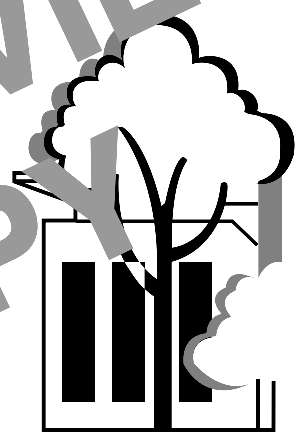
Control Systems

Table of Contents

CONTROL SYSTEMS

Lesson One

Introduction to Control Systems



TPC Training Systems

43701

Lesson

1 Introduction to Control Systems

TOPICS

The Need for Controls
Automatic Control
Control System Basics
Control Methods
Two-Position Control
Floating Control
Proportional Control
Open- and Closed-Loop Control
Control System Operating Power
Self-Powered Control System
Pneumatic and Hydraulic Control Systems
Electric and Electronic Control Systems

OBJECTIVES

After studying this Lesson, you should be able to…

- Explain why control systems are needed and name devices used to control environmental conditions.
- Define the terms used to describe control systems—controlled variable, controller, controlled device, setpoint, control point, and controlled medium—and name the basic elements of a control system.
- Describe the action of two-position, floating, and proportional control.
- Explain how anticipators work.
- Compare open-loop and closed-loop control.
- Compare the basic requirements of pneumatic/hydraulic control systems to those of electric/electronic control systems.

KEY TECHNICAL TERMS

Transducer 1.18 a device that converts a signal from one form of energy to another
Controlled variable 1.19 the measurable physical quantity that is sensed and adjusted by the control system
Setpoint 1.22 the desired value of a controlled variable
Control point 1.22 the actual measured value of a controlled variable
Controlled agent 1.23 a substance that indirectly adjusts the variable in the controlled medium
Error 1.26 the difference between the setpoint and the control point
Equilibrium 1.28 the balanced condition in which the control point equals the setpoint
Control differential 1.33 the difference between the on and off values of a two-position controller
Throttling range 1.46 the amount of controlled variable change, over a specific value span, required to move the controlled device through its entire range
Offset 1.52 a constant difference between the setpoint and the control point
Feedback 1.57 signal from the sensor to the controller

Without some kind of control, air-conditioning and refrigeration systems would have to run either constantly or not at all. Control systems enable the output of the cooling equipment to meet the needs of the load. Controls are used in residential, commercial, and industrial air-conditioning and refrigeration systems. In industrial and commercial applications especially, they are often required to maintain conditions of temperature and humidity within very strict specifications.

In this Lesson, you will be introduced to the terminology of control systems and will study various applications in which they are used. As an installer or service technician, understanding these control functions will enable you to diagnose and describe field problems more accurately and to specify corrective measures and replacement components. In addition, you will learn about several kinds of systems and begin to understand the details of some of the basic, frequently used control strategies.

The Need for Controls

1.01 Controls are required where a condition (room temperature, for example) must be maintained and the load on the system fluctuates. If the load did not vary, no control would be needed. For example, if the weather outdoors and the conditions within an area (number of people, use of appliances and lights, etc.) never changed, you would not need a thermostat. Your heating or cooling system would be designed and sized for the given conditions and would run constantly at just the rate that provided the desired temperature. In reality, however, both weather and indoor conditions *do* change, so controls are needed to match the output of a system to the load.

1.02 Refrigeration and air-conditioning equipment is controlled to maintain the following environmental conditions:

- air temperature
- relative humidity
- air movement
- air cleanliness.

1.03 Air-conditioning and refrigeration systems are typically classified by their specific application as residential, commercial, or industrial. *Residential applications* are found anywhere people live. Typical residential control criteria include:

- temperature (±4°F)
- relative humidity (±15 to 20%).

1.04 *Commercial applications* are found in those places where people work to provide goods or services—in other words, business locations. Commercial control criteria typically include:

- temperature (±2°F)
- static pressure (±0.2 in. water column)
- high-range pressure (±2 psig) (boiler control)
- relative humidity (±5 to 10%).

1.05 *Industrial applications* include factory areas and perishable storage. Although process industries operate with much closer tolerances, typical industrial control criteria include:

- temperature (±0.25°F)
- static pressure (±0.01 in. water column)
- high-range pressure (±0.5 psig)
- relative humidity (±1%).

1.06 These applications use air-conditioning and refrigeration equipment to adjust environmental conditions to meet specific needs. These needs are extremely varied, not only because of the requirements of the application but also because of the expectations of people. The term *comfort conditions* is commonly used to describe conditions in which people feel comfortable. Comfort conditions vary depending on where a person lives, the time of year, the time of day, and other factors that cannot be controlled.

1.07 The following equipment typically is used in the control of the four environmental conditions:

- **Air temperature**—thermostats, boilers, furnaces, mechanical refrigeration, outside air, heating/cooling coils, duct heaters, pumps, and blowers.
- **Relative humidity**—humidistats, humidifiers and dehumidifiers, air washers, fountains, mechanical cooling, and driers.
- **Air movement**—blowers, fans, and dampers.
- **Air cleanliness**—air washers, filters, and purifiers.

Application 1-1

The term "comfort" is very subjective—it means different things to different people. It can also be somewhat psychological.

A large office employed a diverse group of people—men and women, old and young, and of various ethnic origins. Needless to say, they had very different concepts of "comfortable" temperatures, and disagreements were frequent concerning the "right" setting of the single office thermostat.

The building facilities department was called in, and it was decided to zone the heating and cooling to this large office area. As work got under way, the thermostats were installed first. Delays in receiving the actual heating and cooling equipment ran into weeks, but the office manager noticed that the employees had already begun "using" the thermostats, apparently unaware that they were not yet connected to anything. She also noticed that the complaints had stopped. Everyone seemed satisfied, as long as they thought they had control over their own environment!

Automatic Control

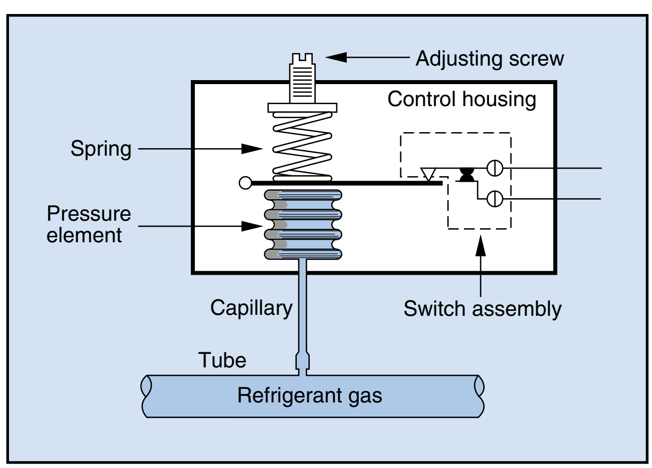
1.08 A control system fails to perform its function not only if it produces an undesired output but also if it causes a process or event to occur at the wrong time. Think of the automobile horn that sounds by itself in the middle of an empty parking lot, for example, or the spark plug that fires too soon or too late. As you can see, the "when" part of a control system's function is very important. In some applications, the "when" requirement may be *periodic* (repeating at regular intervals). In other applications, the "when" may be actuated *on demand* from an operator or external device.

1.09 A *manual control system* is a system that someone must operate by hand. The controller is the hand of the operator, and the device being controlled may be a valve, damper, or on/off switch. An *automatic control system* maintains some variable (temperature or flow rate, for example) at a desired value without assistance from a human operator. An automatic controller monitors the controlled process constantly. If a deviation occurs, the automatic controller causes the controlled device to correct the deviation.

1.10 Today nearly all control systems that regulate refrigeration and air-conditioning processes are automatic. Some older systems might still require human operators to open and close devices manually, but these systems are rare. All complex systems are automatic. These systems maintain preset conditions without human intervention. They relieve you of the job of frequently checking on equipment to make sure it is running safely and maintaining the proper conditions.

1.11 There are two basic types of automatic controls used in refrigeration and air-conditioning systems—safety controls and operating controls. Nearly every system has some of each type, and in some cases, one device can serve

Fig. 1-1. High-pressure cutout control



both functions. You should be able to identify each device in a control system according to what its main job is.

1.12 **Safety controls.** Safety controls are necessary in any system that handles large amounts of energy. Many systems have *limit controls* to keep certain values at safe levels. The high-pressure cutout switch shown in Fig. 1-1 is a typical limit control.

1.13 Many systems contain both high-limit controls and low-limit controls. *High-limit controls* usually monitor conditions in a contained fluid or in an electric circuit. They are designed to stop the system if the monitored condition exceeds a preset limit. Pressure-relief valves and electric circuit breakers are examples.

1.14 *Low-limit controls* also monitor a controlled medium of some kind. When the monitored condition falls below a safe level, the low-limit controls send a signal to a device that increases fluid flow and restores fluid pressure to its proper level. Or, if the condition falls dangerously low, the low-limit controls shut down the entire system. For example, low-limit controls can shut off a compressor if suction pressure falls below a preset minimum.

1.15 Although many safety controls are designed to protect equipment, others are designed to protect people. These controls respond to fire or smoke, for instance, and shut down the building's air delivery system. Safety lockout switches in the air-conditioning system can protect you from injury by preventing someone from restarting equipment while you are working on it.

1.16 **Operating controls.** Most controls used in refrigeration and air-conditioning systems are operating controls. They help the main air-handling and refrigeration equipment perform efficiently, delivering cooling or heating media to the proper places at the proper times. The result of proper control is a conditioned space or a product cooled or dehydrated according to specifications.

1.17 To achieve automatic operational control, systems use different kinds of controlled devices. These devices control the flow of a cooling medium—air, water, or refrigerant. Three kinds of controlled devices are found in refrigeration and air-conditioning systems:

- **Two-position (on/off) devices**—quick-opening valves, butterfly valves, and float valves that start and stop flow

- **Variable-volume devices**—throttling dampers and splitter dampers that control air flow, and proportional valves that control liquid flow

- **Proportional mixing devices**—face-and-bypass dampers and three-way valves that regulate the mixing of two fluids.

1.18 Auxiliary controls work with the main operating controls and sometimes with safety controls. These devices generally help a main device do its job. Common examples include relays and starters, as well as the actuators often needed to operate the controlled device. The system also includes *transducers*, which convert a signal from one form of energy to another. For example, a pneumatic to electric transducer enables a pneumatic controller to work with an electric valve actuator.

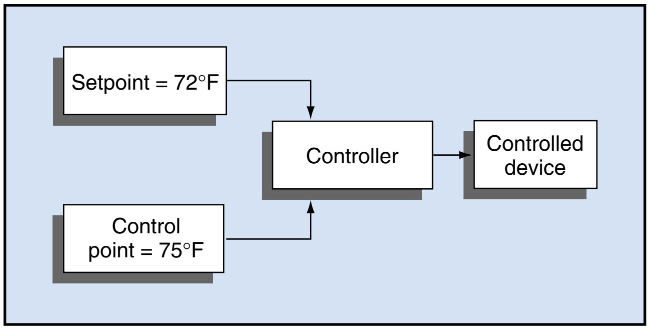
Control System Basics

1.19 The main function of a control system is to maintain a variable at a setpoint. A *controlled variable* is a physical quantity that can be measured. Typical controlled variables include temperature, pressure, relative humidity, light level, and CO_2 concentration. Expressions such as "comfort" and "trouble-free" have little meaning, because the terms mean different things to different people. On the other hand, if the term "comfort" is defined as a temperature of 72°F and 45% relative humidity "comfort" can be controlled.

1.20 Changes in the controlled variable are primarily due to changes in the load or load conditions. The most common cause of changing loads in air-conditioning systems is changing weather. Changes within the air-conditioned space are also important. Internal changes include the number of people occupying a given space, the amount and type of lighting used, and the use of heat-generating appliances.

1.21 In refrigeration applications, load changes are often the result of people entering or leaving the refrigerated space, the addition of warmer product to the refrigerated space, the opening of a door or window in a controlled space, or a reduction of airflow through either the evaporator or the condenser. Because all these conditions change over time, the controlled variable must be changed in order to compensate. These load changes are what makes a control system necessary. The control system cannot be expected to compensate for load changes caused by

Fig. 1-2. Control system elements



broken or incorrectly calibrated components. The equipment must be in good condition for control to be effective.

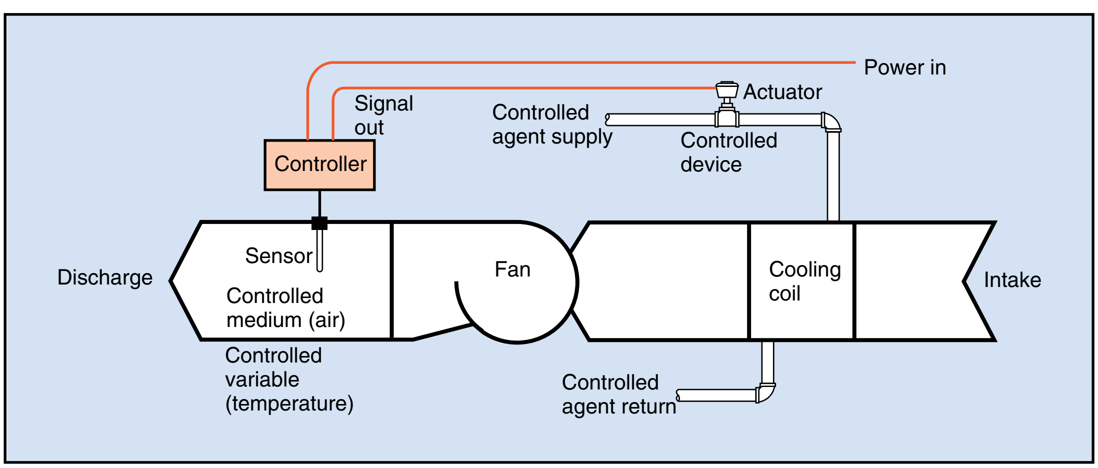
1.22 The *controller* is the device that regulates the operation or performance of another device, called the *controlled device*. The controller sends a signal to the controlled device, often by means of an actuator. The controlled device then moves toward the position that will satisfy the controller. Automatic control requires at least two inputs to a controller. One input is called the *setpoint*. It represents the desired value of the controlled variable. The second input, called the *control point*, is the actual measured value of the controlled variable. To visualize this relationship, refer to Fig. 1-2. The desired temperature (setpoint) in this example is 72°F. The sensor detects an actual temperature (control point) of 75°F. The controller compares the two values and sends a signal to the controlled device or its actuator to make an adjustment that will cause the measured temperature to move toward the setpoint.

1.23 The *controlled medium* is the substance in which a variable is controlled. It is the substance in which the sensor is located. In refrigeration and air-conditioning systems, the controlled medium is usually air. You might sometimes hear the term *controlled agent*. The controlled agent is the substance that is used to adjust the controlled variable within the controlled medium. Examples include chilled water and refrigerant. The controlled device regulates the controlled medium or controlled agent. In air-conditioning and refrigeration applications, the controlled device is usually a valve, damper, or motor.

1.24 To better understand these terms, refer to the typical cooling system shown in Fig. 1-3. The controlled variable is the temperature of the air. The controlled medium is the air flowing across the cooling coil. (Notice the location of the sensor.) The controlled agent is the chilled water flowing through the cooling coil. The valve that regulates the amount of chilled water flowing through the coil is the controlled device.

1.25 The most basic *control system* consists of the following three components—a sensor, a controller, and a controlled device. Each of these elements has a specific purpose. The sensor measures the variable under control. The controller compares the measured value (from the sensor) to the desired value (setpoint) and produces an output to be used by the controlled device. Sometimes two or more elements are combined in one enclosure, as shown in Fig. 1-4. For example, the enclosure of a common room thermostat (controller) includes a bimetallic element (sensor)

Fig. 1-3. Typical cooling control system



connected to energize or de-energize a switch, which activates a motor (controlled device).

1.26 As the value of the controlled variable changes, the signal from the sensor to the controller changes. The controller uses the signal to determine how much the value of the variable deviates from the setpoint and in which direction—that is, whether the value of the variable is above or below the setpoint. The controller produces an output signal to bring the variable back to the setpoint. The difference between the setpoint and the control point is called *error.* As the error increases and decreases, the output of the controller varies in an effort to bring the controlled variable to desired conditions.

1.27 Now that we have defined the various components that make up a system, we will examine different ways in which the controller interacts with the controlled device to enable the system to perform correctly. Although the function of all controllers is the same, their operation is not. The controller must be matched to the application. At the least, it must provide a signal that can be used by the controlled device or its actuator, and it must meet the safety requirements of the controlled medium and agent.

Control Methods

1.28 The aim of any control system is to keep a system in equilibrium. *Equilibrium* exists when the measure of the controlled variable (control point) equals the desired value (setpoint). To illustrate the concept of equilibrium, refer to Fig. 1-5 on the following page, in which a water tank is being filled and drained at the same time. In Fig. 1-5A, the water level in the tank is decreasing because water flows out of the tank faster than it flows in. This system is not in equilibrium. If water level is the controlled variable, equilibrium exists when the rate at which water flowing into the tank equals the rate at which water flows out, as shown in Fig 1-5B. When equilibrium exists in a system, conditions are said to be *satisfied.*

1.29 Controllers are designed to act in several different ways, depending upon the needs of the system. Do they respond by instantly driving a controlled device fully open or fully closed? Or, do they open or close the controlled device slowly as long as the deviation continues? Answers to these questions depend upon the control method that a system is designed to provide.

1.30 The most common methods of control in the refrigeration and air-conditioning industry are as follows:

- two-position control
- floating control
- proportional control.

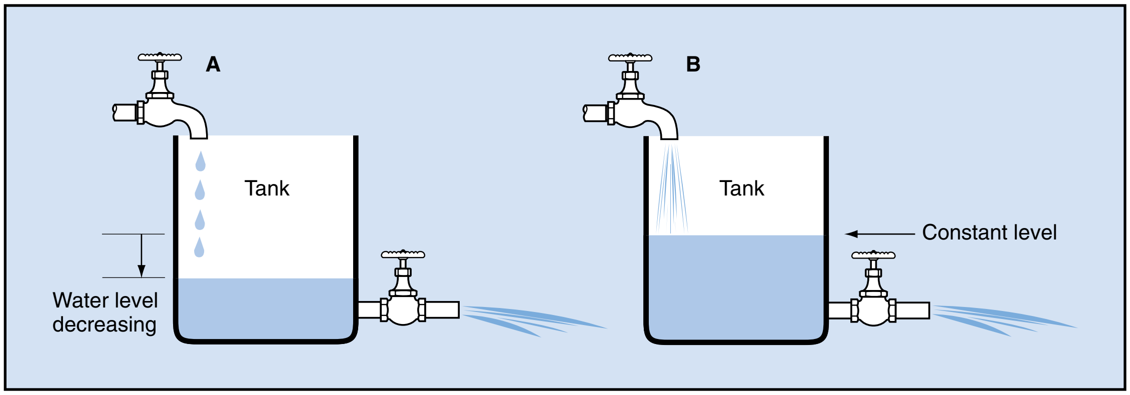
Each of these control methods will be described in the paragraphs that follow.

Two-Position Control

1.31 The simplest and most common method of control is simply to turn the controlled device on and off. This control method is referred to as *two-position*

Fig. 1-4. Typical refrigeration and air-conditioning controls

Fig. 1-5. Equilibrium



control. A common example of a system using this kind of control is a simple cooling system. If the thermostat senses a temperature at a preset amount above the setpoint, the compressor turns on. If the thermostat senses a temperature at or below the setpoint, the compressor turns off. The controlled device (the compressor motor) cannot vary between full on and full off.

1.32 Two-position controllers use a make-and-break contact to start or stop the motor. The controller can close its contacts on either a rise or on a drop in the controlled variable (room air temperature, for example).

1.33 Two-position control operates when the variable under control departs from the setpoint by a predetermined amount called the *control differential*. The control differential is the difference between the point at which the controller signals on and the point at which it signals off. For an example, refer to Fig. 1-6 in which a freezer thermostat is set for -15°F. The contacts close to start the compressor motor if the temperature inside the freezer rises to -10°F. When the freezer temperature falls to -15°F, the contacts open to stop the compressor. In this example, the control differential is 5°F (-15 to -10°F).

1.34 Since a fixed-speed compressor is the device under control in this example, it is not possible to run the compressor at different speeds. Therefore, a two-position control system was selected because the compressor can only be either on or off.

1.35 As you can see in the performance graph in Fig. 1-7, the temperature in this example falls below the setpoint by about 2 or 3°F. Whenever the freezer temperature goes below the setpoint (called *undershoot*), the system uses more energy than required to maintain the desired temperature. When the temperature rises above the "turns on"

Fig. 1-6. Simple two-position control

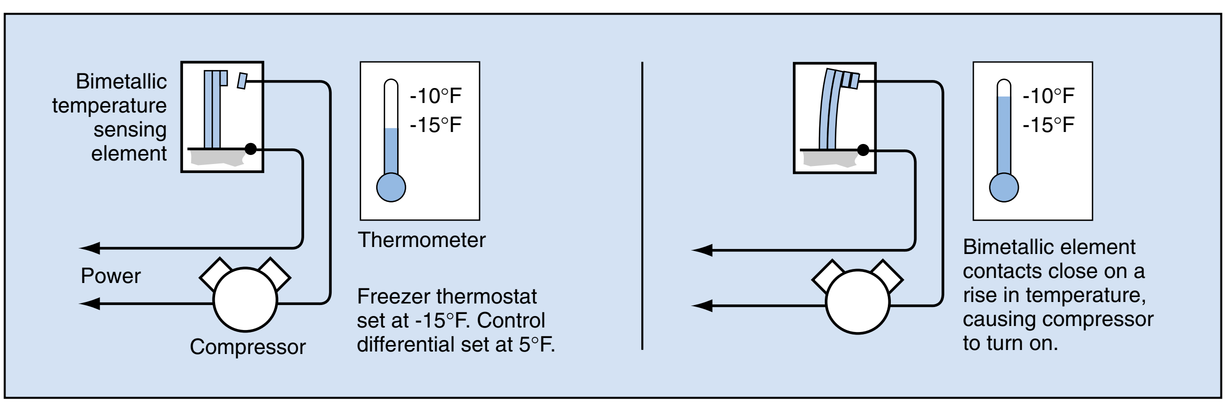
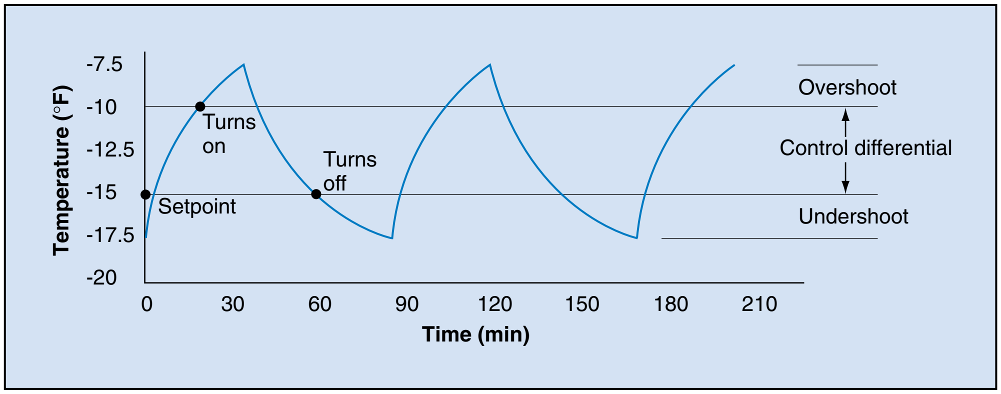


Fig. 1-7. Performance of two-position control



point (called *overshoot*), some product might begin to thaw, affecting quality.

1.36 The graph in Fig. 1-7 illustrates one of the problems associated with this type of control. When the freezer temperature rises to -10°F, the compressor turns on. Because it takes a little while for the cool air to reach the thermostat, the indicated temperature rises a bit more before it begins to fall. When the temperature in the freezer reaches -15°F, the thermostat switches the compressor off. But because cold refrigerant is still circulating in the coils and cold air is still in the ducts, the temperature continues to fall before rising again.

1.37 Thus, the cooling system cycles on and off continuously, and freezer temperature fluctuates up and down continuously. This cycling can cause problems in two-position control systems. They must be set just right or they will cycle either too often or not often enough. The frequency of on/off cycles depends on how fast the controlled variable changes and on the size of the control differential.

1.38 In this example, the control differential is 5°F. If the control differential is increased to 8 or 10°F, the system will cycle less frequently, but the controlled medium (freezer air) will also swing through a wider range of temperatures. Too small a control differential causes the system to cycle frequently (short cycle). The more often you start and stop mechanical equipment, the sooner it will fail. Therefore, a compromise must always be struck with this type of control.

1.39 One of the early methods used to reduce overshoot and undershoot was to add a timing function, called *anticipation*, to the two-position control system. Anticipation "tricks" the controller into action sooner than with pure two-position (on/off) control. That is, the controller anticipates the need to turn something on or off. This function is achieved by means of a resistor that generates a small amount of heat inside the thermostat case.

Fig. 1-8. Anticipation reduces overshoot and undershoot

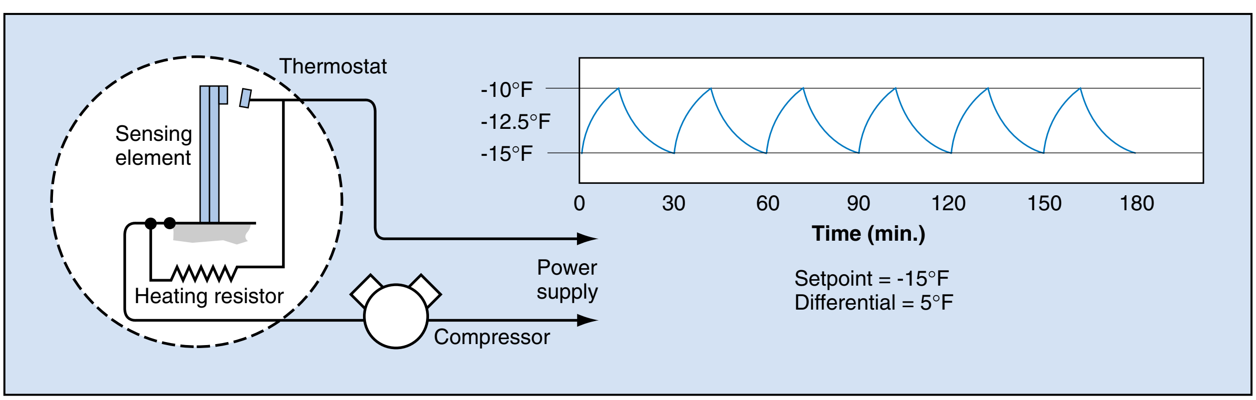
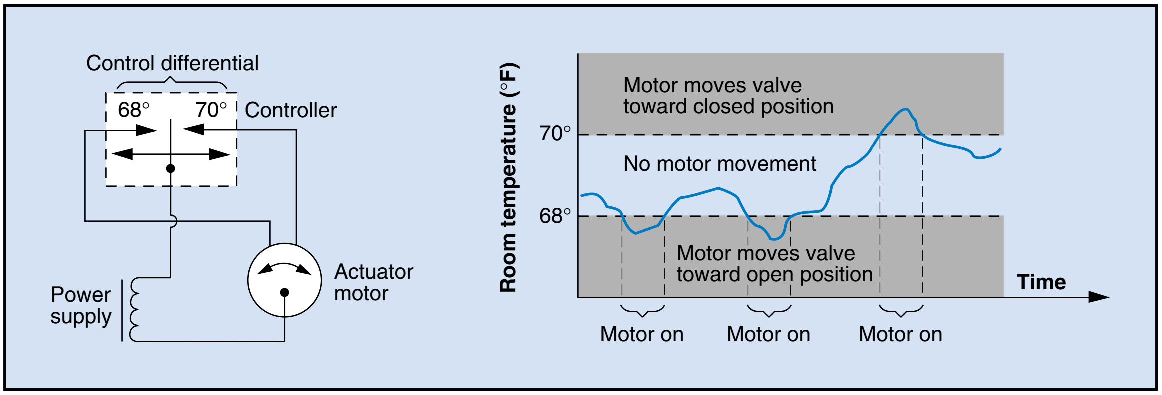


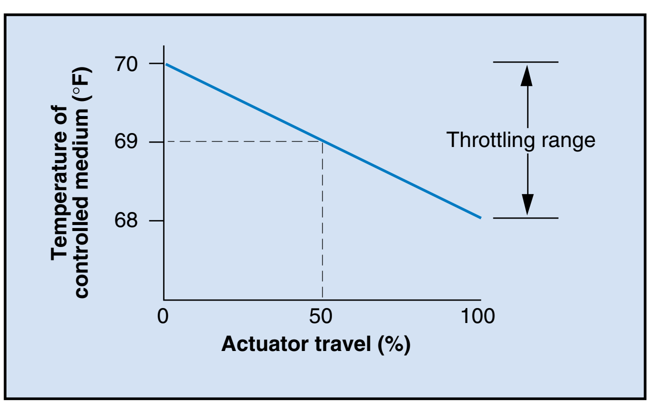
Fig. 1-9. Floating control



1.40 If additional heat is added to the sensor for a cooling application during the time when the compressor is not running, the thermostat "feels" that the freezer is warming up faster than it really is. This action is called *cooling anticipation.* If a heating system is being controlled, then a small amount of heat is added to the sensing element during the time when the thermostat is calling for heat and the heating source (a furnace, for example) is operating. This small amount of heat, added to the thermostat during its call for heat, makes the sensing element warm up faster than normal and reduce the amount of overshoot. This response is known as *heating anticipation.* In comfort heating systems, it reduces or eliminates overshoot toward the end of the run cycle of the furnace.

1.41 As shown in Fig. 1-8 on the previous page, anticipation is used to maintain temperatures closer to the setpoint of the system. In this application, a heating resistor (also called an anticipator) conducts electricity whenever the thermostat is not calling for cooling. The anticipator causes the sensing element to warm up more quickly than normal to "anticipate" a call for cooling. Anticipation is sometimes referred to as *timed two-position control.*

Fig. 1-10. Relationship of actuator position to controlled variable in typical proportional control



Floating Control

1.42 Floating control is an improvement on two-position control because it offers more possibilities. For example, unlike two-position control, a valve does not need to complete its travel to full open or full closed before its position can be changed. Floating control allows the valve to "float" between open and closed. That is, the valve can maintain a position, move toward open, or move toward closed, and it can change position as often as needed. As long as the variable remains within control limits—68 to 72°F, for example—controller output remains the same. If the temperature increases or decreases beyond the operating limits, however, output changes to drive the valve back within limits.

1.43 Floating control operation is shown in Fig. 1-9. A sensing element is attached to a selector that is free to "float" between two contact points. When the selector touches one contact, it drives an actuator motor in one direction for as long as the selector remains on the contact. As soon as the sensed condition has been brought within the preset limits, the contact is broken and the actuator motor stops where it happens to be—usually leaving the controlled device in an intermediate position.

1.44 As you can see, the sensing element is free to move within the control differential. When it makes contact on either the high side or the low side, the actuator motor drives the valve in the appropriate direction from its last position. As a result of this somewhat erratic behavior, the controlled variable "floats" or wanders within the control differential, as shown by the graph in Fig. 1-9.

Proportional Control

1.45 A *proportional controller* can adjust the controlled device to any position between on and off according to how much the measured variable differs from the setpoint. If the difference is small, the controller adjusts the device by a small amount. If the difference is large, the controller adjusts the controlled device by a large amount until conditions are satisfied. In other words, controller output increases as error increases.

1.46 In a proportional control system, the system is always on, and there is constant feedback between the controlled device and the sensing element. The sensing element and actuator work together through the controller so that changes detected by the sensor cause a corresponding response at the actuator and thus a corresponding position of the controlled device. This relationship is shown in the graph in Fig. 1-10. The *throttling range* of the controller is the total amount of change in the controlled variable that is required to move the controlled device from fully open to fully closed. Note that when dealing with proportional controls, the term throttling range replaces the term control differential. It reflects the difference between control at any value within a range and two-position control.

1.47 If the output from the controller *increases* as the variable increases, the controller is said to be *direct acting*. If the output of the controller *decreases* as the variable increases, the controller is *reverse acting*. Before a controller can be specified for use in a system, it is essential that its action, the type of controlled device, and the demands of the application (heating, cooling, humidification, etc.) be understood. For example, a heating system that must fail to the off condition requires a reverse-acting controller. Examples of controller selection criteria are shown in Table 1-1.

1.48 A common example of proportional control is the cruise control in an automobile. The speed of the car is the controlled variable. The controlled device is the throttle valve that limits the flow of gasoline to the engine in the vehicle. Assume the setpoint is 55 mph. The throttle valve is held at a specific position to maintain this set speed. When the car is moving up a hill, the valve must be adjusted to add fuel to provide for the additional load placed on the car by traveling up the hill. When the car begins to travel down a hill, the throttle valve must be adjusted to reduce the flow of fuel.

1.49 Another example of proportional control is shown in Fig. 1-11 on the following page. It is a heating system using an outside-air damper and a return-air damper in what is commonly called an *economizer*. For this system to operate correctly, the output from a direct-acting controller must increase to open a normally closed device (Actuator 2). The increase in output from the controller will close a normally open device (Actuator 1). Since the output from the controller increases as the temperature increases, the discharge air temperature can be controlled by modulating the return air damper and the outside air damper together. In this example, the outside air is cool, and the return air is warm.

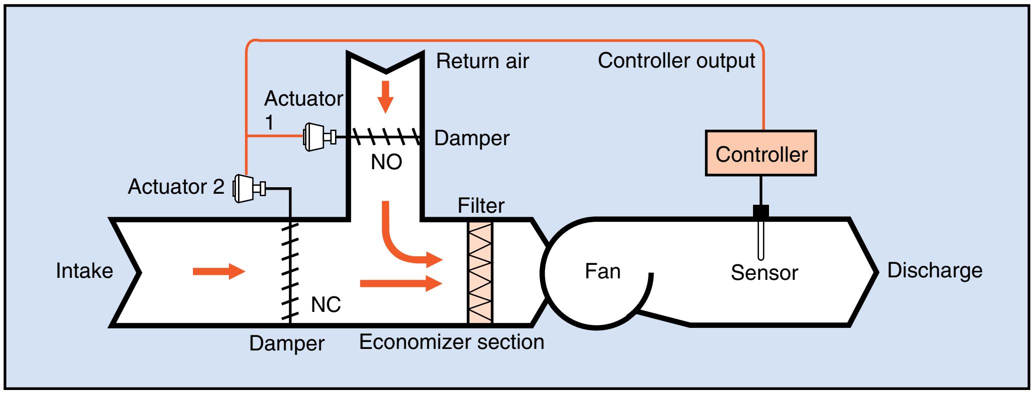
1.50 These examples illustrate the reason for all control systems—that is, a change in the load requires a change in controller output to compensate.

1.51 Consider an application in which space temperature is the variable under control, the medium being controlled is chilled water, and the controlled device is a modulating valve. The throttling range is the temperature difference that causes the valve to travel from fully open to fully closed. In most residential and light commercial air-conditioning applications, the throttling range is about 4°F with the setpoint equal to a value in the middle of the range.

Table 1-1. Examples of controller selection criteria

Desired fail-safe condition of controlled device	Controlled device used for	Controller action required
OFF	Heating	Reverse action
ON	Heating	Direct action
OFF	Cooling	Direct action
ON	Cooling	Reverse action
OFF	Humidifying	Reverse action
ON	Humidifying	Direct action

Fig. 1-11. Proportional control in an economizer



1.52 Another term used when describing proportional control is *offset*, a constant difference between the setpoint and the control point. Offset is caused by load changes or setpoint changes. It is common in systems with proportional control, and a small amount of offset is acceptable. Consider an example of offset in a tank. At a certain outflow rate, an input valve keeps the level in the tank at the setpoint. But if the outflow rate decreases (load change), the sensor detects a rising level in the tank and sends a corresponding signal to the controller. The controller closes the inflow valve proportionately to again balance inflow and outflow based on this information from the sensor. The level in the tank stabilizes, but at a higher level than the setpoint. The difference between the new level and the setpoint is the offset.

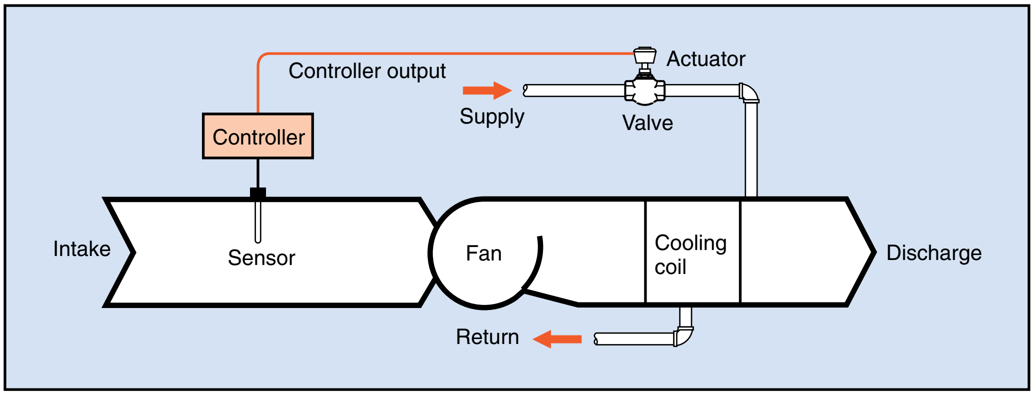
1.53 Depending upon the application, the throttling range must sometimes be adjusted for the system to function correctly. If the throttling range is too narrow, the system will be unstable. This instability can cause the controlled device to travel excessively from one extreme to the other in a very short time, a condition known as *hunting*. Hunting renders the control system useless because the controller is searching for a stable state of equilibrium. Any change in the controlled variable causes a radical change in the output. On the other hand, if the throttling range is too wide, the system lacks adequate control.

1.54 Recall that the output of a proportional controller increases as the error increases. If the error becomes so large that it exceeds the controller output limits, the controller cannot bring the variable back within range. The system is now out of control although it might continue to run. Whenever a system is out of control, there are several possible reasons. The most common is that the design limits of the system were exceeded. In other words, the load was too great for the system to control. Most control systems are designed to operate over a specific range of control values. The control limits for a facility are called the *design conditions.* For example, the design conditions for an HVAC system in Chicago might include an outdoor temperature range of -15 to +95°F.

The Programmed Exercises on the following page will tell you how well you understand the material you have just read. Before starting the exercises, remove the Reveal Key from the back of your Book. Read the instructions printed on the Reveal Key. Follow these instructions as you work through the Programmed Exercises.

1-1. The two basic types of automatic controls used in refrigeration and air-conditioning systems are ________ controls and ________ controls.	1-1. SAFETY, OPERATING Ref: 1.11
1-2. Many control systems contain a(n) ________ to convert signals from one form to another.	1-2. TRANSDUCER Ref: 1.18
1-3. The most basic control system consists of what three components?	1-3. SENSOR, CONTROLLER, CONTROLLED DEVICE Ref: 1.25
1-4. In a controlled system, the difference between the setpoint and the control point is called ________.	1-4. ERROR Ref: 1.26
1-5. A control method that simply turns a device on and off is called ________ control.	1-5. TWO-POSITION Ref: 1.31
1-6. Using a resistor to reduce overshoot and undershoot in a thermostat is called ________.	1-6. ANTICIPATION Ref: 1.39
1-7. With a reverse-acting controller, controller output decreases as the controlled variable ________.	1-7. INCREASES Ref: 1.47
1-8. In an unstable system, the controlled device can sometimes travel from one extreme to another in a very short time. This condition is known as ________.	1-8. HUNTING Ref: 1.53

Fig. 1-12. Open-loop control



Open- and Closed-Loop Control

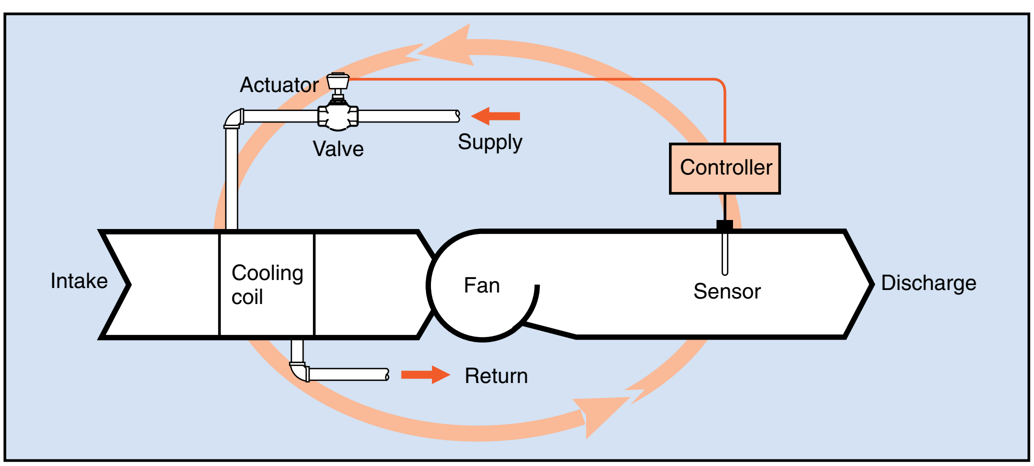
1.55 *Control loops* are used in applications where the condition of the controlled medium is monitored. There are three kinds of control loops: open, closed, and a combination of the two.

1.56 *Open-loop control* does not depend on feedback to assure continuity of control. Open-loop control is generally used to start a compressor when the outside temperature rises above a set value, or to disable a cooling tower when the outside temperate falls below a set value. Feedback is not necessary for the operation of the open-loop system. Figure 1-12 illustrates an open-loop system that initiates cooling when outside air temperature rises above a preset level.

1.57 *Closed-loop control* is the most commonly used control method. It represents 85 to 90% of all control systems in use today. Maintaining the desired condition of the controlled variable in a closed-loop system depends on feedback. *Feedback* is a signal from a sensor to the controller. In closed-loop control, the controller compares that value (for example, temperature) to the setpoint. If the controller finds a difference (error) between this feedback signal and the setpoint, it produces an output signal (called an *error signal*) that adjusts a controlled device. The controller continues to receive information from the sensor and adjust the controlled device according to the error. This corrective action continues until the sensor arrives at the setpoint. This kind of control is very popular because it continuously adjusts the output to compensate for changes in the system. Figure 1-13 illustrates a closed-loop system.

1.58 As an example, you form your own closed-loop control system when you regulate your

Fig. 1-13. Closed-loop control



bathwater temperature by sticking your hand in the water. If the water is too hot, you increase the flow of cold water. If the water is too cold, you increase the flow of hot water. Adjustment continues until your bath reaches the desired temperature.

1.59 A controlled device consists of two main parts—the actuator and the regulator. The *actuator* is the mechanism that converts the error signal into mechanical motion, usually linear or rotary. A pneumatic piston and an electric motor are examples of actuators. The *regulator* is the part of the controlled device that actually modifies the fluid flow in some way. Volume dampers, valve needles, and the pivoting disks in butterfly valves are all examples of regulators.

1.60 The third loop system combines features of the open- and closed-loop systems in what is known as *combination-loop control or reset system control*. Simply stated, the controller changes the value of its setpoint based on an independent variable (outside air temperature, for example). Figure 1-14 illustrates this kind of control. The setpoint changes based on the temperature of the outside air.

1.61 To understand how this system operates, assume that the discharge temperature is to be maintained at 72°F when the outside air temperature is 65 to 70°F. Now suppose that the outside air temperature rises substantially, to 90°F. Knowing this, we want to decrease the discharge temperature to compensate for the increase in outside temperature. This can be done by changing the setpoint of the controller. This automatic setpoint change is called *reset control* and uses both open- and closed-loop control methods.

Control System Operating Power

1.62 The brain of any control system is the controller. Recall that the controller measures a variable, compares this measurement to a setpoint, and produces an output. This output causes changes in the equipment to bring the measured variable closer to the setpoint. A control system can be self powered or externally powered by a pneumatic, hydraulic, electric, or electronic power source. In some systems, these methods are combined. Devices using various kinds of operating power will be described in later Lessons.

Self-Powered Control Systems

1.63 Self-powered control systems (sometimes called self-contained control systems) are the simplest of all automatic controls and require no external power. In a self-powered system, the controller, actuator, and controlled device are combined into a single unit. The actuator derives its power internally, usually from the expansion of a fluid sealed within a bulb-and-capillary arrangement. The self-powered control system illustrated in Fig. 1-15 on the following page uses the power generated in the sensing element to drive the bellows-type actuator against a spring to maintain the correct temperature. As the temperature increases at the sensor, the pressure generated in the sensing element is transmitted along the capillary tube to the bellows on the valve actuator, which acts to adjust the flow of the controlled medium.

Fig. 1-14. Combination-loop control

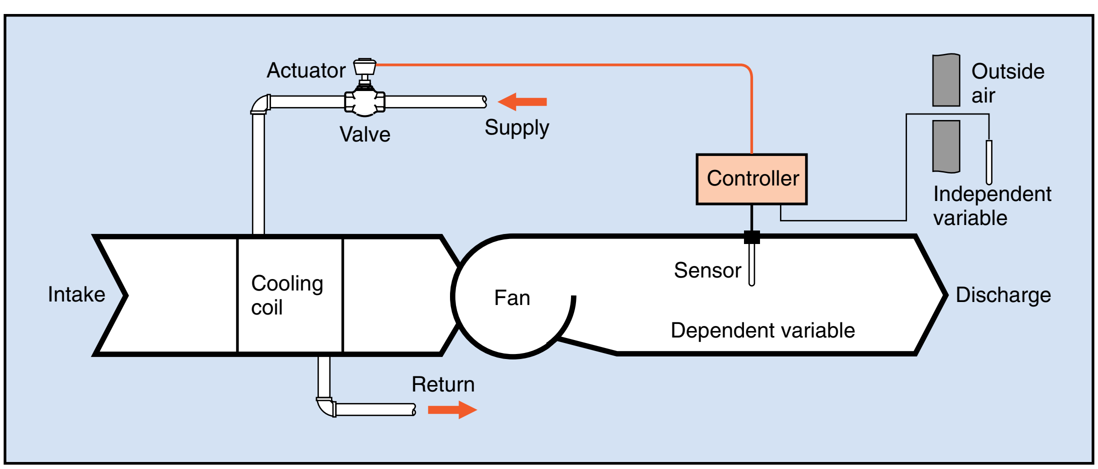
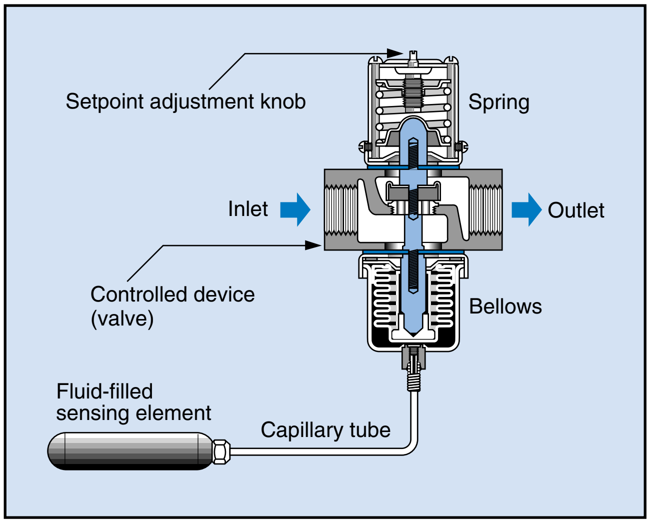


Fig. 1-15. Self-powered control system



1.64 Another common example of the self-powered control system is the *remote-bulb thermostat*. The remote bulb or temperature-sensing element is located in the medium being monitored (water and outside air are common). The controller then operates a two- or three-position switch that controls the equipment for the required action. The device under control (commonly a pump or fan) operates in a full on or off capacity. In these devices, the action is always either on or off, with no mid-position. With a multi-position switch, the device can be stopped in one or more intermediate positions, or run in either forward or reverse.

1.65 The example in Fig. 1-16 shows a common application for the remote-bulb controller as a self-powered control. The switch functions are identified as either three-position (make to open, off, make to close) or two-position (closed or open). Each of these switch positions can be used for a specific actuator. The three-position switch is used to drive an actuator open and turn off, then drive the actuator closed and turn off. This floating control allows the controlled device (typically a valve or damper) to be stopped before it reaches the end of its travel.

1.66 When you compare the operation of the two-position switch to that of the three-position switch, the advantage of the three-position switch becomes obvious. The two-position switch either turns a device on or turns it off. There is no stopping the device in mid position as there is with the three-position switch.

1.67 Another example of a self-powered controller is the common room thermostat typically installed in a residential or small business application. In this example, the power that operates the controller is generated by temperature changes, which cause a bimetallic strip to bend and close a set of contacts. Because the two metals in the strip bend at different rates with a change in temperature, contact points welded to the metal end open and close when the temperature rises and falls. An example is shown in Fig. 1-17.

Pneumatic and Hydraulic Control Systems

1.68 A pneumatically powered controller is operated by air pressure. Most pneumatic controllers provide proportional control. The output varies continuously in response to input. The controller can signal

Fig. 1-16. Self-powered remote-bulb thermostat

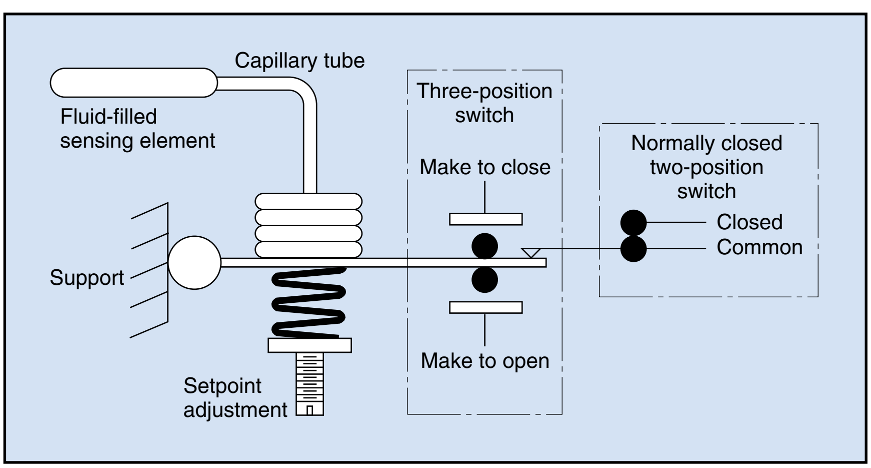
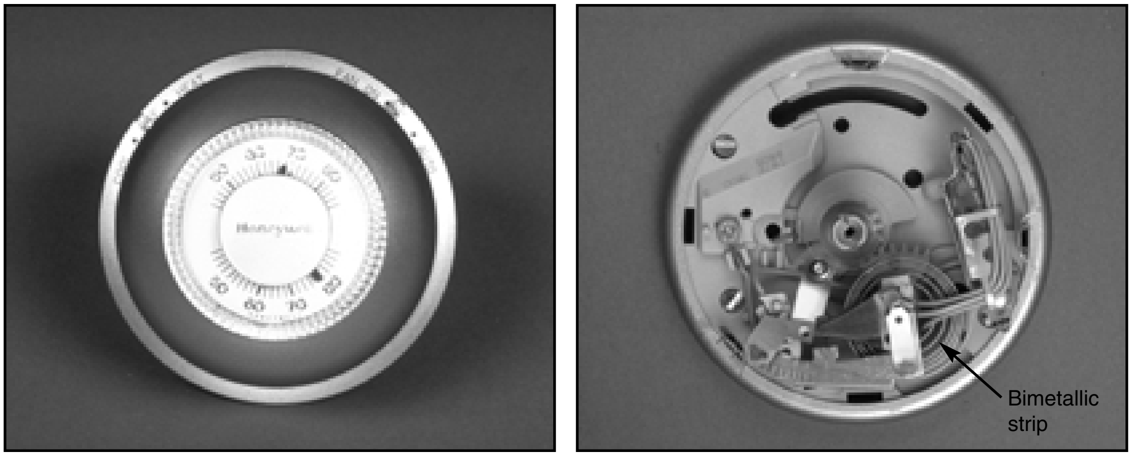


Fig. 1-17. Common room thermostat



the actuator to adjust the position of a valve, damper, or other controlled device as necessary to bring the controlled variable back to the setpoint. Typical pneumatic valve and damper actuators are illustrated in Fig. 1-18.

1.69 All actuators for pneumatic controls have enclosed pressure chambers and movable pistons or disks attached to control rods or valve stems. A diaphragm fits across the pressure chamber to seal it off and prevent air from leaking past the piston.

Fig. 1-18. Pneumatic actuators

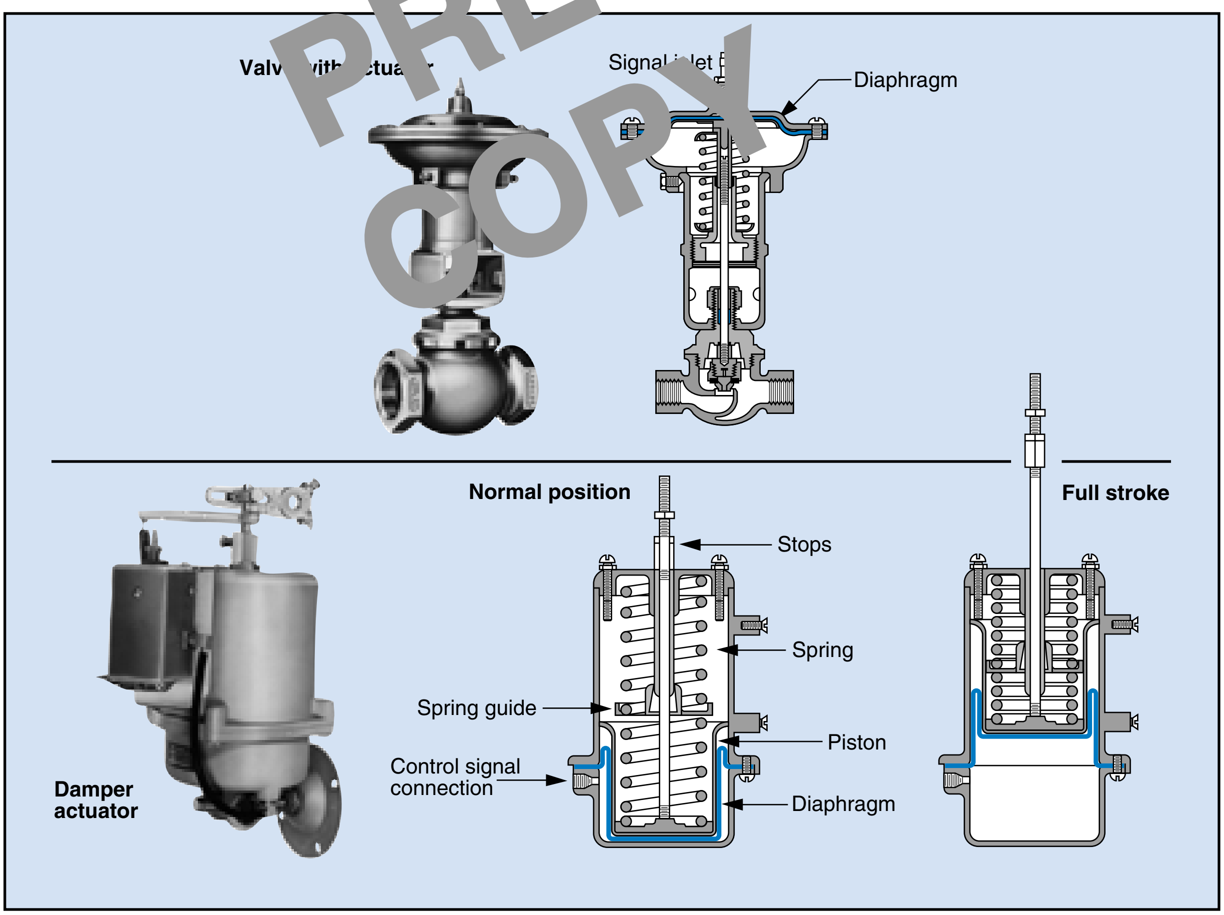


Fig. 1-19. Components of a typical pneumatic control system

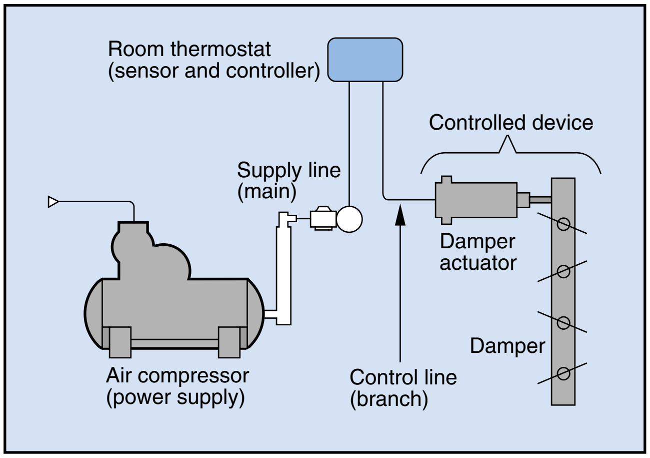
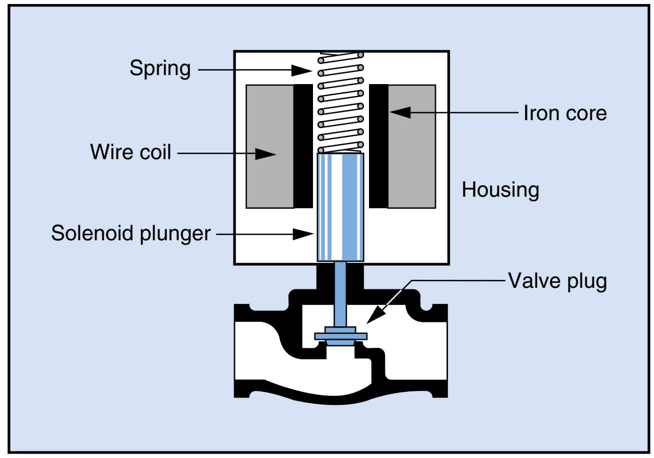


Fig. 1-20. Solenoid valve



When air from the controller enters this chamber, it pushes the diaphragm, piston, and stem a distance proportional to the pressure applied. Damper actuators usually have a long power stroke, while valve actuators have a shorter stroke.

1.70 Pneumatic actuators are spring-loaded to allow the controlled device to return to its normal position when the signal is removed or if the power should fail. Controlled devices are designed to fail to an open or closed position, and the correct kind of operation must be selected for the application. Selection depends on the needs of the system, the fluid being regulated, and the safety precautions required. Valves and dampers are designated as normally open (NO) or normally closed (NC). An NO device closes when it is energized, but opens if power is removed. An NC device opens when it is energized, but closes if power is removed.

1.71 Damper actuators are usually retracted when the signal is removed. However, depending on the linkage arrangement, this can mean the damper vanes are either NO or NC. Similarly, some valves are NO, others NC, while still others are three-position, with any one of the positions being the normal position.

1.72 As shown in Fig. 1-19, the basic pneumatic control system consists of:

- air compressor, with its filters, regulators, and safety devices
- pneumatic controller and sensor
- pneumatic actuator and controlled device
- piping to connect the components.

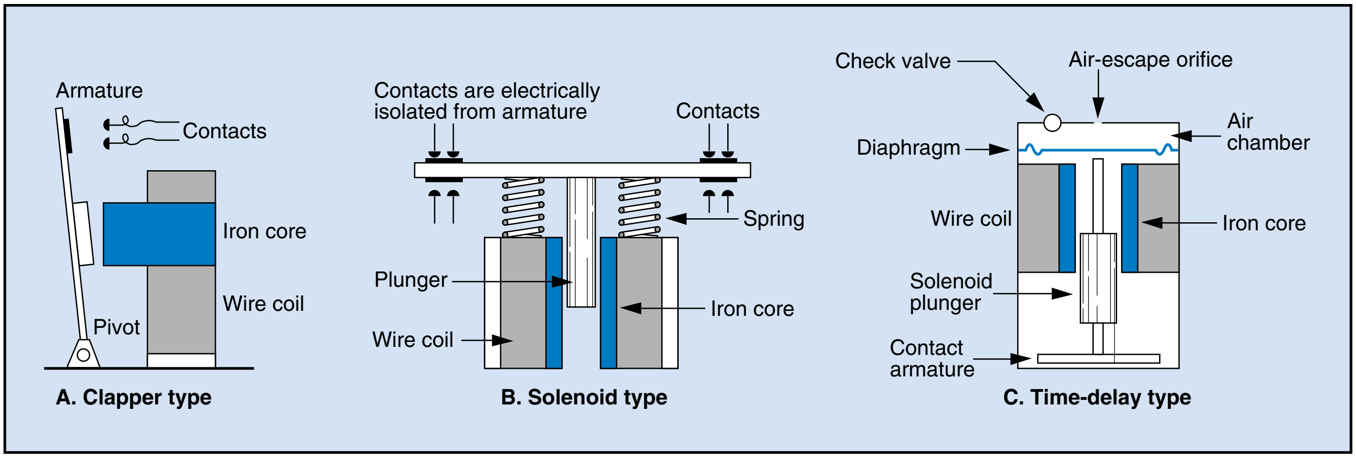
Piping includes both the supply (main) line from the compressor to the controller, and control (branch) lines from the controller to other devices.

1.73 Compressed air is supplied to the controller at a constant pressure, typically 10 to 25 psig. The controller supplies air to the controlled device at varying pressures in response to its sensing element in the controlled medium.

1.74 The controller acts like an automatic pressure-reducing valve. The signals it sends to the actuator consist of small changes in air pressure. These changes in pressure from the controller cause the actuator to move in a way that operates the controlled device. In a system with proportional control, the amount of change in position is proportional to the change in control-line pressure. In a system with two-position control, a *snap-action actuator* moves the controlled device fully open or fully closed when the signal reaches a preset value.

1.75 Hydraulic control systems are similar to pneumatic systems but use hydraulic fluid instead of air to transmit signals and power. Also, because a hydraulic system is closed, a constant volume of fluid is used in the controlling process. In pneumatic systems, on the other hand, air usually is bled off and a continuous supply is required.

Fig. 1-21. Three types of electric relays



Electric and Electronic Control Systems

1.76 The most common power source used in operating a control system is electricity. Most refrigeration and air-conditioning controls are operated by electricity. Electric controls start, stop, regulate, and protect the various system components. Electricity is used in both electrical systems (generally 24 or 120V AC) and electronic systems (generally 0 to 10V DC).

1.77 Electric control systems consist of at least the following components:

- power supply
- electric controller and sensor
- electric actuator and controlled device
- wiring to connect the components.

These components perform the same functions as the components in a pneumatic control system. In fact, many manufacturers supply components for both types of systems.

1.78 The actuators in electric control systems use one or more of the following devices:

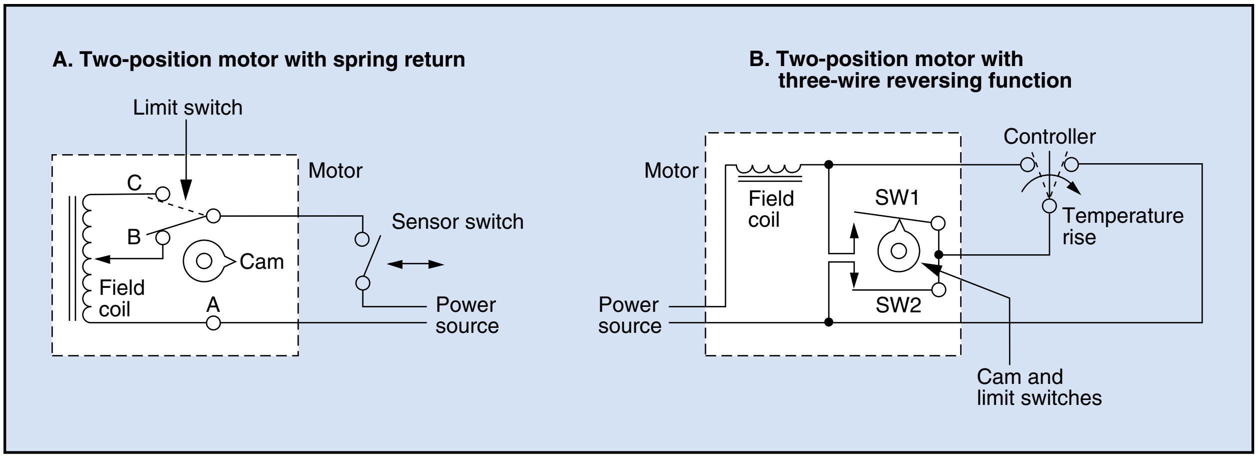
- electromagnetic coils (solenoids, switching relays, contactors, and motor starters)
- two-position motors
- modulating motors.

1.79 A solenoid valve is a typical combination of electric actuator and controlled device. An example is shown in Fig. 1-20. The wire coil and plunger make up the actuator, while the valve disk or plug is the controlled device. When an electric current (the controller output) passes through the coil, magnetic force picks up the iron plunger and the valve opens. When the current stops (signal withdrawn), a spring pushes the plunger down and the valve closes. A normally open solenoid valve has a valve plug that snaps closed when the coil is energized.

1.80 Two or more electric control loops can be interconnected through *switching relays*. Figure 1-21 shows three kinds of relay switches. When a current travels through the wire coil of a relay switch, the relay becomes a controller that either opens or closes a second circuit. A new error signal then travels through the second circuit to another actuator, and so on. In this way, controls in different parts of a cooling system can be *sequenced*, with the various actuators coming into action at the proper time. Electric motors for staged compressors are often started in this way.

1.81 Electric motors can be used as damper actuators or in similar applications requiring linear motion. In these cases, either a two-position motor or a modulating motor is employed.

Fig. 1-22. Wiring schematics for two-position motors



1.82 Two-position controls are the most common electric controls, although they are also made to operate in proportional applications. The most common semi-proportional control method is floating control. In a floating controller, the output is wired using three wires (one wire for the common, another wire for the drive-open command, and the third wire for the drive-closed command). Floating-control systems require that the actuator have the ability to stop and remain at any position along the 0 to 100% travel limits.

1.83 Two-position motors drive their linkages to the full extent of their travel, then stop because a limit switch breaks the circuit. They have no intermediate positions. The motor is held in its extended position by a small electric current passing through its windings. To protect the motor, the current is not strong enough to burn out the windings. When the current stops, a spring returns the motor to its original position.

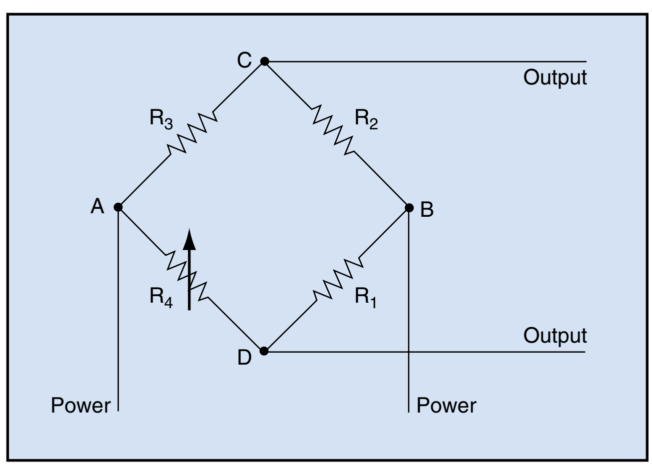
1.84 If the controller has a double-throw switch, a two-position motor can be modified so that the motor can drive its regulated device fully open and fully closed. Figure 1-22 shows sample wiring diagrams for both modes of operation.

1.85 Reversible induction motors and shaded-pole motors also are commonly used to operate automatic dampers and valves. These devices can be stopped at any position along the path of their travel, retained there, and reversed when necessary.

1.86 Electronic controls also use electricity, but at a much lower voltage—usually no more than 10 V. An advantage of electronic devices is their small size. Electronic devices also provide greater accuracy, and therefore tighter control, than other devices.

1.87 The basic principle behind electronic controls is the detection of slight variations in resistance across a bridge circuit. You might be familiar with the Wheatstone bridge, shown in Fig. 1-23. If voltage is provided between A and B, voltage is created between C and D. Three of the four resistances in the bridge circuit are fixed. The fourth is variable and is connected to a sensing element. As the sensing element changes, the resistance in R4 changes, resulting in a slight change in the output signal between C and D. This signal is then amplified and

Fig. 1-23. Wheatstone bridge circuit



is sent to a relay or a transducer, where it is converted into a normal electric or pneumatic signal. From there on, the signal path, actuator, and regulator are the familiar electric or pneumatic types. The term *electronic* applies only to the controller—the rest of the system is generally electric or pneumatic.

Application 1-2

An important, but often overlooked, responsibility of the controls technician is to provide operating instructions to the customer, especially where residential customers are concerned.

A contractor's top technician installed a new residential furnace and thermostat. A month into the heating season, he received a call from the homeowner, who complained that the furnace overheated the house in the morning. Stopping at the home, he performed several cursory checks, all indicating that the system, including the new thermostat, worked perfectly. With patience developed over years of experience with customers, he asked for a description of the problem.

It turned out that the owner was in the common habit of setting the thermostat down at night. Waking to a chilly house, the customer would then set the dial to 80°F, expecting that this would make the furnace run "hotter" or "faster" (the technician wasn't sure which), resulting in a faster morning warmup! The setting would then be forgotten until the house was uncomfortably warm.

The technician patiently explained that the thermostat does not work like an automobile's accelerator. The problem was solved.

1-9. A large majority of control systems in use today are ________-loop control systems.	1-9. CLOSED Ref: 1.57
1-10. The main difference between open and closed control loops is that closed loops include ________.	1-10. FEEDBACK Ref: 1.57
1-11. A controlled device consists of two parts—the ________ and the ________.	1-11. ACTUATOR, REGULATOR Ref: 1.59
1-12. What device is considered the brain of a control system?	1-12. CONTROLLER Ref: 1.62
1-13. A common room thermostat is an example of a(n) ________ controller.	1-13. SELF-POWERED Ref: 1.67
1-14. Most refrigeration controls are operated by what kind of power?	1-14. ELECTRICITY Ref: 1.76
1-15. Two or more electric control loops can be interconnected through ________.	1-15. SWITCHING RELAYS Ref: 1.80
1-16. Electronic controls usually use voltages of no more than ________ V.	1-16. 10 Ref: 1.86

Answer the following questions by marking an "X" in the box next to the best answer.

1-1. Controls are needed to match the output of cooling equipment to the demands of the

- ☐ a. controlled device
- ☐ b. controller
- ☐ c. load
- ☐ d. power source

1-2. The main function of a control system is to control a(n) ________.

- ☐ a. actuator
- ☐ b. load
- ☐ c. setpoint
- ☐ d. variable

1-3. Automatic control operation requires at least ________ input(s) to a controller.

- ☐ a. one
- ☐ b. two
- ☐ c. three
- ☐ d. four

1-4. In a system with a setpoint of 45°F, the actual temperature of 48°F is the

- ☐ a. auxiliary temperature
- ☐ b. control differential
- ☐ c. control point
- ☐ d. load differential

1-5. All control systems include a sensor, ________, and ________.

- ☐ a. actuator; motor
- ☐ b. controller; controlled device
- ☐ c. relay; controller
- ☐ d. valve; actuator

1-6. The most common type of control is

- ☐ a. floating
- ☐ b. proportional
- ☐ c. timed two position
- ☐ d. two position

1-7. If the output from a controller decreases as the variable increases, the controller is said to be

- ☐ a. direct-acting
- ☐ b. floating
- ☐ c. malfunctioning
- ☐ d. reverse-acting

1-8. If a proportional controller provides loose, inadequate control, you should

- ☐ a. change the setpoint
- ☐ b. increase the differential
- ☐ c. reduce the throttling range
- ☐ d. remove the offset

1-9. In a self-powered control system, as the temperature increases at the sensing element, the bellows moves as a result of increased

- ☐ a. heat
- ☐ b. humidity
- ☐ c. pressure
- ☐ d. vacuum

1-10. Pneumatic controls are primarily

- ☐ a. floating
- ☐ b. proportional
- ☐ c. timed two position
- ☐ d. two position

SUMMARY

Air-conditioning and refrigeration controls are needed to match the output of equipment to the demands of the load as conditions change. Various types of controls are used in residential, commercial, and industrial applications to adjust the following environmental conditions—air temperature, relative humidity, air movement, and air cleanliness.

Any variable that can be measured can be controlled. The most basic control system consists of a sensor, a controller, and a controlled device. When a controller detects error (a difference between measured conditions and the setpoint), it sends an to the controlled device. In a proportional control system, this signal is in proportion to the error.

Control systems can be classified as *two position*, *floating*, or *proportional*. The limits of two-position control are set by the *control differential.* Timed two-position control reduces overshoot and undershoot through the use of *anticipators.* The output of a proportional controller increases as error increases. In simple proportional control systems, *throttling range* defines the limits of controller action. Too narrow a throttling range causes short cycling, and too wide a range causes loose, inadequate control.

Control loops provide a means of controlling applications in which the condition of the controlled medium is monitored. *Closed-loop control* uses *feedback* to adjust the controller signal to the controlled device. *Open-loop control* does not include feedback. *Reset system control*, a combination of open- and closed-loop control, adjusts the setpoint based on an independent variable, such as outside air temperature. Control systems can be self-powered or externally powered by a pneumatic, hydraulic, electric, or electronic power source.

Answers to Self-Check Quiz

1-1. c. Load. Ref: 1.01

1-2. d. Variable. Ref: 1.19

1-3. b. Two. Ref: 1.22

1-4. c. Control point. Ref: 1.22

1-5. b. Controller; controlled device. Ref: 1.25

1-6. d. Two position. Ref: 1.31

1-7. d. Reverse acting. Ref: 1.47

1-8. c. Reduce the throttling range. Ref: 1.53

1-9. c. Pressure. Ref: 1.63

1-10. b. Proportional. Ref: 1.68

Contributions from the following sources are appreciated:

Figure 1-4. Honeywell Commercial Div.; Barber Colman Company
Figure 1-17. Honeywell Inc.
Figure 1-18. Johnson Controls, Inc.