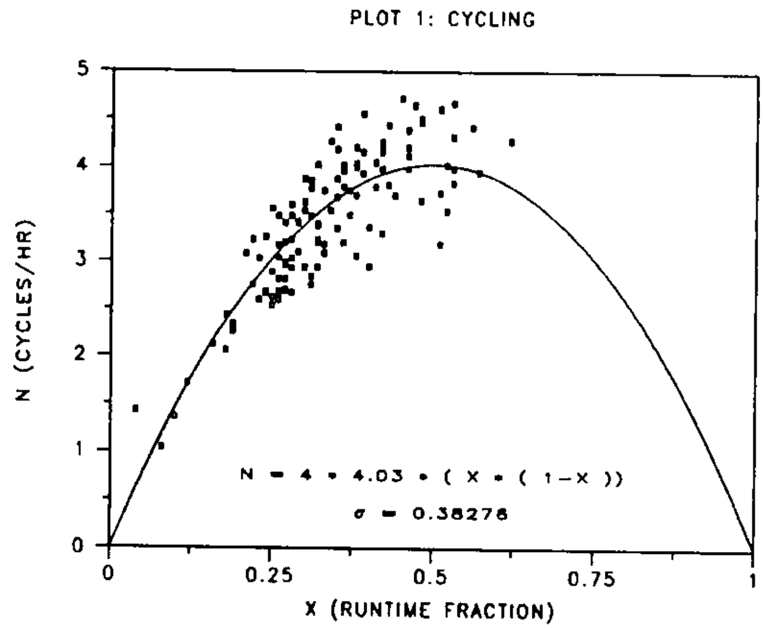
PLOT 6: HUMIDITY

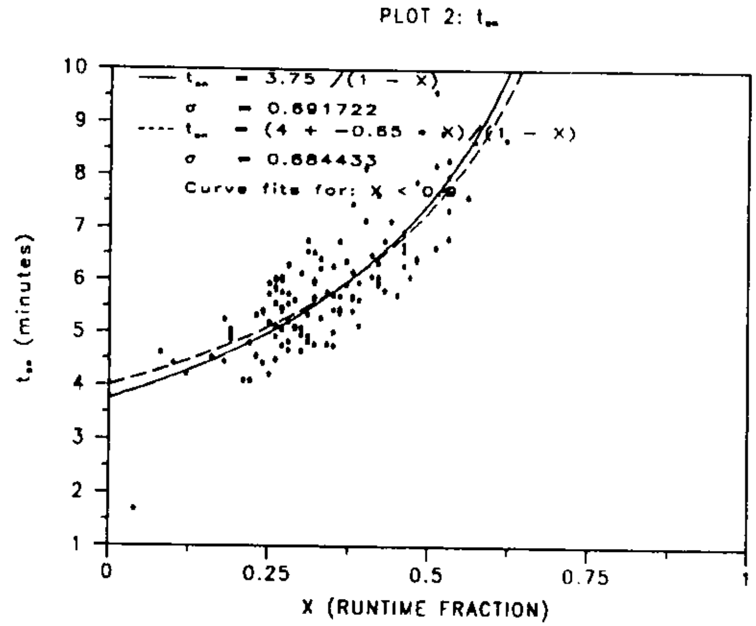


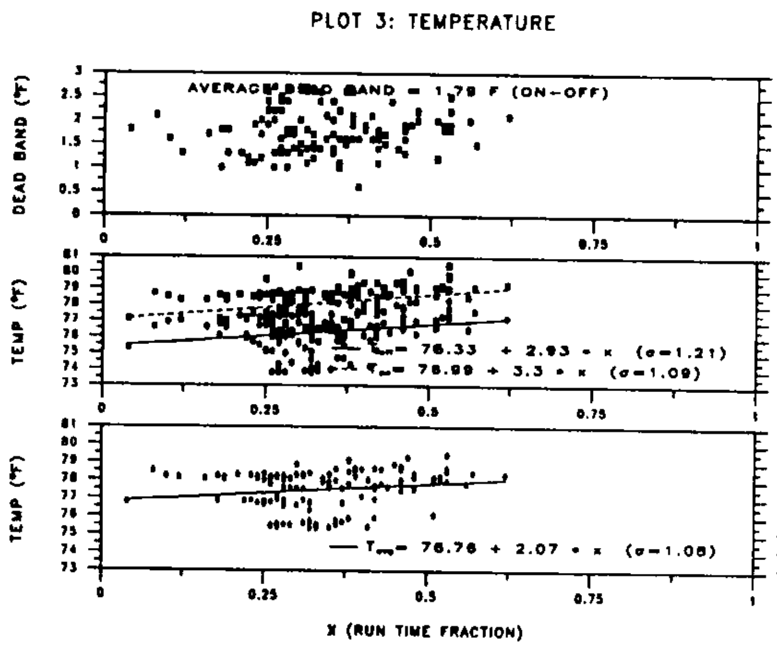
PLOT 7: TEMPERATURE VS TIME (3 DAYS)



THERMOSTAT DATA: KANNAN







SUMMARY OF THERMOSTAT PERFORMANCE DATA

LOCATION: YAROSH2

START DATE: 10/20 OR 293 TIME: 18:13:55 JULEAN HR: 7026.23

END DATE: 10/22 OR 295 TIME: 7: 8:25 JULEAN HR: 7063.14

ELAPSED TIME: 36.91

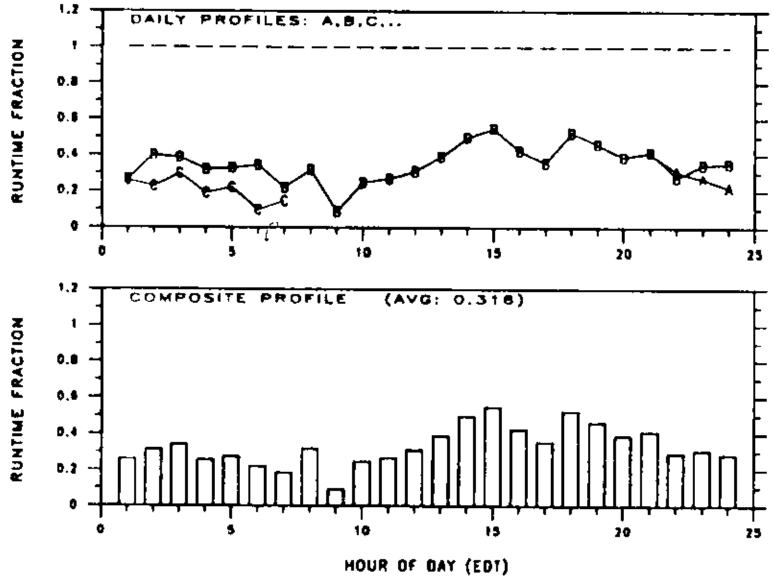
	TOTAL	ON	OFF
AVERAGE TEMP (DEG F)	77.41	76.99	77.61
AVERAGE RH (%)	63.32	63.05	63.45
HOURS	36.91	11.50	25.41
% HOURS		31.16	68.84

SELECTED DATA RANGE:

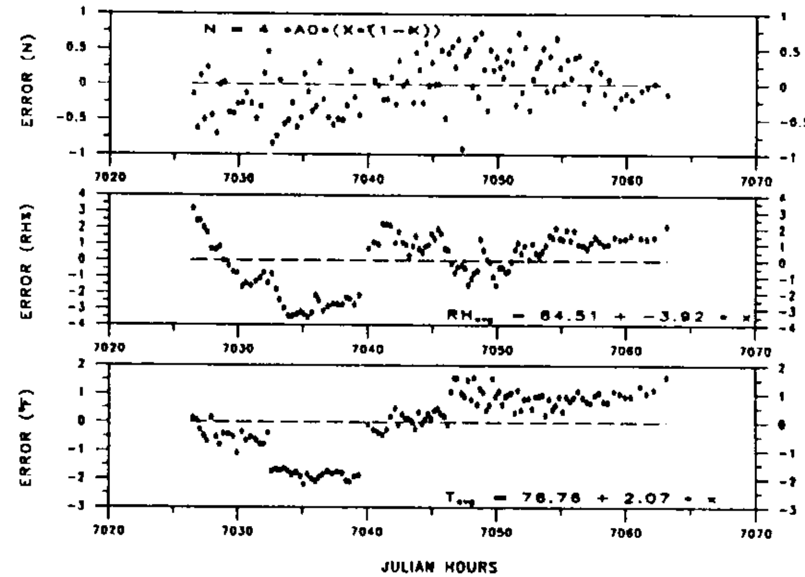
STARTING	293. ,	18. (	7026.000)
ENDING	295. ,	7. (	7063.000)

THERMOSTAT DATA: YAROSH2

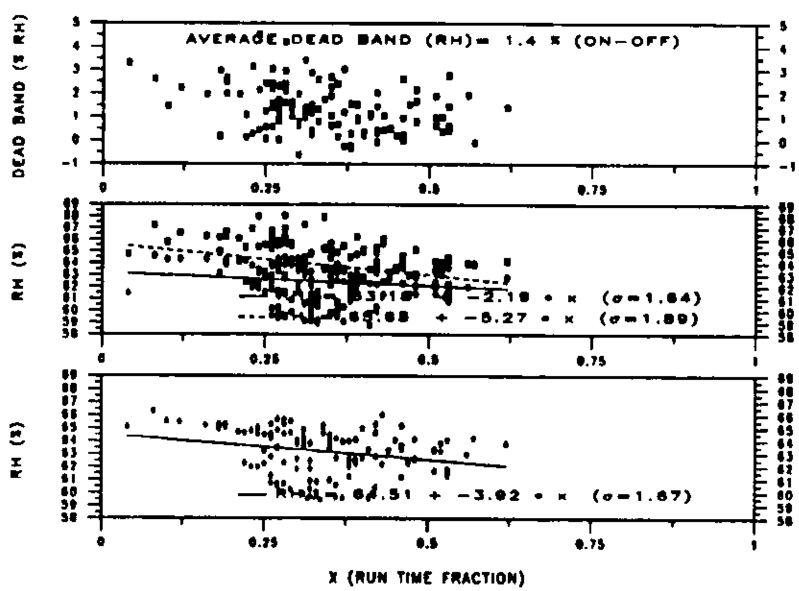
PLOT 4: RUN TIME PROFILES



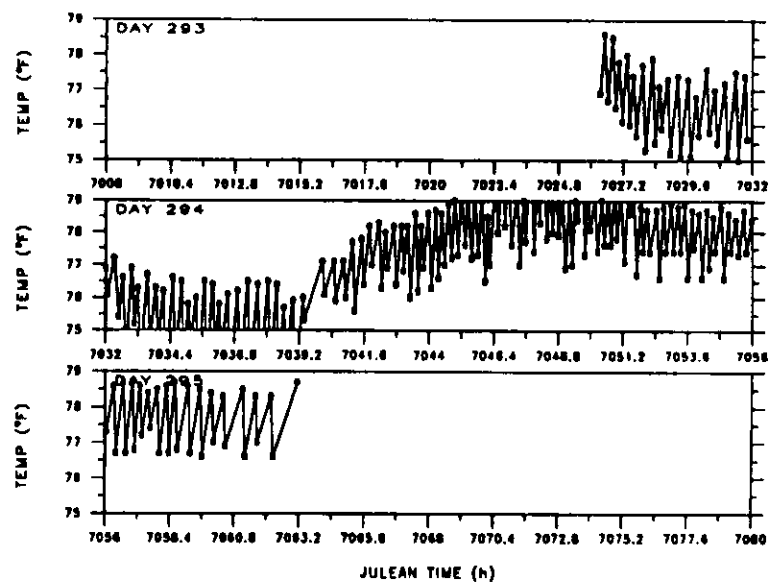
PLOT 5: ERROR ANALYSIS



PLOT 6: HUMIDITY



PLOT 7: TEMPERATURE VS TIME (3 DAYS)



THERMOSTAT DATA: YAROSH2

APPENDIX D

Cycling Rate and Thermostat Parameters From the Literature

TABLE D-1

Cycling Rate Parameters From Literature			
Source	N_{max} (cycles/hr)	$t_{ON,min}$ (minutes)	Comments
Murphy & Goldschmidt (1979)	2.83	**5.3**	Cooling mode in mobile home
Goldschmidt et al. (1980)	**2.8-3.3**	**4.6-5.3**	**Cooling, Mobile home with and without metal chairs**
Parken et al. (1985)	**2.00**	7.5	Cooling, Brick house w/basement
	2.28	6.6	Cooling, Frame house w/ walk-out basement
	1.64	9.1	Cooling, Frame house w/ walk-out basement
Miller & Jaster (1985)	**0.6-2.1**	7.1-25	Heating mode for 9 heat pumps
Hart & Goldschmidt (1980)	3.1	**4.8**	Heating mode
ARI (1984)	**3.125**	4.8	Inferred from cyclic test 6 min ON, 24 min OFF
Given data is bold, other value calculated from equation (A-6) $N_{max} = 60/(4t_{ON,min})$. See Appendix A for definition of N_{max} and $t_{ON,min}$			

TABLE D-2

Measured Thermostat Deadbands (ΔT_{spt}) from the Literature		
Source	Switch Deadband (ΔT_{spt})	Comments
McBride (1979)	0.8°F	Measured in laboratory
Miller & Jaster (1985)	2.5°F	Measured in field tests

APPENDIX E
Derivation of Part Load Efficiency Function

Derivation of Part Load Factor

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

First, define:

$$X = \frac{t_{ON}}{t_{cycle}} \tag{E-1}$$

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

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

$$N = 4N_{max}X(1-X) \tag{E-2}$$

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

Rearranging equation (E-2) results in:

$$t_{ON} = \frac{1}{4N_{max}(1-X)} \tag{E-3}$$

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

$$Q = Q_{ss}(1 - e^{-t/\tau}) \tag{E-4}$$

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

Integrating Q over t_{ON}:

$$q = \int_0^{t_{ON}} Q\,dt$$
$$q = Q_{ss}(t_{ON} - \tau(1 - e^{-t_{ON}/\tau})) \tag{E-5}$$

Then defining:

$$Q_{avg} = \frac{q}{t_{cycle}} \tag{E-6}$$

$$EER_{avg} = \frac{q}{E_{ss} t_{ON}} \tag{E-7}$$

$$EER_{ss} = \frac{Q_{ss}}{E_{ss}} \tag{E-8}$$

$$CLF = \frac{Q_{avg}}{Q_{ss}} = \frac{\text{Load}}{\text{AC Capacity}} \tag{E-9}$$

$$PLF = \frac{EER_{avg}}{EER_{ss}} = \frac{\text{Part Load EER}}{\text{Steady State EER}} \tag{E-10}$$

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

$$CLF = \frac{t_{ON}}{t_{cycle}} - \frac{\tau}{t_{cycle}}(1 - e^{-t_{ON}/\tau}) \tag{E-11}$$

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

$$PLF = 1 - \frac{\tau}{t_{ON}}(1 - e^{-t_{ON}/\tau}) \tag{E-12}$$

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

$$X = \frac{t_{ON}}{t_{cycle}} = \frac{CLF}{PLF} \tag{E-13}$$

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

$$PLF_{i+1} = 1 - 4\tau N_{max}(1-CLF/PLF_i)[1 - e^{\frac{-1}{4\tau N_{max}(1-CLF/PLF_i)}}] \tag{E-14}$$

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:

$$PLF = 1 - C_D(1-CLF) \qquad \text{(E-15)}$$

Where C_D is equal to 0.25 by default.

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

$$C_D \approx 4\tau N_{max}(1 - e^{\frac{-1}{4\tau N_{max}}}) \qquad \text{(E-16)}$$

From the default values used in the cyclic tests in the SEER procedure, τ and N_{max} can be shown to be:

τ = 76 seconds (0.0212 hours)
N_{max} = 3.125 cycles/hour

This results in:

C_D = 0.258

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