POWER ENGINEERING

Fourth Class

Edition 3.5

Energy Plant Instrumentation and Controls

Part A

Unit A-9

PanGlobal
Partner in Education

Published by PanGlobal Training Systems Ltd.
Publishers of Power Engineering Learning Materials

The material in this series is aligned with the SOPEEC Fourth Class Syllabus, dated November 2017, and the IPECC Curriculum, November 2017.
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Printed in Canada
Fourth Class - Part A - Unit A-9 - Energy Plant Instrumentation and Controls
Edition 3.5, September 2024

ISBN13: 978-1-77251-263-2 (Part A Print Set)
ISBN13: 978-1-77251-264-9 (Part A Ebook Set)
ISBN13: 978-1-77251-283-0 (Unit A9 Print)
ISBN13: 978-1-77251-284-7 (Unit A9 Ebook)

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4th Class Edition 3.5 • Part A

UNIT A-9

ENERGY PLANT INSTRUMENTATION AND CONTROLS

Unit Introduction

The physical sciences and their applications in engineering are tools that assist in understanding and making use of the natural environment. By using engineered applications of the physical theories already examined, humans can observe and analyze a vast number and variety of conditions. When these conditions are measured, quantified, and evaluated, the outcomes of physical and chemical interactions can be predicted and controlled. Power Engineers create and manage process conditions. Instruments directly support the acquisition and analysis of physical and chemical conditions in order to facilitate Power Engineers' activities.

The first step to controlling the condition or environment involves the procurement of data. Without measurement, there would be no collection of data, and nothing to evaluate. In the field of instrumentation, measurement is performed by sensors.

The next step to achieving control involves data evaluation. Without evaluation, logical decisions cannot be made. In the field of instrumentation, controllers evaluate and compare the sensed conditions with the desired conditions.

Next, controllers make decisions, based on the evaluation of data. Control involves the application of a decision. Should a valve open or close? Should the pump start now, or later, when the level is lower? Should the fan speed increase, decrease or remain the same? Without decisions, there can be no control: only chaos.

The decision made by the controller must then be applied. Without application, conditions cannot be expected to change as desired. In instrumentation, the control action is made by a final control element, like a valve or air damper.

Finally, the decisions made by a controller must be evaluated. Did the control action bring about the desired change? In instrumentation, this final evaluation is called feedback.

Instrumentation involves the measurement, evaluation, and control of various energies, so that energy exchange achieves the desired outcomes. This unit begins with fundamental control theory, process measurement, and basic components used in control systems. Later chapters cover different systems used by industry today to achieve process control: programmable logic controls, electronic controls, and electrical controls.

Unit Rationale

In many ways, humans are the ultimate process controllers; they observe phenomena, evaluate data, and strive to exert control over their surroundings. However, direct human control has limitations. Today's complex industrial processes operate twenty-four hours a day, 365 days a year. These systems have tens of thousands of sensors and control devices, located throughout plants spread over hectares of land. This is where human limitations become most apparent.

Humans can only exert control during their waking hours. Humans cannot simultaneously access data from tens of thousands of sensors. Nor can they simultaneously analyze the data from all pertinent sensors, in order to make logical control decisions. Humans cannot simultaneously operate the multitude of plant final control elements. By themselves, humans cannot efficiently and safely control today's highly complex industrial processes. However, humans can apply their intellect to the development of instrumentation systems capable of supporting the activities of human operators.

Without instrumentation and control systems, scientific research, manufacturing, and industry as a whole would immediately come to a halt. Power Engineers partner with instrumentation systems to control processes and process equipment. As a team, Power Engineers, and the instruments they employ, keep human industry rolling.

CHAPTER 1

Introduction to Energy Plant Controls and Instrumentation

Learning Outcome

When you complete this chapter you should be able to:

Describe the overall purpose and function of plant instrumentation systems.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe the concept and basic components of a control loop.*
2. *Describe the various means by which control signals are transmitted, and the function of transducers.*
3. *List and describe the types of instruments that are not control loop components.*

Chapter Introduction

A Power Engineer must be familiar with the general plant layout, and have a basic knowledge of plant equipment. A Fourth Class candidate should be able to recognize and identify various instrumentation components involved in plant processes.

There are many ways to categorize instrumentation. At an introductory level, instruments can be broadly organized into two groups:

1. Those that control processes
2. Those that give information and safeguard process conditions

The first group includes the components of a control loop. The second group includes indicators, alarms, and shutdown devices. This chapter will discuss these two groups.

Objective 1

Describe the concept and basic components of a control loop.

Control Loops

There are many ways to implement process control, using mechanical, pneumatic, electrical, analog, and digital techniques. The basic theory is similar for all methods.

There are two basic types of controls: open loop and closed-loop.

Open Loop Control Systems

Open loop control systems simply estimate or predict the action that is necessary to accomplish a desired objective. In open loop control, no check is made to determine whether the corrective action has accomplished the desired objective.

A washing machine is an example of an open loop system. The operator takes a measurement (how dirty the clothes are), compares this with a reference level (how clean the clothes need to be), and predicts how best to run the load (the washing machine cycle, the amount of soap, the water temperature, and how much bleach to use). The operator then starts the machine and hopes that the prediction will achieve the desired result.

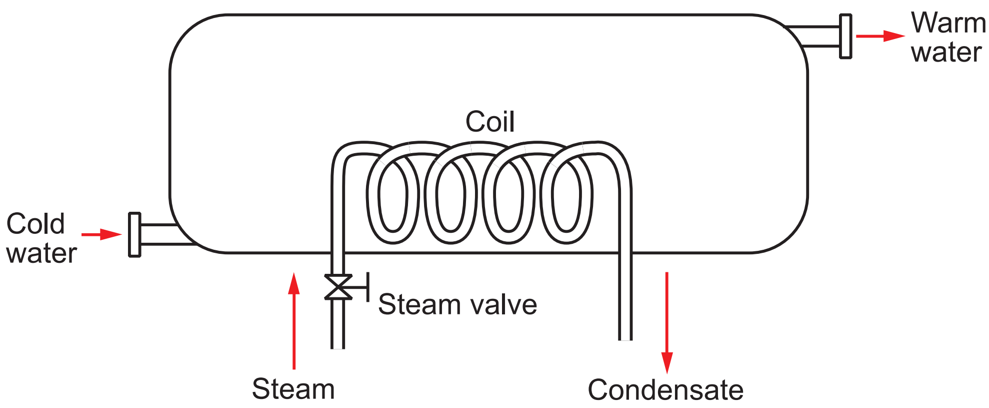
If all predictions are correct, the clothes will be perfectly clean. Thus, open loop control is capable of achieving the desired results. However, if any of the variables deviate from the conditions used to make the prediction, open loop will not give perfect control. Since the washing machine makes no final comparison of the actual and desired results, any **error** in the prediction will produce a difference between the desired and actual results.

An open loop system is therefore defined as "one in which the output has no effect on the input." This system cannot change the position of a control valve, because no data about the process conditions reaches the valve. So, the control device may act in a way that is totally unrelated to the desired process conditions.

In the case of an open loop system, an operator must decide if error exists (the difference between the desired and actual conditions), and whether the error is increasing or decreasing. Then, the operator must manually adjust the position of the control valve. In other words, a human becomes a **controller** that observes the process conditions and manipulates a control valve manually in response to the observed conditions.

The diagram in Figure 1 helps to illustrate open loop control. This process is for heating water using steam. Cold water enters from the left of the heat exchanger. Warm water exits at the right. The device that controls the heating process is a manual steam valve. To maintain the temperature of the water close to the desired value, the steam valve must be manually operated to throttle the steam.

Figure 1 – Manual Control Water Heating System



If variables such as water flow, steam flow, and steam quality are constant, the outlet temperature of the water can be maintained at the desired value by opening the steam valve the correct amount and leaving it there. However, if the temperature of the incoming cold water changes, or if the water flow changes, the outlet temperature will deviate from the desired value. In this case, the steam valve must be manually readjusted.

To compensate for disturbances in the water heating process and maintain the desired water temperature, the operator must check the discharge water temperature frequently to see if there is any error (also called **offset**), and verify whether the error is increasing or decreasing. Then, the operator must adjust the opening of the steam valve to meet the energy requirements of the heat exchanger. This is a manual type of control system.

All open loop systems are manual control systems, and need continuous attention. The desired value of the **process variable** is difficult to maintain when the operator is present, and impossible to maintain when the operator is absent.

Closed Loop Control Systems

Closed loop control systems are automatic control systems. They respond to changes in process conditions regardless of whether an operator is present. As well, depending on how critical the process is, closed loop systems can

a) be tuned to keep the process conditions within narrow or wide parameters,

b) be tuned to respond rapidly or slowly to process deviations, and

c) be configured so that the process conditions always return to the desired condition.

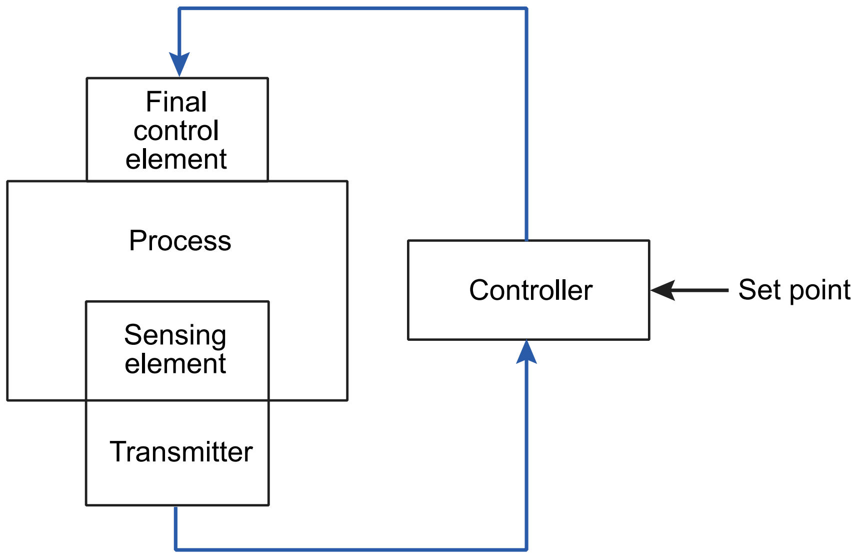
In a closed-loop control configuration, a measurement is made of the variable to be controlled; then it is compared to the desired condition (the **set point**). If error exists between the actual value and the desired value, the controller takes the necessary corrective action.

On Track

Closed loop systems get feedback about process conditions. Open loop systems do not.

An example of a basic closed loop control system is shown in Figure 2. This diagram can be related to the process of heating water with steam. Consider the open loop water heating process described above, with the addition of a **transmitter**, a controller, and an automatic valve.

Figure 2 – Closed Loop Control System



The process box represents the heating of water, performed by the heat exchanger. The **sensing element** can be any one of a variety of temperature sensors. It responds to the temperature of the measured variable (the water leaving the heat exchanger). The temperature transmitter takes the value of the **measured variable** from the **sensor** and transmits it (the process variable) to the controller.

The controller is like a human brain. It compares the process variable (the actual water temperature) to the water temperature set point (the desired water temperature). If there is a difference between the process variable and the set point, the **control output** signal to the **final control element** (an automatic steam valve) changes in proportion to the difference. The change in the position of the final control element changes the energy input to the process, so that the water temperature can be maintained at the set point.

Figure 2 shows a closed loop control system in general terms, so that its concepts can be applied to any process. For example, a process may be to maintain the water level in a tank. The sensing element may be a level sensor, like a float. The set point may be "keep the tank ½ full." The final control element may be a valve that controls the flow of water into the tank, or a valve that controls how fast the tank drains.

Automatic Process Control Principles

Figure 3 shows the open loop water heating system described previously, but with an automatic control system applied to it. The temperature-sensing element and transmitter provide process condition feedback to the hot water controller. The hot water controller positions the final control element (automatic steam control valve) based on the error between the process variable and the temperature set point. The lines with small diagonal slashes are the signal lines between the transmitter and the controller and the controller and the final control element. These slashes show that these lines are pneumatic; therefore, this is a pneumatic control system.

During normal operation, the control valve feeds the required amount of steam into the heat exchanger to keep the hot water temperature at the set point. In other words, the energy flowing into the heat exchanger equals the energy required to maintain the hot water temperature.

In the case of a system disturbance (such as an increase or decrease in water flow through the heat exchanger), the hot water temperature changes. For the following discussion, consider what happens when water flow increases.

When the water flow increases, the heat exchanger no longer provides sufficient energy to maintain the hot water temperature set point. For this reason, the hot water outlet temperature decreases.

The purpose of the temperature sensor is to continuously detect the hot water temperature. Changes to temperature make a physical change to the condition of the sensor (such as its resistance, position, or voltage). The change in sensor condition is interpreted by the transmitter and converted to a signal (the process variable).

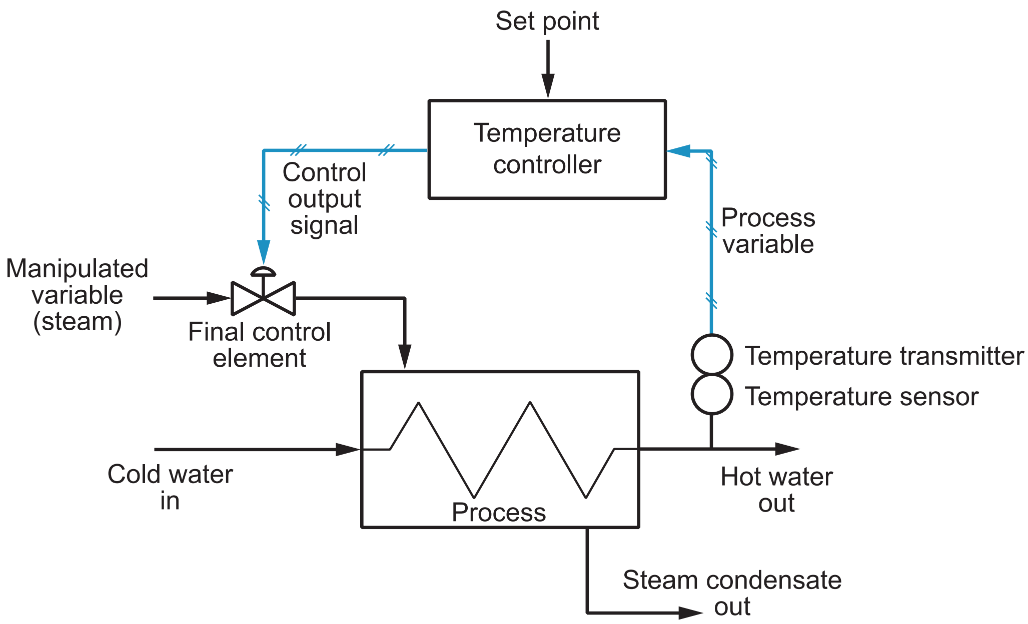
The transmitter outputs the process variable as a signal that the temperature controller can interpret. As the hot water outlet temperature drops, the transmitted process variable signal decreases.

The temperature controller receives the process variable from the transmitter, and a set point (the desired hot water temperature) from another source. The set point is typically entered manually by an operator, but in more sophisticated control systems, a set point may be the control output signal from another controller. The temperature controller compares the process variable with the set point, determines the error between the two, and produces a control output signal that is proportional to the error. In this case, the drop in hot water temperature causes the controller to output a higher signal.

The control output signal goes from the temperature controller to the final control element. The final control element (the steam control valve) has a power source, and can position itself according to the control output signal. In this situation, the increase in the temperature controller output signal causes the steam control valve to open more. This allows more steam to enter the heat exchanger.

When the hot water temperature increases, the opposite sequence of events occurs. The sensor will cause a proportional change in the transmitter output. This will cause the controller output to close the control valve, and reduce the heat energy input to the heat exchanger.

Figure 3 – Automatic Control System



The overall action of this automatic control system is illustrated in Figure 4. Trace the sequence of events, beginning from the change in water flow, to the change in position of the steam control element. Note how a change in the flow of the **manipulated variable** affects the sensed and transmitted value of the measured variable.

Figure 4 – Automatic Hot Water Temperature Control System Flowchart

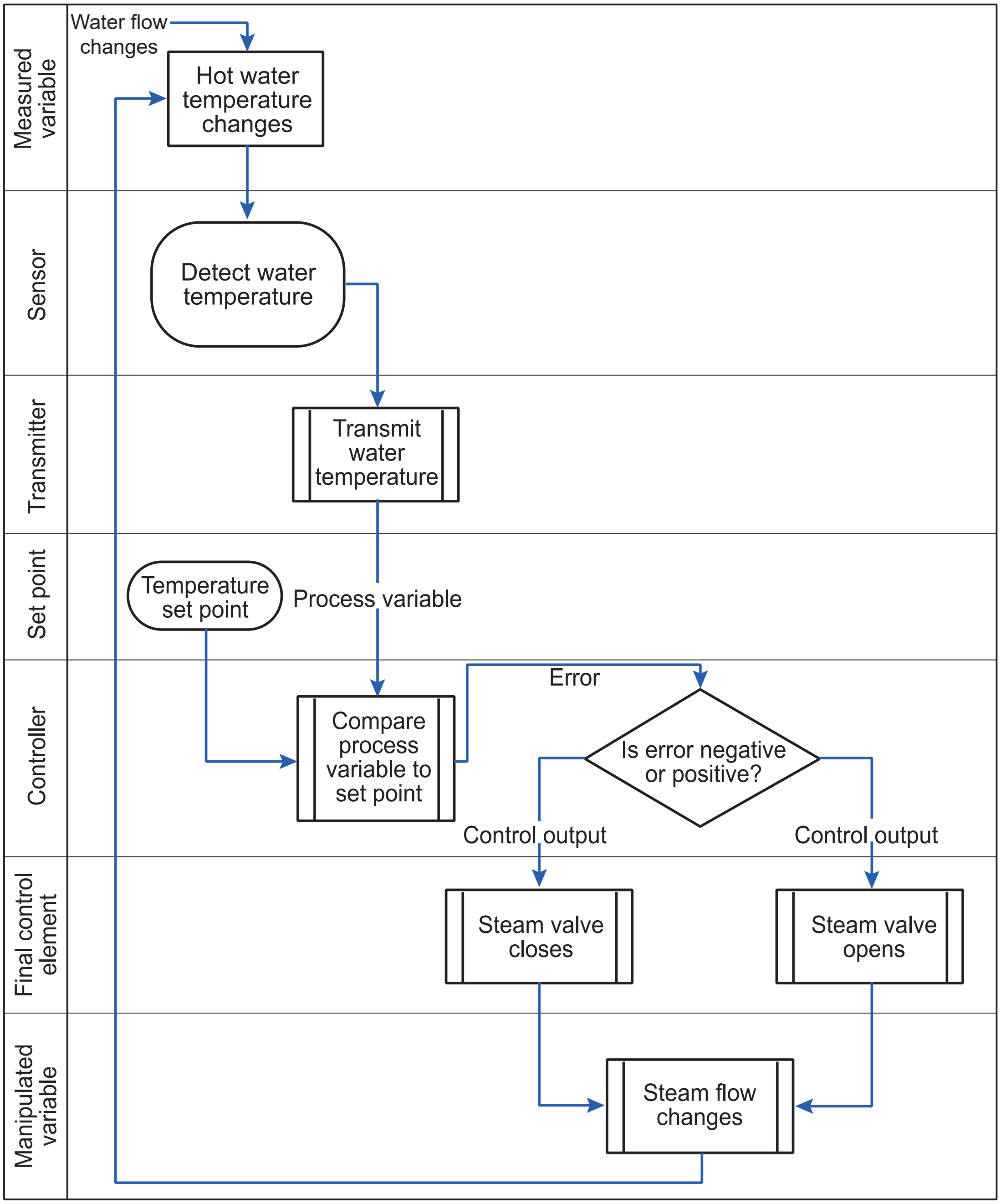
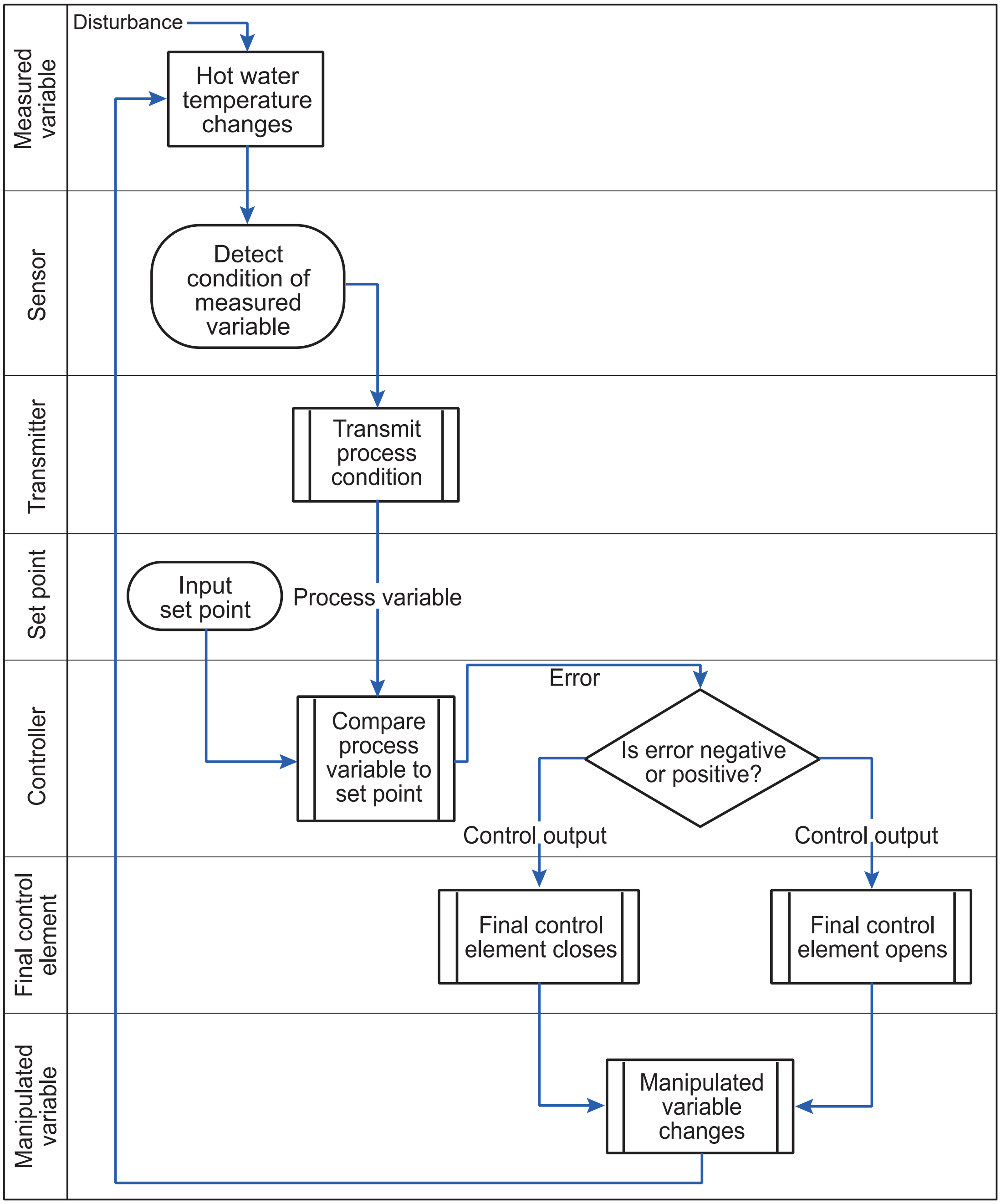


Figure 5 shows the closed loop described in Figures 3 and 4 in general terms that can be applied to any automatic control system. Compare these three diagrams.

Figure 5 – Automatic Hot Water Temperature Control System Flowchart



As can be seen, there are significant differences between the open loop (manual) control system and the automatic (closed loop) control system. The open loop system has no feedback signal to re-position the control valve. An operator must notice changes in temperature on the thermometer, and manually adjust the valve.

In the closed loop system, the controller is continuously informed of the value of the process variable. Corrective action can be made accurately and quickly to keep the process closer to the desired value.

Components and Definitions

Process

A **process** may be defined as an operation that uses energy to produce a change in a material, or an energy conversion. The process may take many forms, such as one of the following:

a) Maintenance of water level in a boiler or tank

b) Control of the flow rate of various liquids and gases

c) Maintenance of pressure in a vessel

Measured or Controlled Variable

All processes have desired outcomes. The measured variable is the process condition to be controlled at a definite desired value. To control this condition, it must first be measured. Examples of measured variables include:

- Pressure
- Level
- Flow
- Temperature
- Composition

Process Variable

The process variable is the current status of a measured variable under control. For example, a measure variable could be boiler drum pressure. The process variable (for example) could be 1710 kPa, which represents the current value of the drum pressure.

On Track

Commonly, measured variables are flow, level, pressure, and temperature. Each variable has a value, called the process variable. These process variables are the actual measurements of the flow, level, pressure, or temperature. For example:

Example of a Measured Variable	Example of a Process Variable
Flow	100 l/min
Pressure	1075 kPa
Temperature	52°C
Level	765 mm

Set Point

A set point is the desired value of a process variable. In Figure 3, the desired temperature of water from the heater could be 80°C. In the previous example, the desired boiler pressure could be 1700 kPa.

Error

Error, often referred to as offset or **deviation**, is the difference between the actual value of the measured variable and the set point. It is the margin by which an automatic controller misses the desired value.

Sensing or Measuring Element

A sensing element, also called detector or sensor, is a device that responds with a physical change (such as a change in position, length, electrical resistance, or generated voltage) when a measured variable changes in value. Sensors convert the measured condition (such as pressure, temperature, or flow) to a movement or signal that can be transmitted to a controller, recorder, or indicator.

Disturbance

A **process disturbance** is a change in a process that cannot be predicted. The disturbance may be a flow rate change, a variation in temperature of a fluid stream, or the variation of several factors which may change independently.

Manipulated Variable

In most cases, the manipulated variable is some form of flow that is adjusted to restore a process variable to a desired set point. In Figure 1, an operator must manually adjust the control valve to permit adequate steam flow to the heat exchanger, so the water will be as close as possible to the desired temperature. Steam flow, then, is the manipulated variable.

Transmitter

Sensing elements must be located where the process measurements are taken. In some control systems, the process controller is located near the sensing element, or the sensing element may be part of a local controller. However, in larger installations, the controller may be in a separate room, a considerable distance from the process. In this case, a transmitter is installed at the same location as the sensing element. The transmitter converts the sensor's condition to a representative process variable signal, and transmits this signal to a controller via some transmission method.

Indicators

Indicators (such as thermometers, pressure gauges, and level indicators) are located in the field, close to their respective processes. Control room displays show the transmitted process values of the operators. Sometimes, the transmitted data may not be up-to-date, or it may be inaccurate. Field indicators show the field operators and maintenance personnel real-time process values. These values can be used to validate the conditions observed by control room operators.

Recorders

Recorders normally consist of one or more pen mechanisms that are positioned according to measured process conditions (pressure, temperature, level, or flow). The recorders make permanent records of process conditions for future reference.

When a recorder is placed near the process at the point of measurement, the sensing element may be located directly in the recorder. If the recorder is in a remote location, the transmitter output signal is used to position the pen.

A recorder pen continuously marks the value of a monitored variable on a chart moving at a constant speed. The time is printed on the chart. An operator can see the current value of the variable, and how it changed with time. An indicator and a recorder may also be built directly into a controller for simultaneous observation and control.

Newer systems input digital data signals into computerized control systems. The values can then be charted, graphed, and printed in a variety ways. The historical data is stored in digital format for future reference.

Controller

The controller is a very important component of an automatic control system. It continuously compares the value of a process variable with a set point. It then responds to the error between the process variable and the set point by re-positioning the final control element. This changes the energy flow to the process by altering the flow of the manipulated variable.

Refer to Figure 3. The controller positions the final control element (the steam control valve) according to the error measured between the set point and the temperature of the hot water (the process variable). The adjustment in the final control element changes the rate of flow of the manipulated variable (steam flow) to bring the process variable back to the set point.

An operator, a computer, or another instrument may adjust the set point signal.

Controllers are normally equipped with an auto-manual transfer station. This allows an operator to switch the process from automatic to manual or vice versa, with little delay and minimum process upset.

Final Control Element

A final control element is used to adjust the manipulated variable. Most final control elements are control valves. Dampers and variable speed motor drives are also common final control elements. The steam control valve in Figure 3 is the final control element in that controller loop. Boilers commonly use air dampers and variable speed drives to control combustion airflow, and control valves to control fuel flow.

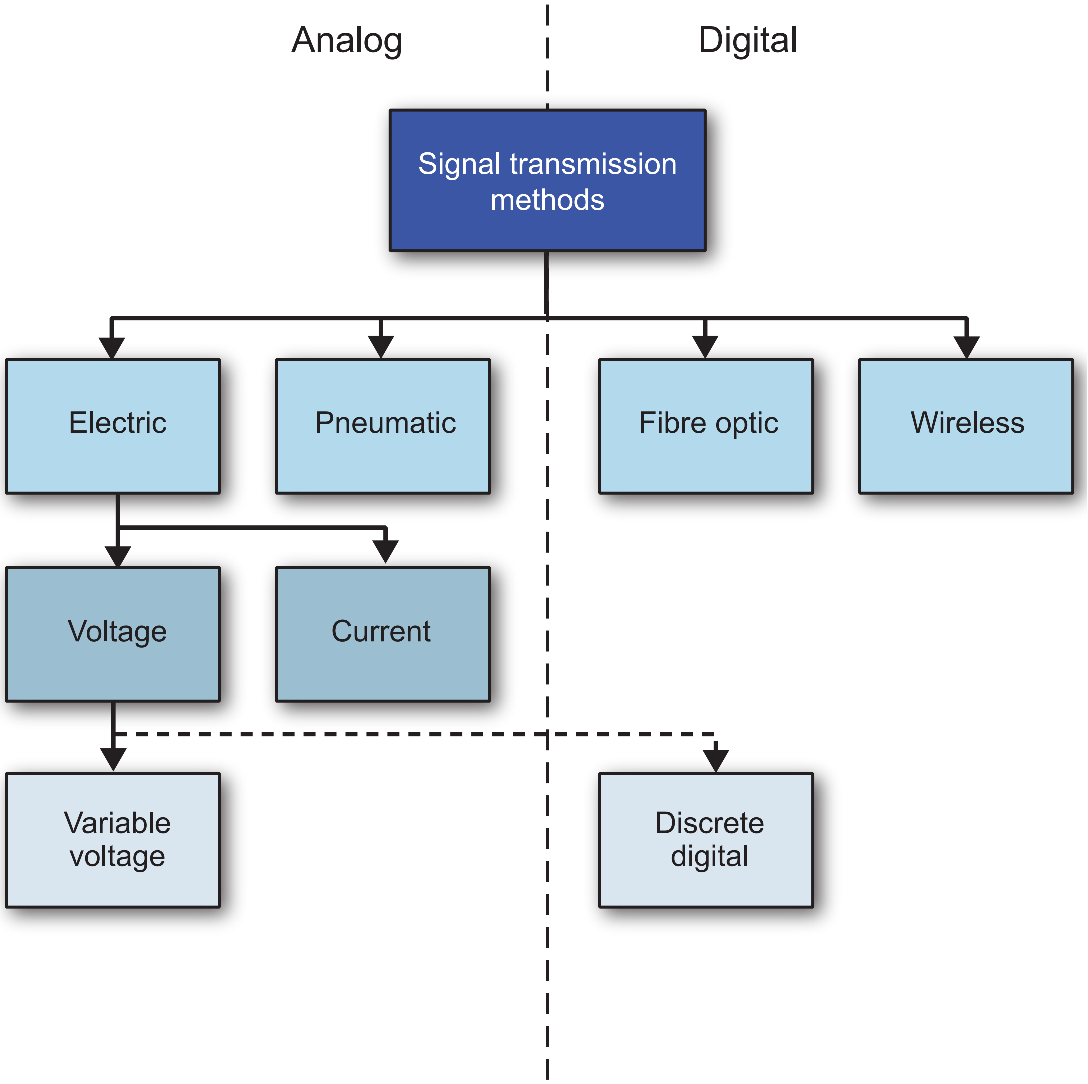
Objective 2

Describe the various means by which control signals are transmitted, and the function of transducers.

Signal Transmission

Signals are information related to the measurement and control of processes. These are often transmitted from one location to another. Figure 6 shows some of the most common methods of signal transmission. Note that these methods convey process information in either analog or digital format. These will be discussed below.

Figure 6 – Signal Transmission Methods



Pneumatic

Pneumatic instruments use variations in compressed air pressure to transmit information. The most common pneumatic signal range is 20 to 100 kPa. The supply pressure for a pneumatic control system is typically regulated to 140 kPa.

Pneumatic control systems are **analog** systems. The pneumatic pressure signal is "analogous" to the process variable (meaning that the pressure represents the process condition). For example, a measured temperature range of 160°C to 220°C could be represented by a pneumatic signal ranging from 20 to 100 kPa. A value of 160°C could correspond to 20 kPa, and 220°C could correspond to 100 kPa. In this example, temperatures over 220°C would also be represented by a pneumatic signal of 100 kPa.

A positive pneumatic pressure (20 kPa) is used to indicate the lowest process variable in the measurement range. Using the above as an example, if the temperature dropped below 160°C (say to 150°C), the pneumatic signal would not drop below 20 kPa. If the pneumatic signal drops below 20 kPa, a fault in the controller or the air supply is likely.

The main advantages of using pneumatic signals are:

a) They are simple and provide trouble-free operation.
b) They may be less expensive than corresponding electronic instruments.
c) They are safer to operate, especially in explosive environments. They present no risk of electric shock, fire, or explosion.

Their disadvantages are:

a) Their signals may be too weak to transmit over long distances.
b) There is always a lag between the time a change in signal takes place at the transmitting location, and the time that the change in signal is sensed at the receiving end. This delay is caused because pressure takes time to build up at the other end of the line when the controller output increases. The longer the transmission lines, the greater the delay.
c) The cost of purchasing and installing tubing for pneumatic signals is greater than for electrical wiring.
d) The compressed air must be kept clean of oil or other contaminants, and must be extremely dry. Dirty or wet air freezes or otherwise plugs pneumatic control lines.

Electrical

Transmission systems may convey process information by using voltage or current signals. Some of the main advantages of using electrical signals over pneumatic signals are:

a) Instant signal transmission (no delays)
b) Precise and accurate signals
c) Quiet operation

Some of the disadvantages are:

a) The electrical signal is more susceptible to corruption by outside influences (such as nearby power lines)
b) Higher initial cost
c) May be unsafe to operate in areas exposed to explosives and flammable materials

Voltage Signals

Voltage signals are transmitted by using electrical conductors as either **discrete digital signals** (on/off) or variable voltage signals.

Discrete Digital Voltage Signals

Signals can convey detailed information about processes, such as precise temperature, level, or flow. However, often it is unnecessary to know the precise condition. It may be enough to know if a particular temperature has been reached, if a level is adequate, or if flow has been established. For this type of information, discrete digital signals are used. This type of information can be described with words like "true/false," "on/off," "start/stop," "in/out" or "yes/no." When used with a digital or electronic control system, these inputs are called **contact closure inputs.**

Discrete input signals are produced by specific types of sensors that will always be in one of two possible states. These sensors are switches that detect level, pressure, temperature, or position (proximity). They change state (open or close) at specific conditions of the measured variable. They provide voltage signals, when they open or close, that correspond to their state.

Controllers send discrete output voltage signals to devices such as motor starters, solenoids, and relays. The output signal either energizes or de-energizes these devices, causing them to start, stop, open, or close. When used with a digital or electronic control system, these outputs are called **contact closure outputs.**

Consider the actions of a boiler combustion programmer. Depending on the programmer, one or more discrete voltage signals (contact closure inputs) from various sensors in the boiler safety circuit are required, before the purge begins. For boiler control, these switches are often called **permissives**. These permissives may be switches for level (boiler low water cut-off), pressure (boiler high-pressure cut-off), or temperature (boiler high temperature cut-off).

When all boiler start-up conditions are met, the combustion programmer sends a discrete voltage signal (a contact closure output) to a motor starter to start the draft fan. Next, the programmer waits for a discrete voltage signal from the airflow-proving switch and low fire start switches. When these signals are received, the combustion programmer sends a discrete voltage signal to the ignition transformer and the pilot solenoid valve to begin a trial for ignition.

Variable Voltage Signals

Like pneumatic signals, voltage signals can also be analog. Variable voltage signals can vary widely in the voltage ranges they use. Some voltages can be millivolt signals (as in the case of a simple thermocouple output), or low voltage signals (such as 0 to 24 volt 3-wire controls). One common signal is 1 to 10 volts, with "1" representing a positive zero value. Regardless, the transmitted voltage represents the process variable.

Variable voltage signals are useful for transmitting signals short distances, so that the voltage signal does not become corrupted. For example, voltage drops over a length of conductor due to conductor resistance. In instrumentation, this voltage drop is called **signal attenuation**. To compensate for signal attenuation, variable voltage signals transmitted over longer distances must be amplified. Also, variable voltage signals can be corrupted by voltages induced from currents flowing in adjacent conductors (referred to as **noise**). To prevent this form of signal corruption, signal conductors can be shielded with a special grounding sheath.

Current Signals

Analog direct current signal transmission is widely accepted and used in industry. By varying current instead of voltage, signal attenuation and noise are reduced. A series circuit, formed by a signal loop, will have the same current at the transmitting and receiving ends, even if transmitted over long distances.

The most common signal range is 4 to 20 milliamps. The "4" represents a positive zero value, like 20 kPa in the pneumatic system.

When required, DC current signals can easily be converted to voltage signals. This is done by placing a known resistance in the series circuit and measuring the voltage drop across this resistance. The voltage variation across the resistance is relative to the current flow, according to Ohm's Law.

Fibre-Optic Signals

The most common form of optical signal transmission involves transmitting light along a fibre optic cable. A fibre optic cable contains very long optical glass fibres coated in plastic. These fibres transmit data using pulses of light. Signals are normally transmitted along a fiber-optic cable in digital format, although analog transmission is sometimes used.

Compared to electrical signal transmission systems, transmitting data using light has a number of advantages. Fibre-optic systems are

- intrinsically safe
- free from induced noise
- less susceptible to signal attenuation, and
- capable of transmitting data much faster than standard metal conductors.

However, fibre-optic cabling is more expensive than metal conductors. As well, expensive **transducers** are required to transform the light signals into electrical signals and vice versa.

Wireless Signals

Wireless transmission can be accomplished using familiar wireless protocols, such as **Wi-Fi** and **Bluetooth**, or protocols tailored for industry, such as **WirelessHART**. These devices all transmit digital signals.

Unlike devices that use Wi-Fi and Bluetooth, WirelessHART devices communicate over a "mesh." This means that each transmitter in a signal communication network acts as a transmitter and as a receiver. Every transmitter can send its own signal and repeat the signal from any other transmitter within range.

The WirelessHART system provides many redundant signal paths. If any one transmitter fails, the signal can take many alternate paths. Using this principle, a WirelessHART network provides built-in insurance against interference.

For example, a pressure transmitter may be mounted near a concrete barrier, a high-voltage transmission line, or a high-power variable frequency drive. These may block or interfere with a wireless signal transmitted directly to a receiver. With a mesh network, the wireless signal can avoid this interference by taking a more roundabout route, hopping from transmitter to transmitter.

WirelessHART devices use 2.4 GHz signals, with 128-bit encryption, to communicate between field devices (transmitters for temperature, pressure, flow, etc.) and a network gateway. The gateway is an electronic device that directs the various control signals over an Ethernet connection to and from a digital controller.

Analog and Digital Signals

Analog Signals

An analog signal can be described as any continuous signal that is infinitely variable. All observable physical conditions – such as sound, light, velocity, and temperature – are analog in nature. All can vary infinitely in intensity or condition. An analog control signal can represent any value of measured variable within a range of predetermined values. These analog signals can vary in magnitude, amplitude, and frequency. A sound wave is a good example of an analog signal.

All pneumatic signals (controller inputs or outputs) are analog by their very nature.

Electronic and digital control systems have provisions for both analog output and analog input signals. Analog input signals may be either variable voltage or variable current signals, and originate from any of a wide variety of transmitters. Analog output signals are sent out by the controller as variable current or variable voltage signals to the various final control elements.

Digital Signals

Discrete digital signals have already been discussed. They are used to transmit and receive information about process conditions that have only two states, such as "on/off," "start/stop," and "open/closed."

For example, a discrete digital start command may be sent to a boiler draft fan, represented by the number one (1). A small electronic contactor controlled directly by the process controller closes. This causes the draft fan motor starter to energize, starting the fan. When the fan is in operation, a windbox pressure switch closes. This switch sends a "closed" signal back to the controller, represented by the number one (1). This confirmation that the fan started may be used as a "run status" signal for the controller.

In this situation, after sending a fan start command, the controller would expect an "air flow switch closed" signal to verify the fan started. Any difference between the "fan start" command and the expected "run status" signal could be presented as an alarm, indicating the fan failed to start or it stopped running when it should be on.

When the fan needs to be stopped, a stop signal sent to the draft fan would be the number zero (0). A contact then opens, causing the fan's motor starter to open, and the fan to stop. When the airflow stops, the windbox pressure switch opens, sending a zero (0) signal to the controller to confirm the fan has stopped.

Contact closure outputs are used to start and stop equipment. Contact closure inputs – simple single throw switches operated by sensing elements – are used as to provide digital run status and permissive information.

Digital signals are also commonly used to transmit analog process information, but in digital form. Like the discrete signals already discussed, digital signals can be inputs or outputs. Digital input signals can provide information about process conditions, such as temperature, flow, and level. Digital output signals can be used to vary the speed of electric motors by using variable speed drives, or to change the position control valves and dampers.

Digital control signals travel at high speed. They are not very susceptible to signal attenuation and noise. Modern computerized control systems can evaluate and process digital signals directly. These signals can be transmitted wirelessly, or over electrical wiring and fibre-optic cables. Digital signal transmission is now the dominant and preferred signal transmission method.

For transmitters to convey analog information as digital information, small computers called **analog to digital convertors** are used. Typically, each local transmitter has its own analog to digital convertor. These convertors repeatedly sample analog process conditions over very short periods of time. For each sample taken, the analog to digital controller assigns a numerical value to the measured variable. After the data conversion, the information is transmitted in digital form to a controller, where it is processed directly with a computer-based controller.

After the controller receives the digital signal and compares it to the set point, the controller sends a digital control output signal to the final control element. The final control element needs a **digital to analog convertor**. This small computer turns digital control output signals into proportional analog signals, so that the final control element can be correctly positioned.

Transducers

A transducer is a device that converts one form of energy into another form of energy. For example, a transducer can convert a physical condition (such as pressure, temperature, level, volume, or flow) into a corresponding signal. This type of transducer is known as a primary transducer. A good example of a primary transducer is a thermocouple that produces a variable millivolt signal, depending on the temperature it is exposed to. In the world of industrial instrumentation, primary transducers are usually called sensors.

Secondary transducers convert the signal from a primary transducer to an analogous electrical or pneumatic signal. Below are some common types of secondary transducers.

Current-to-Pneumatic (I/P) Transducers

In many control systems, the transmitters, recorders, and controllers use variable current input and output signals (4 to 20 mA). However, control valves and other final control elements may require pneumatic signals to open or close. Current-to-pneumatic transducers change variable current signals into variable pneumatic signals to operate final control elements.

Pneumatic-to-Current (P/I) Transducers

P/I transducers receive pneumatic input signals (from 20 to 100 kPa) and produce variable current output signals (4 to 20 mA). In this way, pneumatic sensing devices can transmit proportional variable current signals to electronic controllers.

Voltage-to-Pneumatic (E/P) Transducers

Many control systems use variable voltage signals (0 to 10 V). Voltage-to-pneumatic transducers change variable voltage signals into variable pneumatic signals to operate final control elements.

Pneumatic-to-Voltage (P/E) Transducers

PE transducers convert pneumatic signals into either discrete voltage signals or variable voltage signals. The transducers that produce discrete signals are often called **PE switches**. An example of a PE switch is the pressuretrol of a steam boiler. When the boiler pressure is low, the pressuretrol closes to send the boiler control a “call for heat” signal. When the boiler pressure reaches set point, the pressuretrol signals the boiler control to stop firing.

PE transducers can also convert pressure signals into variable voltage signals. Consider a small packaged boiler firing rate control. Boiler pressure moves a pressure-sensitive bellows that positions a variable resistor. When the resistance changes, the voltage supplied to a voltage-sensitive modulating motor changes. The modulating motor positions the fuel valve and the combustion air damper to change the boiler-firing rate. With this setup, when the boiler pressure drops below set point, the boiler fires harder. The firing rate decreases when the pressure approaches set point.

E/I Transducers

E/I transducers are also called signal convertors. A transmitter may provide only variable voltage signals. However, this transmitter may be used to send signals to a controller that only accepts variable current signals. This type of transducer converts a 0–10 V signal to a proportional 4–20 mA signal.

I/E Transducers

I/E transducers are also signal convertors. This type of transducer converts a 4–20 mA signal to a 0–10 V proportional signal.

Photoelectric Transducer

Photoelectric transducers use light-sensitive sensors to detect light intensity at particular wavelengths. These transducers convert the light intensity to analog or digital signals for control purposes. Boiler flame scanners are common examples. These may detect ultraviolet, infrared, or visible light. As long as a flame scanner detects light from a fire, the burner continues to operate. If the flame goes out, the signal from the scanner ceases. This de-energizes the burner circuit and closes the fuel valves.

Objective 3

List and describe the types of instruments that are not control loop components.

Non-Control Loop Instruments

A process may be equipped with numerous instruments that do not perform routine process control functions as part of control loops. These devices may be used to:

a) Monitor process conditions
b) Sound alarms that draw attention to improper or hazardous operating conditions
c) Shut down equipment when unsafe conditions exist
d) Remotely operate block valves
e) Automatically start or stop process equipment.

Devices in these types of services have special names, depending on their function. The following is a brief overview.

Indicators

Indicators are gauges, typically used to show temperature, pressure, flow, or level. In addition, instruments are manufactured to measure and indicate:

- Control valve position
- Fluid density
- Material composition
- Dew point
- Weight
- Vibration
- Shaft position
- Smoke, heat, and fire
- Presence of toxic gases
- Viscosity
- pH
- Conductivity
- Turbidity
- Rotational speed
- Radiation levels

Indicators may provide local or remote readings, or may be connected to other devices. In many cases, they serve as sensing elements in control loops.

Switches

Switches may act like indicators. For example, high or low-pressure switches may trigger alarms, or light up panel-mounted indicator lamps. Some switches initiate safety shutdown of equipment operating outside of normal operating parameters. A good example of this is a boiler low water cut-off.

Switches are often connected to systems where information is passed from one device to another. The term "relay" is used in this context. A shutdown relay, for example, is a switch that transfers a shutdown signal, often converting the signal in the process. EP switches, for example, receive discrete voltage signals and convert them to pneumatic signals.

Switches come in many different designs. They may be actual mechanical devices or computer "bits." In either case, switches can turn pneumatic, hydraulic, electrical, electronic, or digital signals on or off.

Alarms

Alarms use indicators or switches, as sensing elements. They give visual, audible, or combined warning of unsafe or improper operating conditions. Alarm conditions may be displayed on specially lit panels called annunciators, or on computer terminal screens. This provides a quick indication of problem conditions.

Some alarms have switches connected to dedicated hard-wired circuits. Their alarm points can only be changed by changing the switch set points.

Computer based alarms compare transmitted process variables to "soft" alarm set points that can be changed (if necessary) from central control stations. These soft alarms give operators the flexibility to assign the alarms as desired, during special circumstances like startups.

Alarms are sometimes confused with trips (or shutdown) switches. Although alarms and trips are often connected in shutdown systems, they are separate devices. An alarm itself does not shut down equipment.

Logic Devices

Switches, relays, and indicators can be incorporated into automatic decision-making systems such as **Programmable Logic Controllers (PLC)**. In addition to controlling during routine operation, PLCs may be used to shut down or start up equipment in a very specific sequence. An example is the startup system of an automatic boiler. The burner ignition equipment (igniter and fuel valves) follows a sequence timer, if various permissives, such as air and fuel pressure switches, are satisfied.

Logic systems are also used in batch processing, such as pumping operations, where storage tanks are filled in sequence. Logic systems may use dedicated hard wiring; or may be operated with computer software or PLCs.

In processes such as air compression, where oil pressure, motor current and other conditions must be satisfied during the start sequence, logic systems are often used to control motor starts and stops.

Chapter Summary

In this chapter, control loops were discussed. Open loops are known as non-feedback control systems. Closed loop control systems are referred to as feedback control systems.

Automatic process control principles were explained and compared to manual control systems. A number of key terms were introduced, including:

- Process
- Process variable
- Measured variable
- Manipulated variable
- Controller
- Set point
- Final control element

Various types of signal transmission methods were discussed, including pneumatic, electric, fibre optic, and wireless. Various devices for converting signals – known as transducers – were also introduced.

Finally, non-control loop instruments were covered.

The concepts discussed in this chapter are the building blocks for future learning.

CHAPTER 2

Introduction to Process Measurement

Learning Outcome

When you complete this chapter you should be able to:

Describe the construction and operation of common devices used to measure pressure, level, flow, temperature, humidity, and composition.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. Describe the types of pressure sensing and measuring devices.
2. Describe the types of level sensing and measuring devices.
3. Describe the types of flow sensing and measuring devices.
4. Describe the types of temperature sensing and measuring devices.
5. Describe the types of humidity sensing and measuring devices.
6. Describe the types of gas sensing and measuring devices.

Chapter Introduction

All automated production processes rely on sophisticated sensing and measuring instruments. These devices must accurately detect and measure process conditions so that control systems can take appropriate action. Without accurate sensing and measurement, processes become inefficient, wasteful, or unsafe.

Process measuring devices are used either as stand-alone indicators of process conditions, or as the sensing elements of control, alarm or logic systems. Depending on their specific application, they may provide visual, mechanical, pneumatic, or electronic outputs. Because there are literally hundreds of specialized measurement devices, this chapter will examine the operation and application of the most common types.

Objective 1

Describe the types of pressure sensing and measuring devices.

Pressure Measuring Devices

Pressure is one of the most important measured variables in power plant operation. It includes measurement of steam pressure in a boiler, fuel pressure entering a burner, feedwater pressure, and many others.

Pressure is also involved directly or indirectly in the measurement of other variables, such as level, flow, and density. Since these applied pressures (located in various parts of a plant) can range from a few to many thousand kilopascals, the same type of pressure sensing element cannot be used in all applications.

Manometers

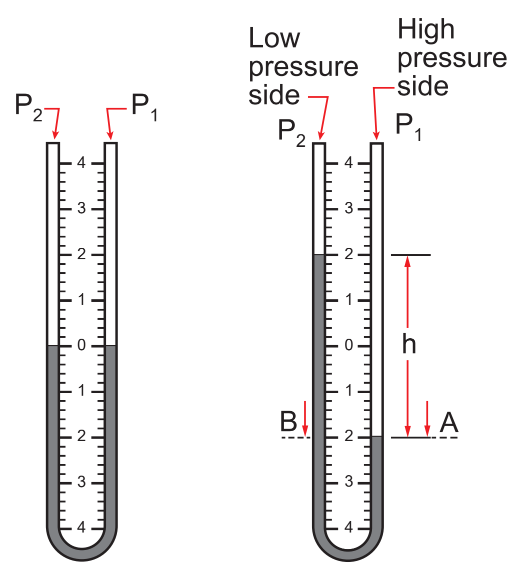
A **manometer** is one of the most accurate and useful devices for measuring pressure in the lower ranges. There are three general types that are used in industry: the **U-tube manometer**, the **inclined manometer**, and the **barometer**.

U-Tube Manometer

The main purpose of a manometer is to measure the difference between two pressures (differential pressure measurement). Manometers can be used to measure low pressures, or even vacuums. A common plant application is the measurement of boiler furnace pressure or draft.

A U-tube manometer can be a simple glass or other transparent material bent into the shape of a letter "U" as shown in Figure 1.

Figure 1 – U-Tube Manometer



The U-tube manometer contains a liquid, often referred to as the manometer fluid. This liquid must not mix or react chemically with the fluid whose pressure is being measured. Typical manometer fluids are water, mercury, and light oils. Mercury was a common manometer fluid in the past, but has been replaced due to its environmental and health hazards. With both sides of the manometer open to the atmosphere, the surface level on one side will be the same as the level on the other side, or $P_1 = P_2$ as in Figure 1(a).

Suppose one end of the U-tube manometer is connected to an unknown pressure source, P_1, while the other end is connected to another unknown pressure, P_2. If P_1 is greater than P_2, the fluid on the right side of the manometer (Figure 1(b)) will be displaced from its previous position, and forced into the left side of the manometer until a balance in pressure is created at points A and B, so the differential pressure can be read from the attached scale.

Pressure at A = Pressure at B, or

$$P_1 = P_2 + \text{the pressure due to the height (or "head") of liquid "h"}$$

$$P_1 = P_2 + h\rho g \text{ and}$$

$$P_1 - P_2 = h\rho g$$

Where:

h = height, meters

ρ = density kg/m³ (Greek letter "rho") ρ

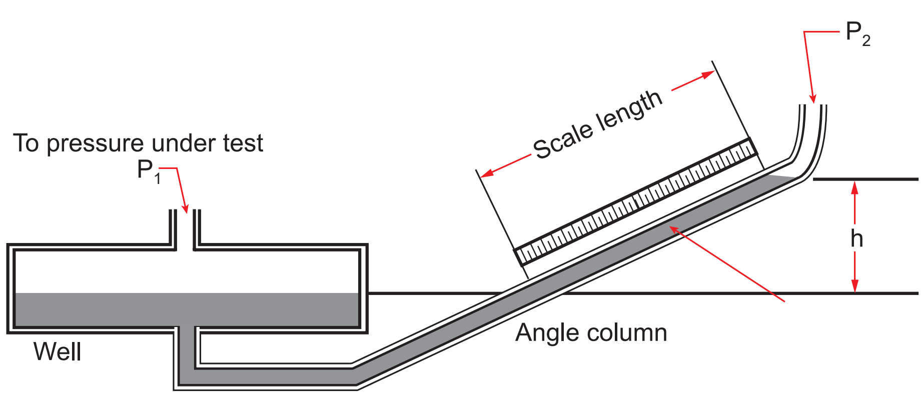
g = gravitational acceleration (9.81 m/s²)

If P_2 is the atmospheric pressure, then the pressure represented by the liquid head, $h\rho g$, would be equal to the amount that P_1 exceeds atmospheric pressure. $P_2 + h\rho g$ would be equal to the absolute pressure applied on the right side of the manometer. If the pressure P_1 is below atmospheric, and P_2 is still the atmospheric pressure, the manometer fluid will be higher on the right side.

Inclined Manometer

Figure 2 is a special design of manometer. Its tube is inclined at an angle to the horizontal while the vertical part contains a well or fluid reservoir. This inclined manometer has a longer scale of measurement than the U-tube for the same differential in pressure, so a more accurate reading can be obtained. It is used where very small pressure differentials must be measured, such as boiler draft and furnace pressure. The inclined manometer is also used to calibrate other pressure measuring devices. The pressure due to the vertical height of a manometer, h, is equivalent to the difference in pressure between P_1 and P_2, where P_2 often represents the atmospheric pressure.

Figure 2 – Inclined Manometer



Barometers

The earth's atmosphere consists of a mixture of gases extending to an altitude of about 75 km. This atmospheric gas mixture has a mass that exerts a pressure of approximately 101.3 kPa on the earth's surface, at sea level. Atmospheric pressure varies with the elevation above sea level, and daily, depending on weather conditions.

One way to measure atmospheric pressure is with a mercury barometer. It consists of a glass tube of uniform bore, approximately 900 mm long, with one end sealed. Refer to Figure 3. The tube is first completely filled with mercury. It is then inverted with the open end submerged in an open dish of mercury. The pressure exerted by the column of mercury, h, is balanced by the pressure of the atmosphere.

Figure 3 – Inverted Mercury Column

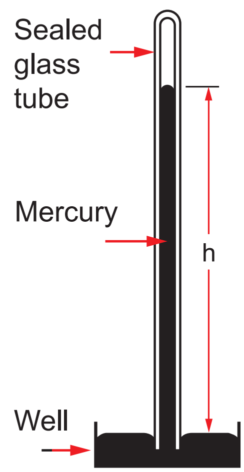
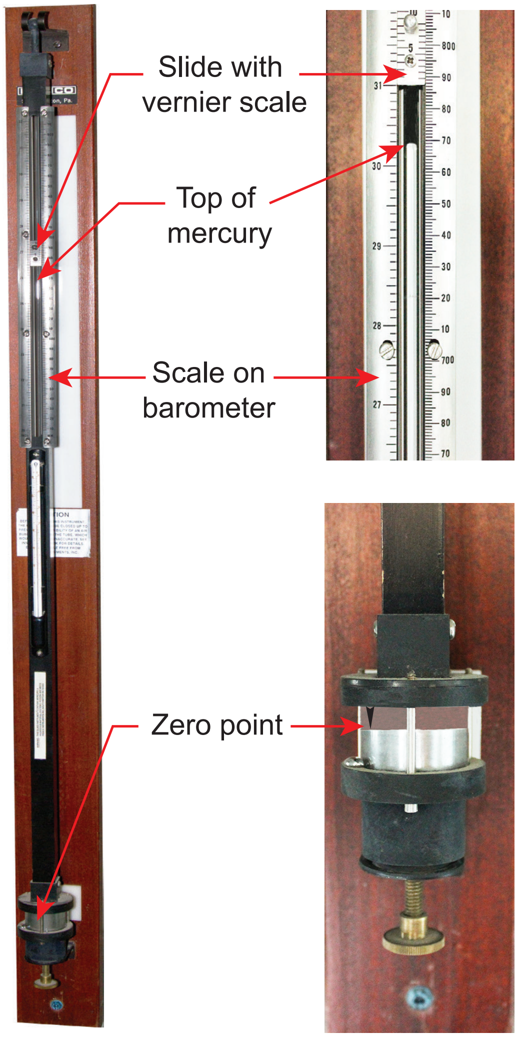


Figure 4 shows the components of an actual mercury barometer. As seen, the mercury barometer is essentially a manometer. Atmospheric pressure is exerted on the surface of the mercury in the well. The surface of the mercury in the sealed glass tube is exposed to a vacuum. In this manner, a barometer measures absolute atmospheric pressure.

Figure 4 – Mercury Barometer



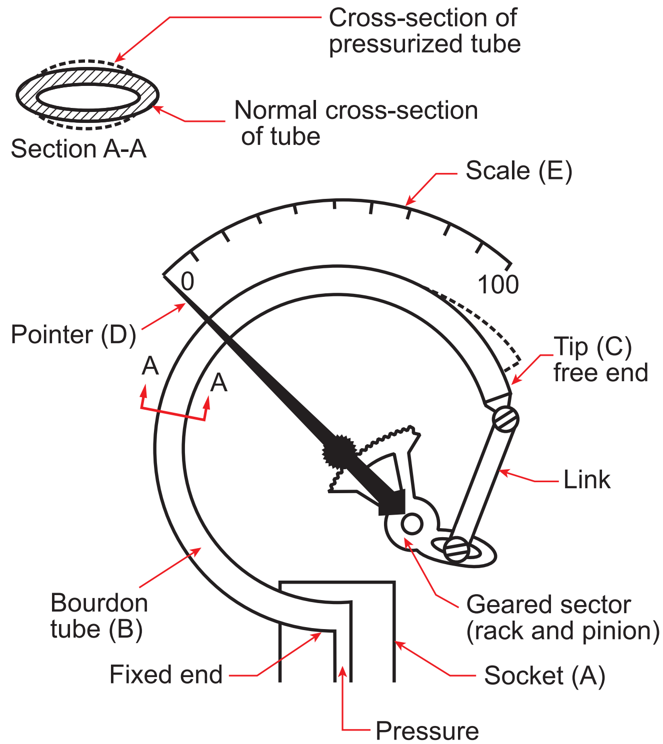
Mercury barometer   Bowl of barometer

Bourdon Tube Gauge

The **bourdon tube** pressure gauge consists of an oval tube in the form of the letter "C," with an arc of about 270°. The free end of the tube in Figure 5 is sealed. The other end is connected to the pressure source through a socket. When pressure is applied to the inside of the tube, the tube becomes slightly more circular in cross section, as shown by the dotted lines in Section A-A. As the tube becomes more circular in cross section, it straightens out slightly, causing the free end to move. This somewhat linear motion of the free end is transmitted through a link to a geared sector and pinion that causes rotation of the pointer. If the applied pressure decreases, the tube will act like a spring, and return to its original shape.

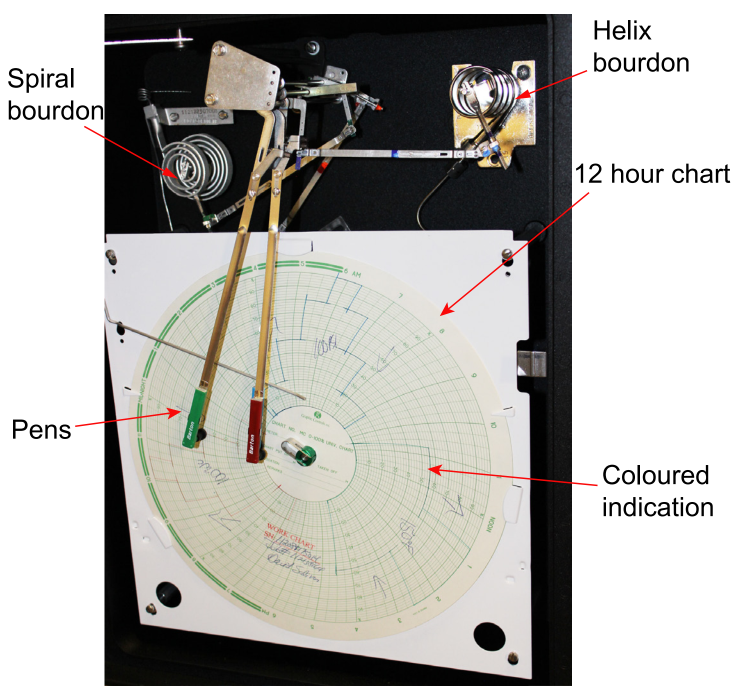
Bourdon tube **pressure gauges** are available in many pressure ranges. Gauges are selected so that normal process pressures occur mid-scale on the gauge, where the gauge has its greatest accuracy. As well, when a typical process pressure is shown mid-range on a pressure gauge, its needle points directly upward. This gives a quick visual indication that the pressure is "normal."

Figure 5 – Bourdon Tube Gauge



A bourdon tube can also be shaped in the form of a spiral or helix, as illustrated in Figure 6. These types are used to develop sufficient power and rotation to position a pen directly on a chart, without the use of gears. A greater degree of rotation is achieved as more windings are added.

Figure 6 – Circular Chart Recorder with Spiral and Helical Bourdon Tubes



The bourdon tube gauge is generally a stand-alone device. It is more versatile and rugged than the manometer, and is probably the most commonly used instrument in industry.

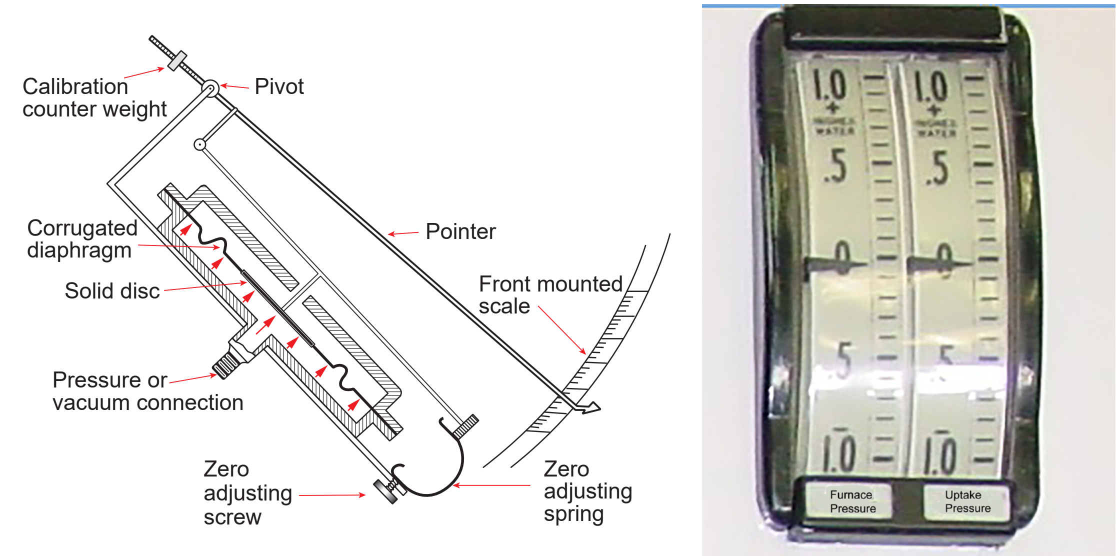
Diaphragm Elements

Bourdon tube gauges are not well suited to low pressure ranges because of the stiffness of their metal parts. A diaphragm element gauge, using more flexible material, can be used in low-pressure applications.

Diaphragms are made of materials such as leather, cotton lined rubber, silk, copper, and stainless steel, depending upon the pressure applied and the temperature of the fluid. The diaphragm is a flat flexible disc. Some discs have concentric corrugations to increase motion and sensitivity. Non-metallic or “limp” diaphragms are used for pressures from 0 to 0.5 kPa. The metallic types are suitable for pressures of 0 to 2500 kPa.

Figure 7 shows an example of a corrugated diaphragm. If the applied pressure is above atmospheric, the diaphragm is forced upwards, and its motion is transmitted to the pushrod that causes the pointer to rise on the scale. When the applied pressure is below atmospheric, the motion of the diaphragm is reversed, so the pointer moves downward. The motion of the pointer can be increased with a link lever mechanism.

Figure 7 – Diaphragm Type Pressure Indicator



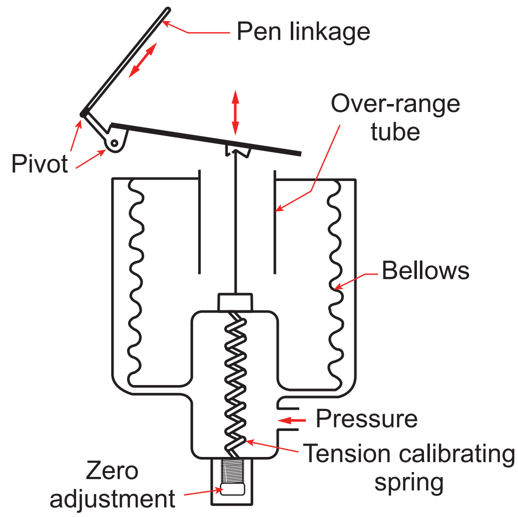
Bellows Element

The bellows element is often used to measure pressure from approximately 250 mm to 35.7 m water head (2.5 to 350 kPa). It consists of a corrugated metal tube that expands in length when pressure is applied internally. Some designs of this device use special calibrating springs (Figure 8) to provide greater accuracy.

The expansion and contraction of a bellows is often used to drive a transducer (i.e. to convert different types of signals). Bellows are commonly used in pneumatic devices to position nozzle and flapper clearances, and in electronic devices to position variable resistors and solenoid cores. Unlike the bourdon tube elements, bellows are often incorporated in control devices rather than as stand-alone devices.

Figure 8 illustrates a bellows used as a low-pressure device. Pressure exerted on the outside of the bellows tends to compress it, stretching the calibration spring. The pressure moves the pen linkage on a chart an amount that is proportional to the applied pressure. When the maximum design pressure is reached, the bellows contacts the over-range tube. This protects the linkage and recording parts from damage.

Figure 8 – Low-Range Bellows Element



Strain Gauges

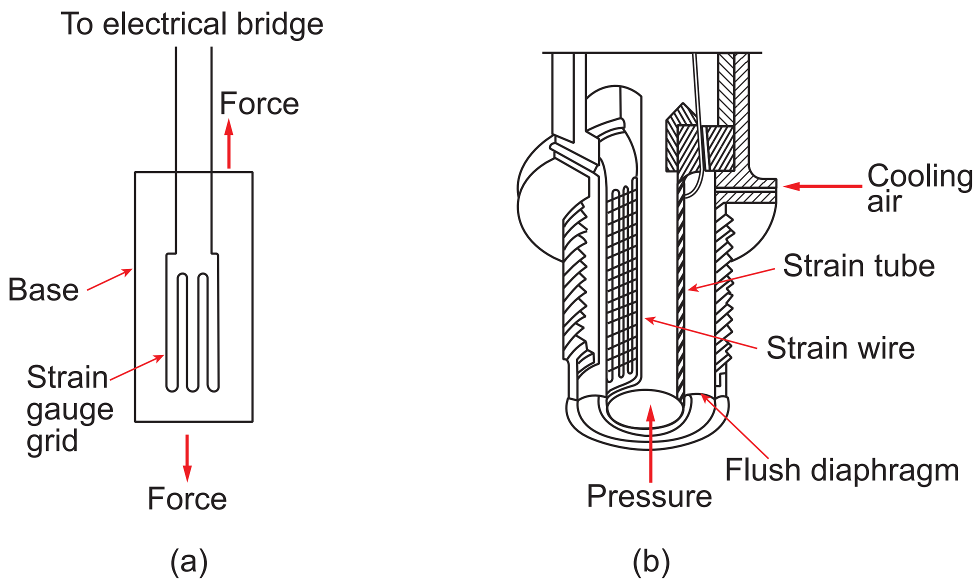
A **strain gauge** is an extremely sensitive transducer that can be used to measure pressure or force exerted on a structure or another type of equipment. This pressure or force is converted into a proportional electrical signal.

The most common type of strain gauge is the resistance type similar to the one in Figure 9(a). It has a fine wire grid, about the size of a small postage stamp, which is cemented to a paper or plastic base. This base is then bonded firmly to the column or shaft on which the force is measured.

When a tensile force is applied, the wire grid will increase in length, while its cross-sectional area will decrease. These two physical changes cause the electrical resistance of the conductor to increase. If the conductor is part of the **Wheatstone bridge** circuit, the voltage imbalance across the bridge will be proportional to the pressure or force. Since the output of a strain gauge is electrical, these devices are well suited as sensing elements for control loops that use electronic signals.

Figure 9(b) shows a strain gauge that can be used to measure the pressure in a cylinder. A change in pressure on the flush diaphragm varies the compressive force on the tube on which the strain gauge is bonded. This causes a proportional change in the electrical resistance of the strain gauge. The imbalance of voltage across the bridge is amplified to provide sufficient power to operate a controller or a recorder.

Figure 9 – Strain Gauges

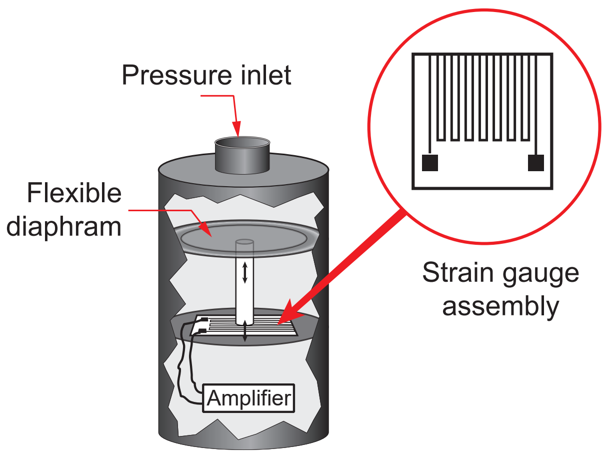


Pressure Sensors

An electronic pressure sensor is usually a transmitter that converts pressure changes into a variable voltage, current, or resistance that can be used by an electronic controller. The bourdon tubes, diaphragms, and bellows already discussed can be combined with variable resistors, **piezoelectric** devices, or strain gauges to transmit pressure variations to controllers.

Figure 10 shows a pressure sensitive flexible diaphragm with an attached strain gauge. The strain gauge resistance changes when pressure causes the diaphragm to flex. The slight changes in resistance are detected, amplified, and transmitted to a control device. The sensor thus becomes a transmitter.

Figure 10 – Resistance Type Pressure Sensor

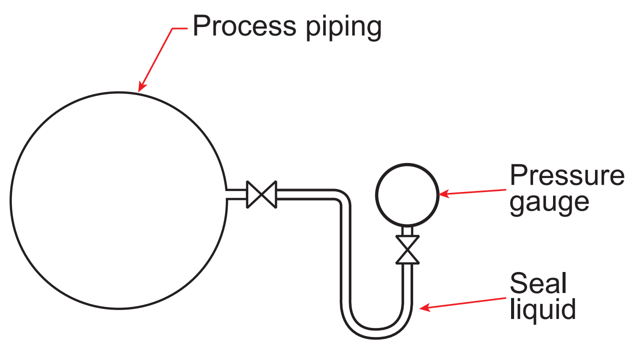


Protecting Pressure Sensing Elements from Process Conditions

Special devices are used to protect pressure-sensing elements against such conditions as high temperature, cyclic pressures, vibrations, and corrosive or congealing fluids.

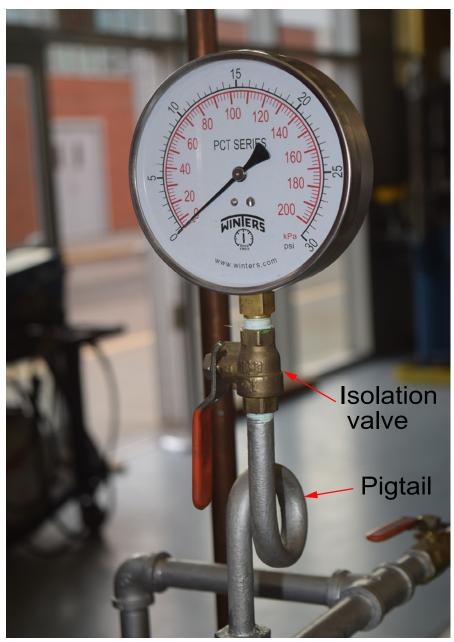
The inexpensive device shown in Figure 11 has a U-shaped tube filled with a sealing fluid that prevents process fluid from entering the pressure-sensing pipe and the sensor. The seal fluid must have a greater density than the process fluid for this system to work.

Figure 11 – Pressure Sensor Liquid Seal



Steam pressure gauges are installed with **siphons** (commonly called **pigtails**) (Figure 12). Siphons function the same as liquid seals, like that shown in Figure 11. However, siphons are shaped in a spiral pattern instead of a "U".

Figure 12 – Pressure Gauge Mounted on a "Pigtail" Siphon

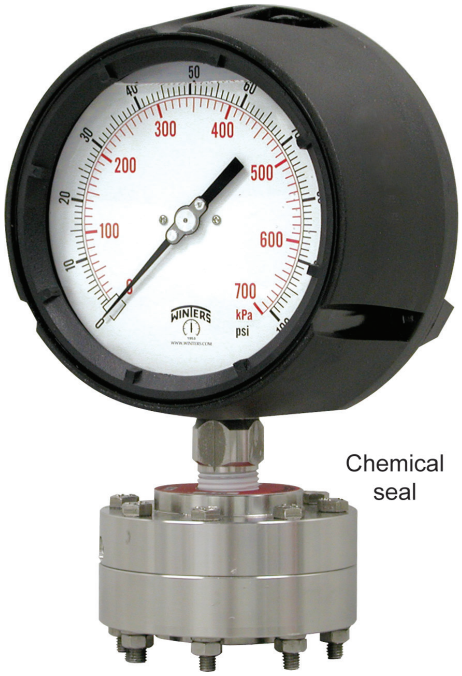


The pigtail siphon maintains a water seal between the steam in the boiler and the bourdon tube in the pressure gauge. This seal prevents steam from entering the bourdon tube: the high temperature of the steam affects the accuracy of the gauge, and can have a detrimental effect on the gauge material.

When installing a gauge and siphon on a boiler, it is important to first fill the siphon with water. This prevents steam from reaching the bourdon tube.

A chemical seal containing a diaphragm (Figure 13) can also be used to protect a pressure-sensing device from process fluids. The chemical seal is made of a diaphragm sandwiched between two flanges. The space above the diaphragm contains sealing fluid. The diaphragm prevents process fluid from entering the pressure sensor.

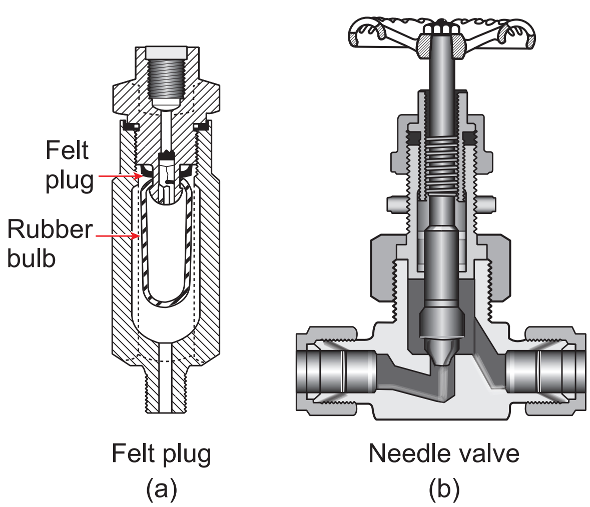
Figure 13 – Diaphragm-Style Chemical Seal



(Courtesy of Winters)

In many different processes, equipment such as reciprocating and metering pumps may produce damaging pressure pulsations. This effect can be lessened by a **pulsation dampener** (or **snubber**), as shown in Figure 14.

Figure 14 – Line Pulsation Dampeners – Felt Plug and Needle Valve



The pulsation dampener in Figure 14(a) consists of a glycerin-filled rubber bulb and a felt plug that connect to a pressure gauge. When the pressure from the process fluid increases, the rubber bulb is compressed. This causes the glycerin to be forced through the felt plug, which restricts the flow. The degree of damping depends on the compression of the felt plug that is adjusted before the bulb is filled with glycerin.

Another practical means of restricting pulsations in the line leading to the pressure gauge can be achieved by means of a needle valve (Figure 14(b)), which is placed between the pressure source and the gauge.

Pressure Gauge Testing

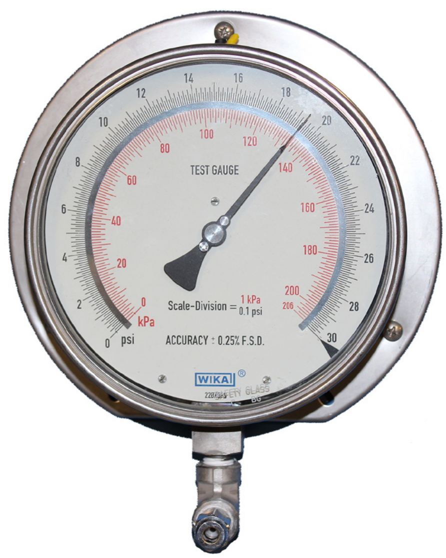
Pressure gauges may lose their accuracy due to wear and tear in the moving parts, metal fatigue of the bourdon tube, excessive vibration, or abuse. In many cases, loss of accuracy becomes obvious when the pointer does not return to the zero mark after the pressure is released. Some of the methods used to check the accuracy of pressure gauges include:

- Test gauge (master gauge) comparison
- Dead-weight tester
- Hydraulic comparator

Test Gauge Comparison

A boiler pressure gauge may be tested while the boiler is in service by connecting an accurate **test** (or **master**) **pressure gauge** to the test connection, and comparing the reading of the boiler gauge to that of the test gauge. This is done by boiler inspectors during their inspections. However, this method only compares the gauges at a particular boiler operating pressure, not over the entire measuring range of the gauge. Figure 15 shows a test gauge for pressures up to 200 kPa.

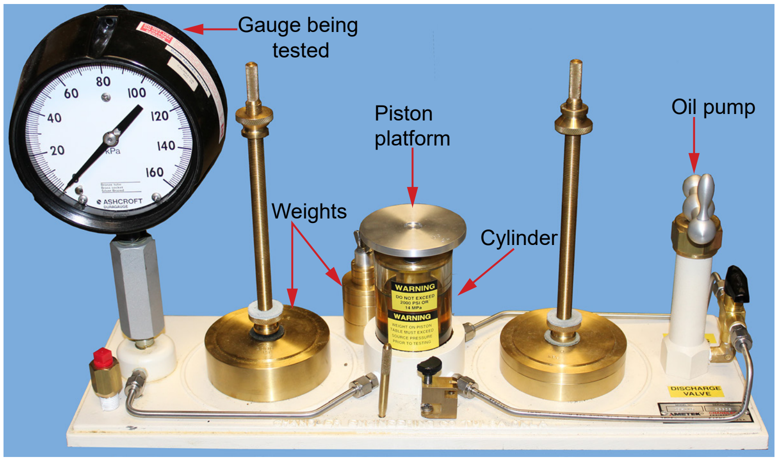
Figure 15 – Master Pressure Gauge



Dead Weight Tester

Dead weight testers (Figure 16) check the accuracy of pressure gauges through their entire measurement ranges. A dead weight tester consists of a hydraulic cylinder filled with oil, a hand pump, and a piston and platform assembly. A number of accurately machined weights are supplied, which fit upon the platform.

Figure 16 – Dead Weight Tester



The gauge to be tested must be removed from the boiler and connected to the dead weight tester. The oil pump is then operated to increase the pressure in the cylinder sufficiently to raise the piston platform assembly off its bottom stop. The force exerted on the oil by the weight of the piston-platform assembly is equal to the force exerted by the pressurized oil acting upon the piston. In other words, the oil under pressure balances the platform assembly. This pressure will be indicated on the gauge.

By placing weights (which are stamped in equivalent units of pressure, rather than mass) on the platform, the pressure in the cylinder may be increased. The pressure shown by the gauge should increase accordingly, if the gauge is accurate.

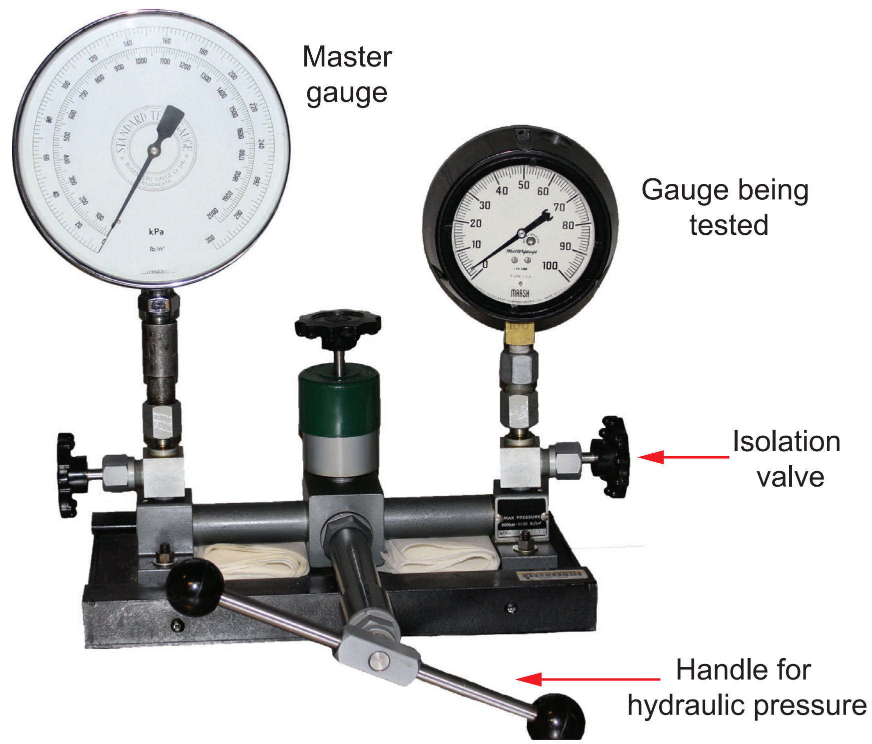
For example, if the weight of the piston-platform assembly has a pressure equivalent of 50 kPa, the gauge will indicate 50 kPa at the beginning of the test. If weights with a 100 kPa pressure equivalent are placed one-by-one on the platform, the gauge pressure should increase by 100 kPa steps until the end of the pressure range is reached.

When performing the test, the platform and piston assembly should be rotated slightly to reduce the effect of friction between piston and cylinder.

Hydraulic Comparator

A less accurate, but still valid method of testing a pressure gauge is by using a **hydraulic comparator** (Figure 17). Both the gauge to be tested and a master gauge are attached to a cylinder. Pressure is produced within the cylinder with a hand pump, and the readings of the two gauges are compared. The accuracy of this method depends on the accuracy of the master gauge.

Figure 17 – Hydraulic Comparator



In both the dead weight tester and the hydraulic comparator, the liquid used to transmit the pressure is usually a medium-weight oil.

Any plant that is in a remote location, or uses a large number of pressure gauges, should have a comparator or a dead weight tester for pressure instrument calibration. However, many smaller plants do not have this testing equipment. In this case, the operator is advised to send the gauges out for regular calibration to a reputable firm that specializes in this type of work.

OBJECTIVE 2

Describe the types of level sensing and measuring devices.

LEVEL MEASUREMENT

Power Engineers regularly monitor and record important levels, including boiler water level, fuel tank level, storage tank level, and others. Some instruments, such as **gauge glasses**, only indicate level. Other level sensing instruments transmit signals to remote indicators and control systems.

Liquid level sensing may be categorized as:

- Single point level detection
- Continuous level monitoring

In single point level detection, the presence of the process material is detected at predetermined levels. Depending on the process, single point detection can be used to start or stop pumps, open or close control valves, trip off equipment, or to sound alarms.

For uninterrupted level measurement, continuous level monitoring is used. In this case, the level of the process material is constantly monitored. A level signal may then be transmitted for monitoring, recording, or control purposes.

Level measurements can be direct or indirect. A direct measurement might involve placing a float on the process fluid surface and tracking its motion. Indirect methods may involve inferring level based upon pressure changes due to changes in height of process fluid.

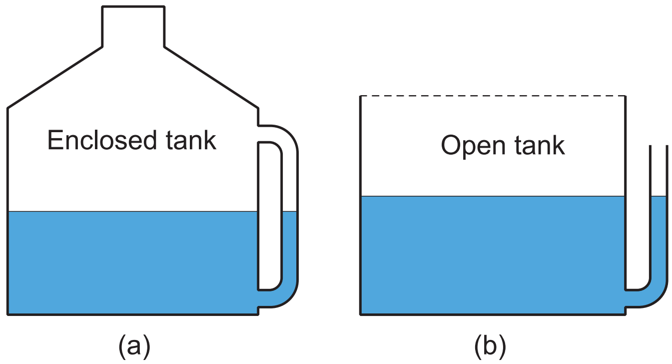
Direct Level Measurement

Gauge Glasses

The gauge glass is the simplest and most common level indicator used in industry. It provides direct visual indication of the process fluid level. Power Engineers will find them installed on refrigeration system liquid receivers, boiler steam drums, lube oil tanks, expansion tanks, and steam separators, to name a few.

If the gauge glass is installed on a pressurized container, a container under vacuum, or a sealed vessel containing toxic, volatile or flammable materials, it will be installed with gasketed leak-tight connections at both ends (Figure 18(a)). The top of the gauge glass will be installed to the vapour space of the vessel, and the bottom to the liquid space. If the vessel is an open tank, only the bottom of the gauge glass needs to be connected (Figure 18(b)). The top may be left exposed to the atmosphere.

Figure 18 – Gauge Glass Applications



Gauge glasses are equipped with valves to permit their isolation and replacement should they break. Some of the isolation valves contain mechanisms to automatically stop process liquid flow from a broken gauge glass. Most gauge glasses have protective shields or barriers to prevent their accidental breakage.

Gauge glasses are available in a variety of styles for various pressure applications.

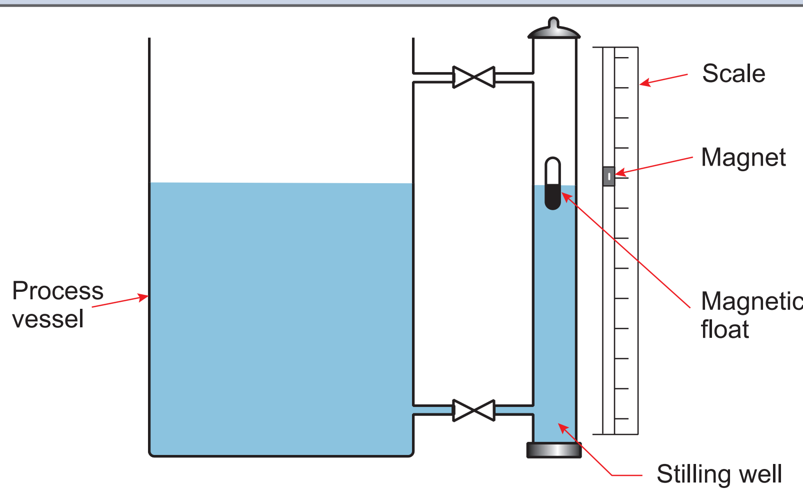
Magnetic Float Gauge

Certain toxic or corrosive materials attack conventional gauge glass gaskets. As well, certain process chemicals attack glass, making conventional gauge glasses unsuitable. In these situations, magnetic float indicators can be used.

Figure 19 shows a magnetic float that is free to travel vertically in a tubular housing made of non-magnetic material, such as stainless steel. The non-magnetic tube is connected to the vapour space and liquid space of a vessel. This housing is sometimes called a stilling well because its isolation valves can be throttled to dampen wave action or level fluctuation in the process vessel. An indicator is magnetically coupled to the float and travels freely up and down an externally mounted scale, following the changes in the process vessel level. The level is read directly from the scale at the location of the magnetic indicator.

The magnetic float can also be configured to operate level control or alarm switches.

Figure 19 – Magnetic Float



Float-Type Level Measurement

Another direct level measurement and indication method commonly used in open tanks is shown in Figure 20(a). The float is attached to a weight by means of cables and pulleys. The float is located inside the tank, while the weight hangs outside, beside a scale marked in units of level. The float is heavier than the weight, but less dense than the process fluid being measured.

Figure 20 – Float-Type Level Measurement and Control

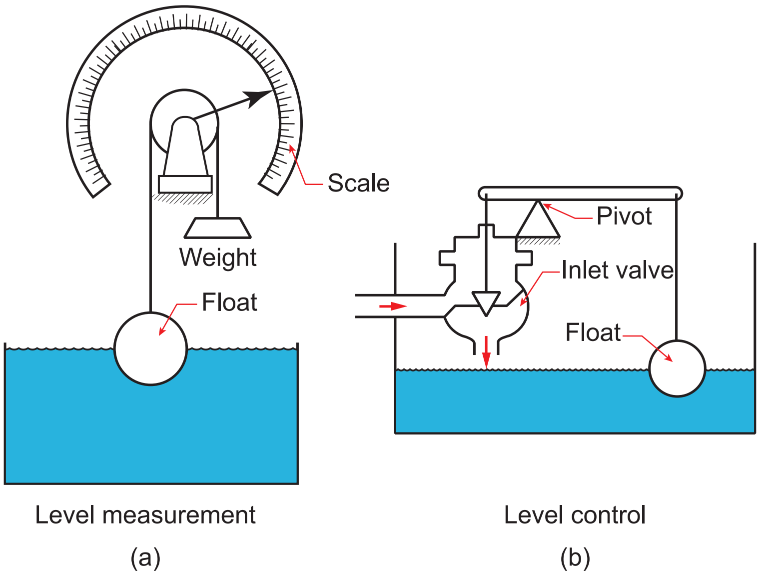
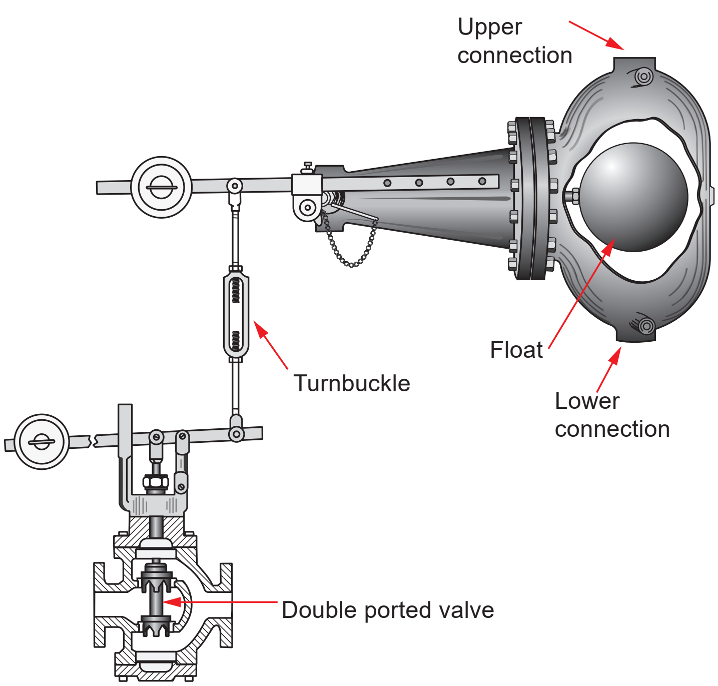


Figure 20(b) shows a float-type level control system where a float positions an inlet valve through a linkage arrangement. By moving the pivot to the left, a greater change in level is required to produce the full range of valve motion.

When it is not practical to have a float in a vessel or tank, a **float cage** (Figure 21) is mounted on the outside, with the bottom part connected to the liquid space, and the top to the vapour space. If the level in the vessel increases, the float rises to open the control valve further so more liquid will flow from the vessel. Note that the cage will be under the same pressure as that in the vessel. Similar float arrangements can be connected to a boiler drum where the float may operate a switch to start and stop a feedwater pump, and to operate a low water-level fuel cut-off in case the boiler water becomes dangerously low.

Figure 21 – Float Cage Unit

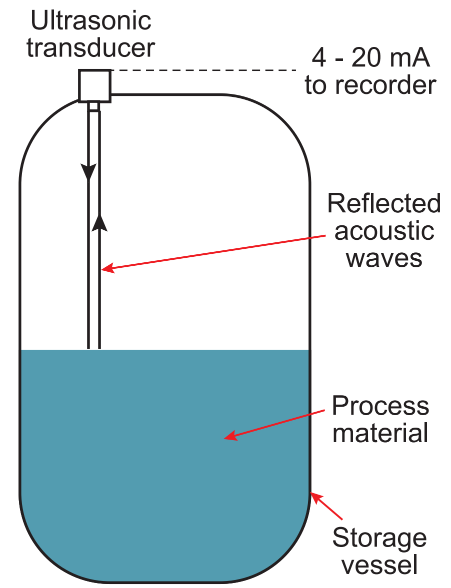


Ultrasonic Transducers

Ultrasonic transducers can be used to provide direct, continuous, or single-point level measurements. Their advantage is that they do not need to physically contact the process fluid. This is especially important in applications that contain process fluids that are corrosive, contain suspended solids, or may create troublesome coatings on instruments.

Ultrasonic level transducers (Figure 22) may be used to measure level, volume, or open-channel flow.

Figure 22 – Ultrasonic Level Transmitter



The level measurement is made by emitting an ultrasonic pulse from the transducer, then measuring the time required for the echo to reflect from the liquid surface and return to the transducer. Sophisticated electronics measure the time of the round trip pulse and, by knowing the speed of sound, calculate the distance. Since speed of sound is temperature dependent, the transducer also measures the temperature in the vessel to compensate for changing temperature.

By inputting the type and geometry of the vessel, the intelligent electronics can calculate the liquid volume in the vessel. In a similar operation, the ultrasonic level sensor can perform open channel flow measurement by converting the level reading into units of volume per time. Common tank, **flume**, and **weir** shapes can be stored in the device's software.

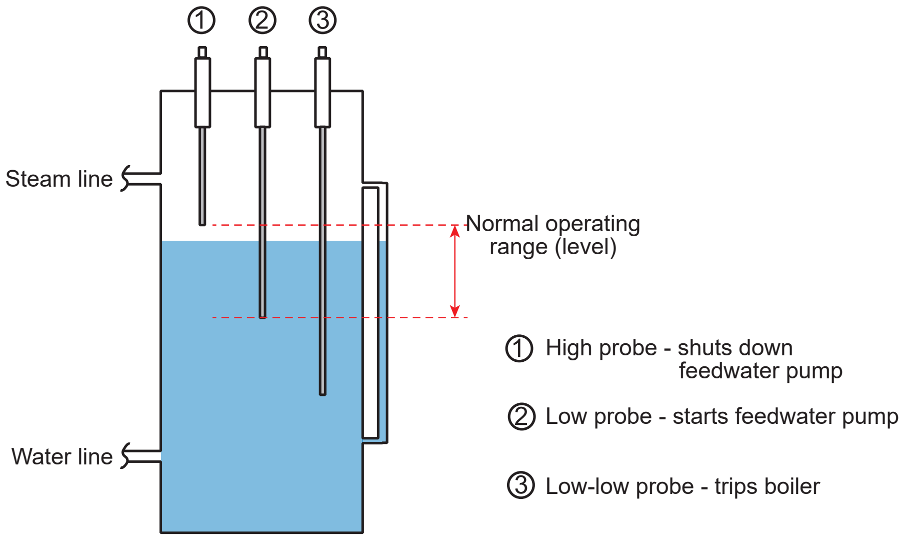
Conductance (Conductivity) Probes

Conductivity sensors work on the principle that many process fluids (including boiler water) conduct electricity. The probes can be thought of as poles of a switch, and the process fluid as the blade that opens or closes the switch. As levels change, probes of various lengths become submerged consecutively in conductive process fluid. If the level drops below the bottom of a probe, the current flow will be interrupted, and the circuit will open. The circuit will close again when the level rises above the bottom of the probe.

Conductivity probes may also be used to generate a digital process control signal, based on the process fluid level. These probes are ideal for point level detection of conductive liquids such as water, caustic soda, and sulfuric acid.

Conductivity probes provide reliable service where point level detection or control is desired. The voltage used with these probes is selected based on the conductivity of the process fluid. Higher liquid conductivity requires lower voltage than liquids with lower conductivity. If the vessel is made of conductive material, such as steel, the vessel itself can be used as one of the sensing probes.

Figure 23 – Conductive Level Probe System



Water column level probes (conductivity)

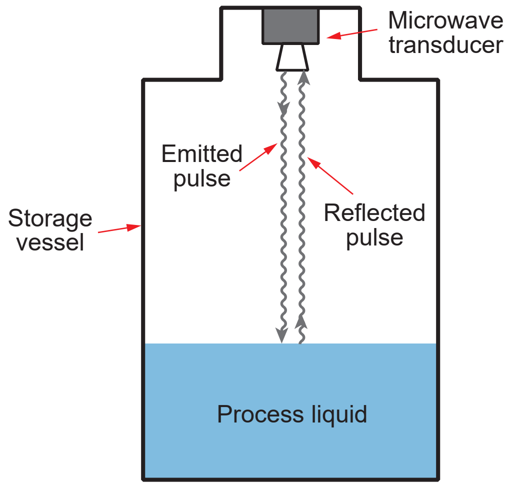
Conductivity level sensors or probes may be used to start and stop feedwater pumps on small boilers, signal process alarms, or instigate process equipment trips. Figure 23 shows conductance probes installed in the water column of a steam boiler where the operating level is kept between the two upper conductance probes. If the level drops below the lowest probe, the boiler burner circuit opens, shutting the boiler fuel valves.

Conductivity probes used with corrosive liquids are manufactured from special metals. Conductance probes have not historically been used in the chemical processing industry, because they may release sparks when approached by conductive fluids. Recently, though, solid-state designs have been made for **intrinsically safe** service.

Radar or Microwave Transducers

Radar (or **microwave**) level sensors work similarly to ultrasonic sensors (Figure 24). Instead of using ultrasonic signals, though, they transmit electromagnetic waves with a frequency of around 10 GHz. These waves reflect back to the sensor when they reach the surface of the process fluid being measured. The time taken for the wave to travel to the liquid surface and back to the transducer indicates the level in the vessel.

Figure 24 – Radar or Microwave Level Detection System



Non-invasive radar level measurement

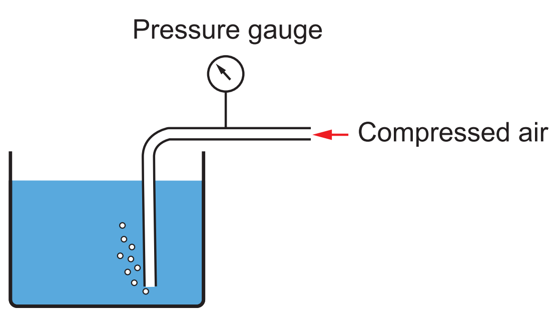
Radar level measurement is highly accurate. It does not require direct contact with the process fluid. Radar transducers are not affected by dust, vapours, or moisture. Unlike ultrasonic transducers, radar transducers can operate in a vacuum.

Indirect Level Measurement

Bubblers

The simplest way to indirectly measure liquid level is to measure the pressure of the liquid at the base of the vessel. To do this, a supply of clean air (or inert gas) is forced through a submerged tube near the base of a vessel. For this method to work the vessel must remain at atmospheric pressure; therefore, its use is restricted to vented or open vessels. Figure 25 shows a simple bubbler system.

Figure 25 – Bubbler



Air is fed into the air line with only enough pressure to cause bubbles to exit the end of the submerged tube. A pressure gauge mounted on the air line reads the hydrostatic pressure of the liquid above the bubble tube opening. If the density of the liquid is known, the pressure can be converted to height (or depth) in metres. Some pressure gauge dials are directly calibrated in liquid depth.

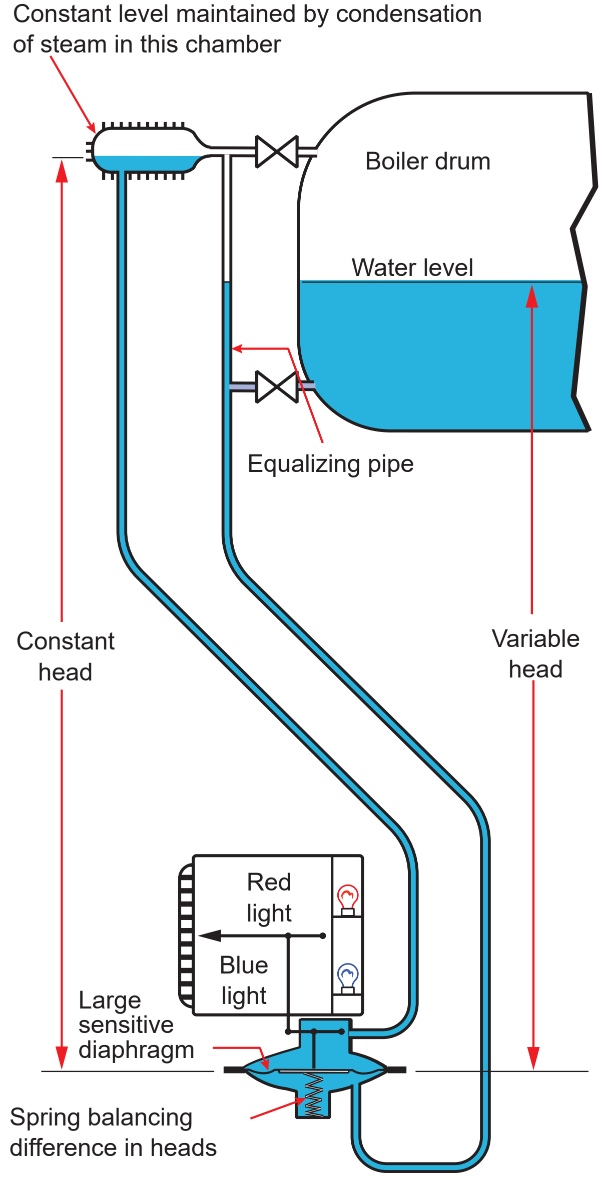
Diaphragm-Type Differential Pressure Level Indicator

Figure 26 shows a level indicator that can be placed in a remote location when a boiler steam drum is higher than the operating floor, and the level gauge (gauge glass) on the steam drum is not visible from the operating floor.

This indicator has a large diaphragm with the upper side connected to the steam space, and the lower side to the water space of the boiler. A **condensing pot** at the boiler drum maintains a fixed head of water or pressure on the upper side of the diaphragm. The lower side is subjected to a varying hydrostatic head as a function of the water level in the boiler. The difference in pressure due to the liquid head between the two sides of the diaphragm is balanced by a spring, so the diaphragm moves in accordance with the water level.

As the water level rises in the drum, the pressure under the diaphragm increases causing it to rise, moving the indicator upwards. Full boiler pressure is exerted on both sides of the diaphragm, so the boiler pressure has no effect on the movement of the indicator. The equalizer pipe ensures that if either the steam connection or the water connection isolation valves are shut, pressure imbalance will not damage the differential pressure assembly (diaphragm, spring, and linkages).

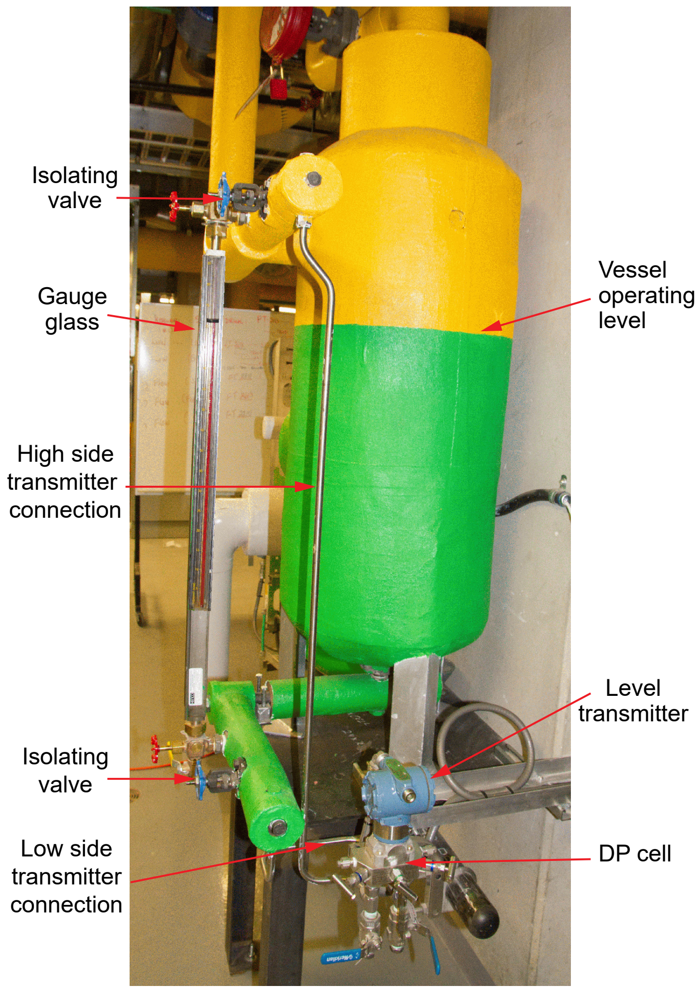
Figure 26 – Remote Water-Level Indicator



Differential Pressure Level Measurement

Figure 27 shows a small vessel that has a water level in the lower section and steam above the water. A gauge glass indicates the water level to the operator. As well, there is a **differential pressure sensor** (**DP-cell**), with a transmitter that provides level information to a controller. The "High Side Transmitter Connection" is filled completely with water, and provides a constant head (or **reference head**) to the DP-cell. The "Low Side Transmitter Connection" pressure varies with the level in the vessel. A diaphragm inside the DP-cell moves with changes in level and varies the transmitter output signal.

Figure 27 – Differential Pressure Level Measurement



If a DP-cell transmitter is used to measure level in an open tank, then one side of the DP-cell bellows is connected to the bottom of the tank, and another port is left open to the atmosphere. This setup will accurately detect and measure the liquid level as function of the hydrostatic head in an atmospheric vessel.

Objective 3

Describe the types of flow sensing and measuring devices.

Flow Measurement

Flow is one of the most widely measured process variables. In power plants, feedwater, makeup water, steam and fuel flows are essential for determining and optimizing plant operating conditions. Many methods are used to measure flow. The instruments used must be suited to the temperature, pressure, density, and cleanliness of the fluid being measured. Here, the most common flow instruments are discussed.

Nutating Disk Meter

A **nutating disc meter**, as shown in Figure 28, has a flat circular disc with a ball-like structure at the center. The bottom part of the ball rests in a socket, while the top center of the ball has a small shaft that turns a gear. The gear drives small dials that rotate to indicate flow (in, say litres/minute), and a counter (or integrator) that totalizes the actual flow (in say m^3).

The flat disc has a slot with a fixed vertical partition. This division plate directs the fluid flow through the meter from the inlet to the outlet. When fluid flows through the meter, the disc wobbles on its ball and socket. This causes the small shaft to nutate; it follows a circular path around the centre of the plate.

Each nutation of the wobble disc permits a discrete volume of fluid to pass through. The rate at which the plate wobbles is proportional to the volumetric flow rate of the fluid.

These meters are commonly used to measure the flow of clean water. Typical power plant applications include measuring:

- Building potable water flow
- Cooling tower makeup water flow
- Boiler water makeup flow

Nutating discs are not suitable for high pressure or high temperature service. Typically, they are limited to 1035 kPa and 120°C. As well, they are not suitable for slurries, dirty fluids, or viscous fluids. Many nutating disc meters are equipped with digital operating heads and transmitters to provide consumption information to central control stations.

Figure 28 – Nutating Disc Flow Meter Operation

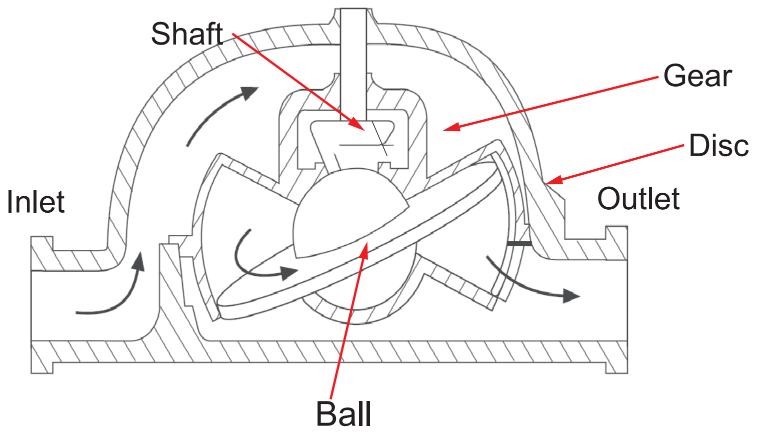
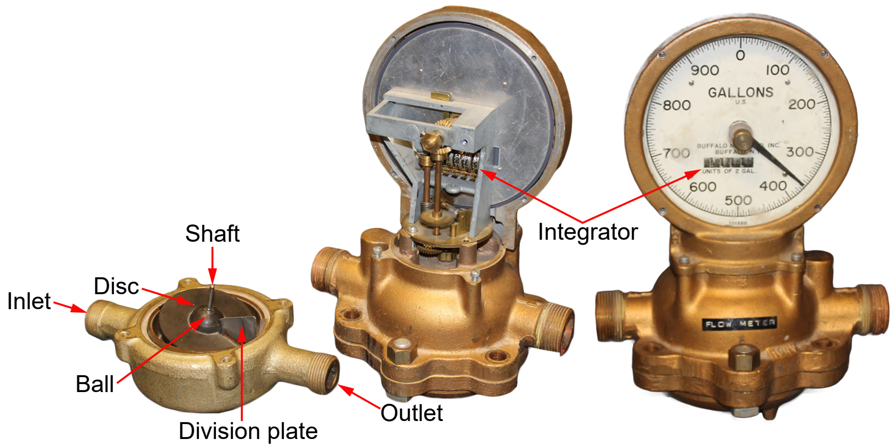


Figure 29 shows two disassembled nutating disc meters. On the left-hand image, the operating head has been removed. The nutating disc, ball, and shaft can be clearly seen. In the right-hand image, the head is in place, and the gear drive for the integrator mechanism is visible.

Figure 29 – Nutating Disc Flow Meter



Head meters

Head type or differential pressure flow meters include a number of sensing devices for fluid flow measurement, such as **orifice plates**, **venturi tubes**, **flow nozzles**, and **pitot tubes**. Orifice plates, venturi tubes, and flow nozzles cause restriction in flow, which causes pressure to decrease across the restriction.

The pressure difference across the restriction is related to the fluid velocity and the flow rate. If the net cross-sectional area of the fluid stream is reduced, the velocity of flow increases. This results in an increase in kinetic energy. Since energy cannot be created or destroyed, the increase in kinetic energy comes as a result of a decrease in potential energy (pressure) downstream of the restriction.

Orifice Plates

An orifice plate (Figure 30) is the most common form of head meter that is used in flow measurement. It consists of a flat metal plate with an opening of a fixed area. The concentric type, shown in Figure 30(a), is the most common. The eccentric and segmental in Figures 30(b) and 30(c) are used in special applications. The outside of the plate is designed to fit inside the bolt circle on standard flanges.

Figure 30 – Orifice Plates

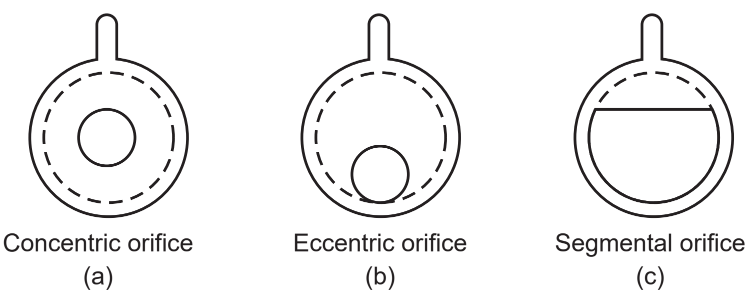
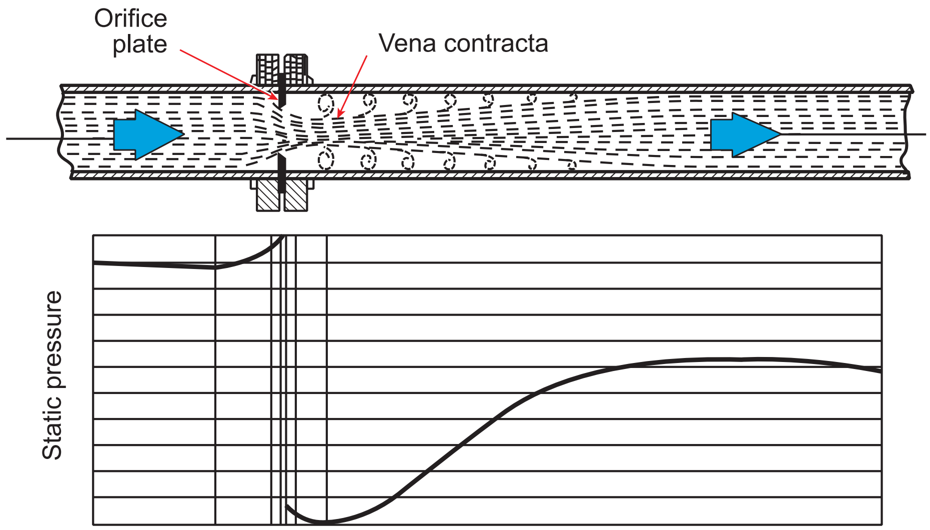


Figure 31 illustrates the pressure drop (the differential pressure) across an orifice plate. Note that the flow pattern decreases in cross-section, downstream of the plate. The point of maximum fluid velocity and greatest static pressure drop occurs at the narrowest point of flow, which is called the **vena contracta**. Downstream of the vena contracta, some of the pressure recovers to its previous value. However, turbulence and friction create a significant permanent pressure loss.

Figure 31 – Pressure Drop Across an Orifice Plate



The pressure differential across an orifice is measured using two pressure connections, one upstream of the plate, and another downstream. Figures 32(a) and 32(b) show two types of connections. In Figure 32(a), the pressure connections (called taps) are located directly on the flanges, while in Figure 32(b) the taps are located on the pipe at a specific distance from the orifice plate.

Figure 32 – Flange and Pipe Taps

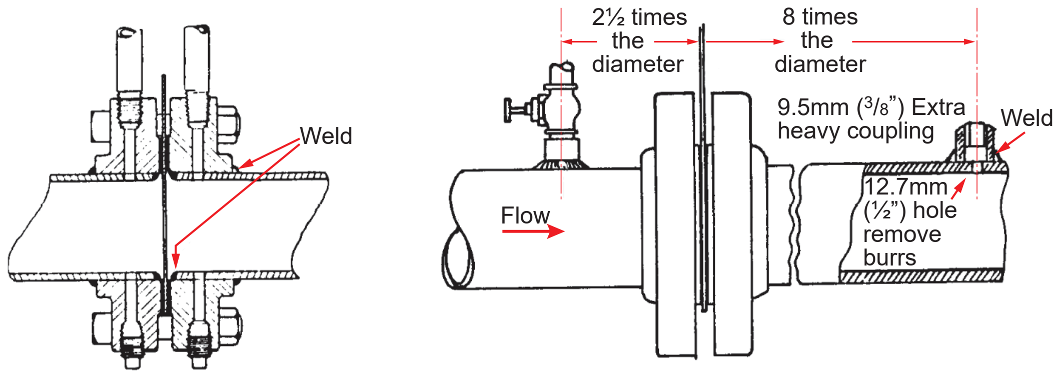


Figure 33 – Pipe Flange

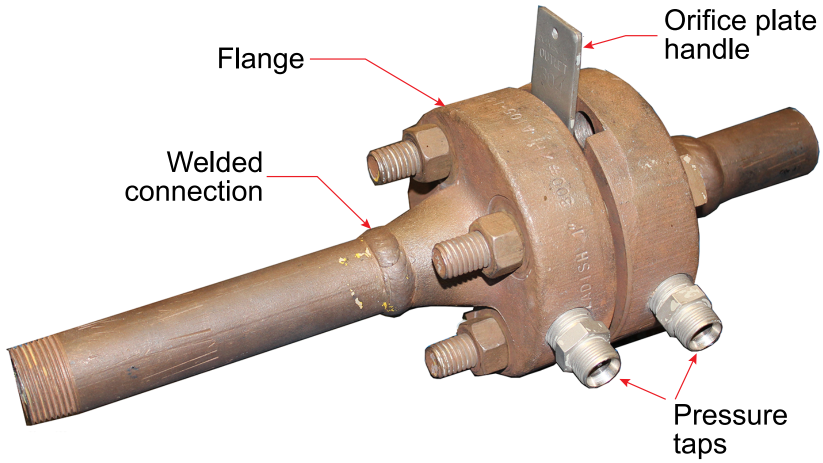


Figure 33 shows a pipe flange with an installed orifice plate and flange taps.

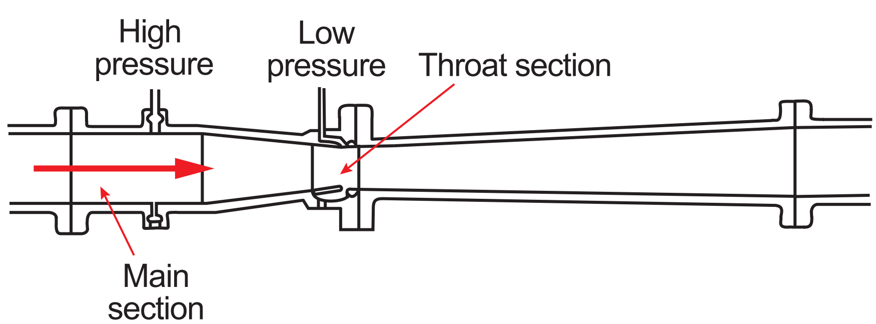
Orifice plates are easy to install and replace. They are inexpensive and available in different sizes to suit the required flow range. However, orifice plates are the least accurate flow-sensing element, and create the greatest permanent pressure loss of all the flow-sensing elements.

Venturi Tube

The venturi tube is a carefully designed length of pipe, designed to be installed between pipe flanges (Figure 34). Its cross-sectional area converges to a minimum, called the throat, and then diverges to the original pipe size. High- and low-pressure connections are installed at specific locations as indicated.

The venturi tube produces the least permanent pressure loss than both an orifice plate and the flow nozzle (90% or more of the upstream pressure is recovered downstream). On the other hand, it has the disadvantages of higher cost and bulkiness. Venturi tubes are frequently used to measure large flows of water.

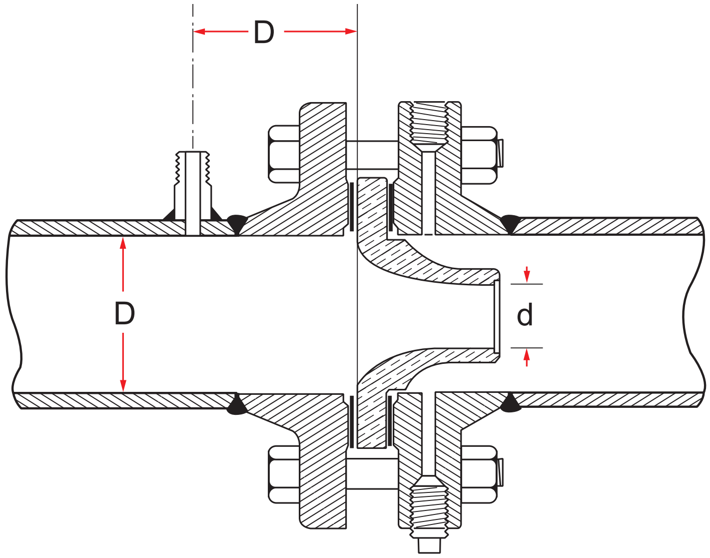
Figure 34 – Venturi Tube



Flow Nozzle

The flow nozzle (Figure 35) is like a venturi tube without the diverging section. Its pressure recovery is better than that of the orifice plate, but not as good as the venturi tube. Flow nozzles are mainly used to measure high velocity flows. The high-pressure connection is located one internal pipe diameter before the inlet face of the nozzle. The low-pressure tap is usually one-half the pipe diameter downstream.

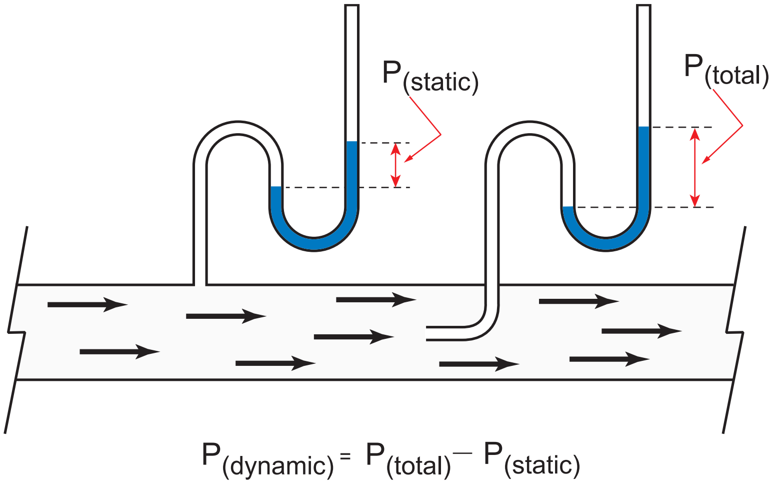
Figure 35 – Flow Nozzle



Pitot Tube

The principle of operation of the pitot tube is shown in Figure 36. The tube on the left measures the static pressure inside the pipe. The tube on the right measures both the static pressure and the pressure due to the fluid velocity. The difference between these two measurements is used to calculate the volumetric fluid flow within the pipe.

Figure 36 – Pitot Tube Measurement Principle



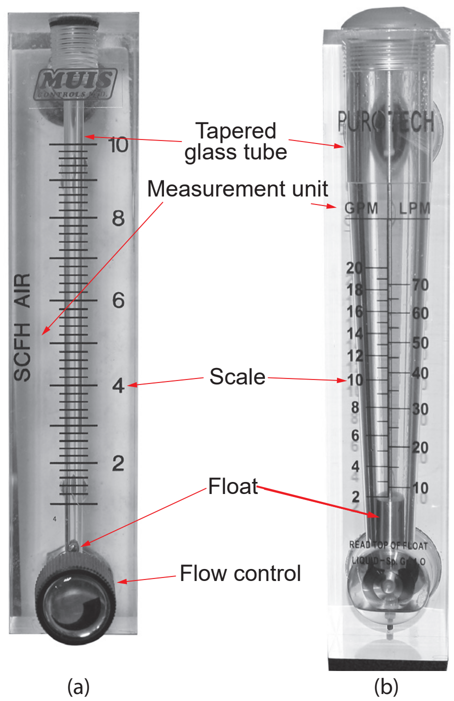
Variable Area Meter

The variable area meter (or **rotameter**) consists of a clear tapered tube marked with a scale. A float inside the tube moves upwards due to the flow of the fluid. As the flow increases, the float moves up the tube until the differential pressure across the float reaches zero.

Figure 37(a) shows a rotameter used to measure and control the flow of air or some other gas. The gas flow can be adjusted by using the flow control knob at the bottom of the tapered tube. An increase in the flow moves the ball float upwards in the tube. The flow rate (in SCFH or standard cubic feet per hour) is read from the scale at the middle of the ball float.

Figure 37(b) is a rotameter used to measure the flow of a liquid. The float moves upward in the tapered tube when flow increases. In this type of meter, the top of the float indicates the flow. The measurement units are shown in GPM (gallons per minute) or LPM (litres per minute).

Figure 37 – Rotameters



Weir

Weirs (Figure 38) are structures used to measure liquid flow. The weir itself is a partial obstruction, often made of metal plate, and placed across an open channel. The weir has a carefully shaped opening or notch that allows liquid to flow through. A float, bubbler, or ultrasonic sensor is placed upstream of the weir to detect the height of water above the base of the weir notch.

The weir causes the height (or head) of the upstream liquid to increase. The flow rate through a weir depends on the head upstream of the weir.

Figure 38 – Weir Flow Measurement Principle

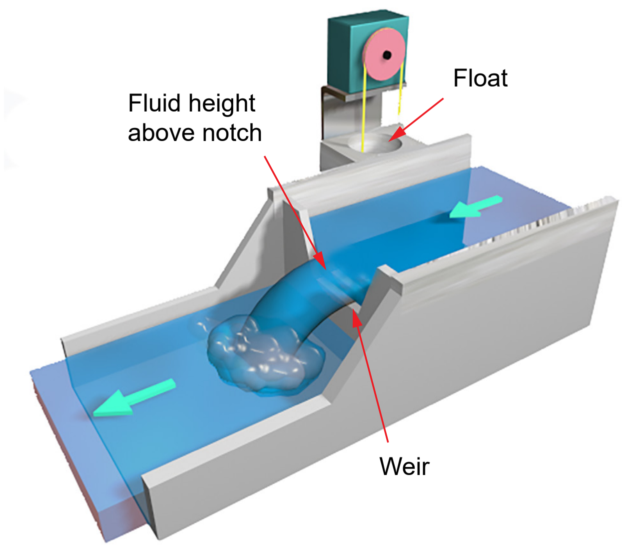


Figure 38 shows a weir with a trapezoidal notch, and a float-type level indicator to measure the height of the upstream liquid.

Weirs can be used to measure the flow of water, wastewater, and sewage. They are not well suited for viscous fluids or slurries.

The base of the weir notch is called the crest. A broad-crested weir has a long crest that runs across the entire flow channel, just below the surface of the water. These weirs are used to measure flows of dam spillways or rivers, and are generally constructed of concrete.

Ultrasonic

Ultrasonic flow meters use ultrasonic transducers to transmit and measure ultrasound passing through a fluid stream. There are two types of ultrasonic flow meters commonly in use:

1. Transit-time flowmeter
2. **Doppler** flowmeter

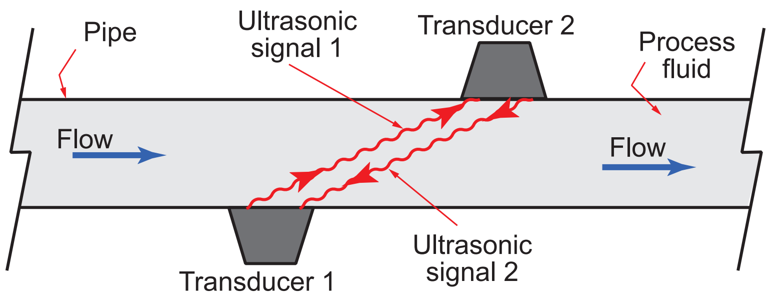
The first type compares the transit time of the sound wave travelling with the liquid flow and the transit time of the sound wave travelling against the flow. The flow measurement is calculated based on the difference between the two transit times. Figure 39 shows an example of a transit-time flowmeter.

The Doppler flowmeter measures the shift in frequency from a sound wave travelling with the flow to a sound wave travelling against the flow (Doppler shift). This method is less accurate than the transit-time measuring system.

The ultrasonic flow meter is accurate and has no moving parts. Ultrasonic transducers may be permanently installed in the pipe, or temporarily attached to the outside of a pipe. If attached to the outside of a pipe, the ultrasonic transducers do not contact the process fluid, which can be a distinct advantage.

These meters are well suited for measuring the flow of gases, clear liquids, and liquids containing sound reflecting particles.

Figure 39 – Ultrasonic Transit-time Flow Meter



Mass Flow Meters

Most flow meters measure the volumetric flow rate. To find the mass flow rate, the volumetric flow rate must be multiplied by the fluid density. This method is fine in many situations. However, if the density of the fluid varies due to changes in temperature, pressure, or composition, this method is very inaccurate.

Mass flow meters compensate for density changes by measuring the mass flowing past a specific point over a unit of time (e.g. kilograms per second). Changes in the density of the fluid will not result in meter inaccuracy.

Figure 40 shows a mass flow meter called a **Coriolis meter**. It has two parallel tubes through which fluid flows. The tubes have a vibration induced into them by an electromagnetic device. The vibration causes the tubes to vibrate toward and away from each other, like a tuning fork. When there is no flow, the distance between the tubes at the inlet will be the same as the distance between the tubes at the outlet. When there is flow through the tubes, the frequency of vibration shifts, changing the distance between the tubes at the inlet and the outlet. The greater the mass passing through the tubes, the greater the difference in the distance between the tubes. This distance between the tubes is measured near the inlet and near the outlet and the difference is used to determine the mass flow rate.

Figure 41 shows a compact Coriolis meter installed in a pipe and with an attached **flow indicator transmitter.**

Figure 40 – Coriolis Flow Meter Principle

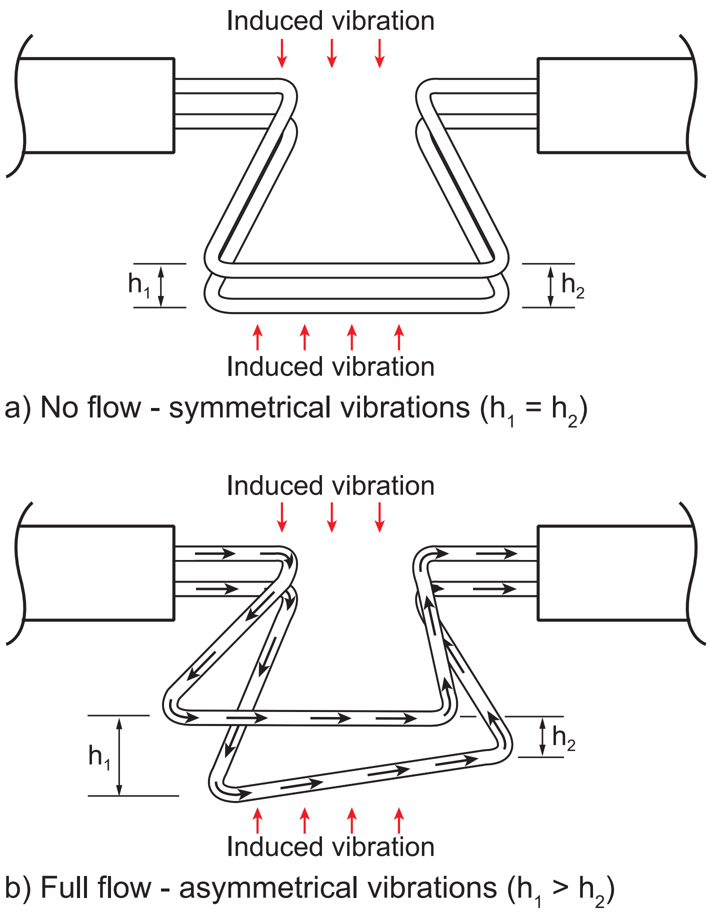
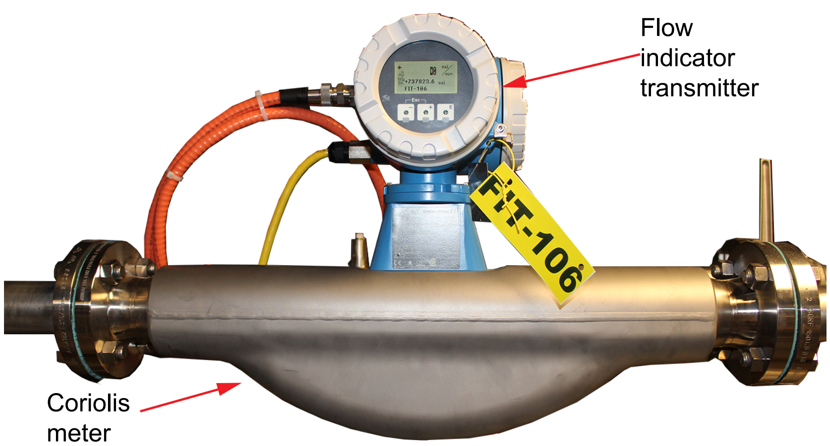


Figure 41 – Coriolis-Type Flow Indicator Transmitter



Coriolis meters are used successfully in the petro-chemical, food and beverage, pulp and paper and pharmaceutical industries. In part, this is because the Coriolis meter can accurately measure viscous fluids and slurries, as well as low viscosity and clean fluids.

Objective 4

Describe the types of temperature sensing and measuring devices.

Temperature Measurement

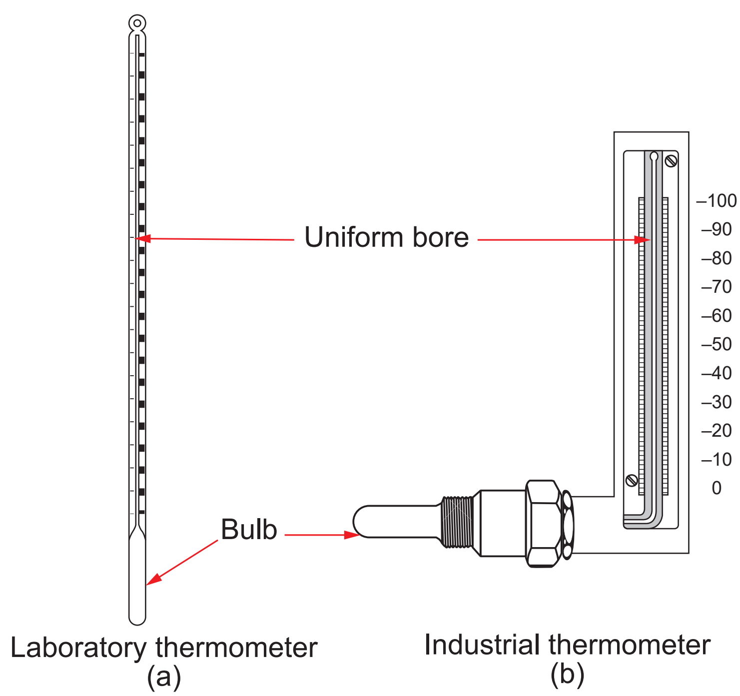
Glass Stem Thermometers

Glass stem thermometers (also called **liquid-in-glass thermometers**) are used extensively in laboratories and industrial settings. These thermometers employ the thermodynamic principle of volumetric expansion of liquids. The thermometer has a liquid-filled bulb, and a glass stem with a uniform bore. When the bulb is heated, the liquid expands through the glass stem until the liquid reaches the temperature of the substance being measured. The temperature is read at the point where the liquid reaches the highest point in the glass stem. The temperature scale is either etched onto the glass stem (Figure 42 (a)), or attached beside the stem (Figure 42 (b)).

Liquid-in-glass thermometers are available in a variety of temperature ranges. However, the type of thermometer used must be selected according to the range of temperatures being measured. When in use, the fluid contained within the thermometer must not freeze or boil. Some thermometers have ranges from –40 to 40°C. Others measure from 10 to 400°C. Very accurate thermometers are generally quite long and have a small range.

Liquid-in-glass thermometers are fragile. For this reason, they are not suited for use in locations where they may be subject to vibration or mechanical injury.

Figure 42 – Glass Stem Thermometers



Alcohol-filled liquid-in-glass thermometers are used extensively for home, laboratory, medical, and industrial applications. Toluene, butane, and other organic liquids are used in liquid-in-glass thermometers for higher temperatures.

Mercury-filled thermometers were quite common in the past. However, mercury has been banned in many countries due to its hazardous and toxic effects on health and the environment. Check site-specific policies and jurisdictional regulations regarding the use of mercury-filled thermometers, to find out if they are permissible.

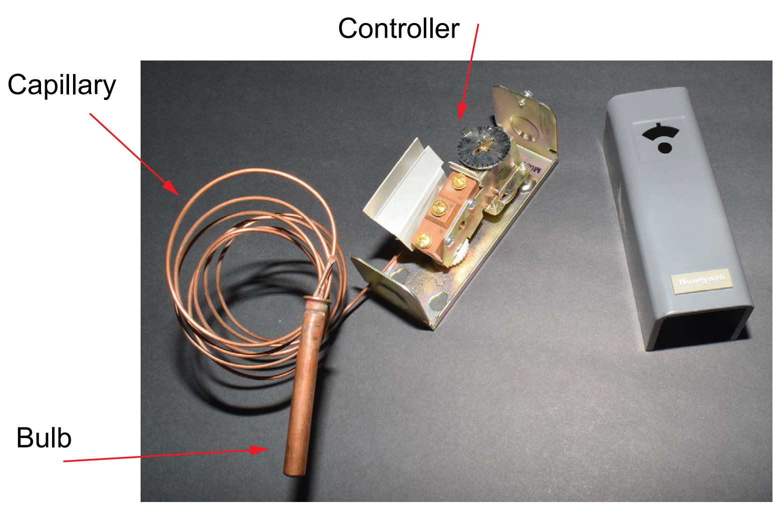
Filled System Thermometers

The **filled system thermometer**, illustrated in Figure 43, can be used to provide an indication of temperature, or to produce a control signal proportional to the measured temperature so it can be used for recording and controlling at a distance.

A basic system consists of a temperature sensitive bulb, a capillary tube, a pressure-sensing device (such as a bourdon tube, bellows, or diaphragm), and an indicating or transmitting device. The system is completely filled with fluid (liquid, gas, or vapour).

With an increase in measured temperature, the fluid in the bulb expands, increasing the pressure in the bulb, capillary, and the pressure-sensing element. Figure 43 shows a temperature controller operated by a filled-system thermometer. The controller has a pressure-sensing element that responds to the increase in fluid pressure in the bulb. This activates a switch, according to the temperature on the set point dial. Some filled system thermometers are only indicators. Others may be used to drive temperature transmitters or recording devices.

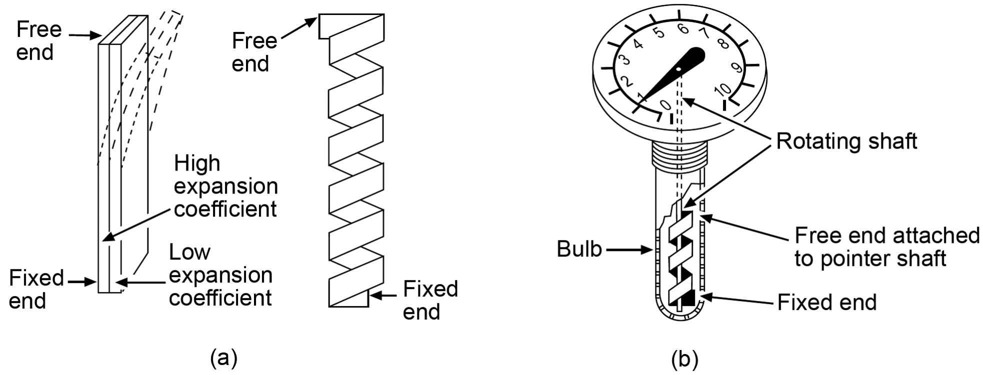
Figure 43 – Temperature Control with Filled System Thermometer



Bimetal Thermometers

The **bimetal thermometer** consists of two thin strips of metal, with different coefficients of expansion, laminated together. When one end is fixed, as illustrated in Figure 44(a), the free end deflects in nearly direct proportion to the change in temperature. Brass and **invar** are the metals often used, because the coefficient of linear expansion of brass is over twenty times higher than that of invar.

Figure 44 – Bimetal Thermometers, Bimetal Strip



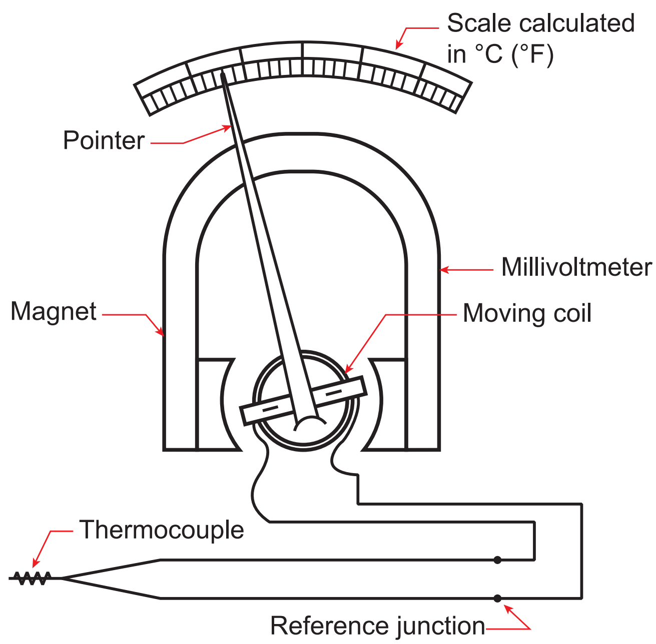
Flat bimetal strips deflect only slightly, unless made very long. To amplify the deflection and still maintain compactness, bimetal strips may be wound into a helix or spiral. Figure 44(b) shows an industrial bimetal thermometer that uses a helical bimetal element whose motion is transmitted to a pointer by a shaft.

Bimetal thermometers are far sturdier and break-resistant than liquid-in-glass thermometers. They are also easier to read. Bimetal thermometers are available for very low temperatures (–70°C), and very high temperatures (550°C), with spans ranging from 50 to 450°C.

Thermocouples

The **thermocouple** is one of the most widely used temperature sensing devices. It consists of two wires, each made of a different metal or alloy (dissimilar metals). These wires are connected at one end to form the **measuring junction**, as shown in Figure 45. The free ends of the two wires are connected to a measuring instrument, either directly or by means of extension wires. The connection to the instrument is called the **reference junction**. When the measuring and reference junctions are at different temperatures, the thermocouple produces a voltage, which causes a current to flow. The magnitude of this generated DC voltage is a function of the temperature difference between the two junctions.

Figure 45 – Basic Thermocouple Circuit



A basic thermocouple and measuring circuit is illustrated in Figure 45. The thermocouple circuit is connected to a millivolt meter whose scale is calibrated in degrees Celsius. An increase in temperature will cause an increase in current flow through the moving coil, and a corresponding movement of the pointer on the temperature scale. In actual practice, the measuring junction of a thermocouple is placed at the point of temperature measurement, while the meter with the reference junction may be some distance away.

Extension wires from the reference junction to the millivolt meter have no effect on the output, as long as both ends of the wire are at the same temperature. Various combinations of metals may be used depending on the temperature range required. Some types of thermocouples and their approximate temperature ranges are shown in Table 1.

Table 1 – Thermocouple Ranges

Type of Thermocouple	Wire Materials	Temperature Range (°C)
Type J	Iron – Constantan	0 - 815
Type K	Chromel – Alumel	–185 to 1260
Type B	Platinum/Rhodium – Platinum	0 to 1860
Type T	Copper – Constantan	–270 to 370

Thermocouples have non-linear response to temperature change. However, their response is almost linear over their designed temperature range, making them useful temperature sensors.

Thermocouples are frequently used as pilot flame detection devices for smaller burners and appliances. Because they are suitable for high temperature, thermocouples are commonly used to transmit high temperature process conditions, like superheated steam temperature.

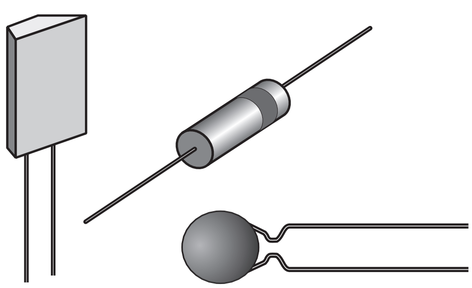
Thermistors

A **thermistor** is a solid state, resistance temperature sensor that may have either a negative or a positive temperature coefficient. Figure 47 shows the response of a thermistor with a negative temperature coefficient. As its temperature increases, this type of thermistor's resistance decreases.

Thermistors look similar to glass diodes or small transistors (Figure 46), and provide quick temperature response. Because the response is non-linear, thermistors are only suitable for measuring temperature over very small spans. However, they are highly accurate for these very small spans.

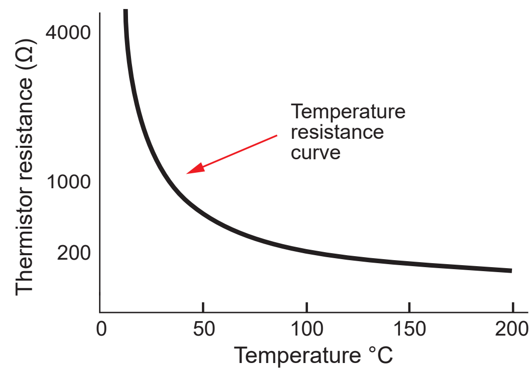
Thermistors are commonly used in HVAC thermostats and temperature transmitters. Thermistors are not capable of measuring temperatures above 315°C.

Figure 46 – Thermistor (Solid State) Temperature Sensor



(Courtesy of Honeywell Inc.)

Figure 47 – Resistance vs Temperature Relationship for Thermistors



(Courtesy of Honeywell Inc.)

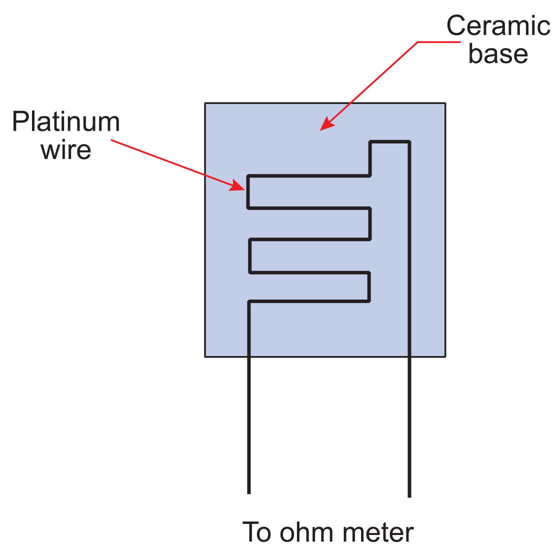
Resistance Temperature Devices (RTDs)

The **resistance temperature device (RTD)** is based on the principle that conductors change in resistance, proportional to their temperature. As a conductor increases in temperature, it increases in resistance. RTDs are made of fine gauge wires wrapped around a non-conducting core, or deposited on a flat ceramic plate. Platinum, nickel, copper, or nickel-iron alloy (**Balco**) wires are commonly used. The fine wire is exposed to the process condition, and its resistance is measured and converted to temperature.

A Balco RTD provides a relatively linear change in resistance from –70 to 200°C. These RTDs are small and respond quickly to changes in temperature. A platinum RTD has a very linear and stable response from –240 to 650°C. Platinum RTDs are the most expensive, but are the most accurate.

Figure 48 shows a platinum element type RTD on a ceramic base. The two wires connected to the platinum wires would be connected to an ohmmeter, which is reading in temperature.

Figure 48 – Platinum Element RTD Sensor



Thermowells

A **thermowell** is a metal sheath used to house temperature sensors, such as liquid-in-glass thermometers, bimetal thermometers, filled system thermometer sensing bulbs, thermocouples, thyristors, and RTDs.

The thermowell:

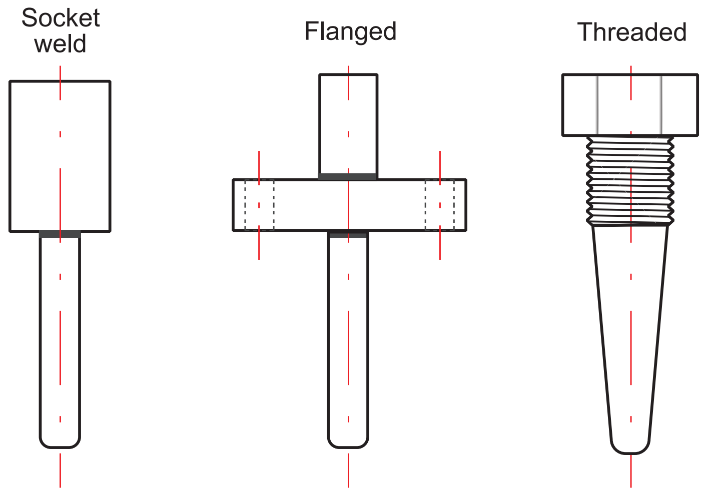
a) Protects the sensing element from the action of harmful atmospheres, corrosive fluids, or mechanical damage.

b) Permits installation of a sensing element into a pressurized system.

c) Permits easy replacement of defective sensing elements without isolating process lines.

The thermowell is a metal tube that is closed at one end. The closed end is inserted into a pipe or vessel. Three types of thermowells are shown in Figure 49. The thermowell may be socket welded, flanged, or threaded into a pipe or vessel. The temperature-sensing device is screwed into the open end of the thermowell.

Figure 49 – Mounting Styles of Thermowells



Pyrometer

To measure high temperature, or temperature from a source that is some distance away from the operator, a **pyrometer** may be used. Both optical and radiation pyrometers are available. These devices operate on the principle that heat is a form of radiant energy that can be measured. As temperature increases, the radiated heat increases.

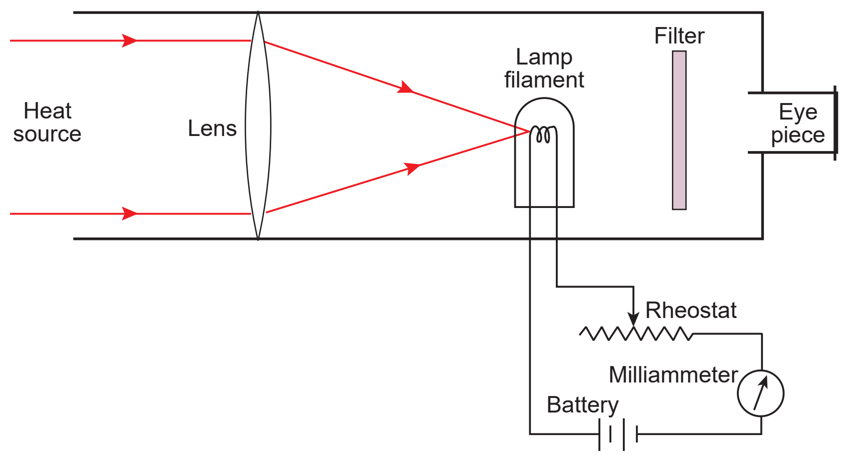
The **optical pyrometer** uses a very narrow band of radiation wavelengths (that of visible light) to measure the temperature of a heated body. Bodies vary in colour predictably, from dull red to bright yellow, with increasing temperature. The optical pyrometer in Figure 50 uses this principle.

In a typical optical pyrometer, the radiation source is viewed through a scope with a lens and an eyepiece. Inside the scope is a small lamp heated by the current from a battery. The current is adjustable with a rheostat. A milliammeter is connected in the lamp circuit. A red optical filter is positioned between the eyepiece and lamp. When looking through the eyepiece, the temperature source is seen as a bright circle. The image of the lamp's filament is seen in the center this circle.

The rheostat is adjusted until the brightness of the filament is equal to that of the temperature source. When the lamp filament appears as bright as the temperature source, the filament image disappears into the heat source image. If the filament is brighter than the source image, it appears bright against a dark background. If the filament is not as bright as the source image, it appears dark against a lighter background.

When the images merge, the temperature is read from the attached milliammeter scale (Figure 50), or (as in some other varieties) read from the dial of the rheostat. The rheostat scale or the milliammeter scale can be calibrated directly in degrees of temperature.

Figure 50 – The Radiation Pyrometer Principle



Infrared Thermometer (Pyrometer)

An **infrared thermometer** (Figure 51) is a digital device that measures the temperature of an object at a distance by detecting its infrared energy emissions. The device has a laser to assist with aiming, so the correct surface temperature reading can be made. The thermometer senses emitted, reflected, and transmitted infrared energy, which is collected and focused onto a detector. Electronic circuitry translates the signal into a temperature reading which the unit then displays.

Infrared temperature detectors:

- Are inexpensive, compact, and portable
- Are easy to use
- Display temperatures in several units of measurement
- Can measure temperatures of less accessible objects from a distance
- Work in ranges from −40°C to 800°C

However, infrared temperature detectors only measure surface temperatures.

Figure 51 – Infrared Thermometer (Pyrometer)

Objective 5

Describe the types of humidity sensing and measuring devices.

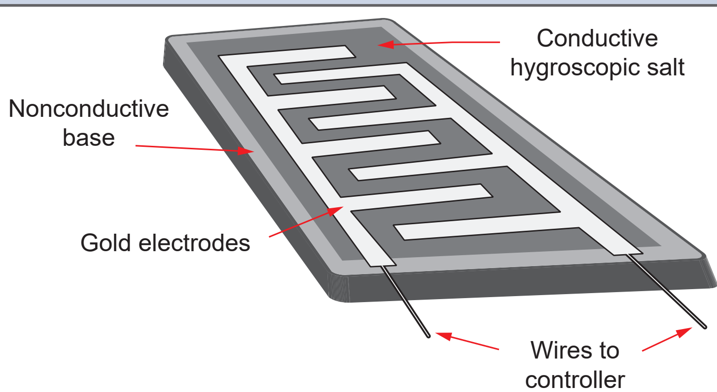
Relative Humidity Sensors (Hygrometers)

Traditionally, relative humidity has been determined with a wet-and-dry bulb **psychrometer**. These devices are still available, and still in use. Psychrometers could be either small portable devices, or permanently installed instruments with supplemental recording or transmitting devices. In either case, two thermometers are exposed to the same atmosphere. One thermometer is kept wet by a wick that draws water from a reservoir. The other thermometer is kept dry.

There must be positive air movement around the thermometers so that they are continually provided with a representative sample of the surrounding atmosphere. After a short period of time, the thermometers read different temperatures. These are called the “dry bulb” and “wet bulb” temperatures. The difference between the two temperatures is a function of the relative humidity, which determines the rate of water evaporation, and hence the temperature of the wet bulb. The dry and wet bulb temperatures can be plotted on a psychrometric chart, and the relative humidity determined.

Today, various other sensing methods are used to determine relative humidity, including the measurement of changes in resistance, capacitance, impedance, and frequency. One method that uses resistance to determine relative humidity depends on a layer of hygroscopic salt such as lithium chloride or carbon powder, deposited between two electrodes (Figure 52). The material absorbs and releases moisture as a function of relative humidity, causing a change in resistance of the sensor. An ohmmeter is connected to the sensor to measure the relative humidity. The device may be used as an indicator or as a controller.

Figure 52 – Resistive (Resistance) Type Relative Humidity Sensor



Another style of **hygrometer** measures the change in capacitance on a metal oxide as the relative humidity changes. Capacitive hygrometers are fairly economical, durable, and have reasonable accuracy.

The absolute humidity of air can also be measured by thermal hygrometers that measure the thermal conductivity of air.

The calibration standard for hygrometers is the gravimetric hygrometer that measures the mass of a sample of air and compares that mass to the mass of an equal volume of dry air.

Objective 6

Describe the types of gas sensing and measuring devices.

Chromatograph

A **chromatograph**, Figure 53(a), is used to analyze the components of a gaseous mixture, or of a liquid in vapor form. It operates on a combination of physical and chemical principles.

> A **physical principle**: If a gaseous mixture is forced through a certain material that resists its flow, smaller compounds, or those with lower boiling points, will pass through more quickly than the ones that are larger, or have a higher boiling point.
>
> A **chemical principle**: Compounds in a mixture of gases or vapours having differing types of chemical bonds will be attracted differently to the bonds of the material it passes through.

A basic chromatograph consists of a separation column, packed with an absorbent material, and installed in an oven that is maintained at a constant temperature. The column is connected to a regulated supply of inert **carrier gas**, such as helium or argon, as indicated in Figure 53(a).

The gas sample mixes with the carrier gas, and flows through the column to a detector. Each component of the gas mixture is identifiable by how much time elapses between the injection of a sample into the column and the emergence of that component (typically the time at the peak height). See Figure 53(b).

Quantitative measurement of each component typically depends on the difference between a value representative of the sample, and a baseline value representative of the carrier gas only. The thermal conductivity detector is commonly used in gas chromatographs to analyze hydrocarbon and flue gas mixtures. It measures the difference between the thermal conductivity of the carrier gas in the reference leg, and of the mixture of the carrier gas and the sample gas in the detector leg. The heat sensitive elements in the detector are often thermistors or semiconductors with rapidly decreasing electrical resistance with increase in temperature.

When a greater quantity of a specific gas passes through the detector, a Wheatstone bridge circuit connected to the thermistors becomes increasingly unbalanced. The resulting imbalance is traced on a chart like that shown in Figure 53(b). Peak heights and peak areas above a base line are used to calculate the quantity of a particular gas component in the mixture.

Figure 53 – Gas Chromatograph with Thermal Conductivity Detector

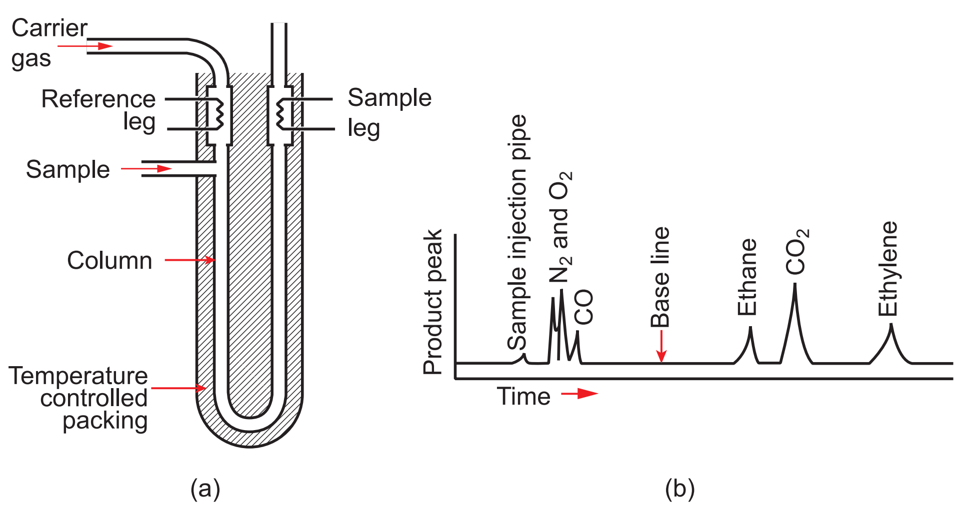
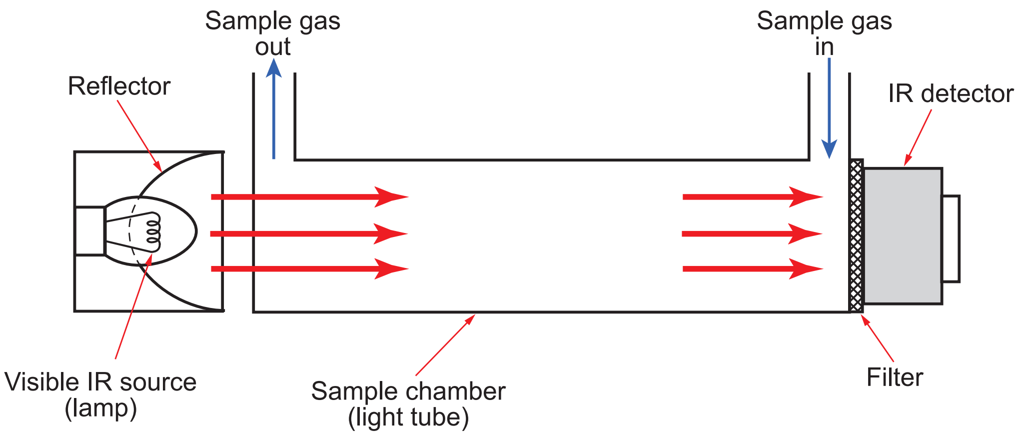


Figure 54 – Gas Chromatograph

CO AND CO_2 ANALYZERS

CO and CO_2 are commonly measured using **non-dispersive infrared radiation (NDIR)** detection. The **NDIR detector** (Figure 55) consists of an infrared (IR) light source, an IR detector, and a sample tube for the gas to pass through. A light filter removes wavelengths of infrared that are not used for measuring carbon monoxide or carbon dioxide (CO and CO_2 strongly absorb light wave frequencies of 4.26 µm and 4.67 µm respectively). The absorption of these wavelengths is measured by the analyzer, and used to determine the concentration of CO and CO_2. The resulting output provides the percent volume of each of the gases being measured.

Figure 55 – Non-Dispersive Infrared (NDIR) Detector for CO or CO_2



Continuous Emissions Monitoring Systems (CEMS)

Continuous emission monitoring systems (CEMS) continuously collect, measure, record, and report emission data to comply with jurisdictional environmental standards. Modern CEMS evolved from basic flue gas monitoring systems that measured oxygen, carbon monoxide, and carbon dioxide for combustion control.

Industrial facilities can use emissions monitoring to:

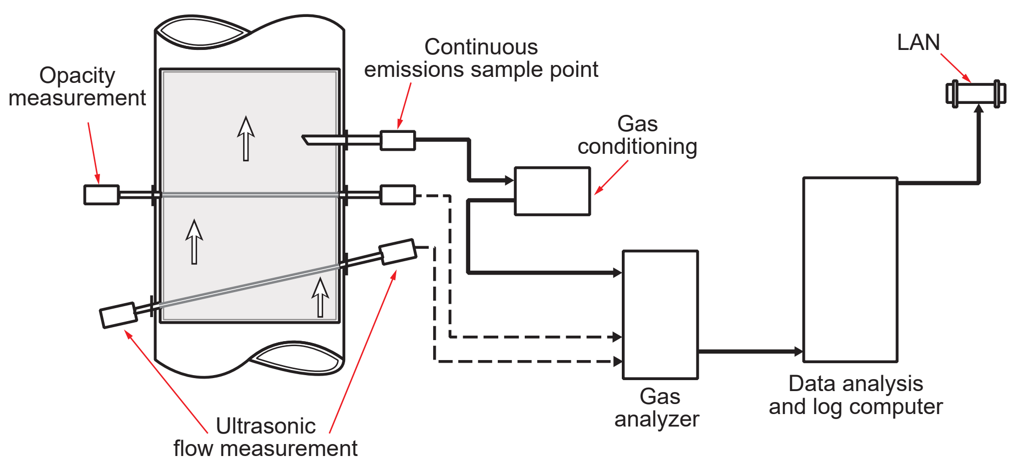
- Document regulatory compliance with emission limits
- Assess and monitor process conditions
- Assess and monitor plant efficiency
- Inform operating decisions
- Determine pollution control device efficiency
- Monitor health and safety within the plant

Figure 56 shows a typical continuous emission monitoring system. This system measures flue gas flow using an ultrasonic flow measurement device. The flow measurement is passed on to the gas analyzer. The **opacity** (how clear the gas stream is) is also measured and sent to the gas analyzer.

The continuous emission sample point draws a gas sample from the main stream, using a pump. This sample is then sent to the gas conditioning section where the gas sample may be diluted to a certain percentage or dried (and moisture content measured), depending on the type of sample and the type of analyzers being used.

The gas analyzer is made of several separate analyzers that measure the different products being emitted. Typical monitored emissions may include oxygen, carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen oxides, hydrogen chloride, mercury, particulate matter, and volatile organic compounds. These measurements are sent to a computer where the data is analyzed and logged. A summary of the results over a measured time span is sent out to the LAN (local area network) for distribution to those that require the measurements.

Figure 56 – Continuous Emissions Monitoring System Setup



Chapter Summary

All modern production processes employ automated control systems and complex instrumentation. This chapter covered the design principles and operation of common process measuring devices for pressure, level, flow, temperature, humidity, and gas composition, used either as stand-alone indicators, or as the sensing elements of control systems.

Further studies will demonstrate how these primary sensing elements integrate into larger control systems.

CHAPTER 3

Basic Control and Instrumentation Components

Learning Outcome

When you complete this chapter you should be able to:

Describe the basic types and functions of transmitters, recorders, controllers, and control actuators.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe the construction and operational principles of instrumentation transmitters.*
2. *Describe the construction and operational principles of instrumentation indicators and recorders.*
3. *Describe the construction and operational principles of instrumentation controllers.*
4. *Describe the construction and operational principles of final control elements.*

Chapter Introduction

Control systems cannot function without instruments that sense process conditions, transmit information, interpret process conditions, make control decisions, and ultimately act to adjust process conditions. These components are sensors, indicators, transmitters, controllers, and final control elements.

Control systems also rely heavily on the ability to represent process conditions and trends visually, so they may be observed, interpreted, and archived for future reference. These instruments (known as indicators and recorders) have evolved greatly since the advent of digital control systems, and are heavily relied on to help operators make control decisions.

This chapter introduces control loop components, provides examples, and explores their operation.

Objective 1

Describe the construction and operational principles of instrumentation transmitters.

Transmitters

In industrial process control, the term transmitter describes a device that converts measurements from a sensor into a signal (most commonly electric, electronic, or pneumatic), and sends the signal to a remote recording device or a controller.

Pneumatic transmitters, similar to those shown in Figure 1, are used to transmit signals over long distances. The part of the transmitter that contains the valve capsule, restrictor, spring, and exhaust valve is called a **pneumatic relay**. The mechanism basic to all pneumatic transmitters is the **flapper-and-nozzle** assembly, shown in Figure 1(a). A sensing element, such as a bourdon tube or bellows, is attached to the link. Changes in process conditions change the position of the link, and the distance between the flapper and nozzle. This change in position is converted into a varying pneumatic output.

The transmitter is supplied continuously with a standard regulated compressed air supply of about 140 kPa. The air passes through a restriction, which has a smaller bore than the nozzle opening. The output of the transmitter is directly proportional to the flapper-nozzle clearance and nozzle pressure (pressure downstream of the restrictor).

When the sensing element moves the flapper away from the nozzle, air bleeds from the nozzle faster than it passes through the restriction. This causes the capsule to collapse as its internal pressure falls to zero. When this happens, the exhaust valve opens reducing the pneumatic output signal.

A tiny change in the nozzle-flapper relative positions causes large changes in output signal. Normally, the transmitter is far too sensitive to changes in measured process conditions. The **feedback bellows** reduces the transmitter sensitivity. When the output signal decreases because the flapper has moved away from the nozzle, the feedback bellows contracts slightly and moves the flapper closer to the nozzle. This increases the range of sensing element motion to produce a desired transmitter output signal change.

For example, without a feedback bellows, a flapper movement of 0.15 mm produces a full-range output signal change from 20 all the way to 100 kPa. With the addition of a feedback bellows, the sensing element may move twenty times that distance to cause a full-range output signal change.

When the sensing element moves the flapper toward the nozzle, the nozzle pressure increases, and the capsule expands as its internal pressure increases. When this happens, the exhaust valve closes, which increases the pneumatic output signal. The feedback bellows now expands slightly, and moves the flapper away from the nozzle, again decreasing the sensitivity of the instrument.

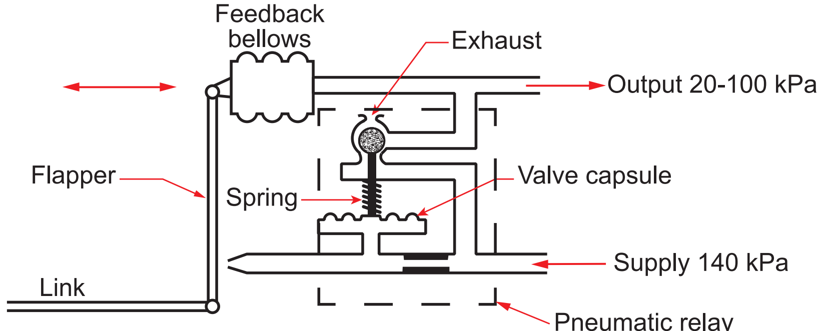
With this device, for each process condition, there is a definite distance between the flapper and the nozzle, and a corresponding definite pneumatic output signal. As the process variable changes from a minimum to a maximum value within the measurement range, the output of the transmitter increases incrementally from 20 to 100 kPa.

Figure 1(b) illustrates a simplified **differential pressure transmitter** that can be used for level and flow measurement. It has two connections: a high-pressure connection and a low-pressure connection. For flow measurement, the high-pressure side is connected to the upstream side of a flow restriction, such as an orifice plate, flow nozzle, or venturi. The low-pressure side is connected to the low-pressure side of the restriction.

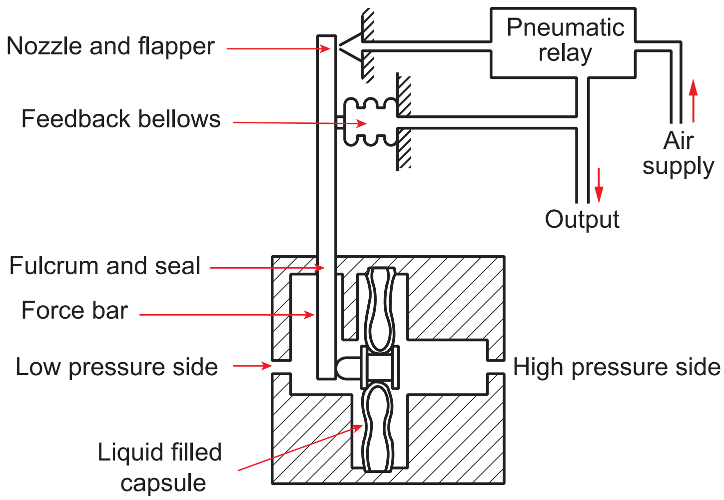
An increase in flow causes an increase in differential pressure. This, in turn, causes the capsule to move slightly to the left, which moves the force bar (that acts as a flapper) closer to the nozzle. This increases the transmitter pneumatic output signal in proportion to the increase in differential pressure across the orifice plate caused by the increased fluid flow. The feedback bellows then expands slightly to increase the flapper-nozzle clearance to reduce sensitivity and aid in the proportional action of the transmitter.

When a DP-cell is used to measure level, the high-pressure side is usually connected to the base of the tank, so that an increase in level will cause a proportional increase in transmitter output.

Figure 1 – Basic Pneumatic Transmitter

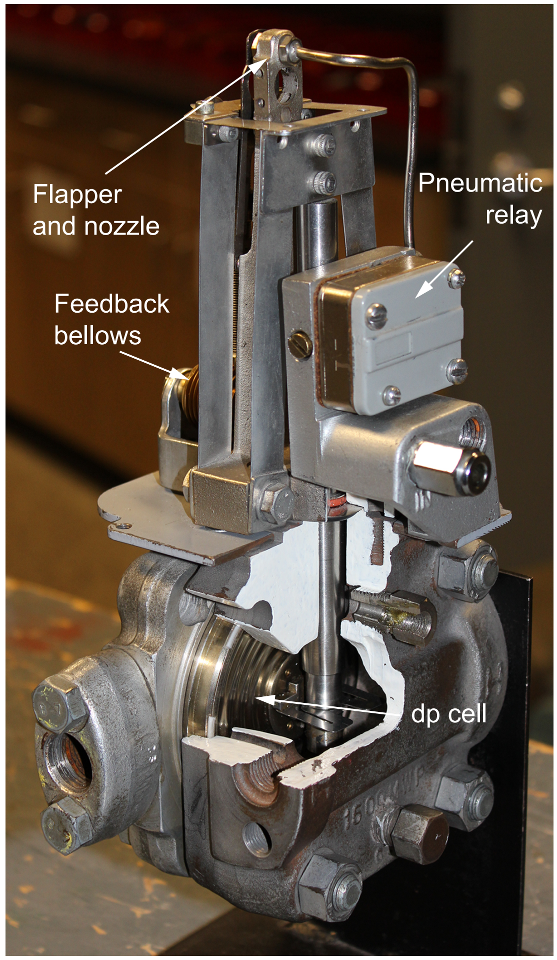


(a)
Basic transmitter principles



(b)
Basic differential pressure transmitter

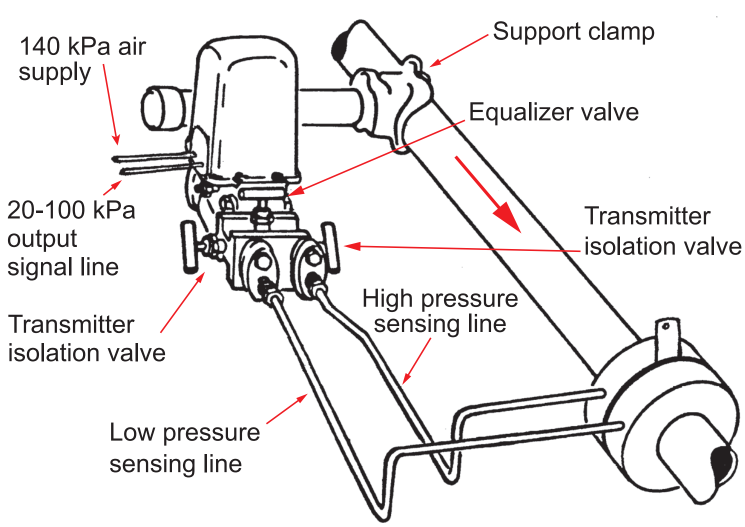
Figure 1 (Cont.) – Basic Pneumatic Transmitter



(c)

Figure 2 shows a sketch of a differential pressure transmitter, as shown in Figure 1, installed to measure flow. Note the sensing lines from the high and low-pressure sides of the orifice plate connecting to the transmitter, and the supply and output air lines going to and from the transmitter.

Figure 2 – Pneumatic Flow Transmitter



Objective 2

Describe the construction and operational principles of instrumentation indicators and recorders.

Indicators And Recorders

There are many ways to display or present the values of measured variables. At times simple mechanical indicators such as bourdon tubes, gauge glasses, and thermometers are quite adequate. At other times, it may be desirable to have a permanent record of process variables that can be used for future reference.

Indicators serve as process variable indication only; they have no other function. Indicators support manual monitoring (usually at scheduled intervals), manual recording, and manual control of processes that only need occasional operator supervision and intervention.

An example may be a thermometer used to measure bearing temperature, which the operator checks and records on hourly rounds. This temperature - while important - changes in magnitude very slowly, and may not require continuous operator attendance. Indicators may be located directly on the process equipment or remotely located, if the process sensor is difficult to access.

Recorders are like indicators, in that they provide real-time process data to process operators. However, they continuously record process information, helping operators observe process trends and conditions between scheduled observations.

Using the previous example, the turbine bearing temperature trend is very important in determining the cooling water flow to the bearing lube oil system. Operators cannot continuously monitor the bearing temperature because they have other duties. Therefore, a recorder can inform the operators of the process conditions between scheduled rounds, so that appropriate control action can take place, based on trends.

Recorders also track process trends so that process variables can be identified historically during critical process disturbances. For example, the temperature recorder in the previous example can show the precise bearing temperature when vibration tripped the turbine off-line.

Recorders can track information from several sensing devices simultaneously. For example, turbine vibration, bearing temperature, bearing cooling water temperature, and bearing cooling water flow can be charted together so that the relationship between all four conditions can be readily compared.

Like indicators, recorders can be field located or remote (such as in a central control room). As well, some recorders have some ability to perform control functions. Recorders provide permanent historical process condition data for important tasks, such as determining efficiencies, troubleshooting deteriorating equipment conditions, scheduling maintenance activities, and demonstrating regulatory compliance.

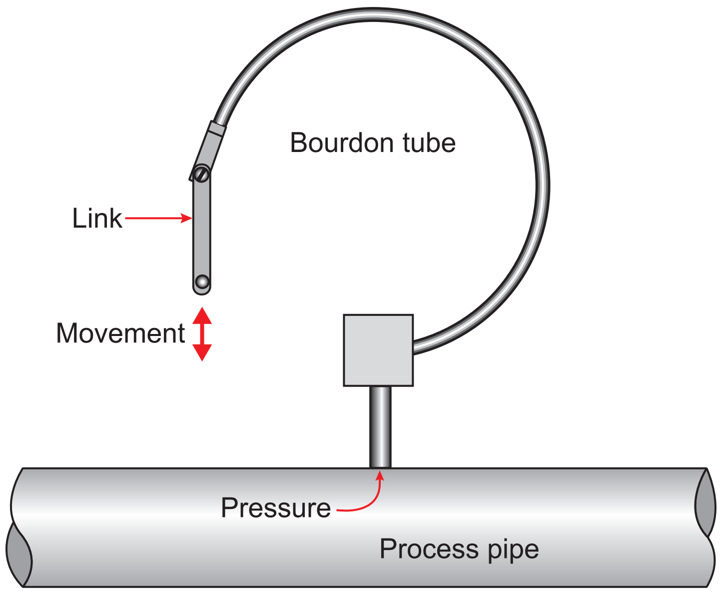
For example, flue gas temperature can be trended alongside steam flow, steam pressure, and fuel flow. Over the period of a few months, under similar steam production conditions, the flue gas temperature and the fuel flow may increase. From this historical data, it can be determined whether the boiler heat transfer surfaces are fouling, and when it may be necessary to schedule a de-scaling.

Controllers do not need indicators or recorders to function correctly. However, nearly every electronic or digital **distributed control system** today combines the controller functions with process variable indication and trending functions. In this way, operators can see real-time process conditions, observe historical data, and use this information to make reasonable set point or control output changes.

Pressure Indicators

Pressure indication is primarily accomplished using bourdon tubes, bellows, and **pressure capsules**. Figure 3 shows a bourdon tube connected to a link. This link could be attached to a pneumatic pressure transmitter (as already described), or a transducer used to convert the process variable to a representative voltage, current, or digital signal. As an indicator, the link could be attached to the sector, pinion, and needle of a pressure gauge. Lastly, the link could be attached to a pen mechanism of a chart recorder. It is common for helical and spiral bourdon tubes to be used for this purpose.

Figure 3 – Bourdon Tube Used for Pressure Indication



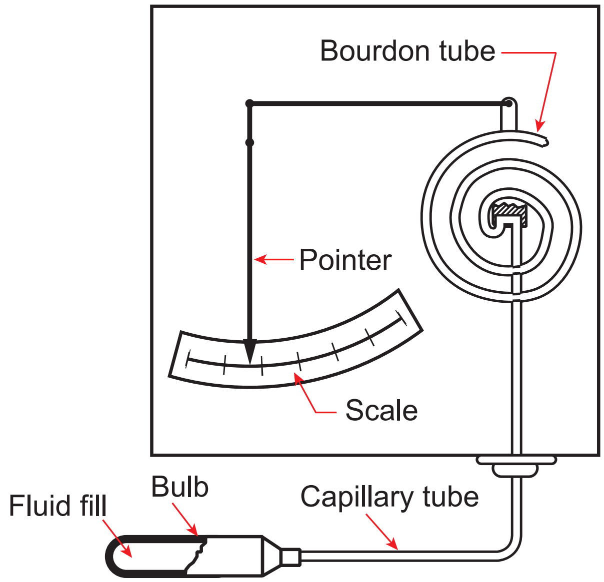
Temperature Indicators

Temperature indication is commonly done with liquid-in-glass and bimetal thermometers. However, temperature indication may also be accomplished using a bourdon tube connected to a **capillary tube** and **sensing bulb**. Figure 4 illustrates this method.

The capillary tube is a small diameter metal tube with a small internal bore that connects a bourdon tube, bellows, or pressure capsule to a sensing bulb. The capillary tube is often more than a metre long. The capillary and bulb may contain a pressurized gas, a liquid, or a volatile liquid. For this reason, the temperature sensing system (the sensing bulb, capillary, and bourdon tube) is called a filled-system thermometer.

The bulb is placed so that it is surrounded by the material whose temperature is being measured. When the temperature increases, the fluid inside the bulb expands and exerts pressure on the inside of the bourdon tube. As with pressure indicating mechanisms, the deflection of the bourdon tube moves a link to operate a transmitter, indicator, or recorder.

Figure 4 – Bourdon Tube Used for Temperature Indication

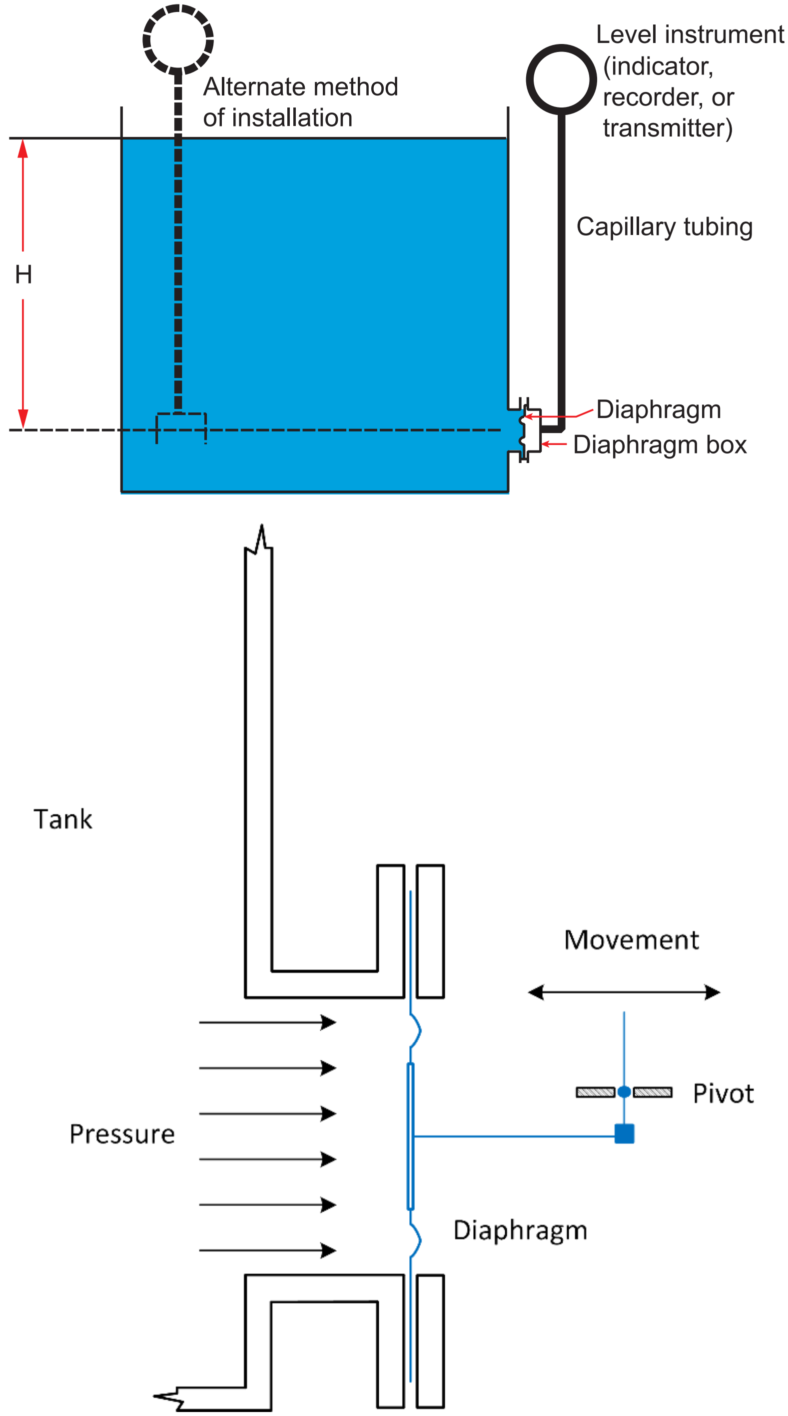


Level Indication

The simplest methods of level indication include gauge glasses and floats. Another way to detect level is to use a sensitive diaphragm, as shown in Figure 5.

The diaphragm is mounted at the bottom of a tank containing a liquid. Pressure, due to the **static head** of the liquid, presses on the diaphragm and deflects it outward. This outward movement is sent by a link through a pivot into the force or movement required to operate a transmitter, indicator, or recorder.

Figure 5 – Diagram Used for Level Indication



The top image in Figure 5 shows placement options for the diaphragm. The bottom image shows details on how the diaphragm operates indicators, transmitters, or recorders.

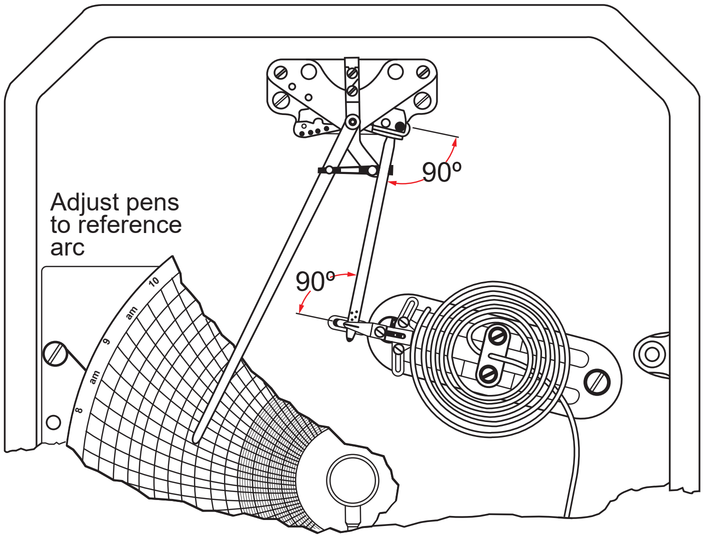
Recorders

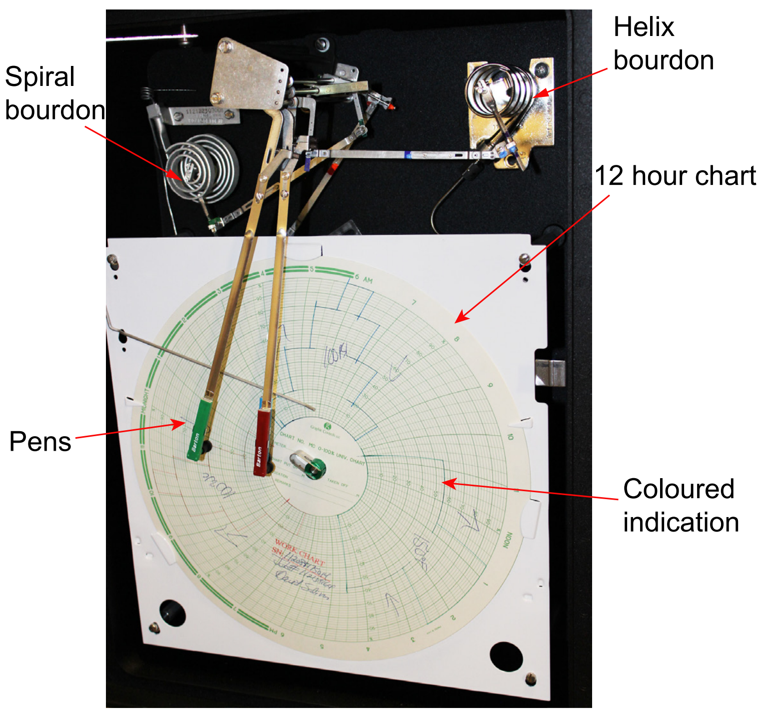
Recorders are used to maintain a permanent record of certain variables for future reference. In the past, the two most common types were the circular chart and the strip chart recorders. With advancements in technology, computerized trending and recording is now widely used in industrial plants.

Circular Chart Recorders

Circular chart recorders (Figure 6) were developed before strip chart recorders. The top image shows a recorder for a single process variable. The recorder in the bottom image can record two process variables simultaneously, in different colours.

Figure 6 – Circular Chart Recorder





These recorders have spiral or helical bourdon tubes connected to recording pens with a link-lever mechanism. When the pressure in the sensing element increases, the movement of the pen will be proportional to the change in pressure in the bourdon tube.

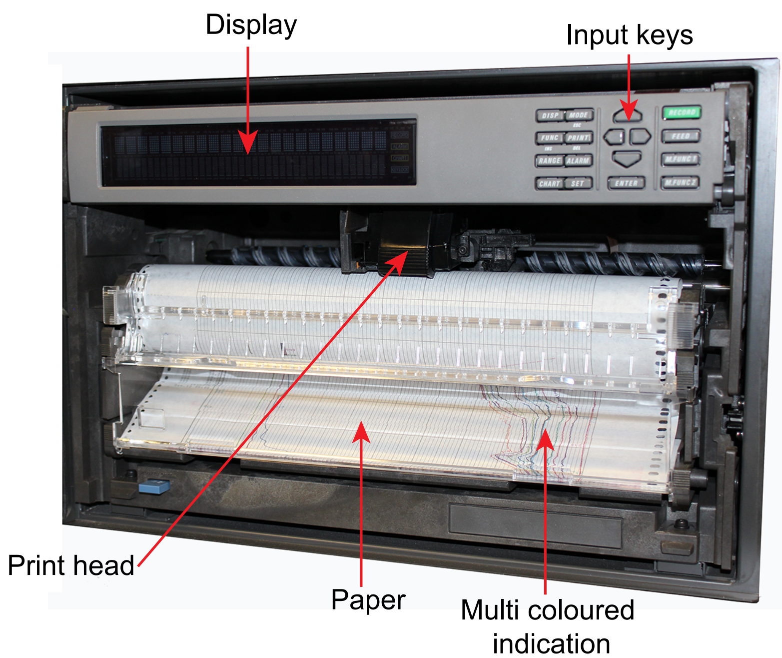
The pressure acting on the bourdon tube is typically a pneumatic signal from a level, flow, pressure, or temperature transmitter. The bourdon tube can also be driven by the fluid pressure changes of a filled-system thermometer.

The replaceable chart is a paper disc with a hole in the centre, which fits on the end of a clock motor. The chart has concentric circles that form the scale for recording the process variable. The "time arcs" are laid out at uniform distances, dividing the chart into regular intervals. The intervals vary, according to the time required for a complete chart rotation. Some charts rotate 360° in 24 hours; others may take up to 7 days. Times are pre-printed directly on the charts. The clock motor may be powered by manually wound springs, electricity, or pressurized gas.

Strip Chart Recorders

One problem with circular chart recorders is that process variable data is difficult to resolve near the low end of the instrument range. Data recorded close to the centre of the chart is more congested and difficult to read. Strip chart recorders, similar to the one in Figure 7, do not suffer from this problem.

Figure 7 – Strip Chart Recorder



Unlike the circular chart recorder, the strip chart moves in a linear fashion, either horizontally or vertically. The time lines run perpendicular to the chart motion.

Older recorders use ink pens. The chart recorder in Figure 7 uses a single multi-colour inkjet print head that prints each process trend line as it travels back and forth across the chart.

Computerized Trending

Computerized control systems display process trends directly on control room monitors. The trend displays often look like strip charts. Some displays mimic the appearance of circular charts.

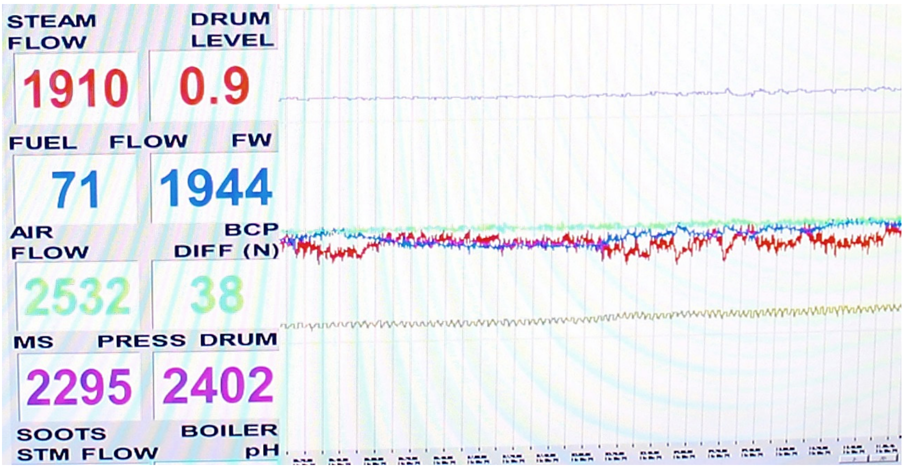
Multiple trends can be viewed on the same screen. Operators can select the data to display, including both process variables and control output signals. This means the operator can directly compare the trends of almost any process condition. This includes items that are not normally recorded by dedicated paper chart recorders (for example valve positions, ambient weather conditions, and machinery speeds). This is helpful for diagnosing operating problems, since the initial process disturbance and its subsequent effects can be easily evaluated.

Each process variable can be scaled individually to help resolve small process changes over short time spans. Computer mouse pointers can be hovered over trend lines to display a digital value of the process variable at a particular point in time.

Printouts can be made if permanent paper records are desired. However, this is not often necessary because the trends are typically backed-up to hard-drive storage on a regular basis.

Figure 8 shows a computerized trend from a thermal generating station.

Figure 8 – Example of a Computerized Trend



Control rooms typically have many monitors, each with information pertaining to particular processes. For example, one monitor may be the main boiler-operating screen, another may be a feedwater system control screen, and another could be a water treatment plant control screen. In addition to these monitors, usually one or more monitors will be dedicated to displaying critical process trends, such as steam flow, feedwater flow, airflow, fuel flow, and drum pressure. By having dedicated process trend screens, operators do not need to open, close, or page through displays to find trends for important process variables.

Objective 3

Describe the construction and operational principles of instrumentation controllers.

Controllers are the brains of a control loop. A controller compares an actual process condition to a desired operating value. Restated in instrumentation terms, a controller compares a process variable to a set point. If there is any difference between the process variable and the set point, a controller modifies its control output signal to adjust a final control element (such as a **control valve**, damper, or variable speed drive).

Controllers can be categorized based on how they react when a process variable is not at its set point. Figure 9 shows these controller categories.

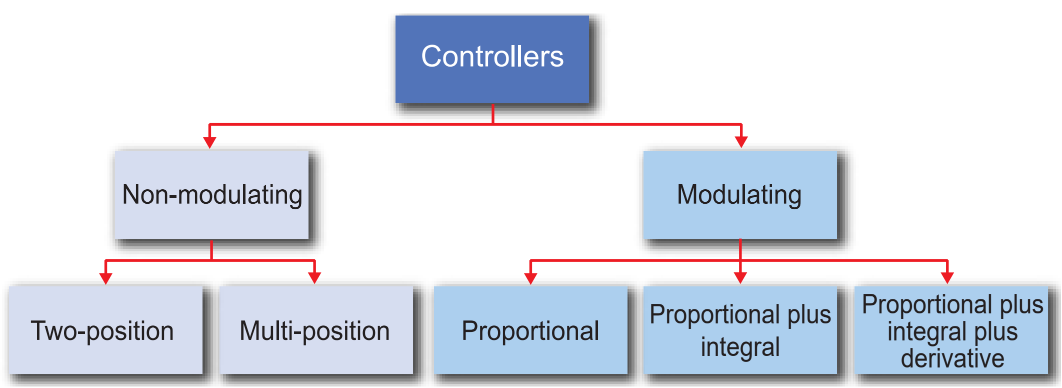
The first category is made of controllers that do not produce proportional control output signals. Instead, the control output signals are limited to a few set signals, depending on the process variable, the set point, and the error. These controllers are inexpensive and adequate where fine process control is not necessary.

The second category is the **modulating controller**. Modulating controllers produce infinitely variable control output signals, based on the infinitely variable error between the process variable and the set point. Modulating controllers combine proportional, integral, and derivative control actions in the following ways, depending on the nature of the process to be controlled:

- **proportional (P)**
- **proportional plus integral (PI)**
- **proportional plus integral plus derivative (PID)**

Fourth Class Power Engineers need to have a basic understanding of how these controllers operate.

Figure 9 – Controller Actions



Non-Modulating Controllers

Two-Position Controllers

Two-position controllers (also called "on-off") compare process conditions to set point values. They respond to error between the set point and process variable, with a discrete contact closure output signal. This signal may be used to start or stop fans and pumps, and open or close solenoid control valves.

A familiar example of a two-position controller is the household thermostat; it controls room temperature by starting or stopping a furnace. The thermostat has a set point manually entered by the homeowner. The furnace remains off until the room temperature drops to particular point lower than the set point. This temperature is called the cut-in point.

When the furnace is on, the burner provides heat at a constant rate (kJ/hour) by consuming fuel at a constant rate. The fuel valve for the furnace is a two-position valve (it can only be fully open or shut), and is open during the furnace run period. The furnace stays on until the temperature rises above the room temperature set point. Then, the main fuel valve closes, and the furnace stops.

Multi-Position Controllers

Multi-position controllers react similarly. However, they have multiple contact closure outputs that operate in sequence, depending of the amount of error between the set point and process variable. Their control output signals are typically "high-low" or "high-medium-low," rather than "on-off." Therefore, a multi-position controller is better able to maintain a set point than a two-position controller.

Modulating Controllers

Proportional Controllers

Unlike the non-modulating controllers, **proportional controllers** send infinitely variable control output signals, depending on the error between the process variable and the set point. The control output signal is thus proportional to the amount of error. For a typical pneumatic controller, the control output signal varies from 20 to 100 kPa. Typical electronic controllers send control output signals that vary from 4 to 20 mA, or from 0 to 10 volts. Digital controllers send control output signals as digital information, which is converted to analog for positioning the final control element.

If the final control element is a control valve or a damper, the controller can position it in the open position, the closed position, or to an infinite number of intermediate positions. Because of this, the final control element is said to "fully modulate" between its open and shut positions.

The control output signal of a proportional controller varies depending on how much the process conditions deviate from set point. For each value of error, the control output signal of a proportional controller has a particular value.

Proportional Plus Integral (Reset) Controllers

The word "offset" refers to when error is constant and persists over time. When offset occurs, proportional controllers cannot return the process variable to its set point. For processes that require fine control of the process variable, proportional controllers that feature **integral action** (or reset) must be used. Reset action, as the name implies, resets or returns the process variable to set point whenever error occurs.

The proportional plus integral controller uses two factors - the size of the error and the duration of the error - to decide how much to adjust the final control element. The integral unit monitors the average error over a period of time, and adjusts the final control element enough to return the process variable back to the set point.

Proportional Plus Integral Plus Derivative Controllers

Further modifications can be made to the proportional plus integral controller by adding **derivative action** (also called **rate**). If the process variable starts to change at a high rate, the derivative action moves the final control element in such a way as to counteract this rapid change. In this way, derivative action limits the speed at which process variables change.

Additional Controller Terms

The following are very common controller terms.

1. Auto/Manual Control

Most (but not all) controllers may be operated manually or automatically, according to the needs of the operator. In automatic control, the control output signal is based on the error between the process variable and the set point. Process variable information is continuously fed back to the controller to adjust the final control element as required.

Under manual control (also known as **hand control**), the operator adjusts the final control element position by hand, directly establishing the control output signal. In manual control, the controller responds to the process but cannot send an automatic control output signal to the final control element.

Manual control is necessary, for example, when a control loop transmitter or controller is being repaired or calibrated. Also, certain processes are started and stopped with controls set to manual, such as when boilers are brought to pressure from cold, or when boilers are taken off-line.

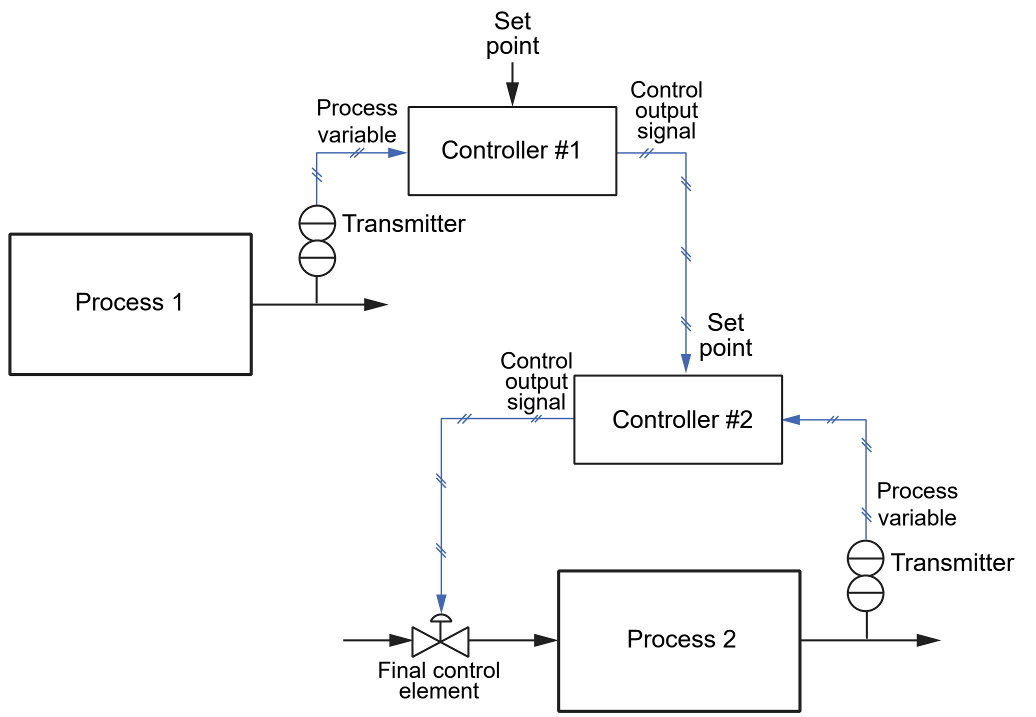
2. Feedback/Feedforward

Most control loops respond to specific process conditions as they change. Since this information is fed back to the controller, such systems are called **feedback** systems. In some specialized control systems, the controller is notified ahead of time about an upcoming process change. The controller can then respond before the change takes place. This is referred to as **feedforward control**.

3. Cascade Control

In some control systems, the output signal from one controller becomes the set point signal for another controller. This is called **cascade control**. Figure 10 shows how the control output signal from one controller can be used to provide the set point of another.

Figure 10 – Cascade Control



Cascade systems may be used for drum level control of larger boilers. In this circumstance, both flow and level information are used to position the boiler feedwater control valve. Some turbines, and other engines, use cascade control for controlling engine speed.

4. Split Range Control

In **split range control**, a single controller sequentially operates two or more control valves.

Refer to Figure 11. In this situation, a single pressure-indicating controller (PIC) operates as a split range device. When the control output signal is between 0% and 50%, control valve "B" modulates from 0% to 100% of its travel range. When the same control output signal is between 50% and 100%, control valve "B" will be fully open, and control valve "A" modulates from 0% to 100%.

Figure 11 – Split Range Control: Both Valves Direct Acting

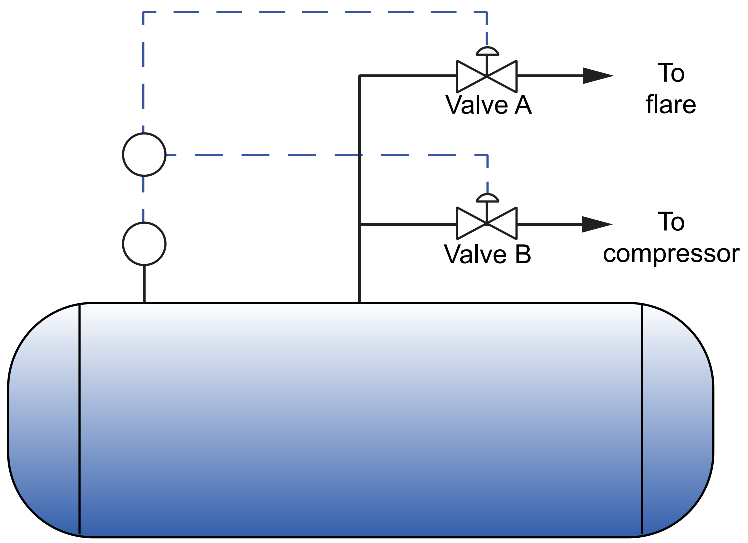


Figure 12 shows another example of split range control. In this situation, the cold water control valve is direct acting (when the control output signal increases, the valve opens), and the hot water valve is reverse acting (when the control output signal increases, the valve closes). The temperature-indicating controller (TIC) tries to maintain a reactor fluid temperature set point by controlling both hot and cold water flows to the reactor jacket.

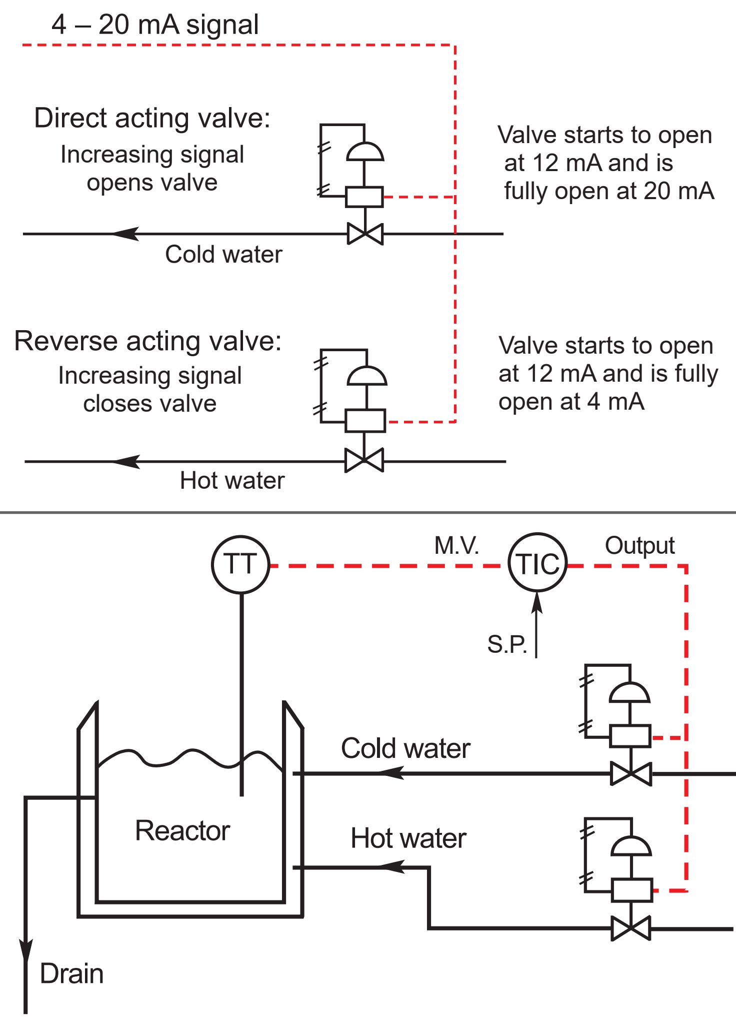
If the reactor fluid is very cold, the controller sends a 4 mA control output signal to both control valves. The cold water valve closes because the signal is below 12 mA (the point at which it begins to open). The hot water valve opens fully to warm up the reactor fluid.

As the reactor fluid temperature reaches set point, the control output signal approaches 12 mA. At 12 mA, both the control valves shut.

If the reactor fluid temperature overshoots (exceeds the set point), the controller signal output rises above 12 mA. At this point, the cold water valve begins to open and cool the reactor fluid, and the hot water valve remains closed.

The opposite sequence occurs when the reactor fluid temperature drops below set point.

Figure 12 – Split Range Control: One Valve Direct and One Valve Reverse Acting



5. High/Low Select Control

High/low select is a specialized control system that has two controllers connected to a single control valve through a select switch or relay. The select switch compares the two control output signals and chooses which one to send to the control valve.

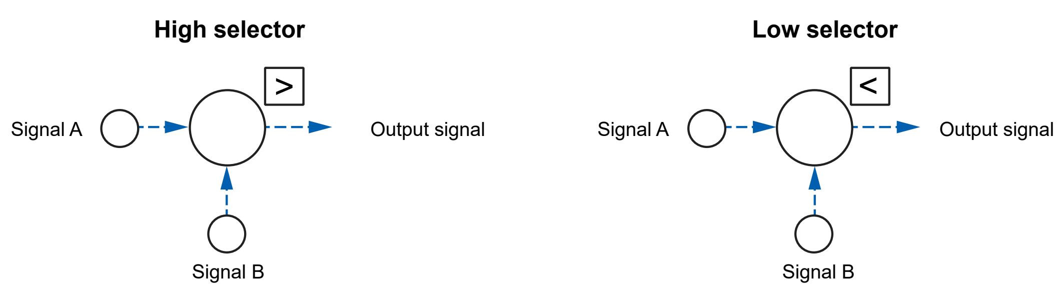
The high-selector relay outputs the input signal that has the highest value (A or B). The low-selector relay does just the opposite; it outputs the input signal that has the lowest value.

Consider Figure 13. If Signal "A" is 5 mA signal and Signal "B" is 7.5 mA, the high selector would put out a 7.5 mA signal. If the same signals were sent to a low selector, the selector output signal would be 5 mA.

High/low select is used in fuel-air ratio control. When output demand rises, airflow increases before fuel flow increases. When output demand falls, fuel flow decreases before airflow decreases.

High and low select features are often used in cascade control strategies, where the output of one controller becomes the set point for another controller. In this situation, it is possible for the primary controller to call for a set point that is unreasonable or unsafe for the secondary controller to try to achieve. If this possibility exists, a selector combined with a manual control station may be placed between the two controllers to limit the cascaded set point signal.

Figure 13 – High/Low Select Control



Objective 4

Describe the construction and operational principles of final control elements.

A final control element is the controlled device that physically changes process conditions by acting on a manipulated variable. The final control element is ultimately responsible for changing the flow of energy through a process, in response to a controller's output signal.

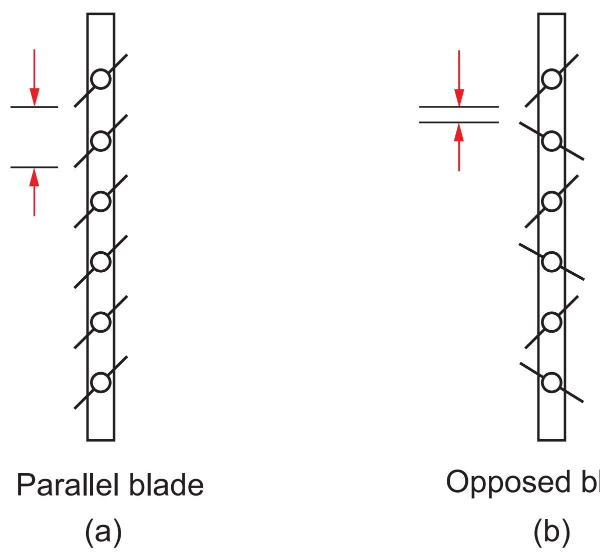
The final control element could be powered pneumatically, hydraulically, or electrically. Some examples of final control elements are control valves, fluid couplings, air dampers, vibratory feeders, screw conveyors, and variable frequency drives.

Even in the age of digital and electronic control systems, compressed air is the most common medium for powering control valves and dampers. For this reason, a plant compressed air system is often referred to as the "heart" of the power plant. Without compressed air, all pneumatically powered control elements would fail.

Dampers

A damper is a device that controls the flow of air through ducts or wall openings. There are two basic types of dampers: parallel blade and opposed blade (Figure 14).

Figure 14 – Parallel and Opposed Blade Dampers

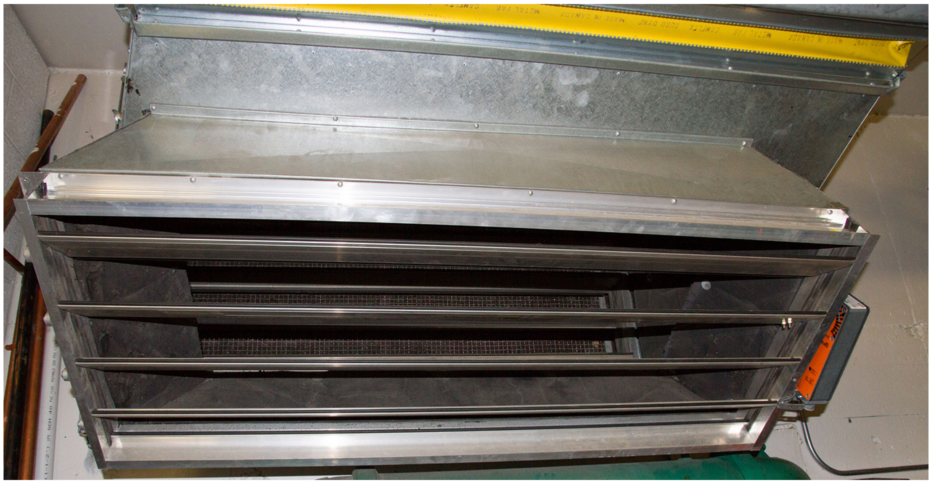


Opposed blade dampers are generally used for modulating control, such as in air mixing to maintain a constant mixed air temperature. A damper set, used to control the cooling air temperature for a diesel engine, is shown in Figure 15.

Figure 15 – Opposed Dampers

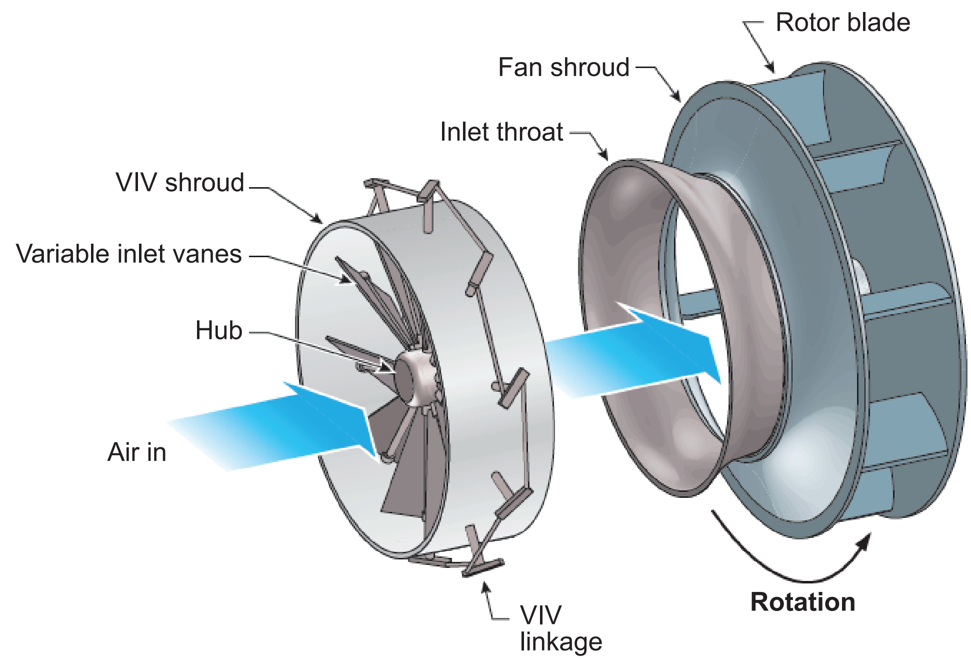
Parallel blade dampers are often used for on-off or open-closed operation, such as those used for exhaust fans. These dampers are fully open when the exhaust fan runs, and fully closed when the fan stops. An example of a parallel damper is shown in Figure 16, which is used to control airflow into a mechanical room when equipment is running.

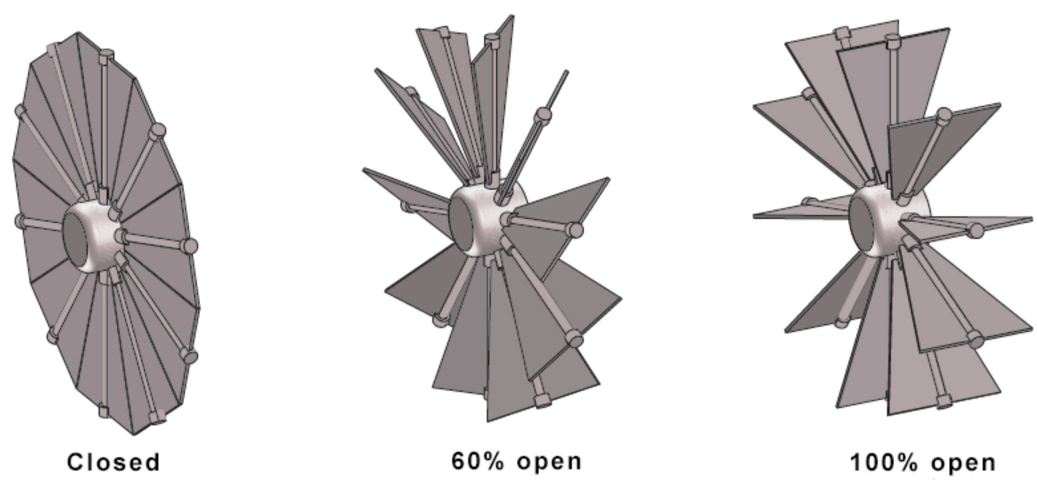
Figure 16 – Parallel Dampers



Another commonly used damper consists of a series of parallel vanes arranged radially around a circular air intake. This **variable inlet vane damper** is shown in Figure 17.

Figure 17 – Variable Inlet Vane Dampers





(Courtesy of Cenovus Energy Inc.)

The reason opposed dampers and parallel dampers have different applications is apparent when looking at what happens as each type of damper begins to open. Refer to Figure 14. Here, both parallel blade and opposed blade dampers are shown approximately one-quarter open. Note the difference between the size of the openings between adjacent blades. The parallel blade damper, when first opening, allows a dramatic increase in airflow. The opposed blade damper, with the same degree of opening, allows much less airflow. The opposed blade damper has a much more precise airflow control, especially at small openings.

Damper Operators

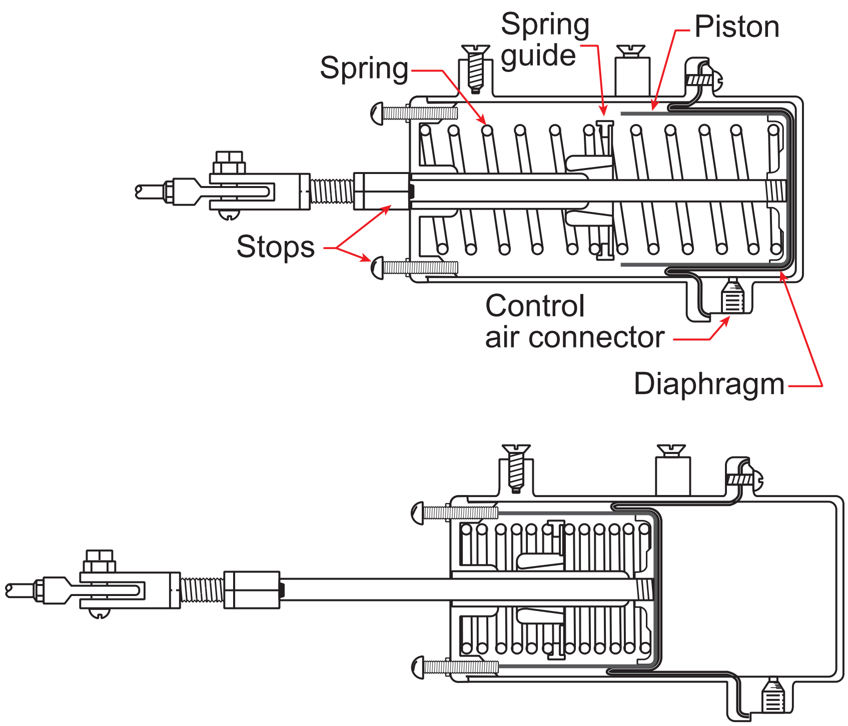
Pneumatic damper operators are available in two types: the metal bellows type and the piston type. The piston type operator is the one most commonly used.

Figure 18 shows a piston type operator in its two extreme positions. Piston operators have long, powerful, linear strokes. The air chamber over the piston is sealed by a rolling diaphragm, which prevents air leakage between the piston and cylinder. A strong spring forces the piston to the un-extended position when the cylinder is not pressurized.

When enough air pressure is applied on the diaphragm by the controller, the piston and stem move outward against the force of the spring. The movement of the stem is used to adjust the damper position. In Figure 15, the damper operator can be seen in the lower right hand side of the image.

The movement of the piston varies proportionally with the air pressure applied. For example, when the range of the control pressure is 20 - 90 kPa, each 7 kPa increase of control pressure will move the piston 1/10th of its stroke. It will reach its half-stroke position when the control pressure is 55 kPa.

Figure 18 – Piston Damper Operator



Pilot Positioners

Pilot positioners are like small controllers. Dampers respond to control output signals. If a damper meets resistance, it will have difficulty moving, and may not assume the correct position required by the controller. The pilot positioner senses the physical position of the damper and compares its position to the output signal from the controller. If there is error between the signal and the damper position, the positioner adjusts the force exerted by the damper drive. This allows the damper to overcome the resistance and assume the correct position.

Control Valves

The majority of final control elements are control valves. This is because in most processes, liquid flow is of primary consideration.

A control valve is a variable resistance or restriction placed in a piping system to control the flow of process fluid (liquid or gas). Control valves can be two-position (open/shut) or fully modulating. The control action depends on the type of valve **actuator** used. For example, two-position valves are often operated with electric solenoids. Fully modulating control valves are usually operated pneumatically, but can also be positioned using electric or hydraulic energy sources.

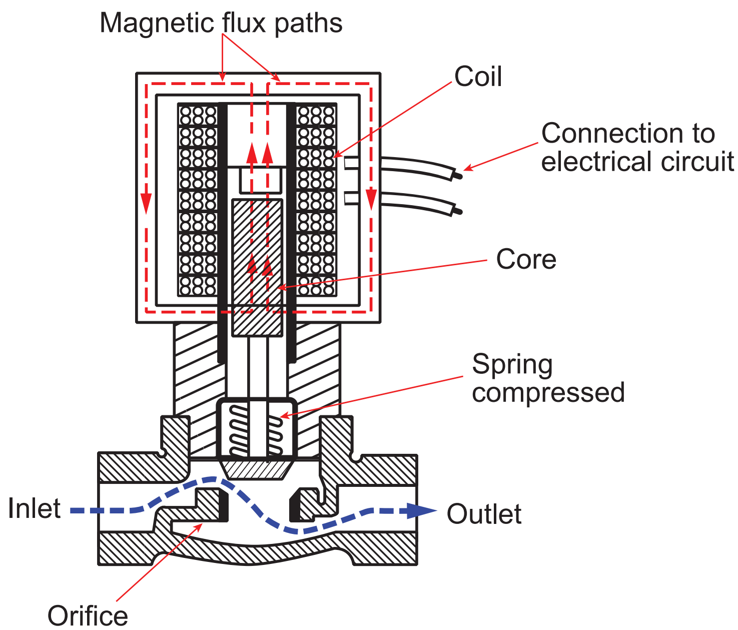
Two-Position Control Valves (Electric Solenoid Valves)

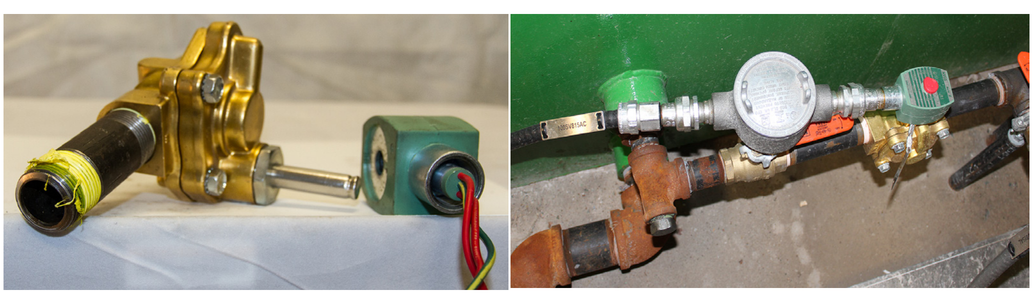
Solenoid valves are one of the most common and simplest type of control valves. They are used in applications where the valve must be either fully open or fully closed.

Figure 19 is a sectional view of a solenoid valve in the de-energized position. This particular valve fails closed. The valve disc is held on its seat by upstream pressure and a compression spring. When the solenoid is energized, the magnetic field of the coil draws the plunger upwards, which opens the valve and further compresses the spring.

When the solenoid coil is de-energized, the spring and the mass of the plunger assembly force the valve shut. Once seated, the pressure differential across the valve helps keep the valve tightly shut.

Figure 19 – Solenoid Valve





Fully Modulating Control Valves

Fully modulating control valves are capable of being fully shut, fully open, or in any intermediate position, based on a control output signal. They are used to throttle flow in accordance with process requirements. For this reason, fully modulating control valves are often globe valves, though other body styles are commonly used.

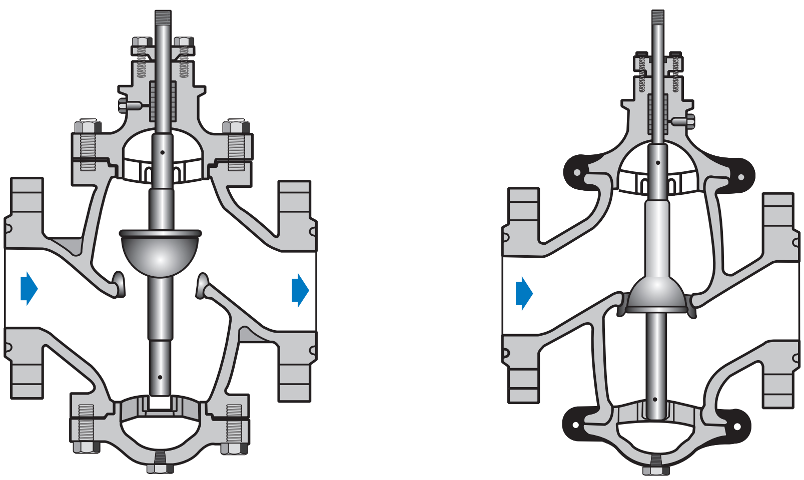
Control Valve Bodies

Valve bodies have different styles or configurations, depending on the service conditions and piping requirements. Control valves may be sliding-stem valves (including globe, gate, cage-guided, and diaphragm types), or rotary-stem valves (including ball valves and butterfly valves).

The most common control valve body style is the single or double-seated globe valve. Single-seated globe valves (Figure 20), are usually used when tight shut-off is required.

In Figure 20(a), the force due to the flow tends to lift the valve from its seat. When the downward movement of a valve plug reduces the rate of flow, the valve is referred to as being “direct-acting.” In Figure 20(b), the valve plug is inverted, so downward movement of the valve plug increases the flow. This valve type is referred to as “reverse-acting.”

Figure 20 – Single-Ported Valves

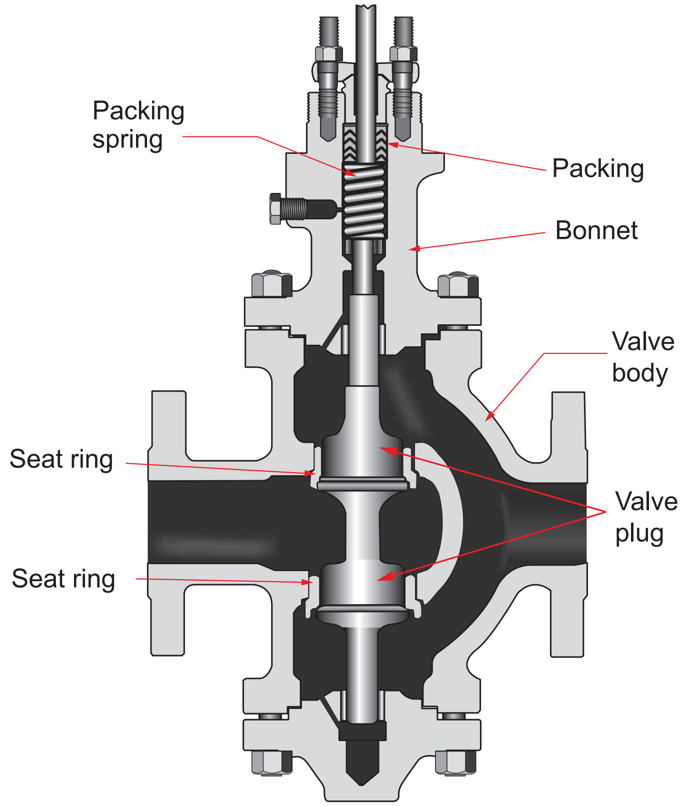


(a) Direct-acting (b) Reverse acting

The double-seated valve, shown in Figure 21, is desirable for flow throttling, because it requires less actuator force to move the valve plugs. This is because the fluid pressure acts on both plugs simultaneously, and the opposing forces cancel each other.

A disadvantage of this type of valve is that a certain amount of leakage can be expected when the valve is in the closed position, as it is almost impossible to fully close both ports at the same time.

Figure 21 – Double-Seated Valve



Actuators

The actuator is the part of a control valve that moves the valve stem. In doing so, the actuator varies the size of the valve opening, according to the size of the control output signal. Actuators must generate sufficient force to overcome the unbalanced forces acting on the valve plug. Actuators are classified according to the input signal and output power used.

Actuators may be powered mechanically, pneumatically, electrically, or electro-hydraulically.

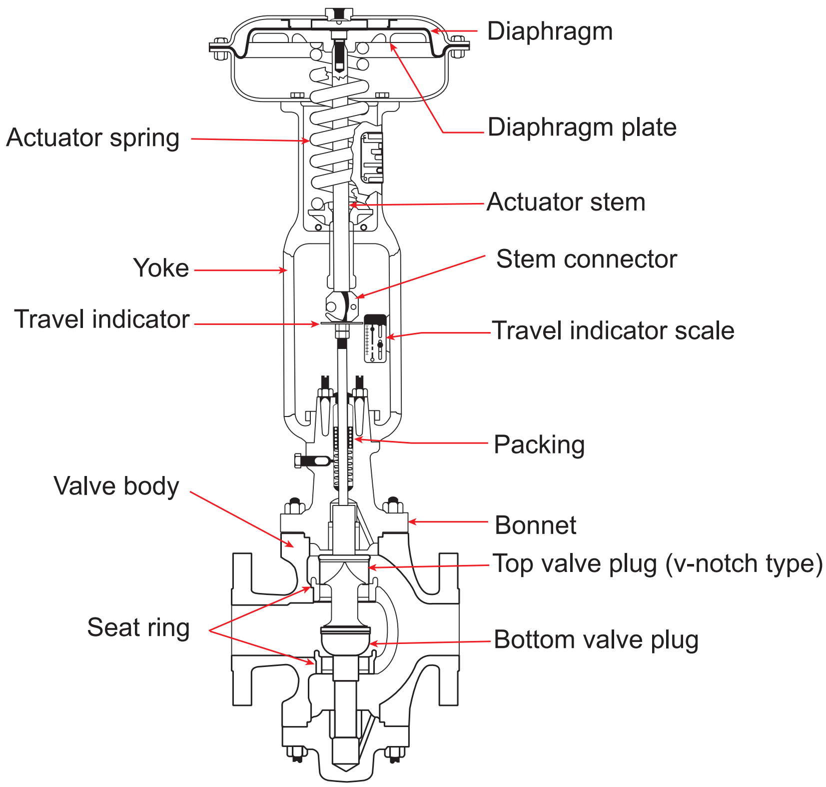
Pneumatic Actuators

Pneumatic valve actuators may be piston or diaphragm types. The diaphragm types are the most common, because they cost less and require little maintenance.

Figure 22 shows a pneumatic diaphragm-style actuator mounted to a valve body. The actuator has a molded flexible diaphragm, and a diaphragm plate inside of a pressure-tight diaphragm case. The diaphragm plate is connected to an actuator stem. An actuator spring opposes the downward movement of the actuator diaphragm and stem.

The valve body has inlet and outlet openings, a seat ring, and two valve plugs connected to the valve plug stem (a double-seated valve is shown). The yoke of the actuator is connected to the top of the valve stem with a stem connector and locknut.

Figure 22 – Control Valve



An increase in control output signal increases the air pressure in the diaphragm case on top of the diaphragm. The increased pressure forces the diaphragm downward against the opposing force of the actuator spring. The motion of the diaphragm causes the valve stem and valve plugs to move closer to their seats, restricting fluid flow through the valve body. When the control output signal decreases, the actuator spring forces the diaphragm and valve stem upward to increase the flow rate.

Valve Positioners

Valve positioners are like pilot positioners used on damper assemblies. Control valves respond to control output signals. If a control valve meets resistance, it may not assume the correct position required by the controller. The valve positioner senses the physical position of the valve stem, and compares its position to the output signal from the controller. If there is error between the signal and the position of the valve stem, the positioner adjusts the force exerted by the valve actuator. This allows the valve to overcome any resistance, and assume the correct position.

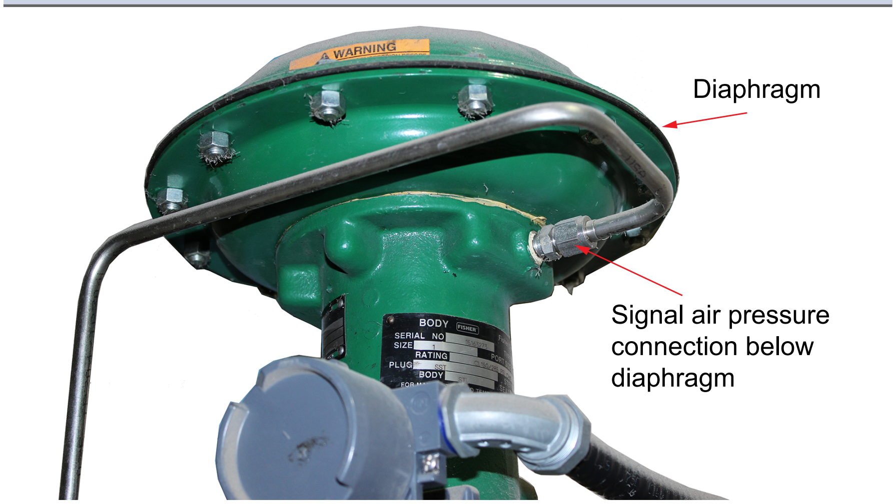
Figure 23 shows a double-seated control valve, with a positioner mounted on the front.

Figure 23 – Control Valve With Positioner

Pneumatic Actuator Action

Diaphragm actuators may be direct or reverse acting. The direct-acting type was illustrated in Figures 22 and 23. In the reverse-acting type shown in Figure 24, the control signal is applied in the chamber below the diaphragm, and the chamber above the diaphragm is vented. An increase in the control output signal causes the diaphragm, the operator stem, and the valve stem upward, against the action of the spring.

Figure 24 – Reverse-Acting Diaphragm Actuator

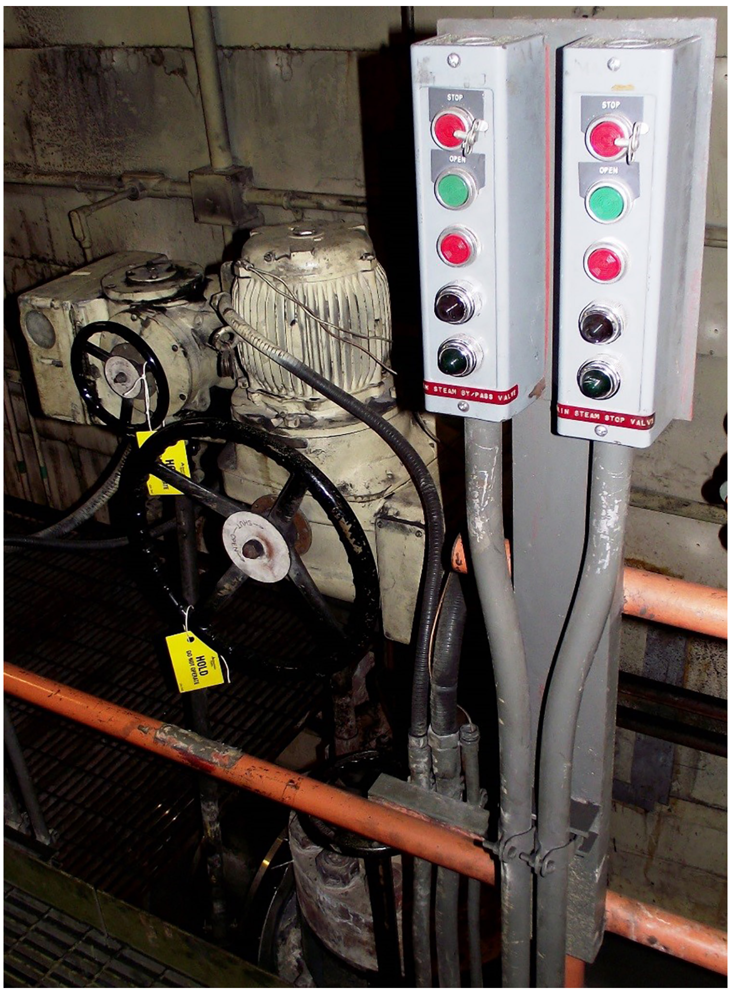


Electric Actuators

Electric actuators for modulating control are powered by electric motors that turn threaded worm gears. When the actuator motor is energized, the worm gear turns a worm wheel. If the final control element is a valve, the worm wheel acts directly on the valve stem threads. This raises or lowers the valve stem.

Electric actuators are often equipped with manual handles so that the final control element can be operated in case of a power outage. Figure 25 shows a control valve with an electric actuator motor, used for high-pressure steam service. Note that it has a local pushbutton control station to open and shut the valve, as well as a manual handwheel for local operation if the electric power fails. The additional control station operates an electric steam bypass valve for charging a steam line.

Figure 25 – Electric Actuator on a Steam Valve



Hydraulic Actuators

A hydraulic actuator consists of a cylinder or fluid motor that uses hydraulic power to create mechanical movement. The mechanical output motion may be linear or rotary.

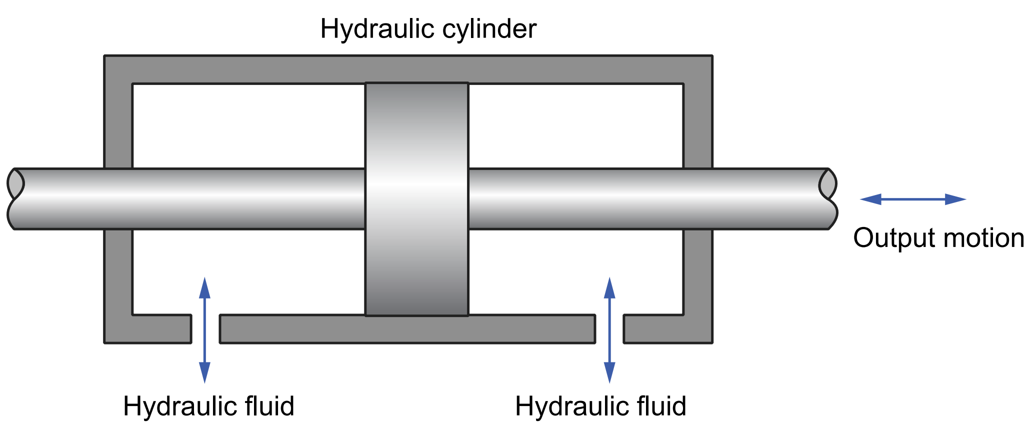
Hydraulic actuators can be positioned precisely and with great stability, which is important for fine process control. There are three main reasons for the precision of hydraulic actuators

1. The hydraulic fluid used to move the output shaft also lubricates the piston, reducing friction.
2. Pneumatic actuators use compressed air, which tends to be elastic, whereas hydraulic fluid is incompressible. Because hydraulic fluid is incompressible, the final control element does not vary in position from forces exerted by the manipulated variable.
3. The pressure used for hydraulic actuators is far greater than that for pneumatic actuators. This high pressure provides far more actuating force, using the same size actuator piston. For example, a hydraulic pressure of 13 800 kPa applied to one side of a 75 mm diameter piston produces a linear force that exceeds 60 kN!

The drawback of hydraulic actuators is that final control elements driven hydraulically have relatively slow acceleration. Therefore, it can take the actuators a longer period of time to move the final control element into its final position.

A hydraulic actuator consists of a hollow cylinder through which a piston moves. A "single-acting" actuator applies hydraulic pressure to just one side of the piston, and the piston can only apply force in one direction. A spring is used to return the piston when the hydraulic pressure decreases. A "double-acting" cylinder applies hydraulic pressure on each side of the piston, as in Figure 26. This type of actuator can apply force in both directions. Any pressure difference between the two sides moves the piston.

Figure 26 – Double-Acting Hydraulic Actuator



Control Valve Failure Mode

Pneumatic control valves fail to operate when their supply air pressure is disrupted (such as when a plant air line ruptures or becomes disconnected, or if the plant air compressor fails). Electrically operated control valves (in particular, solenoid valves) fail when their electric power supply is disrupted. Hydraulically operated control valves fail when their source of hydraulic power is disrupted.

When engineers choose control valves, they must ensure that the valve fails in a safe position. Engineers must first determine what the valve **fail-safe** position is, and then select a valve with the correct action on failure.

Depending on the process application, control valves are selected to do one of the following:

- Fail closed
- Fail open
- Fail in the last position (fail last)

The fail-safe position depends on the action of the actuator (direct or reverse acting) and the action of the control valve (direct or reverse acting). When the supply of motive power to the actuator is interrupted, the actuator spring returns the valve to either an open or closed position.

Consider a safety shut-off valve, controlling fuel flow to a burner. These electro-hydraulic valves open slowly when energized. However, when electric power is interrupted, a powerful spring quickly slams the valve shut, thereby stopping the fuel flow to the burner. In this way, the burner does not receive an uncontrolled (and potentially explosive) flow of fuel.

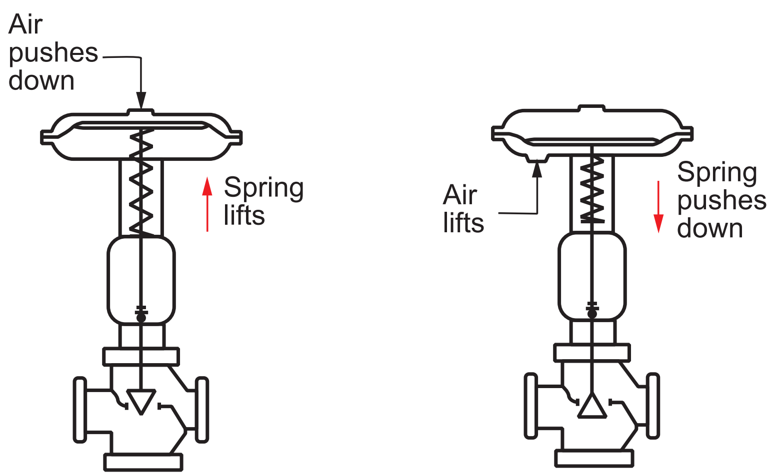
A valve controlling cooling water to a diesel engine, though, should fail open. It is safer for a diesel engine to get too much coolant than too little.

Some process applications require particular valves to fail in their last position. For these applications, special locking mechanisms may be used. Some pneumatic actuators do this by sealing the air in the diaphragm chamber when the supply air pressure drops to an abnormal value. When air pressure returns to normal, the valve resumes normal operation. Electrically operated control valves (other than solenoid valves) typically do not have return springs and therefore fail last.

By combining the correct transmitter action, controller action, actuator action, and valve action, engineers can design processes to remain safe during failure of valve motive power.

Figure 27 shows two different actuator and valve body arrangements that fail open. The first example (Figure 27(a)) shows a direct-acting actuator installed on a direct-acting valve body. The combination reverse-acting actuator/reverse-acting valve body (Figure 27(b)) also fails open.

Figure 27 – Air to Close Valves

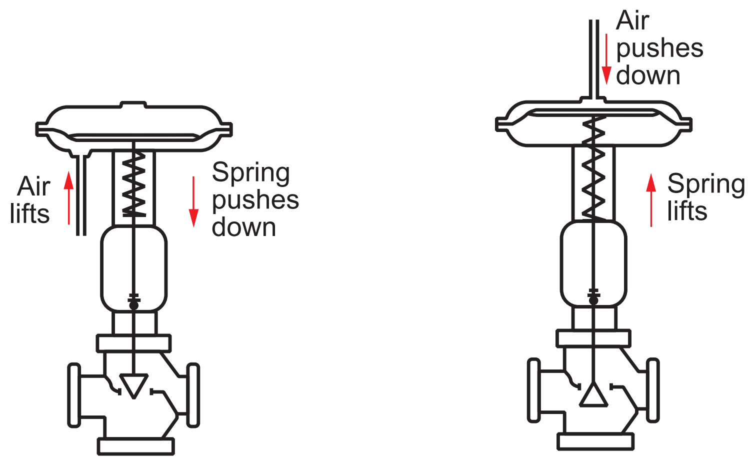


(a) Open on air failure

(b) Open on air failure

Figure 28 shows two different actuator and valve body arrangements that fail closed. The first example (Figure 28(a)) shows a reverse-acting actuator installed on a direct-acting valve body. The combination direct-acting actuator/reverse-acting valve body (Figure 28(b)) also fails closed.

Figure 28 – Air to Open Valves



(a) Close on air failure (b) Close on air failure

Table 1 summarizes the combinations described above.

Table 1 – Failure Action of Control Valve/Actuator Combinations

Action of Actuator	Action of Valve Body	Fail Position
Direct	Direct	Open
Direct	Reverse	Close
Reverse	Direct	Close
Reverse	Reverse	Open

Chapter Summary

This chapter covered the construction and operation of the major control loop components, including indicators, recorders, transmitters, controllers, control valves, dampers, and actuators. The proper interaction of these components assures that processes are controlled safely and efficiently.

Chapter 4

Introduction to Programmable Controllers

Learning Outcome

When you complete this chapter you should be able to:

Describe the operation of programming controls for boilers, including applicable testing and maintenance procedures.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Discuss how programmable controllers work and how they act as sequencers for equipment.*
2. *Describe applications of programmable controllers.*
3. *Explain the HMI (human machine interface) and purpose of touchscreen displays, functions, and alarm handling.*

Chapter Introduction

Programmable Logic Controllers (PLCs) do exactly what their name implies: they control equipment automatically using internal logic that can be accessed and modified to suit particular process control needs. For example, the same brand and model of PLC might be used for controlling a tank level, for batch mixing a slurry or for controlling an incinerator's stack temperature. Each application, though, would require a different programmed set of instructions. Controls engineers and instrumentation technicians design the control sequence, and program the controller for the specific operation it must perform.

Power Engineers interact with PLCs to monitor, start, stop, and troubleshoot a wide range of energy plant processes. Therefore, this chapter introduces and covers:

- Varieties of PLCs
- Structure of PLCs
- Benefits of PLCs
- Applications of PLCs

Objective 1

Discuss how programmable controllers work and how they act as sequencers for equipment.

Development of Programmable Logic Controllers

PLCs were first designed to address manufacturing needs. Consider automotive manufacturers. This industry employs a staggeringly large number of automated processes, including metal forming, welding, machining, and painting to name just a few. Prior to the use of PLCs, these automated production lines were controlled by hard-wired electro-mechanical devices, such as electrical relays, cam timers, and drum sequencers.

Whenever a manufacturer developed a new product, or updated an existing product, teams of electricians would spend countless labour hours re-wiring and re-configuring these hard-wired controls. The first PLCs allowed processes to be easily and quickly re-sequenced and re-configured by merely accessing and re-programming control logic, using special programming language, and computer **interfaces**. This became a huge time and money saver for manufacturing industries. Eventually, the technology became widespread so that practically every energy plant today uses programmable logic control.

The first PLCs only accepted discrete inputs (contact closure inputs), and only sent discrete outputs (contact closure outputs). PLCs have grown to have greater processing power. Because of this, PLCs can now accept and process analog inputs (4 to 20 mA and 0 to 10 V) and digital inputs, as well. In addition to discrete output signals, modern PLCs can also output analog control signals. Because of these features, PLCs can perform both control loop and sequence-of-operation functions equally well.

Structure of PLCs

PLCs are small, rugged computers, designed to withstand the adverse conditions common in industrial sites (such as dust, humidity, vibration, and temperature extremes). Because they must be rugged and reliable, they do not contain moving parts, such as hard drives and cooling fans.

PLCs can be modular or monolithic (self-contained). Larger, more complex PLCs tend to be modular, whereas small PLCs tend to be monolithic.

Modular PLCs can be expanded by adding inputs or outputs in the form of "cards." Cards may be discrete inputs, discrete outputs, analog inputs, or analog outputs. Modular PLCs have the following advantages over monolithic PLCs:

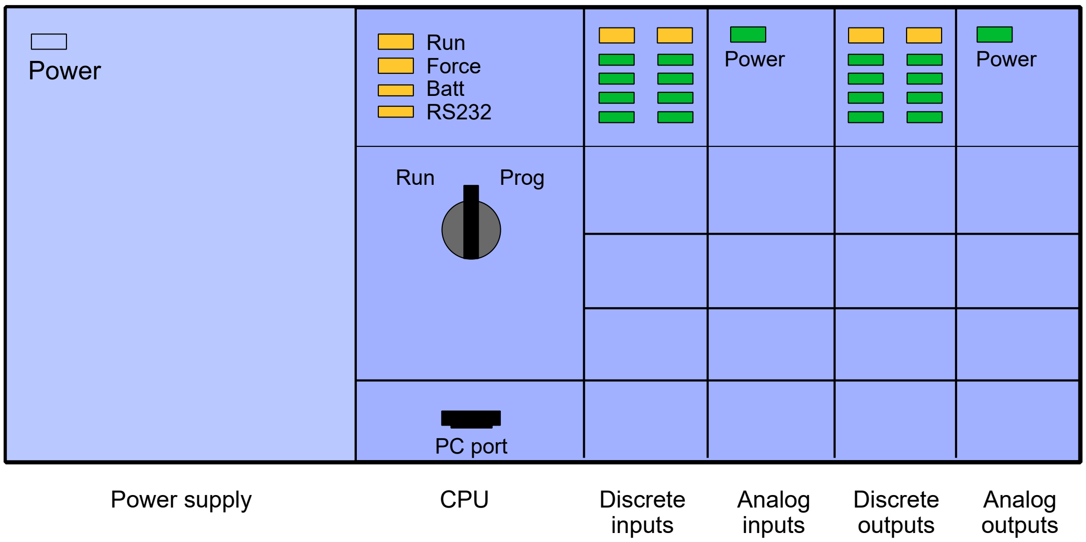
- Input and output cards can be added or removed to adapt to changing process control needs.
- Defective input or output cards can be replaced without replacing the entire PLC.
- Input or output cards can be swapped for other kinds of cards depending on the need.

Consider a failed variable current field transmitter. The failed transmitter could be replaced with a digital transmitter. Because modular PLCs have interchangeable cards, this can be accommodated by merely changing a card to accept the different type of signal and reconfiguring the program.

Figure 1 shows a modular PLC with its various components:

- a power supply
- a **central processing unit (CPU)**
- a discrete input card
- an analog input card
- a discrete output card
- an analog output card

Figure 1 – Modular PLC Components



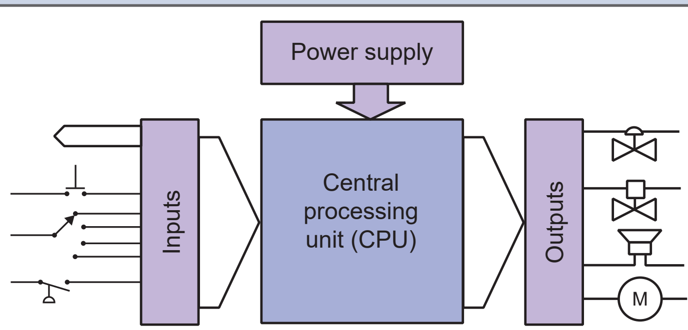
The essential components are the power supply and CPU. As well, the PLC needs at least one input card (discrete or analog), and at least one output card (discrete or analog).

Analog inputs are typically variable current or variable voltage signals from pressure, level, temperature, flow or other transmitters. Analog outputs could be variable voltage or variable current signals for control valves, dampers, or other final control elements.

Discrete inputs may be devices such as manually operated pushbuttons, high or low limit switches, operating limit switches, PE switches, or proximity switches. Discrete outputs may be used for panel lights, warning lights or strobes, alarm horns, motor starters, or EP switches.

Figure 2 shows the essential parts of a PLC, and how they interface with sensing elements and control output devices. The inputs shown include a thermocouple, a momentary contact pushbutton switch, a selector switch, and a pressure-actuated switch. The outputs include a control valve, a solenoid valve, an alarm horn, and a magnetic motor starter.

Figure 2 – PLC Functional Components



Monolithic PLCs are very compact and relatively inexpensive. They perform the same functions as modular PLCs, and accept the same sort of input and output devices. However, they have limited numbers of discrete and analog inputs and outputs, and cannot be expanded.

PLC Logic Operation

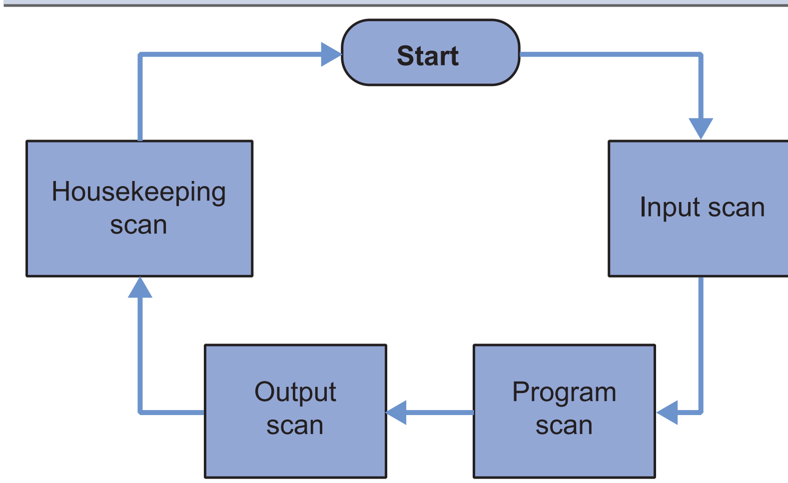
PLCs are commonly used to control sequences of events, like the automatic starting and stopping of equipment. This could be as simple as the sequential starting and stopping of conveyors, or as complex as the startup or shutdown of large steam turbines.

Figure 3 shows the steps a PLC CPU follows when operating as a sequence controller. The CPU completes its control program in four step:

- Input scan
- Program scan
- Output Scan
- Housekeeping scan

After completing this cycle, the program restarts. These four steps will loop for as long as the PLC is in operation.

Figure 3 – PLC Operating Scan Sequence



During the input scan, the PLC checks the state of all the input devices, such as pressure switches, proximity switches, flow switches, manual switches, and level switches. During the program scan, the PLC executes its programmed logic. During the output scan, the PLC energizes or de-energizes output devices, in accordance with the program.

During the housekeeping scan, the PLC communicates with other network devices and programming devices (if being programmed), and performs internal self-diagnostics. The time for the PLC to complete this full cycle (called a **scan cycle**) takes only a few milliseconds.

It may be convenient to think of a PLC's CPU as having numerous internal normally-open and normally-closed switches. In reality, these "switches" are just digital "bits" that represent "ones" and "zeros." The switches can be caused to change state externally, through the change of state of discrete inputs, or they may be caused to change state according to internal programming logic. Some of these internal switches activate contact closure outputs to start and stop equipment.

As well, PLC CPUs have programmable, virtual instruction modules that operate as:

- Counters
- Timers and time delays (on-delay and off-delay)
- Comparative operators (such as greater than, equal, less than)
- Math instructions (such as add, subtract, multiply, divide, square root, and trigonometric functions)

These instructions are combined and utilized as needed for the process being controlled, and remain part of the PLC program.

Objective 2

Describe applications of programmable controllers.

Programmable logic controllers are infinitely programmable. The modular PLCs previously described can be configured and programmed in a myriad of ways, to control nearly any process. However, some programmable logic controllers are more highly customized for a specific function, and have less programming functionality.

For example, some PLCs only have inputs and outputs for specific devices. As well, these PLC-based controls permit only limited programming, such as the configuration of operating set points and limits, alarm set points, ramp-rates, time delays, and external communication. This type of PLC is often customized and installed at the factory by equipment manufacturers. For example, air compressors, HVAC chillers, and automatic power-factor correction capacitor banks come with factory-installed PLCs.

On Track

The following examples are general in nature, and often over-simplified. They are intended to illustrate application of PLCs to logical operating sequences.

Always consult owner's manuals and site-specific information for details about how specific processes and equipment operate.

Lime Slurry Preparation

Consider the production of lime slurry used in a lime-soda water softener. Lime slurry preparation is a batch process. Figure 4 shows the equipment used to prepare batches of lime slurry: a mixing tank, a lime silo, a rotary valve, a screw conveyor, and a make-up water line. A PLC controls the batch mixing process.

The PLC uses four inputs:

- a discrete input for high mixing tank level
- a discrete input for low mixing tank level
- an analog input for lime bin weight (WT)
- an analog input for the make-up water flow (FT)

These inputs send the PLC the information it needs to perform a batching sequence.

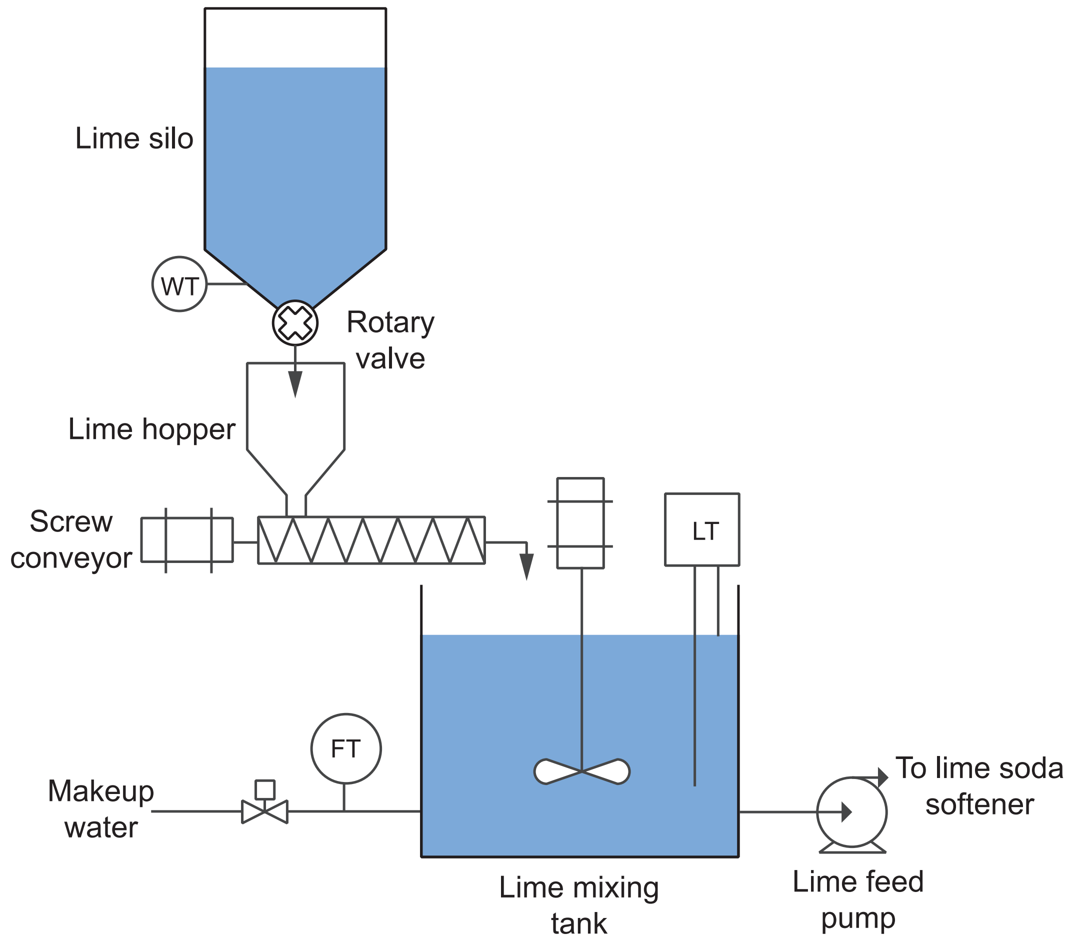
The PLC also uses three discrete outputs to:

- start and stop the rotary valve
- start and stop the screw conveyor and
- open and close the make-up water solenoid valve

The PLC logic is programmed to make batches of 5% lime slurry. To do this, the PLC must know:

- when the mixing tank level is low
- when the mixing tank level is back to normal
- how much water was added
- how much lime must be added to make a 5% solution

Figure 4 – Lime Slurry Batching



When the mixing tank reaches a low level, as determined by the level sensor probe, the PLC starts the solenoid valve for the make-up water line. The flow transmitter verifies that the tank is filling, and reports the flow rate to the PLC. The PLC totalizes the flow, and calculates the actual mass of water added to the mixing tank.

When the mixing tank level reaches the upper probe, the PLC closes the make-up water solenoid, and calculates the mass of water added to the mixing tank. Then, the PLC calculates the amount of lime to add, and starts the rotary valve. The lime silo weight is continually transmitted to the PLC, so it knows when the proper amount of lime has been added to the lime hopper. When the hopper has the correct amount of lime, the PLC stops the rotary valve and starts the screw conveyor. After the lime hopper is empty, the screw conveyor continues for a while on a clean-out cycle, and then stops.

Air Drying

Air dryers are used to remove moisture from the compressed air used to power pneumatic controls and control devices. Many use regenerable **desiccant** media stored inside pressure vessels. As the wet air enters the vessel, the desiccant material adsorbs the moisture, lowering the dew point of the air to tens of degrees below zero.

As the desiccant adsorbs water, it gradually loses its ability to lower the dew point of the compressed air. At some point, the desiccant must be "regenerated" by drying it out. Typically, two desiccant vessels are used in parallel. While one vessel is in service, the other is being regenerated.

Refer to Figure 5. The PLC uses three inputs:

- an analog input for compressed air dewpoint (AIT)
- an analog input for Desiccant Tower 1 internal pressure (PIT 1)
- an analog input for Desiccant Tower 2 internal pressure (PIT 2)

These inputs send the PLC the information it needs to switch over the air dryers for regeneration.

The PLC also uses four discrete outputs to:

- open and close air exhaust solenoid valve "A"
- open and close air exhaust solenoid valve "D"
- open and close Desiccant Tower 1 air inlet solenoid valve "B"
- open and close Desiccant Tower 2 air inlet solenoid valve "C"

The PLC logic is programmed to keep the dry air at a set dewpoint of -40°C. To do this, the PLC must know the value of the dewpoint, which is measured by the dewpoint sensor.

Figure 5 – Desiccant Air Drier Regeneration: Tower 2 in Service

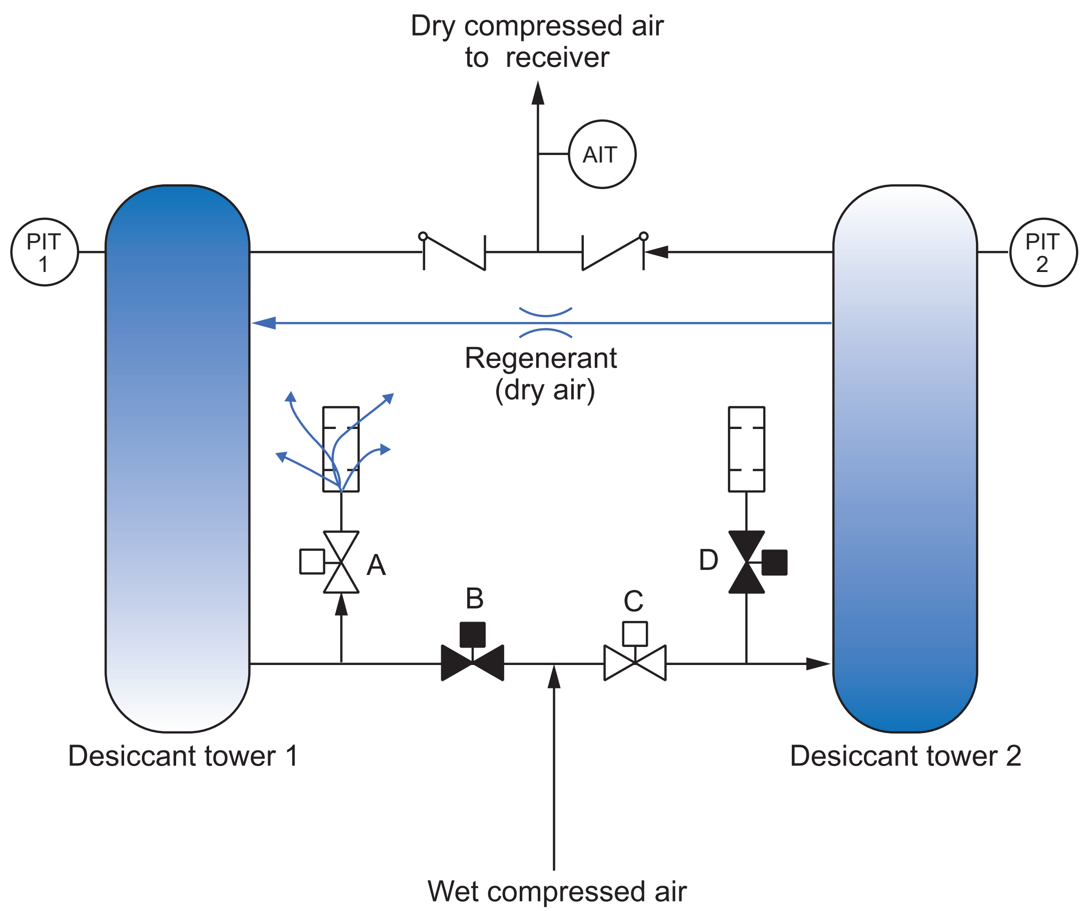


Figure 5 shows Desiccant Tower 2 in service, while Desiccant Tower 1 is being regenerated. The wet compressed air passes through solenoid valve C, Tower 2, and a check valve at the outlet of Tower 2. The air cannot pass freely into Tower 1 because it also has a check valve at its outlet. As the dry air passes to the air receiver, the dewpoint sensor measures the compressed air dewpoint and transmits a 4 to 20 mA signal to the PLC through an analog input.

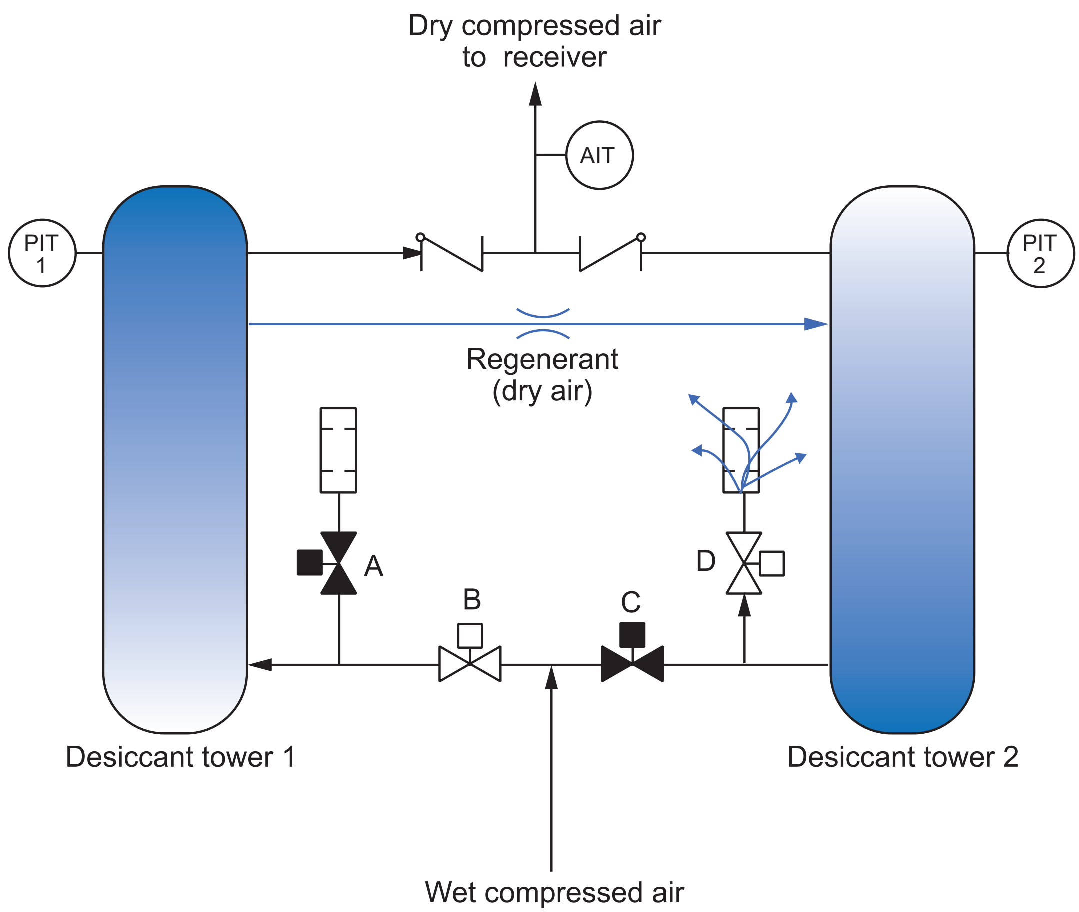
Some of the dry air from Tower 2 is fed though a small cross-over pipe and a restrictor into Tower 1. This air picks up moisture from the desiccant beads in Tower 1, and exhausts the moist air through solenoid valve A and an exhaust muffler. In this way, Tower 1 is continually regenerated, while Tower 2 adsorbs moisture.

When the dewpoint sensor detects that the compressed air leaving Tower 2 is at a particular set value (say, -35°C), the PLC begins a sequence of events:

1. Solenoid valve A closes, allowing Tower 1 to slowly pressurize.
2. When the pressure transmitted by PIT 1 equals PIT 2, the PLC:
    a) opens solenoid valve B
    b) closes solenoid valve C
    c) opens solenoid valve D

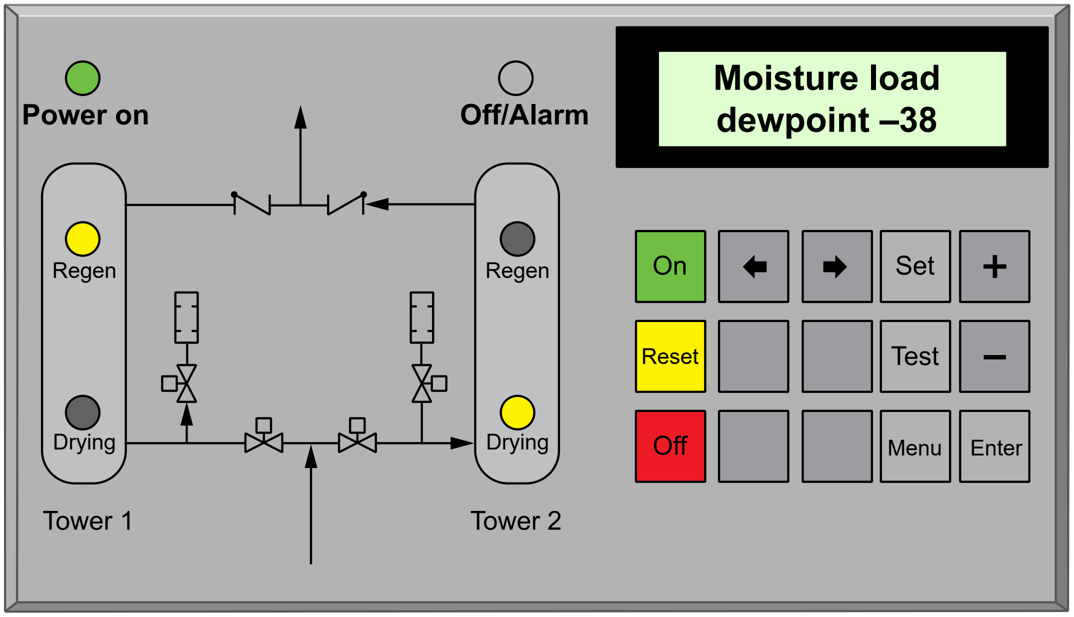
This sequence of events places Tower 1 in service, and Tower 2 begins regenerating (Figure 6).

Figure 6 – Desiccant Air Drier Regeneration: Tower 1 in Service



The drier has a limited number of user programming parameters. Through a human machine interface (HMI), the operator can change display modes, operating and alarm set points, and operating modes, for the most economical operation. As well, the HMI permits the operator to start and stop the dryer, view the dryer tower in service, force a switchover from one tower to another, acknowledge and review alarms, reset alarms and view real-time dewpoint information. A typical HMI is shown in Figure 7.

Figure 7 – Desiccant Air Drier HMI



Burner Management Systems

The **NFPA 85 Boiler and Combustion Systems Hazard Code** defines **Burner Management Systems (BMS)** as:

> *"The control systems dedicated to combustion safety and operator assistance in the starting and stopping of fuel preparation and burning equipment and for preventing misoperation of and damage to fuel preparation and burning equipment."*

Most burner management systems are small programmed combustion controls that offer little or no opportunity for custom program configuration. **Factory Mutual (FM)** is a third-party testing and certification agency for burner management systems. FM identifies these small controllers as those that permit operators and burner technicians to customize *"a limited selection of safety parameters such as purge, trial for ignition and flame failure response time."*

These controllers are made by companies such as Fireye™ and Honeywell™, and are commonly installed on packaged commercial and industrial boilers. They function as flame safeguards, and startup sequence controllers for burners; in this way, they operate like PLCs. Similarly, BMSs have inputs, CPUs, and outputs. Unlike PLCs, they are singular in purpose, and have internal programming that is inaccessible for custom configuration.

As mentioned, PLCs are custom configurable, and can perform nearly any automated task. Though capable of managing burners, PLCs have not often been used for this purpose because they are fully programmable. PLCs used for burner supervision, ignition, and shutdown sequencing can expose plants and their operators to considerable danger, even if initially installed and programmed safely. This is because inexperienced or under-qualified technicians could fully access and alter the control programming. This very real danger was the cause of a 1999 explosion that destroyed an eleven-storey tall utility boiler in the state of Kansas. Therefore, the use of PLCs as burner management systems has progressed slowly and with caution.

Recently, the use of "safety" PLCs has become more widespread. These PLCs differ from conventional PLCs because they have features that make them suitable for use in safety-critical applications. These safety PLCs are currently being applied to certain specialty burner applications.

Factory Mutual-approved burner management systems meet rigorous quality, technical integrity, and performance standards. FM publishes **Standard 7605** *"Approval Standard for Programmable Logic Control (PLC) Based Burner Management Systems"* that they use for approving PLCs for burner management. This standard references the **International Electrotechnical Commission (IEC)** **Standard 61508**, *"Functional safety of electrical/electronic/programmable electronic safety-related systems."*

In Canada, the **Canadian Standards Association B149.3** *"Code for the field approval of fuel-related components on appliances and equipment"* also references **IEC 61508**. CSA allows PLCs designed to **IEC 61508** to be used as primary burner safeguard devices, as long as certain conditions are met. The following points paraphrase some key requirements outlined in **CSA B149.3**:

- The BMS system and program must be designed by a competent person who is completely familiar with all aspects of PLCs, PLC programming and burner operation.
- The PLC must be dedicated to the BMS. It cannot serve any other purpose.
- The PLC program must reside in **electrically erasable programmable read-only memory (EEPROM)**, or other equivalent **non-volatile memory**, so the programming is maintained when the PLC is powered off.
- The BMS must have a **master fuel relay (MFR)**. The MFR must be hard-wired, and must de-energize when there is a component failure, when a critical burner safety limit activates, or when an emergency stop button is activated. The MFR must leave all devices in a fail-safe position, and must only be resettable through manual operator intervention.
- The PLC must have a hard-wired "watchdog timer" that monitors the PLC operating scan rate and sequence, and trips the master fuel relay if the PLC "hangs up."
- All control devices must fail-safe.
- Before the BMS is placed in operation, the designer of the BMS must provide the end user, and the authority having jurisdiction, with documented verification that all devices and safety logic function correctly. This documentation includes:
    i. Functional logic diagrams complete with timer and counter presets.
    ii. Power distribution drawings.
    iii. A list of all error and alarm messages, what the messages mean, and how the operator needs to respond.
    iv. A description of the microprocessor-based system and BMS operation.
    v. A training manual.
    vi. Security procedures, privilege levels, and assignments.
- Accidental program erasure or unauthorized program access must be prevented through access restriction and high-level password protection.
- The end user must not be permitted to alter the PLC program without written approval from the system designer. The end-user must keep the written approval on file until the equipment is decommissioned.

It is difficult and costly to design and certify a PLC for use as a BMS. However, for burner systems that are larger and more complex than those on packaged boilers (like those used for black liquor recovery boilers and rotary lime kilns), it may be reasonable to incur the extra design and certification costs to use PLCs for burner management.

Objective 3

Explain the HMI (human machine interface) and purpose of touchscreen displays, functions, and alarm handling.

Human Machine Interface (HMI)

PLCs are great at controlling processes and sequences. However, alone they cannot provide operators information about process variables, process operating modes, or process set points. As well, PLCs do not permit starting or stopping equipment, changing operating modes and set points, or program changes unless external devices are connected.

For programming, a laptop computer with appropriate software must be plugged into a programming port on the CPU. The software package permits full access to all the PLC operating parameters, including inputs, outputs, and the program itself. This information is required by instrumentation technicians and controls engineers, but is not appropriate for operators.

Operators need to start and stop processes and sequences; observe normal and adverse operating conditions; and acknowledge and reset alarms. For these regular activities, an interface is necessary to provide only the functionality that operators require, without allowing them access to sensitive control programming. This functionality is provided by the human machine interface.

Figure 7 shows a typical HMI for a desiccant air dryer. It shows:

- A simplified graphic of the air dryer system layout
- Which dryer is in service and which is regenerating
- Whether the system is in alarm
- Whether there is a load on the dryer
- The dewpoint of the dry air

By using the keyboard, the operator can:

- Change what is displayed on the readout
- Acknowledge alarm conditions
- Reset the dryer after an alarm or system outage
- Turn the dryer on or off
- Change the compressed air dewpoint set point
- Navigate menu items
- Run a system diagnostic test

The operator does not have sufficient privilege to:

- Reconfigure input or output devices
- Change the sequence of operation
- Alter the communication protocols with networked devices
- Develop different operating modes

HMI interfaces may be small control panels like in Figure 7, or they may be specialized computers (often with touch-screen capabilities). When computerized graphic displays are used as HMIs, the screen may be configured to show the process equipment, piping, system flows, and process variables. These displays are called "mimic diagrams" (Figure 8).

Figure 8 – HMI with Mimic Diagram

The type of HMI in Figure 8 interacts with a PLC that operates a steam turbo-generator. This setup permits two methods of operator interaction with the PLC:

- The touch screen ("Controlled STOP," "Press to Ramp Slow Roll," etc.)
- Hard controls ("Turbine Speed Raise/Lower," "Emergency Stop," etc.)

The hard controls may or may not be hard-wired. If not hard-wired, they communicate with the PLC as discrete or analog inputs.

Modern HMIs support graphic trending, data archiving, and web server abilities to share specific data with networked computers. Some HMIs can log and display data trends over long periods of time, relieving the PLC of this memory-intensive task. To do this, the HMI must receive real-time process data from the PLC. The HMI then records this data using a large memory reserve or a hard drive.

HMIs must draw the attention of operators to alarm conditions. PLCs can be configured to operate horns and strobes when alarm conditions exist. Graphic displays can show alarms in popup boxes on the mimic screen, or on separate dedicated alarm screens. Devices "in alarm" can be configured to flash or appear in a different colour on the graphic display until acknowledged. Alarms can be silenced, acknowledged, and reset with touch-screen fields or physical pushbuttons.

Chapter Summary

Programmable Logic Controllers automatically control equipment with accessible and adaptable internal logic. The same brand and model of PLC can run different sets of instructions. It might be used to batch-mix slurries, sequence conveyor belts, or maintain a process temperature. Controls engineers and instrumentation technicians design control sequences, and program the controller to perform specific instructions.

This chapter examined the main components of PLCs and their functions. Two examples of PLC applications were described to illustrate PLC capabilities as sequencers. Though sequential operations were emphasized, modern PLCs are equally adept at operating control loops.

Power Engineers interact with PLCs to monitor, start, stop, and troubleshoot a wide range of energy plant processes. To do this, operators need to interact with PLCs using human machine interfaces. The HMIs restrict operator access to less critical operating parameters.

CHAPTER 5

Electronic Control Systems and Computer Applications

LEARNING OUTCOME

When you complete this chapter you should be able to:

Describe the design and operation of electronic control systems.

LEARNING OBJECTIVES

Here is what you should be able to do when you complete each objective:

1. *Discuss electronic process control systems.*
2. *Describe computers and how they operate within control systems.*
3. *Describe the applications of computerized control systems and plant computers.*

Chapter Introduction

Computers are found in every modern plant, and serve a variety of purposes.

From a control standpoint, computers may be networked into large distributed control systems, or they may serve as stand-alone controllers. Some computers serve as operator workstations. Other computers are digital controllers. Some computers are servers that permit sharing of data. Personal computers are used to access, troubleshoot, and reprogram control systems.

Computers are used by plant management, operators, storekeepers, and maintenance personnel to plan maintenance, order supplies, set production targets, and input efficient operating parameters. Networking with other computers – including process control computers - permits these various groups to access the information they need to perform their duties effectively.

This chapter describes the various computers and computerized control systems used in modern power plants. It begins with a brief overview of analog and digital control systems. Then, it covers the various computer types, applications, and control system architecture. To understand how computers and computerized control systems handle data, an in-depth view of computer components and how they function, is made in Objective 2. Applications of computerized controls and computers are discussed in Objective 3.

Objective 1

Discuss electronic process control systems.

Electronic Process Control System Principles

Electronic process control systems are well suited to the highly automated processes used in industry. In a simple control system, a process variable is measured and compared with a set point value. A control output signal is generated by the controller and sent to a final control device. This device then influences the manipulated variable to achieve the desired process conditions.

Like other control systems, electronic control systems use:

- Sensors and transmitters (input devices)
- Controllers
- Final control elements (output devices), such as actuators, relays, control valves, and dampers
- Indicating, interfacing, and accessory devices

Sensors are often referred to as transmitters or transducers because their outputs are amplified, or otherwise conditioned signals. These transmitters produce the required voltage or current for an output to a controller, over a desired sensing range.

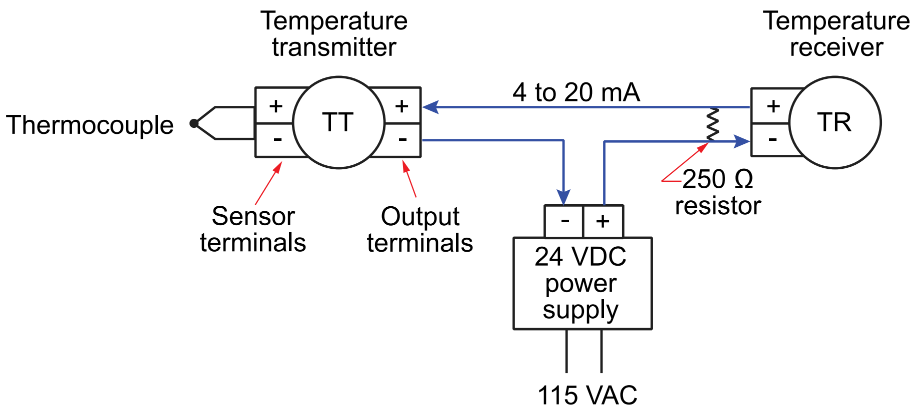
A transmitter regulates its output signal in proportion to the designed range of a measured variable. Variations in the measured variable are converted to variable signals – current or voltage - that are proportional to the measured conditions.

Figure 1 shows a loop-powered 4 to 20 mA signal transmission setup. The power supply for the loop combines a small transformer with a rectifier, and produces 24 VDC from 115 VAC.

The thermocouple (the primary sensing element) generates a variable millivolt signal. The temperature transmitter converts this signal to a variable 4 to 20 mA current. This amplifies the very small millivolt thermocouple signal to a strong enough signal to be transmitted. Variable current is used so the signal can be transmitted with minimal attenuation and noise. The 250 Ω resistor, at the temperature receiver, converts the variable current signal to a variable voltage (1 to 5 V).

The temperature receiver could be a simple voltmeter, calibrated to show the variable voltage directly in temperature units. In an electronic process control system, the receiver is an input/output circuit board (I/O card) linked to an electronic controller. Electronic controllers are digital computers capable of evaluating process conditions and responding automatically to process disturbances, in an appropriate way.

Figure 1 – Loop-Powered Electronic Signal Transmission



Types Of Computer Systems

Servers

A **server** is a central computer that holds a collection of data and software programs. Servers allow connected users to share and store electronic data and applications.

Figure 2 – View of a Server Room

Workstations

Computer workstations are designed for technical applications. Though they appear very similar to personal computers, workstations are faster, more powerful, and have more processing capabilities. Workstations are usually connected to **local area networks (LANs)** and run operating systems that support multiple users.

Personal Computers

Personal computers (PCs) are small, relatively inexpensive computers designed primarily for individual users. Rugged versions of PCs are used to operate process equipment, even in dusty, humid, and hot conditions. Instrumentation technicians often access local control systems using laptop versions of PCs.

Controllers

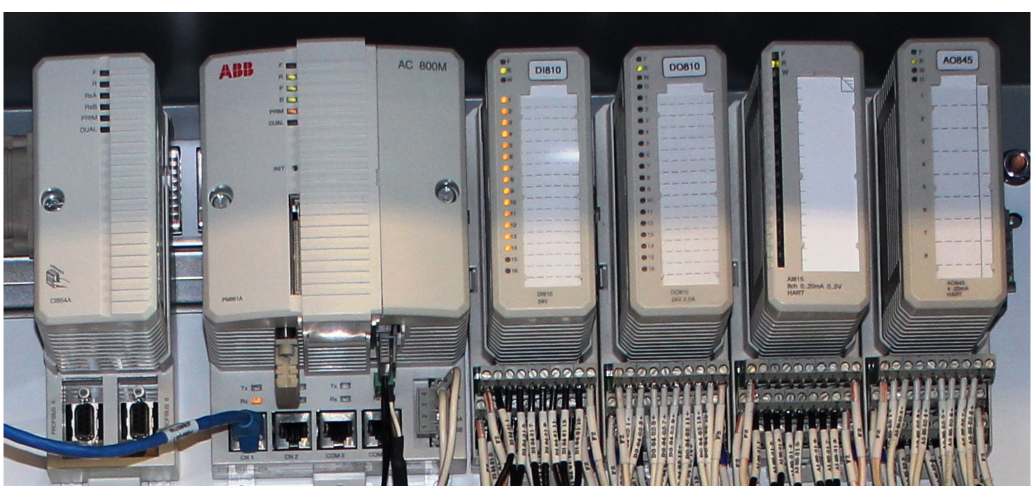
Controllers are small computers equipped with central processing units, communication modules, power supplies, and various accessories. These computers are part of **distributed control systems (DCS)**. They perform process control functions from single or multiple dedicated plant locations.

Figure 3 shows a DCS installation made by DeltaV. The controller is the fourth device from the left. Figure 3 also shows power supplies, and boards for Discrete Inputs, Discrete Outputs, Analog Inputs, and Analog Outputs.

Figure 3 – DeltaV Distributed Control System

Figure 4 shows a similar system by a different manufacturer (ABB). The largest component is the controller (CPU). The modules to the right of the controller are Discrete Inputs, Discrete Outputs, Analog Inputs, and Analog Outputs.

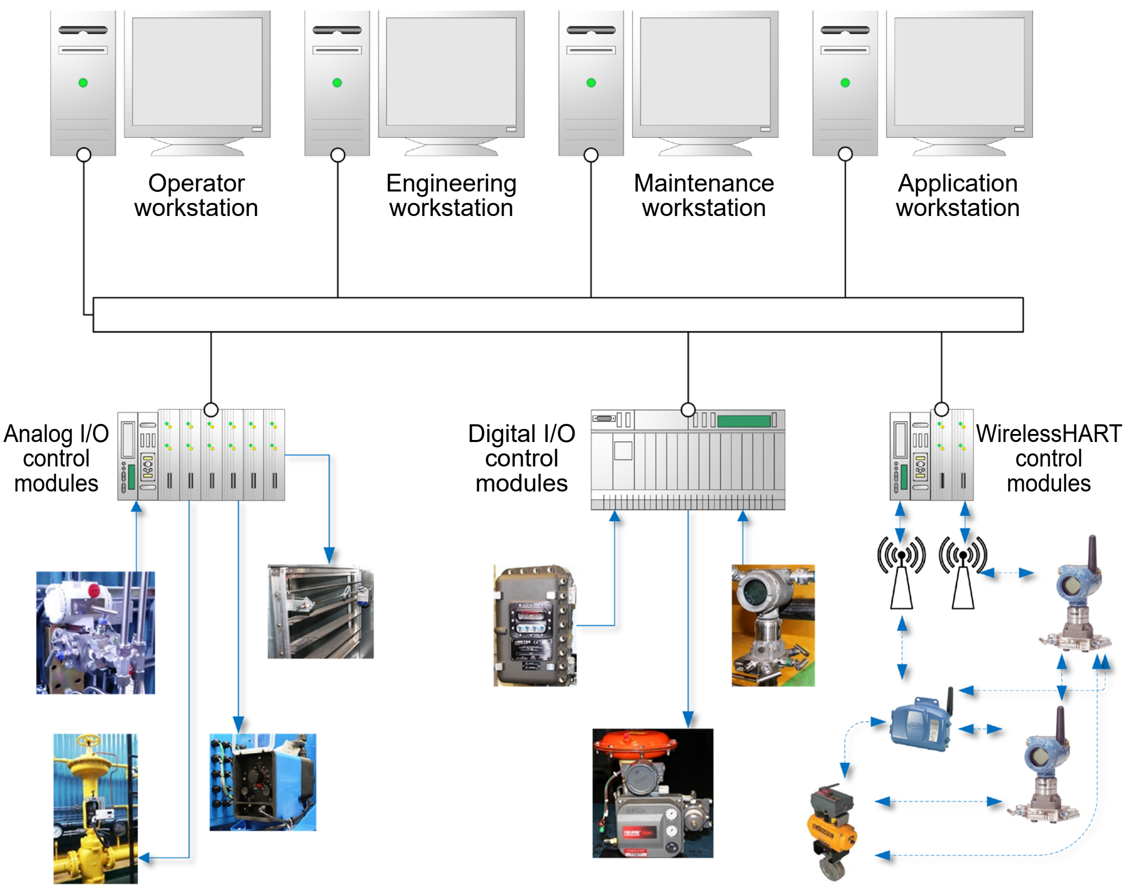
Figure 4 – ABB AC 800M Distributed Control System



Distributed Control Systems (DCS)

Distributed Control Systems are used to control industrial and commercial processes such as electric power generation, oil and gas refining, HVAC systems, and water/wastewater treatment. A DCS typically uses custom designed processors as controllers. These controllers communicate with field devices by using either proprietary or standard protocols.

Figure 5 – Typical DCS System Architecture



The main parts of the DCS are:

- DCS network
- Power supplies
- Input modules
- Output modules
- Controllers
- HMIs and workstations

The controller receives information from input modules and sends information to output modules. The input modules receive information from field transmitters, and the output modules transmit instructions to final control elements. The inputs and outputs can be either analog or discrete signals. The DCS network connects numerous controllers with the HMI consoles.

The HMI consoles are dedicated for particular uses. The engineering workstation has full access to the control system, for programming and system optimization. The operator workstation provides lower level access; operators can shift between manual and automatic operating modes, change set points, and over-ride some control features. The maintenance workstation can monitor equipment and process actions, to facilitate maintenance activities.

Programmable Logic Controllers (PLCs)

Programmable Logic Controllers are rugged, special-purpose, industrial computers, that run extremely reliable operating system software. They are commonly used to control sequences of events, but can run PID control loops, as well. Large PLC systems have racks to plug circuit cards into. These cards contain processors, inputs and outputs, communications ports, and other components to complete a PLC system.

PLCs can be used as networked controllers within a DCS system. The networked PLCs can be accessed from central control stations. Because control programming resides within PLCs, they can continue to provide process control even if separated from the system due to network malfunctions.

Control System Networks

In electronic control systems, many users share the same stored data and applications over networks. Networks often have duplicate redundant systems to insure against network outages.

Industrial computer control systems can have several different types of networks. These can be broadly classified as:

> **Sensor bus networks**: These contain simple devices such as switches, pushbuttons, and proximity sensors.
>
> **Device bus networks**: These are used with more complex devices, such as temperature transmitters and variable speed drives.
>
> **Field bus networks**: These interconnect smart systems, such as controllers and PLCs.

Components and Peripherals

Smart Transmitters

Smart transmitters have built-in microprocessors that handle both digital and analog signals. Smart transmitters can:

- Receive multiple inputs and outputs
- Communicate and change configuration details
- Signal alarms and error conditions

Figure 6 – Smart Transmitters

Display Terminals

The computer communicates with an operator through a colour display monitor. The monitor shows the inputs and outputs in various ways:

- Lists printed on-screen
- Graphical indications, similar to chart recordings
- Representation of a controller automatic/manual faceplate
- Pictorial layouts of the controlled process

Other visual devices include light emitting diodes (LEDs), and liquid crystal displays (LCDs). These displays – often located on field transmitters and PLCs – can give graphical and alphanumeric readouts.

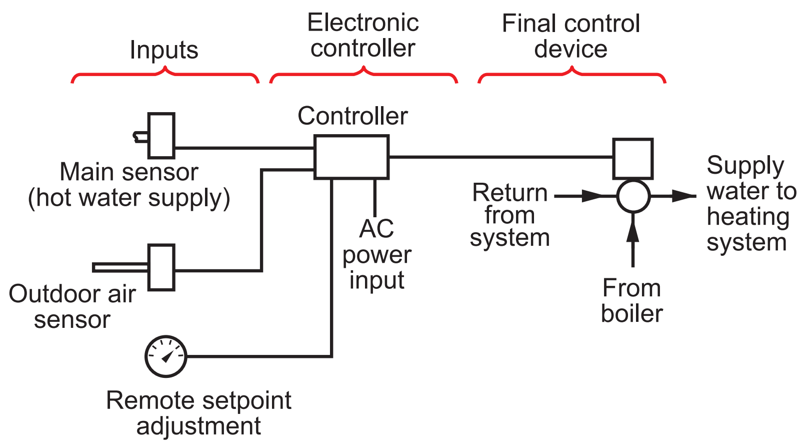
Printers

Printers are used to produce permanent paper records of process trends or process conditions at a particular point in time (as "screen shots"). Many control systems use printers to document alarm conditions and alarm responses as they occur. This is useful for determining exactly when an alarm condition occurred, the sequence of events after the alarm occurred, and which alarm initiated the sequence of events. With this information, operator responses can be evaluated and improved, operation manuals can be revised, and systems troubleshot as required.

Example of a Basic Electronic Control System

Figure 7 shows a schematic of a simple electronic control system with a controller that regulates supply water temperature by mixing return water with water from the boiler. The main temperature sensor is located in the hot water supply from the valve. To increase efficiency and energy savings, the controller varies the supply water temperature set point as a function of the outdoor air temperature. The controller analyzes the sensor data, and sends a signal to the valve actuator to regulate the mixture of hot water to the unit heaters.

Figure 7 – Simple Electronic Control System



(Courtesy of Honeywell Inc.)

Control Modes

The control modes of electronic controllers can be selected by the operator to suit the application requirements. The process controllers are typically configured to have three operating modes:

Manual mode: The controller takes no automatic action. The control output signal is set by a human operator.

Automatic mode with local set point: The set point is determined "locally" by a human operator.

Automatic mode with remote set point: The set point is determined "remotely" by a supervising computer.

Objective 2

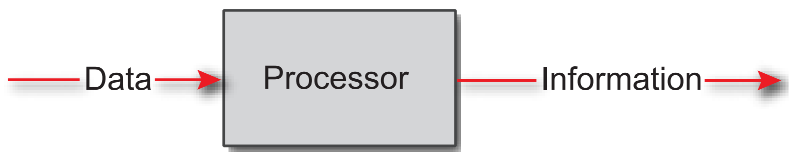
Describe computers and how they operate within control systems.

Basic Operating Principles of a Computer

A computer is an electronic device that takes raw input data, processes it, converts the processed data into meaningful information, and presents the data in an understandable output format.

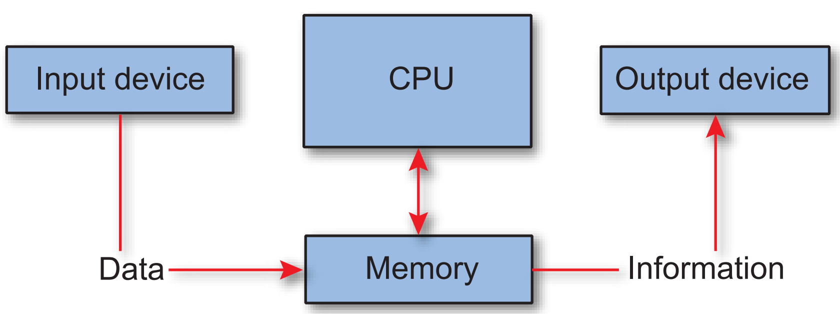
- The data consists of numbers, text, sound, images, animations, and video.
- The process converts numbers, text, sound, images, animations, and video (data) into usable data, which is called information.
- The information consists of numbers, text, sound, images, animations, and video that has been converted by the process.

Figure 8 – Basic Operating Principle of a Computer



Basic computers have four components: an input device, a CPU, memory, and output devices.

Figure 9 – Basic Components of a Computer



Inputs and Outputs

Operator Inputs

The most common method of operator input is through a keyboard. The keys may be mounted under a flexible membrane, to seal them from the dust and dirt common in industrial environments. Spilled coffee on a standard keyboard could be disastrous, but would not damage a membrane keypad.

Some plant control systems use proprietary keyboards with special keys, labelled with functions such as MANUAL, AUTO, SETPOINT, RAISE, LOWER, and ENTER. PLCs often have keys for navigating menus, raising or lowering set points, and selecting various other functions.

Most plants have operator workstations with conventional keyboards. These keyboards have programmable control functions, accessed using the "F1" to "F12" keys on the keyboard. The monitor displays the function of each key. Some function keys may be programmed to save, retrieve, list, or edit data on a disk. Keys can be programmed to call up different operator screens or menus. Using function keys is faster and simpler than typing lengthy commands, or following mouse-click sequences, which is a great advantage for plant control.

Touch screen use has become fairly common, especially on dedicated equipment HMIs. Figure 10 shows an operator HMI that accesses and controls an HVAC chiller. Note that its keyboard has dedicated function keys.

Figure 10 – Chiller HMI

Cursor Movement

Cursors show the location on the display for operator input. Cursors may be boxes or small lines. They may flash, or be of a distinctive colour, so that the operator can clearly see its location. The cursor location can be changed by mouse, joystick, tab button, spacebar, or arrow keys. Arrow keys move the cursor right, left, up, or down on the screen.

Process Inputs

Control system computers may receive process information via discrete voltage signals, through contact closure inputs. These signals may be provided by flow, temperature, pressure, level, or proximity operated switches. Voltages that may harm process computers are kept isolated from the computer using special circuitry.

Transmitters that provide analog 4 to 20 milliamp signals are connected to process computers via analog input terminals. Before the computer can work with these signals, they must be converted to digital code using analog to digital converters.

Transmitters that provide information in digital code require dedicated digital inputs. These digital transmitters are called smart transmitters.

Process computers can collect information from other computerized devices, only if the proper communication language or protocol is used; otherwise, the computers cannot understand each other. This book, written in English, would be of no help to someone who reads only French. The same situation applies when a signal transmits information in a protocol different from that understood by the receiving computer.

Information Output

One of the main functions of a computer is to gather information and present it to operations, maintenance, and management staff. The chief method used is the LCD monitor.

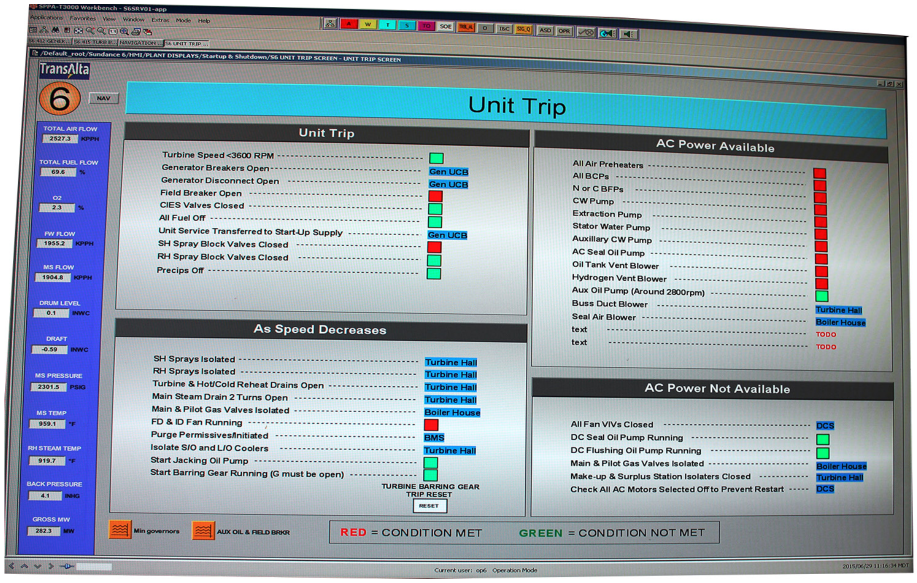
The simplest information display shows only text. Modern systems take advantage of the additional dimension provided by colour. A list of measured points can be displayed on the monitor with colour used to indicate status. A typical system may use:

- Green for normal
- Red for alarm
- Yellow for deviation from normal
- Cyan for a bad reading

A flashing reading can show a change of state.

Figure 11 shows a text display of generating unit trip conditions at a thermal generating station. In this control system, the colour red indicates "satisfied" or "permissive," and the colour green indicates "unsatisfied." The left hand side of the screen provides additional information to the operator about the boiler operating conditions.

Figure 11 – Unit Trip Screen

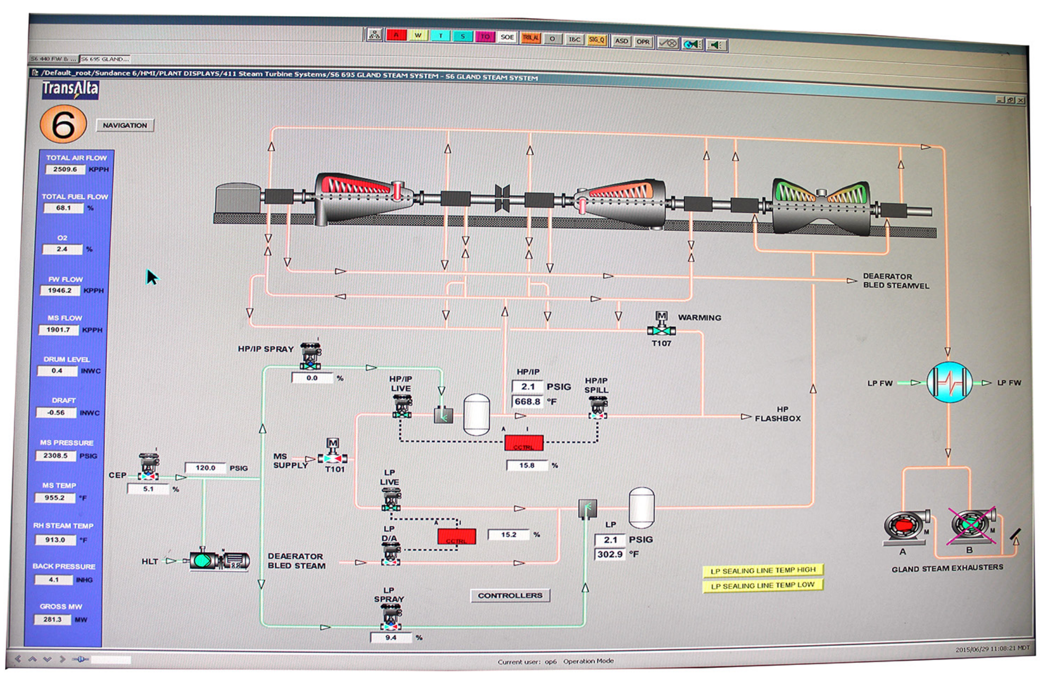


(Courtesy of TransAlta)

Figure 12 shows a graphic of a turbine gland steam control system. Note the graphic representation of the steam turbine, the process lines, and other equipment, including control valves and gland steam exhaust fans.

Motor status is shown in red and green. Valve positions are indicated digitally beside the individual valves. Control valve operating parameters (set points and manual overrides) can be accessed by clicking, with a mouse, on the control valve or the entry field adjacent to the valve. Fan and pump motors can be started and stopped by clicking on the individual components displayed on the screen.

Figure 12 – Turbine Gland Steam Control Screen



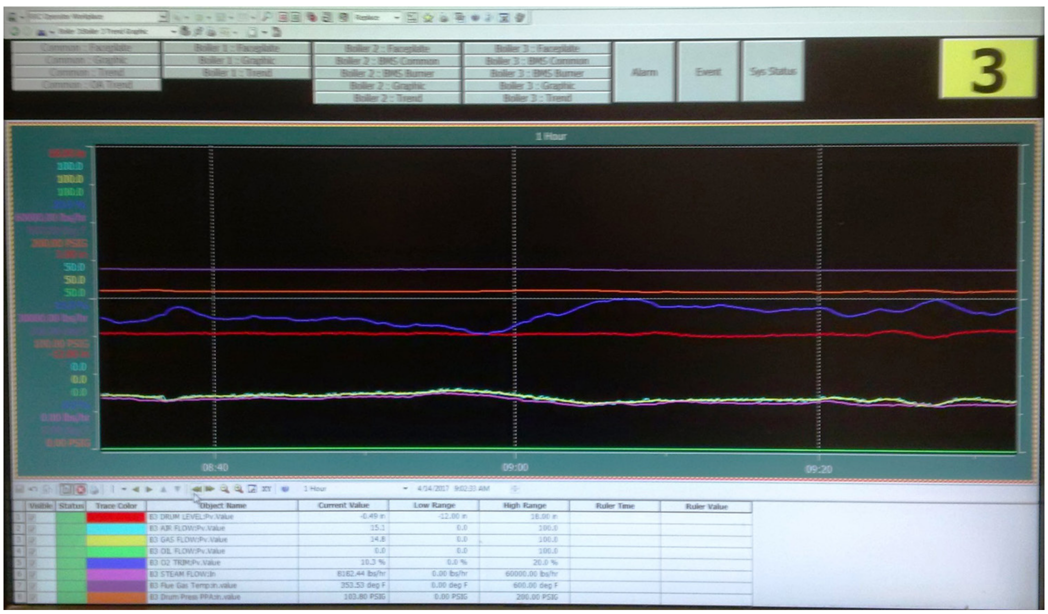
(Courtesy of TransAlta)

Computerized process control systems use electronic displays, rather than paper chart recorders, to show process trends. These displays are user configurable to show the simultaneous conditions of any one of thousands of control parameters, including flows, valve positions, temperatures, levels, and pressures.

An example of a boiler trend is shown in Figure 13.

- The blue line tracks O_2 trim.
- The red line tracks boiler drum level.
- The orange line tracks fuel flow.
- The orange line tracks drum pressure.
- The purple line tracks flue gas temperature.

Figure 13 – Boiler Trend Screen

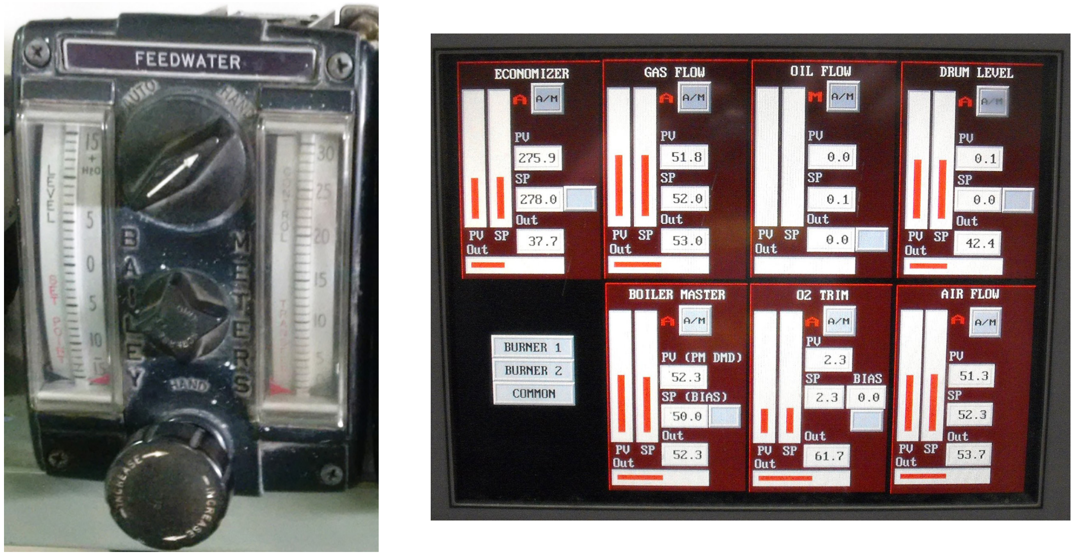


Another common screen display shows one or more controller faceplates which simulate the actions of a pneumatic controller hand/auto station. Figure 14 shows an old Bailey pneumatic control faceplate beside a modern ABB computerized control faceplate. Note the similarity of the features. Each control faceplate has readouts for:

- Process variable (PV)
- Set point (SP)
- Control output (OUT)

Also, each faceplate has an Auto/Manual selector.

Figure 14 – Control Faceplates: Pneumatic versus Computerized



Control Output

A computer can be programmed to start or stop equipment, turn lights on or off, ring alarms, and perform any function that can be operated by a switch. Voltage outputs, known as discrete outputs or contact closure outputs, energize relays that act as switches to turn equipment on or off.

Control valves, dampers, and variable speed drives can be positioned over their operating range by taking the digital output from the computer, and converting it to an analog signal with a digital to analog converter. The equipment to be controlled is wired to terminals known as analog outputs. Some output devices can accept the digital code outputs directly.

PROGRAMS

A computer program is a series of instructions which causes a computer to do a useful task. Without a program, a computer is a useless collection of silicon chips, power supplies, and wires. Once programmed, a computer will repeat the instructions exactly each time it is requested.

Most computers use programs known as software packages, developed by programming specialists. In an industrial plant, the control and monitoring computers have software packages that allow the plant operator to use the computer effectively, without requiring a knowledge of programming. Modern control software operates with familiar "windows," that can be arranged, opened, or closed according to operator preference or need.

Program Data

The software programs required to operate computers are stored on a hard disk, because of the large storage capacity needed, and because program information must be maintained whenever a computer is powered off. Programs are loaded into the computer **random access memory (RAM)** as required. Programs which are always required, and must not be modified are be stored in **read-only memory (ROM)**. Those programs that need occasional modification are stored in **erasable programmable read-only memory (EPROM)**.

User Friendly Systems

Menus are used in control system software packages to make the operation of equipment and control systems user friendly. LCD or touch screens display lists of functions from which the operator can select by pointing to the desired function using the mouse or cursor direction keys, and then clicking the mouse or pushing the RETURN or ENTER key. The operator does not need to memorize any special commands.

Control software often utilizes pull down menus to present further options when an object or command is selected.

Components and Peripherals

Motherboard

A motherboard is the main printed circuit board found in computers. It holds and allows communication between many of the crucial electronic components of a system, such as the central processing unit (CPU), memory, and provides connectors for other peripherals.

Central Processing Unit (CPU)

The main part of any computer system is the central processing unit, commonly referred to as the CPU. This component contains complex circuits which accept input numbers, perform calculations in accordance with a program, and output the results.

Computer Memory

The working memory of a computer is made of silicon integrated circuit "chips" that store information by turning miniature circuits on or off. This memory may be permanent or temporary depending on the type of chip and its purpose.

The amount of memory is equal to the number of circuits that can store information. Each "bit" is a silicon switch that can be on or off. Bits maintain their state until instructed to switch to the opposite state. The state of each bit is either "1" (on) or "0" (off). Bits are collected in groups of eight called "bytes." One megabyte is one million bytes, or 8 million bits.

Random Access Memory (RAM)

RAM is the abbreviation for random access memory. This type of circuit can be used to store (write) and retrieve (read) information. RAM requires power to maintain the stored information. RAM retains its contents while powered on. However, when the power is interrupted, the stored data is lost immediately. Large programs require large amounts of RAM. Insufficient RAM can cause computers to slow down or stop functioning.

Read Only Memory (ROM and EPROM)

Read Only Memory (ROM) is used for program information that must be preserved when the computer is powered off. ROM stores information permanently "burned" onto a memory chip. ROM is used for programs such as the computer start-up sequence. To change these programs, it is necessary to replace the ROM chip.

EPROM is a type of re-programmable ROM, which allows computers to be configured for particular applications.

Hard Disk Drive (HDD)

A hard disk drive is a data storage device used to store and retrieve data, using one or more rigid, rapidly rotating disks coated with magnetic material. HDDs retain stored data even when powered off. Solid state HDDs do not have mechanical rotating disks, but are generally of lower capacity.

Power Supply

A computer power supply converts low voltage AC (say, 115 VAC) to extra-low voltage regulated DC power (say, 24 VDC), required for the internal components of a computer. Some power supplies have a manual selector for input voltage; others automatically adapt to the supply voltage.

Plotters

A plotter is a large-format printer used to produce high quality engineering diagrams and schematics.

Multiplexers

A modern computer processor can complete billions of operations per second. In a plant, this allows process computers to read from many process points, perform control calculations, adjust valves and dampers, start and stop pumps, print out log sheets and display information on operator consoles.

The tasks performed by process computers occur in rapid sequence. Important tasks such as boiler firing rate regulation may be adjusted several times per second. Less critical tasks, such as regular process report printouts, may be done once per hour or once per day.

To read all the input points in sequence, an input **multiplexer** or "mux" is used to select the correct computer input at the correct time. Similarly, an output multiplexer connects the computer output to the correct output device at the correct time. This timing is critical to ensure proper operation.

For example, if a feedwater control task is being done, the input multiplexer connects the boiler water level transmitter to the process computer. The computer compares this signal to the set point and calculates a new feedwater valve position. The signal to position the valve is then directed to the proper location by the output multiplexer. The input and output multiplexers synchronize the input and output signals, so the proper control devices are accessed during each control task.

Analog to Digital and Digital to Analog Converters

Process computers, through specialized I/O boards, accept and transmit discrete, analog, and digital signals. However, the signal processing and computing abilities are all performed with digital information. Digital input and output signals (either discrete or direct digital) are processed by computers directly.

Analog signals vary continuously over a range of values. Analog input signals must be converted to digital format before they can be processed by computers. As well, when final control elements are analog, the digital control output signals from process computers must be converted to analog signals.

For the signal input conversion, a digital equivalent is determined by adjusting an internal voltage in a number of digital steps until it matches as closely as possible to the input. This number is then passed to the CPU for calculation. For output conversion, the process is reversed. The digital number from the CPU switches a number of precision resistors from a regulated power supply, and the switch combination determines the analog output signal.

Data Storage and Backup Strategies

Normally data is stored on hard disk drives, located in individual computers, or in networked locations that serve numerous computers. The data on these hard drives is "backed up" by copying the information to other storage media on a regular basis. This ensures data is not lost. To help ensure security, backed up data should be encrypted.

Data backup can be either online or offline. Online data backup involves "cloud" storage. In this case, the data required to restore systems is only available when connected to the internet. Offline data backup stores data in locally kept hard devices, such as tapes, disks, DVDs, or CDs. Backup media (disks and tapes) must be kept physically secure, to prevent theft of data. Offline data restoration can take place without an internet connection.

Full Backup

A full backup is a complete copy of an entire data set. Although full backups provide the best data protection, most organizations only use them periodically. This is because full backups are time consuming, and often require a large number of tapes or disk.

Full backups may be performed daily for critical data, or at other intervals (such as weekly or bi-weekly) for less critical data.

Incremental Backup

An incremental backup is one that only backs up:

- Files that are new or have changed since the previous full backup
- Files that are new or have changed since the previous incremental backup

For example, a full backup may be performed on a Sunday night. Only the files created or modified on Monday during the day will be backed up Monday night. On Tuesday night, only the files created or modified on Tuesday will be backed up. The same occurs each consecutive night, until the next scheduled full backup.

Incremental backups were developed to take less time than full backups. The main disadvantage to incremental backups is that they can make the restoration of data difficult and time-consuming.

Differential Backup

A differential backup is like an incremental backup, except that consecutive backups save all new or modified files since the last full backup. For example, a full backup may be performed on a Sunday night. Only the files created or modified on Monday will be backed up Monday night. On Tuesday night, the files created or modified on Monday and Tuesday will be backed up. The same occurs each consecutive night, until the next scheduled full backup.

Compared to the entire amount of data stored, very little data is created or changed on a daily basis. Differential and incremental backups take less time, storage space, and labour than full backups. Because of this, differential and incremental backups save companies money.

Objective 3

Describe the applications of computerized control systems and plant computers.

Computerized Process Control

Computerized process control is the predominant control method in modern use. These systems provide efficiency benefits due to higher accuracy, flexibility, and reduced maintenance.

Analog Control Systems versus Computerized Control Systems

Analog control loops receive variable current, voltage or pneumatic inputs from field mounted transmitters. Dedicated analog process controllers use proportional, integral, and derivative control modes to create variable current, voltage, or pneumatic control output signals. These signals are used to position final control elements, and keep processes at set point, in single dedicated control loops.

In comparison, computerized process control systems use the same standard PID control strategies, but can control several loops simultaneously.

Operators must be able to manually and automatically operate control loops. Dedicated analog controllers require separate hand/auto stations for each final control element.

A single computerized operator workstation, however, can switch a multitude of control loops into manual or automatic mode. This requires a much smaller control station than the control rooms that formerly housed numerous analog recorders, hand/auto stations, alarm panels, indicators, lights, and switches.

Logic and Supervisory Systems

Computerized process control is well suited for making decisions based on logic and time. These decisions are made in sequence; therefore, this control method is referred to as “sequencing.”

The basic logic conditions are AND, OR, and NOT. For example, consider an automatic boiler pre-purge sequence. Before starting the pre-purge timer, a process computer must recognize that certain conditions are met. The pre-purge timer will not start until the draft fans are running AND airflow is maximum AND the fuel valve is NOT open.

Another example involves steam turbine supervisory trip logic. The process computer will trip the emergency stop valve of a turbine if the lube oil pressure is too low OR high vibration is detected OR the boiler trips.

A program can be written to check operating conditions and perform a safe automatic equipment startup or shutdown sequence. In the event of a potentially dangerous situation, computers can take immediate corrective action, without operator input. Process computers can also supervise manual operations, and prevent or warn the operator if attempting an action which could be hazardous. Normal operations are continuously checked, and operators are alerted if alarm conditions develop.

Inputs for logic and supervisory computer functions are mainly by contact closure inputs (discrete inputs).

Digital logic signals can also be triggered when analog values exceed or fail to reach predetermined values. These analog signals may produce high, high–high, low, or low–low alarms, as well as trips.

Outputs from logic and supervisory programs are normally switching operations for motor starters and similar tasks controlled by relays. Within process computers, programs can alter set points for other control loops based on logic decisions.

Inventory and Plant Management

Inventory Control

The original business application for computers was accounting and inventory control. It is therefore natural to use computers to control plant inventory. Inventory measurements are taken of raw materials entering and stored at the plant, and finished product stored and delivered to customers. Computer programs can consider customer orders and production rates to ensure adequate inventory is maintained, while avoiding the costs of storing excess inventory.

Computers are also used to maintain inventory of equipment parts, and supplies of consumable goods, used in plants. Purchase orders may be automatically generated when minimum inventory levels are reached.

Maintenance Management

To operate plants efficiently, proper maintenance is essential. The main object is to provide timely and effective preventive maintenance, so that major breakdowns are avoided. Maintenance is normally scheduled on a regular basis (for example, once a week), or based on equipment run times.

A useful function of the computer data storage is to keep track of the operating time for plant equipment. Run time totals are useful in determining when equipment should be lubricated or taken out of service for preventive maintenance. This information would normally be presented as printout by the computer.

The computer can take account of the maintenance staff required and available; the supply of materials; and the run time totals to print out work orders for scheduled maintenance, with allowance for the normal amount of unscheduled maintenance work.

Information on the time and materials needed for each work order is entered into the computer. Then, maintenance cost reports are printed out for the plant management.

Plant Management

Process control computers are capable of very accurate control of the various temperatures, pressures, and other process variables. Modern plants use distributed controls systems, using multiple small process computers, linked together with a communication network. The control computer network can be linked to the plant management computers, which calculate overall plant costs and efficiencies.

The plant manager and administrative staff determine plant production goals. These can be entered into the plant management computer. In sophisticated plants, this computer calculates the most efficient operating parameters, and automatically adjusts control set points through the communication network. Plant operators used to seeing equipment operating at steady temperature or pressure find this disconcerting at first. However, it is important to realize plant efficiency, profitability, and competitiveness can be improved in this way.

Chapter Summary

This chapter covered the basics of electronic control and computer systems. These systems measure process variables, compare them with set points, and produce control output signals. The computerized control systems discussed use small distributed computers, each with central processing units, communication modules, power supplies, and various other accessories.

Many important computer systems are used in modern plants: servers, workstations, personal computers, and process controllers. Custom designed computers are installed in distributed control systems (DCS). Programmable logic controllers (PLC) are special-purpose industrial computers, which may operate alone or as networked components of a DCS. Industrial control system networks are generally classified as sensor bus networks, device bus networks, and field bus networks. Field buses are the most powerful.

All computers require input devices, processors, memory, and output devices. Specifically, complete computer systems are comprised of motherboards, central processing units, read-only memory, random access memory, hard disk drives, power supplies, monitors, keyboards, and pointing devices.

This chapter compared computerized process control with analog process controllers, and found computerized control to be superior. However, unlike analog controllers, computerized control systems need analog to digital, and digital to analog converters. Some control applications require logic and equipment sequencing. Computerized control systems and PLCs were found to be well suited for these tasks. Other plant computer applications covered were inventory control, plant maintenance, and plant management.

Over the past couple of decades, Power Engineering has become increasingly high tech. The activities of modern Power Engineers are not confined to merely steam generation. Power Engineers must understand the electronic computerized control systems used to control the steam plant and all other process areas.

CHAPTER 6

Electrical Control Systems

Learning Outcome

When you complete this chapter you should be able to:

Describe the design and operation of electrical control systems.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe the basic construction and operation of various electric control system components.*
2. *Describe the function of control devices in electric control systems.*
3. *Explain the operating sequence of basic electric control circuits.*

Chapter Introduction

Like all control systems, electrical controls have sensing elements, transmitters, controllers, and final control elements. As well, electrical control systems control the same manipulated variables that pneumatic and electronic control systems do. For this reason, it is important to understand and apply the content of the other chapters in the Energy Plant Instrumentation and Controls Unit to the contents of this chapter.

Previous chapters covered various control system components in detail. This chapter looks at electrical control systems, and the specific components found in these systems.

Objective 1

Describe the basic construction and operation of various electric control system components.

Electrical control systems work by starting and stopping the flow of electric current, or by varying the voltage or current between the controller and the controlled device. They either employ line voltage (normally 120 or 240 volts AC), or they may use extra low voltage (12 or 24 volts) provided by step down transformers.

Electrical controls have certain advantages:

- Electricity is readily available.
- Compared to pneumatic tubing, electric wiring is simple to install.
- The signals received from sensing elements can be used to produce more than one electromechanical output.
- Single controller/actuator combinations are possible, without the need of a source of compressed air.

As well, electrical controls are simpler than electronic computerized controls. Knowledge of control programming is unnecessary to install, adjust, repair, or replace electric controls.

Electrical Control System Components

Switches

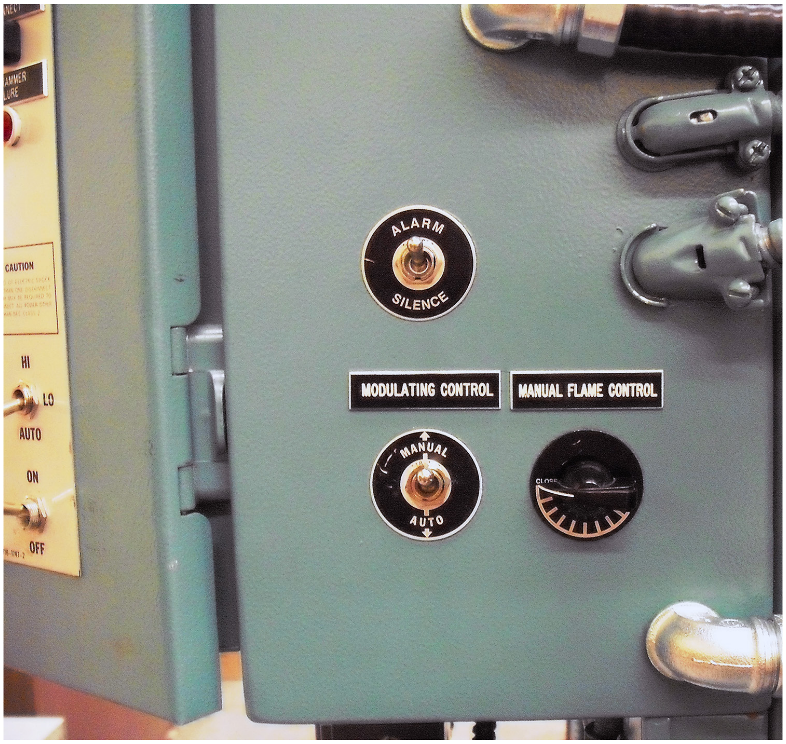
Switches interrupt or divert electrical power supply. They may be operated manually, or by various sensing elements in order to achieve automatic control. The sensing elements may respond to pressure, temperature, level, flow, humidity, and other measured process conditions.

Switches permit operators to manually start and stop equipment, and to transfer equipment between automatic and manual control. Switch varieties include two position (on-off), multi-position selectors, momentary contact, and maintained contact types.

Figure 1 shows four different switches used in the operation of a packaged steam boiler.

- A two-position switch is used to turn the boiler on or off.
- A multi-position selector switch is used to limit the boiler firing rate control to high-fire, low-fire, or to place it in automatic control.
- A momentary contact switch is used to silence the alarm horn.
- A two-position selector switch is provided to place the boiler in automatic or manual control. In manual control, a manual flame **potentiometer** is used to control firing rate. In automatic control, a modulating pressure control (see Figure 9) controls the firing rate based on the limits imposed by the “high–low–auto” switch.

Figure 1 – Manual Switches for Packaged Boiler Control



Electrical Controllers

For many electric controls, the function of sensor, transmitter and controller are combined in a single instrument. Such combined components may control pressure, temperature, humidity, and level, using automatic switches or potentiometers (variable resistances).

Thermostats

The thermostat's function is to maintain the temperature of a heated space or substance at the desired set point. It accomplishes this by regulating the heat supply.

Various designs of thermostats are available. They may be classified according to:

- Their application
- Type of temperature-sensing element used
- Type of control action provided
- Type of switch used
- Voltage applied
- Temperature range

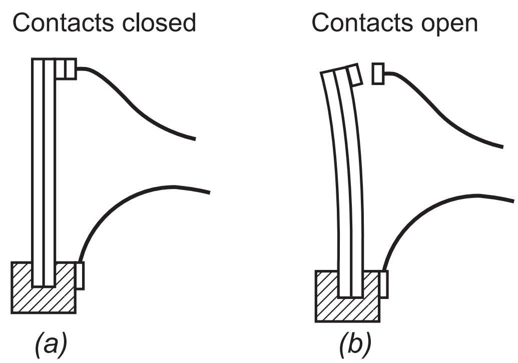
The following types of thermostats are used:

1. Bimetal
2. Remote bulb
3. Immersion (aquastat)
4. Duct
5. Modulating
6. Multi-position

1. Bimetal Thermostat

The bimetal thermostat is commonly used in residences, commercial, and institutional buildings. It has a bimetal sensing element that reacts to changes in temperature and operates a switch. The switch opens and closes the circuit to the controlled device that regulates a heating or cooling supply.

Figure 2 – Operating Principle of Bimetal Thermostats



Bimetal thermostats can be used to control heating or cooling systems. Figure 2 shows a bimetal thermostat operating a single contact, connected to an external circuit.

When used for controlling heat, the following sequence occurs. When the temperature is below set point, the bimetal strip is straight, the switch contacts are closed (a), and the controlled device on the heat supply is energized. As the temperature increases, the metals of the bimetal strip expand at different rates and cause the strip to bend.

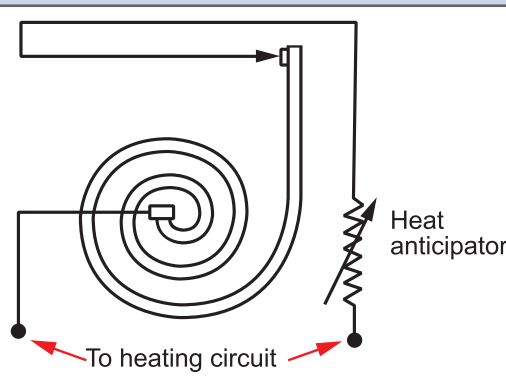
When the temperature reaches the set point, the bimetal strip bends enough to de-energize the heating supply by opening the circuit (b). When the temperature again decreases, the bimetal strip cools, straightens, and closes the contacts again.

When used to control cooling, the bimetal strip is arranged to act in the opposite manner.

The range in temperature between opening and closing of the contacts should be quite small to avoid large swings in temperature. Longer bimetal strips have greater free-end movement, and are therefore more sensitive to temperature change. To have a compact, yet sensitive thermostat, a long bimetal strip is used, but formed into a spiral shape. This will open and close the contacts within a smaller temperature range.

The fixed end of the bimetal strip can usually be adjusted in position to adjust the set point. Figure 3 shows a basic diagram of a thermostat with a spiral coiled bimetal sensing element.

Figure 3 – Thermostat with Coiled Elements



This diagram also shows a heat anticipator, used on most heating thermostats. Heat anticipation gives the thermostat timed two-position action, which prevents the temperature of the room air from overshooting the set point.

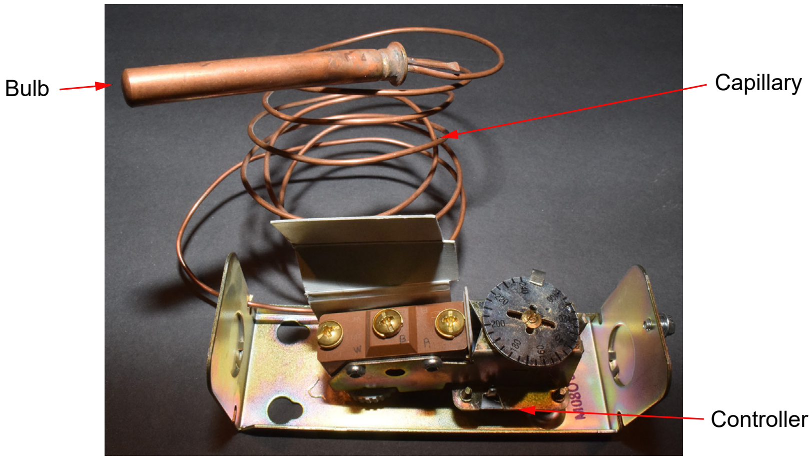
On-off control thermostats are equipped with an open-contact switch or a snap switch. Open-contact switches are only used in light-duty thermostats that control low-voltage circuits. Heavy-duty thermostats, that control high-voltage, heavy currents, or both, require switches that open and close instantly to prevent damage to the contact points from electric arcing. Snap switches are more suitable for these applications.

Mercury switches were once commonly used with bimetal thermostats. However, due to the potential environmental impact of mercury, these switches are no longer used. Thermostats containing mercury must be disposed of in an environmentally responsible manner.

2. Remote Bulb Thermostat

The remote bulb thermostat, shown in Figure 4, is used to control liquid temperatures in boilers or storage tanks. It is designed for use with line voltage or low voltage.

Figure 4 – Remote Bulb Thermostat



This control combines a filled-system thermometer with a bellows-operated switch to toggle the operation of equipment in order to maintain set point conditions. The thermometer may be filled with a vapourizing liquid that varies in pressure with temperature.

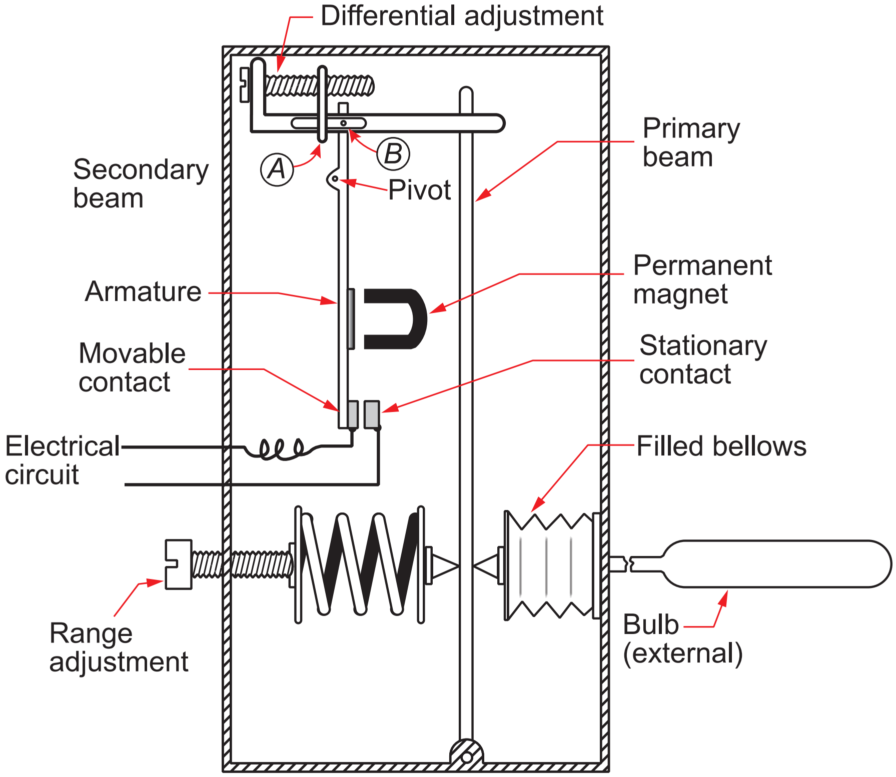
Figure 5 shows two liquid bulb thermostats used as temperature limit controls for a refrigeration compressor. The thermostat on the left shuts off the compressor if its refrigerant discharge temperature exceeds 280°F. Note that it has a manual reset button on the top left-hand side. The thermostat on the right shuts off the compressor if its cooling water temperature exceeds 120°F.

Figure 5 – Liquid Bulb Thermostat

3. Immersion Thermostat (Aquastat)

The immersion thermostat is used to sense and control the temperature of water or other liquids, in boilers, piping, or tanks. The sensing element of this thermostat is liquid filled. The switch is actuated by the expansion and contraction of the liquid when the detected temperature changes.

Figure 6 – Immersion Thermostat



4. Duct Thermostat

The duct thermostat is used to control the air temperatures in ducts and plenums. It contains a bimetal sensing element protected by an open metal guard tube inserted through the wall of the duct or plenum

5. Modulating Thermostat

The operating principle of the electric modulating thermostat is similar to that of the thermostats already described. It employs a bimetal strip, bellows or remote bulb sensing unit, but it differs in the way it operates the final control element. Since a modulating thermostat adjusts the position of the controlled device in direct proportion to the heat demand, a simple on-off switch cannot be used. Instead, this thermostat is equipped with a special regulating mechanism (a potentiometer), that adjusts circuit voltage in proportion to variations in measured conditions.

6. Multi-Position Thermostat

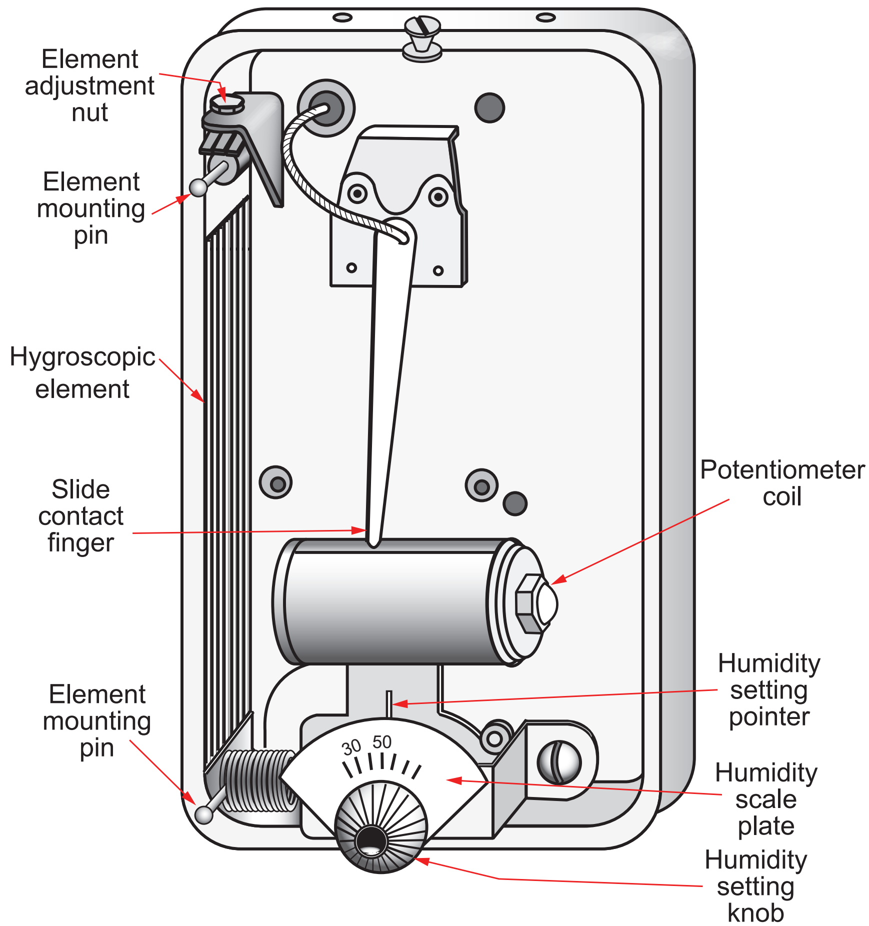
The multi-position thermostat operates like an on-off type. However, it has two or more switches that operate in sequence. Each switch controls a single heating or cooling stage of a multiple-stage system.

Humidity Controllers

A humidity controller (or humidistat) measures the relative humidity of air in a room or an air duct. It responds to a change in humidity and, in doing so, controls the operation of a humidifier.

The sensing device of a humidistat consists of a **hygroscopic** element. Controllers of the electric type usually employ multiple strands of moisture sensitive nylon for this purpose. The nylon increases in length when the humidity of the air increases, and decreases in length when the humidity drops. This change in length is used to activate the controller mechanism, which may be a switch for on-off control, or a potentiometer for modulating control.

Figure 7 – Honeywell Modulating Humidistat



When used with HVAC systems, the humidistat opens the control switch when the humidity set point is reached, and stops the humidifier. The cutout point can be changed by adjusting the dial to the desired relative humidity setting. If the humidity drops below this setting, the element becomes shorter, closes the contacts, and restarts the humidifier.

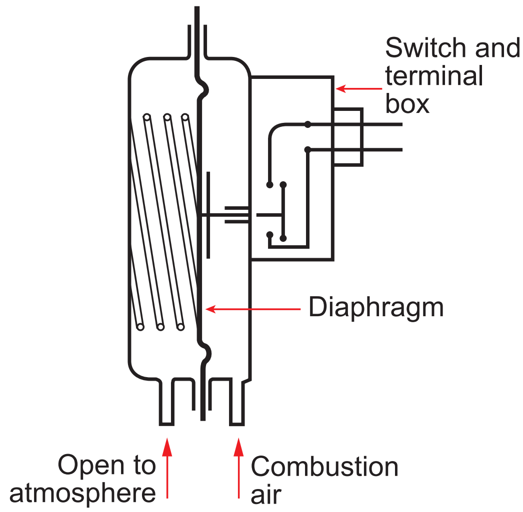
Humidistats should be kept dust free. Covers must permit free air circulation over the sensing element.

Pressure Controllers

Pressure controllers can be divided into two classes, based on the pressure range of the measured variable. High-pressure controllers measure and control high pressures or vacuums, measured in kPa or in mm of mercury (such as steam or lube oil pressure). Low-pressure controllers measure and control low pressures and vacuums, measured in mm of water (for example, boiler windbox air pressure).

High and low-pressure controllers have different size diaphragms. In both types, one side of the diaphragm is exposed to the pressure to be controlled, while the other is in contact with a reference pressure. Pressure can be measured in respect to atmospheric pressure or another reference source. A low-pressure controller is illustrated in Figure 8(a). If the combustion air pressure is too low to deliver the correct amount of combustion air, this device will open an electric circuit and close the fuel valves. Figure 8(b) is a photo of this type of switch, installed on a boiler.

Figure 8 – Combustion Air Pressure Switch



(a)

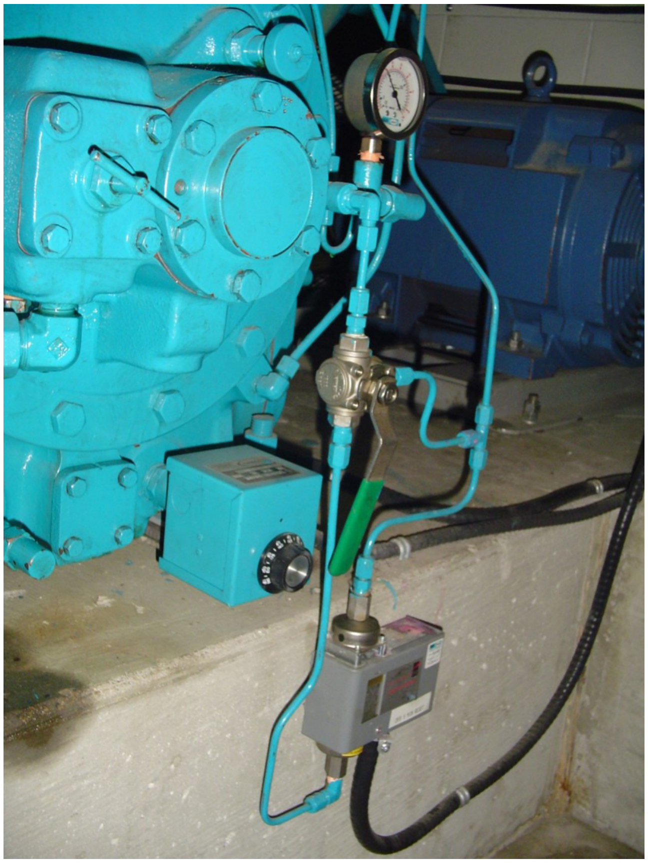
(b)

Pressure controls can be equipped with switches for on-off control, or they could have potentiometers for modulating control. The switch or potentiometer is operated by bellows, pressure capsule, or bourdon tube. Figure 9 shows a fully modulating pressure control, designed to maintain the operating pressure set point of a small high-pressure steam boiler. The pressure set point is indicated on the scale on the left-hand side of the control.

Figure 9 – Modulating Pressure Control

Figure 10 shows a differential pressure control used to sense the lube oil pressure of a refrigeration compressor. It has two opposed bellows that act on a switch, and an internal time delay. One bellows is piped to the lube oil pump output, and the other to the compressor crankcase. The time delay permits the compressor to develop adequate oil pressure on startup.

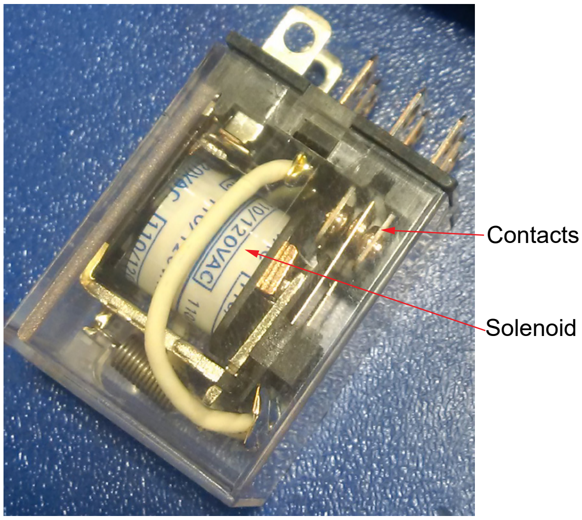
Figure 10 – Differential Pressure Control



Relays

A **relay** is a device that controls large amounts of energy with small amounts of energy. An electrical relay is essentially an electro-mechanical solenoid-operated switch, actuated by a control signal (see Figure 11).

Figure 11 – An Electro-Mechanical Relay



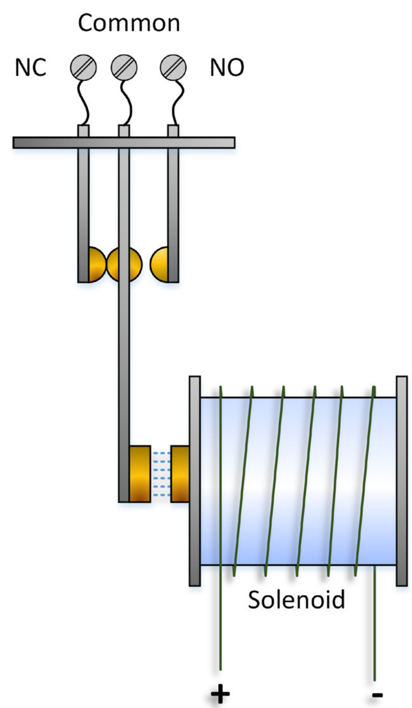
Electrical relays come in many shapes, sizes, and power ratings, to suit specific applications. Relays may have single or multiple contacts within a single housing. Relays that handle higher currents and voltages are called contactors.

Relays may contain normally open (NO) contacts, normally closed (NC) contacts, or both. NO contacts are also called "make" contacts, and NC contacts are also called "break" contacts. NO contacts remain open when the relay solenoid is de-energized, and close when the relay solenoid energizes. The opposite is true for NC contacts.

With a combination of NC and NO contacts, a relay can start, stop, or alternate between different pieces of equipment with a single control signal. This makes relays extremely important for controlling equipment.

Some relays are equipped with automatic timers to provide time-delay functions for special applications. For example, a time delay relay may be used to permit a screw conveyor to complete a clean-out cycle before shutting off.

Figure 12 – Electromechanical Relay Operation



Variable Resistors

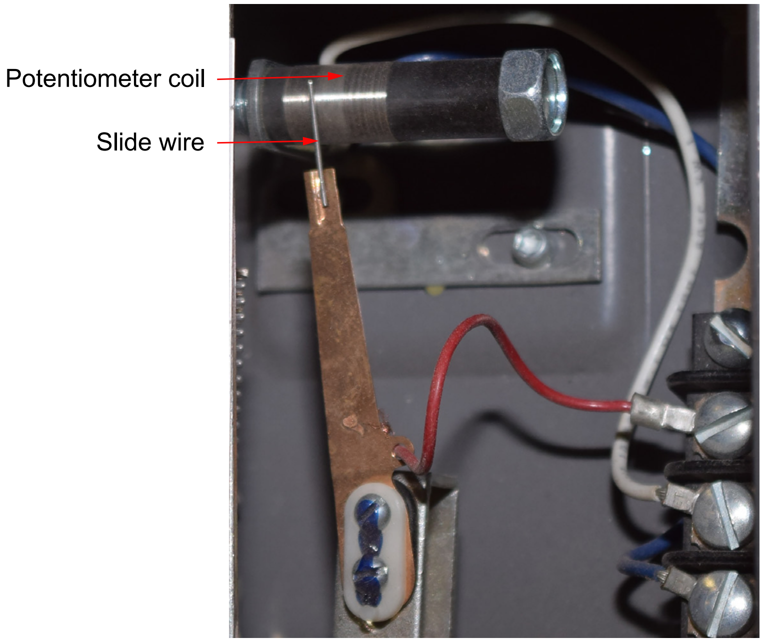
Variable resistors may be used to automatically adjust voltage and current in response to measured process conditions. Variable resistors may also be used to manually adjust the position of final control elements with the turn of a dial. Figure 1 shows such a manual variable resistor, used to adjust the firing rate of a boiler.

Variable resistors include potentiometers, **rheostats**, thermistors, and **photoresistors**.

Potentiometers

A potentiometer is a three-terminal variable resistor, used to vary control circuit voltage between zero volts and the maximum circuit voltage.

Figure 13 – Potentiometer Circuit



Rheostats

A rheostat is a two-terminal variable resistor, used for varying current in a circuit. Like potentiometers, rheostats can be used to vary AC or DC signals. Rheostats are generally more robust in construction than potentiometers. For this reason, they can adjust heavier current flows, such as that for generator excitation.

Thermistors

A thermistor is a thermally sensitive resistor whose resistance changes with temperature. The resistance change of a thermistor is non-linear. However, over a very small temperature range (such as that of air temperatures in an HVAC system), thermistors are suitably linear, reasonably accurate, and highly sensitive.

Thermistors are also self-heating. As the resistance of a thermistor changes, so does the current passing through it. The power it dissipates as heat varies as the square of the current. This varying localized heating causes thermistor error. Where thermistors are used, this error is not considered significant.

Thermistors exhibit either a positive or a negative temperature coefficient. If a thermistor has a positive temperature coefficient, its resistance increases as the operating temperature increases. If a thermistor has a negative temperature coefficient, its resistance decreases as the operating temperature increases.

Thermistors are frequently used in electronic circuits that handle temperature measurement, temperature control, and temperature compensation.

Photoresistors

A photoresistor changes in resistance according to the amount of light that reaches its surface. In a dark environment, resistance is very high (say, several million ohms). When exposed to intense light, resistance drops dramatically (to, say, 400 ohms).

Objective 2

Describe the function of control devices in electric control systems.

Final Control Elements

There are many types of electrically operated final control elements, including valve actuators, damper drive motors, stepper motors, and motor starters. These final control elements can be used to control level, pressure, flow, and temperature. Some final control elements are discrete (open or closed, on or off). Others fully modulate in response to the controller signal.

For example, an electric thermostat may control:

a) A fuel valve in the supply line to the burner of a furnace or boiler.
b) An electric relay that starts or stops a circulating pump in a hydronic heating system.
c) An electric valve in the supply line to steam or hot water radiators.
d) A three-way mixing valve for controlling the temperature of the water supply to a heating system.
e) A three-way diverter valve for controlling the water flow to a heating system.
f) A damper motor that operates air louvers.

A short description of various final control elements follows.

Electric Radiator Valves

An electrically operated, single-seated valve is used for two position (on-off) control of steam or hot water to radiators and other heating coils. The valve and actuator form one assembly. The actuator has a small electric motor that opens the valve when the controller energizes the circuit. A spring closes the valve when the control circuit is de-energized. The actuator can be manually opened during power interruptions. When power is restored, the valve automatically comes under control of the automatic control system.

Solenoid Operated Valves

Solenoids are used to operate two-position valves. Solenoid valves can be either normally closed or normally open. When energized, the solenoid either opens or closes the valve, based upon its design.

Solenoid valves are used where processes only require simple on-off flow control.

Modulating Motors

Modulating motors are electrical actuators used to position valves and dampers, for processes that require fully modulating final control elements. The modulating motor consists of a reversible drive motor and reduction gears, housed in a sealed casing. The motor places the valve or damper in position using a linkage system. Some modulating motors have internal spring mechanisms, and return to their normal position when de-energized. Other modulating motors simply fail in the last position when de-energized.

Figure 14 shows a modulating motor used to position the burner air registers for a pulverized coal burner. Note the register position indicator scale at the top of the motor.

Figure 14 – Modulating Motor for Coal Burner Register

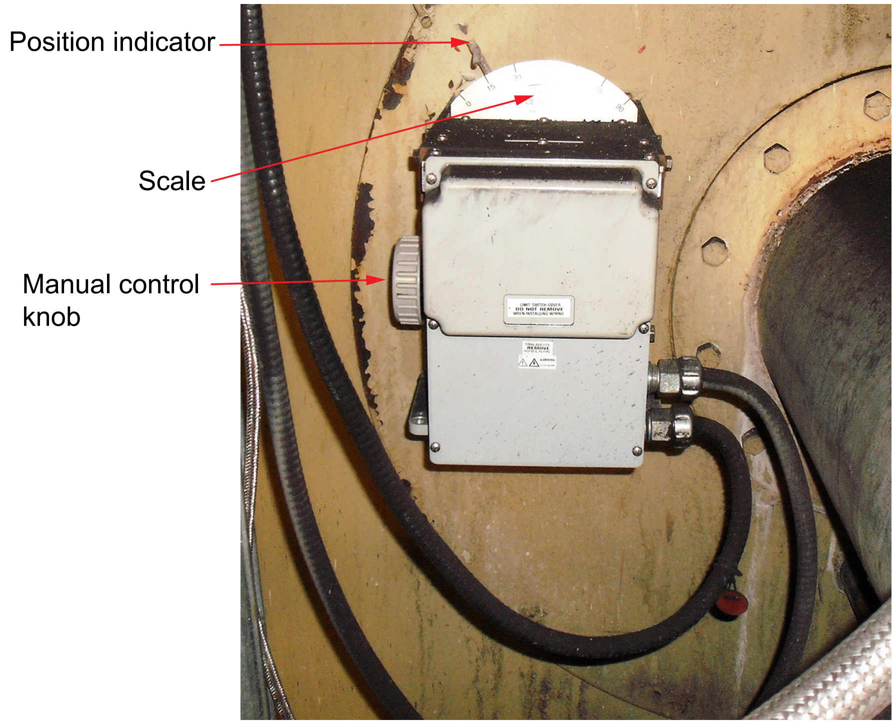


Figure 15 shows a modulating motor used to position both the air damper and the fuel control valve of a packaged watertube boiler. This modulating motor responds to the signal from a modulating pressure control piped to the boiler steam drum (Figure 9).

Figure 15 – Modulating Motor for Positioning a Fuel Valve and an Air Damper

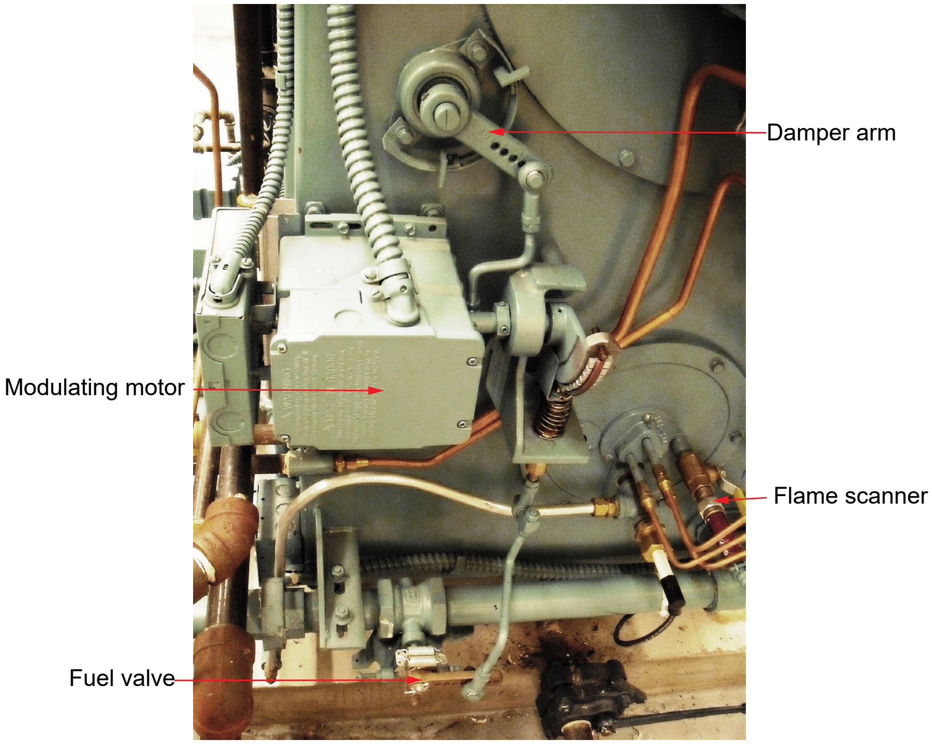
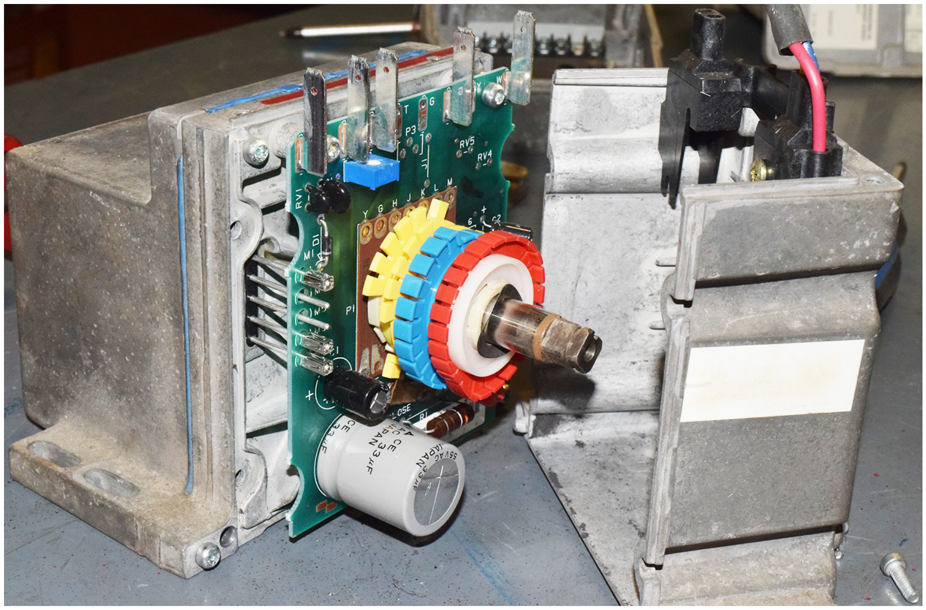


Figure 16 shows a modulating motor with the cover removed.

Figure 16 – Modulating Motor Open View

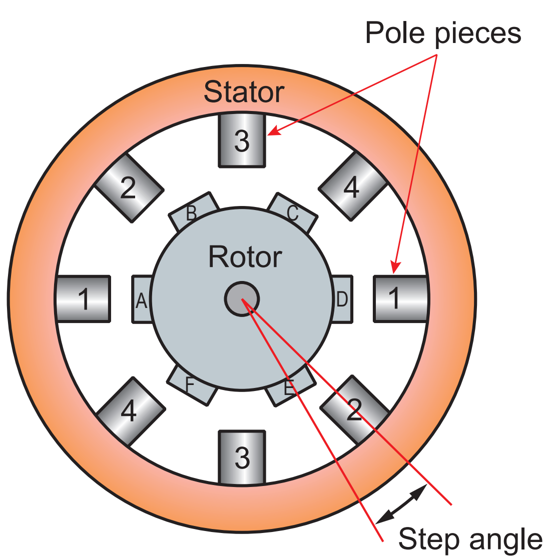


Stepper Motors

Stepper motors are used as electromechanical actuators in industrial control applications. A stepper motor is a brushless DC electric motor that rotates in steps, instead of rotating continuously. With each step, the rotor moves a certain number of degrees, moving the driven load.

Stepper motors have multiple salient electromagnetic pole pieces arranged around an iron stator. The rotor has salient permanent magnets arranged around its circumference that align with the energized stator poles. When a set of pole pieces is energized, the rotor turns a certain number of degrees (the "step angle"), and magnetically locks into position.

Figure 17 – Stepper Motor Construction



Refer to Figure 17. The eight pole pieces are numbered 1 through 4, and are electrically connected to energize in pairs. These pole pairs are energized sequentially by a microprocessor control. The rate of the energization sequence determines the rotational speed of the motor.

Figure 17 shows the orientation of the rotor when pole pair number 1 is energized. The rotor magnets A and D lock into alignment with the energized pole pair. When pole pair number 1 de-energizes and pole pair number 2 energizes, the rotor turns counter-clockwise, until rotor magnets B and E align and lock-in with pole pair number 2. In the example shown in Figure 17, the rotor moves in 15 degree increments.

Some of the advantages of stepper motors include:

- A wide range of rotational speeds can be obtained since the speed of a step motor is proportional to the frequency of the input pulses.
- Maximum torque when at a standstill (if the motor is energized).
- Precise, repeatable positioning of the rotor.
- Rapid starting, stopping and reversing.
- Very slow speed operation.
- High reliability. Like an AC induction motor, the only components that wear are the rotor bearings.

Stepper motors, however:

- Have low efficiency.
- Drop in torque as rotational speed increases.
- Do not accelerate quickly when under load.
- Are difficult to operate at high rotational speed.

Objective 3

Explain the operating sequence of basic electric control circuits.

Basic Electric Control System

To illustrate a basic electric control system, consider a simple warm air heating process. In this system, a thermostat controls the operation of a burner, as follows:

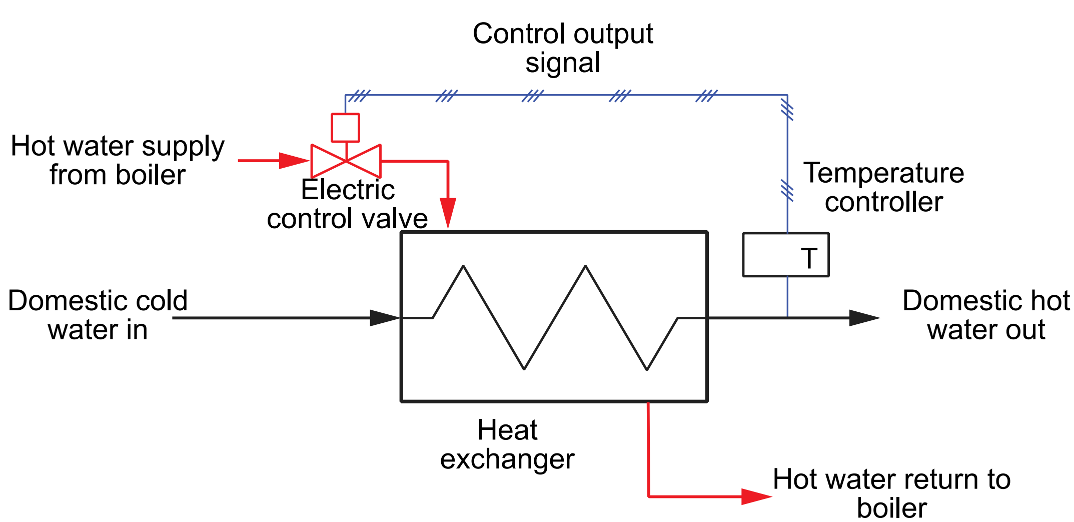
1. A thermostat, which acts as both temperature sensor and controller, identifies that the air temperature is below set point.
2. The thermostat switch (the controller mechanism) closes to send an electric signal to the burner.
3. The burner starts, which raises the air temperature and warms the building.
4. When the air temperature exceeds the set point, the thermostat switch opens, and the burner shuts down.

Electric Temperature Control Heating Domestic Water

The electrical control loop in Figure 18 has two main components: a modulating temperature controller and a modulating electrically actuated hot water control valve. The modulating temperature controller is essentially a thermally operated potentiometer, but with a mechanism to permit set point adjustment. The modulating motor responds to the varying control output signal in proportion to changes in temperature. The blue line shown between the controller and the control valve operator has diagonal hash marks, indicating that the signal being transmitted is electric.

The temperature controller monitors the domestic hot water temperature at the heat exchanger outlet. If the hot water temperature deviates from the set point, the controller transmits an electric control signal to the control valve, proportional to the error. If the domestic hot water temperature is below the set point, the electric temperature control valve opens to admit more boiler water to the heat exchanger. If the domestic hot water temperature is above the set point, the opposite occurs.

Figure 18 – Simple Electric Temperature Control System



Chapter Summary

This chapter covered the basic construction and operation of various electrical control system components such as thermostats, humidistats, and pressure controllers. As well, various switches, relays, and variable resistors were looked at in detail. It was noted that many electrical controllers combine the functions of sensor, controller, and transmitter in a single component.

Like other control systems, the final control elements and controlled devices of electrical control systems can be discrete or modulating. Solenoids and relays can be used to start or stop equipment, such as pumps and fans. Modulating motors and stepper motors can be used to position valves and dampers.

Unit Summary

Due to the increasing use of technology, Power Engineers are required to increase their knowledge of instrumentation, controls, and computerized control systems. This Unit covered the fundamentals of process measurement and control.

The content in this Unit may be grouped in two parts, each consisting of three chapters. The first part covered the principles of automatic control. The second part covered control systems, including programmable logic controls, electronic control systems, and electrical control systems.

The Unit began by introducing pertinent terminology. This included open and closed loop control, process variable, sensor, transmitter, controller, set point, deviation, error, control output signal, final control element, and manipulated variable.

Next, this Unit provided detailed coverage of major control system components, and how they function. Specifically discussed were:

- Sensors that measure pressure, temperature, level, flow, humidity, and composition
- Indicators and recorders
- Analog and digital input and output signals
- Pneumatic, electric, direct digital, fibre optic, and wireless transmitters and transmission methods
- Two-position, multi-position, proportional, integral, and derivative controller action
- Feedback, feedforward, cascade, and split range control
- Human-machine interfaces
- Final control elements, such as valves, dampers, and variable frequency drives

The final three chapters covered control systems. Programmable logic controllers, along with their primary use as sequencers, were found to be capable of handling PID control as well. Electronic distributed control systems – those that utilize variable voltage, variable current, and contact closures for sensing and transmitting – were covered next. The final chapter covered electrical (24-volt and line voltage) control systems. Content included the function of various switches, relays, resistors, and stepper motors.

A self-assessment tool is available on MyPower LMS. Login using the unique user ID and password found on the inside front cover of Unit 1.

Notes

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UNIT A-9

KNOWLEDGE EXERCISES AND UNIT GLOSSARY

Knowledge Exercises – Chapter 1

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. What are the alternative terms for open and closed loops?

2. Sketch a basic automatic process control system, and describe its operation.

Chapter 1 (Cont.)

Objective 2

3. State the most common signal ranges for pneumatic and electric signals.

4. State the difference between analog and digital signals.

5. Give an example of a photoelectric transducer.

Objective 3

6. List the functions of instruments that are not used in control loops.

Knowledge Exercises – Chapter 2

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. How does a manometer operate?

2. List the common type of manometers.

3. Why is an inclined-tube manometer more suitable than a standard U-tube manometer for measuring small pressure differences?

4. How does a strain gauge operate?

5. List the common types of protective devices for pressure sensing elements.

Objective 2

6. How does a conventional float-type level measurement system operate?

Chapter 2 (Cont.)

7. Describe the operation of a magnetic float.

8. How does an ultrasonic level transmitter operate?

9. Why is radar level measurement commonly called microwave?

Objective 3

10. What are the common types of primary flow elements?

11. Explain how flow rate can be directly measured by the variable area flowmeter.

12. What is the principle behind Weir flow measurement?

13. How does a Doppler flowmeter operate?

Chapter 2 (Cont.)

14. Describe the operating principle of Coriolis type mass flow metering device.

Objective 4

15. Describe how liquid-in-glass thermometers work.

16. Describe the operating principle of bimetal thermometers.

17. Describe the operation of a thermocouple.

18. What is the purpose of thermowell?

19. What is an RTD sensor?

Chapter 2 (Cont.)

Objective 5

20. Give three examples of sensors used to detect humidity.

21. How does a psychrometer work?

Objective 6

22. What is a chromatograph?

23. Describe the operating principle of non-dispersive infrared (NDIR) detector for CO/CO_2 measurement.

24. Describe the operation of standard Continuous Emissions Monitoring System (CEMS).

Knowledge Exercises – Chapter 3

Name: ______________________________ Date: ______________________________

Instructor: ___________________________ Course: ____________________________

Objective 1

1. Define the term transmitter.

2. Describe a basic pneumatic transmitter principle.

Chapter 3 (Cont.)

3. Explain the relationship between the output signal of the pneumatic transmitter and the flapper-nozzle clearance.

4. Sketch and describe a differential pressure (DP cell) type transmitter that can be used in the flow measurement process.

Chapter 3 (Cont.)

Objective 2

5. Describe how temperature indication can be achieved using a bourdon tube.

6. Sketch a diaphragm element that can be used to detect liquid level and explain how it works.

Chapter 3 (Cont.)

Objective 3

7. What is the difference between two-position and proportional controllers?

8. Explain the difference between the feedback and the feedforward control principle.

9. Define split range control and provide an example of this system.

Objective 4

10. What is the function of a final control element? List six devices that can be used as final control elements.

Chapter 3 (Cont.)

11. Name one advantage and one disadvantage of double-seated control valves.

12. With regard to control valves, explain what is meant by "fail-safe." Name three possible control valve "fail-safe" modes.

13. Complete the following table:

Failure Action of Control Valve/Actuator Combinations

Action of Actuator	Action of Valve Body	Fail Position
Direct		Open
Reverse	Direct	
	Reverse	Close
Reverse	Reverse	

Chapter 3 (Cont.)

14. What is the purpose of a valve positioner?

Knowledge Exercises – Chapter 4

Name: ______________________ Date: ______________________

Instructor: ______________________ Course: ______________________

Objective 1

1. Sketch the functional components of a modern PLC system, and describe how it functions.

2. Provide five examples of input devices capable of communicating with PLCs.

Chapter 4 (Cont.)

3. Provide five examples of output devices capable of communicating with PLCs.

4. Describe what happens during a PLC scan cycle.

Chapter 4 (Cont.)

Objective 2

5. From the example in the text, explain how the PLC determines how much lime to add to make a 5% lime slurry batch.

6. From the example in the text, explain how the PLC determines when a desiccant tower needs regeneration.

7. What is a BMS?

Chapter 4 (Cont.)

8. How is a BMS similar to a PLC? How are they different?

9. Can PLCs be used as BMSs? Explain your answer.

Chapter 4 (Cont.)

Objective 3

10. Explain why PLCs need HMIs.

11. Describe why operators use HMIs to communicate with PLCs, but instrumentation technicians and controls engineers use personal computers.

Knowledge Exercises – Chapter 5

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. List the typical components of an electronic control system.

2. List the main parts of a DCS.

3. Identify three buses used in industrial control networks, and briefly describe each one.

Objective 2

4. Briefly explain the operating principle of a modern computer.

Chapter 5 (Cont.)

5. What is the difference between RAM and ROM?

Objective 3

6. Compare analog controllers to digital computerized controllers.

7. With regard to the burner of a boiler, what are the logic conditions that must be met before a sequence controller will start the pre-purge timer?

Chapter 5 (Cont.)

8. What are equipment run times used for?

Knowledge Exercises – Chapter 6

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. List six types of thermostats that are used in electrical control systems.

2. With the aid of a sketch, briefly explain the operating principle of a humidistat.

Chapter 6 (Cont.)

3. Sketch a simple electro-mechanical relay, and describe how it operates.

Chapter 6 (Cont.)

Objective 2

4. Sketch a stepper motor and describe its operation.

Chapter 6 (Cont.)

Objective 3

5. Sketch a simple electric temperature control system for heating domestic hot water, using a heat exchanger.

Unit A-9 Glossary

Term	Definition
Actuator	In instrumentation, a type of motor that is responsible for moving or controlling a mechanism or system. It is operated by a source of energy, typically electric current, hydraulic fluid pressure, or pneumatic pressure, and converts that energy into motion.
Analog	In control instrumentation, a condition that can be continuously observed and represented with a continuously variable signal.
Analog to digital convertor	A computerized device used to convert analog data to digital data for the purpose of transmission and signal processing.
Balco	A trade name for a nickel-iron alloy, used for making resistance temperature sensors, consisting of 70% nickel and 30% iron.
Barometer	A scientific instrument used in meteorology to measure atmospheric pressure.
Bimetal thermometer	A temperature sensitive device consisting of two metals mechanically bound, so that the bimetal bends in a particular direction when heated, due to differential expansion.
Bluetooth	A telecommunications standard for how mobile devices can communicate with each other by using a short-range wireless transmission.
BMS	See *burner management systems* (BMS).
Bourdon tube	A pressure-sensitive element that consists of a curved tube, with a flattened elliptical cross-section, which is closed at one end. A pressure applied to the inside of the tube tends to straighten the tube.
Burner management systems (BMS)	A burner control system designed to prevent misoperation of, and damage to, fuel preparation and burning equipment. Burner management systems provide fully automatic, semi-automatic, or fully manual sequencing. These sequences start and stop burners and related equipment, monitor combustion conditions, and provide appropriate response to adverse burner operating conditions.
Capillary tube	A small diameter metal tube, with a small internal bore, used in instrumentation and refrigeration applications.
Carrier gas	In gas chromatography, a high-purity gas (typically helium, argon, hydrogen, or nitrogen) used to transport the sampled gas through the column during the partitioning process.
Cascade control	In an automatic control system, when the set point of one controller is determined by the control output signal of another controller.
Central processing unit (CPU)	In a computer, the electronic circuitry that carries out programmed instructions by performing the basic arithmetic, logical, control, and input/output operations specified by the programming.
Chromatograph	An instrument that separates, analyzes, and quantifies the chemical components of liquid or gas solutions.
Closed loop control system	A combination of control units in which a process variable is measured and compared with a desired value (or set point). If the measured value differs from the desired value, a corrective signal is sent to a final control element to bring the controlled variable to the proper value.
Condensing pot	A large volume pipe fitting in which steam condenses and is stored. This provides a stable reference head for differential pressure-based level or flow measurement, and maintains enough fluid volume for displacement equal to or greater than the varying volume displacement of the flow or pressure-sensitive instrument.

Term	Definition
Contact closure input	In control instrumentation, a discrete voltage signal transmitted to a controller by a sensor-operated, single-pole, single-throw switch.
Contact closure output	In control instrumentation, a discrete voltage signal transmitted from a controller to a final control element, in order to start or stop equipment or processes.
Control output	A signal sent from a controller to a final control element, used to position the final control element in response to process conditions.
Control valve	A final control element that regulates the flow of fluid in a control system.
Controller	A device that operates automatically to regulate a measured (controlled) variable.
Coriolis meter	A flow meter that uses the Coriolis principle to directly measure mass flow.
CPU	See *central processing unit* (CPU).
DCS	See *distributed control system* (DCS).
Dead weight tester	A device for calibrating pressure-sensing instruments, that uses a hydraulic piston on which a load is placed to create a known pressure for the sensing device being calibrated.
Derivative action	A control algorithm that examines how fast a process variable changes per unit of time, and takes action proportional to the rate of change. Also called Rate.
Desiccant	Substance used to collect and hold moisture in a system. A drying agent. Common desiccants are activated alumina and silica gel.
Deviation	In control instrumentation, a departure from a desired value (set point).
Device bus network	A digital information network of interconnected control devices that have sufficient capacity and speed to handle both discrete and analog information.
Differential pressure cell (DP-cell)	A device that measures the difference between two pressures, by using bellows, diaphragms, or similar means. These cells are used to measure certain variables such as flow or level.
Differential pressure sensor	A differential pressure cell.
Differential pressure transmitter	A device that combines the function of a differential pressure cell and a signal transmitter.
Digital to analog convertor	A computerized device used to convert digital data to analog data for positioning final control elements.
Discrete digital signal	In control instrumentation, an input or output signal that can be represented with binary information, such as "on or off" and "stop or start."
Distributed control system (DCS)	A computerized control system with multiple autonomous controllers accessed through a central supervisory control.
Doppler effect	The change in frequency of a wave (or other periodic event) for an observer moving relative to its source. It is named after the Austrian physicist Christian Doppler, who proposed it in 1842 in Prague.
DP-cell	See *differential pressure cell* (DP-Cell).
EEPROM	See *electrically erasable programmable read-only memory* (EEPROM).
Electrically erasable programmable read-only memory (EEPROM)	In computing, stable, non-volatile read-only memory (ROM) that can be erased and reprogrammed repeatedly through the application of higher than normal voltage pulses. Commonly called EEPROM.

Term	Definition
EPROM	See *erasable programmable read-only memory* (EPROM).
Erasable programmable read-only memory (EPROM)	A type of read only memory that can be erased and reprogrammed using voltage pulses.
Error	In control instrumentation, the difference between a set point and the value of a related process variable.
Factory mutual (FM)	A family of companies organized for the purpose of providing industrial loss-prevention services, including insurance, third-party equipment certification, and certification standards development.
Fail-safe	To revert to a safe condition upon de-energization or other malfunction.
Feedback	The part of a closed loop system which provides the controller with information about the controlled variable for comparison to its desired value.
Feedback bellows	A pressure-sensitive component of a pneumatic transmitter that affects its sensitivity.
Feedforward control	A proactive control system that uses process data to predict process conditions, and manipulates the final control element to counteract load changes before the process variable is affected.
Field bus network	A high capacity, high-speed network for communicating between digital, analog, and discrete control devices.
Filled system thermometer	A temperature-sensing instrument comprised of a fluid-filled sensing bulb, a capillary tube, and a pressure sensitive bourdon tube, bellows or capsule. Changes in temperature affect the volume of the liquid contents of the system, affecting the pressure exerted on the pressure-sensitive element. The pressure-sensitive element indicates temperature through additional mechanisms.
Final control element	A device, such as a damper or valve that directly changes the value of the manipulated variable.
Flapper-and-nozzle	The elements found in pneumatic control components that vary control signals by altering the rate by which air bleeds from the pneumatic signal tubing.
Float cage	A large hollow chamber used to house a level sensor (such as a float) external to a process vessel. Float cages dampen the effects of surface agitation and, when equipped with isolation valves, permit servicing of the level sensor without draining the attached process vessel.
Flow indicator transmitter	A device that provides local flow indication, and remote flow signal transmission.
Flow nozzle	A primary flow-sensing element shaped like a converging nozzle, and placed in a pipe, across which a pressure drop occurs dependent on the material flow rate.
Flume	Specially shaped engineered structure used to measure the flow of water in open channels.
FM	See *factory mutual* (FM).
Gauge glass	A fitting used to give a visual indication of the water level in a boiler or other vessel.
Hand control	The manual operation of a normally automatic process or process components.
High/low select	A controller function that can be configured to transmit either the higher or the lower of two control output signals to a final control element.
Humidistat	An electrical control device for maintaining humidity at a set point value .

Term	Definition
Hydraulic comparator	A device that generates pressures with a liquid media for comparing the pressure readings of a pressure-sensing device to a calibrated reference (master) gauge.
Hygrometer	A device used to measure humidity by comparing the wet and dry bulb temperatures of the air or space.
Hygroscopic	Having an affinity for moisture.
IEC	See *international electrotechnical commission* (IEC).
Inclined manometer	A manometer with an inclined scale that permits greater scale resolution and more accurate measurement of small pressure differences.
Indicator	In control instrumentation, a device that provides local or remote information about a particular process condition, but performs no control function. Indicators include devices such as pressure gauges, thermometers, and level gauges.
Infrared thermometer	A non-contact digital surface thermometer that detects infrared radiation emitted by high-temperature sources.
Integral action	A control action that produces a corrective control output signal proportional to the length of time the process variable has been away from the set point.
Interface	In computing, an interface is a shared boundary across which two separate components of a computer system exchange information. The exchange can be between software, hardware, peripheral devices, humans, and combinations of these.
International electrotechnical commission (IEC)	An organization that prepares and publishes International Standards for all electrical, electronic, and related technologies.
Intrinsically safe	Equipment and wiring that is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration.
Invar	A nickel–iron alloy comprised of 64% iron and 36% nickel that has a very low coefficient of thermal expansion.
LAN	See *local area network* (LAN).
Liquid-in-glass thermometers	A temperature-sensing device consisting of a long glass tube with a fine bore, and a liquid reservoir to which the temperature source is applied. The differential volumetric expansion between the glass bore and the liquid causes the liquid to extend through the bore with increasing temperature, and to descend with decreasing temperature.
Local area network (LAN)	A group of computers and peripheral devices that share a common communication system within a defined area, such as a school or a corporate office.
Manipulated variable	The energy type and flow that is controlled by a final control element, in order to produce a desired effect on a measured variable.
Manometer	A liquid-filled, tubular gauge used to measure pressures of gases or vapours.
Master fuel trip relay (MFR)	In a burner management system, an electromechanical safety device that causes sudden simultaneous trips of all fuel burning equipment, including draft fans, fuel valves, and igniters, in the event of adverse operating conditions. A master fuel relay trip will stop all flow of fuel into a furnace.
Master pressure gauge	A pressure gauge with a large graduated scale, with many fine graduations, and calibrated to an agreed standard of accuracy. Master gauges (also called test gauges and reference gauges) are used to verify the accuracy of other pressure-sensing devices.

Term	Definition
Measured variable	The process condition (such as flow rate, pressure, or temperature) to be controlled at a definite desired value.
Measuring junction	In a thermocouple, the connected end of dissimilar wires that is exposed to a heat source.
MFR	See *master fuel trip relay* (MFR).
Microwave	A form of electromagnetic radiation with wavelengths ranging from as long as one meter to as short as one millimeter, with frequencies between 300 MHz (100 cm) and 300 GHz (0.1 cm).
Microwaves	Electromagnetic radiation with wavelengths ranging from as long as one meter to as short as one millimeter, with frequencies between 300 MHz (100 cm) and 300 GHz (0.1 cm).
Modulating controller	A controller that produces infinitely variable control output signals.
Modulating motor	An electrical actuator for positioning a final control element, according to a control signal.
Multiplexer	An electronic device that selects one of several analog or digital input signals, and forwards the selected input into a single line.
Multi-position controller	A controller that produces several discrete control output signals.
NDIR	See *non-dispersive infrared radiation detector* (NDIR).
NDIR detector	A non-dispersive infrared radiation detector.
Noise	In control instrumentation, undesirable components of a signal that interfere with the ability to discern the signal.
Non-dispersive infrared radiation detector (NDIR)	A spectroscopic sensor often used as a gas detector to measure carbon monoxide and carbon dioxide.
Non-volatile memory	In computing, a form of memory that persists when the computing device is un-powered.
Nutating disc meter	A positive displacement flow meter whereby liquid flow causes a disc element to wobble, and its output shaft to oscillate about a fixed point. The oscillating (nutating) shaft is used to drive a flow indicator and an integrator.
Offset	In control instrumentation, when the process variable maintains a steady state deviation from a set point.
Opacity	A measure of how opaque a material is. Opacity is the opposite of transparency.
Open loop control system	A control system in which no comparison is made between the actual value and the desired value (or set point) of a process variable.
Optical pyrometer	A temperature-measuring instrument having a clear incandescent lamp, and an arrangement for matching the brightness or colour of the lamp's filament against the source whose temperature is to be measured.
Orifice plate	A primary flow-sensing element, consisting of a flat, circular plate that is placed in a pipe between flanges. The plate has an aperture smaller in diameter than the pipe, across which a pressure drop occurs, dependent on the material flow rate.
PE switch	A pneumatic-to-electric transducer that provides discrete voltage output signals corresponding to the pressure being measured.
Permissive	In control instrumentation, one or several conditions (such as flow, temperature, level, or pressure) that must be satisfied for a process sequence to proceed.

Term	Definition
Photoresistor	A device that varies in resistance dependent on the degree of illumination.
PI	See *proportional plus integral* (PI).
PID	See *proportional plus integral plus derivative* (PID).
Piezoelectric	The property of certain crystals to set up an electrical potential when subjected to a mechanical strain, or conversely to produce a mechanical force when subjected to an electrical potential.
Pigtail	A small length of pipe used to trap steam condensate to protect a pressure-sensing device from the action of live steam.
Pilot positioner	A device that ensures a damper mechanism assumes the position dictated by a control output signal.
Pitot tube	A primary flow-sensing element having a cylindrical tube with an open end pointed upstream, used to measure the impact pressure of moving fluids. The impact pressure varies dependent on the material flow rate.
PLC	See *programmable logic controller* (PLC).
Pneumatic relay	The part of a pneumatic transmitter that contains a valve capsule, restrictor, spring, and exhaust valve.
Pneumatic transmitter	A signal transmitter that uses a compressed air source, a pneumatic relay, and a sensing element to generate proportional 20 to 100 kPa process variable signals.
Potentiometer	A three-lead variable resistor used in electrical control circuitry.
Pressure capsule	A pressure-sensing element in the form of a hollow circular disc that expands when its internal pressure rises.
Pressure gauge	An instrument designed to indicate fluid pressure on a graduated scale, relative to atmospheric pressure.
Process	An operation that uses energy to produce a change in a material, or an energy conversion.
Process disturbance	A change in a process energy balance that causes a process variable to deviate from its set point.
Process variable	A quantity such as flow, temperature, pressure, or level that may be metered and controlled.
Programmable logic controller (PLC)	An industrial digital computer control system that continuously monitors sensor inputs and custom programmed to control the state of output devices.
Proportional control	A control action whereby a control output signal continuously varies in proportion to changes in a process variable.
Proportional controller	A controller that utilizes proportional control. See Proportional Control.
Proportional plus integral (PI)	A control action that combines proportional control action with integral control action.
Proportional plus integral plus derivative (PID)	A control action that combines proportional control action, integral control action, and derivative control action.
Psychrometer	A device used to measure humidity by comparing the wet and dry bulb temperatures of the air or space. Also called a hygrometer.
Pulsation dampener	A pipe fitting placed between a pressure-sensing device and an oscillating pressure source that reduces the harmful effects of the pressure oscillation on the measuring instrument.

Term	Definition
Pyrometer	A thermometer of any design usable at relatively high temperature (usually above 500°Celsius).
Radar	The use of radio waves and their reflections to determine the position of objects.
RAM	See *random access memory* (RAM).
Random access memory (RAM)	A form of volatile (non-permanent) computer memory that permits the storage, access, and retrieval of data numerous times per second.
Rate	In instrumentation, rate refers to derivative action.
Read only memory (ROM)	A form of non-volatile (permanent) memory that permits access and retrieval of stored data numerous times per second, but does not permit the storage of information after it has been initially written to.
Recorder	A device that provides continuous records of measured variables with respect to time.
Reference head	With regard to the differential pressure method of level sensing, a height of liquid that does not vary with the variable level in a process vessel. The reference head is connected to the high-pressure port of a differential pressure cell.
Reference junction	The junction of a thermocouple that is at a known temperature.
Relay	A circuit device that uses a change in one electrical circuit to effect a change in another circuit, by operating some control device such as a switch.
Resistance temperature device (RTD)	An electrical temperature-sensing element that operates by varying in resistance when exposed to variations in temperature. The resistance is measured and converted into temperature degrees.
Rheostat	A two-lead variable resistor used to vary current in a circuit.
ROM	See *read only memory* (ROM).
Rotameter	A variable area flow-sensing device that measures fluid flow through a graduated tube of increasing cross-section. The flow is measured by observing the position of a floating element suspended in the fluid stream.
RTD	See *resistance temperature device* (RTD).
Scan cycle	The time a programmable logic controller takes, in milliseconds, to communicate with inputs, perform control logic, communicate with outputs, perform self-diagnostics, and communicate with external interfaces.
Sensing bulb	A small, hollow metallic chamber, filled with pressurized liquid, gas, or vapour, and used to detect changes in temperature.
Sensing element	A material or device that undergoes a change in physical or electrical characteristics as the conditions of the measured variable change.
Sensor	In control instrumentation, a transducer whose purpose is to detect some characteristic of a measured variable and report it in another form of energy, often an electrical signal.
Sensor bus network	A simple, relatively slow, low-capacity network, that transmits information from manually or automatically actuated discrete (2-position) process sensors, used primarily for sequencing equipment.
Server	A computer that manages access to a centralized resource, such as a shared hard disk drive, in a network.
Set point	The desired value of the measured (controlled) variable that a control system is designed to maintain.

Term	Definition
Signal attenuation	A degradation or decrease in the strength of a signal, over distance, time, or both.
Siphon	A device, such as a pigtail, used to trap steam condensate for the purpose of protecting a pressure-sensing device from the action of live steam.
Smart transmitter	Single Modular Auto-Ranging Remote Transducer. In process control, a smart transmitter is one with an internal micro-processor, capable of handling digital and analog signal protocols simultaneously. Smart transmitters can be calibrated and diagnosed remotely using HART protocol devices.
Snubber	A pulsation dampener.
Split range control	A control strategy whereby two final control elements are operated consecutively by a single control output signal.
Static head	The pressure exerted at the base of a column of liquid, measured in metres.
Stepper motor	A brushless DC motor that, instead of spinning continuously, rotates in discrete steps.
Strain gauge	A sensing element that measures force by using the principle that electrical resistance varies in proportion to tension or compression applied to the element.
Test gauge	A master pressure gauge.
Thermistor	A semiconductor resistor that varies in resistance with variations in temperature.
Thermocouple	A temperature-sensing element consisting of a pair of dissimilar wires joined at one end, in which an electrical potential is developed in proportion to the temperature of the wire junction.
Thermowell	A cylindrical pipe fitting, enclosed at one end, to protect temperature sensing elements, and to facilitate their immersion or removal without isolating and draining process equipment.
Transducer	In control instrumentation, a device that converts signals of one energy form to another.
Transmitter	In control instrumentation, a mechanical, electrical, or electronic device that sends the value of a process variable from a primary sensing element to a remotely located controller.
Two-position controller	A controller that has two discrete control output signals (typically "off" and "on").
Ultrasonic	Refers to sound energy of a frequency greater than that of audible sound.
U-tube manometer	A manometer with tubular legs of equal length, used for measuring pressure differential.
Valve positioner	A device that ensures a control valve assumes the position dictated by a control output signal.
Variable inlet vane damper	A damper having a series of parallel vanes arranged radially around a circular air intake.
Vena contracta	The point in a fluid stream where the diameter of the stream is the least, fluid velocity is at its maximum, and fluid pressure is at its lowest.
Venturi tube	A primary flow-sensing element consisting of a tube with a convergent section followed by a divergent section. The flow through a venturi tube accelerates through the throat of the tube. This causes a low pressure at the throat that varies with the rate of flow through the tube.

Term	Definition
Weir	A mechanism for determining flow in a liquid stream, comprised of a partial barrier across the horizontal width of the stream, and a level-sensing element that measures the height of liquid upstream of the barrier.
Wheatstone bridge	An electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, of which one leg includes the unknown component.
Wi-fi	A technology developed to permit computers and computerized devices to transmit or receive digital information without the use of hard-wired connections.
WirelessHART	An industrial wireless communication protocol that permits devices to transmit, receive and re-broadcast signals from other WirelessHART transmitters within range, over a mesh-like web of transmission paths.

Additional Workspace

Additional Workspace

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