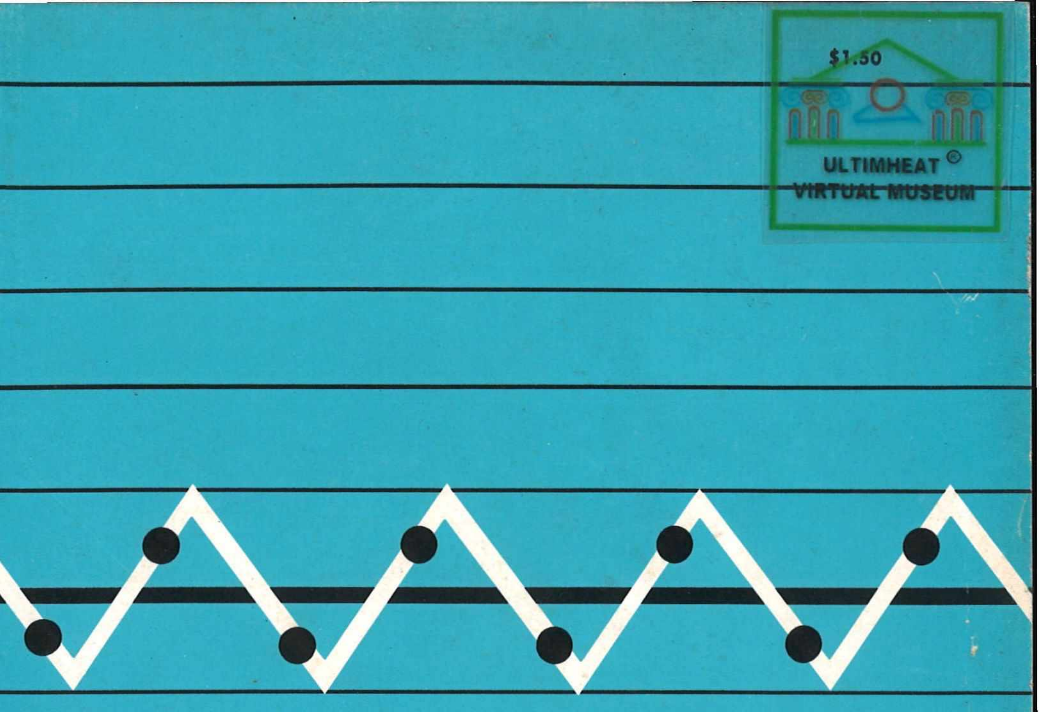

how to get better
TEMPERATURE CONTROL

FENWAL

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Introduction

The results you get with a precision temperature controller, as with any tool, depend on how skillfully it is used. It will produce close control only when the design and operating conditions of the system help it to respond quickly and accurately.

A controller is only one part of a heated system. Its job is to sense temperature at a particular point in the system, and, on the basis of what it senses, actuate some other device which changes the quantity of heat flowing into the system. A controller can respond only to what it sees at its particular location. It cannot react to a temperature rise or fall somewhere in the system until that information arrives at the sensing element. Generally, it cannot compensate for too much or too little heat being put into the system when the heat source is improperly sized. And, most important, it has no way of recognizing whether the temperature in its vicinity truly represents the temperature at the work area. Regardless of the capabilities of the controller, it can control no more closely than the design of the system permits.

This handbook discusses the various considerations in designing a thermal system, suggests how they can be applied, and outlines some practical rules for designers.

1. What is a Heated System?

There are four elements in a heated system, all of which contribute in some way to control performance.

A. *Work (or Load):* The material or product which must be maintained at a controlled temperature. The heat demand of the work may be steady; that is, the same material must be held at constant temperature for a prolonged period, such as a culture in an incubating oven. More commonly, the heat demand of the work is variable and cyclic; that is, cold material periodically enters the system, absorbs heat, is removed and replaced by another batch of cold material. An example of a variable system is a molding press which receives a batch of cool plastic, forms, cures and ejects it and repeats the cycle several times a minute.

B. *Heat Source:* The device which delivers the heat used by the system. The source may be electrical heaters, oil and gas-fired heaters, or any other source. The process may be exothermic; i.e., generate its own heat.

c. *Heat Transfer Medium:* The material which transmits the heat from the heat source to the work. The material may be a solid, liquid, or gas. Its transfer characteristics play a large part in determining how fast temperature changes are transmitted through the system and, consequently, how closely the system can be controlled.

d. *Controller:* The instrument which controls the heat flow on the basis of the discrepancy between the sensed temperature and the controller's set point.

2. The Meanings of "Accuracy"

The term "control accuracy" is frequently used rather loosely to denote several distinct and different concepts. For the sake of clarity, these concepts will be labelled and discussed briefly. (See Figure 1.)

a. *System Bandwidth:* the total temperature variation—measured at some point in the system, usually at the work area. For example (Figure 1), if the maximum and minimum temperatures in a system are 203 and 199°F, the bandwidth is 4 degrees. (Commonly this is referred to as ±2°, though the correct expression is 4°.)

The sensitivity of the controller contributes only partially to de-

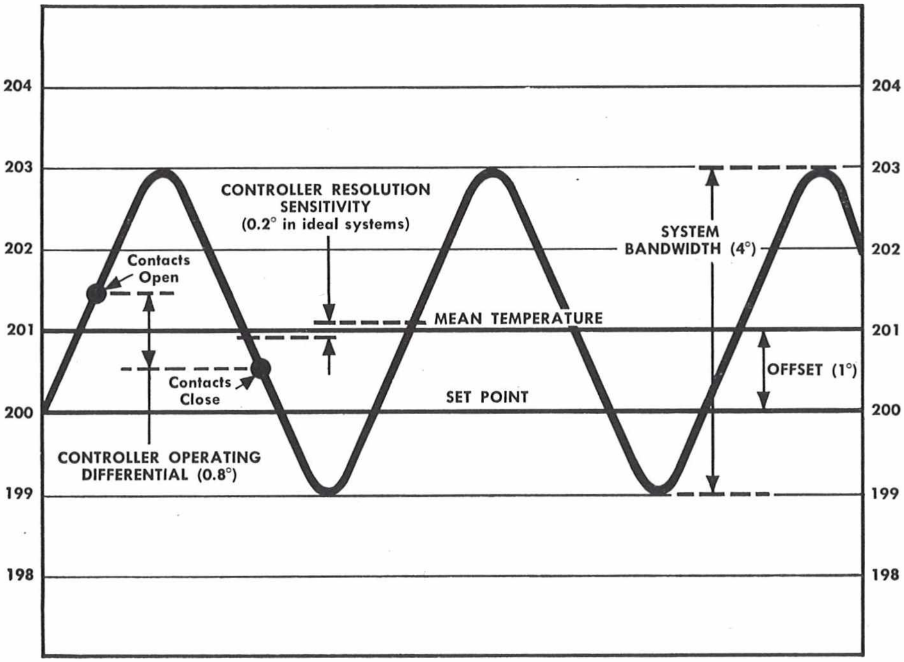


Fig. 1

termining the bandwidth; several other factors relating to the over-all system (described in the following sections) contribute importantly and sometimes decisively. Maintaining a very narrow bandwidth may be the primary goal to prevent overshoot in products or processes which are being heated close to their decomposition, vaporization or other critical point. Narrow bandwidth, by itself, does not guarantee constant temperature, since the mean temperature can drift. In many cases, constancy of mean temperature is relatively more important than a narrow bandwidth.

B. *Mean Temperature:* the numerical average of the maximum and minimum temperatures reached at some point in the system. For example (Figure 1), for a maximum of 203 and a minimum of 199, the mean temperature is 201. In a large number of systems, maintaining the mean temperature relatively constant, rather than maintaining a very narrow bandwidth, is the practical objective. The mean temperature (also referred to as the "control point") may or may not be the same temperature as the controller's set point. When they are not the same, an offset exists.

C. *Offset:* the difference between any two temperatures, such as between the setting of the controller and the mean temperature of the load when the system is at a steady state. In Figure 1, the offset is 1°.

D. *Controller Operating Differential:* the difference between sensing element temperature at make and break of the controller's contacts when the controller is cycled in a specified control system. For example (Figure 1), when the controller's contacts are closed at 200.6 and open at 201.4, its operating differential in that particular system is 0.8 degrees. For some types of controllers the operating differential is affected by electrical load, set point and physical location, so that it is usually larger than the controller's resolution sensitivity.

E. *Controller Resolution Sensitivity* (sometimes called inherent sensitivity): the minimum temperature difference necessary to operate the controller's contacts under ideal conditions.

3. A Practical Approach to Accuracy

The user of a thermal system is interested in one basic question: is the temperature control accurate enough to operate his product or process satisfactorily? Control requirements are far less stringent in a waffle iron than in a crystal oscillator oven. Maintaining exact temperature in a wax applicator tank is less critical than in a laboratory viscosimeter. The point is that exact control of a system takes time, care and money. Moreover, it takes highly sensitive measuring instruments and indicators—and frequent recalibration in service—to tell just how good the control is. Eliminating the last degree or fraction of a degree of temperature deviation is costly and should be done only for sound practical reasons.

Nonetheless, good control *is* attainable with standard instruments. To be sure, control will be no better than the capabilities of the controller, but unless the system is designed as an entity, there is little assurance that the controller *can* deliver what the user expects of it.

4. What Affects Control Accuracy?

System bandwidth and constancy of mean temperature are the overall measures of control accuracy. They are affected by many factors:

1. Temperature Gradients—the range of temperature variation throughout the system at any given instant (See page 10).
2. Thermal Lag—the time delay for a temperature change in one part of the system to be felt in other parts of the system (See page 12).
3. Location of the Controller's Sensing Element—its placement relative to heat source and load (See page 18).
4. Response Speed and Sensitivity of the Controller—these and other characteristics make up inherent controller accuracy. They determine how well it is suited for a given application (See page 32).
5. Heat Balance—the capacity of the heat source in relation to heat demand from the work, plus heat losses. Improper balance can destroy control (See page 24).

5. How Heat Moves

Before analyzing the factors that influence bandwidth in a thermal system, it may be helpful to consider how heat travels in the system. Heat, like water, seeks its own level. It moves only from a higher to a lower temperature zone at a rate depending on the temperature difference and the conductivity or emissivity of the heat transfer medium. The three methods of heat transfer are: conduction, convection and radiation.

A. *Conduction* takes place in solids, liquids and gases. The heat is transmitted in a kind of chain reaction by the rubbing action of a "hot" or higher energy particle with an adjacent "cool" lower energy particle, while the particles remain in the same relative position to each other. A commonplace example is the gradual heating of the upper end of a spoon when the lower end is immersed in a cup of coffee.

B. *Convection* takes place in liquids and gases. It occurs when a stream of warm particles rises, mixes and diffuses into a cooler area. Convection from a heat source at the bottom of the structure is a common method of heating ovens and water tanks. Natural convection currents move slowly and it requires a fairly long time for a container of any reasonable size to reach uniform temperature. This makes accurate control practically impossible. When good control is demanded in ovens and liquid baths, forced convection, produced by blowers, agitators or recirculation lines will be necessary.

c. *Radiation* is a form of energy transmission which is emitted from a heated body. Radiant energy needs no heat transfer medium and thus can travel in a vacuum. The most familiar example of radiant energy is sunlight, which travels through the nearly empty outer space, the denser atmosphere of the earth and is finally absorbed by buildings and pavements. These structures then act as secondary heat sources by radiating much of the absorbed heat back to the surrounding atmosphere.

In most systems all three methods of heat transfer are present. A platen, internally heated by an electric heater, heats the work by conduction. However, heat may be lost from the surfaces of the platen both by convection and conduction to metal parts touching the platen. In an oven the walls and internal structures also become heated and these in turn radiate and convect heat back into the oven cavity.

These secondary heat sources, while useful in maintaining a stable heat level in the system, can nevertheless cause difficulty in a closely-controlled system by creating local concentrations of heat which can bias the sensing element if it is not properly shielded. Conduction and radiation of heat away from the sensing element by supporting fittings and fastenings can similarly produce a sensing error. Thus, the various ways in which heat moves in and out of a system have a direct, practical influence on temperature control.

How the Rest of the System Affects Control Accuracy

1. Thermal Gradient

If you were to measure the temperatures in a thermal system at some instant, starting at the heater and progressing outwards to the edge of the system, you would find few, if any, places along the line of measurement where the temperatures are exactly the same. Rather you would find that the temperature drops progressively as you move farther away from the heat source. This gradual drop existing in a system is called a thermal gradient.

Every operating thermal system has a gradient at all times. Temperature changes are occurring continuously because of heater cycling and heat losses, but these changes are not transmitted immediately through the remainder of the system. As a result there is always a temperature differential or gradient between points, with the highest temperature obtained at the heat source and lowest at the outer edges of the system. Some gradient is essential for heat flow, since heat cannot flow unless there are areas of lower temperature to move into.

The steepness of the thermal gradient changes continuously as the system cycles. It increases as the heater warms up and decreases as the heater cools. The gradient is increased as the temperature at the work drops and as heat loss from the system increases. Figure 2 illustrates these points using a simple thermal system. (In a large system, gradients are more complicated because of the many factors involved, but the same principles apply.)

Assume you have a metal bar containing a heater, sensing element, and a pellet of material representing the work load, the three components being located as shown at the top of Figure 2. If you place a sensitive temperature indicator at various points in the bar and record the temperatures existing at the beginning, middle and end of the operating cycle, you would obtain three temperature curves similar to the ones shown. These represent the temperature gradient in the system at three instants during its continuous cyclic change from minimum to maximum steepness.

Figure 2 illustrates another important point about gradients. That

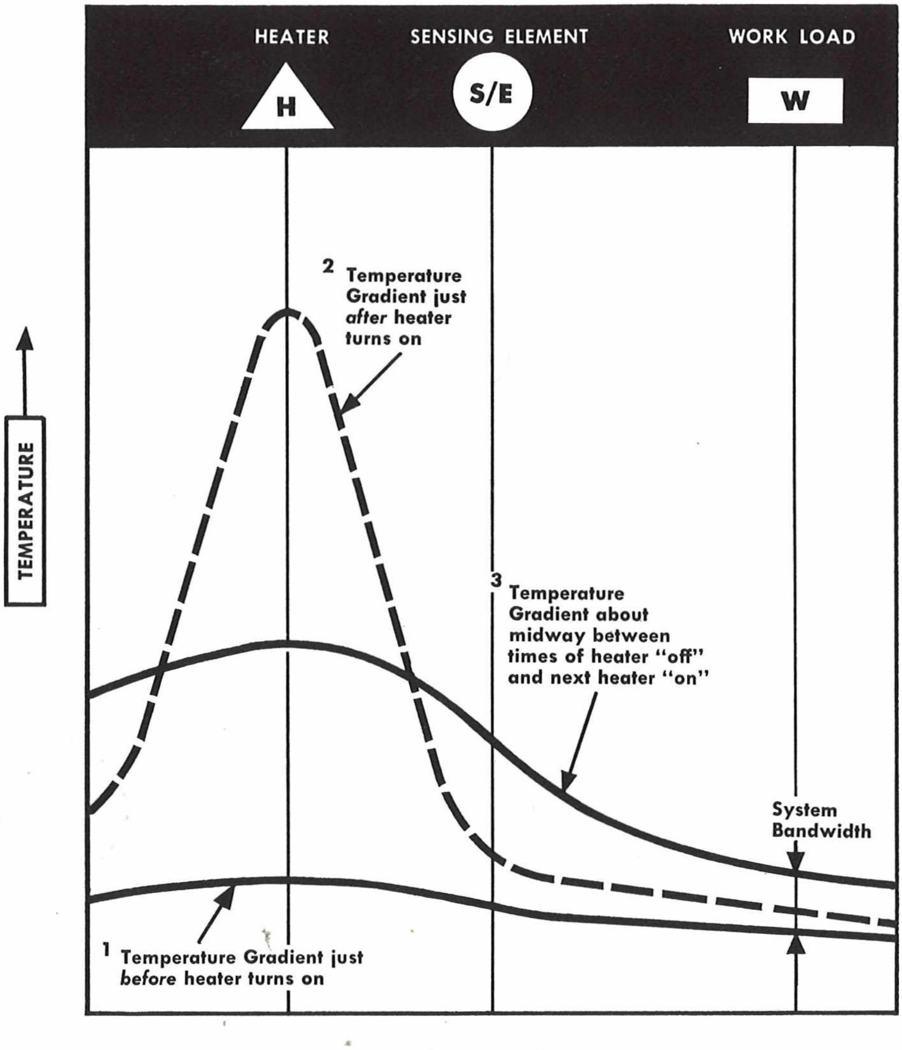


Fig. 2

is, the bandwidth decreases as you get progressively farther from the heat source. Thus, though the heater temperature may vary as much as 1000 or 1200 degrees during its cycle, the total change in temperature at the work can be a few degrees or less. The reason is that the quantity of heat released by the heater is absorbed by the entire system, so that by the time it reaches the work, the heat wave is sufficiently damped to produce a relatively small temperature rise.

A. *Allow for Gradient When Measuring and Controlling Temperature.* Because temperature varies along the gradient, it is important to measure temperature as close as possible to the area you want controlled. If you place the thermometer between the work and the heater, the reading will usually be higher than the temperature in the work area. If you measure the temperature at a low point in the gradient, for example, near the outer surface of the system, it may well be lower than the temperature at the work area. Also, since the slope of the gradient continuously changes during the heating cycle, a sensitive indicator will follow the change, so that you may require an average of the maximum and minimum readings for a more representative temperature.

By the same reasoning, the set point of the controller must be adjusted according to its relative location. The closer to the heater you get, the larger the offset necessary to keep from shutting off the heater too soon. For example, to control the work at 300 degrees when the sensing element is between the work and the heater, you may have to set the controller at 305 or 310 degrees to enable the heater to reach a sufficiently high temperature to produce a useful temperature rise at the work area.

B. *How to Reduce Gradients.* Although thermal gradients are inevitable and necessary, excessive gradients can be troublesome. They can be reduced in these ways (covered in detail in following section):

1. Balancing heater capacity against heat demand. Gradients are influenced by the amount of heat input and heat losses. Too large an input will increase the gradient and the temperature bandwidth.

2. Proper setting and location of the sensing element to control the duration of the heat cycle.

3. Insulating the system to reduce heat loss.

2. Thermal Lag

Figure 3 illustrates a simple thermal system in which the temperature is measured simultaneously at the heat source, sensing element and work area. At time "0" the temperature at the sensing element has fallen to the level which causes it to turn the heater on. The temperature at the heater rises immediately and sharply. However, the sensing element and the work, being located at some distance from the heater, do not feel the heat until later. When the temperature has risen sufficiently around the element (time 3), the controller turns off the heater. The temperature in the heater itself drops quickly but the heat already released continues to flow to the cooler parts of the system, so that their temperature rises even though the heater is off. The work area may reach maximum temperature at about the same time that the heater reaches its minimum. This delay in the distribution of heat through the system is called *thermal lag*. It is present to some extent in every system. It is influenced by the distance between the heat source and the work, and the resistance to heat flow and heat capacity of the heat transfer medium.

Thermal lag is the enemy of accurate control because it handicaps the controller. It withholds from the controller for a certain interval—which may be as much as several minutes in some cases—information about temperature changes in the system. This lag can prevent the sensing element from sensing heat demand soon enough to deliver the heat when needed. It can also delay the arrival of heat at the element so long that the heater has delivered more heat than the system needs to recover from a temperature drop. The result in the first case is temperature undershoot; in the

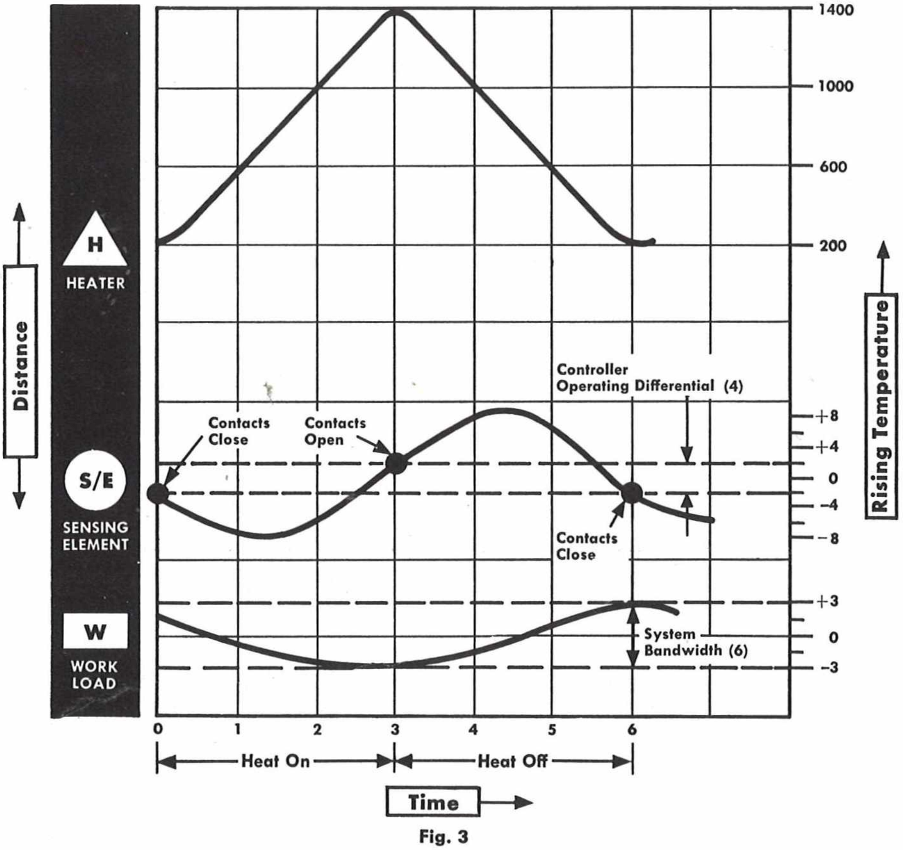


Fig. 3

second case, temperature overshoot. Both can produce an undesirably large bandwidth.

Since thermal lag can never be entirely eliminated, one of the major prerequisites for close control is to reduce lag to the largest extent practical, and to compensate for the remainder. Thermal lag can be reduced by using materials and techniques to speed up heat distribution. The remaining lag can be compensated for by selecting a controller of sufficiently fast response and carefully placing its sensing element at a point where it can sense important temperature changes quickly.

Thermal lag can produce misleading information for evaluating controller performance in a rapidly changing system. In certain systems the lag can be large enough so that, when the sensing element is placed between the heat source and the work area, the controller may call for heat because of reduced temperature in its area, while the temperature at the work is just starting to rise as a result of the previous heating cycle. This effect can seem even more pronounced if the controller has a fast response while the temperature indicator at the work has a large inherent lag, such as is found in many mercury-in-glass thermometers.

3. Selecting the Heat Transfer Medium

The selection of the heat transfer medium has much to do with the amount of thermal lag. All materials delay heat flow, in that they must absorb a certain quantity of heat before their temperature rises. This delay can be thought of as a "thermal inertia" which must be overcome before heat is transmitted through the material, and depends on the thermal conductivity and specific heat of the material.

Solids, liquids and gases are all used as heat transfer media, with metals probably the most commonly used. In most cases the choice is already fixed by the cost, size, and application for the thermal system. However, where close control is the first consideration, the following evaluation of transfer media will be helpful. They are listed in order of decreasing preference for close control, and, in some cases, there may be overlap between individual materials in different classes.

1. Well-agitated liquids
2. Rapidly moving air
3. High-diffusivity metals
4. Low diffusivity solids
5. Stagnant air
6. Stagnant liquids

In considering this list, remember that liquids can provide better temperature control than solids only if agitation or forced convection is used. Most fluids have relatively poor conductivity and extremely slow rates of heat transfer if allowed to circulate by normal convection. High thermal conductivity and low specific heat are the primary characteristics for a good heat transfer and low-lag material.

A. *Thermal conductivity* is a measure of the rate of heat flow through a conducting medium of unit length and unit cross section for a given temperature difference. Various sets of units are used; therefore observe the dimensions carefully and convert to other units if required. In the English system, a common set is BTU/hr/in/ft^2/°F —the number of BTU that flow in one hour through a slab 1″ thick and 1 sq ft in cross section, when the temperature difference between the faces of the slab is 1°F.

B. *Specific heat* is the quantity of heat required to produce a given temperature rise in a given mass of material. In the English system it is the number of BTU needed to raise the temperature of 1 lb of material by 1°F.

The importance of high conductivity for reducing thermal lag is well known, but the importance of low specific heat is sometimes overlooked. Heat capacity, which takes into account the weight and specific heat of a material, can influence the cost of operating a thermal system because it relates to the quantity of heat which must be expended to raise system temperature a given amount. From the standpoint of operating economy this consideration is particularly important in systems whose control temperature must fluctuate frequently over a large temperature range.

C. *Thermal diffusivity* combines the factors of thermal conductivity and specific heat into a single figure and may be useful for evaluating various materials used as heat exchange mediums. Thermal diffusivity is thermal conductivity divided by the product of density and specific heat.

Materials used for heat transfer should have high conductivity and low specific heat, or high thermal diffusivity. This applies not only to the heat transfer medium, but also to the metals used for the sensing element and for thermal wells.

Table 1 lists the thermal properties of some commonly used materials.

4. Proper Location of Components

By now it should be clear that a controller performs no better than the system permits. Thermal lag is one of the major factors in handicapping the controller. Lag can be reduced by proper choice of the heat transfer material. It can be further reduced by a wise matching of the controller with the application (See page 20) by placing the components correctly in the system. Correct placement is essential, because starting with the same heat source, controller and thermal load (including total heat requirements of the work, heat transfer medium and heat loss) you will obtain widely different control accuracies depending on the relative locations of these components.

If the heat source, sensing ele-

Table 1

TYPICAL PROPERTIES OF COMMON MATERIALS

Arranged by Type, and by Thermal Conductivity

	Conductivity $\frac{\text{BTU-FT}}{\text{FT}^2\text{-HR-}^{\circ}\text{F}}$	**Diffusivity*** $\frac{\text{FT}^2}{\text{HR}}$
METALS		
Silver	240	6.5
Copper	224	4.4
Aluminum, 2S	127	3.4
Brass, 85 cu-15Zn	91	1.8
Aluminum, 17S	83	2.2
Aluminum, 75S	70	1.9
Yellow brass, 65 cu, 35Zn	69	1.4
Beryllium copper, 2%	54	1.1
Aluminum, cast 220	51	1.4
Steel, 1020	38	.73
Iron, wrought	35	.66
Nickel, wrought	35	.57
Stainless steel 414, 420, 430	30	.57
Stainless steel 410	28	.53
Lead, pure	20	.94*
Monel	15	.21
Hastelloy D	12	.23
Hastelloy A	9.6	.18
Stainless steel 301, 302, 304, 309,	9.6–	.16
310, 316, 321, 347	8.7	.15
Inconel, wrought	8.6	.15
Inconel "X"	8.5	.15
Hastelloy B	6.5	.12
Invar	6.0	.10
NON-METAL SOLIDS		
Concrete	0.45	
Asbestos board	0.42	
Glass	0.6– 0.30–	
Asbestos, granulated	0.10	
Cork	0.02	
LIQUIDS		
Water—32°F	0.32	
Water—212°F	0.39	
Most other fluids	0.20– 0.07	
GASES		
Hydrogen, 212°F	0.13	
Most other gases	0.02– 0.01	

*Note that, while conductivities decrease by a ratio of 40:1, the diffusivities decrease by a ratio of 65:1, and in the same sequence. The only significant exception is lead. Conductivities may therefore be used *FOR METALS ONLY* as a means for selecting best thermal properties, if information on diffusivity is lacking.

ment and work could be always grouped into a compact area, there would be little problem with control. The short heat path from the heater would enable the sensing element to respond quickly to temperature increases at the heater, cycle frequently and minimize overshoot. At the same time the element is in a position to respond quickly to changes in heat demand at the work and minimize undershoot. Also, the small mass of the transfer medium would reduce inertia and thermal lag throughout the system. The result would be a nearly ideal system with a very narrow bandwidth and little change in mean work temperature.

In the majority of cases this intimate grouping of system elements is not feasible due to the relatively large size of the system and the fact that the heat source is at some distance from the work area. The problem then arises as to where to place the sensing element, because moving it away from either the heater or load affects control in some manner. There is no single answer to the problem. The designer's problem is to arrive at the best compromise for his thermal system.

Recommended approaches for specific systems will be discussed shortly, but it may be helpful to consider first the general consequences of sensing element placement, which apply to all systems.

(1) Placing it adjacent to the heater produces a *narrow bandwidth* at the load, *provided* the heat demand at the work remains fairly constant. The thermal lag to the element is small. It, therefore, senses the temperature change rapidly and cycles the heater frequently. This sharply reduces the possibility of overshoot and keeps the bandwidth small.

(2) Moving the sensing element closer to the work area enables it to respond more rapidly to heat demand of the work. This is particularly necessary for close control of systems in which the heat demand varies considerably at frequent intervals. When the element is near the work, the *mean temperature* will be held at a constant level, but this advantage is offset by increased thermal lag from the heater, and a consequent increase in bandwidth.

Thus, when the work and the heat source are separated, placement of the sensing element involves compromising the advantages of smallest bandwidth and constant mean temperature at the work area. Both cannot be attained at the same time. You must decide which of the two types of accuracy is more important for your system.

A. *Importance of Cycling Frequency.* Precision performance of ON-OFF controls requires frequent cycling of the heat source. (In systems using other than an ON-OFF control mode, frequent cycling is unnecessary.) Rapid cycling produces a series of short bursts of heat which approximates a steady heat input at the load. Infrequent cycling, on the other hand, causes prolonged heating intervals in which large quantities of heat enter the system. This results in wide variation in thermal gradient during the operating cycle and undesirably increases the system bandwidth.

Although rapid cycling is desirable because it reduces bandwidth, there are practical limits to be considered. Excessive cycling decreases the service life of contacts and mechanical components of the controllers, relays, heaters, and other cycled components. The optimum cycling frequency is one that produces the desired system bandwidth without excessive wear on the cycling components.

Cycling frequency can be reduced by moving the sensing element away from the heat source. If this is not practical, you can reduce it by increasing the thermal lag to the element by some artificial means, such as insulating the element with a strip of asbestos, a heat shield or a reflecting strip.

Rapid advances in the state of the art of solid state electronic devices such as silicon controlled rectifiers and thyristors allows their direct replacement for mechanical relays and controllers in electrical heating. These solid state devices can be switched rapidly without the mechanical problems of wear and servicing. However, initial installation costs are somewhat higher.

B. *Preferred Component Location for Various Thermal Systems.* Although in practice thermal systems are not purely steady or variable, they usually are predominantly one or the other. For such systems, the following rule of thumb will be helpful: where the heat demand is relatively steady, the sensing element should be placed closer to the heat source; where the demand is largely variable, it should be nearer to the work area.

Naturally, the characteristics of any individual system, such as complicated thermal gradients or variable heat losses, may require trying several different sensing element locations before deciding on the most desirable one, but the rule of thumb is a good starting point. The guiding principle is that the element should be closer to that area where a temperature change must be sensed with minimum thermal lag. Figure 4 illustrates in greater detail the effect of various bulb locations on the control of predominantly static or dynamic systems. This Figure applies generally to all heat transfer mediums, but some additional considerations apply to liquid and gas systems.

C. *Liquid and Gas Systems.* In liquid baths and ovens where the heat demand is primarily steady, locating the sensing element fairly close to—and above—the heat source should minimize bandwidth. In the arrangement illustated in Fig-to prevent excessive heat input. The second thermostat, installed near the work, will respond quickly to temperature variation in that area.

The control point for each thermostat can be determined empirically to include heat gradient, rate of heat loss, frequency of changes in thermal demand, etc., and other factors peculiar to the individual system. Generally, the thermostat near the working area should be set at approximately the desired control temperature. The thermostat located near the heater would be set at some higher temperature to provide sufficient heat to meet maximum demand and yet prevent the heater from causing overshoot in the work area.

Another approach is to use two heaters, one which remains ON continuously and supplies most of the heat demand. The other, a smaller heater, is controlled by the thermostat.

5. Insulation is Important

Proper insulation has the double-barreled advantage of reducing heating costs while improving control accuracy. As is illustrated in Figure 7, the heat loss from an uninsulated surface is about 16 times that from a surface insulated with 2 in. of mineral wool at a 300°F temperature difference, and this loss becomes substantially greater as the temperature increases. Adequate insulation, therefore, is good economics.

Besides saving heat, another important function of insulation is to minimize temperature gradients within the system. Although gradients cannot be eliminated entirely, they should be as small as possible to keep the temperature nearly uniform throughout the system. Reduction of gradients also lowers the offset required for the controller setpoint, and produces a narrower system bandwidth as the heaters cycle.

Best temperature control with minimum heat input is obtained when the thermal conductivity within a system is high but the conduction of heat away from the system is low. For this reason the system should be thermally insulated from any supporting structures which will carry away heat and increase the gradient. This is particularly important where the heated mass is relatively small compared with the supporting structure; for example, a heated platen in a large press.

If the platen is in direct contact with the surrounding metal of the press, the press would conduct away large amounts of heat, creating high thermal gradients within the platen. Here, the flow of heat between the platen and its support mounting should be reduced by using stand-off bosses to decrease the area of contact. The bosses should be made from material having the lowest conductivity practical within the strength and temperature requirements of the application.

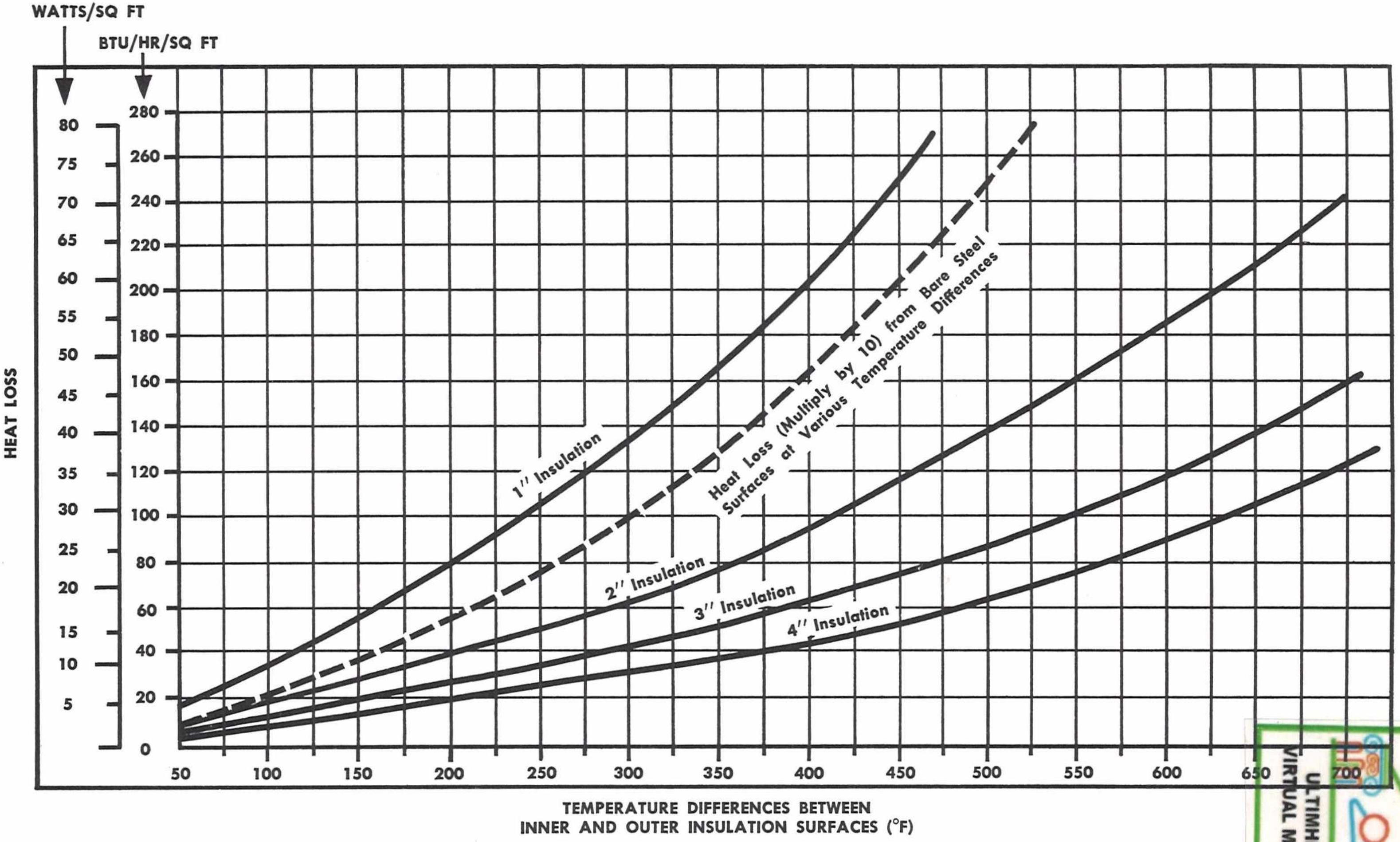


Fig. 7—Comparative heat losses at 80°F room temperature in still air from surface of various thicknesses of mineral wool felt insulation. (Insulation Density = 2.5 Lb/Cu/Ft)

Table 3
SPECIFIC HEATS AND OTHER DATA

(a) Solids

Substance	Average Specific Heat	Heat of Fusion (BTU per lb)	Melting Point (°F)	Weight (lb per cu ft)
Aluminum	0.23	138	1216	160
Antimony	.052	25	1166	423
Asphalt	.40	40	250	65
Beeswax	...	75	144	60
Bismuth	.031	23	520	610
Brass	.10	...	1700	525
Brickwork and Masonry	.220	...	...	140
Carbon	.204	...	...	...
Copper	.10	75	1981	550
Glass	.20	...	2200	165
Graphite	.20	...	...	130
Iron, cast	.13	...	2300	450
Iron, wrought	.12	...	2800	480
Lead, solid	.031	10	621	710
Lead, melted	.04	...	...	...
Nickel	.11	...	2642	550
Paper	.45	...	...	58
Paraffin	.70	63	133	56
Pitch, hard	...	...	300	83
Rubber	.40	...	...	95
Silver	.057	38	1761	655
Solder (50% lead—50% tin)	.04	17	415	580
Steel	.12	...	2550	490
Sugar	.30	...	320	105
Sulphur	.203	17	230	125
Tallow	...	...	90	60
Tin, solid	.056	25	450	455
Tin, melted	.064	...	...	...
Type metal (85% lead—15% antimony)	.040	...	500	670
Wood	.45	...	...	34 pine 50 oak
Zinc	.095	51	787	445

(b) Liquids

Substance	Specific Heat	Heat of Vaporization (BTU per lb)	Boiling Point (°F)	Weight (lb per cu ft)	Weight (lb per gal)
Acetic acid	.472	153	245	66	8.81
Alcohol	.65	365	172	55	7.35
Benzine	.45	166	175	56	7.49
Ether	.503	160	95	46	6.15
Glycerine	.58	...	554	79	10.58
Mercury	.0333	117	675	845	112.97
Oil, cotton-seed	.47	...	...	60	7.76
Oil, olive	.471	...	570±	58	7.75
Paraffin, melted	.71	...	750±	56	7.49
Petroleum	.51	...	...	56	7.49
Sulphur, melted	.234	652	601	...	...
Turpentine	.41	133	319	54	7.22
Water	1.0	965	212	62.5	8.34

(c) Gases and Vapors

Substance	Specific Heat Constant Pressure	Weight (lb per cu ft at approx. 70°F, Atmospheric Pressure)
Acetylene	.35	.073
Air	.237	.080
Alcohol	.453	. . .
Ammonia	.520	.048
Carbon dioxide	.203	.123
Carbon monoxide	.243	.078
Chlorine	.125	.20
Hydrochloric acid	.195	.102
Hydrogen	3.41	.0056
Methane	.60	.0447
Nitrogen	.245	.078
Oxygen	.218	.09
Sulphur dioxide	.155	.179

more than 60% of the time, the heater rating should be increased. If the heater is on less than 40% of the time, the rating is too large and should be decreased.

Procedure for Proper Sizing of the Heat Source. Two factors enter into determining the required heater rating: (1) the amount of heat needed to bring the system up to operating temperature from a cold start within a specified time, and (2) the amount of heat required to satisfy the demand of the system (including losses) during normal operation. Usually the larger of the two will determine the minimum rating. However, where the warm-up requirements are relatively large, special techniques to handle warm-up conditions can be used (see "Preventing Overshoot During Warm-Up." Page 46).

The following problem will illustrate the steps required to deter-

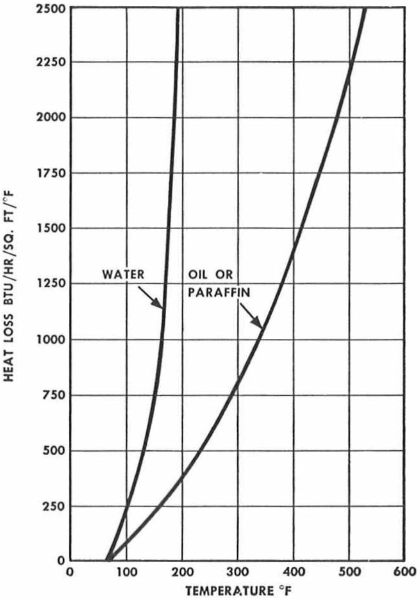


Fig. 9—Heat lost from exposed liquid surface at 70° F ambient temperature

mine heater capacity. Since electric heaters are a commonly used heat source, the problem will be worked out in terms of wattage. The same procedures are followed for all heat sources, but using whatever heat units are appropriate for the particular source.

Problem:

Find the heater capacity required for a paraffin dip tank for applying a temporary protective coating on steel tools. The installation is an open-top steel tank, 1.5 x 2 x 1.5 ft, weighing 140 lb empty. It contains 200 lb of paraffin to be maintained at 150°F. 1500 tools, weighing ¼ lb each, are dipped per hour, consuming 20 lb of paraffin per hour. The tank cools to room temperature (70°F) at night and must be reheated each morning to operating temperature in 1 hour. The sides and bottom of the tank are insulated with 1 in. of mineral wool insulation.

The heater capacity required for any system—either for warm-up or normal operation—is the sum of all the factors that influence the amount of heat which will be absorbed by the process and the amount of heat which will be lost to the surrounding room. Or:

HEAT REQUIRED=

(a) heat absorbed by the system, including work (material being heated), heat exchange medium, and structural materials such as racks, walls, insulation, etc.
(b) heat absorbed by melting or vaporizing materials
(c) heat losses through insulation and/or exposed surfaces
(d) added safety factor to obtain load flexibility and proper heat balance

(See tables 2 and 3, and Figs. 7 and 9 for the physical constants and other data used in solution)

I. WARM-UP HEAT REQUIRED

A. Heat Absorbed

By Paraffin:

(1) to heat paraffin from room temperature to melting point

$$200 \text{ lb x } .70 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (133–70) \text{ deg} = 8{,}820 \text{ BTU}$$

(2) to melt paraffin

$$200 \text{ lb x } 63 \frac{\text{BTU}}{\text{lb}} = 12{,}600 \text{ BTU}$$

(3) to heat from melting point to control temperature

$$200 \text{ lb x } .70 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (150–133) \text{ deg} = 2{,}380 \text{ BTU}$$

By Structural Parts of System

(1) to heat tank metal from room temp. to control temp.

$$140 \text{ lb x } .12 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (150–70) \text{ deg} = 1{,}344 \text{ BTU}$$

Total Heat Absorbed During Warm-Up 25,144 BTU

B. Heat Lost During Warm-Up

(1) from exposed paraffin surface (refer to Fig. 9)

$$3 \text{ sq ft x } 240 \frac{\text{BTU}}{\text{hr-sq ft}} \text{ x } 1 \text{ hr x } \underset{\text{(for avg. loss)}}{\tfrac{1}{2}^{*}} = 360 \text{ BTU}$$

(2) through side and bottom insulation (refer to Fig. 7)

$$13.5 \text{ sq ft x } 28 \frac{\text{BTU}}{\text{hr-sq ft}} \text{ x } 1 \text{ hr x } \underset{\text{(for avg. loss)}}{\tfrac{1}{2}^{*}} = 190 \text{ BTU}$$

Total Avg. Loss During Warm-Up 550 BTU

C. Total Heat Consumed in Warm-Up = 25,144 + 550 = 25,694 BTU

D. Convert to Kilowatt-Hours

$$25{,}694 \text{ BTU x } .000293 \frac{\text{KWH}}{\text{BTU}} = 7.5 \text{ KWH}$$

E. WARM-UP HEATER CAPACITY REQUIRED (+20% safety factor)

$$\frac{7.5 \text{ KWH}}{1 \text{ hr}} \text{ x } 1.20 = 9.0 \text{ KW}$$

*An approximation sufficiently accurate for practical use.

II. CALCULATING HEAT CONSUMED PER HOUR OF OPERATION

A. Heat Absorbed By

(1) heating tools (from 70F to 150F)

$$375 \text{ lb x } .12 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (150\text{–}70) \text{ deg} = 3{,}600 \text{ BTU}$$

(2) tool container (from 70F to 150F)

$$60 \text{ lb x } .12 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (150\text{–}70) \text{ deg} = 575 \text{ BTU}$$

(3) heating paraffin make-up (from 70F to melting pt 133F)

$$20 \text{ lb x } .70 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (133\text{–}70) \text{ deg} = 882 \text{ BTU}$$

(4) melting paraffin

$$20 \text{ lb x } 63 \frac{\text{BTU}}{\text{lb}} = 1{,}260 \text{ BTU}$$

(5) paraffin from melting pt to 150F

$$20 \text{ lb x } .70 \frac{\text{BTU}}{\text{lb-deg}} \text{ x } (150\text{–}133) \text{ deg} = 238 \text{ BTU}$$

Total Heat Absorbed Per Hour of Operation 6,555 BTU

B. Heat Losses During Operation

(1) from exposed paraffin surface

$$3 \text{ sq ft x } 240 \frac{\text{BTU}}{\text{hr-sq ft}} = 720 \text{ BTU}$$

(2) through side and bottom insulation

$$13.5 \text{ sq ft x } \frac{26 \text{ BTU}}{\text{hr-sq ft}} = 350 \text{ BTU}$$

Total Heat Losses Per Hour of Operation 1,070 BTU

C. Total Heat Absorbed + Lost = 6,555 + 1,070 = 7,625 BTU

D. Convert to Kilowatt-Hours

$$7{,}625 \text{ BTU} \times .000293 \frac{\text{KWH}}{\text{BTU}} = 2.2 \text{ KWH}$$

E. HEATER CAPACITY REQUIRED FOR 50% HEAT-ON BALANCE

$$2.2 \text{ KW} \times 2 = 4.4 \text{ KW}$$

Since the heater capacity required for warm-up (9.0 KW) is greater than the capacity required for normal operation (4.4 KW), a total heater capacity of about 9 KW should be used for this installation.

2. Heater Selection

After calculating heater capacity required for the application, the next step is to select the heat source. There are many heating methods available, such as steam or hot-water jackets or coils, Dowtherm and similar heat exchangers, as well as radiant and direct contact heaters. For simplicity, the following discussion will be confined largely to electric resistance heaters, though many of the principles apply to other heat sources.

A. *Installation Method.* The manner in which the heaters are installed can affect uniformity of heat distribution, rate of heat build-up and heating costs in the system, as well as determine the configuration and rating of heaters to be used. The more intimate the contact between the heaters and the material or part being heated, the better is the heat conductivity. Good conductivity improves temperature control and lengthens heater life. The usual methods of installing heaters, listed in decreasing order of heat conductivity are:

1. Cast integral with metal or immersed in liquids or gases
2. Inserted in hole drilled in metal
3. Placed in groove in surface of metal
4. Wrapped around or clamped to the surface
5. Spaced away from surface being heated (except for radiant heaters)

Heaters are manufactured in a variety of shapes and forms to fit the type of installation. Cartridge, strip, ring, tubular and immersion are common configurations.

B. *Selecting the Proper Sheath Material.* The resistance element and outer sheath of a heater are designed for service within certain temperature limits. If the heater is operated consistently at excessive temperatures, the heating element will fail prematurely and the sheath metal will deteriorate rapidly. The sheath metals and their corresponding maximum temperatures are:

Copper	350 F
Lead	400 F
Steel	700 F
Nickel silver	1000 F
Chrome steel	1200 F
Heat Resistant Nickel Alloys	1500 F
Quartz	2000 F

Corrosion problems must also be considered when selecting the proper sheath material. When working with corrosive or oxidizing materials, it is vital to select a sheath material that has good corrosion-resistance at the temperatures in question. For unusual service requirements, consult the heater manufacturer.

C. *Selecting Proper Watt Density.* Because of differences in heat absorption and heat transfer, there is a limit to the *rate* at which various types of materials can be heated safely. If the heating rate is excessive, the area around the heater will become overheated. This localized overheating may deteriorate the material being heated and damage the sheath and heating element. Molasses, for example, will char if it is heated at the same rate that is normally used to boil water.

Heaters are rated on the basis of *watt density*, which is the number of watts produced per square inch of heated sheath surface. The higher the absorption rate of the material, the higher the permissible watt density for the heater. To aid in selecting a heater which will produce a safe heating rate, most heater manufacturers publish recommendations on allowable watt densities for various situations. Table 4 lists optimum heater ratings for some typical applications.

D. *Concentrated vs. Distributed Heat Source.* It is usually preferable to use several heaters whose wattages add up to the required heat input, rather than a single heater of the required capacity.

Table 4

Material Being Heated	Approx. Operating Temp. (°F)	Recommended Watt Density (watt/sq in)
Water	212	35–65
Alkali cleaning solution	212	35
Prestone	300	20–30
Metal melting pot	500	25
Vegetable oil (fry kettle)	...	25
Dowtherm A	600	20
Machine oil (SAE-30)	...	18
Dowtherm E	400	12
Bunker C fuel oil	160	10
Asphalt	300	3–5
Molasses	100	4–5
Glue	...	No direct heating

equally sensitive, they may not necessarily respond within the same time.

Response time depends to a large extent on the operating principle of the controller. For example, a THERMOSWITCH® control will respond considerably faster than an ordinary thermostat with an enclosed bi-metallic element, because its shell is the temperature-sensing element. The housing of the enclosed-element type, on the other hand, acts as a barrier which slows up heat transfer and increases response time. Liquid-filled systems are more rapid than gas-filled systems, because liquids have higher thermal conductivities and thus respond more quickly to temperature changes. Thermo-electric sensing elements are the most rapid of all. In general, response time will be low for sensing elements having low mass (e.g., the thermistor), and a short heat transfer path between the temperature to be sensed and the actual sensing member (e.g., the THERMOSWITCH design). In addition, the probe should be as thin as possible and fabricated from a good thermal conductor.

Fast response is important in two types of applications: (1) where the system temperature changes rapidly and frequently; (2) where the heat transfer medium is a relatively poor conductor, such as gases or slowly-circulating liquids. Speed of response is less important where temperatures remain relatively constant for long periods, where highly accurate control is not essential, or where proportional control is used.

D. *Sensing element dimensions:* these vary depending on the operating principle of the controller. Of the commonly used industrial controllers, liquid-filled controllers are available in a variety of sensing element configurations ranging from long, thin, to short, squat types, and can be adapted to many installation requirements. Where space is a critical consideration, a midget or miniature THERMOSWITCH unit, or a thermistor element no bigger than a common pin, will solve the problem.

E. *Method of adjusting setpoint:* where the sensing element must be placed in a location that is difficult or hazardous to reach, there is little alternative to using a remote-setting controller to adjust the setpoint. Bulb-and-capillary controllers can be furnished with capillary lengths of 10 ft or more; thermistor control leads can be 200 ft long. However, wherever adjustments will be accessible while the system is operating, a local-bulb type controller is a good choice, and will be more economical.

F. *Control mode:* this refers to the method in which the controller attempts to restore system temperature to the desired level. The two most common methods are two-position (on-off) and proportioning (throttling) control. Two-position control results in a certain amount of over and undershoot, which may be excessive under certain conditions. Proportioning control provides one method for preventing overshoot by tailoring the size of the correction to the amount of temperature error. Some Fenwal controllers are designed to operate as on-off controls; others operate in both the on-off and proportioning modes. The advantages and limitations of each control mode will be discussed in detail in a later section.

2. How Temperature Controllers Work

The operating principle of a controller can tell a great deal about the performance to expect. Most of the commonly-used industrial temperature controllers today are based on one of three operating principles. These are: differential expansion of metals; fluid expansion; and electronic. Fenwal manufactures controllers of each type.

A. *Differential expansion controllers:* This familiar principle of sensing temperature makes use of the fact that dissimilar metals undergo unequal changes in length with a given change in temperature. The sensing element in a common class of thermostats consists of two pieces of dissimilar metals fabricated into a strip, coil or disc. As the temperature changes, the element tends to warp or distort and the resulting motion can be used to operate a circuit by moving an electrical contact toward or away from a mating contact. This motion can also be used to overcome the force of a spring-loaded detent, which will actuate a snap switch.

A refinement of the differential-expansion principle is the strut-and-tube thermostat, such as the cartridge THERMOSWITCH unit (Figure 10), and its midget and miniature counterparts. In this design, the bimetals are not bonded together into a single element, but comprise two basic parts of the thermostat. The outer shell is made of the high-expanding material, usually brass or stainless steel and

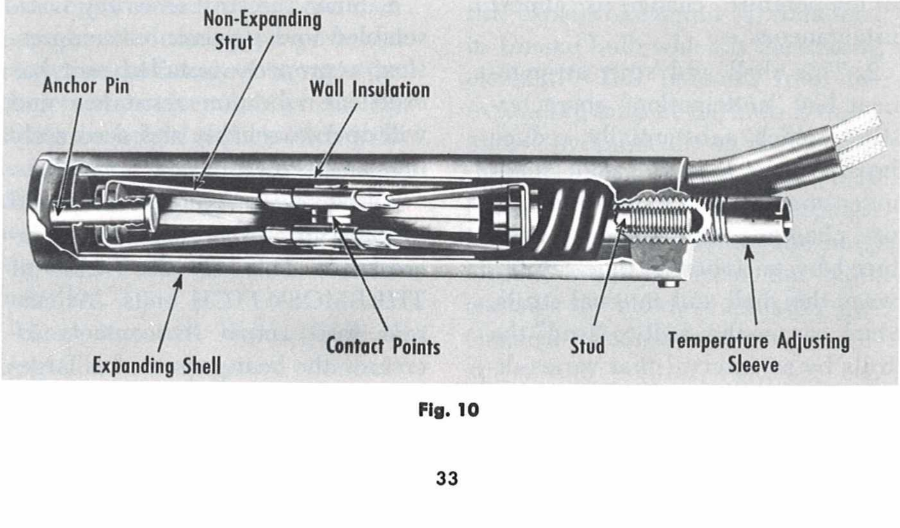


Fig. 10

the strut assembly is made from a low-expanding metal, usually a high nickel alloy. The strut assembly, on which a pair of electrical contacts are mounted, is installed in the shell under tension or compression depending on whether the maximum overshoot capability or maximum setting range is desired. Because each end of the strut assembly is mechanically connected to the ends of the shell, a net change in force is produced on the low-expansion strut assembly as the high-expanding shell expands or contracts with changing temperature. The amount of shell movement necessary to cause the contacts to open or close is set by an adjusting screw and since this movement is a direct function of temperature, the screw setting determines the control temperature. This adaptation of the differential-expansion principle gives several important control advantages:

1. Because the outer shell is the active temperature sensing member, and not merely a housing, response to temperature change is almost instantaneous.

2. This shell and strut arrangement has "anticipation" characteristics, which substantially reduce the amount of over and undershoot under conditions of rapid temperature change. Anticipation is produced by an inherent time lag between the shell and internal struts, which causes the shell to "lead" the struts by an interval that varies directly with the rate of temperature change. With rapid temperature rise, the shell exerts a larger net force on the struts and tends to pull them apart sooner than would be the case when the temperature is rising slowly. The result is several degrees or more of anticipation which help produce closer control.

3. The strut-and-contact assembly operates by slow make and break, which means that every temperature change, no matter how small, causes a corresponding change in the spacing between the electrical contacts. This means that contact action can be produced by a very small temperature change, which accounts for the excellent resolution sensitivity (0.1°F) of THERMOSWITCH controls. On the other hand, thermostatic units whose contacts are actuated by a snap switch or similar detent action, have sensitivities of several degrees since a finite amount of energy must be absorbed to overcome the restraining forces on the contact assembly and thus produce contact actuation.

4. Since the strut assembly is assembled under tension or compression, a properly installed unit has excellent vibration resistance and will operate reliably and accurately under difficult physical conditions.

All current-carrying devices tend to heat up as the current load increases. This is also true of THERMOSWITCH units. As current load across its contacts increases, the heat generated is largely absorbed by the strut assembly on which they are mounted. Heating the strut assembly has the same net effect of raising the setting of the controller. For this reason, although the control will handle loads up to 10 amps, it produces best control at more conservative loads. Where the loads are greater than 3 to 4 amps, much better results will be obtained by using a relay as the load-carrying element with the control handling the pilot load. Another alternative, where electrical load exceeds 3–4 amps and the operating temperature is applicable, is to use the Series 20000 liquid-filled thermostat. In this unit, the current is handled by a snap switch so that the size of the current load has little effect on the controller action.

B. *Liquid-filled controllers:* if a small container is completely filled with an incompressible liquid, the volume of the liquid will change with the temperature. If the container is somewhat elastic, such as a bellows, it will move in response to the changing volume of the liquid. The motion of the bellows can then be transmitted through a push rod or mechanical linkage to actuate the contacts of an electrical switch. By setting the height of the switch with an adjusting screw, the amount of push rod travel required to operate the switch—hence the operating temperature of the unit—can be controlled.

There are two basic types of liquid-filled temperature controllers. The first is the local-bulb thermostat. An example of this type is the Series 20000 unit (Figure 11), in which the sensing liquid, bellows and push rod are all enclosed in a cylindrical shell which is inserted directly in the process. At the top of the shell is the head of the unit containing the control switch and lead wires. This type is non-indicating.

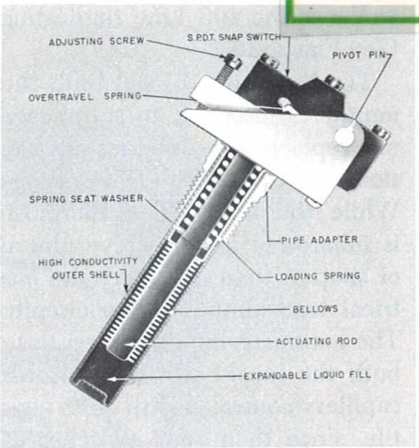


Fig. 11

The second type is the bulb-and-capillary controller. In this type the expansible liquid is contained in a metal bulb which is the sensing element. The pressure from the expanding fluid in the bulb is transmitted hydraulically to the bellows through a thin capillary tube, 6–10 ft long, also filled with the expansible fluid. A separate housing, located remotely from the bulb, contains the bellows, actuating mechanical linkages, indicating mechanism and control switches, etc. A typical bulb-and-capillary controller is the 400 Line (indicating). (See Figure 12.)

The liquid-filled local bulb thermostat is intended to supplement, not replace, the differential-expansion THERMOSWITCH design. While the liquid-filled thermostat is inherently less sensitive, the use of snap switches to carry the electrical load simplifies the circuitry. The load carrying characteristics of both the local-bulb and bulb-and-capillary controllers are quite versatile, since their snap switches can be interchanged for various types of service, including 20 amps at 125 or 250 volts AC, as well as narrow differential, high inrush and manual reset. In addition, switches can be paired to produce control action at two selected temperatures. In the 400 Line controller, the two-switch arrangement can be furnished to permit individual setting or constant differential between the two settings, with indication of one or both settings as well as the process temperature.

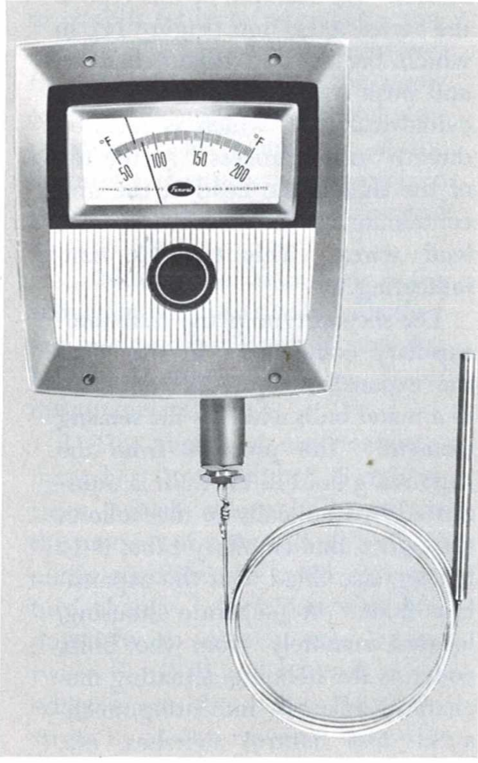


Fig. 12

c. *Thermistor-Actuated controllers:* these controllers, exemplified by the Fenwal Series 561 (Figure 13) and Series 536, represent a relatively new development in temperature control techniques. These are temperature controllers actuated by a thermistor sensing element, connected by lead wires to an electronic amplifier, indicating circuit (if present) and control circuit all contained in a separate housing or chassis. These controllers offer unusual advantages. They are highly accurate and mechanically rugged, have excellent stability with age, utilize a small sensing element, require infrequent calibration and can be located up to 200 ft or more from the sensing element using standard electrical conductors. This performance results from the remarkable properties of the thermistor.

The thermistor is a semi-conducting material made into tiny beads or other shapes by sintering a mixture of metallic oxides. One of the outstanding attributes of the ther-

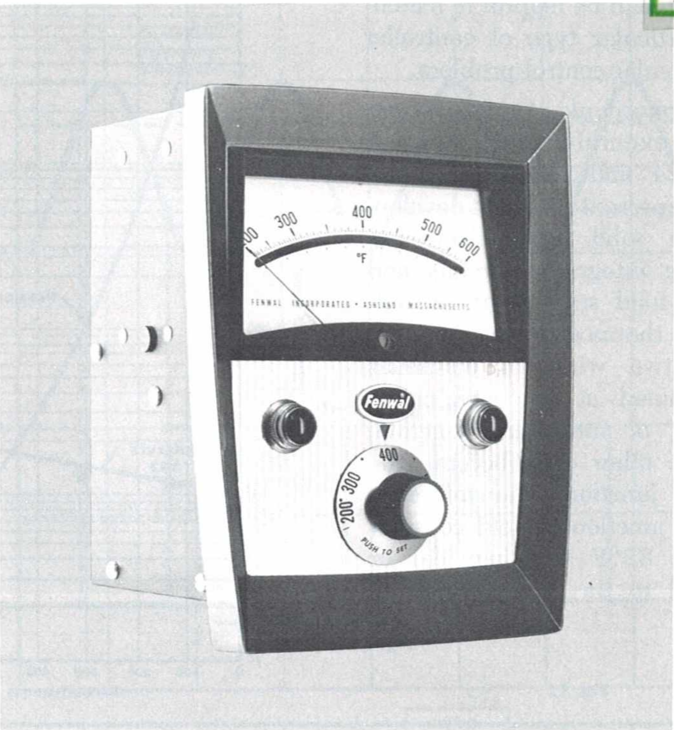


Fig. 13

mistors is that their electrical resistance decreases rapidly per degree of temperature rise. Compared with the sensing elements used in other types of temperature controllers, i.e., resistance bulbs and thermocouples, thermistors produce a very large working "signal." Some thermistors undergo a thousandfold change in resistance between 100 and 600°F, while a resistance bulb may change in resistance by a factor of only 2 over the same temperature range. The output of the commonly used iron-constantan thermocouple varies over an even smaller range of values at these temperatures. (See Figures 14 and 15.)

Since a relatively small change in temperature at the thermistor produces a large change in resistance, the controller has unusually good sensitivity capable of producing stable control well within 1°F in a properly designed system. The sensing and control circuits are relatively more compact, less subject to mechanical shock and generally require less maintenance than those used with a thermocouple or resistance bulb.

Table 5 summarizes the specifications for all types of Fenwal controllers which will be helpful in matching a particular type of controller to a particular control problem.

D. *Thermocouple Actuated Controllers:* exemplified by Fenwal Series 524 and 525 (Figures 16 and 17) represent the latest developments in solid state electronics employing integrated circuits and relay or solid state thyristor outputs. The thermocouple sensor consists of two wires of dissimilar metals joined at one end called the "hot" or measuring junction, while the other ends become the reference junction. The reference or "cold" junction is held constant at either 32°F (melting ice) or calibrated to an equivalent EMF

Fig. 14 ▶

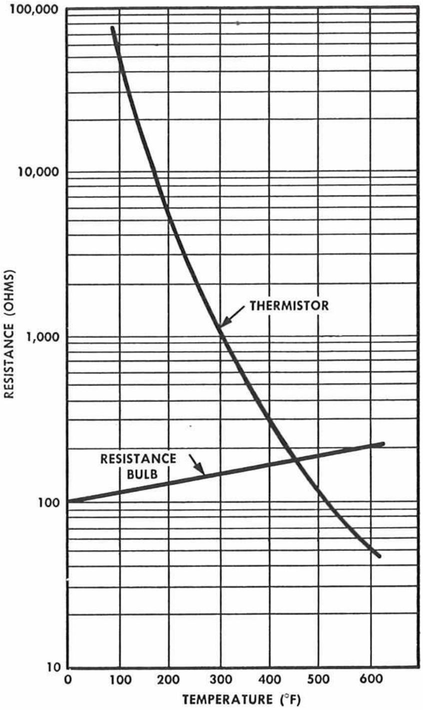
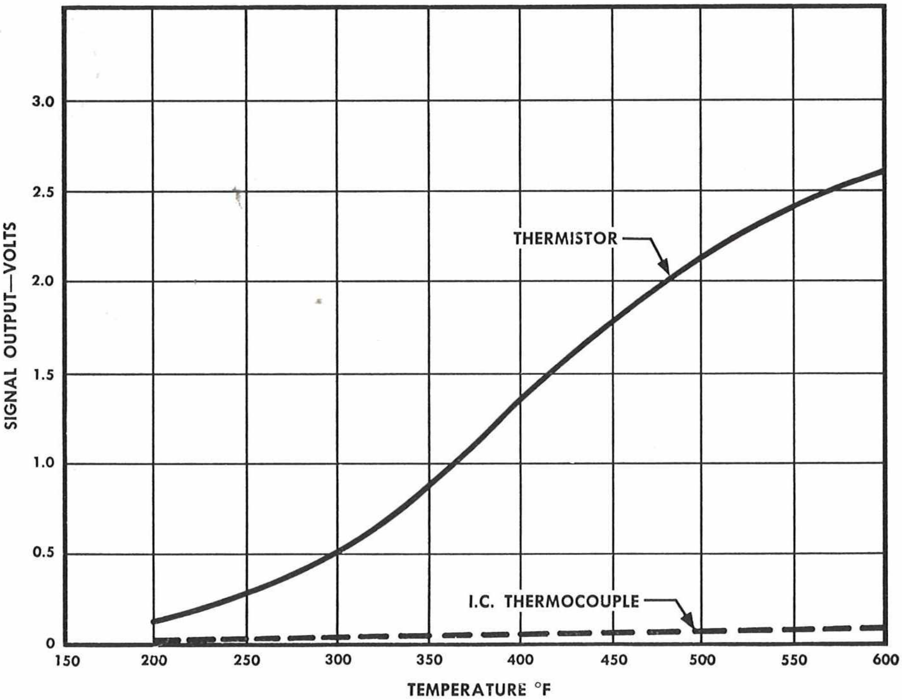


Fig. 15



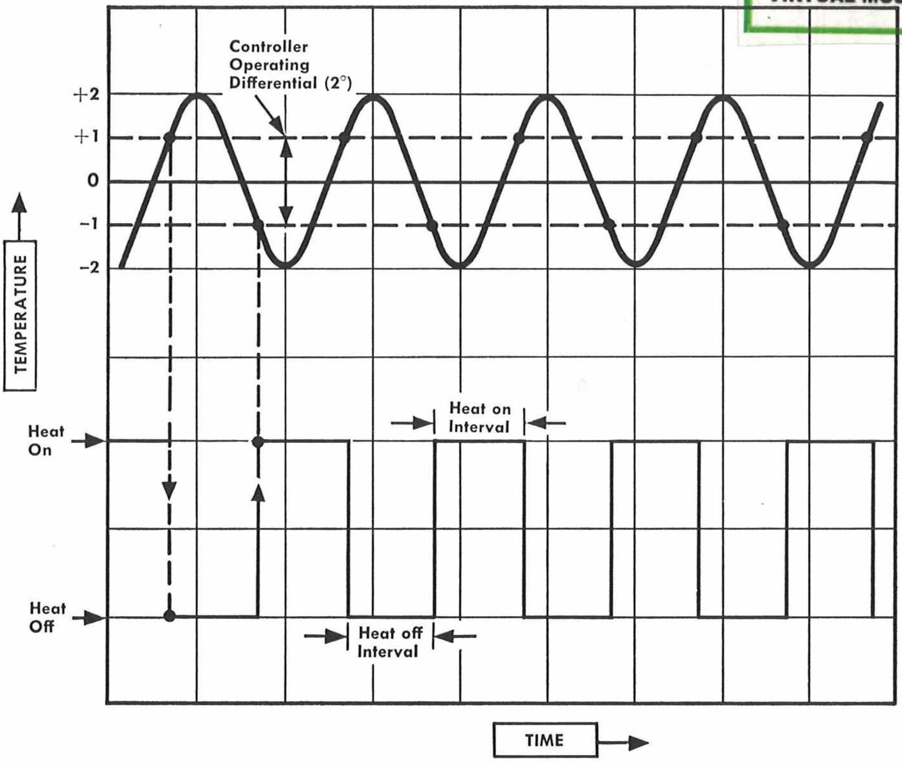


Fig. 16

value. The temperature or difference between the hot and reference junctions develops a DC millivoltage that is linear with temperature within a few degrees. This signal is fed into a bridge balance potentiometer which measures the EMF output and, with amplification to a useful level, controls process temperature through the operation of a relay or solid state device.

The overall thermocouple range is —300 °F to approximately 4000 °F and is derived from several base metal combinations such as iron/constantan, copper/constantan, chromel/alumel and noble metal combinations of platinum or platinum/rhodium with rhodium in varying percentages.

Thermocouple wires are available in commercial and premium grades with wire error limits within 2 °F. Thermocouple sensors generally have a response time about ten times better than a resistance temperature detector and are tip sensitive.

E. *The Platinum Resistance Temperature Detector (RTD):* differs from a thermocouple in that a finely wound platinum wire changes its resistance directly with tem-

Table 5: SELECTION DATA FOR FENWAL CONTROLLERS

Controller Model	Operating Principle	Control Temp. Range (°F)	Operating Differential	Electrical Load Rating	Remote or Local Temp. Adjustment	Temperature Indication	Approximate Bulb Size	Mounting Arrangement	Type of Control
Thermoswitch Series 17,000, through 18,000	Differential Expansion (slow make-and-break)	–100 to +600	1 °F (in well-designed system)	10 AMP, 115 VAC 5 AMP, 230 VAC — — — — Heavy-Duty: 25 AMP, 115 VAC 12.5 AMP, 230 VAC	LOCAL	NON-INDICATING	⅝″ dia, 3⅝″, and up, long Heavy-Duty: 13⁄16″ dia, 3⅝″, and up, long	Cartridge-Type, Threaded or Flanged	ON-OFF (inherent anticipation)
High Temperature Thermoswitch Series 13,100, 15,000, and 16,000		+200 to +1500 others +300 to +1100					⅝″ dia, 9″ long; others smaller		
Midget Thermoswitch Series 67,000 and 12,400		–50 to 500 F	1–5°F (depending on system)	1 AMP, 115 VAC; 1 AMP, 32 VDC — — — — 1 AMP, 48 VAC 1 AMP, 32 VDC			¼″ dia, 2⅜″ long		
Miniature Thermoswitch Series 32,000		–20 to 200 F or –20 to 275 F		2.5 AMP, 115 VAC 2.0 AMP, 28 VDC — — — — 2.5 AMP, 115 VAC 1.0 AMP, 28 VDC	Local; hermetically sealed model factory set		Rectangular: 1 x ½ x ½ in. Circular: ¾″ dia. ½″ to ¾″ high	Surface-or recessed-mounted	ON-OFF
Surface Mounting Thermoswitch Series 30,000		50 to 300 F or 50 to 600 F — — — — plastic-enclosed models: –10 to +167 F	5–10°F (depending on system)	1200 W, 110 V	LOCAL		2⅛ x ½ x 1½ in.	Surface-Mounted	

Thermoswitch Series 20,000, 21,000, and 22,000	Liquid-Filled (Snap-Action)	250- or 200-degree control ranges within limits of −75 and +300	2—8°F depending on switch type and system	Up to 20 AMP, 250 VAC 10 AMP, 125 VDC depending on switch	LOCAL	NON-INDICATING	⅝″ dia., 3⅝″ long	Threaded or Flanged	ON-OFF (Series 22,000 has 2 control switches)
Series 541	Liquid-Filled, Bulb-and-Capillary	650- or 350-degree control ranges within limits of −100 to +700	2—8°F in well-designed system	Up to 20 AMP, 250 VAC 10 AMP, 125 VDC depending on switch	Remote; Capillary Length up to 20′	INDICATING	⅛″, ¼″, ⅜″ dia., Length ?	Cartridge-Type Bulb	ON-OFF (available with 2 control switches)
Series 536	Thermistor-Actuated	−50 to 600	within 1°F in well-designed system	10 AMP, 115 VAC (Spdt Relay)	Remote; Ordinary lead wires up to 200 ft away	NON-INDICATING	3⁄16″ dia., 3″ long (bare probe, if requested, 1⁄16″ dia., 1″ long)	Cartridge-Type, Threaded, or Flanged	ON-OFF and Time-Proportioning
Series 561						INDICATING			
Series193	Thermistor-Actuated	−50 to 750°F	1°F or better	15 AMP Triac	Remote and Local	NON-INDICATING			Proportioning
Series 194	Thermistor-Actuated	−90 to 700°F	1°F or better	10 AMP Relay	Remote and Local (Lead break protection standard)	NON-INDICATING			ON-OFF and Proportioning
Series 19-202	Thermistor-Actuated	−50 to 750°F	1°F or better	8 AMP Triac	Remote and Local	NON-INDICATING			ON-OFF
Series 524	Thermocouple-Actuated	−200 to 2500°F	.1% of range	10 AMP Relay or Triac; or 4-20 ma Driver	Local	INDICATING			ON-OFF and Proportioning
Series 525	Thermocouple-Actuated	0 to 2000°F	1°F or better	10 AMP Triac or Relay	Local	NON-INDICATING			ON-OFF and Pro-positioning
Series 141	Solid State Contactor	To boost current rating or virtually any switching device, 25 AMP and 40 AMP models, 120/240 VAC.							

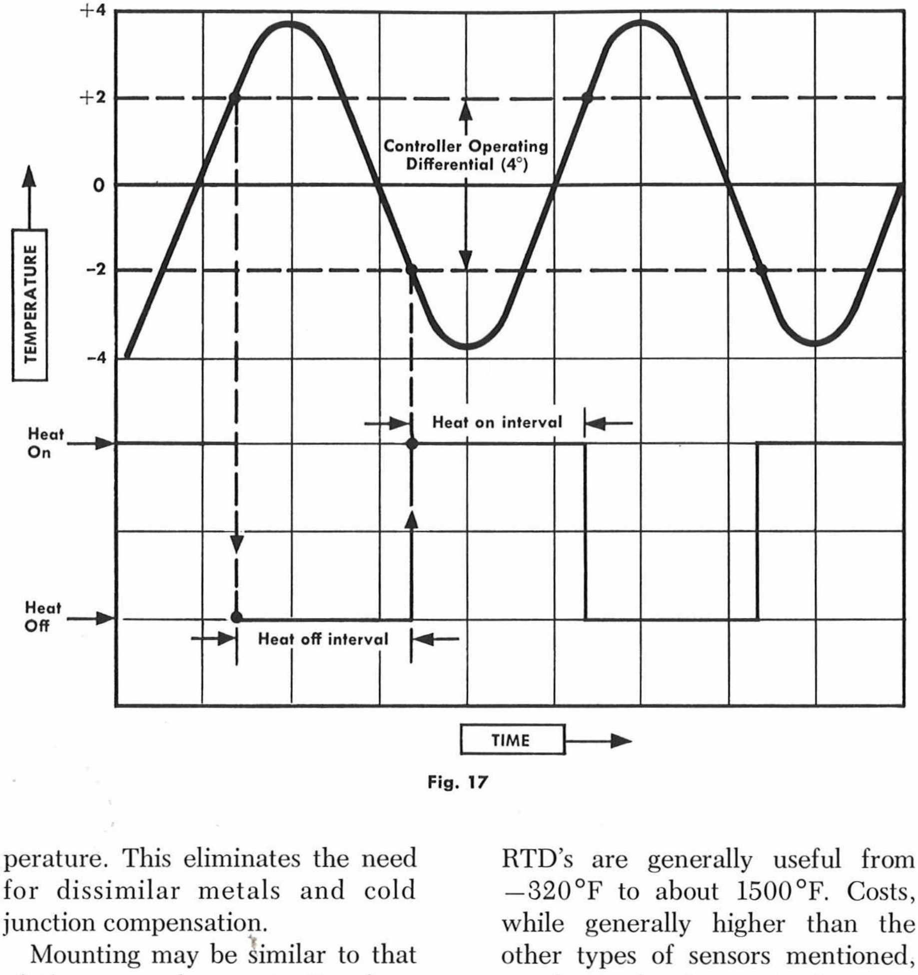


Fig. 17

perature. This eliminates the need for dissimilar metals and cold junction compensation.

Mounting may be similar to that of thermocouples; protection from stress or corrosive environments is achieved by encapsulation and/or installation in thermowells. Two, three or four leads may be provided with connection to a Wheatstone bridge circuit being common. Care must be exercised to avoid resistance change from excess current or heat conducted to the resistance bobbin along its leads.

Platinum RTD's are a better choice when resolution and reproducibility of 1/10 °F are required. RTD's are generally useful from −320 °F to about 1500 °F. Costs, while generally higher than the other types of sensors mentioned, are becoming increasingly more competitive.

3. Types of Control Action

A. On/Off (two position)
B. Proportioning (throttling)
C. Proportioning plus Integral
  (automatic reset)
D. Proportioning plus Integral
  plus Derivative (rate)

A. *On-off control:* in on-off control the controller permits the controlled element (heater, valve, etc.) to be completely ON or OFF, open or closed. No intermediate position is possible. As a result, the size of the corrective action has no relation to the amount of temperature deviation. Full heat (or other action) is supplied regardless of whether the temperature is 2° or 20° below the setpoint. The heat stays until the controller senses that the system temperature corresponds to the setpoint (or more accurately, the higher limit of the controller's operating bandwidth).

The end result of two-position control is that the system temperature oscillates continuously above and below an "average" system temperature (see Figure 16). The size or amplitude of these oscillations determine the system's bandwidth and they are governed by many design factors which have already been discussed.

1. Adjustable differential: most on-off controllers have a fixed operating differential, but in some more elaborate controllers the operating differential can be varied to suit the application. Operating differential is the "dead zone" or the difference between the temperatures at which the controller opens and closes its contacts.

The chief advantage of increasing the operating differential is to decrease the cycling rate and thus the wear on switches, heaters and other cycled components. However, reduced cycling affects control. The effect of doubling the operating differential of a controller in a given system is shown in Figure 17. A comparison between Figures 16 and 17 shows that doubling the operating differential, approximately doubles the bandwidth of the system, and cuts the cycling frequency in half. Since the system bandwidth is strongly influenced by cycling frequency, the operating differential of a controller, if adjustable, should be increased judiciously. The best choice is the one which will reduce the cycling frequency of the equipment as much as possible, without producing an excessive temperature bandwidth in the system.

B. *Proportioning control:* in proportioning control the controller "recognizes" the deviation from the setpoint and proportions the corrective action to the size of the deviation. The proportioning action occurs when the system temperature falls within a range of temperatures known as the proportioning band. At the approximate center of this band is the desired system temperature. Suggestions on setting the proportioning band will be given in a following section.

If we assume a system whose temperature is regulated by positioning an infinitely-variable steam valve, then proportioning action would operate as follows. When the system temperature is at 25% of the proportioning band, the valve would be 75% open. When the temperature rises to the 50% point in the band (the desired control temperature) the valve will be half open. The heat input will balance heat losses, and the system will be in equilibrium. As the temperature rises above the 50% point, less heat is needed to maintain the equilibrium and the valve opening is constricted proportionally by the controller. Above the upper limit of the band the valve is completely closed; below the lower limit, completely open.

In true proportioning control, the controlled element, for example a valve, can be moved to any position from 0 to 100% open, as required by the size of the deviation from the control point. However, in the case of temperature control of electrically-heated systems, the proportioning action is produced by varying the ratio of time-on to time-off during a base reference cycle. Thus, if the reference cycle is 15 seconds and the controller remains on for 7.5 seconds of each cycle, it produces the same effect as operating the heaters at half wattage. Similarly, if the time-on is 5 seconds for each 15-second cycle, this is equivalent to operating the heaters at one-third wattage. The Series 561 controller is a time-proportioning controller of this type.

The virtue of proportioning control is that the system temperature does not oscillate continuously around the desired value, as it does in the case of on-off control. Since the corrective action is tailored to the size of the deviation to be corrected, the system has less opportunity to overshoot or undershoot. This action is particularly helpful in systems which go through frequent work cycles where the system is cooled down by the addition of cold material and then must be brought up to temperature quickly. Under these conditions, the temperature tends to overshoot in each recovery cycle and the throttling action of proportioning control is most helpful in combating this tendency.

1. Selecting the proper proportioning band: ideally the proportioning band for any particular system should be just wide enough to accommodate the time lags in the system. This means that if the system is constructed so that the controller can quickly sense the effects of its control action, the corrective action can be relatively large; where there is a substantial lag between the action and the sensing, the corrections should be modest, otherwise the system temperature may never stabilize. If the proportioning band is too wide, the offset or droop effect becomes more pronounced. If it is too narrow, the advantages of proportioning control are lost and the system temperature will oscillate around the desired control temperature duplicating the effect of on-off control.

The proportioning band for a given system can be established by operating the system at the desired temperature with the controller functioning on the on-off control mode at minimum differential and noting the limits of overshoot and undershoot encountered. The proportioning band should then be set to just exceed these temperature excursions.

2. Droop: there is, however, an inherent limitation in proportioning control. The size of the corrective action depends only on the size of the difference between the system temperature and the setpoint. But this corrective action can fit only one set of equilibrium conditions. That is, suppose a steam-heated system is so constituted that when the temperature drops to 40% of the proportioning band, a 60% valve opening will supply enough heat to return the temperature to the setpoint. If the steam pressure drops, or there is a sudden increase in the amount of material being processed, or something else occurs to change the heat input or heat loss, then a 60% valve opening will not produce a large enough corrective action for the new conditions. A proportioning controller cannot correct the valve position without a change in sensing element temperature. This will result in the system being controlled at progressively lower temperatures having, in effect, a "droop."

However, by the nature of proportioning control, the droop cannot go below the lower limit of the proportioning band under normal operating conditions. Thus, a narrowing of the band will reduce droop. Droop can be corrected by resetting the setpoint above or below the original setting or by rotating a manual reset adjustment (if provided) so that the system stabilizes at the desired temperature. Droop also can be corrected by adding INTEGRAL ACTION or automatic reset to the controller.
In this variation (PI), the integrator adds a signal to the controller action so that the output of the controller is proportional to the time integral of the input. In other words, reset recognizes the deviation between actual process temperature and setpoint and supplies a signal to correct for this deviation. This signal moves the proportioning band up or down to cause agreement over a period of time. By design, reset action occurs only *within* the proportioning band. This type of operation is termed to have *anti-reset windup* which prevents a large reset charge causing overshoots on startup.

Reset is generally measured in "repeats per minute" which is another way of saying that the reset rate will integrate the error (droop) and offset this error with an opposite signal to restore process temperature to the desired value in one minute. In most devices, reset rate is fixed – but, in some units, user adjustments from 1/10 repeat per minute (10 minutes per repeat) to 10 repeats per minute (6 seconds per repeat) can be made. Startup should be made with the minimum repeats per minute (longest reset rate – essentially proportioning mode only). Proportioning band (if adjustable) should be adjusted so that oscillations cease. Then reset should be made in incremental steps.

3. Most PI controllers rely only on the error between the process and desired temperature to deter-

mine output power. This is analogous to noting only the position of a car to determine when to apply the brakes as it approaches a stop sign. Any good driver also will note the speed of the car (although subconsciously) and anticipate the earlier braking required at higher speeds.

To overcome overshoots in a proportioning controller, *DERIVATIVE* action is added to PI units to take account of the rate at which temperature is changing and adjust controller power output accordingly. For example, if temperature is rising rapidly to the setpoint, power is turned off sooner than it would be if the rise were slow. In effect, derivative action anticipates thermal lags within the system and shifts the proportioning band by an amount determined by the rate of change of the input sensor. The magnitude of the shift is determined by a derivative time constant. This is defined as the offset per unit rate of change. In the Series 525 PID units, for example, the time constant is about 7 seconds and so, for every degree per second rate of change of temperature at the sensor, the proportioning band is moved 7 degrees in the direction that helps control, i.e., if the process temperature is rising, the power output is reduced, corresponding to a temperature 7° higher up in the proportioning band.

Controllers employing proportioning plus automatic reset plus rate are called three-mode controllers (PID).

4. HELPFUL HINTS FOR ADJUSTING PROPORTIONING CONTROLLERS

A. Rapid cycle time provides better control and prolongs heater life; if relay output is used, relay life is shortened.

B. Bandwidth should be adjusted so that oscillations just cease. Wide bandwidth provides stable control, but droop is larger.

C. Automatic reset adjusted properly eliminates droop. Too fast a reset rate causes unstable operation (system oscillates). With too little reset rate, system response is slow.

D. If rate time constant is too short, overshoot occurs (virtually no rate). If rate time constant is too long, oscillations can be caused by on-off action.

E. *System Startup:* Adjust reset for lowest repeats per minute (largest reset time) and rate for shortest time. This is essentially proportioning only control. Adjust reset in incremental steps so that droop is eliminated with minimum amount of oscillations. Adjust rate so that slight power line changes are nullified in shortest period of time without oscillations.

General Operating Techniques

1. Preventing Overshoot During Warm-Up

In many thermal systems the temperature must never exceed a certain maximum. Such a system might be a process in which a material is being processed or treated close to its decomposition temperature or boiling point. In such systems the possibility of overshoot, particuarly on initial heat-up, can be a serious problem.

A. *Anticipation:* two types of controllers can produce the anticipation needed to prevent overshoot during warm-up cycles: proportioning and differential expansion. Proportioning control is, of course, highly effective since it continuously reduces the heat input as the temperature rises toward the set-point. The advantages and limitations of proportioning control have already been described.

When the expense of a proportioning control is not justified, the differential expansion THERMOSWITCH unit will produce a considerable degree of anticipation. The amount of anticipation produced increases with increasing rate of temperature change in the system. Where overshoot is a particular problem, various THERMOSWITCH units can be supplied to produce the desired degree of anticipation for any particular application.

Figure 18 illustrates the effect of varying degrees of anticipation on reducing overshoot during initial warm-up. Note that a proportioning controller can eliminate overshoot entirely while keeping warm-up time to a minimum.

Location of the thermostat with respect to the heater also will affect the amount of anticipation. The shorter the distance between the heater and thermostat, the greater the anticipation effects.

B. *Extra warm-up heaters—single thermostat control:* another approach to obtaining rapid warm-up without overshoot is to use two sets of heaters. The circuit is connected so that the heaters will operate during the warm-up cycle, but when the control temperature is closely approached or reached, one of the heaters is switched out of the circuit leaving sufficient capacity to deliver the basic control heat. Both heaters can be operated by a single thermostat, provided some switching mechanism is inserted to reduce heat input after the first cycle. For example, during warm-up one of the heaters can be connected to a hold-

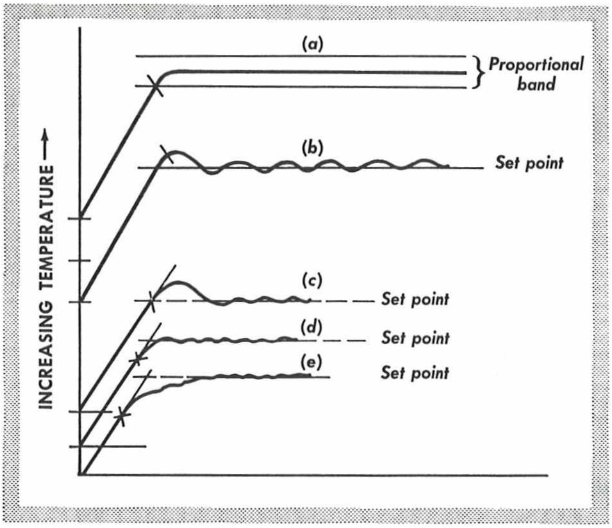


Fig. 18—Anticipation and overshoot characteristics of various temperature control methods: *a*, average-position action (time-modulated proportional) control; *b*, simple two-position action control; and *c*, *d* and *e*, two-position controllers with little, moderate and considerable anticipation, respectively. Beginning of control action is denoted by *X*

ing relay in series with the temperature controller. After the first controller cycle, the relay and its associated heater drop out of the circuit.

Another way to reduce warm-up heat using just one thermostat is to reduce the voltage supply after the warm-up interval. This can be accomplished by using a voltage selector relay which switches the power supply from 220 volts to 110 volts after the first cycle. If desired, a variable transformer can be inserted in the low voltage power supply line to provide exactly the proper voltage for the heat output required by the application. Relay action can also be applied in other ways, such as changing the connection of two heaters from parallel to series.

This general technique of using high heating capacity for warm-up has one significant limitation. The higher heating rate during the first cycle tends to exaggerate overshoot to some extent. This can be reduced by installing one of the warm-up heaters close to the thermostat, so as to produce an extra amount of anticipation. Since this heater will be inoperative after the warm-up interval it will not produce excessive anticipation which might interfere with control under normal operating condition.

c. *Extra warm-up heaters—two thermostat control:* the use of two thermostats, instead of one, can permit rapid warm-up without either producing overshoot or requiring any compromises in control during the normal operating cycle. The added thermostat is set to actuate at a temperature lower than the desired system temperature and switches off the warm-up heaters at some selected temperature. In the interest of reducing warm-up time, the setpoint of this thermostat should be as close as possible to the control temperature without producing overshoot. The warm-up thermostat and its heaters should be electrically independent of the control heaters and their thermostat. Another alternative is to use a step-down voltage supply arrangement to supply the heaters, using the warm-up thermostat to switch from the high- to the low-voltage source through a relay. Figure 19 illustrates two typical arrangements for avoiding overshoot based on one and two thermostats in the circuit.

2. Installation and Service Tips

One of the truisms of control is that the controller can respond only to what its sensing element "sees." Here are some important points which will insure that the sensing bulb does its job accurately.

A. *Proper location of sensing element:* in an earlier section we discussed at length the effect of locating the bulb at various points between the heat source and the load. (See page 19.)

In large chambers and long ovens, where there is a continuous flow of work in and out, it is sometimes impossible to place the sensing element at a point where the temperature is reasonably representative of temperatures elsewhere in the system. This creates a problem when the temperature of the work must be closely controlled during the entire process. In such cases control can be improved by

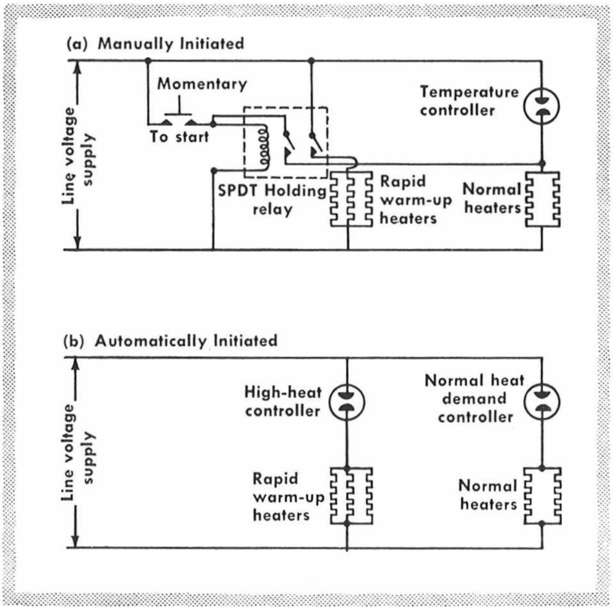


Fig. 19—Two simple methods of obtaining rapid warm-up. At *a*, the rapid warm-up heaters are held in the circuit by a holding relay until the temperature controller cycles; a controller with anticipation characteristics prevents initial temperature overshoot. At *b*, two controllers are used with the high-heat controller set below the desired temperature. The latter system has the advantage of automatically supplying extra heat whenever the temperature falls below the high-heat controller setting

using several controllers, each controlling a group of heaters, spotted at intervals along the direction of travel. In this way each controller can be responsive to the temperature existing at its particular location, and no undue reliance is placed on the ability of any one sensing element to respond to temperature changes at remote points. Remember that temperature gradients exist in every system and unless it is placed right at the point where the temperature must be controlled, the setpoint of the controller will have to be offset to compensate for the temperature difference existing at the sensing element's location.

B. *Good installation practice:*

1. Immerse the bulb completely. The sensing element must be completely immersed in the controlled medium, whether gas, liquid or solid, in order to give accurate response. If it is only partly immersed, the temperature reported to the controller may not be the actual temperature in the system, but an average of system temperature and the temperature around the exposed surface of the element. It should be insulated from brackets, bushings, etc., which are not at the same temperature as the bulb or which can conduct heat away to cooler parts of the structure. Otherwise it will be cooled and sense a lower temperature than the one actually existing.

2. Help the sensing element to "see." Any condition which tends to insulate the sensing element will slow down its response and introduce control inaccuracies, regardless of how good the controller is. When installed in an oven, the element must be installed where it is exposed to moving air and should not be buried in brick work, oven walls or shielded by some structure which will prevent its full length from being exposed. It should be placed so that it cannot be covered by accumulations of dirt, scale, sludges or any other materials that will insulate it from the process. Where such as accumulation does occur, clean the sensing element as often as necessary.

When the sensing element is imbedded in a solid, such as a platen, bearing, etc., there should be minimum clearance between it and the solid. Any air space will act as an insulator. The element should contact as much of the surface as possible. Thus, it should be cylindrical over its entire length, rather than tapered, to permit complete contact with the sides of the socket. A special heat transfer compound can also be used to fill in voids and irregularities in the hole.

In liquids and gases, good heat transfer between the sensing element and the medium can be obtained only if the fluid is moving fast. For that reason, the element should be placed in an active moving stream which is part of the general circulation of the system. In addition, without good circulation, there will be hot and cold spots in the system as well as a large sensing lag.

Do not locate the sensing element close to or parallel with walls and ducts that may be considerably hotter or cooler than the gases or liquids flowing past it. Watch out for radiation from hot surfaces or from the heat source impinging directly on it. This type of radiation can make the element considerably hotter than the actual temperature around it and cause what appears to be an offset in calibration. If it is not possible to avoid radiation by relocation, install a shield to intercept the radiation before it can heat the element.

3. Physical protection: install the sensing element where it cannot be knocked or jolted by moving parts of the system, doors, trays, etc. To protect it against corrosion and chemical attack, use stainless steel sensing elements and capillaries or install it in a thermal well of a corrosion-resistant metal.

Besides protecting the sensing element, thermal wells are a great convenience wherever it must be inserted through a tank wall, since it can be removed for replacement or adjustment without draining the tank. To insure good heat transfer, make certain it fits snugly in the well. Where the clearance is excessive, fill the air gap with a conducting material, such as graphite metallic filings or powder. Occasionally, open wells, which are simply open-end pipes, are used to protect capillaries from vapors and other undesirable materials which lie on the surface of a bath. The top of the well should be high enough above the liquid to keep the capillary out of range of the vapors.

3. Readjusting a Controller

A convenient and reproducible method for accurately readjusting a controller is to use it to control the temperature of a small heated test block.

A test block such as is illustrated in Figure 20a is a quick and accurate method for reliable temperature setting, since the unit being set actually controls the temperature of the block. Temperature testing kits are available from Fenwal but may be produced by boring out an aluminum block, or other block of good heat transfer properties, to receive a cartridge heater, a thermometer reading in tenths of degrees if possible, and the sensing bulb of the controller. Figures 20b and 20c, respectively, illustrate the wiring arrangements for setting up a heater block to cycle a thermostat whose contacts open on rising temperature, and one whose contacts close on rising temperature.

4. Trouble-Shooting a Thermal System

Table 6 lists some common temperature control problems and suggested remedies.

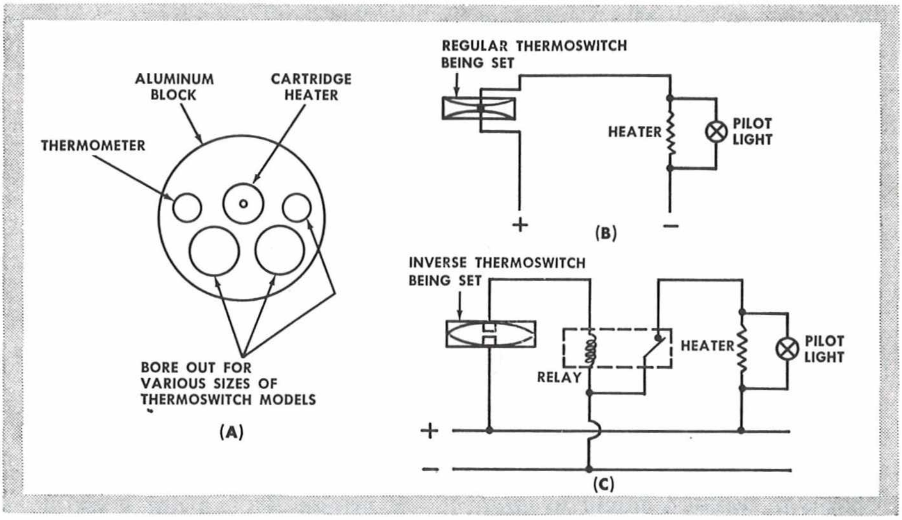


Fig. 20

Table 6
TROUBLE SHOOTING A THERMOSTAT INSTALLATION

Symptom	Possible Cause	Corrective Action
1. Shifting Control Point	1.1 "Head Effect." Sensing element is influenced too much by ambient temp. in relation to the influence of the process temp. Control point shifts when room temp. or breeze changes.	1.1 Insulate head. Provide better thermal conduction between process and sensing element. If a metal block, provide a tighter fit; use conducting grease. If liquid, increase circulation. If air, increase circulation, use fins, immerse bulb deeper into process, use extended length sensing element.
	1.2 Gradient in Process. Sensing element does not sense same temp. as the area in the process to be controlled. Difference between them varies with heat demand. Symptoms are similar to "head effect."	1.2 Insulate the process. Use as little metallic conduction to surroundings as possible. Shield from breeze. Minimize ambient temp. fluctuations, if possible. Use aluminum, brass, or other high conductivity metal if a block. Increase stirring if a liquid or air. Relocate thermostat to be nearer the area to be controlled.

Table 6 (continued)
TROUBLE SHOOTING A THERMOSTAT INSTALLATION

Symptom	Possible Cause	Corrective Action
(Continued) 1. Shifting Control Point	1.3 "Droop," applicable only to proportional controls without automatic reset. Control point droops when conditions demand more "ON" time.	1.3 Readjust manual or automatic reset, if provided. Reduce proportional band until the cyclic differential begins to be affected. Reduce **variations** in heat demand, if possible, by shielding from breeze and from extreme ambient temp. fluctuations. Relocate sensing element to cooler part of process. Sometimes simple, non-proportional control does a better job.
	1.4 Inadequate heat, during intervals when breeze is strong, air is cool, process temp. is set high, and/or line voltage to heater is low. Heat remains "ON" during this interval.	1.4 Increase heater size, or use a variac or equivalent and adjust the heat supply voltage as required.
	1.5 Thermostat is not correctly applied. May have failed due to excessive current, voltage, vibration, temperature, contamination of contacts, mechanical abuse, corrosion, etc.	1.5 Use a control rated for the job. Use a relay to reduce the current and/or voltage sensed by the control. Isolate control mechanism with shock mounts, if sensing bulb is remote. Avoid contamination, especially silicones, by suitable ventilation or use a sealed switch.
	1.6 Control is not ambient compensated. Control temp. goes down as ambient temp. goes up.	1.6 Some controls, particularly these with remote liquid filled bulbs, are sensitive to ambient temperatures. Where ambient temperature fluctuates, controls with compensator should be used.
2. Wide Cyclic Control Band of Uniform Amount	2.1 Control has wide differential. Poor choice of thermostat.	2.1 Use a control with a narrower differential. Most sensitive controls are more likely to require a relay.
	2.2 Control is sluggish to respond to a fast temperature change. Poor choice of thermostat.	2.2 Use a control which can follow process changes faster. Sensing element follows changes fastest when ratio of weight to external area is minimum. For liquid filled elements use longer, thinner bulbs. Fins help in ovens with moving air. May have adverse effect in ovens with only natural circulation. In extreme case use a proportional control.

Table 6 (continued)
TROUBLE SHOOTING A THERMOSTAT INSTALLATION

Symptom	Possible Cause	Corrective Action
(Continued) 2. Wide Cyclic Control Band of Uniform Amount	2.3 Sensing element improperly installed.	2.3 In metal block get a good fit between sensing element and block. Use conducting grease. Insert element fully. In liquid avoid a well if sensing bulb is heavy. Light weight elements, typically expanding tube types, are not much affected by a well. In either case effect of well is minimum when fit is good and/or grease is used. In air avoid dead corners. Insulate the sensing element as much as possible from any mounting that remains at essentially constant temperature.
	2.4 Control is not properly adjusted.	2.4 Decrease the controller differential, if adjustable. If a proportional control of the time modulating type, try increasing the proportional band.
	2.5 Thermal system design is inadequate.	2.5 Try placing the thermostat nearer the heater. Couple the heater to the process intimately. In metal blocks a cartridge heater should fit snugly. Use high conductivity metal for the block. Improve the insulation between process and surrounding bodies. Use multiple heaters to distribute heat. In liquid systems use increased circulation; place thermostat downstream of heater. In ovens use increased circulation. Place thermostat nearer to heater. Use a "maintenance" heater.
	2.6 Heat output is excessive.	2.6 Heat should be on about 50% of time. Excess heat causes overshoot. Processes require less heat at lower operating temperatures, therefore it may be necessary to disconnect some of multiple heaters or use a variac or other voltage control.
	2.7 Defective thermostat.	2.7 Replace with new one. Compare results.
3. Wide Cycles, Non-Uniform Cycling	3.1 Excessive electrical load. Contacts stick or contact heating affects active element of thermostat.	3.1 Reduce heat controlled directly by thermostat. Use relay, or split the load by using maintenance heat.

Table 6 (continued)

TROUBLE SHOOTING A THERMOSTAT INSTALLATION

Symptom	Possible Cause	Corrective Action
(Continued) 3. Wide Cycles, Non-Uniform Cycling	3.2 Contacts are contaminated.	3.2 Use sealed switch if contamination cannot be avoided by ventilation or by eliminating the cause of contamination. Silicone insulation on high temp. wiring should not be within the same tight compartment with contacts.
	3.3 Control not adjusted correctly.	3.3 If a proportional control of the time modulating type, the pulsing rate may need to be increased.
	3.4 Defective control.	3.4 Sliding parts may be sticking due to dirt, corrosion, or mechanical damage. Try new control.
	3.5 Contacts are either actuated or damaged by vibration.	3.5 Minimize vibration if possible. Change orientation to avoid vibration parallel to contact movement. "Slow make" switches usually respond to capacitor wired in parallel with switch.
	3.6 Contacts are damaged by direct current.	3.6 Consult thermostat mfg. for recommendations. Special contact materials sometimes help. Arc suppression is not always advisable.
	3.7 Relay sticks.	3.7 Avoid overload. Avoid contamination of relay contacts. Orient the relay correctly if affected by gravity.
4. Cycles Too Fast	4.1 Control is too sensitive.	4.1 Use a control with greater differential. Use a control having great thermal lag, such as a larger diameter bulb in liquid filled elements. Increase the lag by using air space or other insulation around sensing element. Use two controls with interlocking relay if differential must be extremely wide, and especially if the control band limits may need individual adjustment.
	4.2 System design is poor.	4.2 Move thermostat further from heater.
5. System Overshoots Excessively at Warm-up	5.1 Thermostat is sluggish.	5.1 See Section 2.2. Also, use a thermostat with "anticipation" and/or proportional control.
	5.2 Sensing element improperly installed.	5.2 See Section 2.3.
	5.3 Thermal system design is inadequate.	5.3 See Section 2.5.

Table 6 (continued)
TROUBLE SHOOTING A THERMOSTAT INSTALLATION

Symptom	Possible Cause	Corrective Action
(Continued) 5. System Overshoots Excessively at Warm-up	5.4 Excessive heat.	5.4 Reduce heater output. "ON" time should be about 50% after cycling begins.
	5.5 Auxiliary controls may be required.	5.5 Use 2-step heat when a fast warmup heater is cut off below the control point by another thermostat, or by a two-step control.
6. Relay Chatter	6.1 Mechanical vibration is excessive.	6.1 See Section 3.5.
	6.2 Contacts are contaminated.	6.2 See Section 3.2.
	6.3 Auxiliary equipment is required.	6.3 Capacitance wired in parallel with "slow make" thermostat usually helps. In extreme case use a time delay relay.
	6.4 Wrong type of thermostat.	6.4 Use suitable thermostat. Snap-acting locally actuated thermostats are usually better on vibration. In extreme case use types with remote sensing element.
7. Process Temp. Does Not Agree With Thermostat Calibration	7.1 "Head Effect."	7.1 See Section 1.1. If offset remains constant, merely recalibrate.
	7.2 Gradient in process.	7.2 If disagreement is variable, see Section 1.1. If error is constant, re-calibrate to match the process.
	7.3 "Droop," applicable only to proportional controls without reset.	7.3 See Section 1.3.
	7.4 Control is not ambient compensated.	7.4 See Section 1.6.
	7.5 Control is damaged.	7.5 Avoid temperature exposures beyond the ratings. Liquid filled remote bulbs may be damaged by plunging into hot medium. Control may be damaged by forcing the temp. adjustment.

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