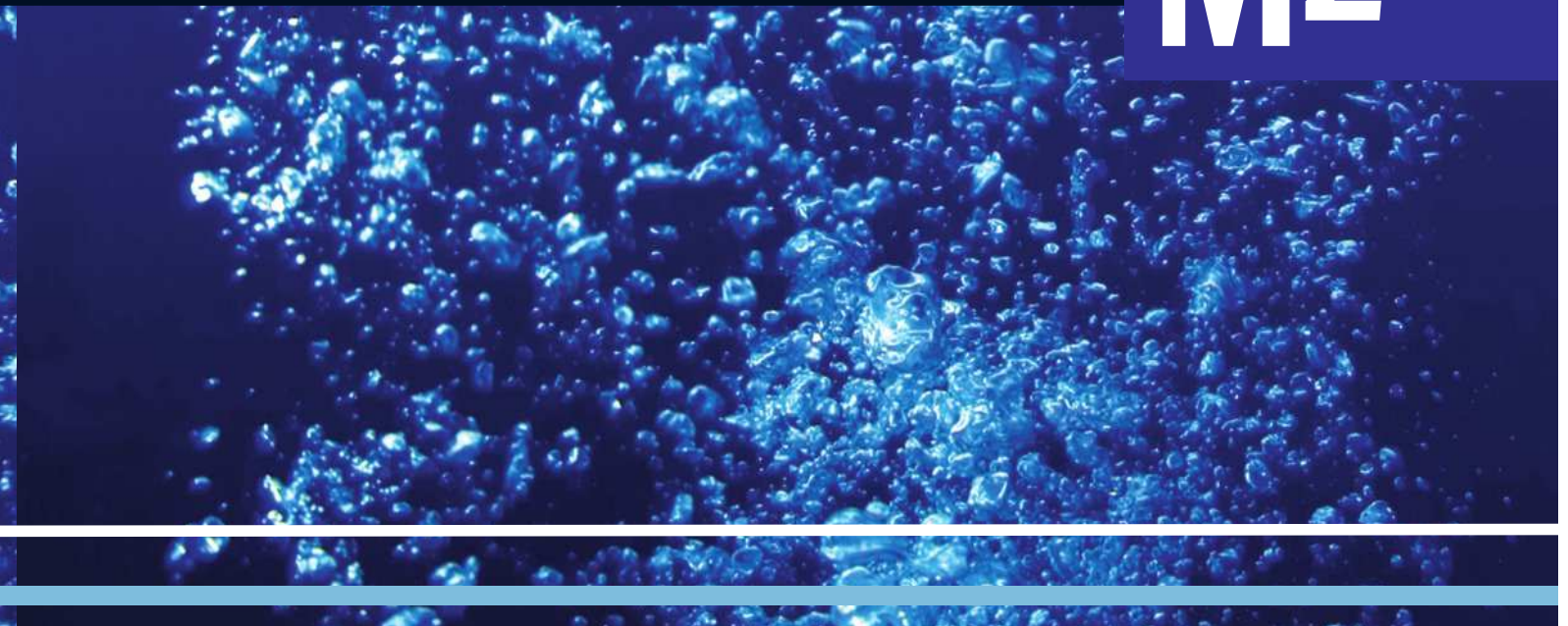


Instrumentation & Control

MANUAL OF WATER SUPPLY PRACTICES

M2



Third Edition



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AWWA MANUAL M2

Third Edition



American Water Works Association

MANUAL OF WATER SUPPLY PRACTICES—M2, Third Edition
Instrumentation and Control

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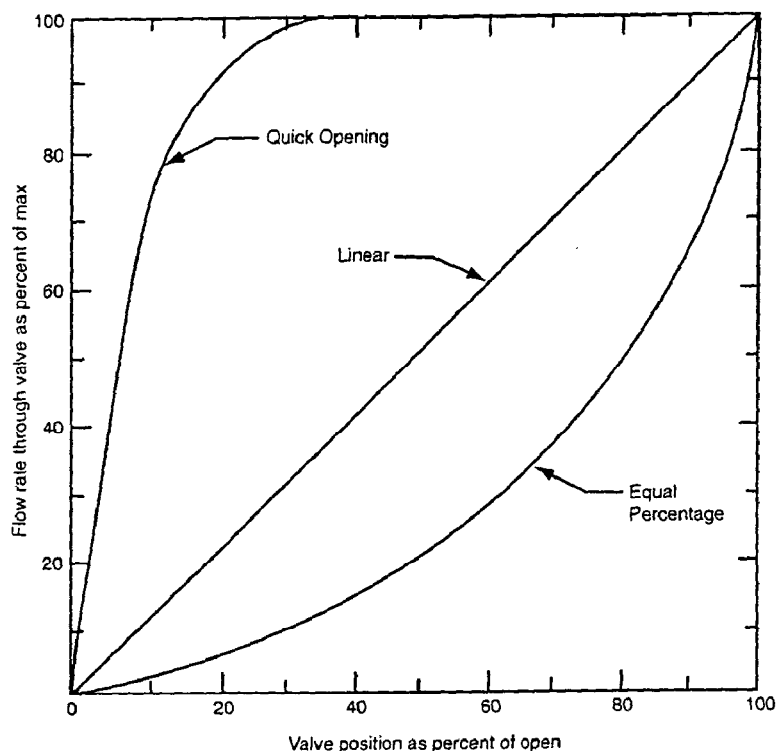
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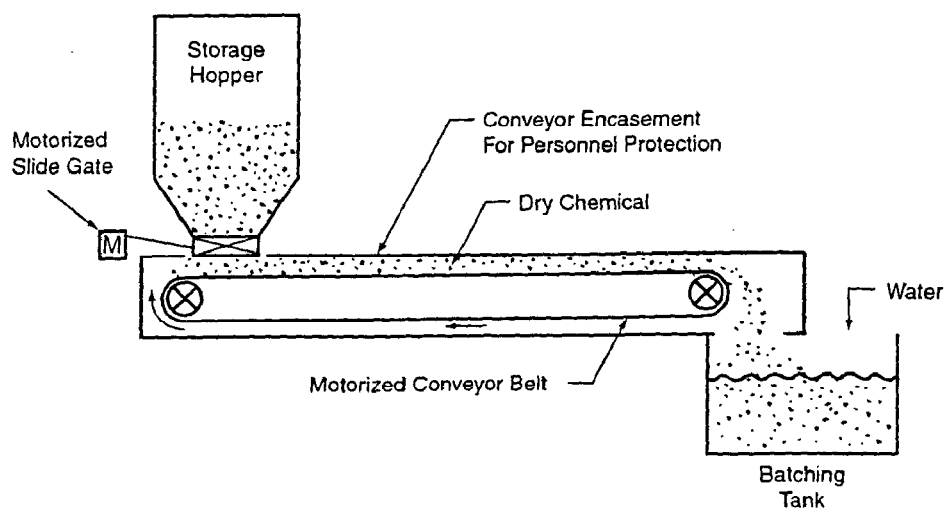
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Corrections to figures:

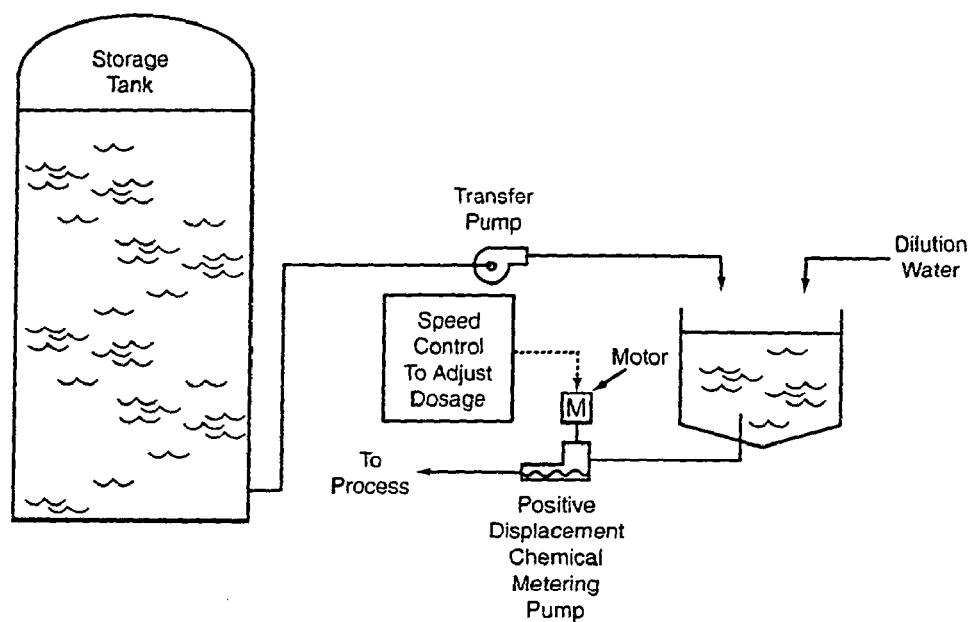
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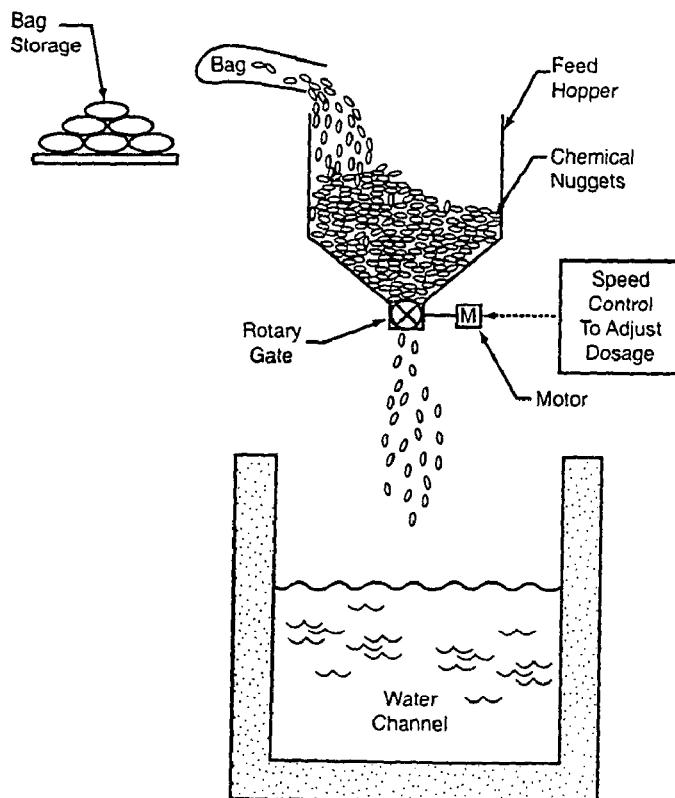
On page 158, Figure 8-16 should be as follows:



On page 158, Figure 8-17 should be as follows:



On page 159, Figure 8-18 should be as follows:



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Foreword

The Distribution Division of American Water Works Association authorized the formation of the Committee on Automation and Instrumentation in 1968 and the division's board of trustees set a scope for the committee as follows:

Assemble and disseminate information on automatic and remote operation and instrumentation of pumping stations and distribution and supply systems, including valves, storage tanks, and booster pumps.

To accomplish part of this assignment, the committee prepared this manual. This third edition of M2 includes basic information on electrical power distribution and updates the automation and instrumentation technology that has changed rapidly since the second edition in 1983. Computer technology in particular is evolving with great speed and will continue to do so. On the other hand, much of the theory and principles remain the same.

This manual is written primarily for the operator of any water utility, large or small, who would not necessarily have technical background but who would be searching for basic explanations and general information. The manual discusses equipment, terms, and expressions an operator encounters wherever electrical systems, automation, and instrumentation are found in water distribution, treatment, and storage systems.

The size and complexity of the centralized water system facilities vary with the size and complexity of the utility. However, the basic principles of electrical power distribution, automation, and instrumentation apply in each case.

The committee, which is now under the Engineering and Construction Division, has been renamed, Instrumentation and Control, and the M2 manual is now titled *Instrumentation and Control*.

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Acknowledgments

The Automation and Instrumentation Committee of the Engineering and Construction Division of the Technical and Educational Council of the American Water Works Association developed this edition of M2. The committee has been renamed Instrumentation and Control. The following committee members assisted:

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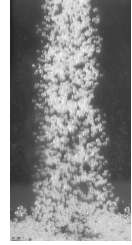
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Chapter 1

Introduction

Just as *water utility system* varies in definition, so does *automation and instrumentation*. However, to provide a framework for this manual the following definitions will be used (AwwaRF/JWWA 1994):

Automation: the replacement or elimination of intermediate components of a system or steps in a process, especially those involving human intervention or decision making, by technologically more advanced ones.

Instrumentation: both the technology and installation of equipment to monitor and control operations and carry out information processing associated with observation or adjustments of operations.

In the broadest sense, an instrument is defined as a device that performs a specific job. In a water utility, an instrument is usually a measuring or control device. In an automatic system, the controlling factor, such as flow or pressure, has to be reliably sensed or measured. Automation and instrumentation are closely associated because one depends on the other.

THE WATER UTILITY SYSTEM

To provide a consistent approach, the following paragraphs apply to water treatment and distribution systems, their important elements, the operator's responsibilities, and automation and instrumentation's role.

A water distribution system delivers potable water, at a suitable pressure, in the amount required at customer service connections, through a piping network. The distribution system can consist of elements such as main pumping stations, booster pumping stations, storage reservoirs, standpipes, elevated tanks, water mains, valve stations, and wells. The operator has the duty to maintain the elements of the system and to see that they perform correctly and reliably.

An operator's main responsibilities are supervision and control. *Supervision* means examining system performance information and deciding if it is acceptable. If, in the operator's opinion, performance is unacceptable, then the operator must

change an element or make an adjustment to the system to bring performance back to an acceptable condition. This is called *manual control*. When instruments are provided to make the necessary change or correction without the intervention of the operator, the system is called *automatic control*. However, regardless of the extent to which automatic control is used, the operator still may need to intervene manually during abnormal or emergency situations.

Because treatment plants, distribution system pumping stations, storage reservoirs, and other facilities may be at various, separate locations, the information needed to supervise and control the system must be gathered at some centralized point near the operator. Provision must also be made at this central location for remote control of any of the facilities that the operator may be required to regulate or change.

The operator will usually be working through some intermediate or intervening instrument to cause the systems to perform. Some of the instruments will be entirely mechanical, such as levers, chains, and cables; some will be hydraulic systems, using water or oil pressure for power sources and control; some will be pneumatic systems, using compressed air for power, control, and instrumentation; and some will be electrical systems for power, control, and instrumentation. A swing check valve will close automatically, for example, when not forced open by the flow of water through it. An indicating pointer can be positioned by a system of cable and pulleys to provide position indication. Oil or water pressure can be used to hold a valve closed, whereupon the loss of pressure will cause it to open automatically. Similarly, compressed-air pneumatic systems can be arranged to cause devices to operate automatically; pneumatic instrumentation and control systems are used extensively. Electricity is used more than any other source of power for control and instrumentation.

Generally, an electrical system, together with various mechanical, hydraulic, and pneumatic subsystems, allows an operator to supervise and control the water system. These electrical systems may include any or all of the following:

- Power system, using local, remote, or automatic control
- Telemetry, monitoring, and alarm system
- Communication system, data acquisition, and data processing

Operations are performed automatically for several reasons:

- the operator does not have to do them
- the operator cannot do them
- they can be done faster and better automatically
- they can be more efficient

As with automation, instrumentation is an extension of the operator. Instruments see, feel, measure, and record information for the operator. Instruments can perform a variety of operations, including:

- | | | |
|---------------|--------------|----------------|
| • measuring | • monitoring | • comparing |
| • remembering | • signaling | • regulating |
| • calculating | • switching | • transmitting |
| • receiving | • recording | • indicating |

- integrating
- timing
- converting
- summing
- anticipating
- detecting
- programming
- analyzing
- alarming

Each individual instrument is a single device with a specific task. Collectively, instrument systems can seem extremely complex; but the operator who understands each device and its unique function will be able to use each instrument as an aid to efficient supervision and control. An operator should be acquainted with all the automatic controls and instruments in use in the utility. This will give the operator the confidence needed to use the equipment effectively. With a broad knowledge of instrumentation and its applications, the operator becomes the driving force to seek operational improvement through the technology of instrumentation.

HOW TO USE THIS MANUAL

This manual introduces the major topics of automation and instrumentation. While not an exhaustive source of specific details, the manual can be used to identify water utility system automation and instrumentation elements. At a pumping station, for example, an operator will be able to examine an item of equipment and understand what it does, how it works, and identify the functions of its associated devices. Having identified a device, the operator may refer to the operations manual for further information. By using the plans of the station, equipment instruction manuals, equipment nameplate data, and other general information, the operator should be able to learn the names of the various devices and become acquainted with the intended purpose of an overall assembly of the equipment. This assembly can, for example, include a pump, motor, motor starter, and pump discharge valve, together with instrumentation and protective devices working together to perform a function as a complete unit.

This procedure can be used to learn more about local and remote controls, metering, and instrumentation. This manual can be used to understand their functions, as well as their relationships to the connected equipment.

This operator's manual may cover considerably more material than would apply to many small facilities; yet the manual may not mention every device found in a particular system. In these cases, the operator is encouraged to seek other references, some of which can be found in this manual.

The chapter arrangement of this manual is intended to group related topics. The second and third chapters review the hydraulic and electrical principles used in automation and instrumentation, as well as the basics of electric motor controls. The fourth and fifth chapters discuss instruments that measure process variables such as flow, pressure, level, and temperature. These types of instruments are called *primary instrumentation*. The sixth and seventh chapters present *secondary instrumentation*, those instruments that respond to and display information from primary instrumentation. The eighth chapter looks at the final control elements, such as pumps and valves. The last three chapters introduce the basics of automatic and digital control elements.

The topics of each chapter are introduced in the following paragraphs.

Chapter 2 Hydraulics and Electricity briefly reviews hydraulics and electrical power as the subjects relate to automation and instrumentation. Water utility operators are usually more familiar with hydraulics than electricity, and knowledge of both is necessary to get the most out of this manual.

Chapter 3 Motor Controls introduces the principles of the controls that stop and start motors, as well as the control of variable speed motors. The chapter also discusses motor control logic and presents motor control diagrams.

Chapter 4 Flowmeters discusses the most common flowmeters in service in water supply systems. These include the Venturi meter (Venturi), modified Venturis, orifice plate, magnetic, turbine and propeller, sonic, vortex, averaging Pitot, and rotameter. Also included are open channel flowmeters—weirs and flumes. Topics covered are basic theory, installation, maintenance, advantages, and disadvantages.

Chapter 5 Pressure, Level, Temperature, and Other Process Measurements introduces the primary sensors associated with three process variables encountered in water utility systems: pressure, level, and temperature. This chapter will touch on, in general terms, analytical instrumentation that is finding wide use in water systems, particularly in water treatment plants. An overview is also included of many of the less common sensors in use today.

Chapter 6 Secondary Instrumentation explains the pneumatic systems (those using air pressure) and electronic systems that control secondary instrumentation. Topics include the air supply system, pneumatic controllers, recording and indicating hardware, computing devices, converters, and applications.

Chapter 7 Telemetry is remote metering, taking a measurement at one location then transmitting it to another location. Specific topics include transmitting devices, output devices, controllers and function modules, communications, and various types of telemetry.

Chapter 8 Final Control Elements provides an overview for those applications that can produce a change in the process of treating and distributing water: valves and pumps. In general, this chapter describes the various types of final control elements and how they operate within an automated system.

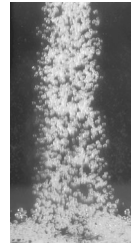
Chapter 9 Basics of Automatic Process Control discusses how the elements presented in the previous chapters work together in a process that occurs without continuous operator input. The chapter provides basic information on process control and the most common techniques used to automate process control in water utilities.

Chapter 10 Digital Control and Communication Systems shows how computer and digital technology enable operators of process control systems to quickly recognize status changes and respond immediately. This chapter introduces the concepts, hardware, and software of digital control.

Chapter 11 Instrument Diagrams presents the standard instrument diagrams or process and instrument diagrams frequently used in the water utility systems.

REFERENCE

AwwaRF/JWWA (American Water Works Association Research Foundation/Japan Water Works Association). 1994. *Instrumentation & Computer Integration of Water Utility Operations*. Denver, Colo.: AwwaRF/AWWA.



Chapter 2

Hydraulics and Electricity

This chapter presents the basics of hydraulics and electricity. A basic knowledge of the physics of hydraulics (fluid mechanics) and electricity is required for any designer or operator to understand the system. Hydraulics topics include flows, pressures, elevation, valve positions, and other physical parameters that are sensed and transmitted for either monitoring or control. Topics on electricity include basic electricity, distribution concepts, power factor, and safety.

HYDRAULICS

In water systems, hydraulics explains how water acts in tanks, open channels, and pipes. The principles of hydraulics can be used to design sensing devices such as Pitot tubes, Venturi flow tubes, and ultrasonic, magnetic, and other static and dynamic sensing devices. Water, as a medium for transmitting force, can be applied to cylinders, pilot valves, and transmitter mechanisms. Hydraulics can be used to predict hydraulic surge and cavitation in order to properly design, control, and operate systems in a safe and efficient manner. Hydraulic friction in closed conduits and its relationship to flow directly determine the sizing of lines and valves, head losses, and the operation of different system configurations.

The three branches of hydraulics are

- Hydrostatics (liquids at rest)
- Hydrokinetics (liquids in motion)
- Hydrodynamics (forces exerted by or on a liquid in motion)

Properties of Liquids

Three basic characteristics of liquids are that

- they are virtually incompressible.
- they have unlimited directional movement.
- they can assume any form or shape.

Density of water. For most hydraulic equations, density, expressed as weight per unit volume, of pure water is assumed to be 62.4 lb/ft^3 (999.6 kg/m^3). This density is correct only at 52°F (11°C). As the temperature of water changes, its density changes.

- At higher temperatures water is less dense. At 200°F (93°C) density = 60.135 lb/ft^3 (963 kg/m^3).
- At lower temperatures water is more dense. At 39°F (3.9°C) density = 62.424 lb/ft^3 ($1,000.03 \text{ kg/m}^3$).
- At 32°F (0°C) water freezes. Ice is less dense than liquid water; therefore, it floats.

Dissolved minerals and salts will add to the weight of water. The density of seawater is 64 lb/ft^3 ($1,030 \text{ kg/m}^3$). Pure water at 39.2°F (4°C) is the standard used to determine the specific gravity of other liquids, assuming both are at atmospheric pressure, 14.7 psi (101 kPa). For these conditions, pure water is at its maximum density, 62.4266 lb/ft^3 ($1,000 \text{ kg/m}^3$).

Incompressibility. Although liquids are shapeless, they are generally less compressible than a solid. When a force is applied to a confined liquid, the liquid acts in a manner very similar to a rigid solid. A pressure of 1 psi (6.9 kPa) will reduce a volume of water by 1 part in 300,000. For each drop of water added to a full container, a drop must come out or the container will burst. This is also true in a pipeline: a gallon in requires a gallon out.

Density and specific gravity. Pressure exerted by a liquid depends on its weight density. For example, water weighs 62.4 lb/ft^3 or 0.036 lb/in.^3 (999.6 kg/m^3).

Viscosity. Viscosity is the internal frictional resistance a liquid offers to flow or motion. It increases with a decrease in temperature. Liquids such as polymers may have a viscosity that greatly affects the suction characteristics of chemical pumping equipment. Water is one of the least viscous liquids, whereas oil and molasses are more viscous.

Water used for backwashing a filter will have a different viscosity in the winter than in the summer. This affects the expansion of the filter bed. It would take $1,000 \text{ gpm}$ ($0.063 \text{ m}^3/\text{sec}$) at 86°F (30°C) but only 420 gpm ($0.026 \text{ m}^3/\text{sec}$) at 32°F (0°C) to expand the bed equally.

Hydrostatics

Hydrostatics is the study of liquids at rest.

Hydrostatic pressure. Pressure, as the word is commonly used, means the intensity of force per unit area. Pascal's law states that pressure exerted at any point in a liquid acts equally in all directions and that this pressure acts at right angles to the surfaces of the containing vessel. As the example shown in Figure 2-1 illustrates, a 10-ft head in a tank is applied at the base of the tank in all directions, to the bottom and sides—downward and outward. The vertical distance between two horizontal levels in a liquid is defined as the head of liquid.

Every square inch of the bottom of the tank has the same head exerted on it. Similarly, at a depth of 5 ft, the pressure head is 5 ft in all directions.

The pressure at any point in a liquid depends on

- Height of liquid above the point
- Density of the liquid
- Any additional pressure applied to the surface

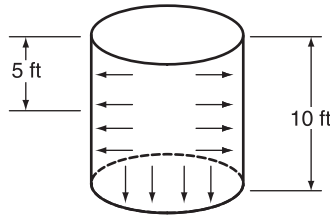


Figure 2-1 Pressure in a tank

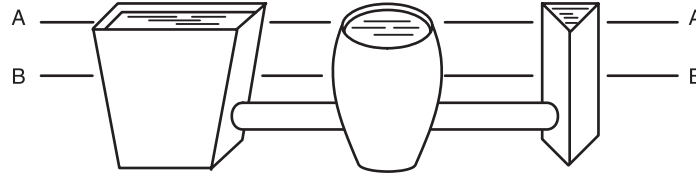


Figure 2-2 Pressure in containers of various shapes

All fluids will *seek their own level*; that is, the surfaces of any connected volumes of water will equalize at the same elevation. This is true even if two nonmiscible liquids (those that will not mix together in the same container) are placed on top of each other, such as water over mercury.

Effect of container shape on pressure. One of the corollaries of Pascal's law is that pressure is not altered by the physical shape of the container. To illustrate this, an arbitrary horizontal reference plane (called a datum plane) is used to measure hydraulic elevations, regardless of the container shape or pipeline grade. In Figure 2-2, with B–B as a datum plane, the pressure at B will be the same in each container; the same is true if A–A is used as the datum plane.

Hydraulic elevations, as referenced against the datum plane, can be positive or negative (above or below the datum plane). Sea level is commonly used as a reference plane.

Atmospheric pressure. All gases have weight, so the weight of air acting on the free surfaces of a liquid is another force to consider in evaluating hydraulic systems. Air weighs 0.075 lb/ft³ (1.2 kg/m³) at sea level.

Atmospheric pressure is

$$2,116 \text{ lb/ft}^2 \text{ (101.3 kPa), or}$$

$$(2,116 \text{ lb/ft}^2)/(144 \text{ in.}^2/\text{ft}^2) = 14.7 \text{ lb/in.}^2, \text{ or}$$

$$(2,116 \text{ lb/ft}^2)/(62.4 \text{ lb/ft}^3) = 33.9 \text{ ft of water, or}$$

$$(2,116 \text{ lb/ft}^2)/(848.6 \text{ lb/ft}^3)/(12 \text{ in./ft}) = 29.9 \text{ in. of mercury.}$$

Vacuum. A perfect vacuum is a space containing nothing: no solids, no liquids, and no gases. A perfect vacuum is unattainable, and the amount of vacuum is equal to the amount that the pressure is below atmospheric pressure.

Liquids below atmospheric pressures obey Pascal's law just as they do at positive pressures. Negative pressures, referred to as negative heads, will be found in devices such as pumps, eductors, and Venturi tubes. Sensed pressures, both

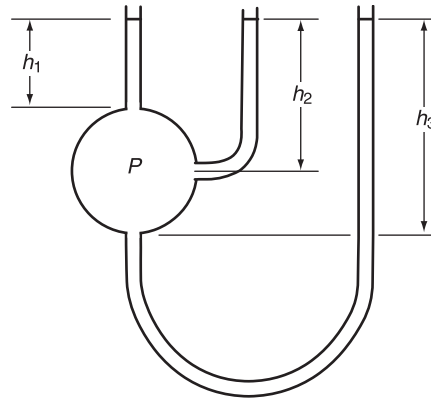


Figure 2-3 Water level in an unpressurized system

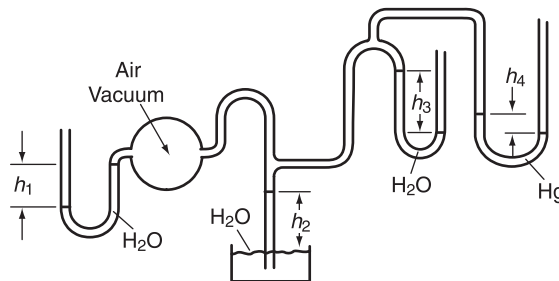


Figure 2-4 Fluid levels in a vacuum system

negative and positive, provide information, which is converted into flows, elevations, and pressures necessary to operate a water utility. The methods of conversion and instrumentation used in the process will be discussed later in this manual.

Summary of hydrostatics. The hydraulic arrangements in Figures 2-3 and 2-4 illustrate the basics of Pascal's law, under both positive and negative pressures, for a liquid under static conditions. The use of piezometric tubes can show the pressure at any point in a hydraulic system (see Figure 2-7). The figure shows that no matter where a group of piezometric tubes are connected, if cut through the same plane, the water level will be the same in every tube.

Similarly in Figure 2-4, a vacuum can be pulled on a system such that if $h_1 = 12$ in. (120 mm), h_2 and h_3 will also equal 12 in.

Hydrokinetics

Hydrokinetics describes the characteristics of liquids in motion.

Liquid flow. Some of the elementary characteristics of flow are volume, velocity, laminar flow, turbulent flow, and the energy involved.

Volume is the quantity of liquid that passes a known point in a hydraulic system, and velocity is the rate or speed of the liquid passing that point.

The velocity of the liquid flow increases as the cross-sectional area decreases. Also, the velocity decreases as the cross-sectional area increases (Figure 2-5). The flow velocity at B is two times that at A, because the area at B is half that at A; therefore, a constant flow is maintained throughout the length of the pipe.

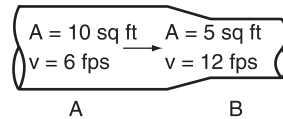


Figure 2-5 Flow velocity as a function of cross-sectional area

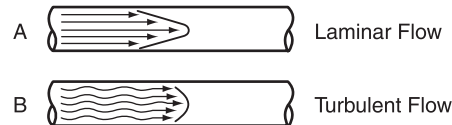


Figure 2-6 Flow-velocity profiles

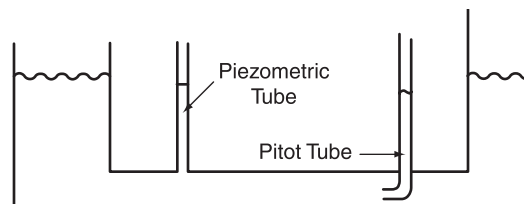


Figure 2-7 Determination of static pressure

Laminar and turbulent flow. If the average velocity is low, the flow of the liquid will be laminar; i.e., all the particles move parallel to each other without interaction. As flow rate increases, these particle streams will continue to run parallel until some critical velocity occurs, when the streams will waver and suddenly break up into turbulent flow.

Turbulent flow produces random motion of the liquid, even in a direction at right angles to the flow. The velocity distribution in the turbulent region is more uniform. However, even under these conditions, a thin layer of liquid at the pipe wall moves in laminar flow. If the velocity profiles of laminar and turbulent flow are measured and plotted, they will look something like those in Figure 2-6.

Measurements. Two conditions of flow in a closed conduit can be easily determined: static pressure and relative velocity. First, the static pressure at any point in the system can be determined with a piezometric tube (Figure 2-7) perpendicular to the pipe flow direction. The measurement should be taken at a point where the direction of the flowing fluid is not changing. Second, the relative velocity within the pipe can be measured using a Pitot tube. This device, with its tapered tube pointing into the flow, measures the velocity only at its opening. It does not, therefore, find the true mean velocity of the velocity profile that exists within a pipe, as shown in Figure 2-6. Several readings must be taken across the pipe at prescribed locations in a plane (a traverse) to calculate the average (or mean) velocity.

Energy and head. Water flow has potential energy (capacity to do work) because of its elevation, velocity, pressure, or any combination of these. Each energy form may be expressed as equivalent pressure or head in feet (or meters), or in pounds per square inch (or kilopascals). Also, each energy form can be converted to

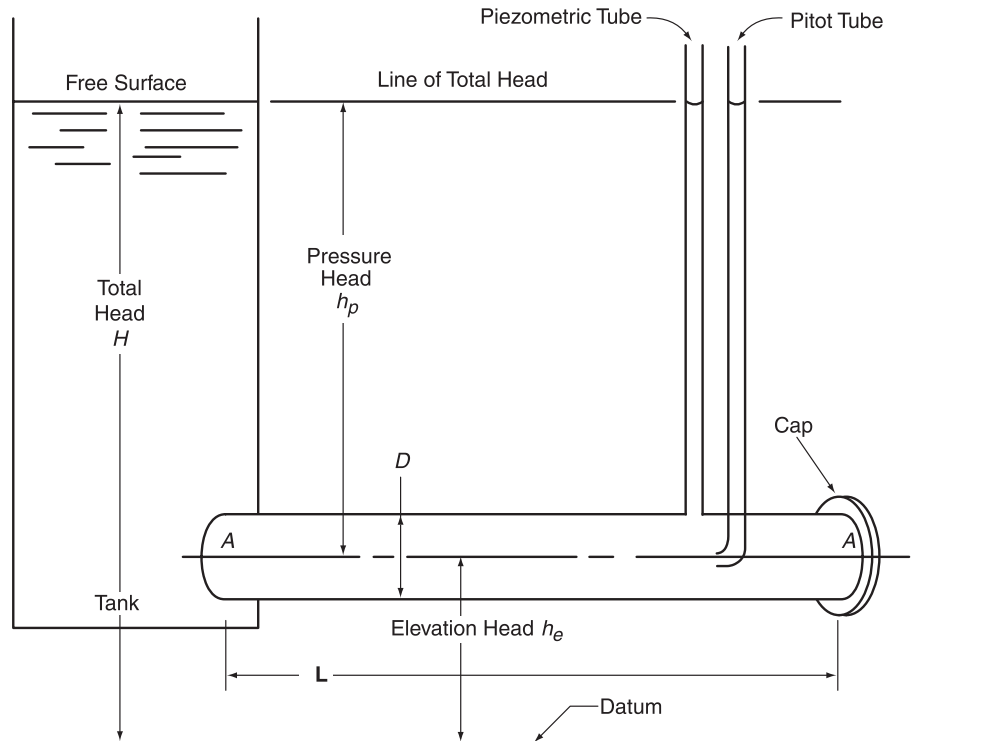


Figure 2-8 Water in pipe with pressure, no flow

the other two. The sum of these three energy forms is called the total head, H , (Figure 2-8). If water flowed through a smooth pipe without friction, the total head would remain the same at any section of the pipe (Figure 2-9). This would be true even if the diameter (D) of the pipe or its elevation changed.

Elevation head: h_e . In hydraulics, differences in elevation are measured above a selected datum plane. The pipe in Figure 2-9 is at the same elevation above the datum at all points; therefore, h_e is constant. If point 2 were higher than point 1, as in Figure 2-10, h_e at point 2 would increase and pressure head, h_p , at point 2 would decrease because part of h_p would be used to lift the water at point 2, where the energy would show an increase in h_e .

Velocity head: h_v . When water flows in a pipe, a part of the total head, H , is converted to kinetic energy (energy of motion) capable of lifting the water through a height, h_v , equal to the difference in elevation, h_e , if the water and pipe had no friction. This can be seen by the difference in levels in a Pitot tube, which senses velocity head (kinetic energy), and a piezometric tube, which senses static head energy (potential energy) at the point of measurement (Figure 2-11).

A body falling freely through a height, h , will attain a velocity expressed as:

$$v = \sqrt{2gh} \quad (2-1)$$

Where:

v = velocity, theoretical, ft/sec (m/sec)

g = acceleration constant of gravity, 32.16 ft/sec² (9.8 m/sec²)

h = vertical height or head, ft (m)

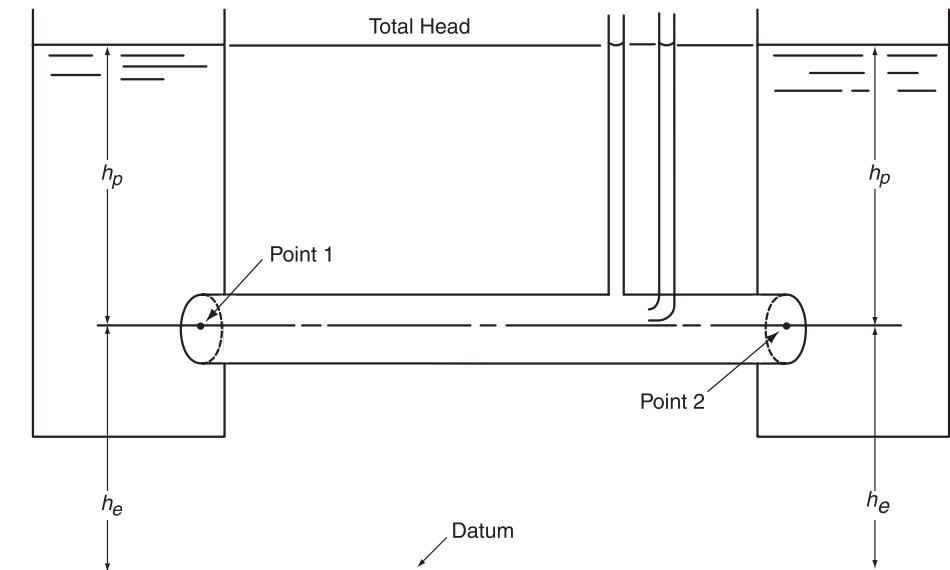


Figure 2-9 Total head

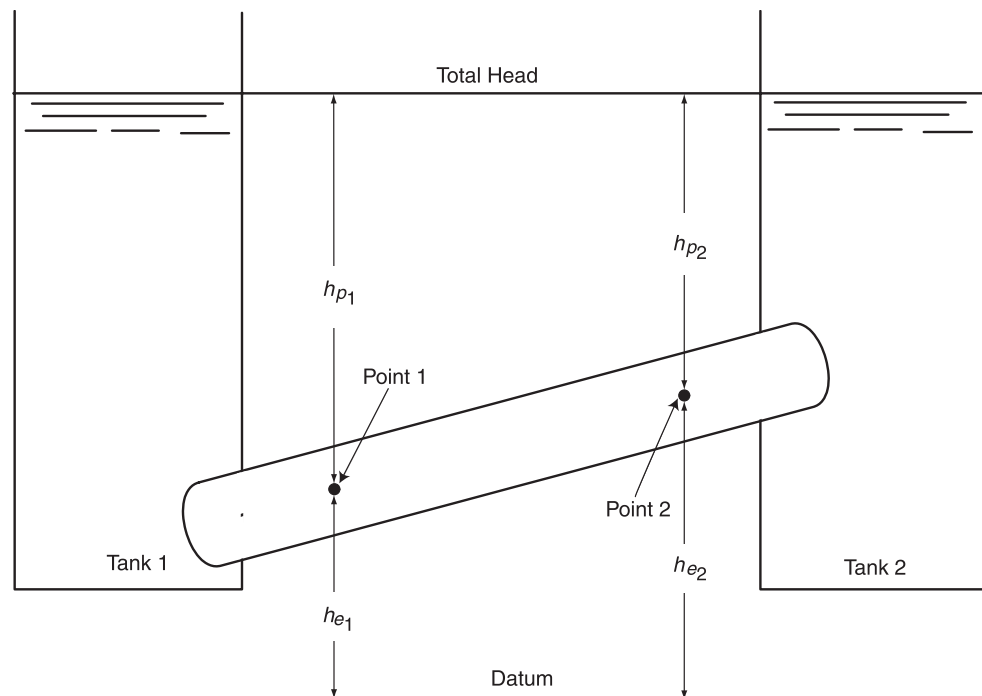


Figure 2-10 Elevation head

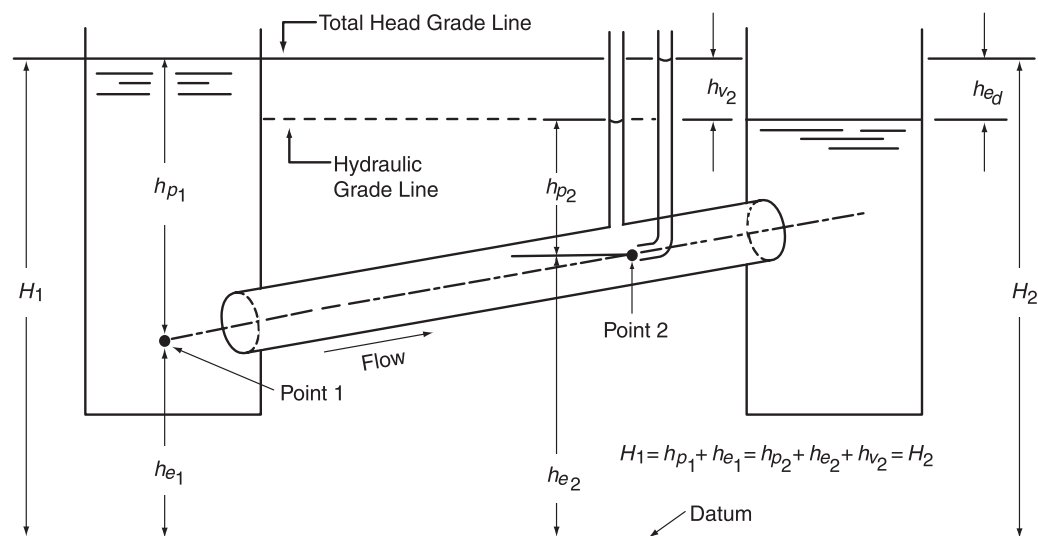


Figure 2-11 Flowing without friction

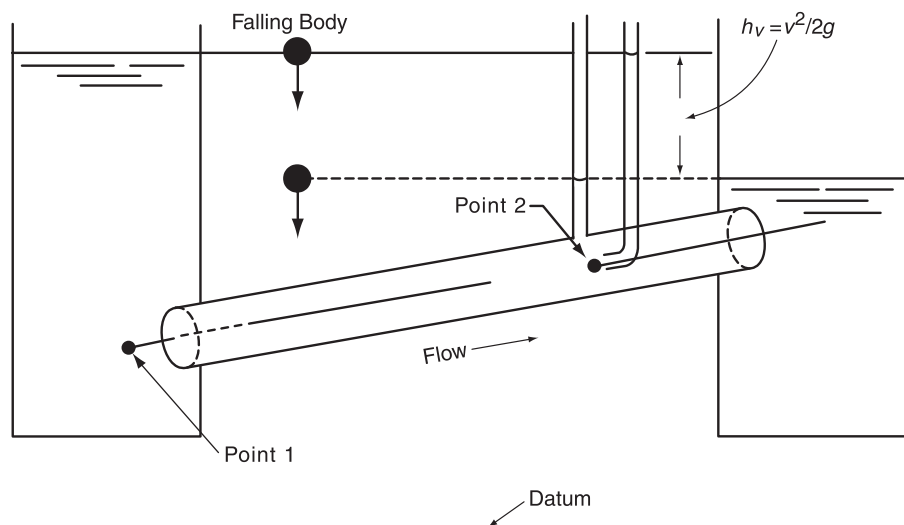


Figure 2-12 Velocity head

Water flowing through a pipe without friction is essentially falling through a height equal to the difference in elevations between two points (Figure 2-12). Consequently, the water in the pipe attains the same velocity as a falling body through a height equal to the velocity head, h_v , and this may be expressed as:

$$v = \sqrt{2gh} \quad (2-2)$$

If a Pitot tube is inserted into the pipe, the energy of velocity will lift the water in the tube to a height equal to the difference in elevations, or to the total head minus the sum of the pressure head, h_p , and elevation head, h_e , or the head, h_v , causing the

velocity. Consequently, h_v is called velocity head (represents kinetic energy) and can be expressed as:

$$h_v = v^2/2g \quad (2-3)$$

Pressure head: h_p . Pressure head, h_p , is equivalent to the pressure per unit area exerted against the walls of the pipe. It is the only part of the total head, H , that can be measured by a piezometric tube, manometer, or pressure gauge (and represents potential energy).

Friction head: h_f . When water flows from one point to another, turbulence, pipe roughness, and the frictional forces within the fluid cause friction, which generates heat, and therefore, head loss. Energy is not lost, because energy can be neither created nor destroyed; the energy is converted to heat.

Therefore, the rules for flow indicate that when water flows from one point to another, the sum of the elevation, velocity, and pressure heads at the second point must be equal to the total head at the first point, minus the friction head:

$$h_e + h_v + h_p = H - h_f \quad (2-4)$$

In Figure 2-13, because h_f is a continuously increasing value between point 1 and point 2, pressure head, h_p , decreases continuously between these same points. Because velocity head, h_v , is constant, the total-head hydraulic grade slopes in the magnitude of the increase of h_f while h_p decreases.

Total head: H . The combined effects of head can be summarized as follows: total head, H_1 , at any point in the system is the sum of the elevation head, h_e , pressure head, h_p , and velocity head, h_v , at that point. The total head, H_2 , at a second

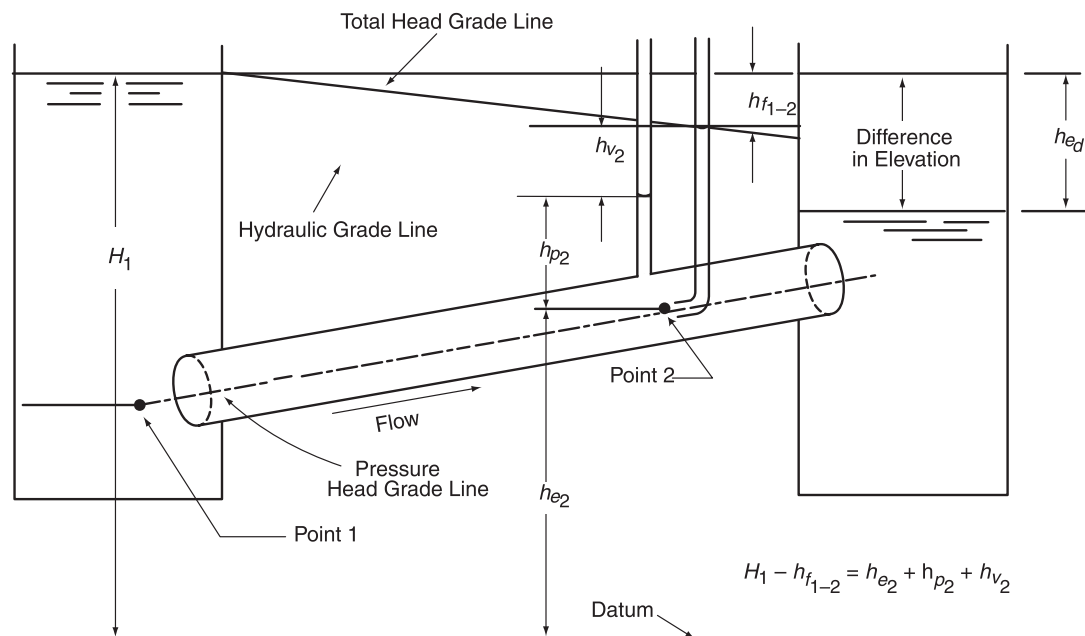


Figure 2-13 Flowing with friction

point, equals the total head, H_1 , at the first point, minus the head loss, h_f , caused by friction between the points:

$$H_2 = H_1 - h_f \quad (2-5)$$

Quantity flowing in straight pipe—no friction. If the flow is zero, water will stand at the line of total head in both the piezometric tube and the Pitot tube. No velocity head, h_v , exists. The volume, V , contained in length of pipe, L , between two points is determined as follows:

$$V = A \times L \quad (2-6)$$

Where:

V = Total volume, in ft^3 (m^3)

A = Area of pipe cross section, in ft^2 (m^2)

L = Length of section, in ft (m)

If water flowed without friction, water in the piezometric tube would stand at a height, h_v , that was a distance below the line of total head, H , because that part of H is converted to velocity head, h_v , producing velocity, v .

As explained in the previous section, velocity, v , will be the same at all sections of a pipe of constant cross-sectional area. The hydraulic grade line drawn through the water elevation in a series of piezometric tubes will be parallel to the total head grade line.

The quantity, Q , in cubic feet (or cubic meters) for length, L , will flow past a point in a time period, t . Therefore,

$$L/t = \text{Velocity, } v, \text{ in ft/sec (m/sec)} \quad (2-7)$$

Where:

t = time, in seconds

Therefore, the equation for still water in pipe, $Q = A \times L$, is changed to the following for flowing water:

$$Q_t = A \times v \quad (2-8)$$

Where:

Q_t is equal to volume rate of flow in ft^3/sec (m^3/sec)

However, velocity is produced by the conversion of part of the total head, H , to velocity head, h_v . Velocity, v , is expressed as follows:

$$v = \sqrt{2gh_v} \quad (2-9)$$

Substitution yields:

$$Q_t = A \times \sqrt{2gh_v} \quad (2-10)$$

Quantity flowing in straight pipe—with friction. Water flows in the presence of friction. A part of the total head, H , is converted to velocity head, h_v , and a part of the total head, H , is lost in friction, h_f (Figure 2-14).

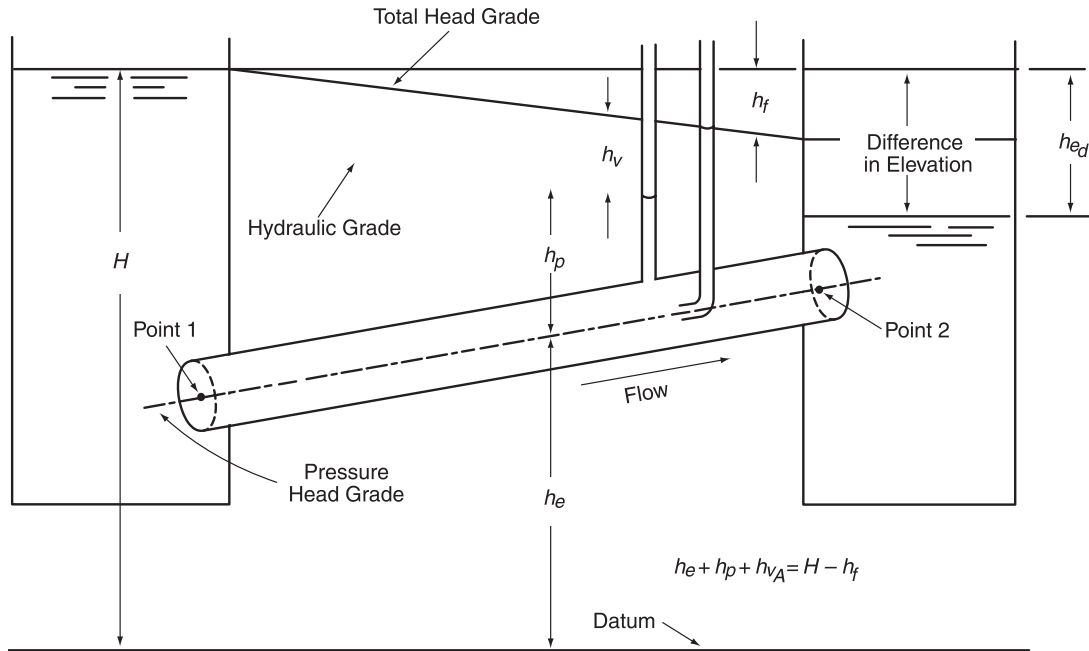


Figure 2-14 Flowing with friction

The value of friction, h_f , increases with distance between any two points. The pressure head, h_p , is decreased by the same amount that friction head, h_f , increases. Because the total head, H , includes the pressure head, the total head is decreased in the same amount. The water elevation in a series of piezometric tubes will stand below the total-head grade, and the hydraulic grade line will slope.

The velocity head, h_v , discharged through an orifice is decreased by a small amount (usually 1–2 percent) equal to the head loss caused by the orifice contraction, h_f , at the discharge point.

$$h_{v \text{ total}} = h_v - h_{f \text{ discharge orifice}} \quad (2-11)$$

For a given total head, H , and a given head condition at the discharge point, the actual velocity, v_A , and velocity head, h_{vA} , will be less than the theoretical velocity, v , and velocity head, h_v . However, because the cross-sectional area of the pipe is constant, the actual velocity head, h_{vA} , and the actual velocity, v_A , will be constant.

The actual quantity, Q_A , corresponding to the actual velocity head, h_{vA} , can be expressed as:

$$Q_A = A \times \sqrt{2gh_{vA}} \quad (2-12)$$

However, h_{vA} is some unknown part of h_v , because $h_{vA} = h_v - h_f$ and the value of h_f is unknown.

The value of h_f varies with length and diameter of pipe, and the surface characteristics of roughness of the pipe. The head loss in friction can be expressed:

$$h_f = f \times \frac{L}{D} \times \frac{v_A^2}{2g} \quad (2-13)$$

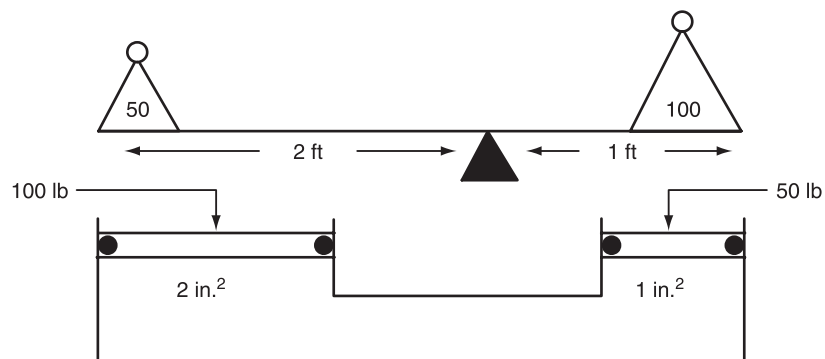


Figure 2-15 Mechanical leverage compared to hydraulic force

Where:

D = pipe diameter

f = the friction factor for the pipe in question

Combining the last two equations yields:

$$Q_A = A \times \sqrt{2g \left[h_v - \left(f \times \frac{L}{D} \times \frac{v_A^2}{2g} \right) \right]} \quad (2-14)$$

This equation is not practical for determining actual quantity because too many unknowns exist: the theoretical velocity head, h_v , the friction factor, f , the actual pipe diameter, D , and the actual velocity, v_A . Therefore, to measure accurately the actual quantity, Q_A , some type of measuring device with known physical characteristics that can be bench tested must be used. Flowmeters serve this function to varying degrees.

Hydrodynamics

The forces of hydraulics are analogous to those of mechanical leverage, as shown in Figure 2-15 and discussed in the following paragraphs. The transmission of force in a hydraulic system is basic to chemical-pump equipment and cylinder-operated butterfly valves.

Force in hydraulic systems. Pascal's law states that a force applied to a confined liquid is transmitted equally in all directions throughout the liquid, regardless of the shape of the container. Transmission of pressure can be defined as force divided by the area over which it is distributed.

In Figure 2-16, 200 lb of force, F , applied to piston 1 will impart 20 psi to the liquid. Piston 2 will see the 20 psi and with its 10-in.² area,

$$20 \text{ psi} = F/10 \text{ in.}^2$$

$$\text{or } 20 \times 10 = 200 \text{ lb of force}$$

Piston 3 will also see 20 psi; but with its 20-in.² area, it will produce 400 lb of force:

$$20 \text{ psi} = F/20 \text{ in.}^2$$

$$\text{or } 400 \text{ lb of force}$$

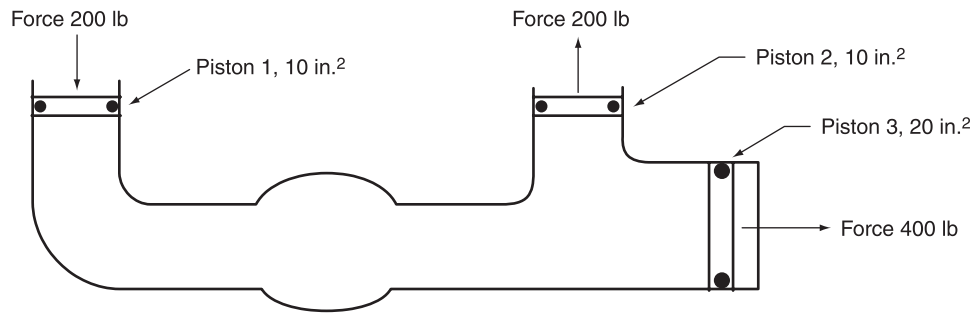


Figure 2-16 Hydraulic force

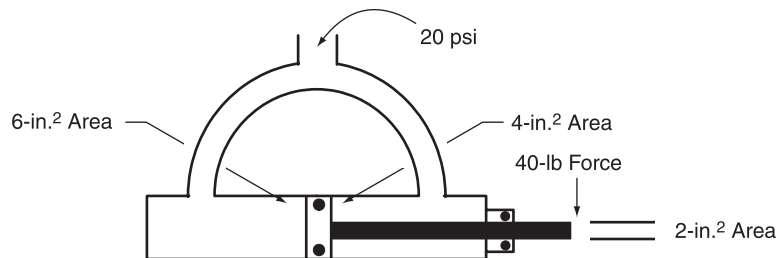


Figure 2-17 Differential areas

This multiplication of forces by the difference in area between two pistons is a principle commonly used in hydraulic equipment. Note that the shape of the connecting pipe has no effect on the forces.

The transmission of forces by hydraulic fluids can also be described as differential areas. In Figure 2-17, a single cylinder has a single piston rod extending through one of the cylinder end caps. The effective area on the left side of the piston is 6 in.². The effective area on the right side of the piston is 4 in.², because the rod occupies 2 in.². Consequently, there is a force of 120 lb on the left side of the piston and 80 lb on the right, leaving a net force of 40 lb on the end of the rod. The net effect is the result of the area differential created by the rod because all other effective areas balance out.

Energy and work. Work is defined as a force moving a mass through a distance, and the amount of work is the product of the force multiplied by the distance. Without friction, the work input will be equal to the work output.

Energy includes work, together with other forms of energy into which work may be converted, and the forms that can be converted into work. Work must involve motion, whereas energy can be at rest and still exist as energy. The two, work and energy, are always interchangeable. Because energy is never created or destroyed, the total energy output in all its forms will always exactly equal the total energy input; this is the law of conversion of energy. This law holds even if usable output does not equal the input. For example, the seal on a cylinder shaft has friction. Consequently, some of the work imparted to the cylinder is consumed by the friction, which, in turn, generates heat. The total energy input equals the usable output plus the heat energy resulting from friction.

ELECTRICITY

Electricity is the primary type of energy used to power the majority of equipment used in the transport, treatment, and distribution of water. Electricity is usually delivered to a single point in most facilities by the local electrical utility and then distributed within the facility using equipment owned and operated by the water utility.

This section is not intended to make the reader an expert in electrical systems, but rather to describe the basic principles and equipment used in electrical power distribution. Water utility operators will better understand how their facilities operate and their options for meeting different operating requirements.

This section explains the following:

- Basic Electricity—physical laws that govern how electricity behaves
- Distribution Concepts—basic techniques used in electrical power distribution and commonly used electrical diagrams
- Safety—basic safety issues and the equipment used to enhance safety in electrical circuits
- Power Factor—what power factor means, how it impacts efficiency, and how to improve it in a facility
- Lightning and Surge Protection—protecting people and equipment from lightning and other electrical surges

Basic Electricity

Electricity is the movement of electrical charge from one place to another. Electrical charge results from atoms that have more electrons than protons (a negative charge) or fewer electrons than protons (a positive charge). Positive charges always attract negative charges, and negative charges always attract positive charges. Conversely, positive charges always repel other positive charges, and negative charges always repel other negative charges. This attraction or repulsion is called an electrical force, which can be quite substantial. By manipulating these charges according to the laws of physics, electricity can be very useful.

All atoms have one or more protons in their center, or nucleus, which attract an equal number of electrons on the outside edge of the atom. Atoms which have an equal number of electrons and protons are electrically balanced; they have no charge. Because an atom's electrons are attracted to their protons by an electrical force, they have to be forced out of the atom to create an electrical charge. Electrons can be forced out of an electrically balanced atom in several ways. Each of these is briefly explained below:

Physical—Electrons are forced out of atoms colliding with nearby atoms. When atoms on the surface of one material collide with the atoms on the surface of the other material, some of the electrons bump into the electrons of the other atoms and move from one material to the other. When an electron is knocked out of an atom, the electron becomes negatively charged. Therefore, the atom becomes positively charged because it now has more protons than electrons.

The dislodged electron is called a *free electron*. A free electron remains free only if there is no atom with extra protons available to neutralize it. It can move through material without becoming attached to an atom. This

kind of charge movement is called *static electricity*, which occurs in material that does not easily conduct electricity. One of the most dramatic forms of static electricity is lightning.

Thermal—Heat is a form of energy, and when atoms are heated, their movement increases. Heat can cause electrons to free themselves from atoms, becoming free electrons. This process works most effectively in materials that easily conduct electricity, like metals.

Magnetic—Magnetism is an electrical force that pushes or pulls charges. While magnetism does occur in nature, it is usually not strong enough to cause a noticeable amount of electricity. One exception is the aurora borealis or *northern lights*. The aurora borealis occurs near the North Pole where the earth's magnetic field is strongest. Strong magnetic fields can be created, and most electricity is made by passing a conductor through a magnetic field.

Chemical—Some chemical compositions (molecules) containing more than one type of atom can cause atoms to trade or give up electrons. This causes the atoms to become electrically charged, resulting in positively charged atoms and several free electrons. Corrosion and the electric charge found in batteries are examples of this process.

Photovoltaic—The energy in light rays can cause free electrons. Common examples include the photocells used to power small calculators, remote terminal units in supervisory control and data acquisition systems, and space satellites. The photovoltaic process occurs in materials that do not retain electrons very well. Special composite materials are made that perform more efficiently.

Conductors and insulators. Because any atom can be stripped of one or more of its electrons, any material can be a conductor of electricity. Materials are classified by how easily they conduct electricity. Three basic categories are used:

- Conductors—materials, usually metals (because they have more electrons than nonmetals), easily forced to carry electricity
- Semiconductors—materials easily forced to carry electricity only under certain circumstances
- Insulators—materials, usually nonmetals, that can only be forced to carry electricity by applying a very strong voltage

Physical laws. To predict how an electric charge will behave under certain conditions, it must be quantified. These electrical quantities are similar in concept to the common properties used to describe the movement of water from one place to another. As each electrical property is introduced below, its corresponding water flow quantity is also stated.

Because the amount of charge associated with one electron (or the absence of one electron) is so small (like a drop of water), a larger amount of charge, the coulomb, is used in measurement. A coulomb of electrical charge (similar to a gallon of water) is the charge of 6.25×10^{18} (6,250 million billion) individual electrons.

As water flow is the movement of water particles, electricity is the movement of charges. The velocity of electrical movement is the number of charges moving per unit of time. This velocity is called current, which is abbreviated by the letter *I* in

formulas and measured in a unit called an ampere. Amperes are often referred to as amps. One ampere is equal to one coulomb moving past a point in one second, which is similar to the flow of water measured in gallons (or liters) per second.

The velocity of a charge is determined by the amount of force pushing it and by the type of material it is moving through. The force that pushes an electrical charge is called an electromotive force, or EMF. EMF is abbreviated by the letter E in formulas and is measured in volts. E is also referred to as *electrical potential* or simply *potential*. In a water system, the force that pushes water through a pipe is called the head and is measured in feet of water column. Often the amount of EMF used is several thousand volts; a kilovolt (kV) is one thousand volts.

The material a charge moves through will provide some resistance (R in formulas) and is measured in ohms. Resistance is similar to the coefficient of friction in a pipe. Conductors have low values of resistance, while insulators have high values of resistance.

These three properties of electricity (EMF, current, and resistance) are related by the formula called *Ohm's law*, which states that one volt of EMF will cause one ampere of current to flow through one ohm of resistance. Written mathematically, it would be:

$$E = I \times R \quad (2-15)$$

Therefore, if any two quantities are known, it is simple to calculate the third quantity.

These electrical properties are popularly known by their units of measurement. That is, EMF is called *voltage*; current is called *amperage*; and resistance is called *ohmage*. All electrical properties use metric units. All electrical units are named for the name of the scientist that first discovered and defined the electrical property. For example, the EMF unit, volt, was named for the Italian scientist, Volta, whose early experiments with frog legs led to the discovery of EMF.

Another electrical quantity is power, P , which is a measure of the amount of electrical energy needed per unit of time to cause a specific current to flow through a specific resistance. Power is measured in units called *watts*. As with voltage, large amounts of power are measured in kilowatts (kW), equal to 1,000 watts. Electrical power measured in watts can be calculated by multiplying the voltage by the amperage as shown in the following formula:

$$P = E \times I = I^2 R = \frac{V^2}{R} \quad (2-16)$$

or:

$$1 \text{ watt} = 1 \text{ volt} \times 1 \text{ ampere} \quad (2-17)$$

A joule is the metric unit of energy. One watt is defined as one joule of energy flowing past a point in one second. The English unit of power is a horsepower, and the English unit of energy is a calorie. Calories are related to joules by the following equation:

$$1 \text{ calorie} = 4.18 \text{ joules} \quad (2-18)$$

while horsepower is related to watts by the following equation:

$$\begin{aligned} 1 \text{ horsepower} &= 746 \text{ watts} \\ 1 \text{ hp} &= 550 \text{ ft-lb/sec} \end{aligned} \quad (2-19)$$

Most electrical motors are rated in horsepower, so converting between the metric and the US customary unit systems of measurement is not necessary. However, a motor's rating is the amount of mechanical power that it delivers and not the electrical power that is required to make it run. Because of the power factor and motor inefficiencies, approximately 1,000 watts (1 kW) is required to power each horsepower of a motor.

Other factors. In addition to quantifiable factors of electricity, other factors explain electrical power distribution systems. One factor is that the system must have a continuous path for the current to flow from the source of power to the load where the work is performed and back to the source. This complete path is called a circuit.

Another factor is that electricity can be easily created in two fundamental forms—direct current (DC) and alternating current (AC). Direct current is the flow of charge in one direction only. In alternating current, a charge flows in one direction, stops, then flows in the other direction, then stops. This cycle is repeated endlessly until the circuit is broken.

The number of times this cycle is repeated in a specific time period is called the frequency. Frequency is measured in hertz, the number of cycles that occur in one second. Both DC and AC are useful, but because of safety and the ability to change voltages more easily, AC is most commonly used for power distribution applications.

These few electrical parameters and their relationships to each other are all that is necessary to understand the basics of electrical power distribution systems as presented in the remainder of this chapter.

Distribution Concepts

Electrical energy needs to be delivered from the place where it is made to the place where it is to be used. In remote locations, electricity may be generated by small generators or stored in batteries. However, for most sites, electricity is generated by an electric utility and delivered through wires to individual customer sites similar to the way water is distributed through pipes to customers by the water utility. In fact, most of the concepts of electrical distribution are the same as the concepts of water distribution. Two major differences make electricity slightly more complicated: electricity requires a return path and a higher degree of safety awareness than water. The return path requires another wire, whereas water distribution uses only one pipe.

Electricity is very dangerous. Very small amounts can kill a person, and if a large amount of electricity is pushed through a small conductor, it can cause a fire. For this reason, electricity distribution is strictly controlled by several rules developed by the National Fire Protection Agency (NFPA) and published in the National Electric Code (NEC). In the US, it is illegal to violate any rule in the NEC. Some jurisdictions amend the NEC with more stringent rules. Therefore, changes should not be made to an electrical distribution system by anyone who is not knowledgeable of the NEC and any local amendments. The NEC is updated and published every three years; always refer to the latest edition when checking current requirements.

Because the electrical power distribution within the water utility's facilities requires using equipment owned and operated by the water utility, electricity must be distributed from the point of connection to the electric utility to the individual pieces of equipment used within the facility. Understanding electrical distribution systems is aided by using diagrams. These diagrams are similar to water system schematics and are called *one-line diagrams* or *single-line diagrams*, even though a circuit may have as many as four wires. Each line on the diagram shows the

electrical path from the source to the load. The specifics of these paths are unique to each facility but follow some general concepts.

Each piece of electrical distribution equipment has a standard symbol used in one-line diagrams. As each piece of equipment is introduced and described, the current standard symbol will be shown and a *generic* single-line diagram will be developed step by step. When single-line drawings are made during the design stage of a facility, a map legend is always made to define the symbols used in that set. Because the symbols vary, the legend of a drawing should be referred to.

Conductors. Wires are the primary distribution path for electricity, and some information about wires is needed to understand distribution systems. Wires are made out of metal because it is a good conductor of electricity. Copper and aluminum are commonly used metals; copper is a better conductor than aluminum, but it is more expensive, heavier, and more rigid than aluminum. Aluminum is difficult to terminate properly and requires special techniques to ensure terminations do not overheat. Because the disadvantages of copper are more significant when the conductors need to be large, aluminum is typically used only for larger wire sizes.

Smaller wire sizes are standardized using a system called the American Wire Gauge (AWG). The AWG system has sizes numbered from 1 to 40, with 40 being the smallest. Electrical power distribution is limited to wire sizes 18 and larger. The smaller sizes are used for smaller electronic applications. After establishing the AWG, wire larger than No. 1 became necessary, so the next larger size was called 0 or *one-ought*. Larger sizes added 0s, so 00 (*two-ought*), 000 (*three-ought*), and 0000 (*four-ought*) conductor sizes were adopted. When wire larger than AWG 0000 is needed, the wire is sized by its cross-sectional area measured in thousands of circular mils (MCM). A circular mil is the area of a circle with a diameter of one mil (one thousandth of an inch). Common sizes of large wire are 200 MCM, 350 MCM, 500 MCM, 750 MCM, and 1,000 MCM.

Electrical wires must be insulated from their surroundings while they are carrying electricity. The insulating material used depends on the application, ambient temperature, likelihood of contact with moisture, oil, or other chemicals, voltage level to be insulated, cost, and other factors.

The size of the wire, its material of construction, and the material used to insulate it determine how much current a wire can safely handle. This capacity is called the ampacity of the wire. Ampacities of the various sizes of wire in copper and aluminum are in the NEC for several types of insulating materials.

Ensuring that too much electricity does not flow through a given conductor is critical to distributing electricity. Overloading a conductor may cause a fire or the breakdown of insulating material, allowing the electricity to escape and become dangerous. For this reason, all approved conductors of electricity, such as wires, switches, and transformers, have maximum current ratings. To ensure that too much current does not flow through the device, a current-limiting device, such as a fuse or circuit breaker, must be used. Current-limiting devices must always be used and *must never be replaced with devices having a higher rating than originally installed or shown on the design drawings for the facility*. If there is ANY doubt about the correct size to use, a qualified electrician or electrical engineer should be consulted. Because these devices are designed to protect conductors from abnormally high currents, they will blow or trip if something is wrong. A qualified electrician should be consulted before replacing fuses or resetting circuit breakers.

Utility service connection. Electricity is typically delivered to a facility at a single point. Wires may come from the utility on electrical poles or underground, usually at a high voltage. The amount of voltage depends on the amount of electricity that the facility needs; the higher the amount of energy, the higher the delivery

voltage. Standard voltage levels vary from utility to utility, but some common values are 480 volts, 4,160 volts, 13,800 volts, 21,000 volts, and 69,000 volts. This energy is metered by the electric utility to measure watt-hours (the amount of energy used). The meters may also measure watts of demand (the highest level of power used at one time) and may include a clock when time-of-day billing is used. A switch is usually located on the upstream side of the meter and on the downstream side of the meter to allow the electric utility to service the meter or disconnect from their system for maintenance. These switches are called *disconnect switches* or just *disconnects*. The downstream side of the meter terminals or disconnects is the usual place for customer connections. Because this equipment is owned and operated by the electric utility company, it is usually kept inside a locked enclosure.

Voltage levels. In general, the goal of electrical power distribution is to deliver the required power to the equipment. For example, a current of 30 amps at 120 volts will deliver 3,600 watts, and a current of 15 amps at 240 volts will also deliver 3,600 watts. Is one better than the other? The answer is *yes* because larger currents require larger, more expensive wires. However, to insulate against higher voltages requires thicker, more expensive insulation. The deciding factor is that the power lost in the wire on the way to the equipment (similar to head loss in a pipe) depends on the resistance of the wire and the current flowing in the wire and not the voltage. Using the power equation, $P = I \times E$, and substituting the formula for E as given by Ohm's law, $E = I \times R$, then the power equation becomes:

$$P = I \times (I \times R) = I^2 \times R \quad (2-20)$$

If the resistance of the wire for R is used in the equation, the power lost to heat from the electricity flowing through the wire is the result.

If the current, I , doubles (to get more power) and the resistance is cut in half (to keep the voltage drop consistent) by using wire that is twice as big, then the power loss will be twice as much. Therefore, it is less expensive to increase the voltage and not the current for larger amounts of power. Utilities usually transport large amounts of power at high voltages.

Three-phase power. Another technique used to carry current to deliver more power not requiring the increase of current or voltage is to use three wires (phases) instead of two. Three-phase power only works with AC and cannot be used with DC. Three-phase power saves both the energy loss associated with increasing the current and the insulation cost associated with increasing the voltage. Seventy-three percent more power can be sent with only a 50 percent increase in wire costs. For small loads, however, the reduction in wire size using three-phase power results in wire so small that it is easily broken and therefore not very practical. For this reason, three-phase AC power is normally used only for loads larger than one-half to three-fourths horsepower.

Voltage conversion. Because electricity is usually delivered at a voltage much higher than needed, it must be converted or *stepped down*. This conversion is performed by a transformer. Transformers may be used to step voltage down or up but are most often used to step voltage down. Transformers may also be used to convert currents and are often used to reduce currents to permit sensitive instruments to measure large power conductor currents. These are called current transformers, sometimes referred to as CTs. Transformers have coils of wires called *windings*. They contain two sets of windings, one connected to the source of power (the primary winding) and one connected to the load (the secondary winding). The symbol for a transformer is shown in Figure 2-18.

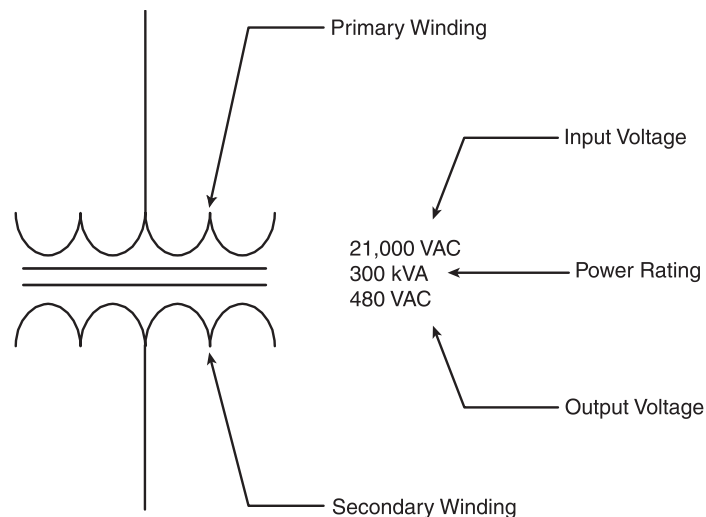


Figure 2-18 Transformer symbol

Transformers produce heat and larger ones require special treatment to withstand the heat. Excessive heat causes the insulating material between the windings to break down and eventually short the windings together. To accommodate higher temperatures, windings are commonly immersed in oil. The oil acts as the insulator between the coils of the windings and permits the transformer to run hotter than dry types of insulation. Transformers that do not use oil are referred to as *dry-type* transformers. Because oil-filled transformers are fire hazards, they are not permitted indoors. Additional cooling can be provided for either dry-type or oil-filled transformers by adding fans to blow air across them.

If the electric utility delivers the energy at the same voltage level at which it will be used (for example, 480 volts), then a step-down transformer is provided by the electric utility, although the transformer may be located on the water utility's property. These transformers are often located inside a fenced enclosure locked by the electric utility company. In larger facilities where the delivered voltage is quite high (such as 21,000 volts or higher), the voltage may be stepped down to an intermediate level, typically 4,160 volts (2,300 volts is common in older facilities).

Switches, enclosures, and current-limiting devices provide disconnection and safety protection for transformer installations, and all of these together are called a *substation*. Generic single-line diagrams showing a metering facility and substation with electric-utility-owned transformer and with water-utility-owned transformer are shown in Figures 2-19 (a & b).

Distribution. After the voltage is reduced to a level suitable for in-plant distribution, the electricity is directed to a bank of switches called *switchgear*. Switchgear directs the electricity to several different areas in the facility where it can be further stepped down in voltage or distributed to several loads in the area. These remote areas are called *load centers*. Switches allow each area to be isolated in case of a problem without affecting other areas of the plant. These separate paths are called *branch circuits* or *branches*. Each branch has a switch with a current-limiting device. Figure 2-20 shows the generic single-line diagram with the switchgear added. A plant switchgear is often located in a locked room to prevent unsafe or unauthorized operation.

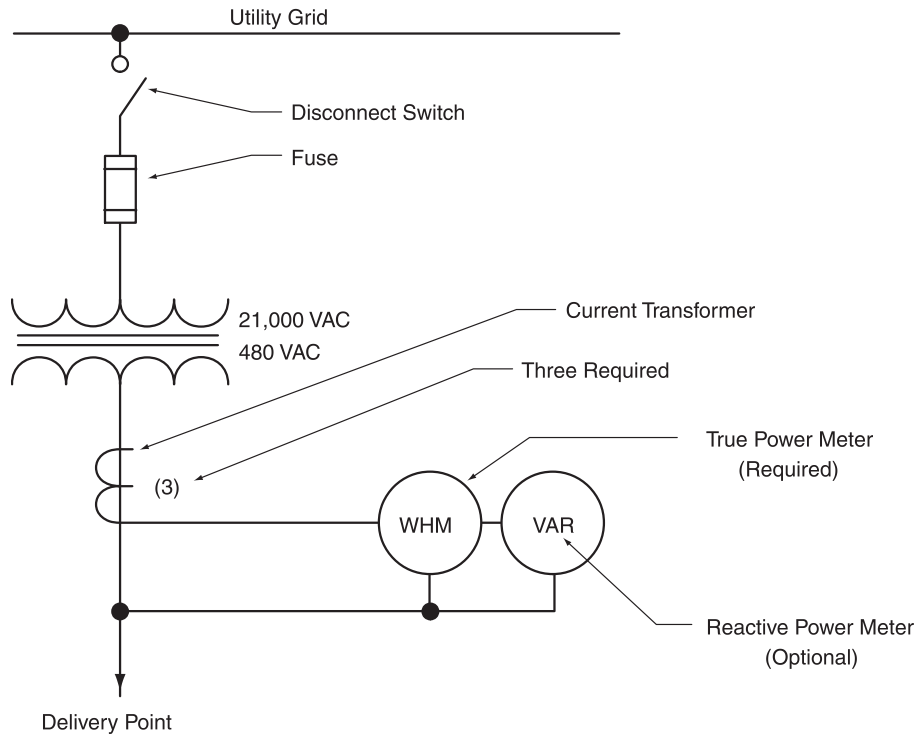


Figure 2-19a Delivery voltage at 480 VAC using electric utility's transformer

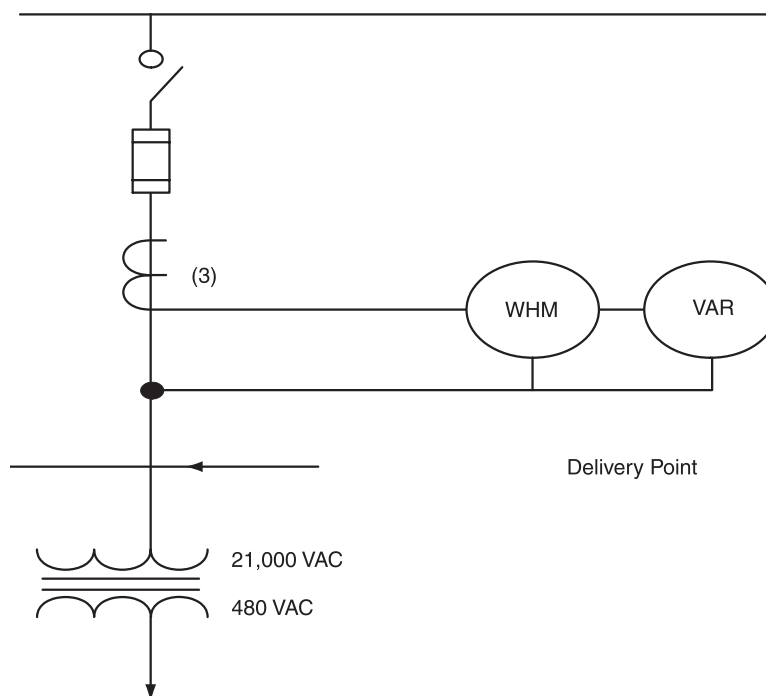


Figure 2-19b Delivery voltage at 21,000 VAC using water utility's transformer

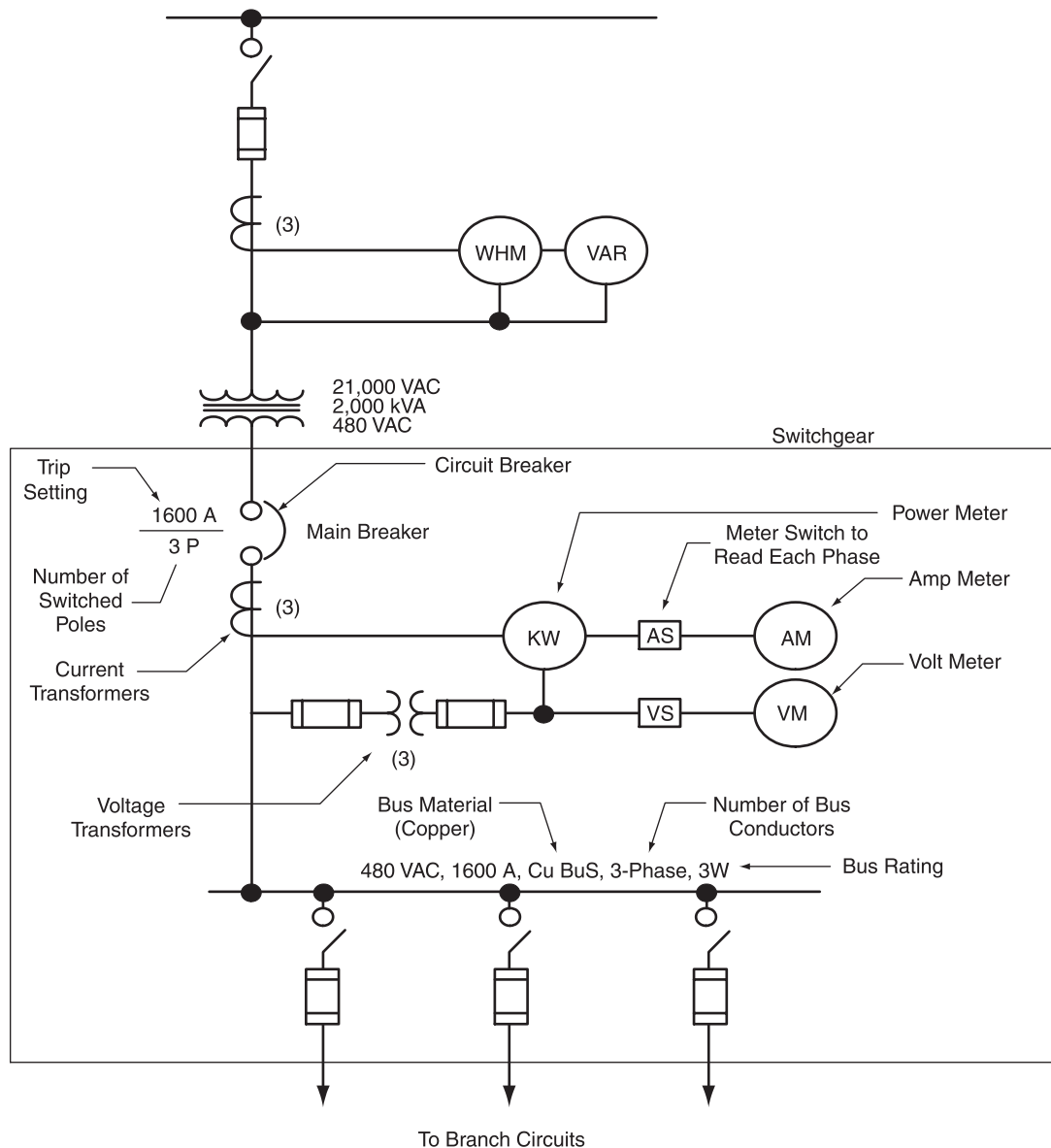


Figure 2-20 Main substation with switchgear

Load centers are also composed of switches. The switches control electricity to individual pieces of equipment or a group of small loads such as lighting. Load centers can have large switches arranged similarly to switchgear; they can also have special switches called *motor starters*, described in chapter 3, Motor Controls.

When several motor starters are installed in one location, the assembly is called a *motor control center*, or simply MCC. Load centers can also be a wall panel of small fused switches or circuit breakers. Load centers might also have substations on their upstream side to reduce the in-plant distribution voltage to a lower level before feeding the energy to the switches.

Equipment requiring more than one-half horsepower operates at 480 volts and smaller equipment at 208 volts or 120 volts, making it necessary to use transformers on the downstream side of a load center to reduce the voltage. When this occurs, the first load center is called a primary load center, and the smaller one is called a secondary load center. Often, these secondary load centers are small panels containing small circuit breakers, such as the ones used in residences. Figure 2-21 illustrates the generic single-line completed to show the electricity being delivered to load centers and on to individual pieces of equipment.

Functionally, the load center does exactly what the substation and switchgear for the plant do except for a smaller area and smaller amount of electricity. The number of load centers and their capacity is determined by the amount of electricity needed to be controlled and the amount and size of equipment requiring electricity.

Reliability. The reliability of the electrical power distribution system must be considered when any facility is built or modified. Reliability of electrical power distribution equipment is typically quite good, and electrical system failures are rare. However, when they do fail, the ability to treat or distribute water will stop. Therefore, if the process is critical, electrical systems will need some form of backup. Backup systems for electrical power distribution include having more than one source of power, more than one path for the electricity to access the load, or both.

A backup or secondary source can use power from the electric utility, a generator, or batteries. Which is appropriate depends on how much energy is needed. When large amounts of energy are needed, such as for large treatment plants, the second source from the electric utility is used. If the facility's capacity, and therefore the amount of energy, can be reduced in the backup mode or if the facility is small, a standby generator can be used to supply enough energy until the electric utility can re-energize the main feeder. For small critical loads, such as remote communications or plant exit lights, batteries are more economical.

For critical electronic loads, such as computers and instrumentation, an uninterruptible power supply (UPS) can be used. A UPS is composed of a rectifier, a battery, and an inverter. The rectifier is connected to the main source of AC electricity and converts the AC to DC, keeping the batteries charged. The batteries are connected to an inverter, which converts the DC energy in the batteries back to AC power. The output of the inverter is used to power the equipment. When the main power fails, the batteries continue to power the inverter, which in turn continues to power the critical loads. This prevents an interruption of power when the main power fails. UPSs can provide power to critical loads for a few minutes or up to several hours, depending on the size of the batteries.

Multiple paths are used within a facility to protect against failure of in-plant electrical distribution equipment. They can also provide alternative paths around equipment that is de-energized for maintenance purposes. Normally, only one extra path is provided. The extra path can include extra transformers, switches, and wires, depending on the importance of the loads. When a facility's electrical power distribution system has these extra paths, it has a *split* or *double-ended* architecture. As with secondary sources of electricity, these extra distribution paths may have as much capacity as the primary distribution paths or have reduced capacity depending on load importance.

Safety. Electricity is dangerous, and a small amount can be deadly. Electricity can cause fires, especially in areas where volatile chemicals, such as gasoline or paint, are stored. To help make electricity safe, electrical equipment has special devices and enclosures designed to prevent excessive heat and sparks and to prevent someone from touching a part of the system that carries current. Electrical systems

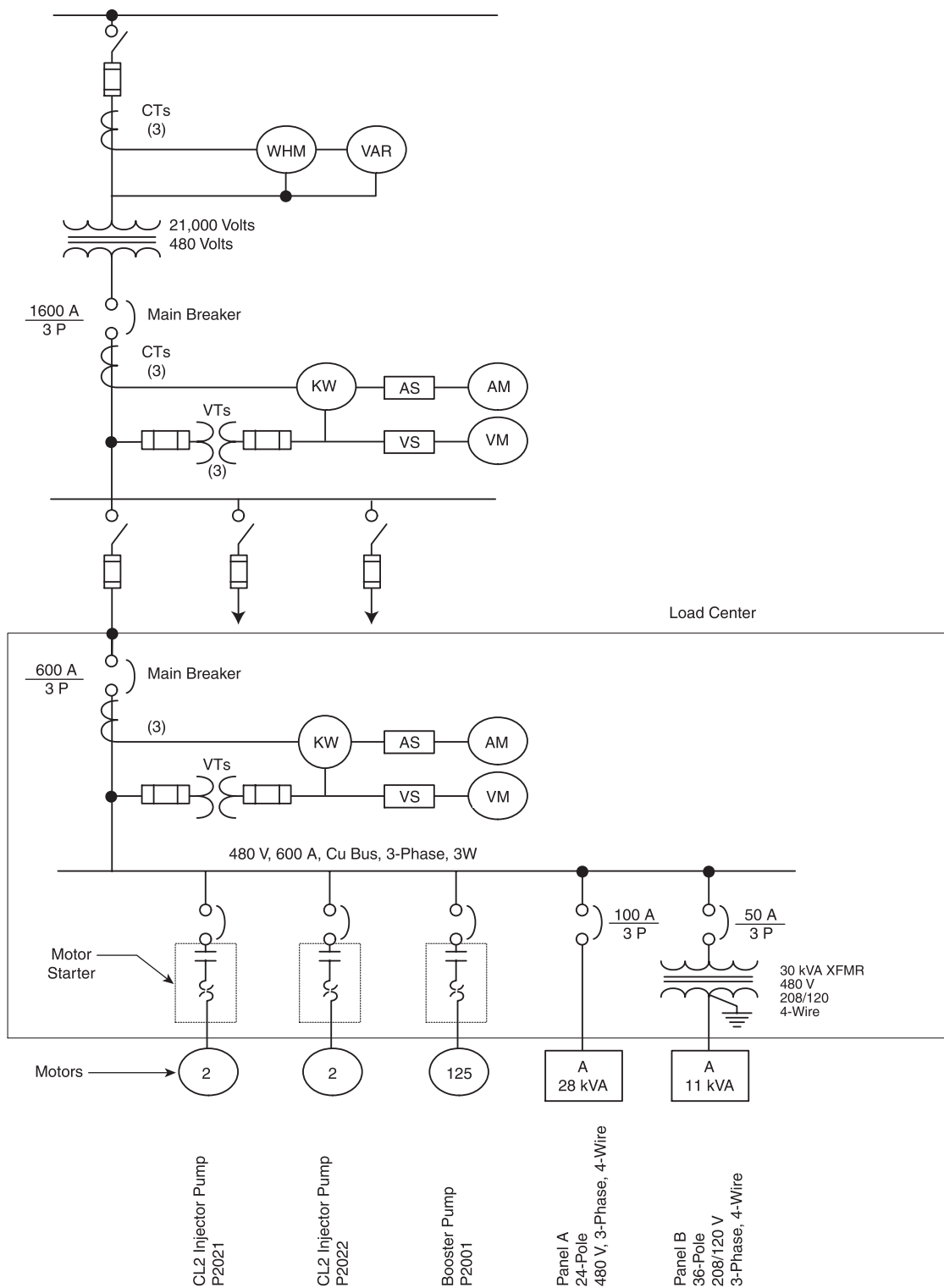


Figure 2-21 Complete one-line with load center and motors

should never be modified or opened except by a person trained in proper maintenance procedures.

Personnel hazards. A small amount of electricity can kill because the human body's nervous system uses small amounts of internal electricity to send the signals that control muscles and vital organs. A current as small as 20 milliamperes (20 thousandths of an ampere) can cause the heart or lungs to stop. A person must never touch any portion of an electrical distribution system that may be carrying current.

How an electric shock affects a person depends on whether the current is DC or AC, how much current flows through the person, and what part of the body it flows through. DC shocks are quite dramatic and cause the body to jerk. The electricity causes one or more muscles to contract or extend depending on the direction of current through the body. DC shocks usually disconnect the person from the current. In AC systems, the danger is much greater because the person cannot release the current source. AC current causes the muscles to contract and extend at the frequency of the current, at 60 hertz in power systems.

DO NOT TOUCH a person who is being shocked, as the current will also shock you. The only way to help is to stop the electricity. If the switch cannot be located, the person should be pushed or pulled off the electrical equipment using a nonconducting material, such as dry wood, dry leather, or plastic. A stick can be used to push, while a belt or shirt can be removed and used like a rope to pull the person off the equipment.

After stopping the electricity from flowing through the person, call for emergency medical assistance, without leaving the victim alone. If the person is unconscious, check for heartbeat first, and then see if the victim is breathing. Standard first-aid techniques for cardiopulmonary resuscitation, or CPR, should be used to reinstate pulse and breathing until medical help arrives. The victim should be treated for shock and trauma by being laid down, covered to maintain warmth, and reassured. Electrical shock victims should always be checked by a doctor as soon as possible.

Fire hazards. Electricity causes fires by generating heat that occurs when current flows through a conductor. The amount of power lost or heat produced is proportional to the amount of resistance and the square of the current. Anything that carries electricity is going to create some heat. Problems occur when the amount of heat is enough to cause a fire. Electricity can also generate heat by arcing, which is a natural consequence of opening an electrical circuit while electricity is flowing. Because switches and other devices will open energized electrical circuits during normal operation, they must be designed to prevent arcing from igniting fires.

Wire sizes, insulating material, and switches that safely handle the required current without overheating should be used. This will prevent spontaneous combustion in the air around the conductors. The amount of heat that causes spontaneous combustion is called the lower explosive limit (LEL). The LEL is determined by the content of the air. For example, excess oxygen or volatile flammable chemicals, such as gasoline, lower the LEL and, therefore, lower the safe operating temperature. Consequently, the intended use of the area is considered when the electrical system is designed. To help standardize safe design practices for electrical distribution systems, the NEC has defined or classified areas by the degree of fire danger that they pose.

NEC area classifications have three categories. The first type is defined by whether flammable components will be present in the atmosphere of the area. The

second classification is based on how flammable these components are. The last classification is based on whether the flammable components are dust, vapor, or gas.

During the design or modification of a facility, the proper area classification is determined, and the electrical system is designed to not exceed the safe operating temperature for that area. Therefore, if an area's use is changed from a lower level of fire danger to a higher level of fire danger, the electrical system must also be changed to ensure that normal operation cannot cause fires.

Fires caused during operation usually occur when more excess current flows in a portion of the system, or a lower LEL (more explosive) is present. Electrical systems are designed with several automatic methods to prevent fires from occurring, but these safety systems can fail.

Whenever an electrical fire does occur, the electricity should be shut off, a call for help should be made, and an effort made to extinguish the fire. Calling for help before trying to extinguish the fire is important; *do not let the fire block an exit route*. When fighting electrical fires, *do not use water if the electricity cannot be turned off*. *Water conducts electricity and electrocution may occur*. Use a fire extinguisher rated for electrical fires. It should be marked with a large, uppercase *C*. The extinguisher may also be marked with an *A* or a *B*, which indicates that it is suitable for other types of fires.

Safety systems. To minimize the danger of electricity, electrical distribution systems are designed to reduce the likelihood that electrical shock or excessive heat will occur. Because these safety systems are not foolproof, understanding the basics of these systems will maximize their effectiveness. Safety systems that are discussed in this section are

- Grounding
- Overcurrent and overtemperature
- Ground fault
- Encasement

While other protection systems exist, these are the most common and will have the greatest impact on safety.

Grounding. Electrical current will always take the path of least resistance back to its source; current can be diverted by offering a path of lower resistance. Electrical system design provides very low resistance paths back to the place where the electricity originates. These very low resistance paths are called the grounding systems. Their main purpose is to divert electricity away from places where people might inadvertently come into contact with the system.

The earth is an excellent conductor of electricity and is frequently used as part of the grounding system. When used for this purpose, the electrical grounds are made by driving a metal ground rod, sometimes called *earths*, several feet into the ground to get a good connection. In some locations, the soil is too dry or has too many insulating compounds and does not make a good ground conductor. In these locations, a grid or large mesh made of metallic wires is buried in the ground to make the earth a better conductor. These are called *ground grids*.

Grounding systems provide an easier path than human bodies, thereby protecting people against electrocution. The grounding system must never be circumvented. This is especially true in wet areas because water conducts electricity fairly well, especially dirty water. If someone is standing in water and touching an energized circuit and if the water is touching a grounded surface like a metal water pipe, electrocution may occur.

Portable power tools are often designed to be grounded by plugging them into a power receptacle with a three-prong plug. While many light-duty tools designed for home use have plastic cases and rely on double insulation to protect the user from electrocution, industrial-grade tools have metal cases and rely on the facility's grounding system to provide safe operation. If receptacles do not have the hole for the third prong, they are not grounded. *Therefore, do not use the tool with those receptacles.* Using a converter from three-prong to two-prong (called a *ground buster*) will circumvent the ground system and may cause electrocution.

As with industrial-grade power tools, most enclosures for electrical equipment and wires are made out of metal. Normally, all the current-carrying components inside these enclosures are insulated from the metal case so the case is not normally energized. However, if the insulation fails because of aging or mechanical failure, the normal current-carrying conductors can touch the case and cause the case to become energized. This is referred to as a *ground fault* or *grounding short*. To reduce this possibility, the cases are grounded, offering a low resistance path from the metal case back to the source of the electricity. This path is called the *ground path*, which is usually a wire connected from the case to the source of the electricity. The wire is referred to as the *equipment grounding conductor* and does not carry current during normal operation. Current flows in the wire only when the normal current path is inadvertently shorted to the case. The circuit will function normally if the grounding conductor is cut or broken; however, the protection against electrocution will be lost.

Overcurrent and overtemperature. Overcurrent and overtemperature systems are designed to prevent too much current from flowing in a conductor. Overcurrent can be detected by the rise in heat or the rise in magnetism. To protect against overcurrent, it must be detected and then the circuit must be de-energized until the cause of the overcurrent can be located and fixed. *Electrical circuits must never be operated without their overcurrent devices installed and operational, otherwise the risk of fire increases.* Two basic devices are used: fuses and circuit breakers.

Fuses are conductors made of special metals that melt at a temperature slightly higher than the temperature associated with the maximum expected current. If the current rises above normal, the fuse wire actually melts and opens the circuit. Once this happens, the fuse is useless and is said to be *blown*. To get the circuit working again, the cause of the overcurrent must be corrected and the fuse replaced.

Fuses are rated by the amount of current that they can carry without blowing and by the amount of time they take to blow at various overcurrent values. In general, they are available as both fast acting and delayed action. Fuses come in a wide variety of ratings and case styles. A replacement fuse must be one that has the same case style because fuse holders are designed to accept only one type.

Circuit breakers are switches designed to carry their rated current but will *trip* open if the rated current is exceeded. When a circuit breaker trips, the cause of the trip should be fixed and the breaker reclosed to place the circuit back in operation. Because they do not have to be replaced, they are less expensive to maintain than fuses. However, they are more expensive to buy and cannot be made with the precision of fuses. There are two mechanisms commonly used to open or trip the switch—thermal and magnetic. Circuit breakers are available with either or both mechanisms installed.

Thermal circuit breakers have a bimetal strip that will bend when heated. As the current increases above the breaker's rating, the strip bends until it trips the breaker. These circuit breakers operate relatively slowly and are comparable to delayed-action fuses.