NBS BUILDING SCIENCE SERIES 150

Low-Voltage Room Thermostat Performance

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ABSTRACT

To predict performance of low voltage electric thermostats in a dynamic building system, a computer model representing two types of thermal feedback was developed. Unlike the information obtained from existing test standards, this model allows thermostat performance to be determined under any load conditions. As input to the model, the basic parameters of thermostat performance were first identified and then determined experimentally in a controlled laboratory facility. The experimental results from the tests were used as input parameters for the simulation model. Based upon the results from the simulation model and test results on four commercially-available thermostats, a switch-feedback model computer simulation is recommended for studying low-voltage room thermostat performance.

Key words: room temperature control; temperature controller; thermostat evaluation; thermostat modeling; thermostat test; two-position control

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1. INTRODUCTION

Almost all heating and cooling systems installed in residential houses and small buildings use "on-off" type mechanical thermostats for temperature regulation. The thermostat, an important part of a closed control loop, acts within a dynamic system created by characteristics of the heating and cooling plant, the overall thermal characteristics of the building and the load changes -- both internal and external -- to regulate the space temperature. Although each component in the loop influences the temperature level and the energy consumption of the building, as well as occupant comfort, it is particularly important that the behavior of the thermostat be understood and analyzed. To simulate and predict the performance of the thermostat within a dynamic system requires a thermostat model that is compatible with dynamic models of the whole system (plant, building, and load).

The present mechanical thermostat test standard adopted by the National Electrical Manufacturer's Association (NEMA) [1 & 2]* determines thermostat performance in an oversimplified dynamic environment. This standard assumes a certain fixed relationship between the heating/cooling plant performance, building thermal characteristics, and weather variations in which only three load conditions can be assessed. The NEMA test standard can measure thermostat performance within fixed constraints, but the results of the NEMA tests cannot be used to make detailed time--history predictions of the thermostat interactions within a more complex and realistic environment. The need exists for a dynamic, physically oriented model to predict thermostat performance within a complex, dynamic building system.

This report identifies four parameters necessary for predicting thermostat performance and uses a combination of experimental data and mathematical equations to calculate values of the parameters. These values are used as constants in a computer program which simulates thermostat performance, as represented by two different conceptual models, as a function of time and dynamic variations in the building system. The simulation results predicted from the two conceptual models are compared with experimental data for four thermostats. One conceptual model, the switch-feedback model, is shown to be in closest agreement with the observed test results.

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* Numbers in brackets indicate references cited at the end of the report.

2. MECHANICAL THERMOSTATS AND THERMOSTAT MODELS

2.1 MECHANICAL THERMOSTAT PHYSICAL DESCRIPTION

The thermostats covered by the NEMA standards can be described as wall-mounted, low-voltage room thermostats that control the heating and cooling of a structure. All of these thermostats contain certain functional components including a temperature sensing element, an on-off signalling and switching mechanism, and a protective case. Most thermostats also include an anticipating element (anticipator) which produces local heating of the sensor to increase the system cycling rate, resulting in reduced space temperature variation, as well as improved thermostat and system performance.

The actual construction of mechanical thermostats varies depending on manufacturer and model. Generally, for cooling applications, most thermostats have anticipators closely coupled with the sensing elements, with the heat transfer from the anticipators to the sensing elements occurring mostly by conduction. Thus, the anticipator can act directly on the thermostat switch without much delay from the sensor. However, significant differences in thermostat construction occur for the heating mode. These differences require two different conceptual models for representation -- a switch feedback model and a bimetal feedback model. Some thermostats rely more on conduction heat transfer to transmit heat from the anticipator to the sensor and others depend more on convective heat transfer from the anticipator to the sensor. The parameters needed to define these models will be discussed in the next section.

2.2 CONCEPTUAL MODELS OF MECHANICAL THERMOSTAT PERFORMANCE

The basic thermostat with secondary feedback consists of a two-position switch. a temperature sensor (usually a bimetal strip or coil), and an anticipating element as described previously. Two conceptual models of the dynamic performance of such thermostats have been used in simulations of residential heating systems [3, 4, 5, 6]. These models are presented schematically in figures 1 and 2.

Development of a workable computer simulation for each conceptual model requires physical (experimental) determination of four basic thermostat parameters. Two parameters can be used to describe the performance of the basic thermostat components including the sensor, and switching-signalling mechanism. They are:

- τ_{sen} -- the sensing element thermal time constant and,
- T_{swd} -- the thermostat switch differential

The sensing element time constant, τ_{sen}, is related to the time required for the thermostat sensing element to reach the temperature of the surrounding air and may be approximated by a first order response [5]. The switch differential, T_{swd}, relates the difference in the switch on or off temperatures, due to switch design and construction.

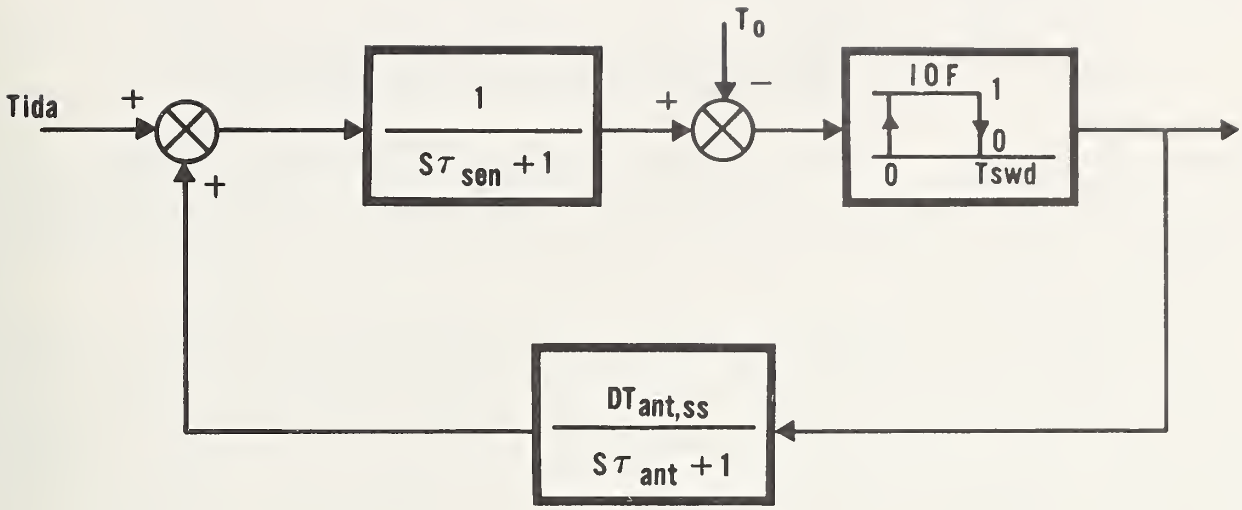


Figure 1. Bimetal feedback model of a thermostat

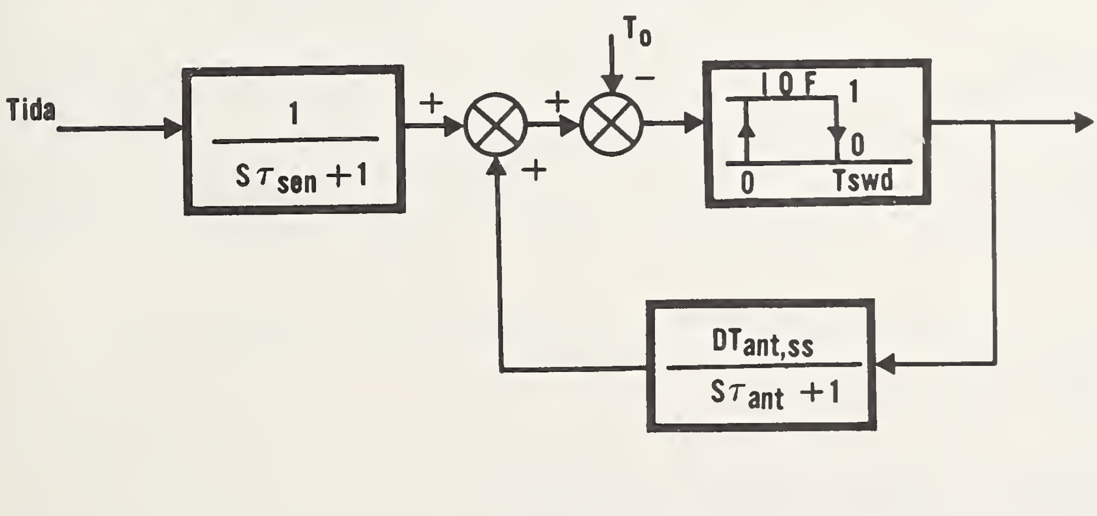


Figure 2. Switch feedback model of a thermostat

The addition of the anticipating element -- usually a small resistive heater -- adds the additional two parameters to be considered in the modeling of thermostat performance, namely:

- τ_{ant} -- the anticipating element thermal time constant and,
- $DT_{ant,ss}$ -- the steady-state anticipator temperature rise.

These parameters are somewhat misnamed in that each is a measure of the anticipator's effect on the sensing and switching element and not singly concerned with the anticipator. All of these parameters are listed and identified in table 1 along with the nomenclature for other variables that will be used throughout this report.

In these models, the ambient air influences the thermostat temperature through a time constant which accounts for the thermal dynamics associated with the thermal capacitance of the sensor. For heating, when the sensor temperature T_{sen}, (not the air temperature) rises above $T_o + T_{swd}$, the thermostat switches OFF, and the output of the switch block, IOF, is taken as "0". When the sensor temperature falls below the set point, T_o, the thermostat comes ON, calling for heat, and the output, IOF, goes to "1". The effect of the anticipator is accounted for with a second time-constant block. The second time constant is attributed to the thermal dynamics of the anticipator and sensor.

2.2.1 Bimetal Feedback Model

The thermostat model shown in figure 1, identified as the bimetal feedback model, has been previously used at NBS in control loop analysis of heating and cooling in residences and small building models. In this model the ambient air (T_{ida}) influences the sensor temperature (T_{sen}) through the sensor time constant (τ_{sen}). The anticipator, characterized by a second time constant (τ_{an}) and temperature rise ($DT_{ant,ss}$), also acts through the sensor time constant to produce the localized heating effect on the sensor. The latter two parameters in this model are defined as those of the air surrounding the sensor.

In the bimetal feedback model, the only way to affect the sensor temperature, T_{sen}, is through the sensor time constant, τ_{sen}. This places a fundamental restriction on the value of the anticipator time constant. In particular, with a typical sensor time constant around 15 minutes, and an effective anticipator temperature rise of 4 or 5 degrees, simulations and calculations both show that the anticipator time constant must be short in order to result in reasonable cycle rates.

The state equations of the sensor and anticipator for this model are:

$$\frac{dT_{sen}}{dt} = \frac{1}{\tau_{sen}} (T_{ida} + DT_{ant} - T_{sen}), \text{ and}$$

$$\frac{dDT_{ant}}{dt} = \frac{1}{\tau_{ant}} (IOF \times DT_{ant,ss} - DT_{ant}).$$

Table 1. Nomenclature for Variables Used in Thermostat Models

IOF	Variable describing thermostat state, 1 when ON, 0 when OFF
T_{opd}	Thermostat operating differential
T_{sen}	Sensor temperature
T_{ida}	Room air temperature
T_o	Thermostat set point (Does not necessarily coincide with indication on thermostat)
T_{swd}	The switch differential of the mechanical switch
τ_{sen}	Thermal time constant of the sensor
τ_{ant}	Thermal time constant associated with the anticipator (see text)
DT_{ant}	Temperature rise effect of sensor when the anticipator is ON (see text)
$DT_{ant,ss}$	Steady-state temperature rise effect of sensor when the anticipator is on (see text)
t	Time
FR	Falling temperature ramp rate
RR	Rising temperature ramp rate
s	The Laplace operator

2.2.2 Switch Feedback Model

The block diagram of this model is shown in figure 2. As in the bimetal feedback model, the ambient air (T_{ida}) influences the sensor temperature (T_{sen}) through the sensor time constant (τ_{sen}). However, in this model, the anticipator parameters τ_{ant} and DT_{ant} are defined as the effect of the anticipator on the sensor itself, not to the air surrounding the sensor. The anticipator contribution is added directly to the sensor without acting through the time lag induced by the sensor time constant. Thus, the time required to make the thermostat switch is much shortened.

In the switch feedback model, the temperature distribution along the sensor at equilibrium (steady state) would be different for the two excitations. For the ambient air, a uniform distribution would prevail. For the anticipator a non-uniform distribution would be found. The sketch in figure 3 is a rough version of what might be found with an anticipator tightly coupled only to the center support of a coiled spring sensing element.

The state equations of the sensor and anticipator for switch feedback are:

$$\frac{dT_{sen,1}}{dt} = \frac{1}{\tau_{sen}} (T_{ida} - T_{sen,1}),$$

$$\frac{dDT_{ant}}{dt} = \frac{1}{\tau_{ant}} (IOF \times DT_{ant,ss} - DT_{ant}), \text{ and}$$

$$T_{sen,2} = T_{sen,1} + DT_{ant}$$

In the next sections, a description of the experiments to obtain the values of the four parameters will be given. The experimental parameter values were then used in a computer simulation. At the same time the response of several thermostats to known changes in test chamber conditions were measured. Finally, the output from the simulation models were compared with experimental results to determine which conceptual model best predicts thermostat performance in a total system.

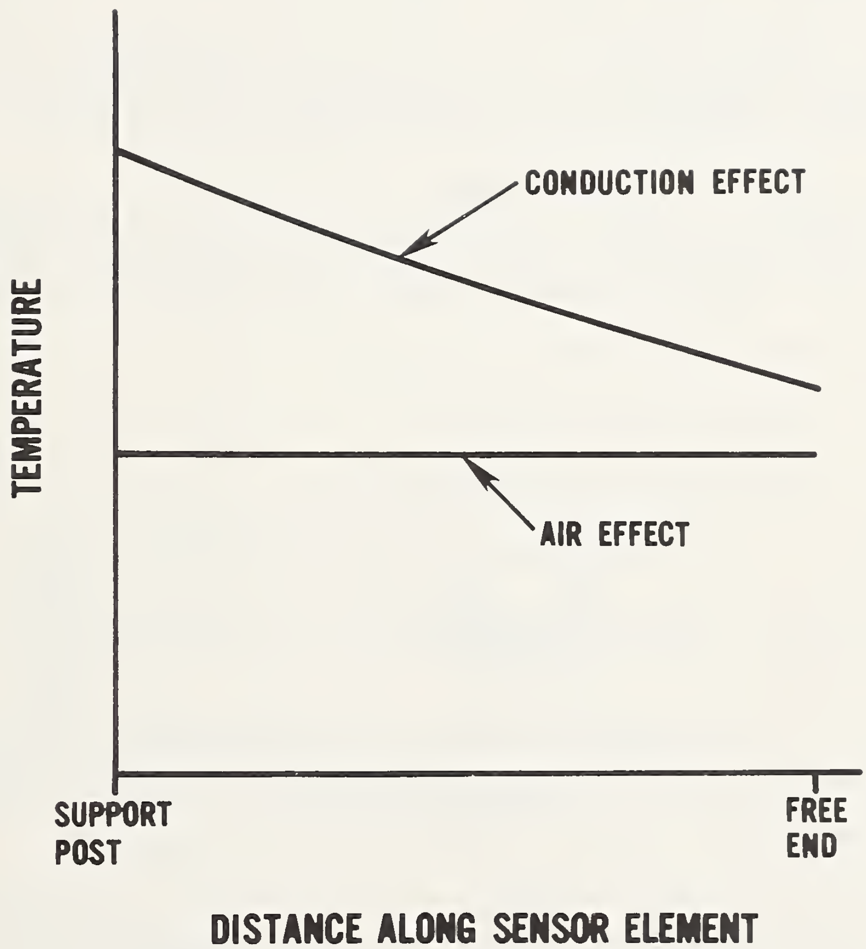


Figure 3. Conceptual representation of sensing element temperature distribution at steady state of a switch feedback model

3. EXPERIMENTAL FACILITIES AND GENERAL TEST PROCEDURES

3.1 RATIONALE FOR EXPERIMENTAL EVALUATION

The performance characteristics of thermostats may be assessed by experimental methods. As mentioned earlier, NEMA has a simplified test standard [2]. That standard provides some operating characteristics which are used generally to describe thermostat performance. Three important operating characteristics are listed below with NEMA's definitions.

- Operating differential -- the difference between cut-in and cut-out points as measured at the thermostat under specified operating conditions.
- Cycle time -- the time which elapses between successive cut-in points.
- Droop -- the deviation in the cut-in point which results from a change in the duty cycle, heating load or cooling load.

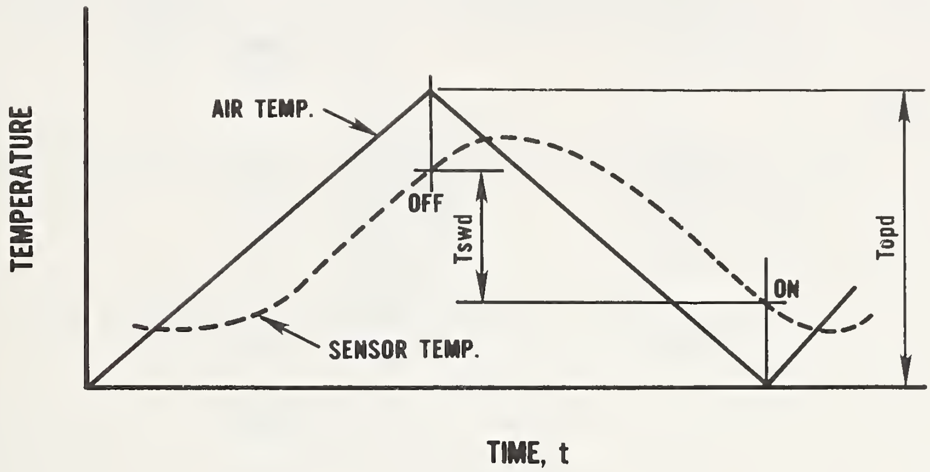
To assess the operation and performance of a thermostat under dynamic plant and building conditions, as opposed to certain fixed plant and building characteristics such as those used in the NEMA test method, computer model simulation is necessary. This simulation requires the determination of the values of:

- T_{swd} = thermostat switch differential,
- τ_{sen} = thermostat time constant,
- τ_{ant} = anticipator time constant, and
- $DT_{ant,ss}$ = anticipator temperature rise at steady state.

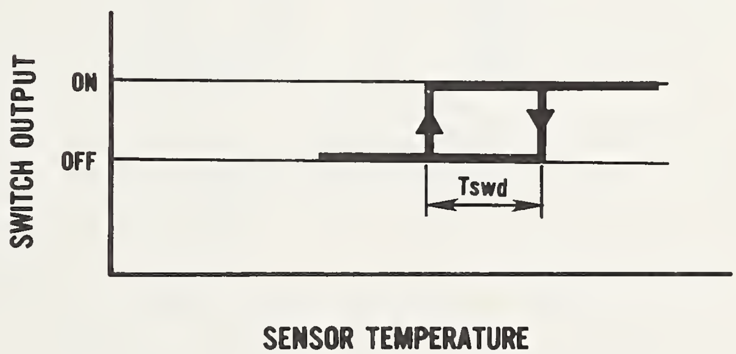
In addition to these four design parameters, the thermostat set point, an operating parameter, must also be known.

Direct measurement of the temperature of the thermostat sensor and anticipator is difficult, if not impossible. However, if the thermostat is placed in a temperature controlled test chamber, an output process that can readily be observed is the thermostat transition from OFF to ON, and ON to OFF, following a step or ramp change in the air temperature of the chamber.

The transition points from ON to OFF and OFF to ON define characteristic temperature points for each thermostat. Given a thermostat with a switch point of T_o as defined by the OFF to ON transition temperature, the ON to OFF transition will occur at a sensor temperature of $T_o + T_{swd}$ where T_{swd} defines the switch differential of the thermostat under test. Figure 4 is a diagram of the response of a thermostat to a ramped input for a given switch differential and element time constant. In this representation, the thermostat "controls" the input ramp direction and reacts to the ensuing change in temperature. This is similar to events occurring in an actual thermostat installation.



a. Air and sensor temperature relationship



b. Switch positions to element temperature

Figure 4. Air and sensor temperature relationship, and switch positions to element temperature

Measurements of the chamber air temperature and the time between thermostat transitions are used to obtain the thermostat parameters by using some of the equations presented later in the thermostat responses section (4.3).

A block diagram of the complete experimental test system, as constructed, is shown in figure 5. The system is composed of several sub-units, each of which is discussed individually.

3.2 TEST CHAMBER

All thermostat tests were conducted in a NEMA type test chamber as shown in figure 6. This chamber contained:

- The thermostat under test;
- A controllable air supply with provision for controlling air velocity and air temperature at the thermostat;
- Provision for measurement of air flow with a hot-wire anemometer,
- Several sets of copper-constantan thermocouples, and an associated ice bath reference.

Air circulated downward in the test chamber and was returned through the recirculation duct where electric heating wire was placed for chamber air temperature control. The entire test box was housed in a 10' x 10' x 9' (3.05 m x 3.05 m x 2.74 m) high environmental room which was controlled at lower temperature than the test chamber to provide cooling necessary for the test box during temperature ramp down tests. The speed of the circulation fan was adjustable by varying the supply electric voltage through an adjustable autotransformer. A manual damper located in the circulation duct was also used to adjust the air velocity of the test chamber in conjunction with the auto-transformer. The air velocity at the thermostat was checked and maintained manually. The variance in air velocity within the horizontal and vertical planes 1 to 4 inches (2.54×10^{-2} to 10.16×10^{-2} m) in front of the center of the thermostat was within $\pm$ 6 ft/min (3.05×10^{-2} m/s) during the experiment. The velocity at 1" (2.54×10^{-2} m) in front of the center of the thermostat was 30 ft/min (1.52×10^{-1} m/s) and the variance in velocity at this point was within $\pm$ 3 ft/min (1.52×10^{-2} m/s) during a 5-minute duration. A hot-wire anemometer was used to check the air velocity at the beginning and the end of each test. The thermostat mounting panel was suspended in the chamber on shock cords to minimize the interference of the thermostat by outside disturbances.

The primary difference between this chamber and that of the NEMA standard was the lack of a cooling coil in this chamber, which limited step-down temperature input capability. The high capacity electric heating wire gave satisfactory step up chamber temperature changes, however.

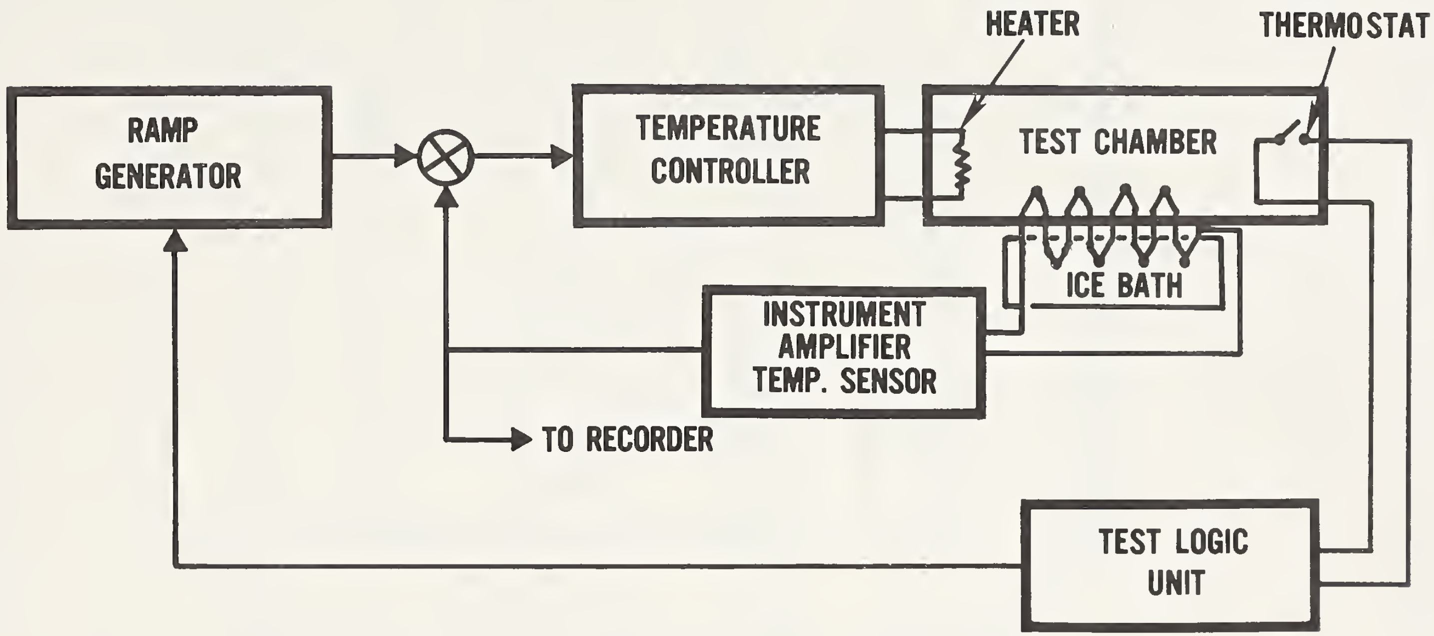


Figure 5. The thermostat test system

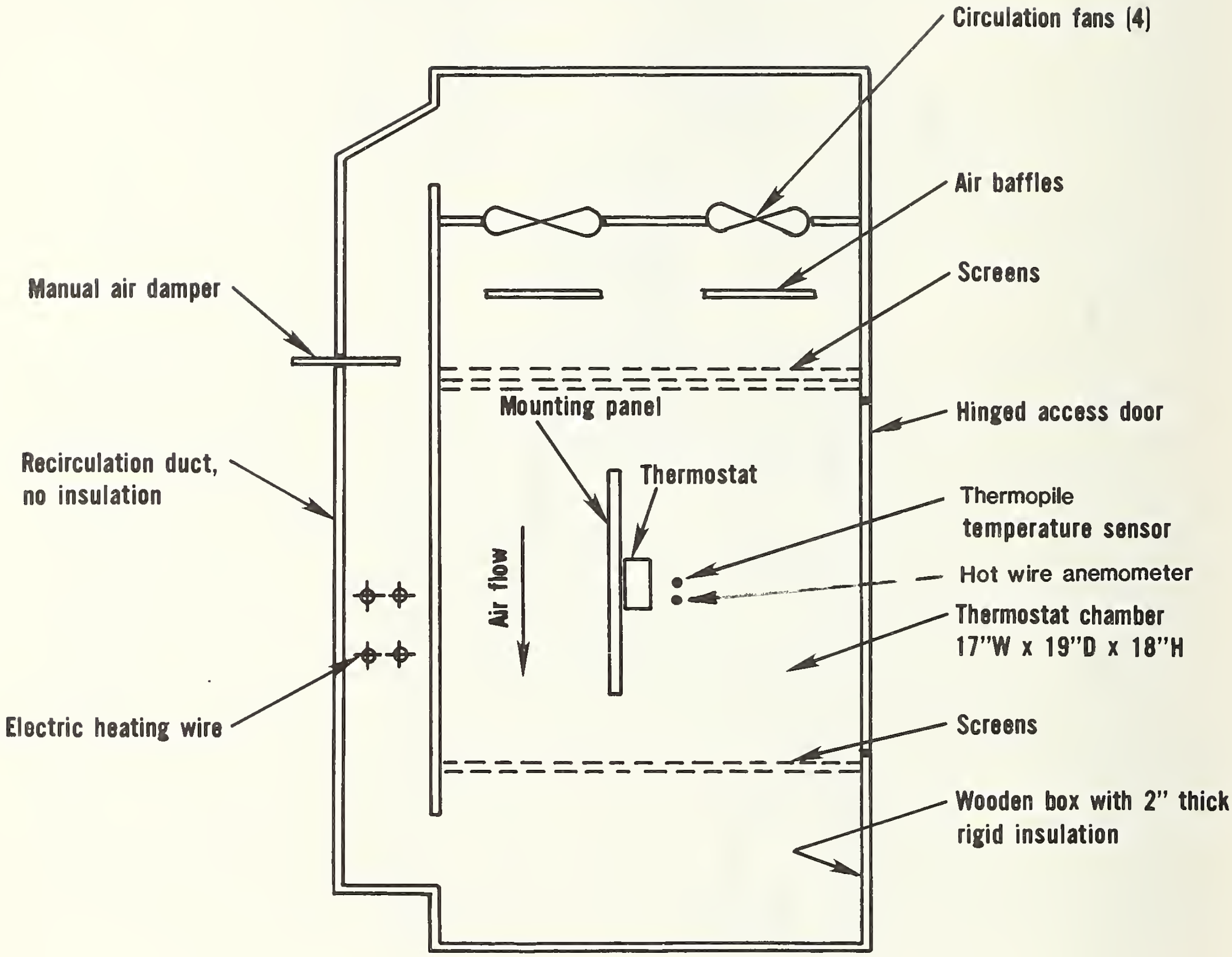


Figure 6. Thermostat test chamber

3.3 MEASUREMENT AND CONTROL SYSTEM

The chamber temperature measurement and control system consisted of a digital ramp (temperature) generator, a test logic unit, a temperature sensor, and a proportional controller. The system was capable of:

- Generating all appropriate test signals, including ramps at any desired rate, and step ups of any reasonable size;
- Generating an electrical indication of the air temperature applied to the thermostat;
- Using the test input and electrical temperature indication to control the air temperature applied to the thermostat;
- Recording the control signal and the measured temperature;
- Operating with the anticipator on or off, as required; and
- Providing a means for thermostat control of the applied air temperature.

3.3.1 Digital Ramp Generator

The digital ramp generator produced an increasing or decreasing binary count that was converted to a discretely stepped ramp in a D/A convertor. The digital ramp generator consisted of:

- A pulse generator with provision for controlling the frequency output;
- Logic to provide the necessary control signals for an up/down counter,
- One-shot multivibrators to provide very short count signals to minimize noise problems in the counter;
- A ten bit binary counter built from three four-bit counter chips, and
- A D/A converter block to convert the counter ouput to an analog signal.

In operation, the output of the counter went to the D/A converter which drove an operational amplifier. The converter and amplifier were calibrated so that each count corresponded to .01°F for .01 volt. For example, a ten volt signal resulted in a change of ten degrees.

Figure 7 shows the general signal flow in the digital ramp generator.

3.3.2 Test Logic Unit

The primary function of the test logic unit was to provide an up/down binary signal for the counter, based on the thermostat ON or OFF state, and to provide a varying load for the anticipator, or provision for disabling the anticipator if desired.

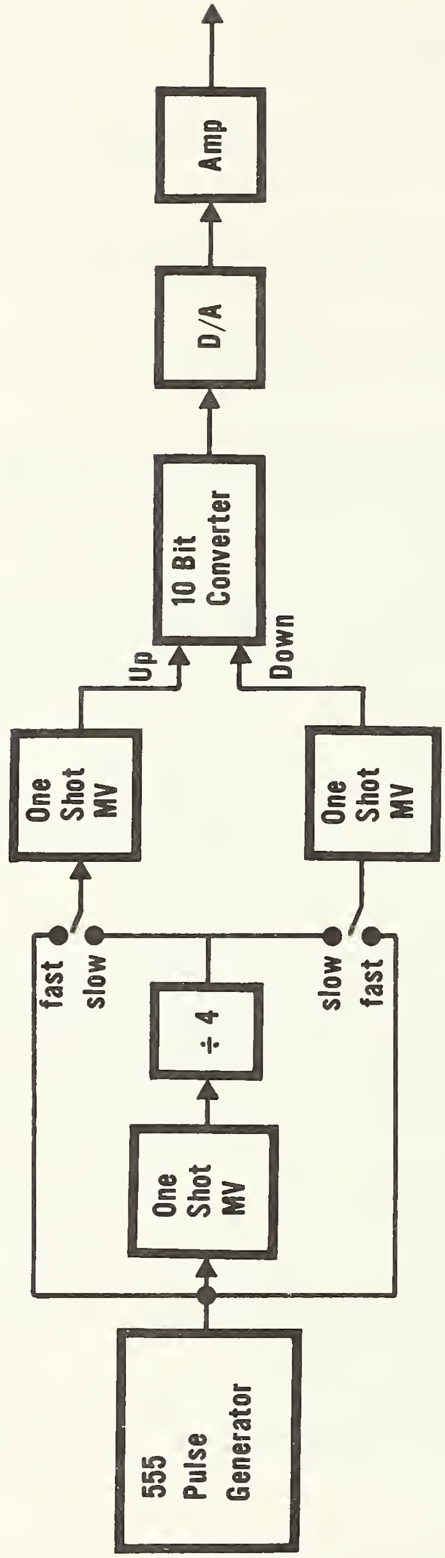


Figure 7. Digital ramp generator

The test logic unit served as an interface between the thermostat and the rest of the circuitry while electrically isolating the thermostat. A 24 volt transformer, which served as an isolation transformer, provided 24 volts to drive the anticipator. The anticipator current could be varied from zero to one ampere.

When the thermostat contacts were closed, a 24 volt signal appeared across a rectifier-type detector. This signal produced a DC voltage to drive an optical isolator which produced a logic level output of one when the thermostat was ON (about 3 volts) and zero when OFF (less than one volt).

3.3.3 Temperature Sensing Circuit

The temperature sensing circuit consisted of a thermopile comprised of eight junctions and an ice-bath reference. It provided an output signal indicating the air temperature in the test chamber. An instrumentation amplifier and an operational amplifier were used to amplify the thermopile output. Zero and gain adjustments were provided to produce a 0 volt output at 70°F and a 10 volt output at 80°F under normal operation. Voltage output was monitored on a digital voltmeter and recorded on a strip chart recorder. The measurements of chamber temperature were monitored using a thermopile of four junctions connected to a temperature indicator.

3.3.4 Proportional Controller

A proportional controller provided proportional, derivative, and integral (PID) control of the wire wound electric heater in the test chamber. The controller was used to amplify an input signal consisting of the algebraic difference between the ramp generator control signal and the temperature sensing circuit ouput voltage. During the test program, the controller provided heat input rates corresponding to 0.062°F per hour, which gave essentially constant ambient temperature.

3.4 GENERAL TEST PROCEDURES

Experimental tests were set up and conducted under conditions prescribed by the NEMA test procedures to the extent possible. These procedures included the specification of the test chamber, thermostat installation, anticipator setting, thermostat duty cycles, and corresponding temperature input ramp rates. Duty cycles of 20, 50, and 80 percent were used in tests requiring slow ramps where the corresponding temperature ramp rates were (+8/-2)°F/h, (+6/-6)°F/h, and (+2/-8)°F/h. Measurements and calculations were made of the thermostat operating differential (T_{opd}), cycle rate, and droop, as well as the thermostat parameters as discussed previously. Part 4 of the NEMA Standard, "Testing and Performance," [2] is included for reference in appendix A.

Before the start of any test, a settling period was provided to allow the thermostat system to come to an equilibrium. For stepped temperature ramp or anticipator input tests, this settling period consisted of application of a constant temperature input (+0.062 °F/h) for a time period not less than four estimated sensor time constants, usually 1 1/2 to 2 hours. For the slow ramp tests, a quasi-steady state was assumed to exist when successive high and low switch points were free of transient drift, i.e., successive readings differed by less than 0.1°F.

All temperature measurements were taken in degrees Fahrenheit, since this temperature scale is used exclusively for home thermostats in the United States.

4. RESPONSE EQUATIONS AND MEASUREMENT METHODS FOR OBTAINING THE VALUES OF THE FOUR THERMOSTAT PARAMETERS

4.1 THERMOSTAT COMPONENT RESPONSE ANALYSIS

A series of measurements of thermostat component response was used to calculate the values for the thermostat parameters noted earlier. These measurements involved different combinations of test chamber conditions and thermostat operating characteristics.

The input to a thermostat in an actual installation can never be exactly specified. However, simple excitations, such as step and fixed-rate ramp temperature changes, can be used in a laboratory to observe the response of the thermostat. The observed thermostat responses to these excitations, then, may be used to calculate values for the various parameters discussed in the previous section.

All of the mathematical models of thermostat response contain exponential terms with time constants for either the sensor or the anticipator. If the time of the tests are held long, it may be assumed that all such exponential terms have decayed to insignificance. Therefore, asymptotic, steady-state forms will be discussed for all responses.

In this report, the terms "slow ramp" denotes those ramps in which transients decay to insignificance. For a "very slow ramp" the term "RR τ_{sen}" is also significant. With a "very slow ramp," however, the entire thermostat is at the same temperature as the air and changes slowly. With a "slow ramp," the thermostat comes to a uniform temperature, but a small temperature difference exists between the air and the sensing element depending on the ramp rate and the time constant of the sensor. This is shown in figure 8.

4.2 EQUATIONS REPRSENTING THERMOSTAT RESPONSE

A series of equations representing the sensor temperature as a function of various combinations of simple excitations and anticipator activator were developed. The following are mathematical representations of some of the possible sensor responses subjected to a step or ramp temperature change of the space air with the anticipator either disabled or activated. The sketches in the following paragraphs depict the possible temperature variations of the space air and the sensor. Temperature is shown on the ordinate and time is shown on the abscissa. In all cases, the thermostat and the space air are in equilibrium at t=0, with this initial temperature represented as $T_{ida,0}$. $T_{ida,1}$ is the space air temperature after the step jump. Other notations are as shown in table 1.

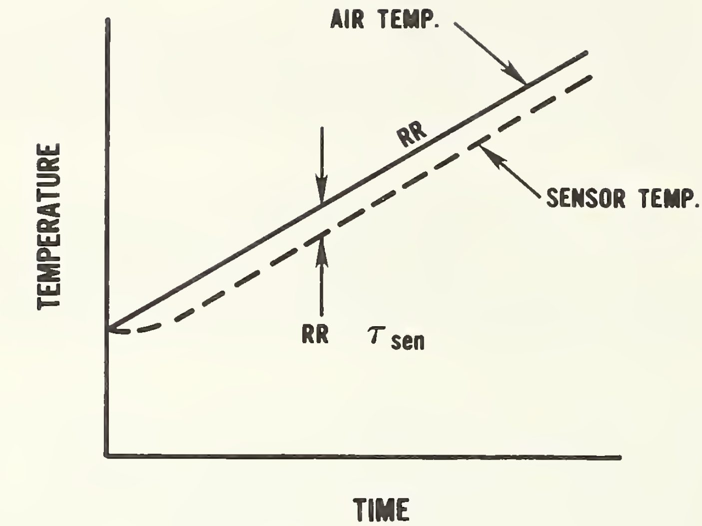
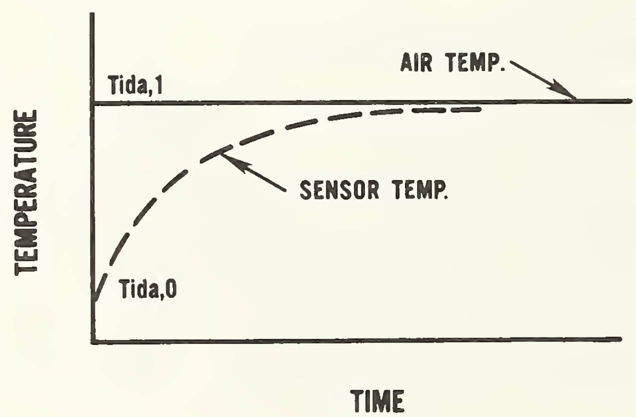


Figure 8. Sensor response to a slow ramp temperature change

a. Sensor temperature (T_{sen}) as a function of a step up of space air temperature, with the anticipator disabled (both models)

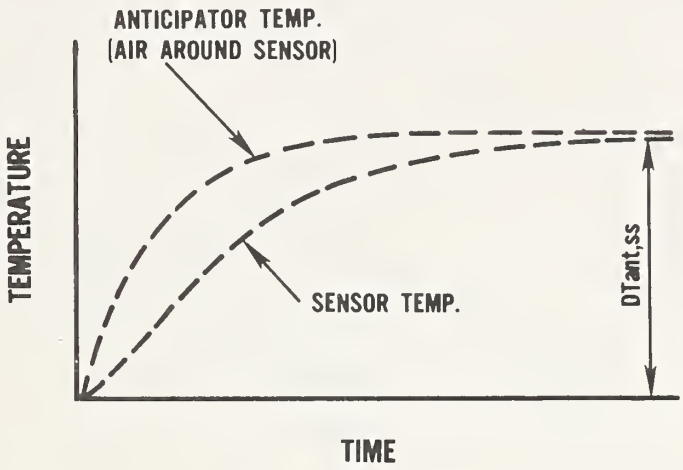


$$T_{sen}(t) = T_{ida,0} + (T_{ida,1} - T_{ida,0})(1-e^{-t/\tau_{sen}})$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,1}$$

b. Sensor temperature with space air temperature constant and anticipator activated, (bimetal feedback model)

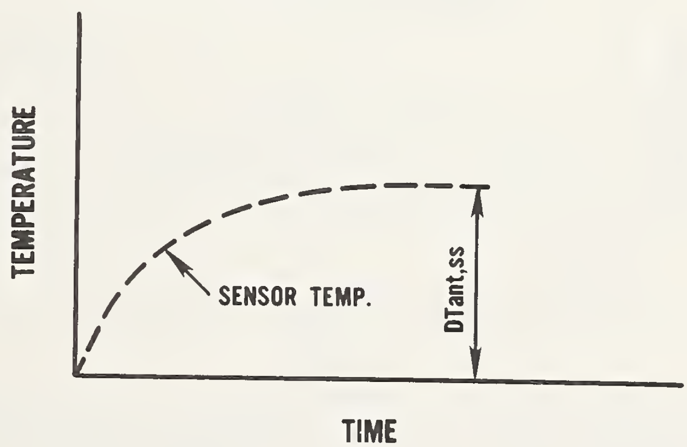


$$T_{sen}(t) = T_{ida,0} + DT_{ant,ss}\left[(1-e^{-t/\tau_{sen}}) + \frac{\tau_{ant}}{\tau_{ant}-\tau_{sen}}\left(e^{-t/\tau_{sen}} - e^{-t/\tau_{ant}}\right)\right]$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,0} + DT_{ant,ss}$$

c. Sensor temperature with space air temperature constant, and the anticipator activated, (switch feedback model)

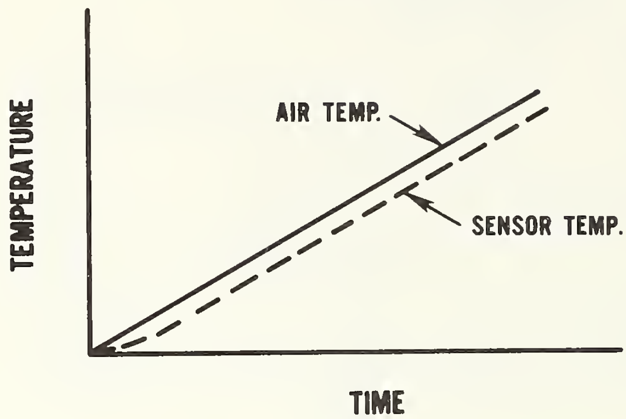


$$T_{sen}(t) = T_{ida,0} + DT_{ant,ss}\,(1-e^{-t/\tau_{ant}})$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,0} + DT_{ant,ss}$$

d. Sensor temperature after a rising ramp of space air temperature, with the anticipator disabled (both models)

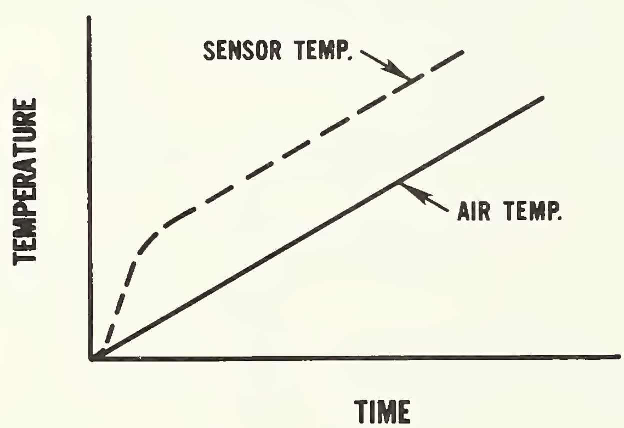


$$T_{sen}(t) = T_{ida,0} + (RR)t - (RR)\tau_{sen}(1-e^{-t/\tau_{sen}})$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,0} + (RR)t - (RR)\tau_{sen}$$

e. Sensor temperature after a rising ramp of space air temperature, with anticipator activated (bimetal feedback model)

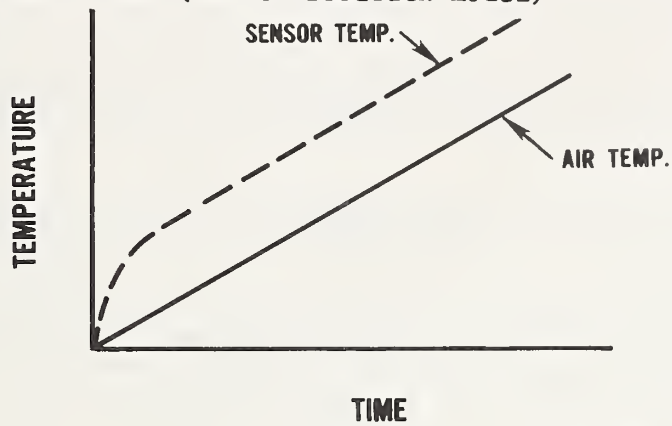


$$T_{sen}(t) = T_{ida,0} + (RR)t - [(RR)\tau_{sen} - DT_{ant,ss}](1-e^{-t/\tau_{sen}})$$
$$- \frac{DT_{ant,ss}\ \tau_{ant}}{\tau_{ant} - \tau_{sen}}(e^{-t/\tau_{sen}} - e^{-t/\tau_{ant}})$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,0} + (RR)t - [(RR)\ \tau_{sen} - DT_{ant,ss}]$$

f. Sensor temperature after a rising ramp of space air temperature, with anticipator activated (switch feedback model)



$$T_{sen}(t) = T_{ida,0} = (RR)_t - (RR)\ \tau_{sen}\ (1-{}^{-t/\tau_{sen}})$$

$$- DT_{ant,ss}\ (1-e^{-t/\tau_{ant}})$$

Asymptotic at large t:

$$T_{sen}(t) = T_{ida,0} + (RR)t - [(RR)\ \tau_{sen} - DT_{ant,ss}]$$

Values for the constants, T_{swd}, τ_{sen}, $DT_{ant,ss}$ and τ_{ant}, given in these equations, are be determined sequentially. Experimental results are used to calculate T_{swd}. This value is then combined with experimental data to calculate τ_{sen}, and so forth. The experimental procedure is described in section 4.3.

4.3 MEASUREMENT METHODS

Values of the four constants, T_{swd}, $DT_{ant,ss}$ and τ_{ant}, were determined by inserting experimentally obtained data into a sequential series of thermostat response equations. It should be noted that some parameters may be determined by more than one method. The measurement procedure and response equation is described for each constant in turn.

a. Measuring Switch Differential T_{swd} and Set-Temperature T_o--Very Slow Ramp Method

The switch differential and set-temperature may be measured using very slow ramps with the anticipator disabled. For a very slow ramp, all transient (time constant) effects are negligible in the steady state, and the temperature lag, $(RR)\tau_{sen}$, due to ramp rate (RR) and sensor time constant (τ_{sen}) is insignificant. If this condition can be achieved, then a quasi-steady state exists, and it can safely be assumed that the sensing element of the thermostat is at the same temperature as the test chamber air. Under these conditions, a reasonable way to measure set temperature and switch differential is as follows:

- Set the anticipator resistance to zero.

- Turn the thermostat ON and set at a temperature not too far below the expected value of $T_0 + T_{swd}$.

- Slowly ramp the chamber temperature up until the thermostat switches from ON to OFF. The chamber temperature at which this occurs is very close to $T_0 + T_{swd}$.

- Ramp down until the thermostat switches back ON. The chamber temperature at which this occurs is close to the set-temperature T_0.

While this method for measuring set point and switch differential seems reasonably direct, some precautions should be observed. It is assumed that the applied ramp is very slow, so that all transients die out, and the lag (RR) τ_{sen} is negligible. If the time-constant is expected to be approximately a quarter of an hour, then for a 0.1°F error, the ramp rate must be less than 0.4°F/hr. If sufficient care is not taken, then ramp rate can lead to an excessively long test, especially if the set point is not well known.

b. Measuring Sensor Time-Constant τ_{sen} -- Step Temperature Method

Once the set-temperature and switch differential have been determined, it is possible to measure the sensor time constant by applying a step to the chamber temperature while the anticipator is disabled. In this situation, the procedure for measuring the sensor time constant is:

- Bring the system to steady state by applying a constant chamber temperature, $T_{ida,0}$. To achieve steady state, the thermostat input must be held at this value for a time that permits all transients to decay, usually at least four time constants. Since the time constant is being measured, some reasonable estimate must be used.

- Step up the chamber temperature to a new value, $T_{ida,1}$. The response to this step is shown in paragraph 4.2a.

- Record the elapsed time t until the thermostat switches from ON to OFF, or when the sensor temperature reaches $T_0 + T_{swd}$.

- From the sensor response equation of paragraph 3.1a, solve for the sensor time constant.

$$\tau_{sen} = - t/(\ell n \, [\frac{T_{ida,1} - T_0 - T_{swd}}{T_{ida,1} - T_{ida,0}}])$$

c. Measuring Switch Differential T_{swd}, Set-Temperature T_0 and Sensor Time Constant τ_{sen} -- Slow Ramp Method

An alternate method for determining switch differential, set temperature, and sensor time constant is to disable the anticipator and conduct two ramp tests at different ramp rates. Figure 9 shows the test chamber air and sensor temperatures as a function of the ramp tests, once they have stabilized.

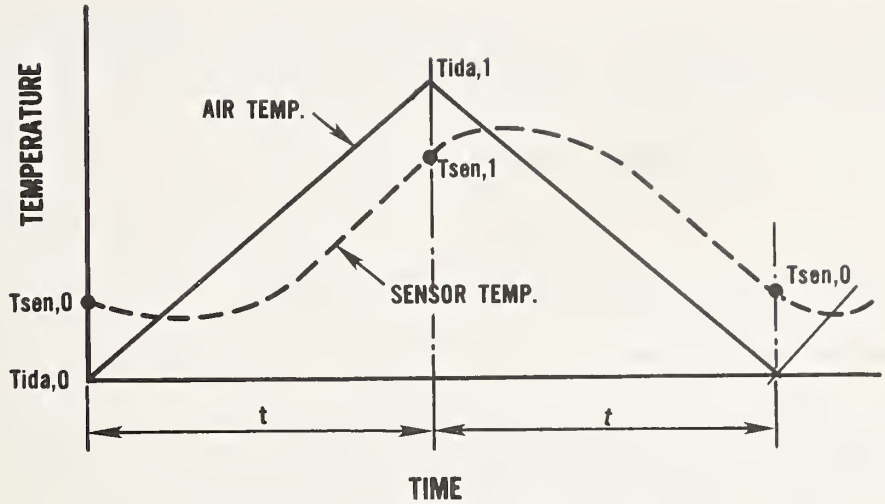


Figure 9. Air and sensor temperature under ramp test

While the chamber air temperature is ramping up, the sensor temperature at the switching off point can be determined by (similar to the response shown in paragraph 4.2.d):

$$T_{sen,1} = T_{sen,0}\, e^{-t/\tau_{sen}} + t_{ida,0}\,(1-e^{-t/\tau_{sen}}) + (RR)t - (RR)\tau_{sen}\,(1-e^{-t/\tau_{sen}})$$

Similarly for ramping down, the sensor temperature at the switching on point is:

$$T_{sen,0} = T_{sen,1}\, e^{-t/\tau_{sen}} + T_{ida,1}\,(1-e^{-t/\tau_{sen}}) + (RR)t + (RR)\tau_{sen}\,(1-e^{-t/\tau_{sen}})$$

Substracting one equation from the other and using the relations

$T_{sen,1} - T_{sen,0} = T_{swd}$,

$T_{ida,1} - T_{ida,0} = T_{opd}$, and

$T_{ida,1} = T_{ida,0} + (RR)t$

we have

$$T_{opd}\,(1+e^{-t/\tau_{sen}}) = T_{swd}\,(1+e^{-t/\tau_{sen}}) + 2\,(RR)\tau_{sen}\,(1-e^{-t/\tau_{sen}})$$

The same equation may be used for two ramp tests. If the subscripts f and s denote the representation of the faster and slower ramps and using E_f for $e^{-t_f/\tau_{sen}}$ and E_s for $e^{-ts/\tau_{sen}}$, we have

$$T_{opd,f}\ (1+E_f) = T_{swd}\ (1+E_f) + 2(RR)_f\ \tau_{sen}\ (1-E_f)$$

and

$$T_{opd,s}\ (1+E_s) = T_{swd}\ (1+E_s) + 2(RR)_s\ \tau_{sen}\ (1-E_f)$$

Solving for the sensor parameters:

$$\tau_{sen} = \frac{1}{2}\ \frac{(T_{opd,f} - T_{opd,s})\ (1+E_f)\ (1+E_s)}{(RR)_f(1-E_f)(1+E_s)-(RR)_s(1+E_f)(1-E_s)}$$

$$T_{swd} = \frac{T_{opd,f}(RR)_s(1+E_f)(1-E_s) - T_{opd,s}(RR)_f(1-E_f)(1+E_s)}{(RR)_f(1+E_f)(1-E_s) - (RR)_s(1-E_f)(1+E_s)}$$

Since the time constant of the sensor appears exponentially on the right hand side, these two equations are impossible to solve analytically. However, they may be used iteratively to obtain the parameter values.

If a thermostat has a very small time constant and relatively large switch differential, the transient effect of the sensor fades before the switch changes. Then these two equations become

$$\tau_{sen} = \frac{1}{2}\ \frac{T_{opd,f} - T_{opd,s}}{(RR)_f - (RR)_s}$$

$$T_{swd} = \frac{T_{opd,f}(RR)_s - T_{opd,s}(RR)_f}{(RR)_f - (RR)_s}$$

and the set-temperature is

$$T_o = T_{ida,0} + RR\tau_{sen}.$$

d. Measuring Steady State Anticipator Temperature Rise $DT_{ant,ss}$ -- Slow Ramp Method

The steady state temperature rise of the thermostat sensor due to the anticipator, $DT_{ant,ss}$, can be determined from the asymptotic solutions to the sensor response given in paragraphs 4.2e and 4.2f using a slow ramp. The procedure consists of initially bringing the thermostat system into a steady state equilibrium condition at $T_{ida,0}$. This temperature should be low enough that the switch will not turn on before the sensor transient dies out. With the air and sensor in equilibrium, a slow ramp temperature input is applied and the anticipator is turned on. The asymptotic sensor response is

$$T_{sen} = T_{ida,0} + (RR)t - (RR)\tau_{sen} + DT_{ant,ss}$$

At the thermostat ON to OFF switch point,

$$T_{sen} = T_o + T_{swd} \text{ and } T_{ida,0} + (RR)_t = T_{ida,t}$$

therefore

$$DT_{ant,ss} = T_o + T_{swd} = T_{ida,t} + (RR)\tau_{sen}.$$

where $T_{ida,t}$ is the air temperature at the switch point.

e. Measuring Anticipator Time Constant τ_{ant} by Activating the Anticipator

The anticipator time constant τ_{ant} may be determined by activating the anticipator after the sensor and the test chamber air are in equilibrium. So that the anticipator heat will turn the thermostat switch from ON to OFF, the chamber air temperature should be kept higher than the thermostat cut-out temperature, minus the steady state anticipator temperature rise. In equation form, it is represented by

$$T_{ida,0} > T_o + T_{swd} - DT_{ant,ss}.$$

The elapsed time from ON to OFF is recorded.

From paragraph 4.2b the sensor temperature at switch OFF point for the bimetal feedback model can be represented by:

$$T_{sen} = T_o + T_{swd} = T_{ida,0} + DT_{ant,ss} \,(1-e^{-t/\tau_{sen}})$$
$$+ \frac{\tau_{ant}}{\tau_{ant} - \tau_{sen}} \,(e^{-t/\tau_{sen}} - e^{-t/\tau_{ant}})$$

Although the values of T_o, T_{swd}, $T_{ida,0}$, $DT_{ant,ss}$, t, and τ_{sen} are all known from previous tests, τ_{ant} may be difficult to determine, since the anticipator and sensor temperature history curves do not converge before the sensor is ON (see sketch of sensor and anticipator temperatures in paragraph 4.2b). Because of the relatively high thermal diffusivity of air and because most thermostat anticipators have very small thermal mass resistant heaters, the anticipator time constant of the bimetal feedback model should be very short. Test results by McBride indicate that the anticipator time constant is almost instantaneous [5]. If this assumption is acceptable, then τ_{ant} vanishes from the sensor response equation and the equation becomes

$$T_o + T_{swd} = T_{ida,0} + DT_{ant,ss} \,(1-e^{-t/\tau_{sen}})$$

Then, this equation may be used to check the assumption of $\tau_{ant} = 0$.

For the switch feedback model, the sensor temperature at the switch off point as given in paragraph 4.2c is

$$T_{sen} = T_o + T_{swd} = T_{ida,0} + DT_{ant,ss} \, (1 - e^{-t/\tau_{ant}})$$

or

$$\tau_{ant} = - \frac{t}{\ln \left[\frac{T_{ida,0} + DT_{ant,ss} - (T_o + T_{swd})}{DT_{ant,ss}} \right]}$$

All variables on the right hand side are known and the anticipator time constant may be calculated.

5. COMPUTER MODELING

The values calculated by solving the equations given in section 4 were used in a computer simulation of thermostat performance. This program simulated thermostat performance based on the two conceptual models discussed in section 2. The program uses the experimental results for the parameters identified in previous sections and user assigned rates of building air temperature change during heating plant ON and OFF periods to calculate the space temperature variations. Using the space temperature variations, one can readily calculate the thermostat operating characteristics such as operating differential, cycling rate and droop. Although any user assigned rates of air temperature change can be easily used in the program, this segment of the program may be replaced with a set of more realistic building and plant sub-programs to simulate performance of the thermostat-plant-building system. The listing of this program is given in appendix B.

The computer program was used to calculate the output of the two conceptual models of thermostat performance using NEMA ramp rates. NEMA ramp rates are 2, 6, and 8°F/hr., with both positive and negative slopes controlled by the thermostat states. The results of the simulation model, which were then compared with the NEMA test results, are presented in section 6.

6. RESULTS AND DISCUSSION

Four thermostats (numbers 1-4) were tested in the laboratory using the procedures discussed in section 4.3. Thermostat number 1 was a clock thermostat. Thermostats 2 and 4 had single loop anticipator wires. Thermostats 1 and 3 had wound anticipator wires. Thermostats 2 and 3 had combination heating and cooling mercury-bulb switches and the other two thermostats had individual heating and cooling switches. The values obtained for the basic parameters for each thermostat during the tests, as well as other related data are reported in table 2. The sensor time constants, switch differentials, and set temperatures were determined by using the method described in paragraph C of section 4.3.

Table 2. Parameter Test Results

Thermostat Number	1	2	3	4
Sensor time constant, τ_{sen}, in minutes	15.00	19.13	17.25	21.75
Switch differential, τ_{swd}, in °F	1.5	1.7	1.2	1.4
Anticipator steady-state temperature rise, $DT_{ant,ss}$, in °F	5.2	5.5	7.0	7.6
Anticipator time constant for switch feedback model, τ_{ant}, in minutes	11.2	10.8	11.6	12.6
Anticipator current setting, in amps	0.65	0.58	0.65	0.48
Set temperature, T_o, in °F	75.6	73.9	75.5	75.3

The adjustable anticipators of the thermostats were set approximately in the middle portion of the range between the highest and lowest setting. The measured current data are reported in table 2. The thermostats were set to a nominal temperature of 75°F.

Tests were conducted to measure the thermostat operating performance according to NEMA test procedures. The NEMA test procedures require that the test chamber temperature rise and fall at 6°F/hr to obtain the thermostat cycling rate at 50 percent building load. As discussed in paragraph 4.3e, the anticipator time constant should be very short for the bimetal feedback model. Several computer runs for thermostat No. 1 were made with different anticipator time-constant values to compare the calculated thermostat operating performance with the experimental data. Table 3 indicates that with a very short anticipator time constant (τ_{ant} = .1 minute), the simulated performance was closest to the experimental results. Therefore, the assumption of a very small anticipator time constant for the bimetal feedback model is valid.

Table 3. Comparison of Thermostat No. 1 Performance, Experimental vs. Simulation, Using Different Anticipator Constants in the Bimetal Feedback Model

	NEMA Test	Simulation				
τ_{ant}, minute	--	0.1	1	2	4	10
Maximum Temperature, °F	74.0	74.1	74.1	74.4	74.5	74.9
Minimum Temperature, °F	73.5	73.3	73.2	73.0	72.9	72.6
Operating Differential, °F	0.5	0.8	1.0	1.4	1.6	2.3
Rise/Fall Periods, Minute	5/5	8/8	11/11	14/15	16/16	23/23

Tables 4 to 7 compare thermostat performance obtained by the NEMA test procedures with the computer simulation results for both conceptual models. During the simulations, the anticipator time constant was assumed to be 0.1 minute for the bimetal feedback model. The use of 0.1 minute as the anticipator time constant in the bimetal feedback model simulation greatly increased the number of integration steps, resulting in longer computing time than for the switch feedback model simulation. Generally, the results from the switch feedback model were in closer agreement with the experimental results than were the results from the bimetal feedback model.

It should be noted, however, that part of the difference between the simulation and the NEMA test data resulted from experimental and computational errors in developing the thermostat parameters since the parameter values were determined by sequential tests and calculations. Errors in early tests and calculations thus were entered into succeeding calculations. In addition, temperature measurement errors, undecayed transient errors, and steady-state differences between the sensor and test chambers air temperature during range tests also occurred. As a result, the simulation cycle rates, which are the inverses of the rise/fall periods given in tables 4 through 7, were generally much smaller than those for the NEMA test reuslts. Although all simulations represented more than eight hours of thermostat operation, not all iterations reached stable conditions, depending on the assumed initial input data for the sensor, air, and anticipator temperatures. Nevertheless, the maximum and minimum temperature of most of the simulations were within 0.3°F of the corresponding test data.

Table 4. Comparison of Thermostat Performance, Experimental vs. Simulations, Thermostat No. 1

	Ramp Rate °F/hr	NEMA Test	Bimetal Feedback Model	Switch Feedback Model
Maximum Temp., °F		74.0	74.1	74.1
Minimum Temp., °F	+6/-6	73.5	73.3	73.4
Operating Diff., °F		0.5	0.8	0.7
Rise/Fall Periods, min.		5/5	8/8	7/7
Maximum Temp., °F		75.2	75.6	75.6
Minimum Temp., °F	+8/-2	74.8	74.9	75.0
Rise/Fall Periods, min.		3/12	6/22	5/17
Maximum Temp., °F		72.6	72.6	72.5
Minimum Temp., °F	+2/-8	72.1	71.9	71.9
Rise/Fall Periods, min.		12/3	22/7	20/5
Droop, °F		2 6	3.0	3.1

Table 5. Comparison of Thermostat Performance, Experimental vs. Simulations, Thermostat No. 2

	Ramp Rate °F/hr	NEMA Test	Bimetal Feedback Model	Switch Feedback Model
Maximum Temp., °F		72.1	72.6	72.4
Minimum Temp., °F	+6/-6	71.5	71.4	71.6
Operating Diff., °F		0.6	1.2	0.8
Rise/Fall Periods, min.		6/6	12/12	8/8
Maximum Temp., °F		73.9	74.1	73.9
Minimum Temp., °F	+8/-2	73.4	73.1	73.2
Rise/Fall Periods, min.		4/16	9/30	5/20
Maximum Temp., °F		70.6	70.9	70.7
Minimum Temp., °F	+2/-8	70.1	69.9	70.1
Rise/Fall Periods, min.		15/14	30/8	20/5
Droop, °F		3.3	3.2	3.1

Table 6. Comparison of Thermostat Performance, Experimental vs. Simulations, Thermostat No. 3

	Ramp Rate °F/hr	NEMA Test	Bimetal Feedback Model	Switch Feedback Model
Maximum Temp. °F	+6/-6	73.0	72.9	72.9
Minimum Temp., °F		72.5	72.3	72.4
Operating Diff., °F		0.5	0.6	0.5
Rise/Fall Periods, min.		4/4	6/6	15/15
Maximum Temp., °F	+8/-2	75.0	74.9	74.9
Minimum Temp., °F		74.4	74.4	74.5
Rise/Fall Periods, min.		3/10	5/14	3/12
Maximum Temp., °F	+2/-8	70.3	70.8	70.7
Minimum Temp., °F		70.0	70.3	70.3
Rise/Fall Periods, min.		9/3	15/5	12/3
Droop, °F		4.4	4.1	4.2

Table 7. Comparison of Thermostat Performance, Experimental vs. Simulations, Thermostat No. 4

	Ramp Rate °F/hr	NEMA Test	Bimetal Feedback Model	Switch Feedback Model
Maximum Temp., °F	+6/-6	72.2	72.6	72.5
Minimum Temp., °F		71.6	71.8	71.9
Operating Diff., °F		0.6	0.8	0.6
Rise/Fall Periods, min.		5.5/5.5	9/18	6/6
Maximum Temp., °F	+8/-2	74.2	74.8	74.6
Minimum Temp., °F		73.8	74.1	74.2
Rise/Fall Periods, min.		3/13	6/20	3/12
Maximum Temp., °F	+2/-8	69.5	70.3	70.2
Minimum Temp., °F		69.0	69.6	69.8
Rise/Fall Periods, min.		12/4	20/6	12/3
Droop, °F		4.8	4.5	4.4

7. CONCLUSION

In this paper, four parameters of thermostat operation were identified. Test procedures for obtaining these parameters were developed using both experimental data and mathematical calculations. In addition, a computer program was developed to simulate two different types of thermostat operation. As input, this program used the four parameters to simulate thermostat performance. The performance of four mechanical thermostats was also determined using the NEMA test procedure. The simulation results for the switch feedback model were in better agreement with the experimental test data than were the results from the bimetal feedback model. In addition, because the anticipator time constant can be determined experimentally and shorter computing time is required for simulation, the switch feedback model is recommended over the bimetal feedback model for use in low-voltage room thermostat studies. It also provides some clues to the probable operational characteristics of thermostats within a dynamic system. Thus, the switch feedback model, in which the anticipator works directly upon the sensor, is seen as a better model of actual performance than the bimetal feedback model. This model may then be combined with heating plant and building models to predict dynamic building thermal performance.

The authors wish to acknowledge Mr. Lih Chern for his assistance in editing and running the computer programs of the models.

8. REFERENCES

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APPENDIX A. NEMA STANDARD FOR TESTING THERMOSTAT PERFORMANCE

Part 4

TESTING AND PERFORMANCE

DC 3-4.01 DIELECTRIC TESTS

Thermostats shall be capable of withstanding for 1 minute without breakdown the application of a 50/60-hertz alternating potential of 500 volts applied between uninsulated low-voltage live-metal parts of opposite polarity (with contacts closed) and between uninsulated low-voltage live-metal parts and the enclosure and grounded dead-metal parts.

As an alternate, the dielectric test on thermostats may be conducted for 1 second with a 50/60 hertz test voltage of 600 volts.

NEMA Standard 3-8-1978

DC 3-4.02 ENDURANCE

Thermostats shall be capable of thermally operating at the maximum rated electrical load for at least 100,000 cycles at a rate of not more than 4 cycles per minute.

NEMA Standard 7-19-1972

DC 3-4.03 ENVIRONMENTAL TESTS

A. General Conditions

All environmental tests shall be conducted in accordance with the equipment and operating instructions described in Part 7.

All tests shall be conducted with the air velocity through the test chamber set at 0.15 m/s (30 feet per minute) in the downward direction.

All tests shall be conducted with the scale setting at a point between 21°C (70°F) and 27°C (80°F). A different setting may be used if required to complete the performance tests within the range of the test equipment.

All tests on anticipating-type thermostats shall be conducted with anticipators in place and connected. Where more than one choice of anticipation is supplied, the manufacturer's instructions for electrical load under test shall be followed.

1. Thermostats having adjustable anticipators shall be set at the midpoint of the anticipator range and tested with current represented by the setting.

2. Thermostats with fixed-series anticipators shall be tested at the midpoint of the manufacturer's specified anticipator rating.

3. Thermostats having fixed-parallel-voltage-type anticipators shall be tested at their current and voltage rating.

All tests on nonanticipating-type thermostats shall be conducted at the manufacturer's specified rating.

All tests on thermostats which have heat-generating elements shall be conducted with those elements energized as they would be in normal operation.

B. Differential Test

The differential tests shall be conducted with the test equipment set for uniform rates of temperature change of 3.3°C (6°F) per hour. Tests shall be conducted at 50 percent duty cycle.

The thermostat under test shall be connected so that it determines the direction on the temperature change during the cycle.

The operating differential shall be recorded.

C. Cycle Rate Test

The cycle rate test shall be conducted at 20, 50 and 80 percent duty cycle and recorded.

The thermostat under test shall determine the direction of temperature change during the cycle with the rate change set as follows:

Percent Duty	Rate of Change, °K/Hour(F)			
	Heating Thermostat		Cooling Thermostat	
	Rise	Fall	Rise	Fall
20	4.4(8)	1.1(2)	1.1(2)	4.4(8)
50	3.3(6)	3.3(6)	3.3(6)	3.3(6)
80	1.1(2)	4.4(8)	4.4(8)	1.1(2)

The thermostat shall be allowed to cycle until it has stabilized to a uniform rate.

D. Droop Test (Heating and Cooling)

The effective operating droop value shall be recorded as the average temperature difference between the cut-in points at the 20 percent and 80 percent duty cycles as determined from the cycle rate test.

NEMA Standard 3-8-1978

E. Test Data Forms

The test data may be presented in one or both of the following forms:

1. Test Data Form--See Fig. 4.1.
2. Test Data Curves--The curves shown on Fig. 4.2 are typical effective droop and cycle rate curves which graphically represent the test results tabulated on the test data form shown in Fig. 4.1. A curve can be shown for each electrical load tested.

Authorized Engineering Information 3-8-1978

Electrical Load		Operating Differential		Effective Operating Droop Value °C(°F) 20% to 80% Duty Cycle	Cycle Rate Heating or Cooling
Volts	Amperes	Heating	Cooling		

Fig. 4.1
Test Data Form

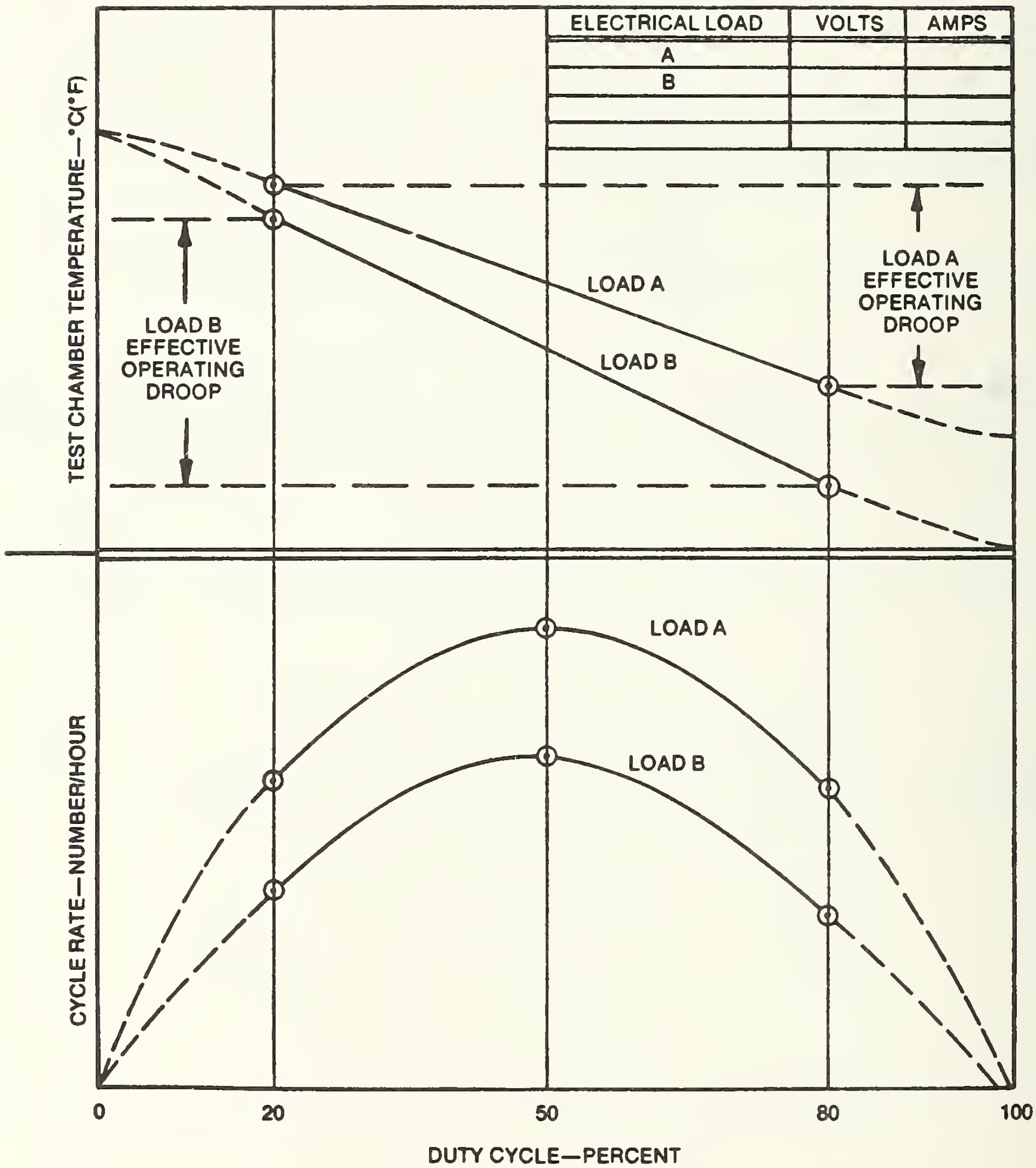

Fig. 4.2
Test Data Curves

APPENDIX B. PROGRAM FOR SIMULATING THERMOSTAT PERFORMANCE

```
C
C PROGRAM FOR SIMULATION OF THERMOSTAT
C
      DIMENSION X(10)
C
C THE ARRAY,X, CONTAINS THE 'STATES' OF THE SYSTEM.
C
      COMMON TSEN,TSWD,TZERO,TANT,DTANTS
      COMMON IOF
      COMMON RR,FR
1111  FORMAT (' INPUT THE THERMOSTAT PARAMETERS.')
      WRITE (6,1111)
1112  FORMAT (' USE E10.4 FORMAT.')
      WRITE (6,1112)
1113  FORMAT (' TSEN      TSWD      TZERO     TANT      DTANTSS')
      WRITE (6,1113)
1001  FORMAT (8E10.4)
      READ (5,1001) TSEN,TSWD,TZERO,TANT,DTANTS
      WRITE (6,1002) TSEN,TSWD,TZERO,TANT,DTANTS
1115  FORMAT (' INPUT THE TWO RAMP RATES (DEGF/HR).')
      DT=TANT/5.0
      IF(DT.GT.1.0) DT=1.0
      TSTEP=1.0/DT+0.00001
      ISTEP=IFIX(TSTEP)
      WRITE (6,1115)
      READ (5,1001) RR,FR
      WRITE (6,1002) RR,FR
      RR=RR/60.
      FR = FR/60.
1120  FORMAT (' NOW INPUT DATA FOR THE DIGITAL SIMULATION.')
      WRITE (6,1120)
1002  FORMAT (1X,9E12.6)
      WRITE (6,1002) DT
1122  FORMAT (' INPUT THE NUMBER OF INTEGRATION STEPS.')
      WRITE (6,1122)
1123  FORMAT (' USE I3 FORMAT.')
      WRITE (6,1123)
1003  FORMAT (10I5)
      READ (5,1003) ITER
      WRITE (6,1003) ITER
1124  FORMAT (' INPUT THE NUMBER OF SIMULATION STATES.')
      WRITE (6,1124)
      WRITE (6,1123)
      READ (5,1003) N
      WRITE (6,1003) N
1125  FORMAT (' INPUT THE STARTING VALUE OF THE STATES.')
      WRITE (6,1125)
      READ  (5,1001) (X(I), I=1,N)
      WRITE (6,1002) (X(I), I=1,N)
1130  FORMAT (1H1,' TIME AND STATES')
      WRITE (6,1130)
      T=0.
      IOF = 1
      WRITE (6,1002) T,(X(I), I=1,N)
      DO 100 I = 1,ITER
      CALL EULER (X,T,DT,N)
      II=I/ISTEP
      III=II*ISTEP
      IF(I.NE.III) GOTO 100
      WRITE (6,1002) T,(X(J), J=1,N)
100   CONTINUE
      STOP
      END
```

```
      SUBROUTINE XDOT (X,XD,T,N)
      COMMON TSEN,TSWD,TZERO,TANT,DTANTS
      COMMON IOF
      COMMON RR,FR
      DIMENSION X(10), XD(10)
C ************************************************
C
C THERMOSTAT MODEL  ( BIMETAL FEEDBACK )
C
C X(1) = SENSOR TEMPERATURE
C X(2) = ANTICIPATOR TEMPERATURE
C IOF = 1 WHEN ON, = 0 WHEN OFF.
C
C ************************************************
      TIDA = X(3)
      XD(1) = -(X(1)/TSEN) + (TIDA + X(2))/TSEN
      XD(2) = -(X(2)/TANT) + (DTANTS*IOF/TANT)
C
C PROGRAM SEGMENT FOR THE NONLINEAR FUNCTION
C
      IF (T .EQ. 0.) IOF = 1
      IF (IOF .EQ. 1) TSW = TZERO + TSWD
      IF (IOF .EQ. 0) TSW = TZERO
      IF(X(1) .GE. TSW) IOF = 0
      IF(X(1) .LE. TSW) IOF = 1
C
C END OF THERMOSTAT MODEL SEGMENT
C
C
C ************************************************
C
C NEMA BOX SEGMENT
C
C
C DEFINE PARAMETERS
C
C RR IS THE RISING RAMP RATE
C FR IS THE FALLING RAMP RATE
C
      XD(3) = FR + (RR-FR)*IOF
      RETURN
      END
C
C
C
      SUBROUTINE EULER (X,T,DT,N)
C
C EULER DOES EULER INTEGRATION OF DIFFERENTIAL EQUATIONS
C
      DIMENSION X(10), XD(10)
      CALL XDOT(X,XD,T,N)
      DO 100 I=1,N
      X(I) = X(I) + XD(I)*DT
100   CONTINUE
      T = T + DT
      RETURN
      END
EOF:123
0:>
```

```
      SUBROUTINE EULER (X,T,DT,N)
C
C EULER DOES EULER INTEGRATION OF DIFFERENTIAL EQUATIONS
C
      DIMENSION X(10), XD(10)
      CALL XDOT(X,XD,T,N)
      DO 100 I=1,N
      X(I) = X(I) + XD(I)*DT
100   CONTINUE
      T = T + DT
      RETURN
      END
C
C
C
      SUBROUTINE XDOT (X,XD,T,N)
      COMMON TSEN,TSWD,TZERO,TANT,DTANTS
      COMMON IOF
      COMMON RR,FR
      DIMENSION X(10), XD(10)
C ************************************************
C
C THERMOSTAT MODEL    ( SWITCH FEEDBACK )
C
C X(1) = SENSOR TEMPERATURE
C X(2) = ANTICIPATOR TEMPERATURE
C IOF = 1 WHEN ON, = 0 WHEN OFF.
C
C ************************************************
      TEMSEN = X(1) + X(2)
C
C PROGRAM SEGMENT FOR THE NONLINEAR FUNCTION
C
      IF (T .EQ. 0.) IOF = 1
      IF (IOF .EQ. 1) TSW = TZERO + TSWD
      IF (IOF .EQ. 0) TSW = TZERO
      IF(TEMSEN .GE. TSW) IOF = 0
      IF(TEMSEN .LE. TSW) IOF =1
      TIDA = X(3)
      XD(1) = -(X(1)/TSEN) + (TIDA/TSEN)
      XD(2) = -(X(2)/TANT) + (DTANTS*IOF/TANT)
C
C END OF THERMOSTAT MODEL SEGMENT
C
C
C ************************************************
C
C NEMA BOX SEGMENT
C
C
C DEFINE PARAMETERS
C
C RR IS THE RISING RAMP RATE
C FR IS THE FALLING RAMP RATE
C
      XD(3) = FR + (RR-FR)*IOF
      RETURN
      END
EOF:124
0:>
```

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10. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

To predict performance of low voltage electric thermostats in a dynamic building system, a computer model representing two types of thermal feedback was developed. Unlike the information obtained from existing test standards, this model allows thermostat performance to be determined under any load conditions. As input to the model, the basic parameters of thermostat performance were first identified and then determined experimentally in a controlled laboratory facility. The experimental results from the tests were used as input parameters for the simulation model. Based upon the results from the simulation model and test results on four commercially-available thermostats, a switch-feedback model computer simulation is recommended for studying low-voltage room thermostat performance.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

room temperature control; temperature controller; thermostat evaluation; thermostat modeling; thermostat test; two-position control..

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