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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

NOTES ON THE DESIGN OF TEMPERATURE CONTROL UNITS

● **THESE NOTES** deal with a type of temperature control unit often used to control the temperature of a quartz bar or plate, for use as a frequency standard or frequency monitor. The general principles discussed are applicable to other types of units if account is taken of differences in the thermal properties of the materials or medium involved.

Referring to Figure 1, the conditions of the problem can be visualized as three objects, a heater H, a controlled space within a metal box B, and a thermostat T, all enclosed in some form of thermally insulating box. These three objects each have heat capacities; they are interconnected by thermal impedances, along which drops in temperature occur, dependent on the rate of heat flow and on the values of the thermal impedances.[1] Each of the three objects is also connected to the ambient, surrounding the entire unit, by a thermal impedance.

To reduce the fluctuations in average heat flow, the magnitude of which depends on the sensitivity of the thermostat and thermal impedance between the thermostat and heater, it is evident that the thermostat should be as sensitive as possible and the thermal impedance between heater and thermostat should be low.

[1]O. M. Hovgaard, "Application of Quartz Plates to Radio Transmitters," *Proc. I. R. E.*, Vol. 20, No. 5, May, 1932, p. 767.

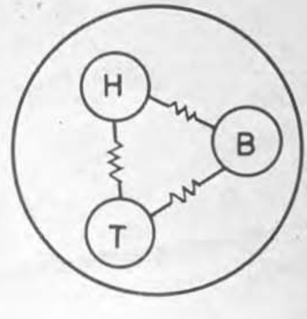


FIGURE 1. Schematic representation of temperature control system composed of a heater, *H*, a metal box, *B*, and a thermostat, *T*, in an insulating container.

To reduce the fluctuations in temperature in the controlled space, the impedance between the controlled space and the thermostat should appear as a low-pass thermal filter, to remove the variations caused by the operating temperature differential of the thermostat. In an elementary form, the metal wall of the box serves this purpose. The filtering action can be increased to almost any desired degree through the use of multi-layer walls and through grading or tapering the distribution of materials forming the wall.[2]

The remaining thermal impedances should be as high as possible. That of the heater to the ambient determines the power loss, and the cost of operation, of the unit; the initial cost of the insulating container can therefore be fairly high.

The heat capacities of the heater and thermostat should be low, so that small increments in heat energy supplied result in immediate changes in temperature at the thermostat.

Because of practical considerations, such as the use of standard forms of resistors for the heater, mountings for the thermostat, and materials for the unit, the thermal impedances which should be negligibly small can only be brought to effective minimum values. It is the purpose of the following discussion to indicate how the performance can be improved by effectively equalizing temperature drops and by effectively regulating the magnitudes of impedances by electrical rather than mechanical means.[3]

In order for the thermostat to operate, the amount of heat energy released in the unit, per thermostat cycle, less the energy lost during the input period must be, at least:

$$\Delta H = (W_i - W_0)pq = MS\Delta T \quad (1)$$

where:

W_i = Rate of heat energy input
= Heater watts

W_0 = Rate of heat energy output
= Loss watts

p = Thermostat period, seconds

q = Fraction of the period that heat is supplied

pq = "ON" time, seconds

M = Mass associated with thermostat

S = Specific heat of M

and

ΔT = Temperature differential required to operate thermostat.

The heat energy released per thermostat cycle is:

$$H_{\text{in}} = W_i pq \text{ watt seconds} \quad (2)$$

The heat energy lost per thermostat cycle must be the same, or else the temperature of the unit would change:

$$H_{\text{out}} = W_i pq \text{ watt seconds} \quad (3)$$

[2] W. A. Marrison, "Thermostat Design for Frequency Standards," *Proc. I. R. E.*, Vol. 16, No. 7, July, 1928, p. 976. This article contains useful data on thermal properties of common substances likely to be used in constructing units of this description.

[3] V. J. Andrew, "The Design of Temperature Control Apparatus for Piezo Oscillators," Review of Scientific Instruments, Vol. 3, No. 7, July, 1932, p. 341.

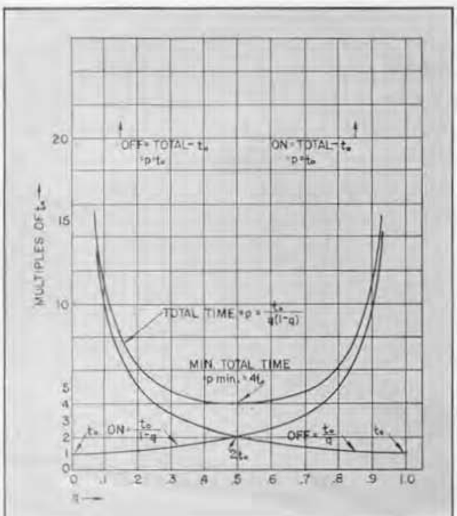


FIGURE 2. Performance of thermostat under conditions of no "overshooting" (ΔH = constant) and constant heater power (W_i = constant) for varying ambient temperature.

The energy lost during the "ON" time, or the fraction q of the total period, p, is:

$$qH_{out} = W_i pq^2 \text{ watt seconds} \quad (4)$$

The *net* heat energy input, per thermostat cycle, is then

$$\Delta H = W_i pq - W_i pq^2 \text{ watt sec.} \quad (5)$$
$$= W_i pq(1 - q) \text{ watt sec.} \quad (6)$$
$$= (W_i - W_0)pq \quad (1)$$

From the last two equations:

$$q = \frac{W_0}{W_i} \quad (7)$$

The loss from the unit can be expressed in terms of its conductivity:

$$W_0 = J(T - T_a) \text{ watts} \quad (8)$$

where:

J = conductivity of the unit to the ambient in watts per degree C.

T = temperature of unit, °C.

T_a = ambient temperature, °C.

For a unit approximately 9 inches cube, with balsa wood walls 1 inch thick, $J = 0.37$ approximately.

The conductivity can be obtained approximately by calculation from $J = KA/d$, where K = conductivity of the wall material, A is the average of inner and outer areas, and d is the thickness of the walls. Usually it is more satisfactory to determine W_0 by observing the operation of the thermostat under known heater power (Equation 7).

Since the thermostat operates between the same "ON" and "OFF" temperatures, ΔT (Equation 1) is constant, and consequently ΔH is constant. This implies that there is no "overshooting," that is, that ΔH is no greater than that necessary to operate the thermostat. We can now predict the operation of the thermostat provided that we determine the heat energy increment, ΔH, and the rate of heat loss of the unit, W_0.

Our obvious interest would be to determine the performance for constant power input and varying ambient temperatures. It will be very useful to determine the performance for constant ambient temperature and varying power input for two reasons; first, observations are more easily carried out and, second, "overshooting" is readily disclosed. As will be brought out later, the performance of a unit may be limited as much by "overshooting" as by large changes in ambient temperature.

Case I — Constant Power Input; Varying Ambient

Since ΔH is constant and W_i is constant, we have

$$\Delta H/W_i = pq(1-q) = t_0, \text{ a constant.} \quad (9)$$

The operation of the thermostat is shown in Figure 2, where the significance of the constant t_0 is evident.

From (9), we can write

$$\text{"ON" time} = pq = t_0(1 - q)$$
$$\text{"OFF" time} = p(1 - q) = t_0/q \quad (10)$$
$$\text{and PERIOD} = p = t_0/q(1 - q)$$

From (9), it is seen that, for an increased input power, t_0 is decreased, and that the thermostat operation is speeded up.

Case II — Constant Ambient; Varying Power Input

In principle, this case is covered by finding a value of t_0 for each value of input power, W_i, from Equation 9. For each value of t_0, a set of curves like those of Figure 2 is obtained, but each set is to a different scale. On each set of curves a single operating point is found corresponding to the given fixed ambient temperature, that is, to the value of W_0. The final over-all characteristics would then be the curves connecting these operating points.

Practically, it is not necessary to plot the curves corresponding to each value of t_0. Instead, the operating points can be found as in the first case, except that there are different values of t_0 for each point. For the fixed ambient temperature, W_0 is constant. Therefore, since the energy increment ΔH is constant, the heat energy lost during the "OFF" time is constant, or

$$W_0 p(1 - q) = \text{constant} \quad (11)$$

$$\text{the "OFF" time} = p(1 - q) = \text{constant} \quad (12)$$

and $\Delta H = (W_i - W_0)pq = \text{constant}$ from which it is evident that, as W_i is increased, the "ON" time, pq, must decrease.

It is important to note Equation 12; if, as the input power is increased, the "OFF" time increases, it is positive evidence of "overshooting."

Results for this second case are shown in Figure 3, on the basis that $\Delta H = 95$ watt seconds and $W_0 = 13$ watts. As the power input is increased, note that the period decreases and that the "OFF" time remains constant.

In Figure 4 are shown the performance curves of a given temperature control unit. This unit was constructed with the thermostat mounted on the outer face of the box, B, with the heaters disposed around all six faces of the box, but not in direct thermal contact with the walls of the box.[4] This construction insures that the average controlled space temperature will not depart appreciably from the thermostat operating temperature. The variations in controlled space temperature, as shown in Figure 4, are not large, and for many purposes would not be troublesome. The remainder of this discussion is devoted to reducing these small variations to the greatest possible degree, without materially altering the mechanical design of the unit.

It is evident that the curves are not of the form expected from Figure 3. The period decreases at first, as the heater power is increased, then passes through a minimum and finally increases again. The "OFF" time increases, with increasing power, following the energy increment curve; the energy increment is not constant. *The average controlled space temperature rises as the heater power is increased.*

This performance is largely due to a high thermal impedance between the heaters and the thermostat. The average controlled space temperature, being a function of power input, will change with any factor causing a change in power input; that is, *either ambient temperature changes or line voltage changes*. It will also be noticed that, because of the delay in temperature rise at the thermostat (causing the energy increment to be too large), the "OFF" time must increase to allow this extra heat energy to escape. The "ON" and "OFF" times are consequently very long.

[4] J. K. Clapp, "Temperature Control for Frequency Standards," *Proc. I. R. E.*, Vol. 18, No. 12, December, 1930, pp. 2003.

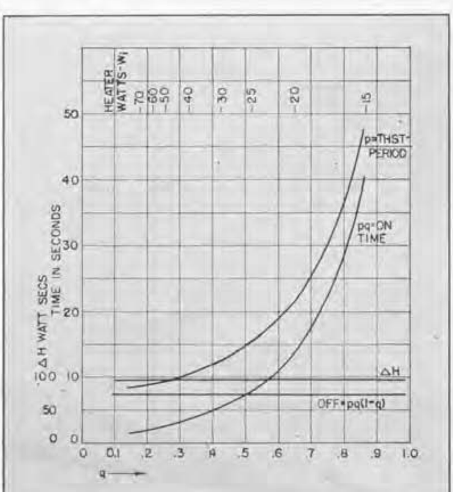


FIGURE 3. Performance of thermostat under conditions of no "overshooting" (ΔH = constant) and constant ambient temperature for varying heater power, W_i. ΔH assumed as 95 watt seconds; W_0 assumed as 13 watts.

This unit was modified by dismounting the thermostat from the metal box (enclosing the controlled space) and supporting it in such a position that the controlled temperature was about 63.5°C. (instead of 60.0°C., the thermostat temperature). A thermostat heater, of the lowest practicable thermal capacity, was then wound directly over the thermostat bulb. The thermostat heater power was then adjusted so that the average controlled space temperature was close to 60.0°C. The thermostat heater was connected in parallel with the main heaters.

This arrangement overcomes the high thermal impedance, between the main heater and thermostat, by using a proportional amount of power close to the thermostat. (The significance of the differences in controlled space temperature will be discussed later.)

The performance of this arrangement is shown in Figure 5. Immediately we notice that the energy increment and "OFF" time curves are nearly horizontal, rising slightly only at the highest input powers. The period of the cycle decreases continuously as the input power is increased. All times have been greatly reduced. The average controlled space temperature is constant, within the limits of accuracy of measurement. Comparison of Figure 5 with Figure 3 shows how closely the performance follows the theory.

"Overshooting" has been practically eliminated at all but the highest input powers. It must be borne in mind that, for any given construction, if excessive input power is used, "overshooting" can always be made to occur.

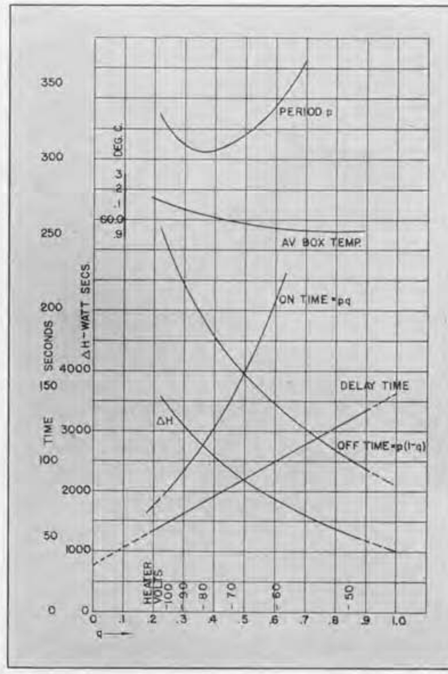


FIGURE 4. Performance curves of a given temperature control unit, at constant ambient temperature, for varying heater power, W_i. Compare with Figure 3.

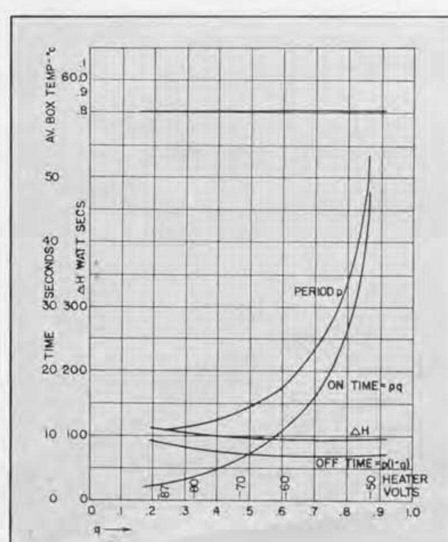


FIGURE 5. Performance curves of a given temperature control unit, modified by reducing the thermal impedance between thermostat and heaters, at constant ambient temperature, for varying heater power, W_i. Compare with Figures 3 and 4.

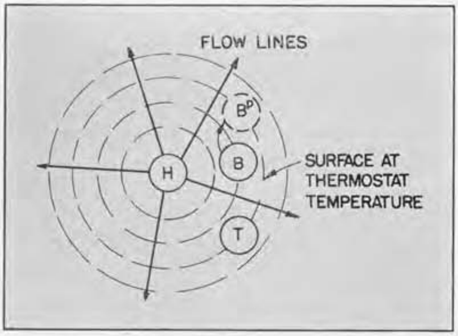


FIGURE 6. Schematic representation of heat flow from a heater, *H*, and equal temperature shells surrounding the heater.

Having established a means of preventing "overshooting," we next consider the gradient conditions in the unit. Turning to Figure 6, a series of constant temperature surfaces, at every point perpendicular to the lines of heat flow, can be considered as surrounding the heater. (In an actual unit, such surfaces would be very complex, since there are generally several heater units.) The thermostat is on one such surface, corresponding to the operating temperature of the thermostat. If the metal box, B, is inside of, outside of, or on the thermostat surface, the gradient conditions can be represented by Figures 7, 8, and 9 respectively.

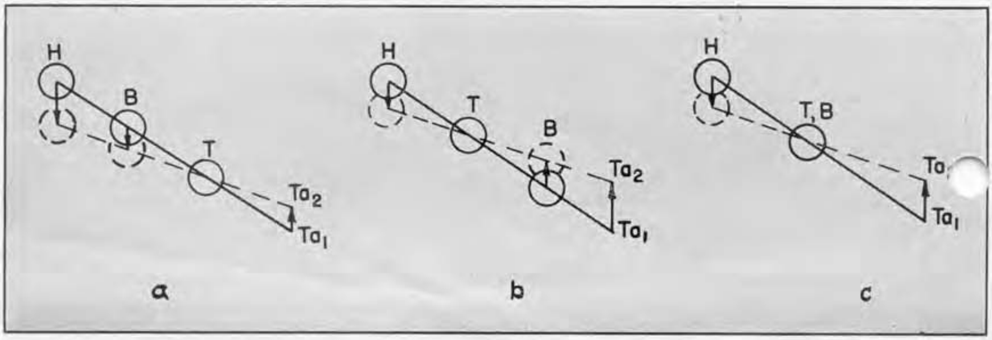
In Figure 7a, the box is assumed to be on a constant temperature shell lying inside of the thermostat shell as at B, Figure 6. At a given ambient temperature, T_{a1}, a certain amount of heat flows through the thermostat shell. The product of this heat flow and the impedance between the shell and ambient is the temperature drop from the shell to the ambient, $T - T_{a1}$. Now if the ambient changes to a higher value T_{a2}, the heat flow must be reduced, since the impedance does not change. The average heater temperature must therefore be reduced, with an accompanying proportional reduction in temperature of the box, B. In this case, as the ambient temperature *rises*, the controlled space temperature *falls*.

Similar considerations apply to Figure 7b, except that, as the ambient *rises*, the controlled space temperature also *rises*.

If the box, B, is brought to the temperature of the thermostat shell as at B[1], Figure 6, or vice versa, there should be no change in controlled space temperature with changes in ambient (Figure 7c). This can be accomplished by moving the objects in the assembly relative to each other, or by effectively moving them through the use of a thermostat heater.

Final adjustment of the thermostat heater power is then made on the basis of reducing the changes in controlled space temperature, with ambient changes, to zero. If the thermostat

FIGURE 7 (a, b, c). Schematic representation of gradient conditions, with change of ambient temperature, for various relative positions of heater, *H*, controlled space, *B*, and thermostat, *T*.



heater power is too small, conditions correspond to Figure 7a; if too large, to Figure 7b; and if correct, to Figure 7c. Measurement of the controlled-space temperature for two or more ambient temperatures and for different thermostat heater powers will disclose the power for which $dT/dT_a = 0$. The small readjustment required to bring this about does not appreciably alter the performance shown in Figure 5.

Tests on the unit described in connection with Figure 5 gave the following results:

Thermostat Heater Power — Watts	dT/dT_a
0.090	+0.018
0.064	+0.0022
0.045	−0.016

Elimination of "overshooting" and proper adjustment of the thermostat heater power reduced the changes in controlled space temperature by nearly 100 to 1. With the thermostat heater power at 0.064 watts, changes in ambient are reduced by 0.0022 or to 1/450th within the controlled space.

—J. K. Clapp

STANDARD FREQUENCY BROADCASTS

● **A NEW SCHEDULE** for broadcasts of standard frequencies and standard time intervals was announced by the National Bureau of Standards on May 22, 1944.

"This service comprises the broadcasting of standard frequencies and standard time intervals from the Bureau's radio station WWV near Washington, D. C. It is continuous at all times day and night, from 10-kilowatt radio transmitters except on 2500 kilocycles per second where 1 kilowatt is used. The services include: (1) standard radio frequencies, (2) standard time intervals accurately synchronized with basic time signals, (3) standard audio frequencies, (4) standard musical pitch, 440 cycles per second, corresponding to A above middle C.

"The standard frequency broadcast service makes widely available the national standard of frequency, which is of value in scientific and other measurements requiring an accurate frequency. Any desired frequency may be measured in terms of any one of the standard frequencies, either audio or radio. This may be done by the aid of harmonics and beats, with one or more auxiliary oscillators.

"At least three radio carrier frequencies are on the air at all times, to insure reliable coverage of the United States and other parts of the world. The radio frequencies are:

2.5 megacycles (= 2500 kilocycles = 2,500,000 cycles) per second, broadcast from 7:00 P.M. to 9:00 A.M., EWT (2300 to 1300 GMT).

5 megacycles (= 5000 kilocycles = 5,000,000 cycles) per second, broadcast continuously day and night.

10 megacycles (= 10,000 kilocycles = 10,000,000 cycles) per second, broadcast continuously day and night.

15 megacycles (= 15,000 kilocycles = 15,000,000 cycles) per second, broadcast from 7:00 A.M. to 7:00 P.M., EWT (1100 to 2300 GMT).

"Two standard audio frequencies, 440 cycles per second and 4000 cycles per second, are broadcast on the radio carrier frequencies. Both are broadcast continuously on 10 and 15 megacycles. Both are on the 5 megacycles in the daytime, but only the 440 is on the 5 megacycles from 7:00 P.M. to 7:00 A.M., EWT. Only the 440 is on the 2.5 megacycles.

"The 440 cycles per second is the standard musical pitch, A above middle C; the 4000 cycles per second is a useful standard audio frequency for laboratory measurements.

"In addition there is on all carrier frequencies a pulse of 0.005-second duration which occurs at intervals of precisely one second. The pulse consists of 5 cycles, each of 0.001-second duration, and is heard as a faint tick when listening to the broadcast; it provides a useful standard of time interval, for purposes of physical measurements, and may be used as an accurate time signal. On the 59th second of every minute the pulse is omitted.

"The audio frequencies are interrupted precisely on the hour and each five minutes thereafter; after an interval of precisely one minute they are resumed. This one-minute interval is provided in order to give the station announcement and to afford an interval for the checking of radio-frequency measurements free from the presence of the audio frequencies. The announcement is the station call letters (WWV) in telegraphic code (dots and dashes), except at the hour and half hour when a detailed announcement is given by voice.

"The accuracy of all the frequencies, radio and audio, as transmitted, is better than a part in 10,000,000. Transmission effects in the medium (Doppler effect, etc.) may result at times in slight fluctuations in the audio frequencies as received; the average frequency received is, however, as accurate as that transmitted. The time interval marked by the pulse every second is accurate to 0.00001 second. The 1-minute, 4-minute, and 5-minute intervals, synchronized with the seconds pulses and marked by the beginning or ending of the periods when the audio frequencies are off, are accurate to a part in 10,000,000.

"The beginnings of the periods when the audio frequencies are off are so synchronized with the basic time service of the U. S. Naval Observatory that they mark accurately the hour and the successive 5-minute periods.

"Of the radio frequencies on the air at a given time, the lowest provides service to short distances, and the highest to great distances. Reliable reception is in general possible at all times throughout the United States and the North Atlantic Ocean, and fair reception throughout the world."

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