12.0 PUMPS

Learning Objectives

After studying this chapter, you should be able to:

1. Define and/or explain the following:
   a. Head
   b. Net positive suction head (NPSH)
   c. Cavitation
   d. Shutoff head
   e. Pump runout

2. Describe the construction and operation of a centrifugal pump.

3. Describe the causes and effects of cavitation on the operation and internal components of a centrifugal pump.

4. Describe the construction and operation of a reciprocating positive displacement pump.

5. Describe the purpose/operation of the following:
   a. Stuffing box
   b. Shaft sleeve
   c. Sealing water
   d. Mechanical seals

6. Draw an operating characteristic curve for a typical centrifugal pump and explain the shape of the curve; combine the pump curve with a typical system head-loss curve and explain the location of the operating point.

7. Discuss factors which shift the operating point on a pump curve.

8. Draw operating characteristic curves for centrifugal pumps in series or parallel operation.

9. Draw an operating characteristic curve for a typical positive displacement pump and explain the shape of the curve and the location of the operating point.

10. Use the centrifugal pump laws to determine new pump operating conditions created by a change in pump speed.

11. Describe the construction and operation of a jet pump.

12.1 Introduction

A pump is a mechanical device used to move a fluid. A pump does work on the fluid, thereby giving it energy to move. This chapter will discuss the major types of pumps used in reactor plants (centrifugal pumps, positive displacement pumps, and jet pumps), the general construction of these pumps, and some operational characteristics of each.

12.1.1 Head

Before the discussion of pumps can begin, the fluid mechanics term "head" should be discussed. Most of the early investigations into fluid mechanics used open (not closed cycle) piping systems involving elevated tanks connected by piping to a measurement point. The amount of elevation of the tank level above the measurement location produced a corresponding fluid pressure or flow velocity in the piping at the measurement point. Because the early investigators could not easily measure fluid pressure or flow velocity at a given location, they characterized these systems by the height of the elevated tank levels. During intervening years, the term "height" gradually evolved into the slang term "head" through usage. Therefore, simplistically, the pressure of a noncompressible fluid at a specific measurement point in a piping system can be visualized as the pressure resulting from a column of the fluid rising vertically above the measurement point to a certain height or "head." This height or head is measured in units of feet (usually feet of water).

The first law of thermodynamics (the general energy equation) can be used to show that in a closed piping system the net energy change around the system will be zero. When the piping system contains an incompressible fluid (like the water in many reactor plant systems), the steady-state energy equation reduces to the Bernoulli equation.

The Bernoulli equation can be written in many ways. For pump applications, a modified version of the equation that includes pump head and system head-loss terms is given below in Equation 12-1:

$$z_1 + \frac{(v_1)^2}{2g} + \frac{P_1}{\gamma} + H_p = z_2 + \frac{(v_2)^2}{2g} + \frac{P_2}{\gamma} + H_f \ , \tag{12-1}$$

where

z = fluid height above reference (ft),

v = average velocity of fluid (ft/sec),

P = pressure of fluid (lbf/ft^2),

γ = weight density of fluid (lbf/ft^3),

H_p = head added by pump (ft),

H_f = head loss due to fluid friction (ft), and

g = acceleration due to gravity = 32.2 ft/sec^2

Since the work done by the pump in a closed piping system is proportional to the pump's pressure increase that provides the driving force for constant flow, pump work is often expressed in terms of pump head. Pump head is the measure of the energy the pump must supply to the fluid to enable the fluid to overcome all the friction losses resisting its flow around the system. As an energy term in the general energy equation or the Bernoulli equation, the correct unit for specific pump head is foot-pounds force per pound mass. As a matter of convention, however, the unit of pump head is often abbreviated to feet. It can again be visualized as the height of a column of the fluid that would produce a pressure equal to the pressure increase supplied by the pump.

Similar to the pump head term, the remaining terms in the Bernoulli equation for a noncompressible fluid piping system are called the pressure head (corresponding to the internal fluid pressure at the measurement point), the velocity head (corresponding to the fluid velocity), and the potential head (corresponding to the fluid height above reference level). The velocity head and potential head can be converted to pressure head. Even the friction losses can be calculated as pressure drops and then converted to head losses. Therefore, all of these head terms are normally expressed in units of feet, and they mean the corresponding height of fluid (usually water).

12.2 Principles of Liquid Pumping

There are three basic pumping principles for forcing fluid flow through a channel or conduit:

1. By action of centrifugal force
2. By volumetric displacement
3. By transfer of momentum from another fluid.

Each of these pumping principles is used in one of the major types of pumps that will be briefly discussed in the following sections.

12.2.1 Centrifugal Force

Though the physical appearance of the many types of centrifugal pumps varies greatly, the basic function of each is to increase the kinetic energy of fluid by the action of centrifugal force and then to convert part of the kinetic energy to pressure.

In general, centrifugal pumps have these characteristics:

1. The discharge is relatively free of pulsation.

2. The mechanical design lends itself to high through-puts, which means that capacity limitations are rarely a problem.

3. They are capable of efficient performance over a wide range of pressures and capacities even at constant-speed operation.

12.2.2 Volumetric Displacement

Discharge of a fluid from a vessel by partially or completely displacing its internal volume with a second fluid or by mechanical means is the principle upon which positive displacement pumps operate. Included in this group are reciprocating piston and diaphragm machines, rotary vane and gear types, fluid piston compressors, and air lifts.

The large variety of positive displacement pumps makes it difficult to list characteristics that are common to all. However, for most types it is correct to state that:

- They are adaptable to high-pressure operation.
- The discharge normally pulsates unless an auxiliary damping system is employed.
- Mechanical considerations limit maximum through-puts.
- They are capable of efficient performance at extremely low through-put rates.

12.2.3 Transference of Momentum

Acceleration of one fluid for subsequent transfer of its momentum to a second fluid is a principle commonly used in pumping from inaccessible areas. Jet pumps, ejectors, and eductors are included in this category.

These pumps are normally relatively inefficient performers. On the other hand, the absence of moving parts and simplicity of construction often justify their use in severe services or inaccessible locations.

12.3 Centrifugal Pumps

A centrifugal pump has two main parts: a *rotating element*, including a shaft and an impeller, that is used to impart kinetic energy to a fluid through centrifugal force; and a *stationary element* made up of a casing or housing that is used to convert some of the kinetic energy to pressure energy.

In a centrifugal pump, the liquid is forced, by atmospheric or system pressure, into a set of rotating vanes. These vanes constitute the impeller, which discharges the liquid to its periphery at a high velocity. Some of this velocity is then converted into pressure energy by the expanding area volute that surrounds the impeller. Figure 12-1 shows a basic centrifugal pump with an impeller, a volute, and the basic liquid flow path.

If the pump is one in which the head is developed by a single impeller, it is called a single stage pump. Often, the total head to be developed exceeds the amount that can be provided by one impeller. To obtain increased head, two or more impellers operating in series are used, each taking its suction from the discharge of a preceding impeller. For this purpose, two or more single stage pumps can be connected in series or all the impellers may be incorporated into a single pump casing. In the latter case, the unit is called a multistage pump as shown in Figure 12-2.

Other pumps that look like centrifugal pumps, but are not truly centrifugal, can be found in power plants. Examples include the propeller and mixed flow pumps commonly used in main circulating water systems. Propeller pump impellers provide axial flow rather than radial flow. In a propeller pump, momentum is transferred to the fluid by a pushing action similar to an airplane propeller. Mixed flow refers to pump impellers that range broadly between radial flow and axial flow.

12.3.1 Casings

The volute casing pump (Figure 12-1) derives its name from the spiral-shaped casing surrounding the impeller. This casing section collects the liquid discharged by the impeller and converts fluid velocity energy into pressure energy.

A centrifugal pump volute increases in area from its initial point until it encompasses the full 360 degrees around the impeller and then flares out to the final discharge opening. The wall dividing the initial section and the discharge nozzle portion of the casing is called the tongue of the volute or the "cut-water."

In a single-volute pump casing design (Figure 12-3A), uniform or near uniform pressures act on the impeller when the pump is operated at design capacity (which coincides with the best efficiency). At other capacities, the pressures around the impeller are not uniform (Figure 12-3B), and there is a resultant radial reaction (F). A graphical representation of the typical change in this force with pump capacity is shown in Figure 12-4A. Note that the force is greatest at shutoff.

For any percentage of capacity, this radial reaction is a function of total head and the width and diameter of the impeller. Therefore, a high-head pump with a large impeller diameter will have a much greater radial reaction force at partial capacities than a low-head pump with a small impeller diameter. The radial reaction forces are an important consideration in sizing the shafts and bearings used in a pump. Pumps designed only to withstand the radial forces developed at nominal capacity may not be able to withstand the forces developed at sustained high or low capacity operation.

Because of the increasing application of pumps which must operate at reduced capacities, it has become desirable to design standard units to accommodate such conditions. One solution is to use heavier shafts and bearings. Except for low-head pumps in which only a small additional load is involved, this solution is not economical. The only practical answer is a casing design that develops a much smaller radial reaction force at partial capacities, such as the double-volute casing design.

The application of the double-volute design principle to neutralize radial reaction forces at reduced capacity is illustrated in Figure 12-4B. Basically, this design consists of two 180 degree volutes. A passage external to the second volute joins the two into a common discharge. Although a pressure unbalance exists at partial capacity through each 180 degrees of arc, forces F_1 and F_2 are approximately equal and opposite. Thus, little, if any, radial force acts on the shaft and bearings. Figure 12-5 is a good representation of a double-volute casing pump.

12.3.2 Impellers

12.3.2.1 Classification of Impellers by Suction Types

In a single-suction impeller, the liquid enters the suction eye on one side only (see Figure 12-2). A double-suction impeller is, in effect, two single-suction impellers arranged back-to-back in a single casting (Figure 12-6), the liquid enters the impeller simultaneously from both sides, while the two casing suction passageways are connected to a common suction passage and a single suction nozzle.

12.3.2.2 Classification of Impellers by Mechanical Type

Impellers may also be classified according to their mechanical design. They may be:

- Completely open,
- Semiopen, and
- Closed.

Strictly speaking, an open impeller consists of nothing but vanes, attached to a central hub for mounting on the shaft without any form of a sidewall or shroud (like an old windmill). The disadvantage of an open impeller is structural weakness. If the vanes are long, they must be strengthened by ribs or a partial shroud. Generally, open impellers are used in small, inexpensive pumps or pumps handling abrasive liquids. One advantage of open impellers is that they are capable of handling suspended matter with a minimum of clogging.

The semiopen impeller incorporates one shroud or impeller backwall. This shroud may or may not have pump-out vanes, which are vanes located on the back of the impeller shroud. Their function is to prevent foreign matter from lodging in back of the impeller and interfering with the proper operation of the pump.

The closed impeller, which is almost universally used in centrifugal pumps handling pure liquids, incorporates shrouds or enclosing sidewalls that totally enclose the impeller waterways from the suction eye to the periphery. Although this design prevents the liquid leakage that occurs between an open or semiopen impeller and its side plates, a running joint must be provided between the impeller and the casing to separate the discharge and suction chambers of the pump. This running joint is usually formed by a relatively short cylindrical surface on the impeller shroud that rotates within a slightly larger stationary cylindrical surface in the casing. Normally one or both surfaces are part of a replacable wear ring. The leakage joint can be repaired by replacing the wear rings when wear eventually causes excessive leakage.

If the pump shaft terminates at the impeller so that the latter is supported by bearings on one side, the impeller is called an overhung impeller. This type of construction is normally the best for end-suction pumps with single-suction impellers.

12.3.3 Pump Shafts

The basic function of a centrifugal pump shaft is to transmit the torques encountered during starting and operation while supporting the impeller and other rotating parts. It must do this job with a deflection less than the minimum clearance between rotating and stationary parts. The loads involved are:

- The torques,
- The weight of the parts, and
- The radial and axial hydraulic forces.

In designing a shaft, the maximum allowable deflection, the span or overhang, and the location of the loads all have to be considered, as does the critical speed of the resulting design.

12.3.3.1 Critical Speeds

Any object made of an elastic material has a natural frequency. When a pump rotor or shaft rotates at a critical speed (some multiple of its natural frequency), minor unbalances will be magnified and can create strong vibration.

12.3.3.2 Rigid and Flexible Shaft Designs

The lowest critical speed is called the first critical speed, the next higher the second, and so forth. In centrifugal pump nomenclature, a rigid shaft means one with an operating speed lower than its first critical speed. A flexible shaft is one with an operating speed higher than its first critical speed. Once an operating speed has been selected, the designer must select the relative shaft dimensions to operate above or below the first critical speed.

During startup, the first critical speed can be reached and passed without significant danger because frictional forces on the shaft and impeller tend to restrain the deflection. However, the time required to pass through the critical speed must be short. Once the first critical speed is passed, the pump will run smoothly until the second critical speed is reached, and so on for the third, fourth, and all higher critical speeds. Designs rated for 1,750 rpm are usually of the rigid-shaft type; high-head designs for 3,600 rpm pumps are frequently of the flexible-shaft type.

12.3.4 Stuffing Boxes

Stuffing boxes have the primary function of preventing leakage at the point where the shaft passes through the pump casing. If the pump handles a suction lift, the pressure at the interior stuffing box end will be below atmospheric, and the stuffing box inhibits inward air leakage.

A stuffing box usually takes the form of a cylindrical recess that accommodates a number of rings of packing around the shaft or shaft sleeve as shown in Figure 12-7. On some installations a sealing box is used. The sealing box consists of a lantern ring or seal cage that is used to separate the rings of packing into approximately equal sections. The packing is compressed to the desired fit on the shaft or sleeve by a gland that can be adjusted in the axial direction. The bottom or inside end of the box may be formed by the pump casing itself, a throat bushing, or a bottoming ring.

12.3.4.1 Shaft Sleeves

Pump shafts are usually protected from erosion, corrosion, and wear at stuffing boxes, leakage joints, internal bearings, and in the waterways by renewable shaft sleeves. The most common shaft sleeve function is that of protecting the shaft from wear at the stuffing box.

12.3.4.2 Seal Cages

When a pump operates with a suction lift or a suction pressure below atmospheric pressure, the inner end of the stuffing box is under vacuum, and air tends to leak into the pump. For this type of service, packing is usually separated into two sections by a lantern ring or seal cage as shown in Figure 12-8. Water or some other sealing fluid under pressure is introduced into the seal cage and allowed to flow in both axial directions. This arrangement prevents the inward leakage of air. A similar arrangement can also be used for pumps handling flammable or chemically dangerous liquids to prevent external leakage of the pumped liquid when the inner end of the stuffing box is under pressure.

12.3.4.3 Sealing Water Arrangements

When a pump handles cool, clean water, sealing water for the stuffing boxes is usually provided from the pump discharge or, in multistage pumps, from an intermediate stage. An independent supply of sealing water should be used if any of the following conditions exist:

- Suction lift in excess of 15 feet,
- Discharge pressure under 10 psi,
- Water temperature over 250° F, and
- Hotwell or condensate pump application.

If the suction lift exceeds 15 feet, establishing an initial suction (priming) may be difficult because of air infiltration through the stuffing box. A discharge pressure under 10 psi may not provide sufficient sealing liquid pressure. Hotwell (or condensate) pumps operate with as much as 29 inches vacuum, and air infiltration can occur when the pumps are idle.

12.3.4.4 Stuffing Box Packing

Basically, stuffing box packing is a pressure-breakdown device. The packing must be somewhat plastic so that it can be adjusted for proper operation. It must also absorb frictional heat without failing or damaging the rotating shaft or shaft sleeve. The frictional heat must be removed by the fluid leaking past the packing, an external sealing liquid, or by some other means such as a cooling-water jacket.

There are numerous stuffing box packing materials, each adapted to some particular class of service. The principal types include:

<u>Asbestos packing</u> - Comparatively soft and suitable for cold-water and hot-water applications in the lower temperature range. It is the

most common packing material for general service under normal pressures.

Metallic packing - Composed of flexible metallic strands or foil with graphite or oil-lubricant impregnation and with either an asbestos or plastic core. The impregnation makes this packing self-lubricating for its startup period. The foils are made of various metals such as babbitt, aluminum, and copper. Metallic packing is used for the higher temperature range.

The use of the conventional stuffing box design and composition packing for sealing a rotating shaft has drawbacks for many conditions of service. Probably the biggest single drawback is the difficulty of attaining proper packing tightness. If the packing is undertightened, leakage along the shaft will result. If the packing is overtightened, the packing or the shaft can be damaged. In the ordinary stuffing box, the sealing between the rotating shaft or shaft sleeve and the stationary portion of the box is accomplished by the rings of packing compressed by the stuffing box gland. The leakage around the shaft is controlled by tightening or loosening the gland nuts. Usually, some small amount of leakage is needed to cool and lubricate the packing. Attempts to reduce or eliminate all leakage may result in excessive gland pressure. The additional frictional heat caused by excessive gland pressure can damage the packing or can wear and score the shaft or sleeves so that achieving a good seal becomes impossible.

12.3.5 Mechanical Seals

The mechanical seal was developed to overcome the limitations of the stuffing box, particularly for service applications involving high pressure and the need for minimum shaft leakage. In a packing gland the sealing and wear surfaces are the axial surfaces of the shaft. In a mechanical seal the sealing surfaces are located in a plane perpendicular to the shaft. Usually, a highly polished peripheral surface is connected to the rotating shaft and a matching surface is attached to the stationary casing of the pump. Figure 12-9 shows the details of a typical mechanical seal.

The polished or lapped surfaces of the mechanical seal are constructed from dissimilar materials. One surface rotates and the other remains stationary. These surfaces are held in continual contact by spring or differential fluid pressure, forming a nearly fluid tight seal between the rotating and stationary members with very small frictional losses. To obtain a pressure breakdown between the internal pressure and the atmospheric pressure outside the pump, a small flow of liquid past the seal surfaces is required. Also, this leakage cools and lubricates the surface. The leakage may be only a drop of liquid every few minutes or even a haze of escaping vapor such as steam. Thus, even though leakage is negligible, by design, a rotating mechanical seal does not entirely eliminate all leakage. Additionally, some wear always occurs with service, and this wear can lead to additional leakage with time.

A mechanical seal is similar to a bearing in that it involves a close running clearance with a liquid film between the faces. The lubrication and cooling provided by this film reduces wear, as does a proper choice of seal face materials. Mechanical seals do not operate satisfactorily with only air or gas for cooling and lubrication. If a liquid pump is run "dry," the associated mechanical seal can rapidly fail.

12.3.5.1 Internal and External Seals

There are two basic seal arrangements:

1. The external assembly, in which the rotating element is located outside the housing assembly. This is shown in Figure 12-10A.

2. The internal assembly, in which the rotating element is located inside the housing assembly and is in contact with the liquid being pumped. This is shown in Figure 12-10B.

The pressure of the liquid in the pump tends to force the rotating and stationary faces together in the inside assembly and to force them apart in the external assembly.

12.3.5.2 Double Seals

Two mechanical seals may be mounted inside a housing to make a double seal assembly as shown in Figure 12-11. Such an arrangement is used for pumps handling toxic or highly inflammable liquids that cannot be permitted to escape into the atmosphere. It is also applicable for pumps handling corrosive or abrasive liquids at very high or very low temperatures. For these applications, a clear filtered, and generally inert sealing liquid is injected between the two seals.

12.3.6 Bearings

The function of bearings in centrifugal pumps is to keep the shaft or rotor in correct alignment with the stationary parts under the action of radial and transverse loads. Bearings that give radial positioning to the rotor are known as line bearings, whereas bearings that locate the rotor axially are called thrust bearings. In many applications the thrust bearings actually serve both as thrust and radial bearings.

Because of the large amount of heat generated by the bearing itself or the heat in the liquid being pumped, some means other than natural cooling to the surrounding air must occasionally be used to keep the bearing temperature within proper limits. If the bearings have a forced-feed lubrication system, cooling is usually accomplished by circulating oil through a separate water-to-oil cooler. Otherwise, a jacket through which a cooling liquid is circulated is usually incorporated as part of the bearing housing.

The most common bearings used on centrifugal pumps are various types of ball bearings. Roller bearings are used less often, although the spherical roller bearing is used frequently for large shaft sizes where the choice of ball bearings available is limited.

12.3.7 Cavitation

The formation and subsequent collapse of vapor-filled cavities in a liquid due to dynamic action is called cavitation. The cavities may be bubbles, vapor-filled pockets, or a combination of both. The local pressure must be at or below the vapor (saturation) pressure of the liquid for cavitation to begin, and the cavities must encounter a region of pressure higher than the vapor (saturation) pressure in order to collapse. Dissolved gases may start to come out of solution shortly before vaporization begins. The formation of gas bubbles may be an indication of impending cavitation, but true cavitation requires vaporization of the liquid.

When a fluid flows over a surface having a convex curvature, the pressure near the surface is lowered and the flow tends to separate from the surface. Separation and cavitation are completely different phenomena. Without cavitation, a separated region contains turbulent eddying fluid at pressures higher than the vapor pressure. When the pressure is low enough, the separated region may contain many vapor pockets which fill from the downstream end, collapse, and then re-form several times each second. The collapsing bubbles cause pump noise and possibly pump vibration. The vapor-filled bubbles will also collapse rapidly upon reaching any region where the pressure is above the vapor pressure. The life cycle of a cavitation bubble is short, approximately 0.003 seconds.

Bubbles that collapse on a solid boundary may cause severe mechanical damage. Bubbles distort into toroidal-shaped rings during collapse and produce ring-shaped indentations in the metal boundary. Local pressure on the order of 10^4 atmospheres have been estimated during collapse of a bubble. All known materials can be damaged by exposure to bubble collapse for a sufficiently long time. Cavitation damage usually manifests as pitting on the affected surface.

Centrifugal pumps begin to cavitate when the suction head is insufficient to maintain internal fluid pressures above the vapor pressure throughout the flow passages. The most sensitive areas usually are the low-pressure sides of the impeller vanes near the inlet edge and the front shroud where the curvature is greatest. Axial flow and high-speed impellers without front shrouds are especially sensitive to cavitation on the low-pressure sides of the vane tips and in the close tip-clearance spaces. Sensitive areas in the pump casing include the low-pressure side of the tongue and the low-pressure sides of diffusion vanes near the inlet edges. As the suction head is reduced, all existing areas of cavitation tend to increase and additional areas may develop. Apart from the noise and vibration, cavitation damage may render an impeller useless in as little as a few weeks of continuous operation. In multistage pumps, cavitation usually is limited to the first stage, but second and higher stage cavitation may result if the flow is reduced by lowering the suction head.

12.3.8 Suction Head

12.3.8.1 Net Positive Suction Head

The net positive suction head (NPSH) is a statement of the minimum suction conditions required to prevent cavitation in a pump. The required or minimum NPSH must be determined by test and usually will be stated by the manufacturer. The available NPSH must be at least equal to the required NPSH if cavitation is to be prevented. Increasing the available NPSH provides a margin of safety against the onset of cavitation. NPSH is normally measured in feet (of pumped fluid).

12.3.8.2 Net Positive Suction Head Available

The net positive suction head available ($NPSH_A$) can be calculated by adding the static pressure head plus the velocity head. and subtracting the vapor (saturation) pressure head. for the pumped fluid temperature, all measured at the pump suction. $NPSH_A$ is normally measured in feet (of pumped liquid). This relationship can be expressed as shown in Equation 12-2:

$$NPSH_A = \frac{P}{\gamma} + \frac{v^2}{2g} - \frac{P_{SAT}}{\gamma}, \qquad (12\text{-}2)$$

where

$NPSH_A$	=	net positive suction head available (ft),
P	=	static pressure (lbf/ft^2)
v	=	average fluid velocity (ft/s),
P_{SAT}	=	saturation pressure (lbf/ft^2) of the liquid, and
γ	=	weight density (lbf/ft^3).

Since $NPSH_A$ depends upon the saturation pressure and velocity of the liquid, $NPSH_A$ at a point cannot be monitored directly by a plant instrument or gauge. However, the terms in equation 12-2 can be used to identify actions that can be taken to increase $NPSH_A$ to reduce or prevent cavitation. To increase the $NPSH_A$, either the static pressure on the system should be increased, or the temperature of the pumped fluid should be decreased (to reduce its satuation pressure). From an operational standpoint, static pressure can be increased by increasing the discharge pressure of an upstream pump or by increasing the liquid height in an upstream surge or head tank. From a design standpoint, static pressure can also be increased by decreasing the head losses in upstream piping. At first glance, it would appear that increasing the velocity head will also increase $NPSH_A$. This is true if the velocity head is increased without decreasing the static pressure head. However, attempting to increase velocity head simply by increasing the flow through the pump in question will not necessarily increase $NPSH_A$ and may likely decrease $NPSH_A$. The reason for this is that increasing the flow without a change in pump geometry will increase the velocity head, but the increased velocity will greatly increase the friction losses through the pump. The greater friction losses will decrease the static pressure head term and may more than offset any benefit from the increased velocity head term.

Normally the static pressure head term is significantly larger than the velocity head term so Equation 12-2 can be approximated with the following equation with little loss in accuracy.

$$NPSH_A \equiv \frac{P - P_{SAT}}{\gamma}$$

12.4 Positive Displacement Pumps

A number of different types of positive displacement pumps can be found in power plants. A common type of positive displacement pump is a reciprocating pump. Another type of positive displacement pump is a special centrifugal pump such as the one sometimes used for condenser air removal systems.

A reciprocating positive-displacement pump is one in which a plunger or piston displaces a given volume of fluid for each stroke. The basic principle of a reciprocating pump is that a solid will displace an equal volume of liquid. For example, an ice cube dropped into a full glass of water will spill a volume of water out of the glass equal to the submerged volume of the ice cube.

In Figure 12-12, a cylindrical object, a plunger, has displaced its volume from the large container into the small container. The volume of displaced fluid (B) is equal to the plunger volume (A). The volume of the displaced fluid equals the product of the cross-sectional area of the plunger times the depth of submergence.

All reciprocating pumps have a fluid-handling portion, commonly called the liquid end, which has:

- A displacing solid called a plunger or piston.
- A container to hold the liquid called the liquid cylinder.
- A suction check valve to admit fluid from the suction pipe into the liquid cylinder.
- A discharge check valve to admit flow from the liquid cylinder into the discharge pipe.
- Packing to seal tightly the joint between the plunger and the liquid cylinder to prevent the liquid from leaking out of the cylinder and air from leaking into the cylinder.

These basic components are identified on the rudimentary liquid cylinder illustrated in Figure 12-13. To pump (i.e., to move the liquid through the liquid end) the plunger must be moved. When the plunger is moved out of the liquid cylinder as shown in Figure 12-13A, the pressure of the fluid within the cylinder is reduced. When the pressure becomes less than that in the suction pipe, the suction check valve opens and liquid flows into the cylinder to fill the volume being vacated by withdrawal of the plunger. During this phase of operation, the discharge check valve is held closed by the higher pressure in the discharge pipe. This portion of the pumping action of a reciprocating positive-displacement pump is called the suction stroke.

The withdrawal movement must be stopped before the end of the plunger gets to the packing. The plunger movement is then reversed and the discharge stroke portion of the pumping action is started as shown in Figure 12-13B.

Movement of the plunger into the cylinder causes an increase in the pressure of the liquid contained therein. This pressure immediately becomes higher than the suction pressure and causes the suction check valve to close. With further plunger movement, the liquid pressure continues to rise. When the liquid pressure in the cylinder reaches that in the discharge pipe, the discharge check valve is forced open, and liquid flows into the discharge pipe. The volume forced into the discharge pipe is equal to plunger displacement less very small losses. The plunger displacement is the product of its cross-sectional area times the length of the stroke. Plunger movement continues until the bottom of the cylinder is reached. The motion is then reversed, and the plunger begins another stroke.

The pumping cycle just described is that of a single-acting reciprocating pump. It is called single-acting because it makes only one suction and only one discharge stroke in one reciprocating cycle.

Many reciprocating pumps are double-acting (i.e., they make two suction and two discharge strokes for one complete reciprocating cycle). Most double-acting pumps use a piston as the displacing solid, which is sealed to a bore in the liquid cylinder or to a liquid-cylinder liner by piston packing. Figure 12-14 is a schematic diagram of a double-acting liquid end. In addition to a piston with packing, it has two suction and two discharge valves, one of each on each side of the piston. The piston is moved by a piston rod. The piston rod packing prevents liquid from leaking out of the cylinder. When the piston rod and piston are moved in the direction shown, the right side of the piston is on a discharge stroke, and the left side of the piston is simultaneously on a suction stroke.

The piston packing provides a seal to prevent leakage of liquid from the high-pressure side to the low-pressure side. When the motion of the piston is reversed, the left side of the piston begins its discharge stroke, and the right side begins its suction stroke. The motion of the piston is controlled by a driving mechanism. The most common type of driving mechanism is a crank and throw device.

12.4.1 Liquid End Construction

The liquid end consists of the cylinder, plunger or piston, valves, stuffing box, manifolds, and cylinder head as shown on Figure 12-15. The cylinder is the body where the pressure is developed. Cylinders on many horizontal pumps have the suction and discharge manifolds made integral with the cylinder. Vertical pumps usually have separate manifolds.

When a cylinder contains the passages for more than one plunger, it is referred to as a single cylinder. When the cylinder is used for one plunger, it is called an individual cylinder. Individual cylinders are used when internal stresses are high. A plunger or piston is used to transmit the force that develops the pressure. Pistons are generally used for water pressures up to 1000 psig, and they are most frequently used on duplex double-acting pumps. They are sometimes used on triplex pumps.

The stuffing box of a pump is shown in Figure 12-16 and consists of the box, lower and upper bushings, packing, and gland. It is usually removable for maintenance.

The cylinder liner provides wear protection for the cylinder walls. On double-acting pumps, the liner has packing to prevent leakage from the high pressure to the low side of the cylinder.

The manifolds are the chambers where liquid is dispersed or collected for distribution before or after passing through the cylinder. On horizontal pumps, the suction and discharge manifold is usually made integral with the cylinder. Some horizontal and some vertical pumps have only the discharge manifold integral with the cylinder. Most vertical pumps have the suction and discharge manifold separate from the cylinder.

The valves used in the pumps may be single valves or a cluster of valves which provide the same valve area. Valve covers are usually used to provide accessibility to the valves without disturbing the cylinder or manifolds.

12.4.2 Pulsations

The pulsating output characteristics of a reciprocating pump is an extremely important consideration for pump application. The magnitude of the discharge pulsation is mostly affected by the number of plungers or pistons on the crankshaft. Figure 12-17 compares the discharge rate for a single double-acting (simplex) pump with the discharge rate for a triplex (3-piston) single-acting pump.

12.4.3 Flow Characteristics

The flow characteristics of duplex (2-piston) and simplex pumps are shown in Figure 12-18. The flow from a simplex pump is fairly constant, except when the pump is at rest. However, an uneven pulsating flow is produced because the flow must stop for the valves to close and for the forces on both sides of the liquid piston to reverse. This can be compensated for, in part, by installing a pulsation-dampening device on the discharge side of the pump or in the discharge line. The mechanism of a duplex pump is such that just before one piston completes its stroke, the other piston starts up and overlaps the first, eliminating the sharp capacity drop.

12.4.4 Net Positive Suction Head Requirements

Although the mechanics of cavitation in a positive displacement pump differ from a centrifugal pump, positive displacement pumps still have a requirement for adequate NPSH. The NPSH required ($NPSH_R$) is the required head of clean liquid at the suction connection centerline to ensure proper pump-suction operating conditions. For any given plunger size, pump speed, flow rate, and vapor pressure, there is a specific value of $NPSH_R$.

A change in one or more of the above conditions will change the $NPSH_R$. For a given plunger size, the $NPSH_R$ changes approximately as the square of the pump speed. Figure 12-19 shows an $NPSH_R$ curve for a triplex pump versus plunger diameter and pump speed.

For positive displacement pumps, it is a good practice to have the actual NPSH at least 3 to 5 psi greater than the $NPSH_R$. This margin prevents the release of vapor and entrained gases in the suction system. Released vapors and gases under repeated compression and expansion can cause damage to the internal passages similar to cavitation.

12.5 Jet Pumps

The term jet pump describes a pump with no moving parts that utilizes fluids in motion (motive fluid) to produce a pumping action. A pictorial representation of a jet pump is shown in Figure 12-20. The motive power is provided by a high-pressure stream of fluid directed through a nozzle designed to produce the highest possible velocity. The resultant jet of high-velocity fluid creates a low-pressure area in the mixing chamber causing the suction fluid to flow into this chamber. Ideally, there is an exchange of momentum at this point producing a uniformly mixed stream traveling at a velocity intermediate to the motive and suction velocity. The diffuser is shaped to gradually reduce the velocity and convert the energy to pressure at the discharge with as little loss as possible. The three basic parts of any ejector are the nozzle, the diffuser, and the suction chamber or body.

As mentioned in section 12.2.3, ejectors and eductors are types of jet pumps. Ejectors with steam as a motive fluid are used to remove air from some plant condensers. Eductors with oil as a motive fluid are used in the lube oil systems of some main turbines.

12.6 Operating Characteristics of a Centrifugal Pump

12.6.1 Single Pump Operations

The volumetric flow rate ($\dot{V}$) of a centrifugal pump is related to the pressure differential (ΔP_p) or head (H_p) developed by the pump. Analysis of various pumps shows that these terms depend upon variables such as pump efficiency, power supplied to the pump, the rotational speed, the diameter of the impeller, and the fluid density and viscosity. The relationship between ΔP_p or H_p and is given by a pump characteristic curve.

A typical pump characteristic curve is shown in Figure 12-21. Pump head, plotted on the vertical axis, is the difference between the discharge head and the inlet (suction) head of the pump (ΔP_p). Volumetric flow rate ($\dot{V}$), plotted on the horizontal axis, is the rate at which fluid is flowing through the pump. The curve presented in Figure 12-21 is for one constant speed (N) for the pump impeller. The curve will shift if the speed is changed. The effect of increasing pump speed on the relationship between H_p and is shown in Figure 12-22 ($N_2 > N_1$).

Multistage centrifugal pumps were briefly introduced in section 12.3. Multistage pumps are typically employed when pump discharge pressures are required to exceed 150 psig. Depending upon the system requirements, two, three, four, or more stages may be needed to achieve the required pump head and flow conditions. In a multistage pump, a single stage consists of one impeller and associated components. The first stage impeller discharges into the suction side (eye) of the second stage impeller and so on. The impellers are connected to the same pump shaft. Each stage develops a pressure rise (increase in head) that builds upon prior stages. This technique of coupling stages is sometimes referred to as cascading. The characteristic curve for a typical three-stage centrifugal pump is given in Figure 12-23.

12.6.2 Centrifugal Pump Laws

Centrifugal pump characteristics generally obey what is known as the centrifigal pump laws. These pump laws are only exact for very controlled conditions, but they are sufficiently accurate under most normal operating conditions. The laws state that the flow rate ($\dot{V}$) or capacity of the pump is proportional to the pump speed; the discharge head (H_p) is proportional to the square of the pump speed, and the power or brake horsepower (BHP) required by the pump motor is proportional to the cube of the pump speed. The centrifugal pump laws are summarized in the following equations:

Flow Rate ($\dot{V}$) $\propto N$
Head (H_p) $\propto N^2$
Power (BHP) $\propto N^3$

Where typically flow rate is measured in gallons/minute (gpm), discharge head is measured in feet or psi, power is measured in horsepower or kilowatts, and pump speed is measured in rpm.

To understand the utility of these laws, assume that a centrifugal pump motor has a slow and fast speed and the fast speed is twice the slow. In slow speed the pump delivers 400 gpm with a head of 30 psi and a power input of 80 kW. If the speed is increased to fast (speed is doubled) on this particular pump, the new flow rate would be 800 gpm, the head would increase to 120 psi, and the input power would increase to 640 kW.

12.6.3 Operating Point

The point at which a pump actually operates in a given system depends on the flow rate and head loss of the attached system. For a given system, volumetric flow rate in the system is related to system head loss by a system head-loss curve. By drawing a system head-loss curve and the pump characteristic curve on the same graph, the point at which the pump will operate is the point of intersection of the two curves. This point is called the operating point. In Figure 12-24, the operating point for the centrifugal pump in the original system is the intersection of the pump characteristic curve and the solid line system head-loss curve.

The opening and closing of a valve in the system will change the system head-loss curve. In Figure 12-24 the system with the open valve has a flow rate equal to $\dot{V}_0$ and a total system head loss equal to H_0. To maintain the flow rate, the pump must develop a pump head (H_p) equal to H_0. In the system described by the dotted line head-loss curve, a valve has been partially shut to reduce the system flow, which increases the system's head-loss. For this system, the pump will develop a pump head (H_p) equal to H_1 which corresponds to a new flow rate of $\dot{V}_1$. The new operating point for the pump becomes H_1 and $\dot{V}_1$.

Just as opening or closing a valve in a system will change the system head-loss curve and the pump operating point, pump degradation due to factors such as the wearing of internal parts can also change the pump operating point. In the case of pump wear, the head and flow developed for a particular pump speed and system condition decrease because of increased clearances within the pump. This results in a change to the pump operating point as shown in Figure 12-25.

12.6.4 Shutoff Head and Runout Conditions

At the extreme ends of a centrifugal pump characteristic curve are the pump shutoff head and pump runout conditions. The pump <u>shutoff head</u> is the pump head at which the maintainable flow rate is reduced to zero. At the shutoff head, the resistance to flow is greater than the power the centrifugal pump can impart to the fluid; therefore, the flow rate through the system is zero. Shutoff head is normally achieved by closing the pump discharge valve, but it can also be achieved by increasing the pressure downstream of the pump beyond the pressure capability of the pump. Operating a pump under shutoff head conditions is sometimes referred to as <u>deadheading</u>.

When a centrifugal pump starts, it accelerates until it reaches its rated speed. While accelerating the pump, the pump motor requires a starting current much higher than the current normally required to operate the pump at its rated speed. The longer the pump takes to reach its rated speed, the longer the high starting current must be supplied. To limit the time the starting current is required, many centrifugal pumps are designed to be started with the discharge valve shut. With the discharge valve shut, the pump reaches its rated speed more quickly, and less work and starting current is required because no liquid is being pushed through the pump. When the pump reaches its rated speed and the discharge valve is opened, the current to the pump motor quickly attains the normal value.

Prolonged pump operation at shutoff head conditions is undesirable. With no flow, the liquid in the impeller is "churned" and the heat generated by the churning may overheat the pump. Pump overheating can cause warped vanes, damaged bearings, or binding in the pump's moving parts (i.e., pump seizure). To avoid these complications, pumps required to operate at low capacity or at shutoff conditions for any length of time should be fitted with recirculation lines. Recirculation lines normally run from the discharge side of the pump back to the inlet of the pump or to some other point on the suction side. These lines permit a small amount of flow through the pump when the discharge valve is shut. This small amount of flow, usually regulated by an orifice, is sufficient to prevent the pump from overheating.

Heat generated by pumping can be used to elevate the temperature of a system. For example, when the reactor is shutdown, the reactor coolant pumps can be operated to increase the temperature of the reactor coolant. As another example, pump heat is commonly used to warm various balance of plant systems such as the main turbine and generator lube oil sytems.

At the other extreme of the centrifugal pump characteristic curve is the pump runout condition. When pump runout occurs, the system backpressure is very low and fluid flows through the pump without absorbing much energy from the pump. Under these conditions, volumetric flow rate reaches a maximum level, but the pumping process is inefficient, and the pump can experience extreme mechanical stress. The limiting condition for operation under these maximum flow rate conditions is called pump runout. One common occurrence indicating pump runout for a motor-driven pump is a large increase in motor current. Excessive current through the motor windings can cause rapid overheating. In this case, pump runout for the motor-driven pump is defined as the volumetric flow rate at which motor overheating can occur.

12.6.5 Multiple Pump Operations

To increase the volumetric flow rate in a system or to compensate for large flow resistances, centrifugal pumps are often used in parallel or in series. Figure 12-26 depicts two identical centrifugal pumps operating in parallel at the same speed.

Since the inlet of each pump and the outlet of each pump are at identical points in the system, each pump must produce the same pump head. The total flow rate in the system, however, is the sum of the individual flow rates across each pump.

When the system characteristic curve is considered with the pumps-in-parallel curve, the operating point represents a higher volumetric flow rate than one pump and a greater system head loss. As shown in Figure 12-27, a greater system head loss occurs with the increased fluid velocity resulting from the increased volumetric flow rate. Because of the greater system head loss, the volumetric flow rate is actually lower than the flow rate potentially achieved by using two pumps.

Centrifugal pumps are used in series to produce a combined head that is greater than the head developed by one individual pump. As illustrated in Figure 12-28, two identical centrifugal pumps operating at the same speed with the same volumetric flow rate contribute the same pump head. Because the inlet to the second pump is the outlet of the first pump, the head produced by both pumps is the sum of the individual heads. The volumetric flow rate from the inlet of the first pump to the outlet of the second remains the same because they are in series. The same principles apply for using two non-identical centrifugal pumps (e.g. a condensate and feedpump) in series.

As shown in Figure 12-29, using two pumps in series in a system does not actually double pump head because of the increased resistance to flow in the system. The two pumps provide adequate pump head for the new system head loss and also maintain a slightly higher volumetric flow rate.

12.7 Operating Characteristics of a Positive Displacement Pump

Ideally a positive displacement pump provides a constant volumetric flow rate independent of the pump discharge pressure. The pump discharge can assume any value at constant flow rate. The pump characteristic curve for an ideal positive displacement pump is shown in Figure 12-30.

In the actual case, increasing pump discharge pressure causes some fluid to leak past the piston or plunger. Thus, the actual characteristic curve bends to the left at the top, indicating that net flow rate in the actual case is less than the ideal case. At some point, the discharge pressure could become great enough (assuming system piping does not rupture) to stop the motion of the piston or gears. This would inevitably damage the pump. Therefore, discharge pressure of a positive displacement pump is typically limited by pressure relief devices to keep the discharge pressure below a predetermined setpoint.

Chapter 12 Definitions

HEAD	-	The fluid pressure at a given point in a piping system measured in feet (usually feet of water), which represents the equivalent elevation of a tank level above the measurement location.
NET POSITIVE SUCTION HEAD (NPSH)	-	A statement of the minimum suction pressure (or head) conditions required to prevent cavitation in a pump.
CAVITATION	-	The formation and subsequent collapse of vapor filled cavities in a liquid due to dynamic action.
SHUTOFF HEAD	-	The pump discharge head at which the pump output flow rate is reduced to zero.
PUMP RUNOUT	-	The abnormally high flow rate at which motor overheating can occur due to drawing excessive current.

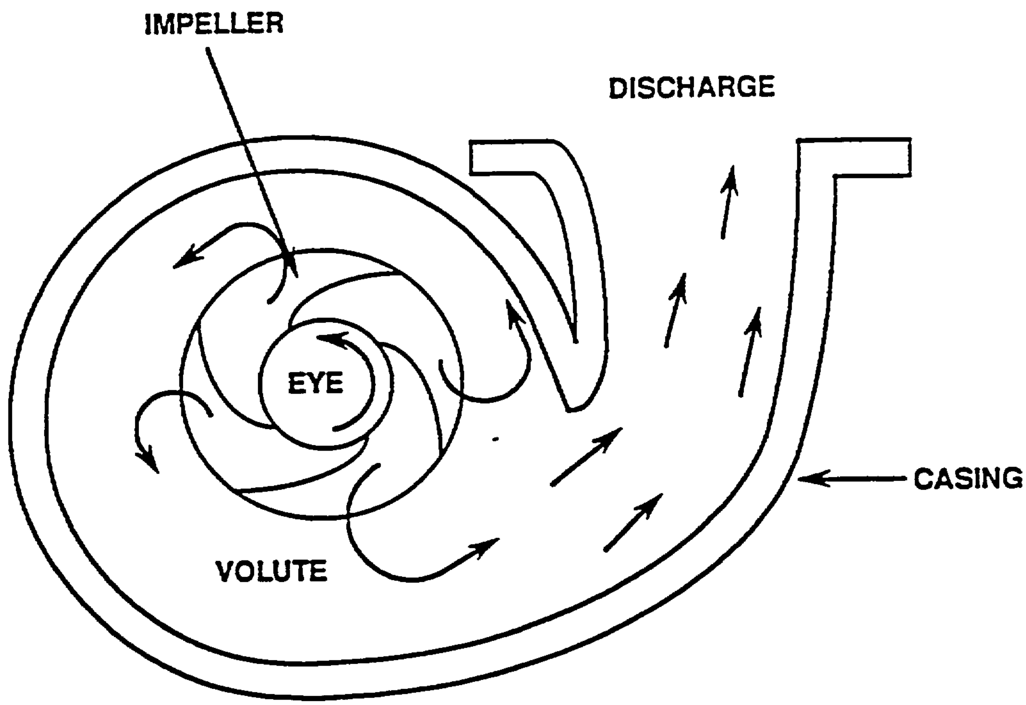


Figure 12 - 1. Volute Casing Pump

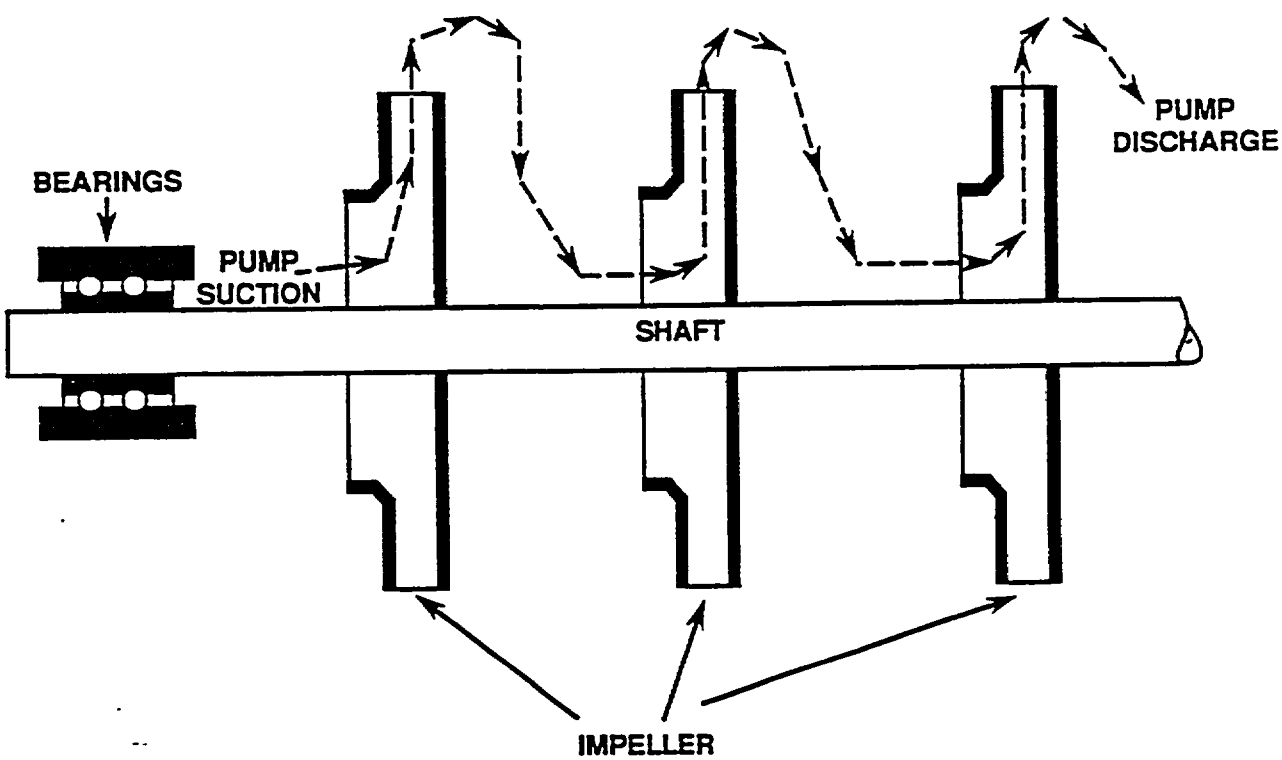
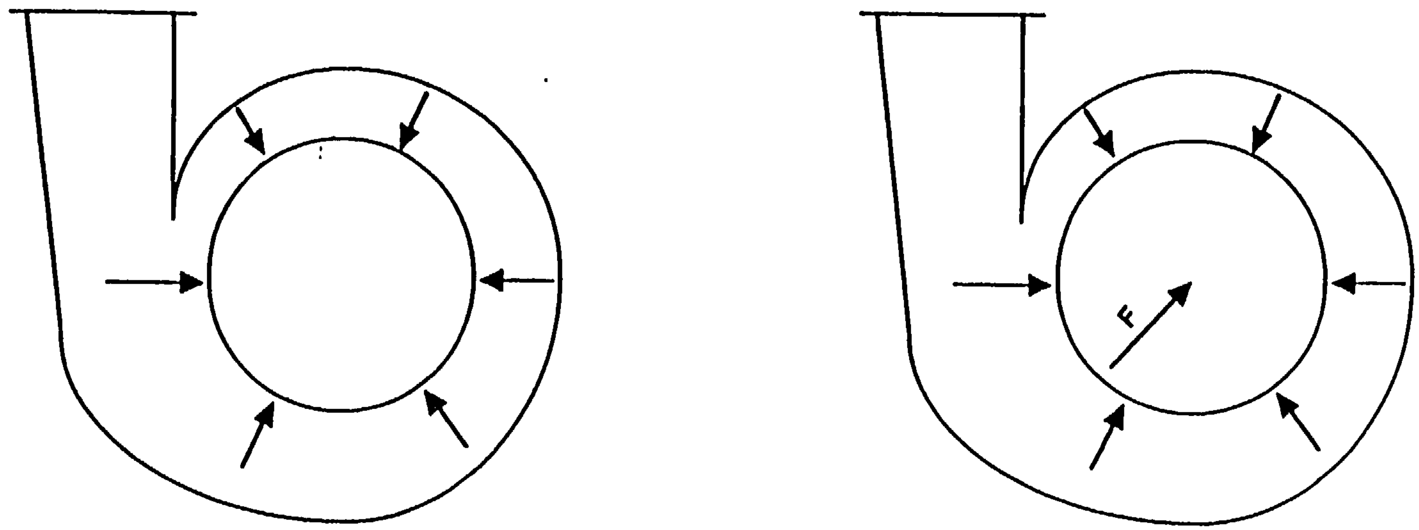


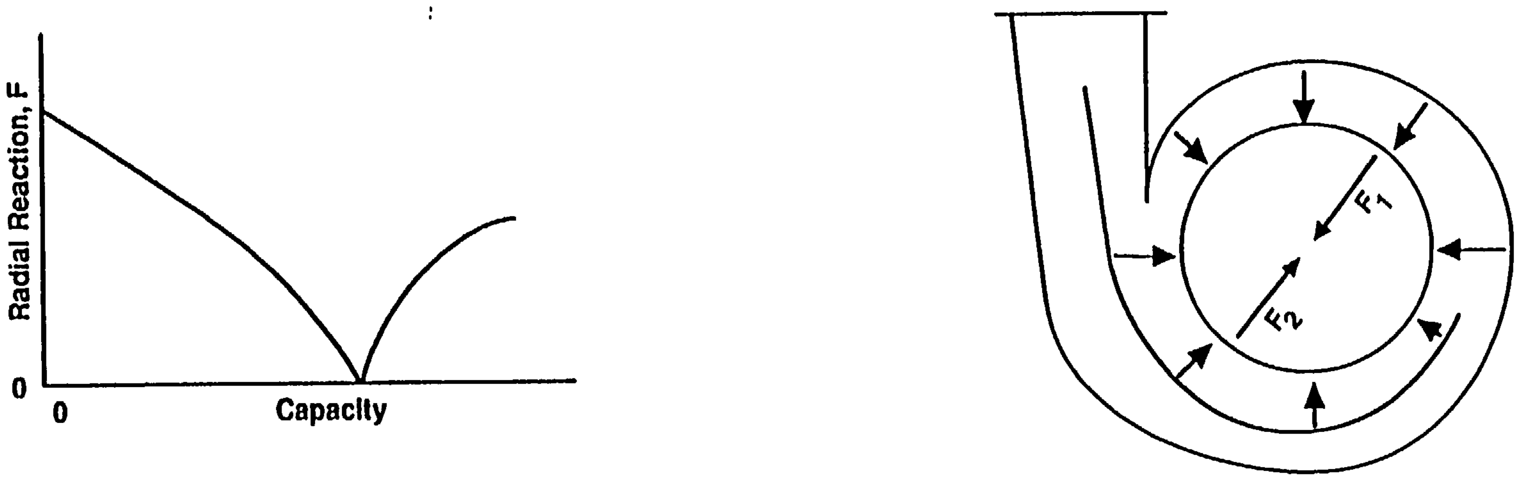
Figure 12-2. Multistage (Three) Pump Impeller and Shaft Assembly



A. Uniform casing pressure exists at design capacity resulting in zero radial reaction.

B. At over or under capacities, uniform pressures do not exist in a single-volute casing resulting in a radial reaction *F*.

Figure 12-3. Radial Reaction Forces in Pumps



A. In a single-volute pump, magnitude of radial reaction *F* decreases from shutoff to design capacity and then increases again with overcapacity . With overcapacity the reaction is roughly in opposite direction from that with part capacity.

B. In a double-volute pump the pressures are not uniform at part capacity operation. The resultant forces F_1 and F_2 for each 180° volute section oppose and balance each other.

Figure 12-4. Radial Reaction Forces in Single-Volute Versus Double-Volute Pumps

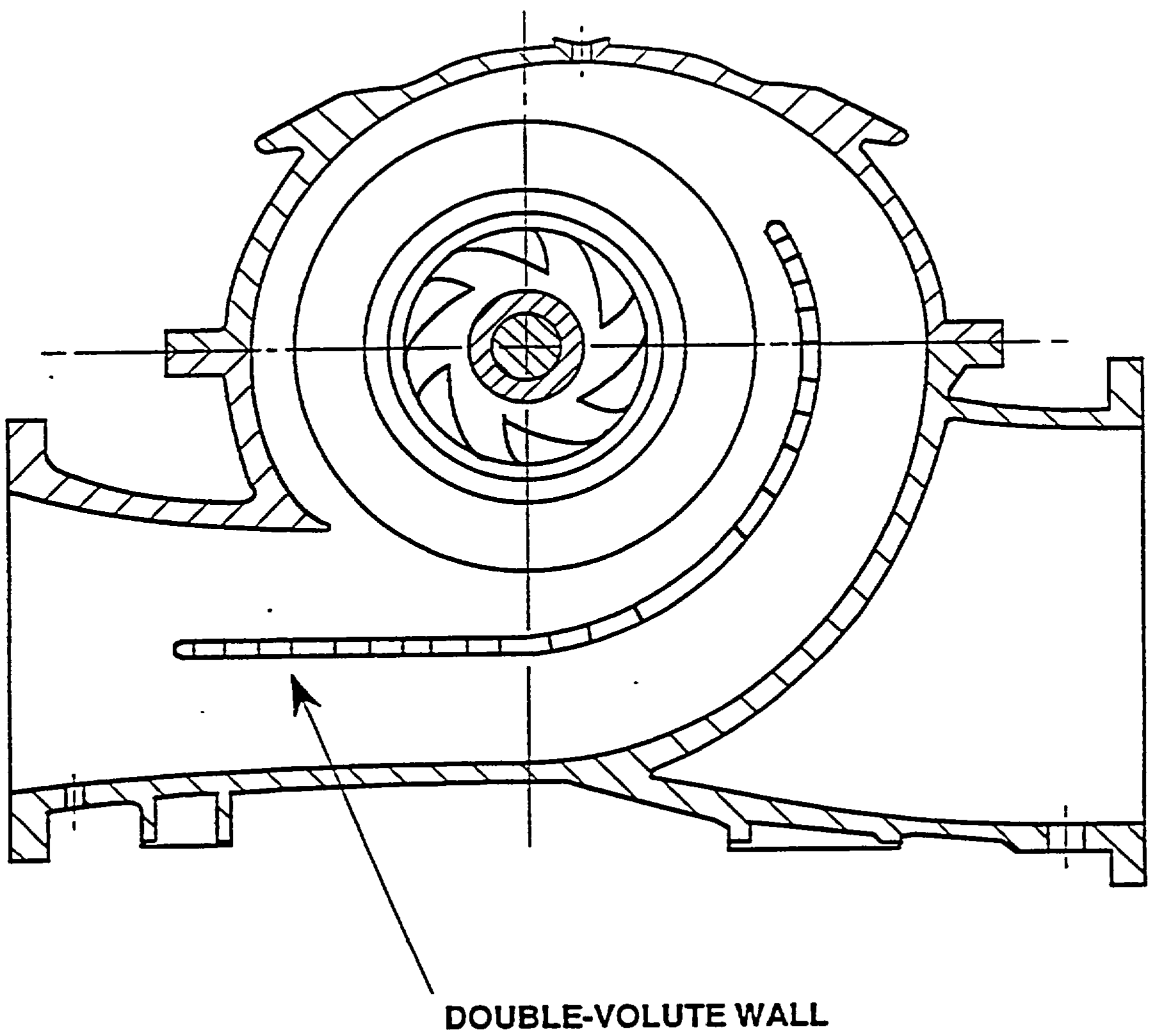


Figure 12-5. Double-Volute Casing Pump

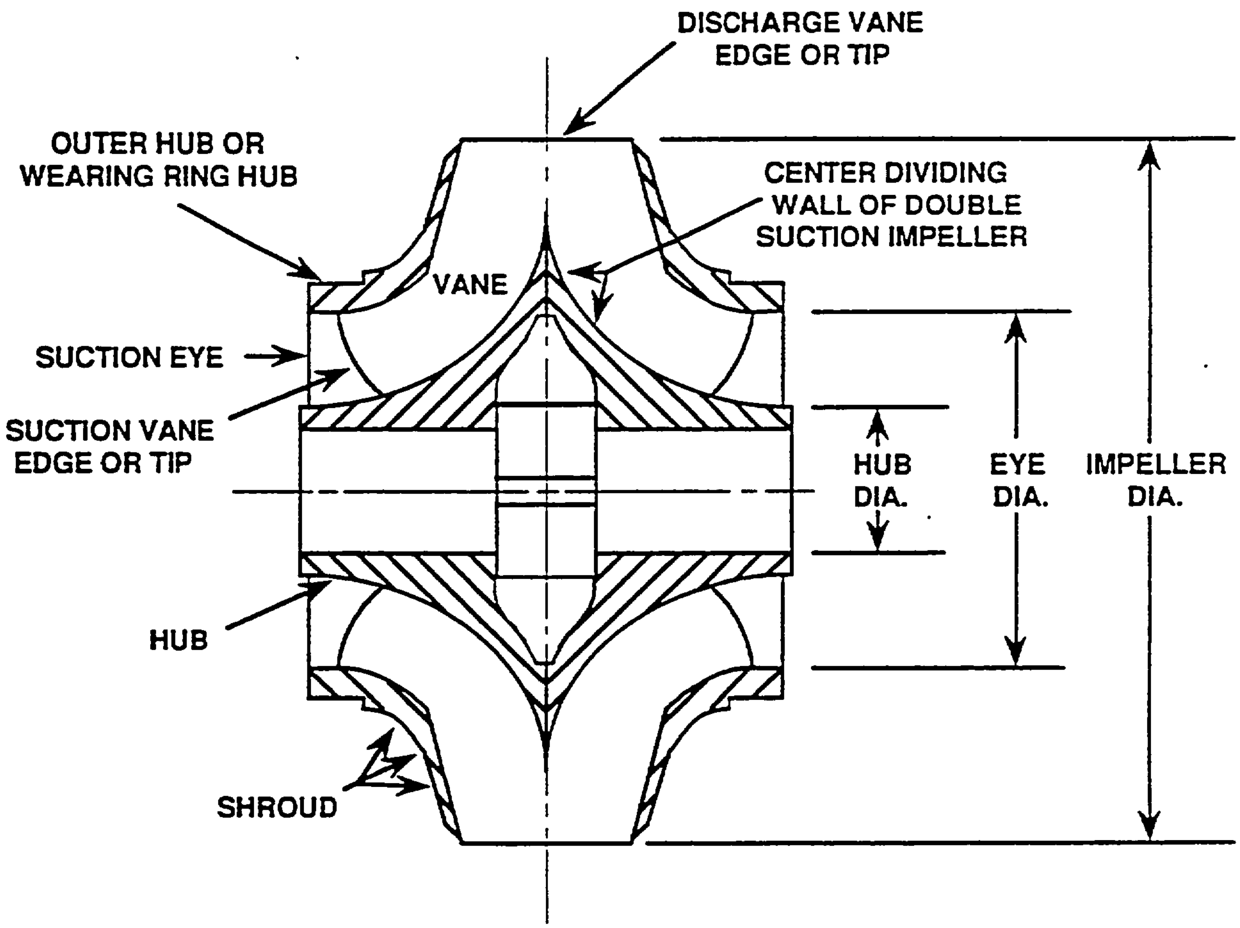


Figure 12-6. Double-Suction Impeller

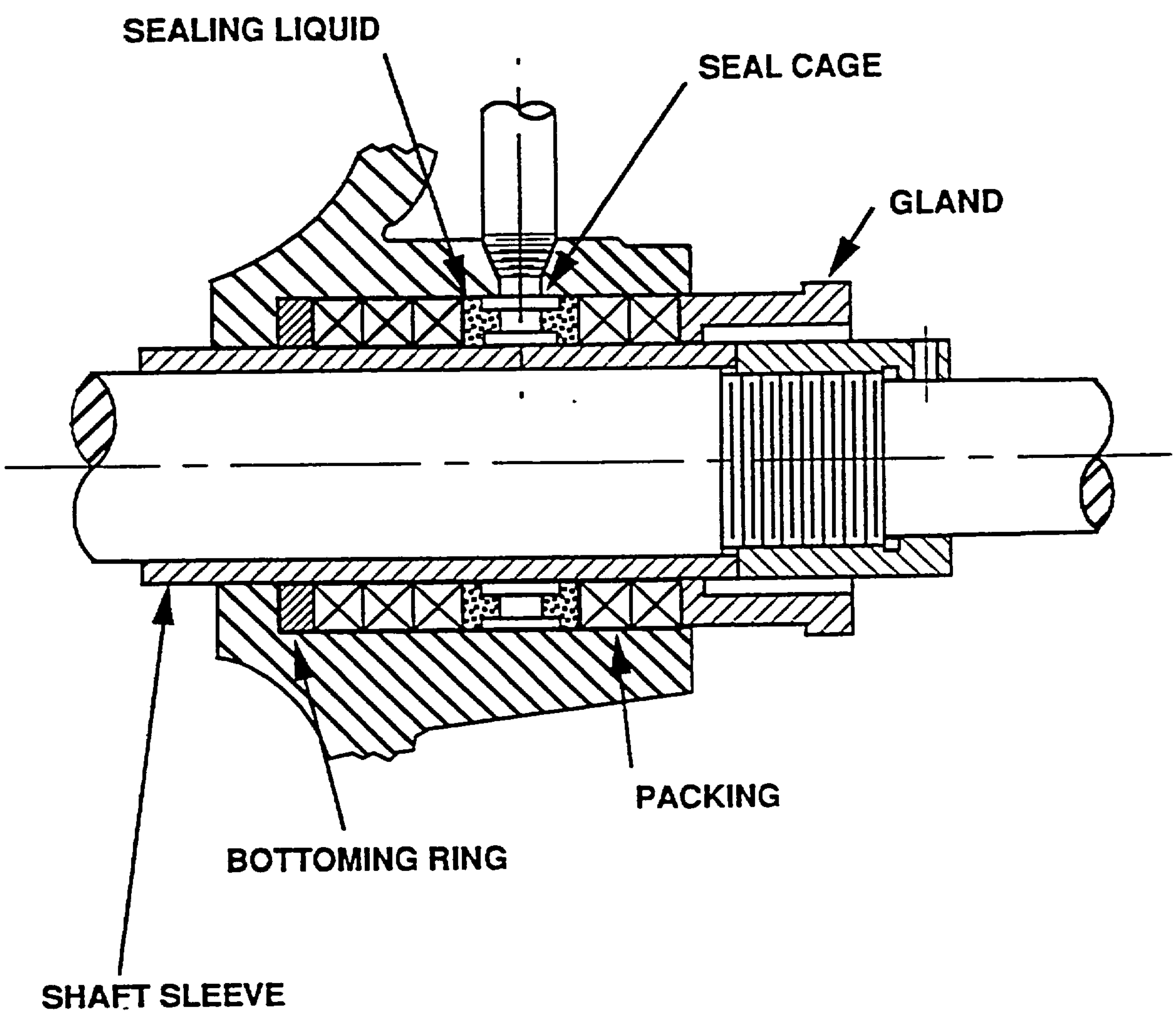


Figure 12-7. Conventional Stuffing Box with Bottoming Ring

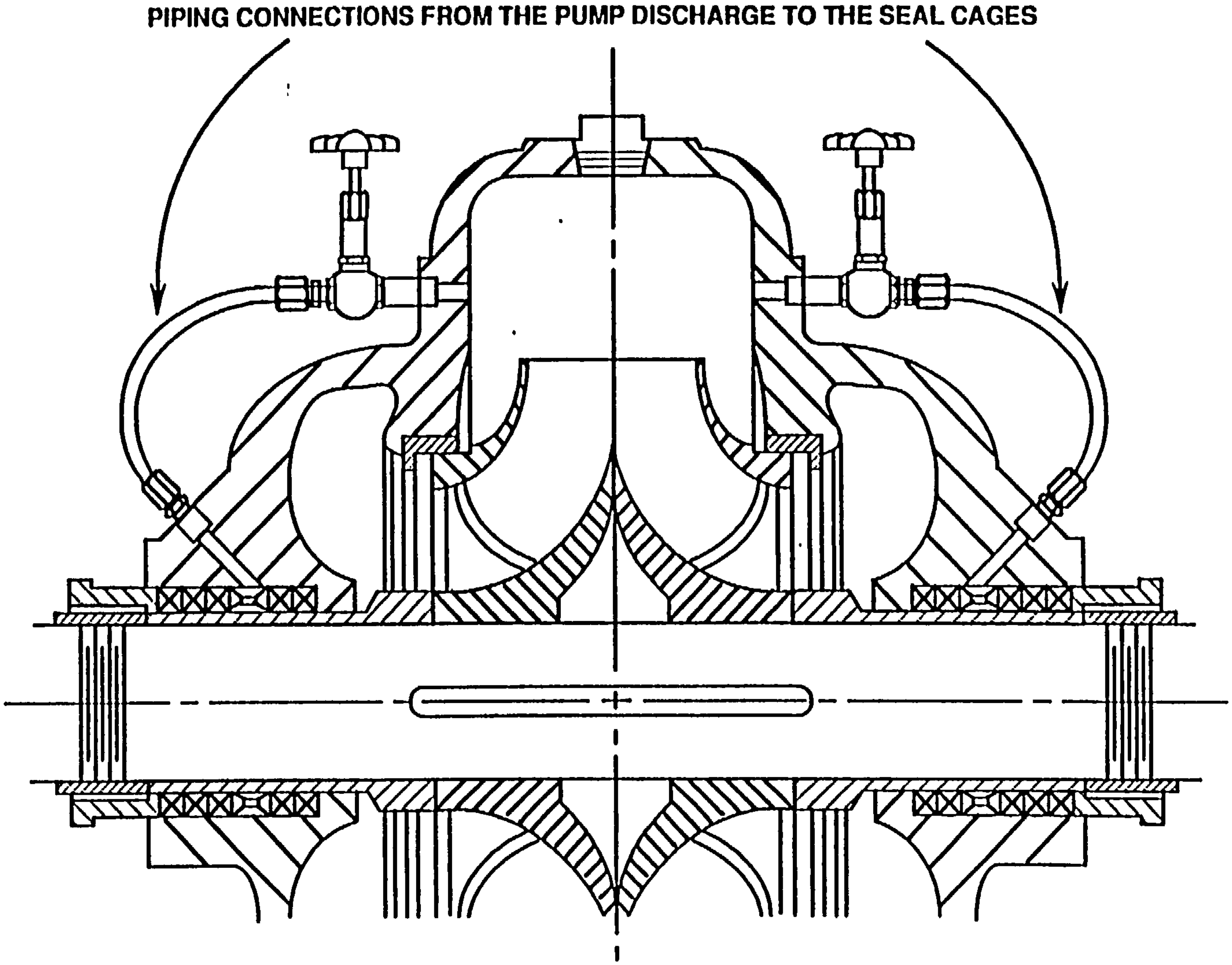


Figure 12-8. Seal Cage Arrangement

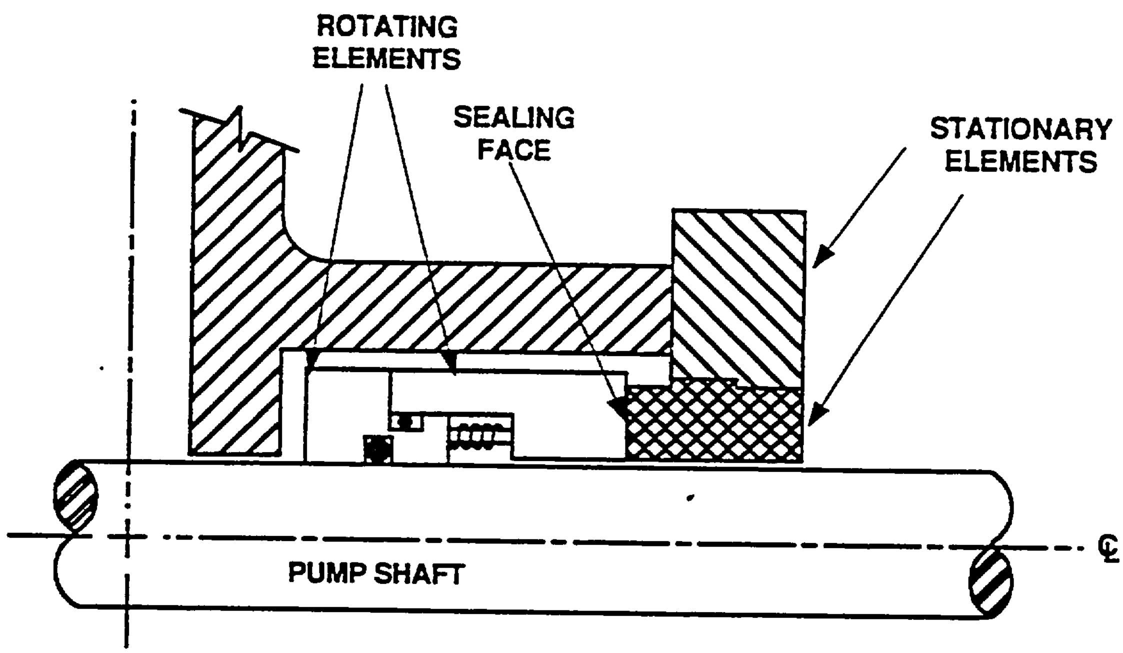
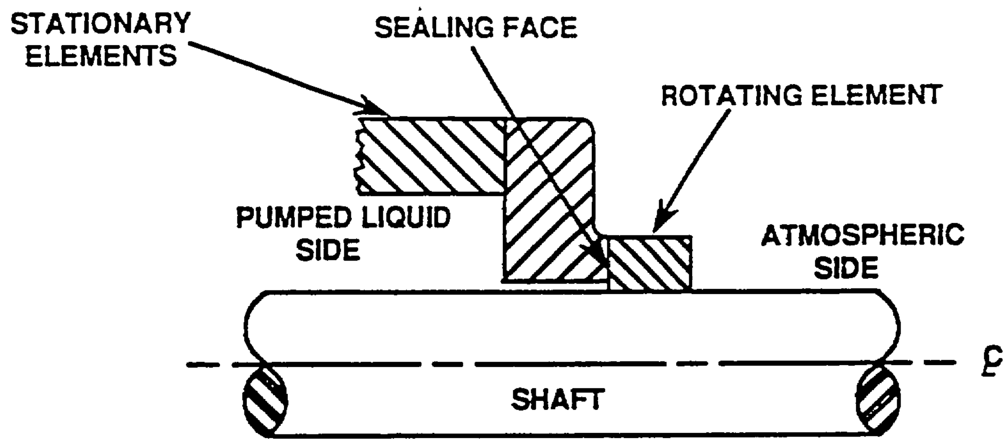
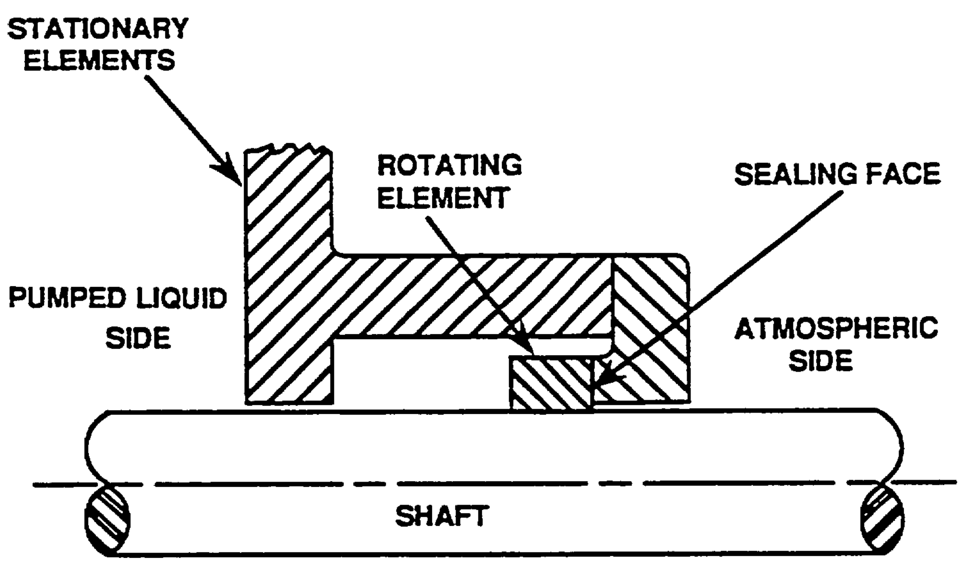


Figure 12 - 9. Typical Mechanical Seal Construction



A. External Assembly Seal



B. Internal Assembly Seal

Figure 12 - 10. Internal Versus External Pump Mechanical Seal Assemblies

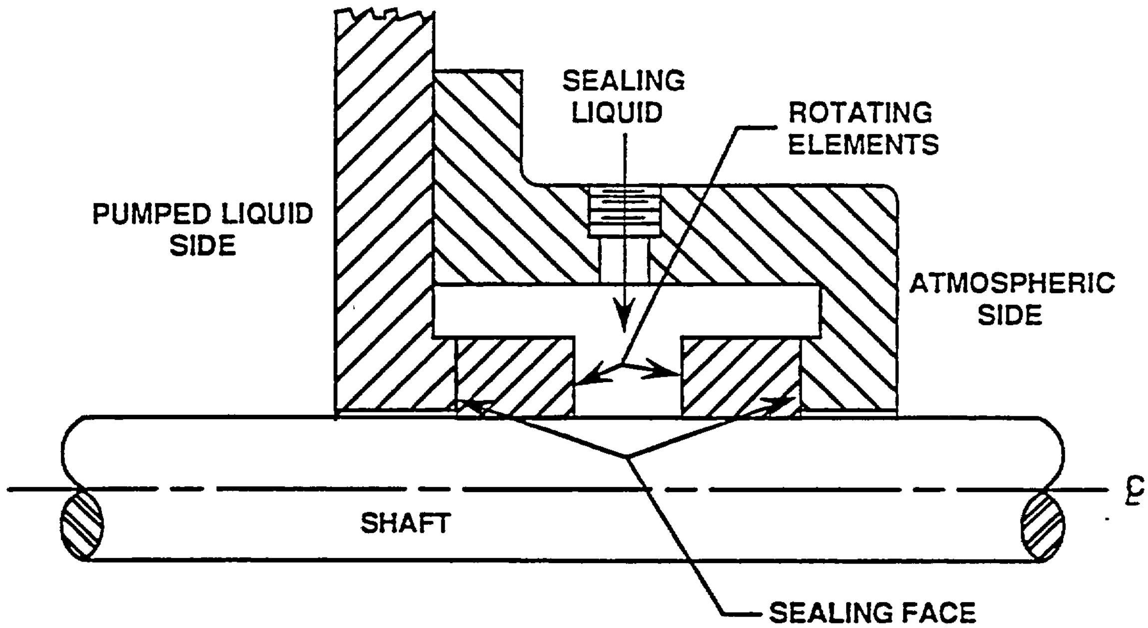
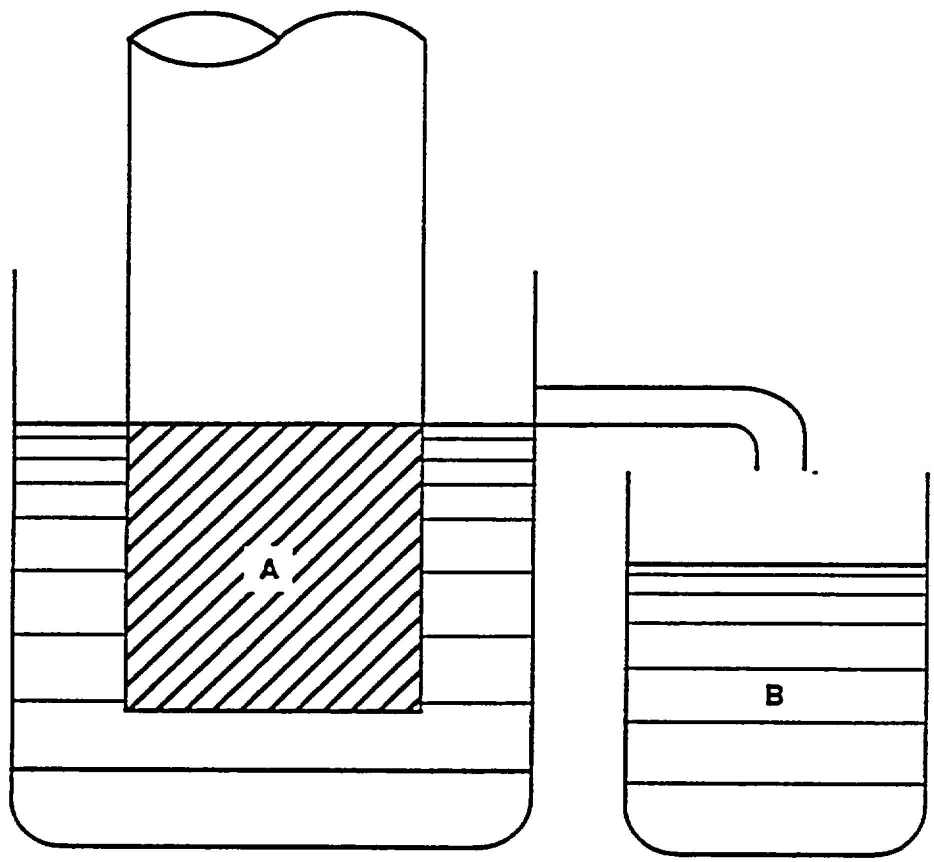
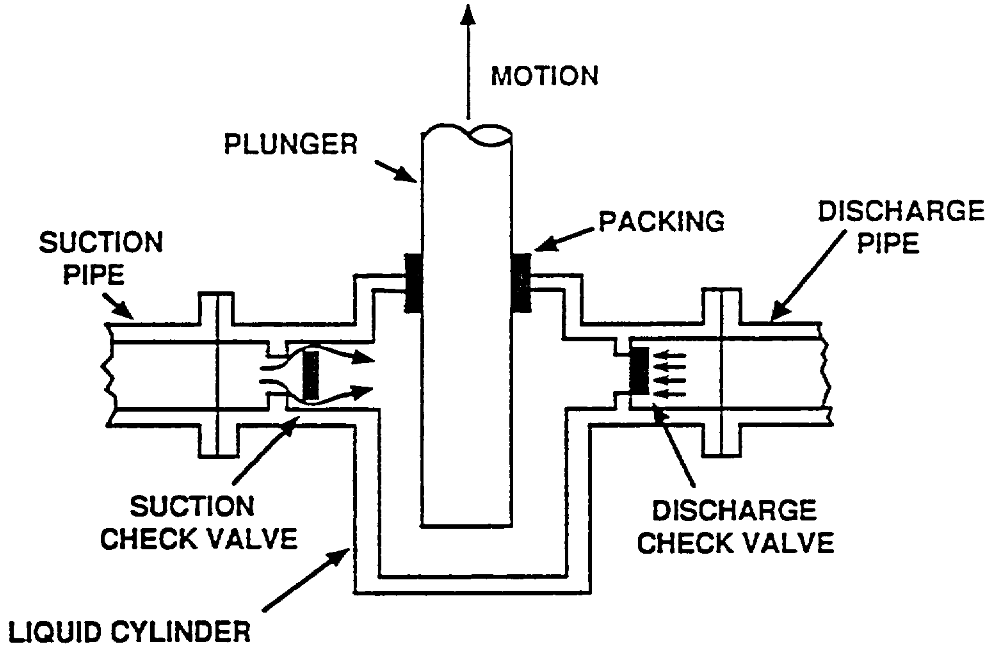


Figure 12 - 11. Double Mechanical Seal

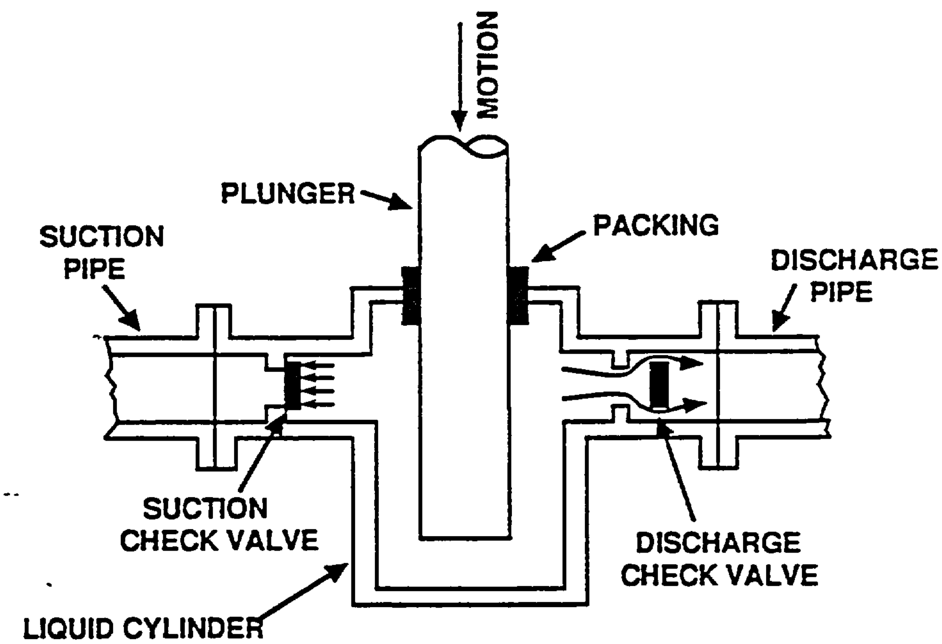


A SOLID (A) WILL DISPLACE A VOLUME
OF LIQUID (B) EQUAL TO ITS OWN VOLUME

Figure 12-12. Displacement of a Solid in a Liquid



A. Schematic of a Reciprocating-Pump Liquid End During the Suction Stroke



B. Schematic of a Reciprocating-Pump Liquid End During Discharge Stroke

Figure 12-13. Suction and Discharge Strokes of a Reciprocating Pump

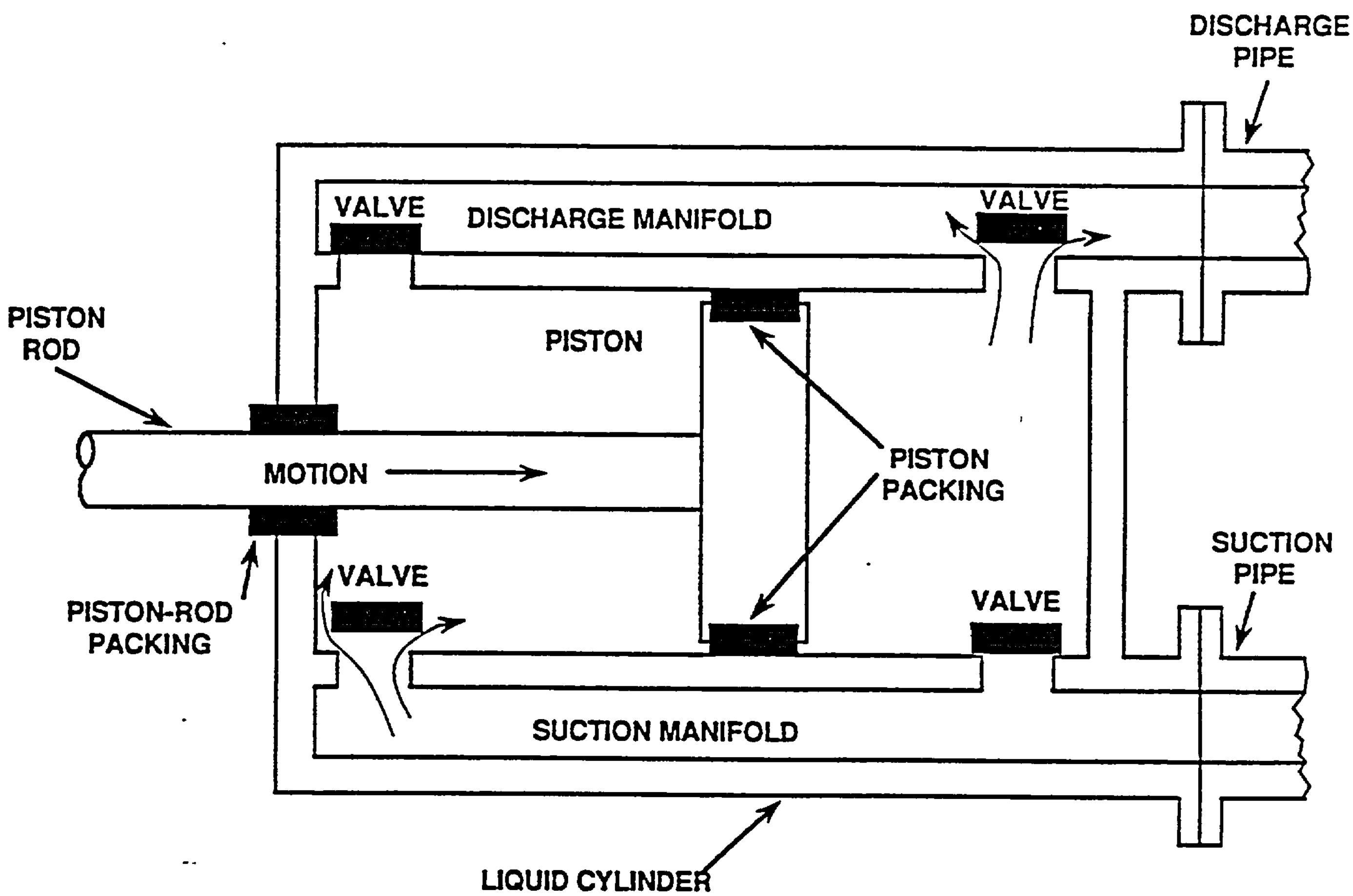


Figure 12-14. Schematic of a Double-Acting Liquid End Reciprocating Pump

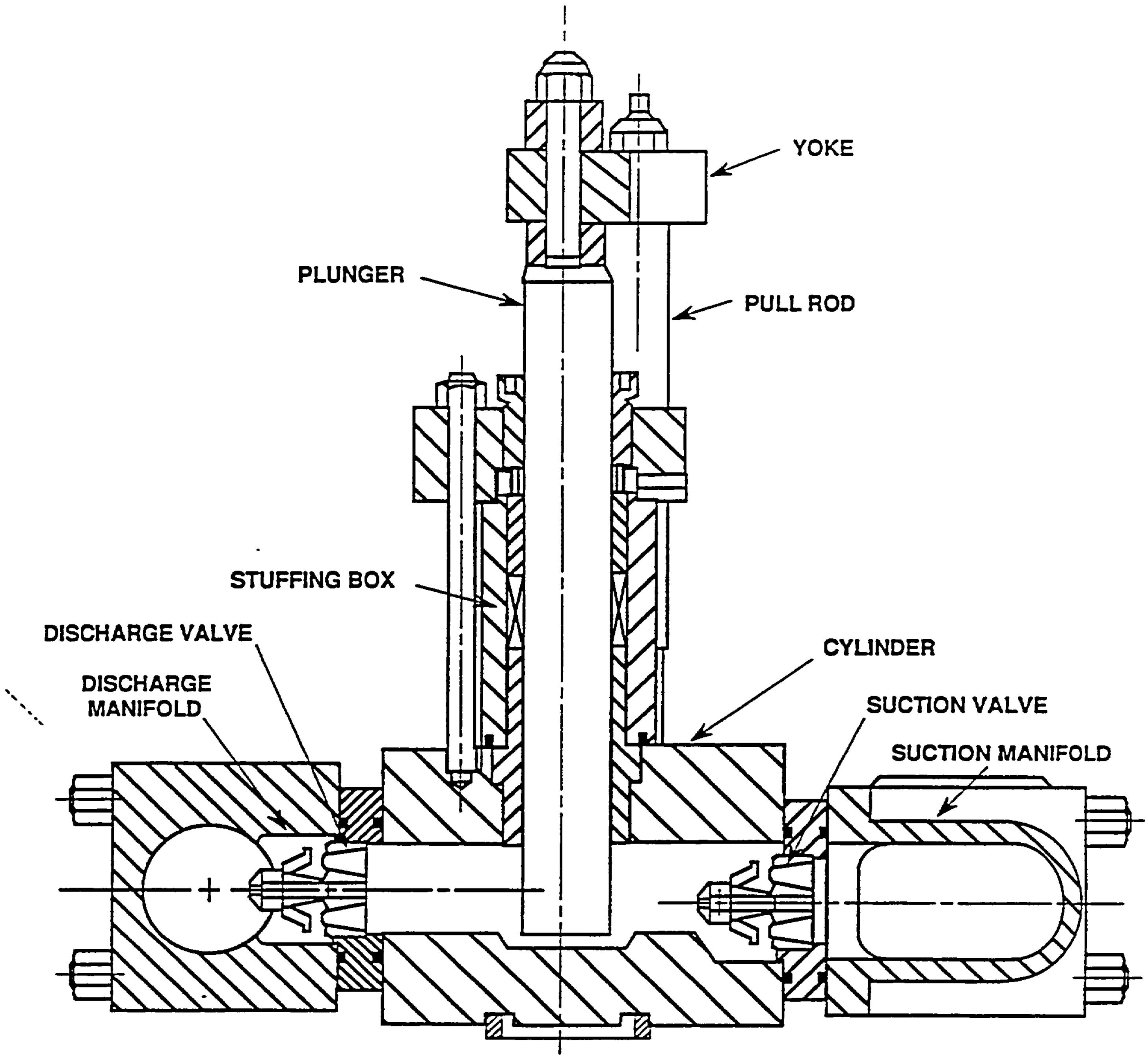


Figure 12-15. Liquid End, Vertical Pump

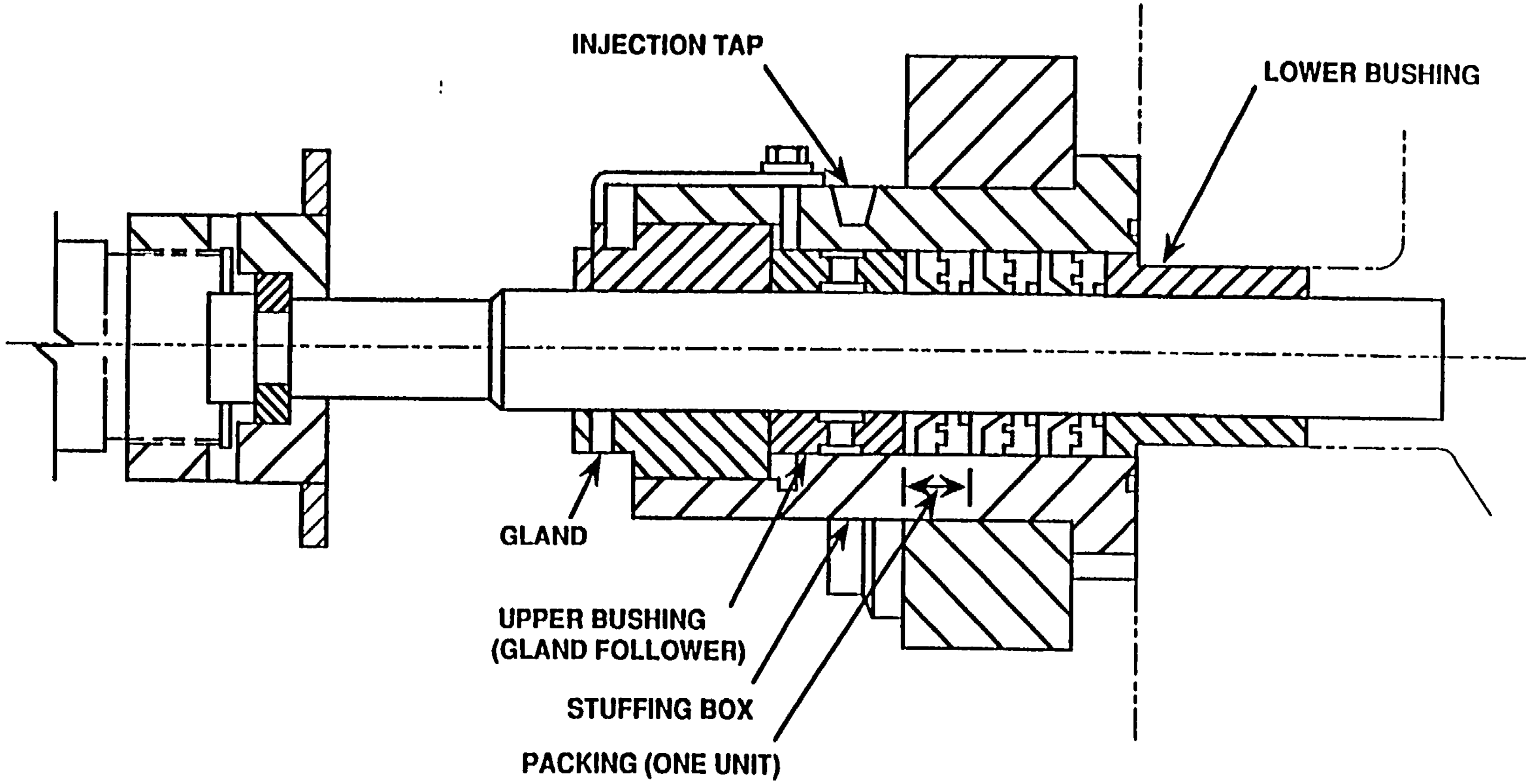
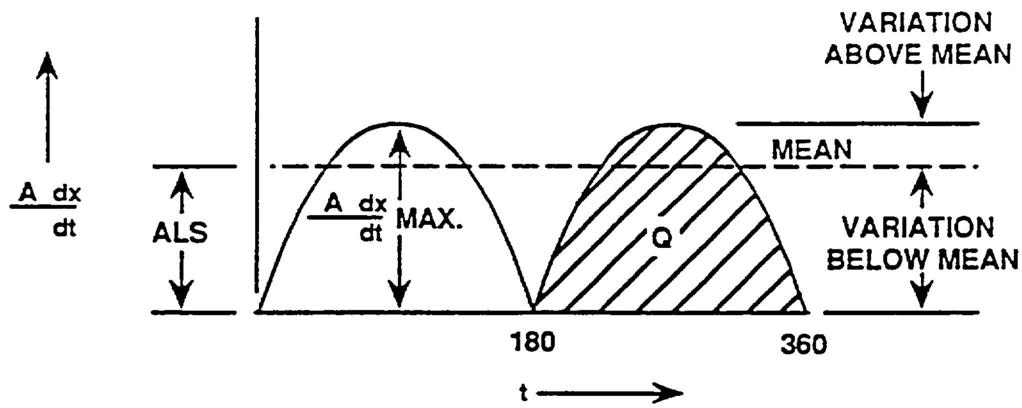
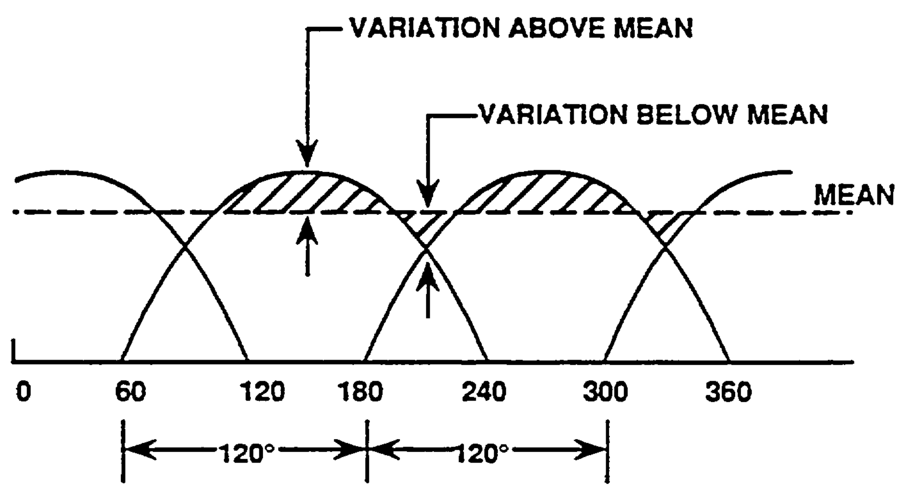


Figure 12-16. Stuffing Box



A. Single Double-Acting Pump



B. Triplex Single-Acting Pump

Figure 12-17. Discharge Rates for Single Double-Acting and Triplex Single-Acting Pumps

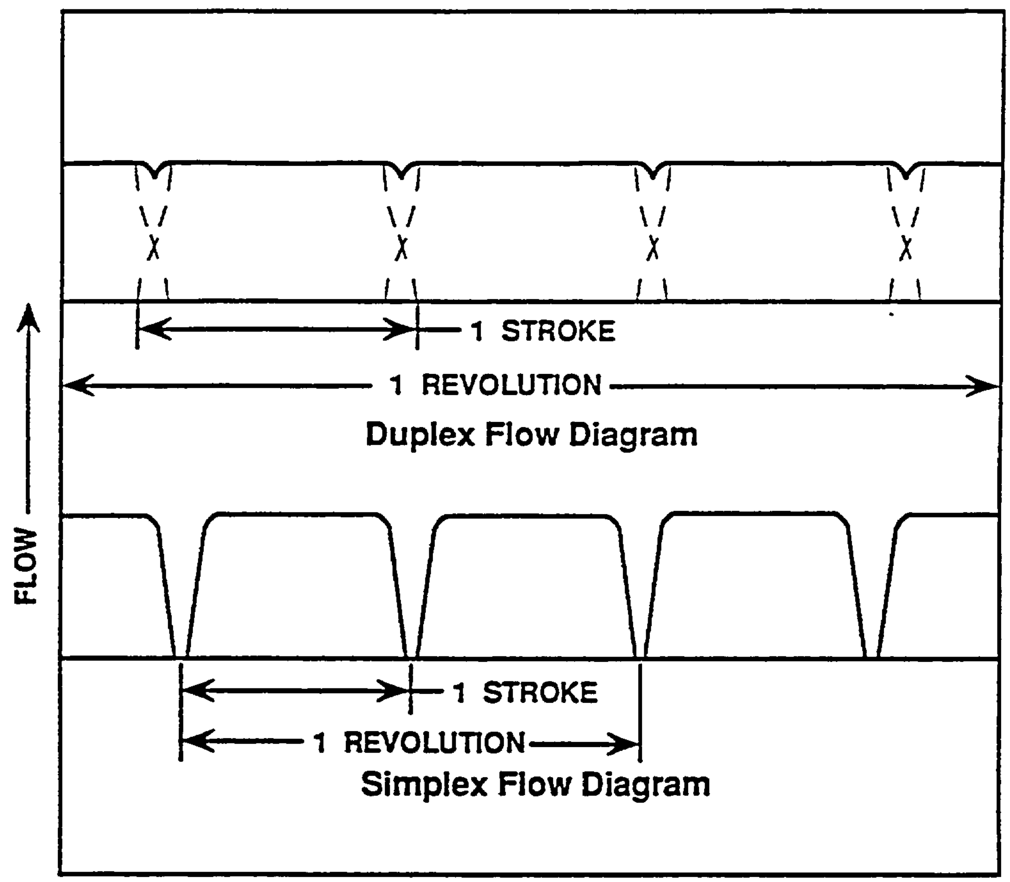


Figure 12-18. Flow Characteristics of Simple and Duplex Pumps

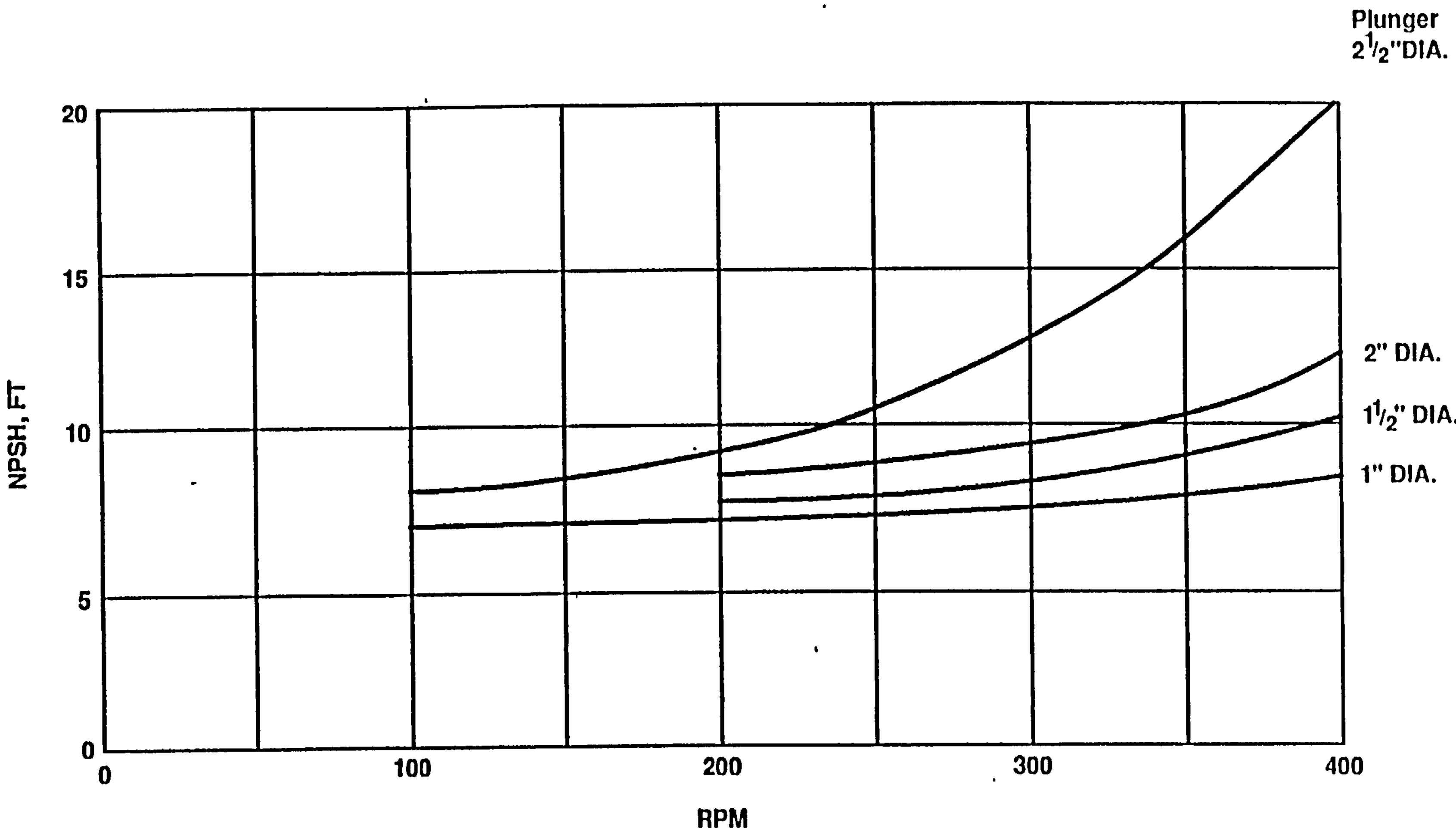
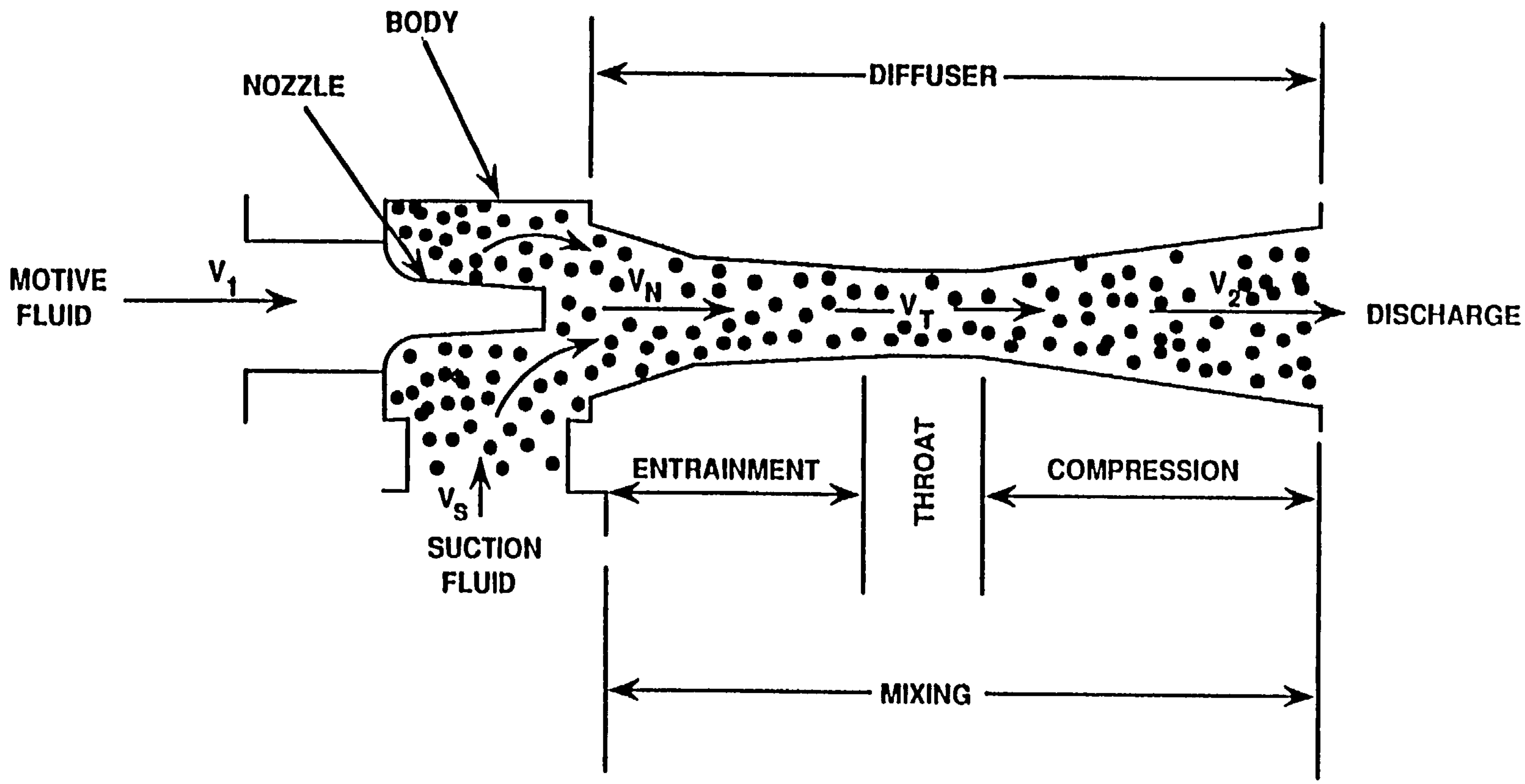
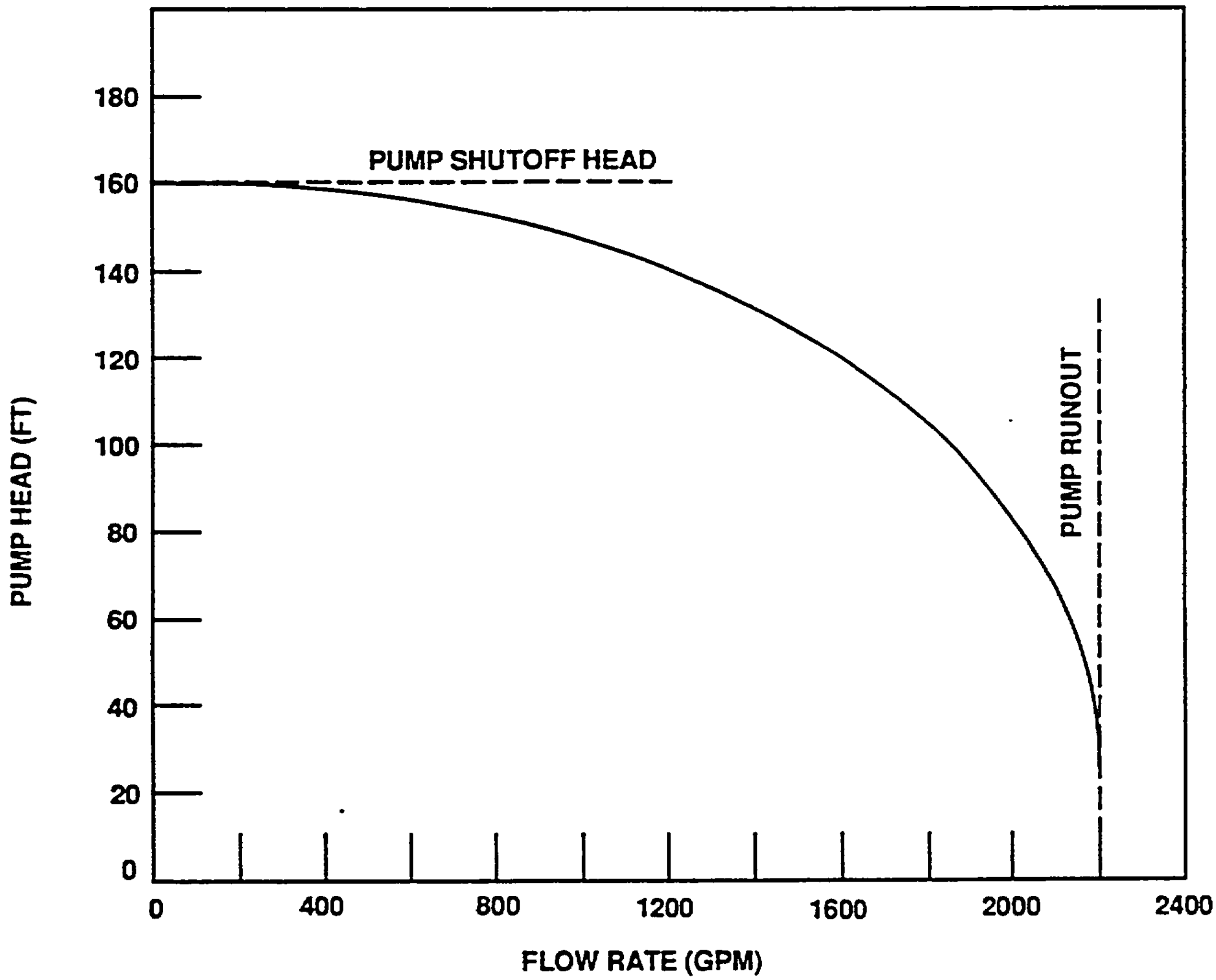


Figure 12-19. Required NPSH for a Triplex Pump



Jet Nozzles convert pressure energy into velocity while diffusers entrain and mix the fluids and change velocity back into pressure

Figure 12-20. Jet Pump



NOTE: CURVE IS FOR A CONSTANT SPEED.

Figure 12-21. Centrifugal Pump Characteristic Curve

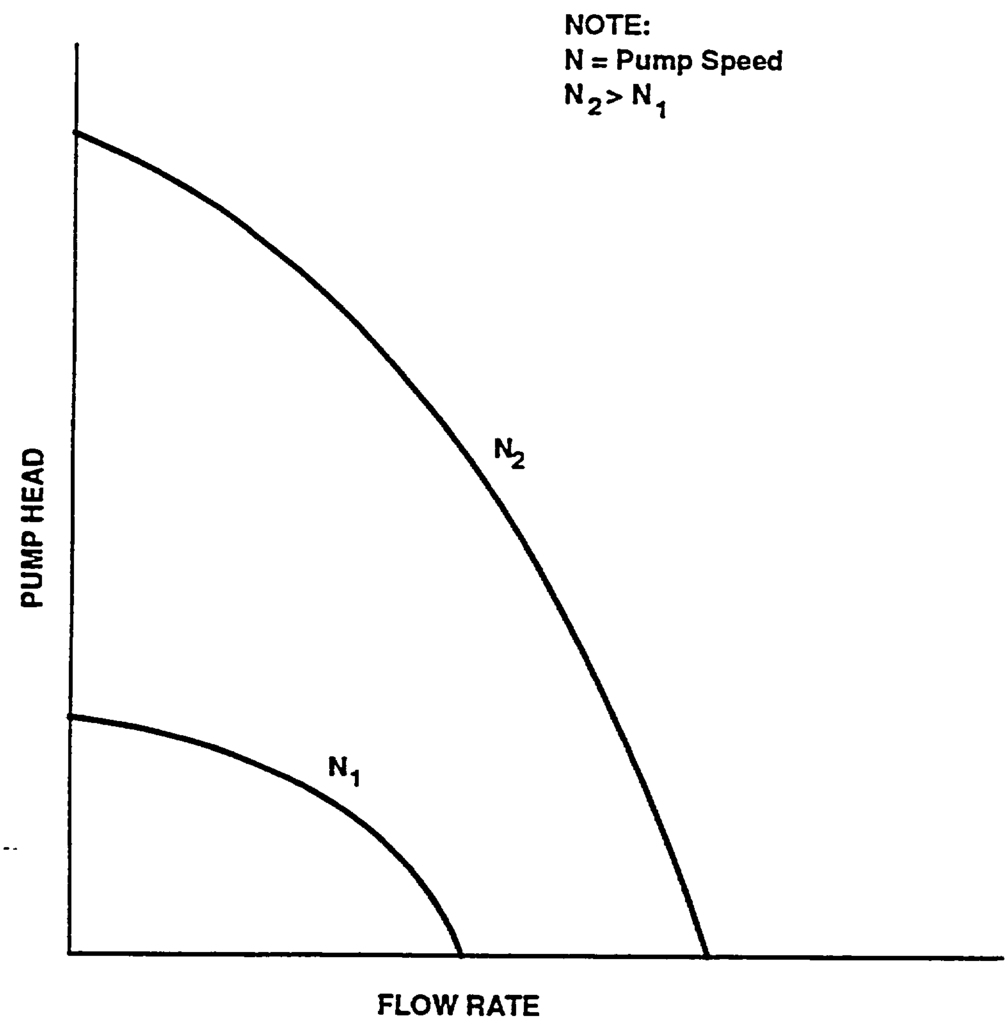


Figure 12 - 22. Changing Speeds for Centrifugal Pump

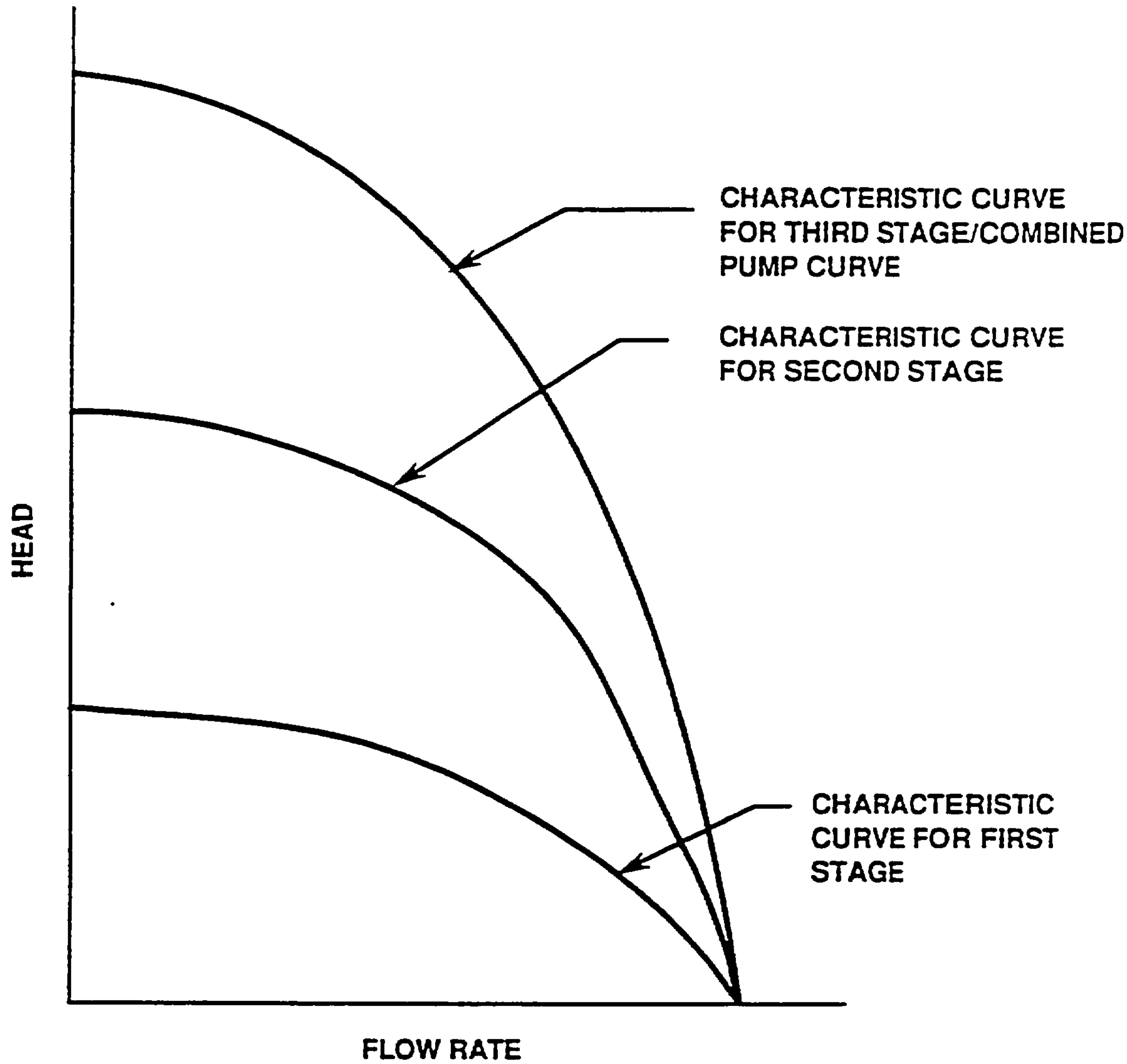


Figure 12-23. Characteristic Curves for a Three Stage Centrifugal Pump

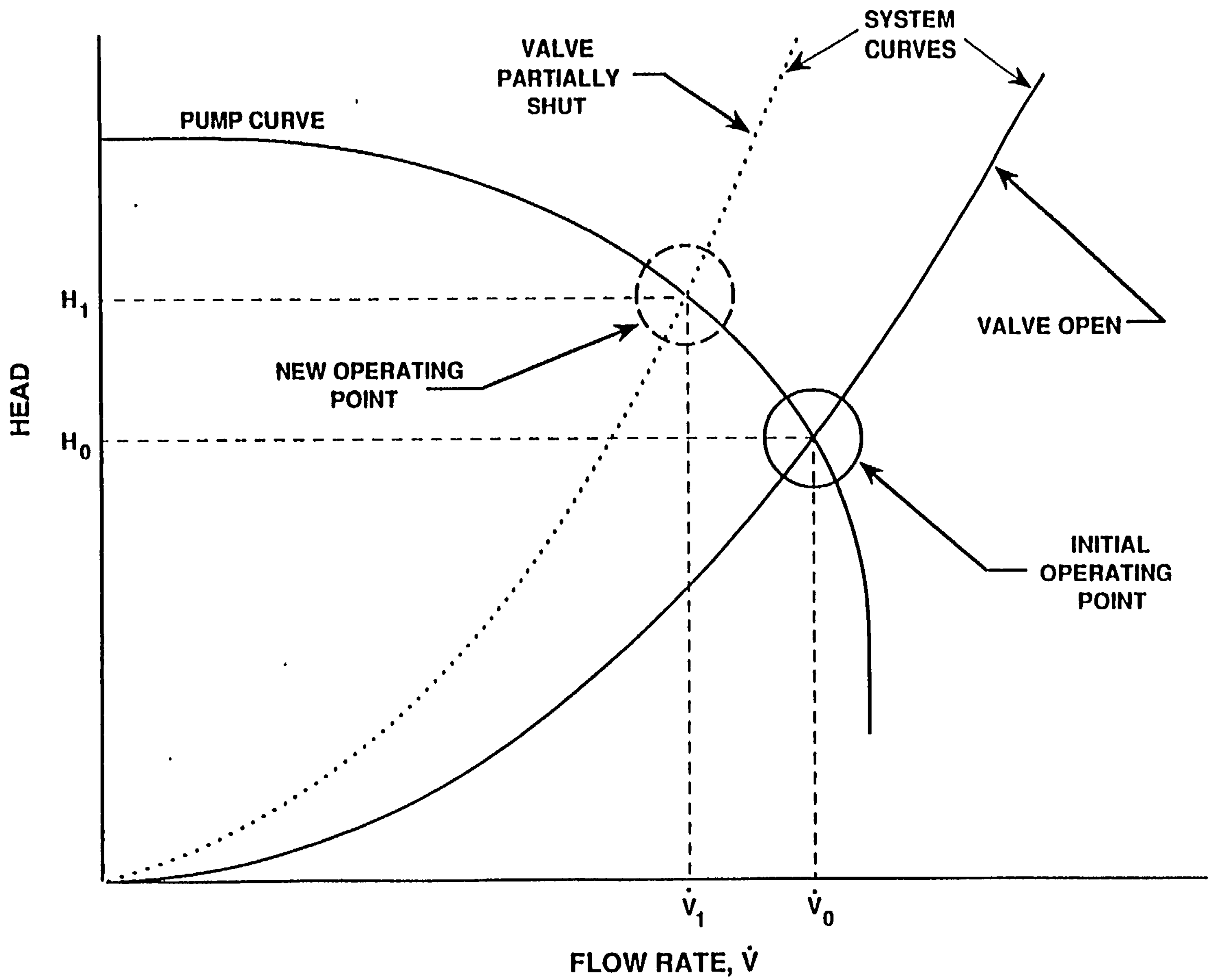


Figure 12-24. Operating Point for a Centrifugal Pump

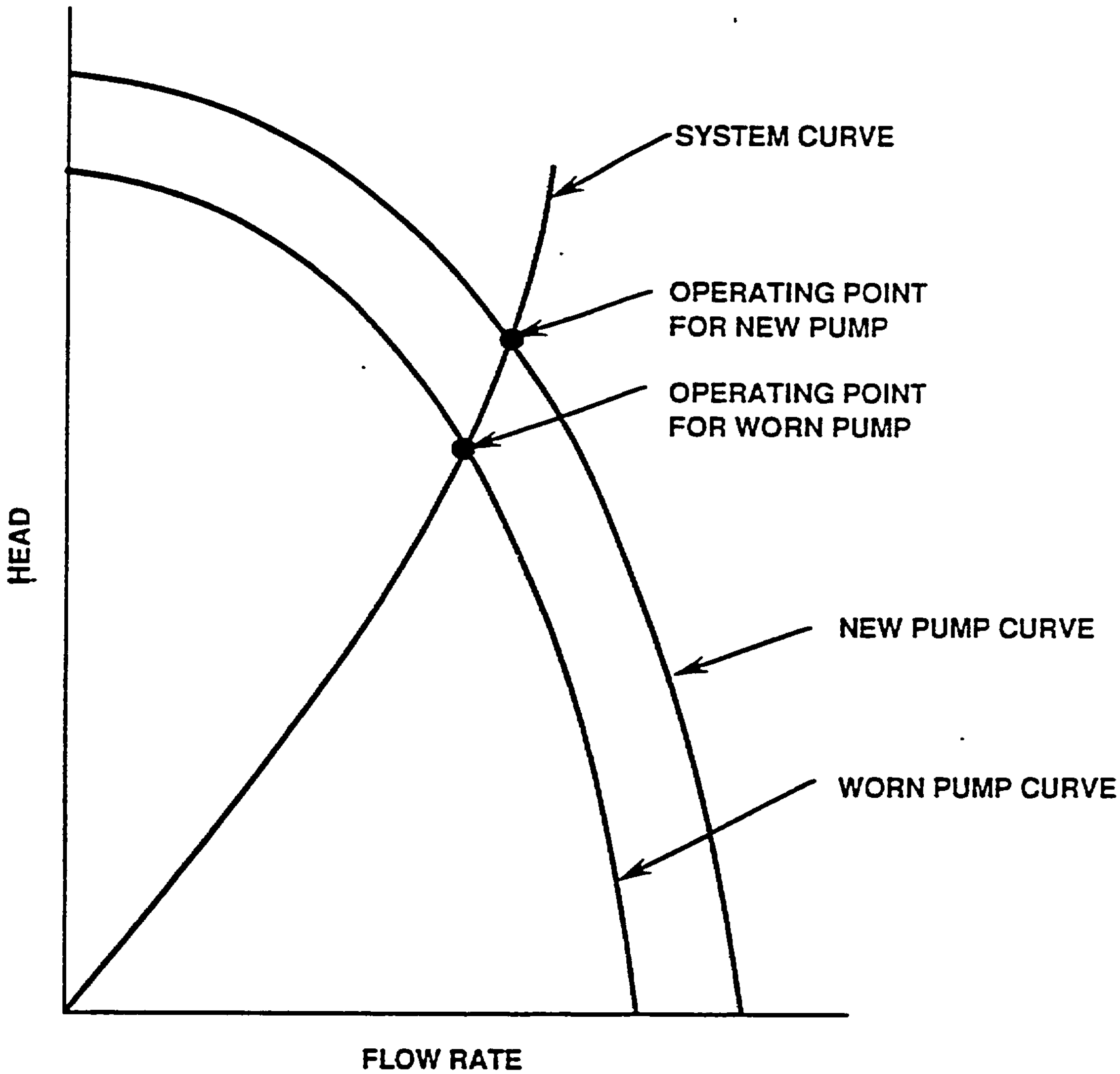


Figure 12-25. Change in Operating Point Due to Pump Wear

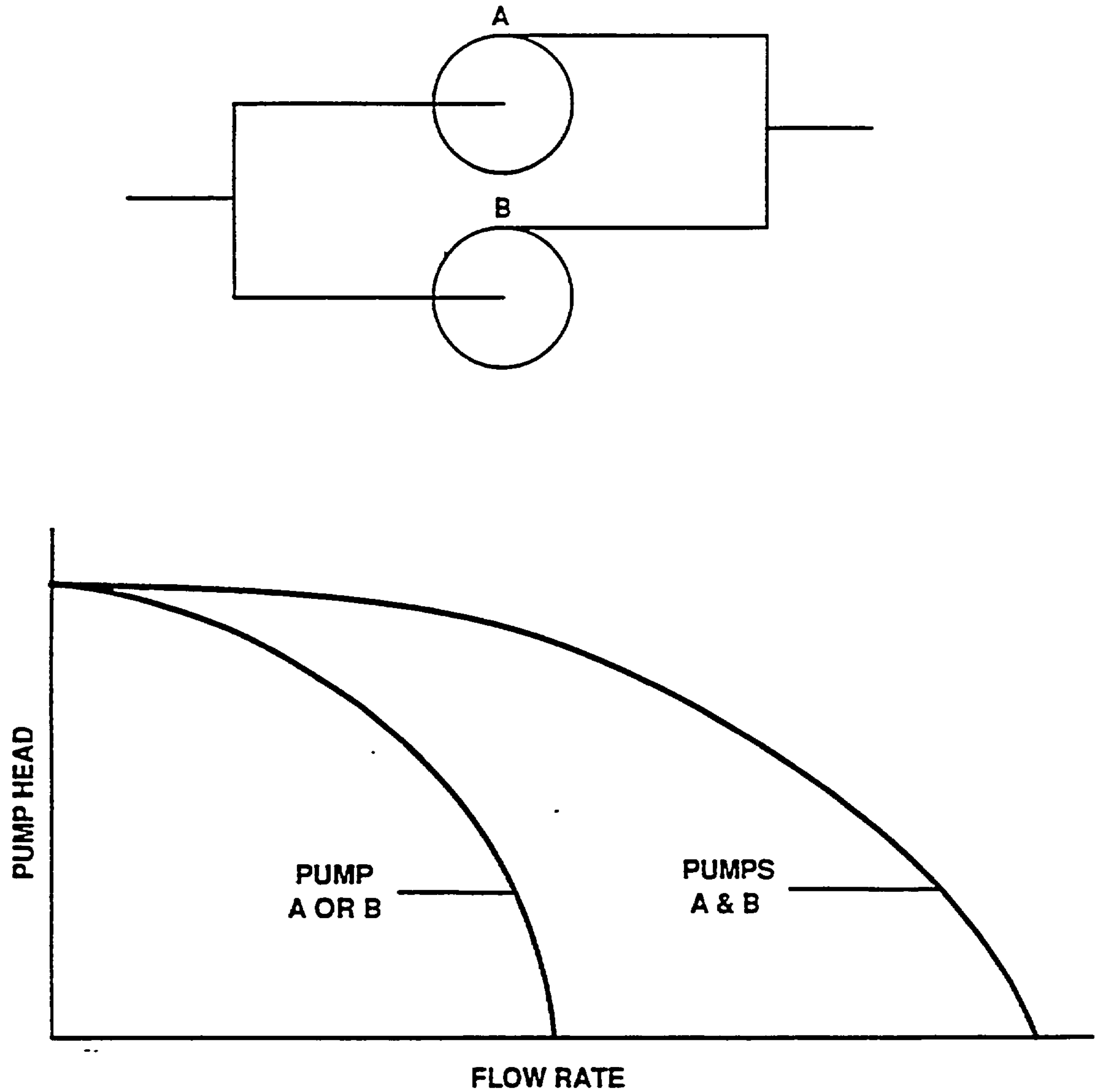


Figure 12-26. Pump Characteristic Curve for Two Identical Centrifugal Pumps Used in Parallel

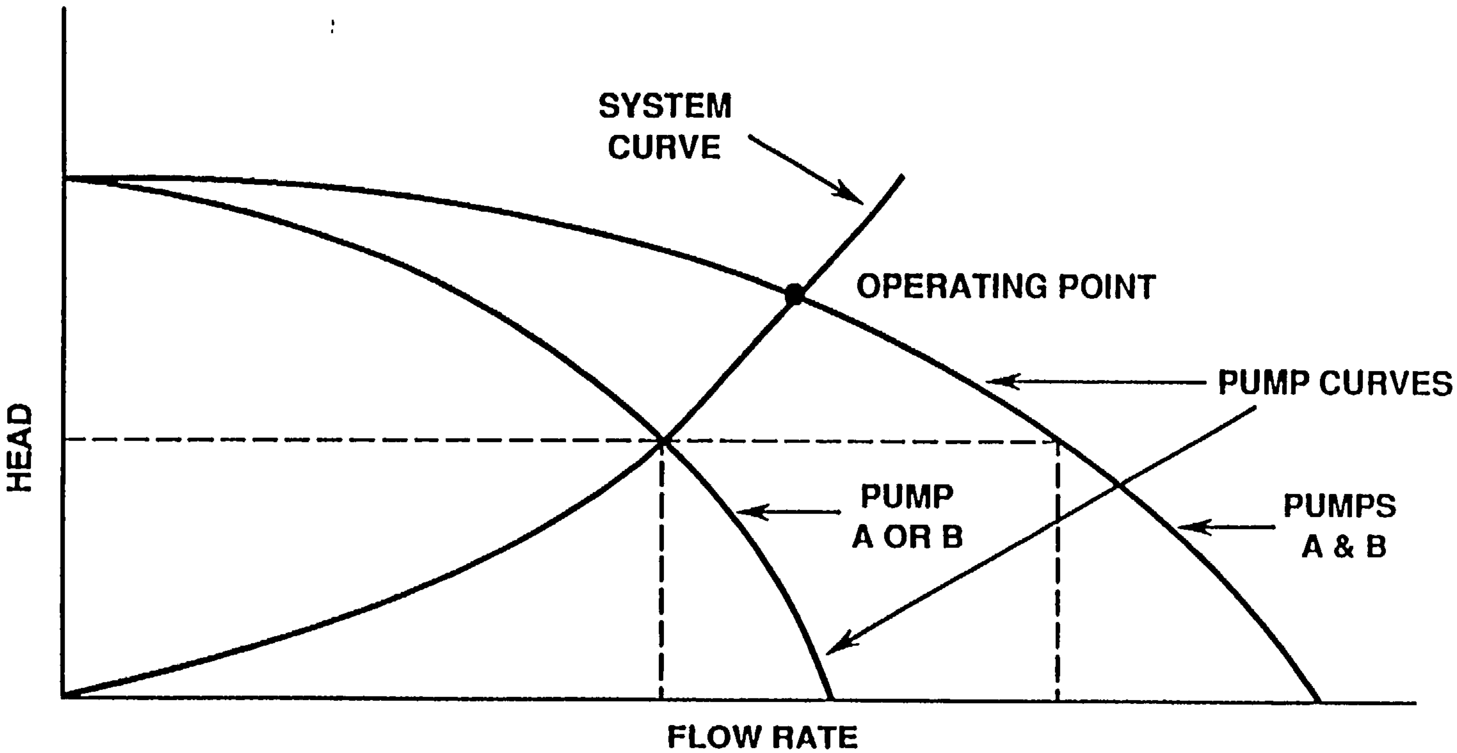


Figure 12-27. Operating Point for Two Centrifugal Pumps in Parallel

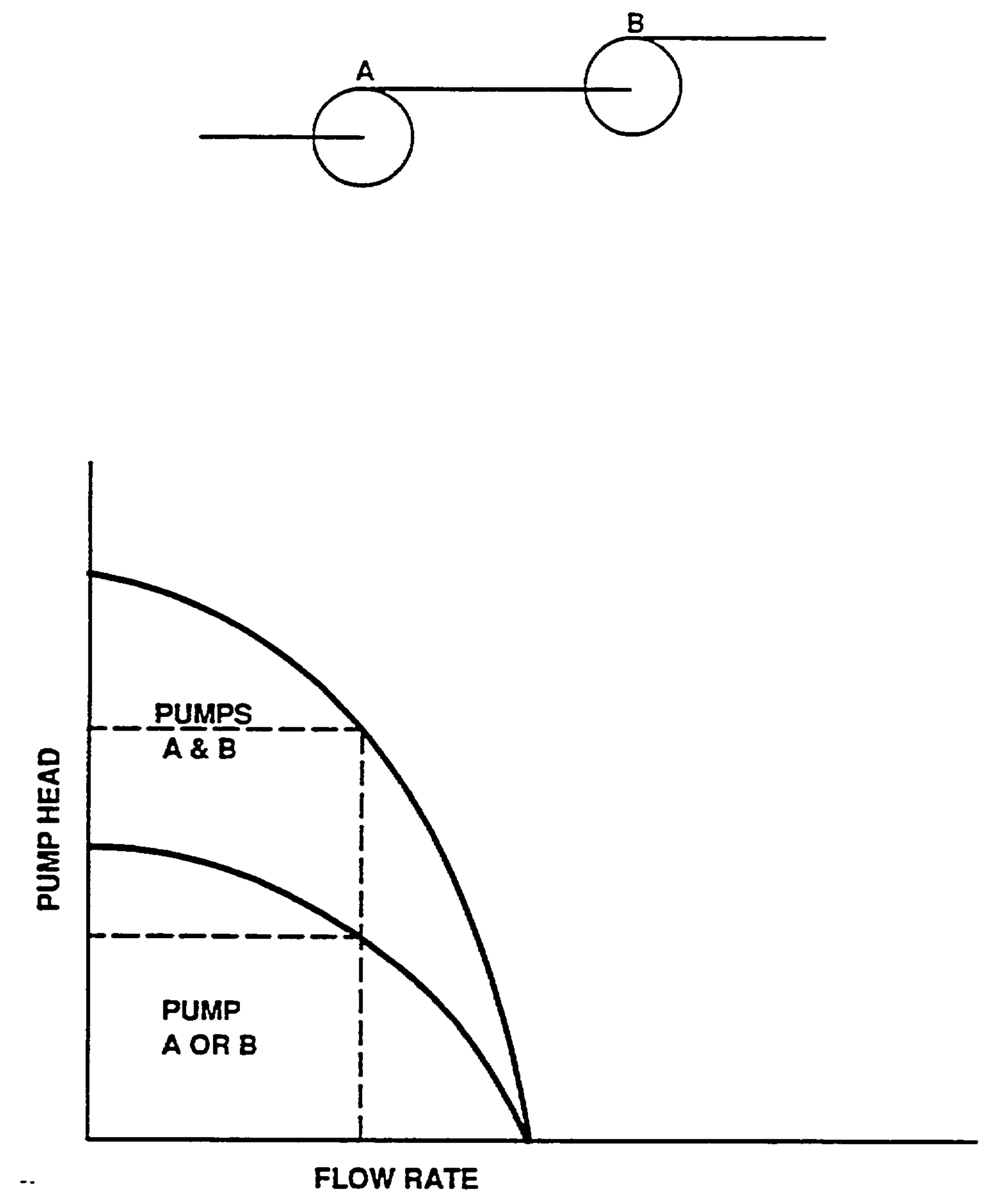


Figure 12-28. Pump Characteristic Curve for Two Identical Centrifugal Pumps Used in Series

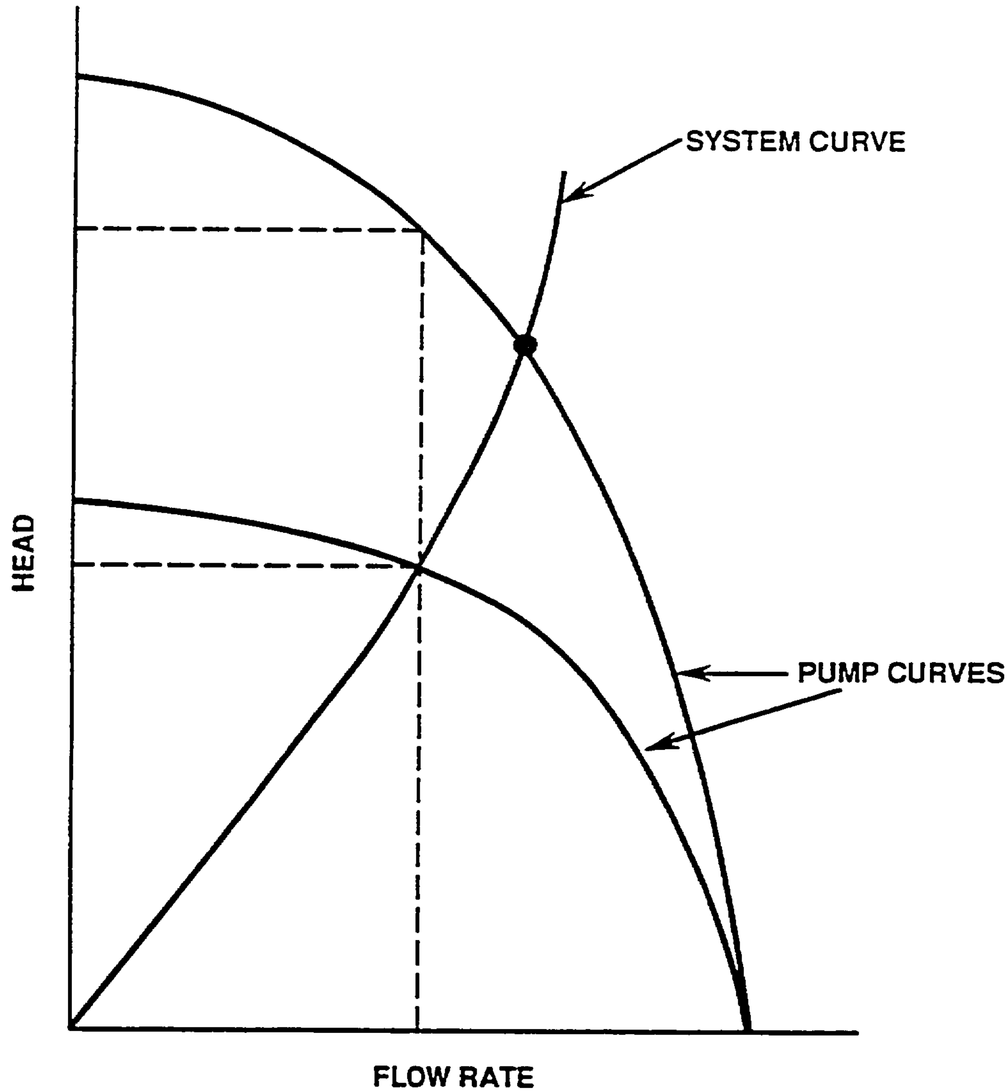


Figure 12-29. Operating Point for Two Centrifugal Pumps in Series

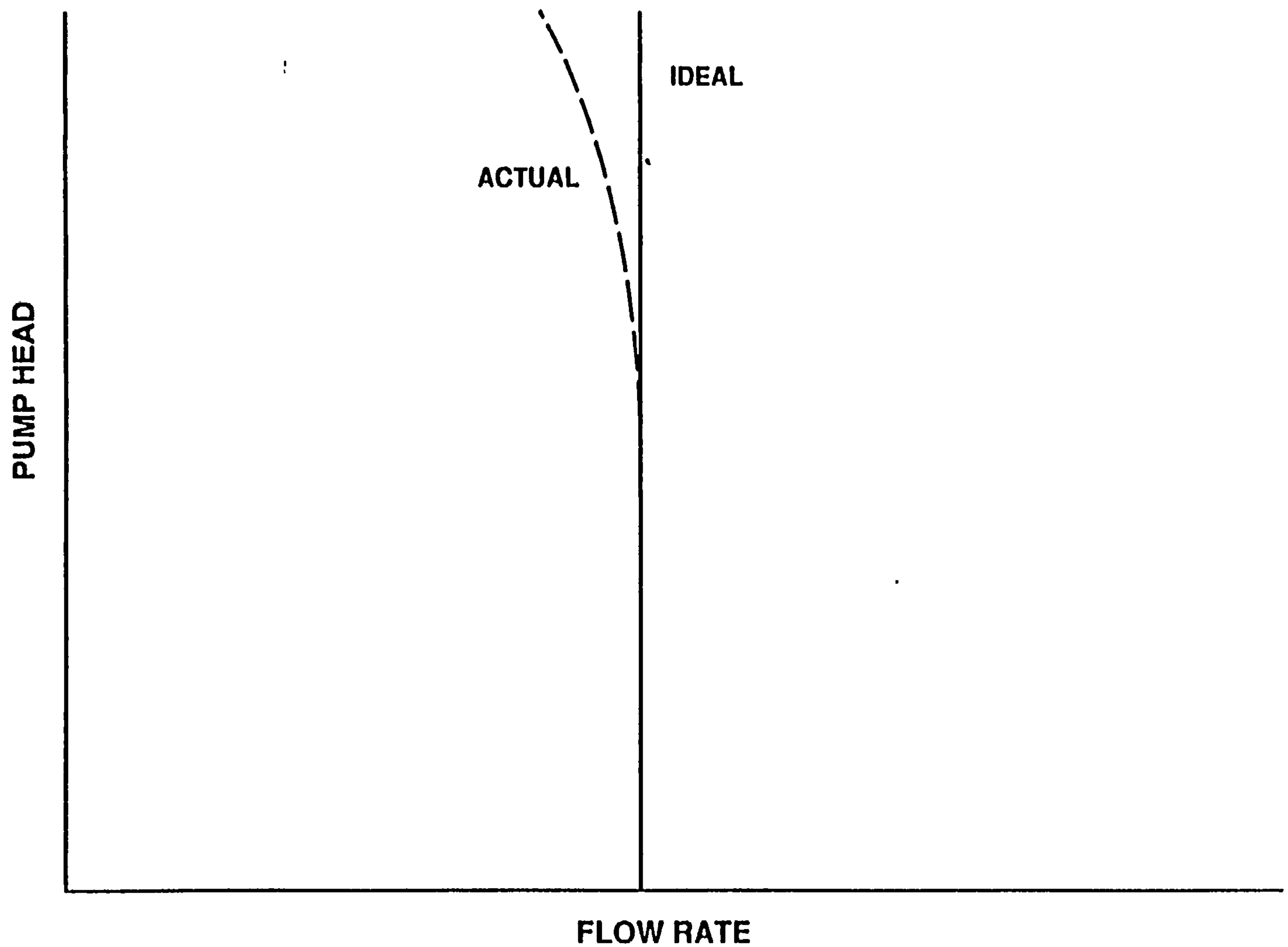


Figure 12-30. Positive Displacement Pump Characteristic Curve

13.0 DIESEL GENERATORS

Learning Objectives

After studying this chapter, you should be able to:

1. Describe the purpose and basic operation of an emergency diesel generator.

2. Describe the purpose and basic characteristics of the following emergency diesel generator auxiliary systems:
   a. Starting system
   b. Fuel transfer system
   c. Fuel injection system
   d. Cooling water systems
   e. Lubricating oil systems

3. Explain the terms scavenging, supercharging, and turbocharging.

4. Explain measures taken to allow an emergency diesel generator to be started and loaded within 10 seconds without damage.

13.1 Introduction

All nuclear power plants must have a reliable emergency electric power source capable of coming on line within seconds of a loss of normal (turbine generator) *and* backup (offsite distribution) electric power supplies. The emergency power source must have a capacity equal to the safety-related equipment loading that would be imposed if a major accident occurred simultaneously with the loss of the normal and backup power supplies. This rapidly available, high capacity function is normally provided by emergency diesel generator sets.

13.2 General

The diesel engine generator set is the choice for most emergency power sources for nuclear plants because of its ability to accept rapid loading and its superior efficiency and reliability.

The diesel engine offers a number of advantages including:

- high reliability in operation,
- low fuel cost,
- high power per pound of engine,
- low fuel consumption per hp hour,
- low fire hazard, and
- high sustained torque.

The diesel engine is highly reliable. When supplied with clean fuel, a diesel engine can be depended on to operate continuously for long periods of time.

Diesel fuel has a heat value of 139,500 BTUs per gallon, compared to 124,500 BTUs for gasoline. The maximum air to fuel ratio for the diesel is 40 to 1; for gasoline engines, it is 18 to 1. The diesel burns more air than spark ignition engines and is remarkably free from exhaust emissions of hydrocarbons and carbon monoxide.

The odor of the diesel exhaust is unpleasant, but both carbon monoxide and hydrocarbons are less in the case of the diesel than in a gasoline engine. These characteristics are of particular interest because of the attention now being focused on exhaust, crankcase, and fuel tank emissions and their contribution to air pollution.

13.2.1 Four-Stroke Diesel Engine

On a four-stroke diesel, all events occur during four strokes of the piston or two revolutions of the crankshaft (see Figure 13-1).

Starting with the piston at the top of its stroke and the air intake valve open, the piston moves down drawing air into the cylinder (1). Shortly after the piston reaches the bottom of its stroke the air intake valve shuts. As the piston moves upward, the cylinder is sealed and the air is compressed (2). The temperature of the air increases as it is compressed and fuel is injected shortly before the piston reaches the top of its stroke (3). The fuel is immediately ignited by the hot air and combustion commences. Due to the heat of combustion, the gases expand and force the piston down on the power stroke (4). Just before the bottom of the stroke, the exhaust valve opens and remains open throughout the exhaust stroke (5). The air intake valves open near the end of the exhaust stroke to allow incoming air to purge the cylinder of exhaust gases and aid in cooling.

13.2.2 Two-Stroke Diesel Engine

Most nuclear plant emergency diesels use a two-stroke cycle. A two-stroke cycle consists of a down stroke and an up stroke. Each down stroke includes a power event, and each up stroke contains a compression event.

In the two-stroke diesel (see Figure 13-2), both valves at the top of the cylinder are exhaust valves. Air intake ports (holes) in the lower cylinder wall are opened or closed depending on the position of the piston in the cylinder. When the piston is near the bottom between strokes, the intake ports are open and air is forced into the cylinder by a blower (air pump). The fresh air entering the cylinder pushes (scavenges) the residual exhaust gases from the cylinder through the open exhaust valves (see Figure 13-2A).

As the piston rises, the exhaust valves close and the blower continues to force additional air through the intake ports causing the air pressure in the cylinder to increase above atmospheric pressure (supercharging). As the piston continues to rise, the intake ports are closed and the continued upward movement of the piston compresses the air in the cylinder (see Figure 13-2B).

When the piston nears the top of the up stroke, the injector sprays fuel into the cylinder. The fuel and air mixture are ignited by the heat generated from the compression of the air. The combustion process produces a rapid increase in the temperature and pressure of the gas in the cylinder, which pushes the piston down. The expanding gas works on the piston, producing power (see Figure 13-2C).

13.3 Diesel Systems

The systems described below are for diesel generator sets in common use as standby or emergency power sources at commercial nuclear plants. These systems are outlined in general terms, and both major and minor differences are to be expected when the descriptions are applied to specific cases. Each system is defined briefly below, and the subsequent subsections give more detailed information on each. The systems include the following:

Starting System: The starting system provides motive power to turn the engine through several cycles. This is necessary because some minimum speed is needed to attain the cylinder pressures required for self-firing. Most emergency units use compressed air stored in accumulators for this purpose.

Fuel System: This system provides storage space for supplies of fuel oil, and pumps to transfer the oil from delivery point to storage and from storage to the engine. Strainers and filters ensure clean fuel at the fuel injection point.

Cooling Systems: The heat produced by the combustion process and friction in the diesel engine is removed by various cooling systems. A closed cycle, cylinder jacket cooling water system provides cooling water flow to remove excess combustion heat from the spaces around the cyclinders. Another closed cycle cooling system provides water flow to cool the lube oil which circulates through the engine, absorbing heat generated by friction between moving parts. A reliable plant cooling system, often called Nuclear Service Water or simply Service Water, provides cooling flow to the heat exchangers used in the diesel closed cycle cooling systems.

Scavenging, Supercharging, and Turbocharging Systems: Waste gases from the combustion process are swept out of the cylinder, or scavenged, by air slightly above atmospheric pressure supplied by blowers attached to the engine. Supercharging is the delivery of intake air above atmospheric pressure to improve the combustion process. In some smaller units the supercharge is provided by a blower driven by an auxiliary shaft geared to the engine crankshaft. Larger units use turbochargers to provide the supercharge. Turbocharging is a supercharging method that uses hot exhaust gases to drive a turbine that in turn drives an attached supercharging blower.

Governing Systems: These systems control engine fuel supply rates to maintain speed, startup acceleration rates, idling speed, and overcome load change effects.

13.3.1 Starting System

Starting of any diesel engine depends upon the development of sufficiently high air temperature on the compression stroke to ignite the fuel.

A highly reliable rapid start system is imperative for a standby emergency diesel engine. Compressed air stored in accumulators is the most reliable motive power available. Figure 13-3 is a typical starting air system. The stored capacity must be sufficient to provide several successive starts without recharging.

The most common air start system on nuclear plant emergency diesel generators is the direct cylinder injection type. Some older, smaller diesel engines may use air driven motors or DC powered electric motors as starters. The following paragraphs describe the important elements of diesel starting systems:

Direct Cylinder Injection (see Figure 13-4): In this starting method, air distribution valves send blasts of compressed air to the engine cylinders in the proper firing order. The compressed air pushes the pistons down in the proper order, achieving the same rotation as the combustion power strokes. Variations on this method include single multiport distribution valves and individual cylinder supply valves whose opening and closing is controlled by gearing to the engine crankshaft. The end result of either method is that the crankshaft is rapidly rotated and adequate compression is developed in the cylinders to ignite the fuel when it is delivered.

Battery-powered DC solenoid valves control the air supply to the air distribution valves. Redundancy is ensured by using separate air flasks and backup batteries for solenoid operation. In a typical air-start system, only half the available air-start system is required to provide startup of the diesel.

Air-driven Motors: These motors are similar to those used to drive such equipment as large pneumatic drills and engine jacking motors. When compressed air is admitted to the air motors, rotary motion of the motor shaft causes a spring-loaded pinion gear to engage a driven or "bull" gear on the diesel crankshaft. Once the engine speed is above a certain point (200 to 250 rpm), the air motor pinion gear is disengaged, the starting motor air supply is shut off, and fuel flow to the engine is started. As many as eight starting motors may be used to accelerate a large diesel engine.

DC Electric Motors: Electric starting motors operate in much the same way as air-driven motors. When the starting sequence is initiated, a solenoid operates the engagement mechanism which pushes the drive pinion into mesh with the ring gear on the engine flywheel. This action closes the starting contactors and permits the motor to crank the engine. DC motors are used because emergency diesels must provide power when all AC power is lost and a battery is the only source of starting power.

13.3.2 Fuel Systems

Diesel fuel oil systems (see Figure 13-5) include main supply tanks with at least a 7-day, full-load capacity (This is generally consistent with technical specification requirements); "day tanks" with a filtered and purified "ready" supply; pumps, filters, and purifiers for transferring the oil; and engine-driven high pressure fuel pumps to deliver the fuel to the fuel injectors. The final stage of fuel oil delivery is the fuel injection system.

The diesel fuel injection system meters the quantity of fuel required for each cycle of the engine and develops the high pressure required to inject fuel into the cylinder at the correct instant of the operating cycle. It controls the rate at which the fuel is injected and atomizes and distributes the fuel throughout the combustion chamber. Fuel injection must start and end abruptly. The following paragraphs describe the important elements of efficient fuel injection:

Pressure: The above shows that the diesel fuel injection system is not a simple device. To build up the pressure required to inject the fuel into the engine with its compression ratio of approximately 15 to 1, a high degree of precision is required. Some systems develop up to 5000 psi at the rated load and speed.

Metering: The metering of the fuel must be accurate. The quantity must be varied with the load on the engine, and the same amount of fuel must be delivered to each cylinder for each power stroke. If the quantity of fuel varies in the different cylinders, the power per cylinder will vary and rough operation will result, with excessive vibration.

Timing: The fuel must be injected at the correct instant. Early or late injection results in loss of power. If the fuel is injected too early in the cycle, compression will not be at the maximum, the air temperature will be low, and ignition will be delayed. If the injection is late, the piston may be past top dead center and power will be less because maximum expansion of the burned fuel will not take place. The injection must start instantly, continue for the prescribed time, and then stop abruptly for maximum efficiency.

Injection Rate: Fuel is not injected in one single spurt, but extends over a period of time. If the fuel is injected too fast, it has the same effect as too early injection. Similarly, if the injection is too slow, and it extends over too long a period of time, the effect is similar to late injection. The rate of injection varies with different engines, and is affected largely by the type and contour of combustion chambers, together with engine speed and fuel characteristics.

Atomization: Fuel is spurted into the combustion chamber as a spray. The degree of atomization is dependent on the type of combustion chamber. Proper atomization increases the surface area of the fuel that is exposed to the oxygen of the air and results in improved combustion and maximum development of power. To avoid simultaneous combustion of all droplets of the spray, the spray is usually formed of some fine droplets to start ignition and larger droplets for prolonged combustion. The extent of atomization is controlled by the diameter and form of the nozzle orifice, the injection pressure, and the density of the air into which the fuel is injected.

13.3.2.1 Injection System

A mechanical injection system forces fuel through spray nozzles into the combustion cylinders using fuel pressures ranging up to 5000 psi. The purpose of the injection system is to develop the extremely high fuel pressures required for injection.

Four general systems of mechanical fuel injection have been developed as diesel fuel injection systems have evolved. They are the unit or cylinder injector system, the common rail system, the pump controlled (or jerk pump) system, and the distributor system. Because the unit injector system is the most common method used on nuclear plant emergency diesel engines, it is the only one that is discussed in detail. The other systems are described briefly for information purposes only.

Common Rail System: The common rail system consists of a single high pressure pump that develops pressures in the range of 1,500 to 7,000 psig and distributes fuel to a common rail or header to which each cylinder injector is connected by tubing. The major disadvantage of this system is the presence of high pressure fuel lines outside the engine.

Pump Controlled System: This system is also known as the jerk pump system and provides a single positive displacement injection pump to supply the cylinder injectors. The pump is separately mounted and is driven by an auxiliary shaft geared to the engine crankshaft. The high pressure fuel is delivered to the individual cylinder injectors by suitable high pressure tubing.

Distributor System: Several injection systems use distributor devices similar to the air distributor valves used in air start systems. One system provides a high pressure metering pump with a distributor that delivers high pressure fuel to the individual cylinders. Another design provides low pressure metering and distribution. The high pressure needed for injection is provided by the individual cylinder injection nozzle assemblies which are operated by an auxiliary shaft geared to the engine crankshaft.

Unit Injector System: This system combines a positive displacement pump and an injector into a single unit on each cylinder. A major advantage of the unit injector system is the elimination of high pressure fuel lines. Operations of the cylinder injector pump is normally accomplished using push rods and rocker arms driven by a cam shaft that is geared to the engine crankshaft.

The push rods and rocker arm assemblies transform the rotary motion of the cam shaft into rectilinear motion of the injector plunger. As the plunger moves up (away from the injector nozzle), it uncovers the fuel inlet port, admitting fuel oil into the space under the plunger. When the pump plunger moves down, on its delivery stroke, the fuel is compressed to a pressure sufficient to overcome the force of the spring loaded valve in the injector nozzle. As the valve is forced open, the fuel is sprayed into the cylinder.

The ability of the unit injector pump to meter the supplied fuel oil to the correct amount is accomplished through the design of the plunger and the engine fuel controls. The entire plunger can rotate in the injection pump body. As the plunger rotates farther, the compression stroke continues longer before the fuel flow into the cylinder stops. A longer effective compression stroke means a greater amount of fuel is sprayed into the cylinder. The rotation of the plunger in the injection pump body is controlled by the engine governor control assembly which will be discussed later in this chapter.

13.3.3 Diesel Engine Lube Oil System

The diesel engine lube oil system provides a continuous flow of oil to all surfaces requiring lubrication and to the pistons for cooling. Two lube oil pumps operate in parallel to provide continuous lubrication. The electrically driven auxiliary lube oil pump operates at all times to deliver lube oil flow through an electric heater, lube oil filter, and main lube oil strainers. The shaft driven oil pump provides lube oil flow through a thermostatically controlled valve and heat exchanger, and through the main lube oil strainers. This pump provides the main source of lubrication during engine operation. A typical generator lube oil system is shown in Figure 13-6.

The lube oil heaters automatically energize when oil temperature falls below 125°F and engine speed is less than 125 rpm. While the engine is operating, the lube oil cooler and the thermostatically controlled bypass valve control oil temperature between 144°F and 160°F. Lube oil out of the cooler flows through strainers and into the engine through internal lube oil passages.

13.3.3.1 Rocker Lube Oil System

To protect the crankcase oil from contamination by cooling water or fuel leaks, the cylinder valves and associated rocker arm units are lubricated by a separate system on large diesel engines. This system consists of an engine driven oil pump that takes a suction on the engine mounted rocker oil reservoir and pumps oil to lubricate the valve train. Refer again to Figure 13-6. The lube oil then drains from the cylinder heads back to the rocker oil reservoir. The system also includes a motor driven prelube pump to ensure a supply of oil while the engine is starting up or shutting down.

13.3.4 Cooling Systems

Most of the heat generated in a diesel engine is normally removed by a cooling water system. An example of a diesel engine cooling water system is shown in Figure 13-7. Heat generated due to friction is absorbed in the lube oil circulating through the engine. The heat is then given up to a cooling water system in the lube oil coolers. (The plant shown in Figure 13-7 calls the cooling water system Nuclear Service Water (NSW), but it can also be called Essential Service Water or simply Service Water.) Heat generated by combustion in the cylinders and miscellaneous engine components are carried away by the jacket water cooling system. This system is cooled by nuclear service water in the jacket water heat exchanger. Most emergency diesel engines have a turbocharger (see 13.3.5.3) with an associated intercooler that is cooled by an intercooler water system with an intercooler heat exchanger. The intercooler heat exchanger, jacket water heat exchanger, and lube oil cooler are all cooled by nuclear service water.

The water jackets surrounding the diesel cylinders are designed to remove the heat of combustion from the cylinder walls. During engine operation the water jackets are supplied with jacket water cooling flow by a shaft driven jacket water pump. The jacket water system temperature is maintained by a thermostatically controlled valve that bypasses some return flow around the heat exchanger. This system maintains water temperature out of the heat exchanger between 165°F and 185°F. When the diesel is shutdown, an electric auxiliary jacket water pump will automatically start to maintain flow through the cylinder water jackets. When the water jacket temperature falls, the jacket water heaters will energize to keep the engine warm (145°F to 150°F).

Similiar system arrangements are provided in the lube oil cooling system and the intercooler system. When the engine is running, automatic thermostat valves adjust the heat exchanger flow rates to maintain the proper lube oil or intercooler water temperature. When the engine is shut down, auxiliary pumps and heaters are used to maintain warm lube oil and intercooler water temperatures that keep the associated engine components warm.

13.3.5 Scavenging Air, Supercharging, and Turbocharging Systems

The diesel air intake system supplies clean air for combustion and forces exhaust gases (remaining from previous power stroke) from the combustion chambers. The removal of the exhaust gases is called <u>scavenging</u>. If exhaust gases are not removed, they will dilute incoming air and reduce combustion efficiency. In addition (particularly in two-stroke engines), incoming air provides cooling for the pistons and combustion chambers (excessive temperatures also reduce combustion efficiency).

Scavenging must be accomplished in a relatively short portion of the operating cycle. In the two-stroke engine the process takes place at the end of the downstroke (expansion) and the early part of the upstroke (see Figure 13-8).

Note that in the two-stroke cycle, air intake continues after the exhaust has closed. The scavenging occurs through approximately a quarter of the cycle. The exact opening and closing of the ports will vary with different engines.

In the case of the four-stroke cycle, the scavenging occurs through almost half of a crankshaft rotation, or approximately twice as long as in the two-stroke cycle. As a result, combustion chamber temperatures are reduced and a larger portion of the gases is swept from the cylinder.

Air may be supplied for scavenging as a result of the difference in air pressure between the low pressure created in the combustion chamber as the piston moves down in the cylinder, and the normal atmospheric pressure existing at the air intake. This is known as a naturally aspirated system. It is used extensively in motor vehicle engines of the four-stroke type and in some large industrial engines of the two-stroke type.

Because of the resistance to the flow of air through the manifold and valves, the air obtained by the naturally aspirated method is often not sufficient to provide complete removal of the exhaust gases. To overcome this problem, crankcase scavenging, superchargers, and turbochargers have been developed.

These devices compress the air and force it into the cylinder. More air is forced into the cylinder and burned gases that may have remained in the cylinder from the previous power stroke are forced out so only clean air remains. Such power scavenging is particularly necessary in the case of two-stroke engines.

13.3.5.1 Crankcase Scavenging

Crankcase scavenging systems use the diesel piston movement as an air pumping device. The underside of the piston is open to the sealed crankcase section. Atmosphere-to-crankcase check valves open to allow air flow into the crankcase as the piston is moving up. The low pressure created by the piston movement brings air into the crankcase. When the piston starts down, crankcase pressure begins to increase. This causes the crankcase check valves to seat and opens aspirator check valves to connect the crankcase area to the upper cylinder area. This method of scavenging is inefficient and generally not found in large diesel applications.

13.3.5.2 Blower Scavenging

The Roots-type blower (see Figure 13-9) is used extensively for scavenging two-cycle engines. When the piston is at the bottom of its stroke just starting upward, both intake and exhaust ports are open. The blower pushes air through the intake valves forcing exhaust gases (left from the previous cycle) out through the exhaust valves. When the pistons are about one quarter of the way up, the valves close and the intake ports are covered by the piston. Exhaust gases will have been expelled and the cylinder is full of fresh air. The rest of the stroke is an ordinary compression stroke at the end of which fuel is injected and combustion takes place.

Figure 13-9 shows that air passes from the blower into an air manifold or chamber, and enters the cylinder through ports that are evenly distributed around the cylinder. This provides better distribution of air throughout the cylinder and improved scavenging results.

The Roots-type blower is essentially a gear pump with rotors of either two, three, or four lobes each, enclosed in a suitable housing. This blower is also called a positive displacement rotary blower. The rotors are designed so that they do not come into contact with each other or with the housing. Clearances are made as small as manufacturing methods permit and are approximately 0.005 inch.

One of the two rotors is directly driven through gears from the crankshaft, and the shafts of the two rotors are connected together through gearing. A major advantage is that air delivery is almost directly proportional to engine speed.

13.3.5.3 Supercharging and Turbocharging

Power that can be developed by an internal combustion engine is dependent to a considerable extent on the type of fuel used and how efficiently the fuel is burned. That efficiency, in turn, is dependent on an adequate supply of air to ensure complete combustion of the fuel.

By increasing the initial amount of clean air in the combustion chambers, the fuel can be burned more efficiently and, as a result, the power is increased. Since the size of the combustion chambers is fixed, the amount of air is increased by using blowers to increase the initial air pressure. Also, the exhaust valves are closed before the air intakes are closed. This process is known as supercharging, and the blower equipment is called a supercharger or a turbocharger (see Figure 13-10). In general when the blower is driven mechanically by gearing from the engine, like the Roots-Type blower, the device is called a supercharger. When the device is driven by the exhaust gases from the engine, it is called a turbocharger.

The purpose of supercharging is not only to scavenge the burned gases, but also to force in air at a pressure above atmospheric pressure. The higher pressure means that the initial cylinder air is at a greater density than atmospheric. The combination of using a blower and shutting the exhaust ports before the air intakes are closed creates a higher initial air density in the cylinder.

The major advantages of supercharging are: (1) increased horsepower from an engine of given weight, and (2) increased fuel economy.

The output of an engine can be increased about 50% by supercharging without materially increasing bearing loads or heat stresses on parts such as pistons, rings, and valves. With the use of intercoolers (to reduce the temperature of the supercharged air, and increase its density), the increase in developed power is even greater.

A centrifugal blower, or compressor, is used as the air pump in supercharged systems. The blower is operated at speeds ranging up to 5000 rpm for large diesels that operate in the 900-rpm range. Although the blower may be driven by an auxiliary shaft from the crankshaft, in most nuclear plant emergency diesels it is driven by the hot exhaust gases expanding through a turbine (turbocharging). Turbocharging is more efficient than supercharging because the output of the engine is not used to drive an auxiliary shaft to the compressor; instead, some exhaust energy that otherwise would be wasted is used to turn a turbine that drives the compressor.

In turbocharger systems, cooling water supplied to the intercooler reduces the air temperature after it has been compressed by the blower. Cooling water is also normally supplied to cool the turbine itself because exhaust gas temperatures can exceed 1300°F.

13.3.6 Governor Systems

A governor is a device designed to control the speed of an engine. It does this by varying the flow of fuel in accordance with the requirements of the load, speed, electrical frequency, and other conditions.

Governors are often included in the design of the fuel injection system, and may be classified as mechanical, hydraulic, or electric.

It is desirable that diesel engine governors have certain characteristics. For example, when a nuclear plant emergency diesel generator is the sole power source for its safety-related vital bus, engine speed should be maintained at a constant value regardless of the load. This characteristic is known as isochronous operation.

When a diesel generator is operated in parallel with other generators, it is desirable to have a negative ramp speed variation from no load to full load. This characteristic is known as speed droop.

Speed droop is expressed as a percent of rated speed:

$$\text{Speed Droop} = \frac{S_{NL} - S_{FL}}{S_{NL}} \times 100 ,$$

where

S_{NL} = No-load speed, and
S_{FL} = Rated full-load speed.

For example, if the no-load speed is 947 rpm and the full load speed is 900 rpm, the speed droop is

$$\frac{947-900}{947} \times 100 = 5\% .$$

13.3.6.1 Engine Controls

To control an engine means to keep it running at a desired speed, either in accordance with or regardless of the changes in the load carried by the engine. The degree of control required depends on two factors: the engine's performance characteristics and the type of load it drives.

In diesel engines, a varying amount of fuel is mixed with a constant amount of compressed air inside the cylinder. A full charge of air enters the cylinder during each intake event. The amount of fuel injected into the cylinder controls combustion and thus determines speed and power output of the diesel engine. A governor regulates the flow of fuel.

13.3.6.2 Mechanical Governors

With a mechanical governor (see Figure 13-11), an increase in engine load and the consequent drop in engine speed reduces rotational speed of the flyweights. The speeder spring then overcomes the reduced centrifugal force on the speeder rod, moves the rod down, and in turn opens the engine fuel valve farther. Conversely, when load is reduced and engine speed increases, centrifugal force on the flyweights causes the speeder rod to rise and close the fuel valve.

The mechanical governor has built-in, permanent speed droop; steady speed on an engine fitted with this type of governor falls when load is applied and rises when load is reduced. Therefore, true isochronous operation cannot be achieved. Also, precise speed control demands a prompt, sensitive governor. These attributes are not easy to provide in a mechanical device.

13.3.6.3 Hydraulic Governors

Hydraulic governors (see Figure 13-12) fulfill the requirements of sensitivity, speed of operation, and, most importantly, isochronous control; they superseded mechanical governors in the evolution of engine controls. Instead of using the centrifugal force of the flyweights to act directly on the fuel control mechanism, the speeder rod is linked to a small pilot valve controlling hydraulic oil flow to and from the fuel control servomotor.

Stability and speed droop control can be built into a hydraulic governor by a feedback mechanism such as the one in Figure 13-13. In this design, a link has been added connecting the servopiston to the pilot valve and speeder rod. Now, as the servopiston is moved to increase fuel flow and increase speed, the linkage acts on the pilot valve and speeder rod to reduce the speed settings.

To prevent continuous hunting because of overcorrecting the fuel setting, a hydraulic governor must have a mechanism that will discontinue changing the fuel control setting slightly before the new setting has actually been reached. This mechanism is called a compensating device.

One type of compensating device is illustrated in Figure 13-14. The pilot valve plunger operates in a movable pilot valve bushing in which are located the parts that control the oil flow. The receiving compensating plunger controls the movement of the valve bushing during a speed change. The compensating action of the valve bushing is controlled hydraulically by transfer and leakage of oil between the compensating receiving plunger and the compensating actuating piston. The rate of compensation is adjusted by regulating the oil leakage through the compensating needle valve.

Hydraulic governors are more sensitive than mechanical governors. The mechanical governor is more commonly used on small engines which do not require extremely close regulation of fuel. Hydraulic governors are more suitable for larger engines which require more accurate regulation of fuel.

13.3.6.4 Electric Governors

Control of a diesel engine speed to the close tolerances required to maintain a precise generator frequency is usually found only in an electric governor arrangement. The electronic circuits of the electric governor allow precise control in three control modes: load control, speed control, and starting (acceleration) control. An example of an electric governor is provided in Figure 13-15.

The magnetic pick-up and the speed sensor provide a DC voltage signal proportional to the speed of the engine. The load sensor provides a DC signal proportional to the kW output of the generator from the current and voltage monitored at the output of the generator. When the generator is producing output power, it may be operated in either of two modes: single unit control or parallel unit control, depending on whether the unit is alone on the electrical bus or is sharing the bus load with other generator units (parallel operation).

When the diesel generator is the only supplier of the electric bus, the action of the governor is to maintain constant speed, regardless of the load. The mode selector in this case will be set to *isochronous* (constant-speed) operation. This condition could occur at a nuclear plant when the normal offsite electric power system is unavailable and when the diesel generator set is required to carry all vital bus loads. When the diesel generator is operating in the isochronous (constant-speed) configuration, the load sensor and droop control circuit are bypassed. The machine will attempt to run at constant speed even if it is heavily and rapidly loaded.

When the diesel generator is paralleled with the distribution grid or other larger generators, the load sensor and droop control circuit are needed to allow adjustment of the load carried by the diesel generator. If the diesel is paralleled with the distribution grid, attempting to operate in the isochronous mode could either severely overload the generator or cause shutdown on reverse current, depending on whether the diesel speed reference is set above or below the distribution grid frequency. During parallel operations the diesel generator frequency is fixed by the infinite bus frequency. Therefore, in the isochonous mode, the speed reference signal could not be matched, and the governor system would go unbalanced trying to match the speed control signal.

The droop mode of operation utilizes a portion of the load sensor output to oppose the action of the speed reference signal. As the speed reference signal attempts to maintain speed during a load increase, the speed droop signal counteracts the speed reference signal, resulting in droop, or decreasing speed as load increases. With this arrangement, the droop signal will increase as the load increases, and the diesel generator can be adjusted to take a specific amount of load when operating in parallel with the grid.

Nuclear plant emergency diesels also have a ramp generator for rapid startup acceleration to bring the diesel up to speed from a standing start in less than 10 seconds. This time is critical during nuclear unit emergency conditions concurrent with a station blackout. Rapid restoration of power to emergency core cooling systems is necessary to prevent reactor overheating.

Some speed setting control circuits also have a minimum speed circuit for unit warmup or gradual cooldown before unit shutdown.

13.4 Emergency Starts

The industry-wide requirement for emergency diesel generator readiness is that each generator must be capable of being started, accelerated, and connected to its vital bus at full rated voltage and frequency within 10 seconds of receiving an emergency start signal. Although nuclear diesel generators have been designed to be capable of accomplishing this rapid start from a cold condition, such a fast startup from cold conditions places extraordinary stress on a diesel engine. Industry experience has shown that diesel engine breakdown problems can be significantly decreased if measures are taken to keep the diesel engine warm between emergency starts. Therefore, all nuclear plants have improved on the initial design of their diesel generator packages by adding systems or components designed to keep the engine internals warm and ready for an emergency start. These improved readiness measures normally include one or more of the following:

Jacket cooling water is heated by automatically controlled heaters and circulated through the cylinder water jackets to keep the cylinders and pistons warm. Cooling water to the jacket water coolers is isolated until the diesel generator is running.

Diesel lube oil is heated by automatically controlled heaters and continuously circulated past the engine moving parts to keep the engine bearings and rotating shafts warm. Cooling water to the lube oil coolers is isolated until the diesel is running.

For diesel generators with turbocharger intercoolers, the cooling water to the intercooler is kept warm so the pistons and cylinders are not hit with an initial blast of cold air before being rapidly heated by combustion.

13.5 Emergency Responses

At almost all nuclear plants, the following signals will automatically start the emergency diesel generators:

Loss of power or sustained undervoltage on the diesel generator vital bus; and

Safety injection (emergency core cooling) actuation signal.

On a loss-of-power (LOP) start, the diesels will approach rated speed and output voltage within about 10 seconds, and the diesel generator output breakers will automatically close onto the vital buses. The same LOP signal that starts the diesel will simultaneously disconnect the large emergency loads and all nonvital loads from the vital buses (load shedding). After the diesel output breaker has closed to restore power to the emergency bus, the load sequencer will automatically connect on the large emergency loads in a predetermined order (load sequencing).

On a safety injection (SI) start without a loss of power, the diesels will start and accelerate to rated speed, but the diesel generator output breakers will not close. (At some plants the diesels will accelerate only to an "idle" speed.) The diesels will then remain running in standby until they are stopped by an operator when it is clear that they will not be needed. If a loss of power occurs on the vital buses after an SI start, load shedding will simultaneously occur, the output breaker will immediately close, and load sequencing of large emergency loads will occur as described for the LOP start.

Recall that the basic purpose of the diesel engine is to provide the relative motion needed for emergency voltage generation. The other requirement for voltage generation is the existence of a magnetic field. The diesel generator magnetic field must be available to start voltage generation even if all offsite and onsite power is lost. Some small diesel generators may use permanent magnets to establish an initial magnetic field, but the large units used for emergency power at nuclear plants normally use a special DC power circuit to energize or "flash" the generator field initially.

The field flashing circuit consists of either a special battery or connections to the station vital service battery. The actuation of an automatic start signal closes contacts in this circuit, energizing (flashing) the diesel generator field, and starting the voltage generation when the diesel starts rotating up to rated speed. When the diesel output voltage is capable of energizing its own field, the field flashing contacts are reopened.

Most diesel generator units have some or all of the following protective trips for the diesel engine:

- Engine overspeed,
- Low lube oil pressure,
- High crankcase pressure,
- High jacket water temperature, and
- Low cooling water pressure/flow.

On an emergency start (LOP or SI) some or all of these protective trips may be automatically overridden by the emergency start signal. When the diesel is started for periodic load testing or other parallel operations, all of the protective trips are enabled.

The trips for the diesel generator output breaker operate similarly to the diesel engine trips. For routine or test starts, the breaker will have a full array of protective trips such as overcurrent, phase differential current, reverse power, and undervoltage. On an emergency start (LOP or SI), most of these trips will be overridden, normally leaving only the phase differential current trip active.

Chapter 13 Definitions

SCAVENGING - The removal of the combustion exhaust gases from a diesel engine cylinder (and replacement with clean air).

SUPERCHARGING - The use of a gear-driven blower to force scavenging air into a diesel engine cylinder to produce a pressure above atmospheric for the start of the compression stroke.

TURBOCHARGING - Same as supercharging, except that the blower is driven by a turbine that uses exhaust gases from the engine.

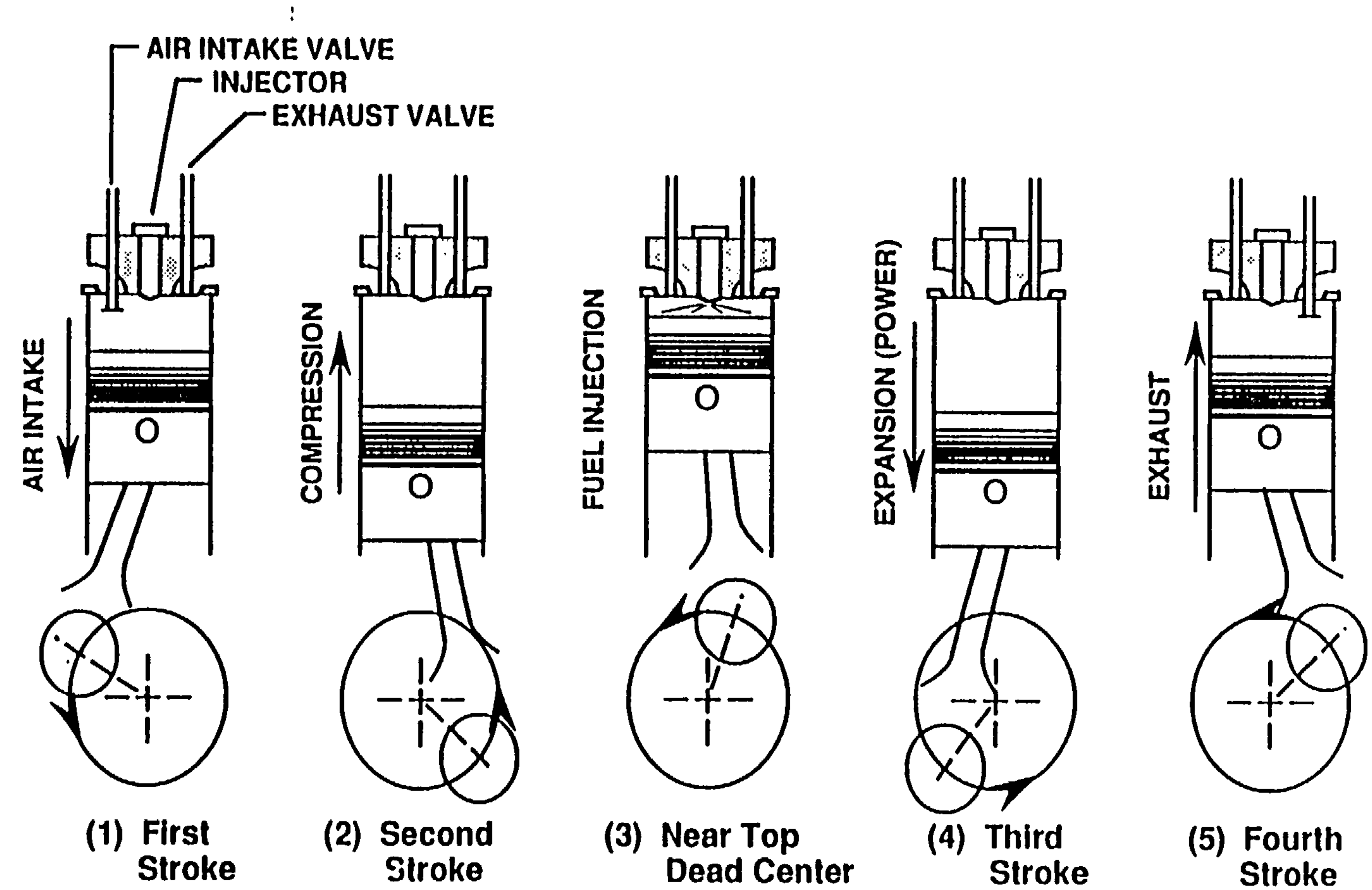
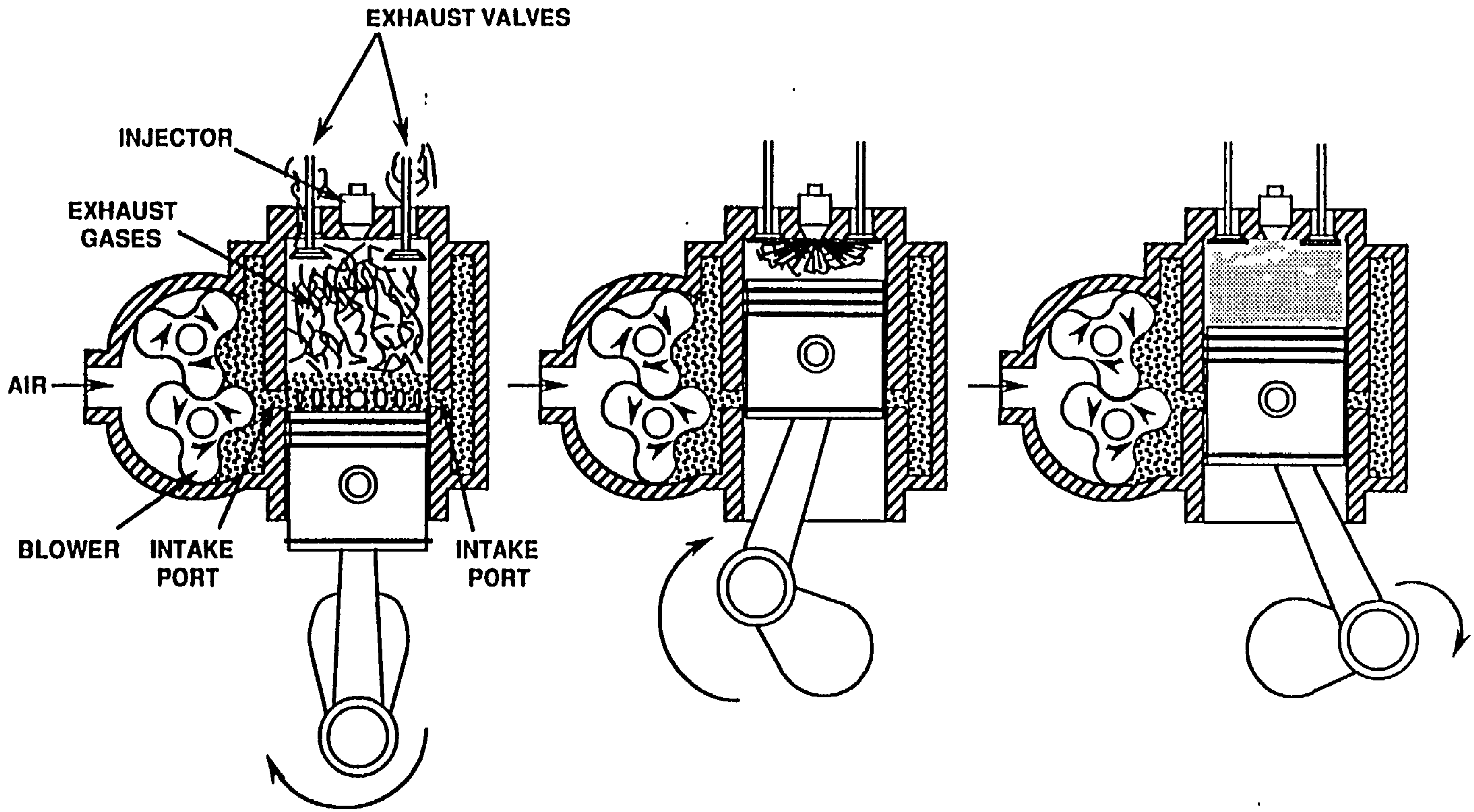


Figure 13 - 1. Four-Stroke Diesel Engine Cycle



A. BETWEEN STROKES (NEAR BOTTOM)
AIR INJECTION
EXHAUST SCAVENGING

B. UP STROKE
SUPERCHARGING
COMPRESSION
FUEL INJECTION

C. DOWN STROKE
EXPANSION
EXHAUST COMMENCES

Figure 13-2. Two-Stroke Diesel Engine Cycle

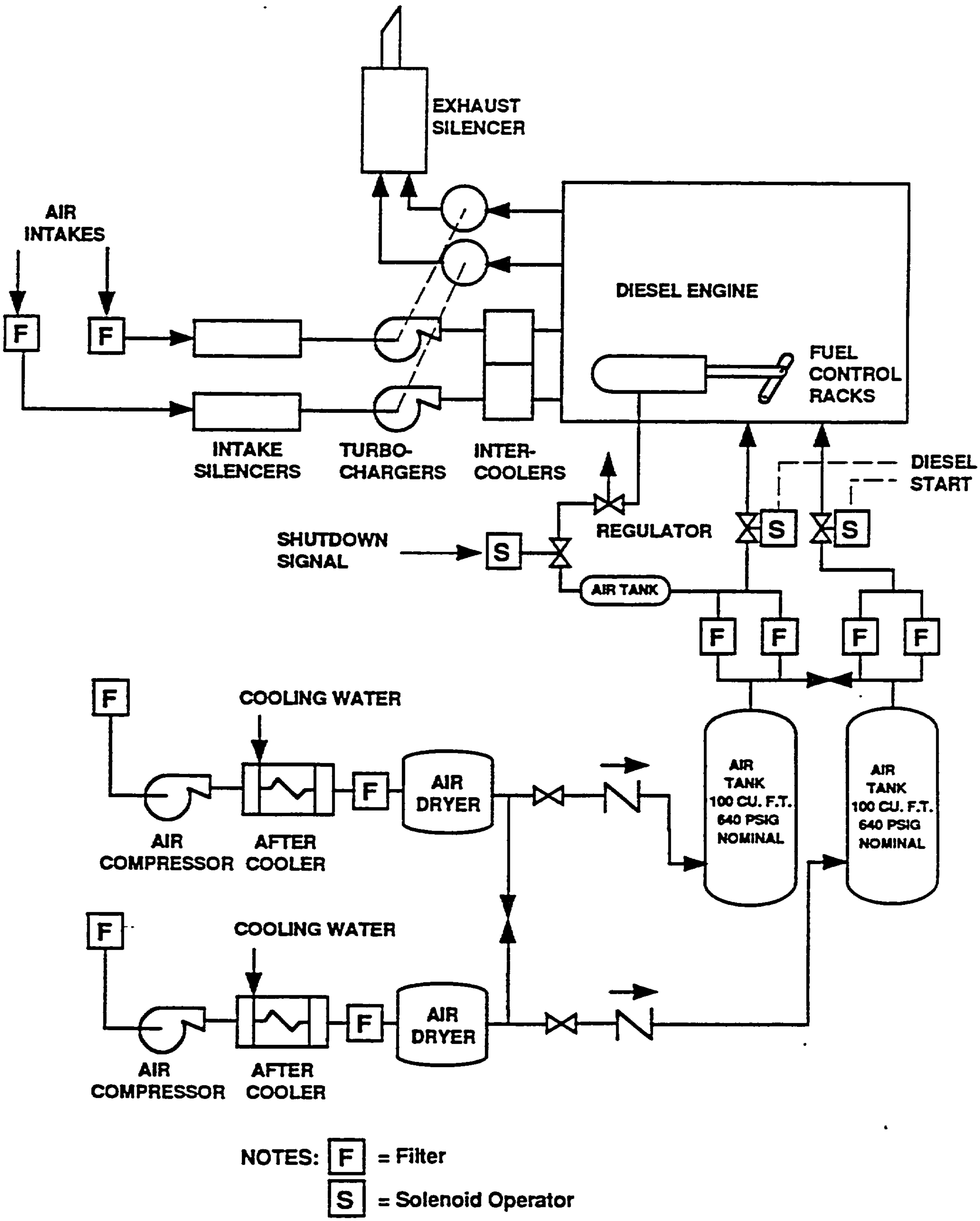


Figure 13 - 3. Typical Diesel Air Starting System

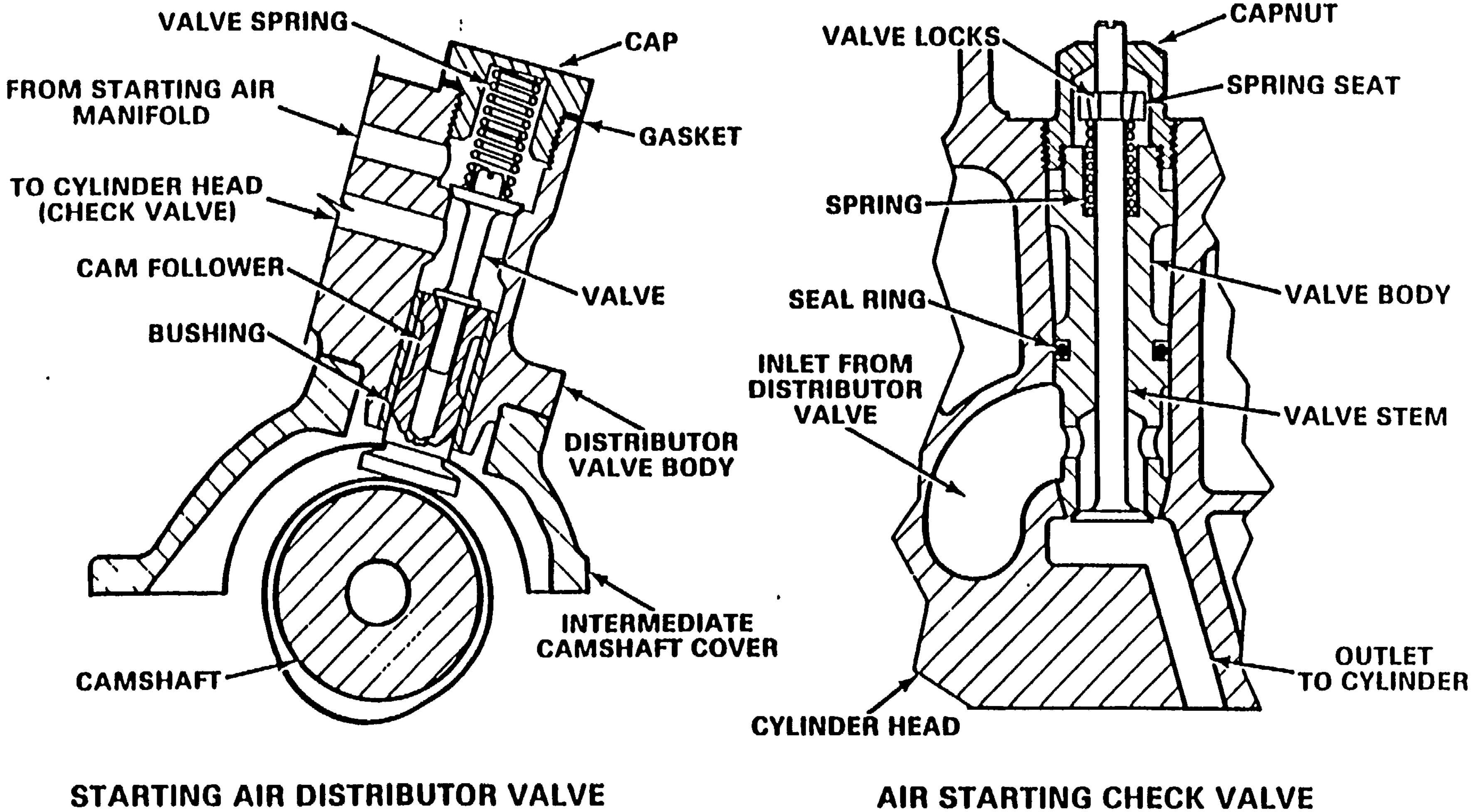


Figure 13-4. Air Start Valves

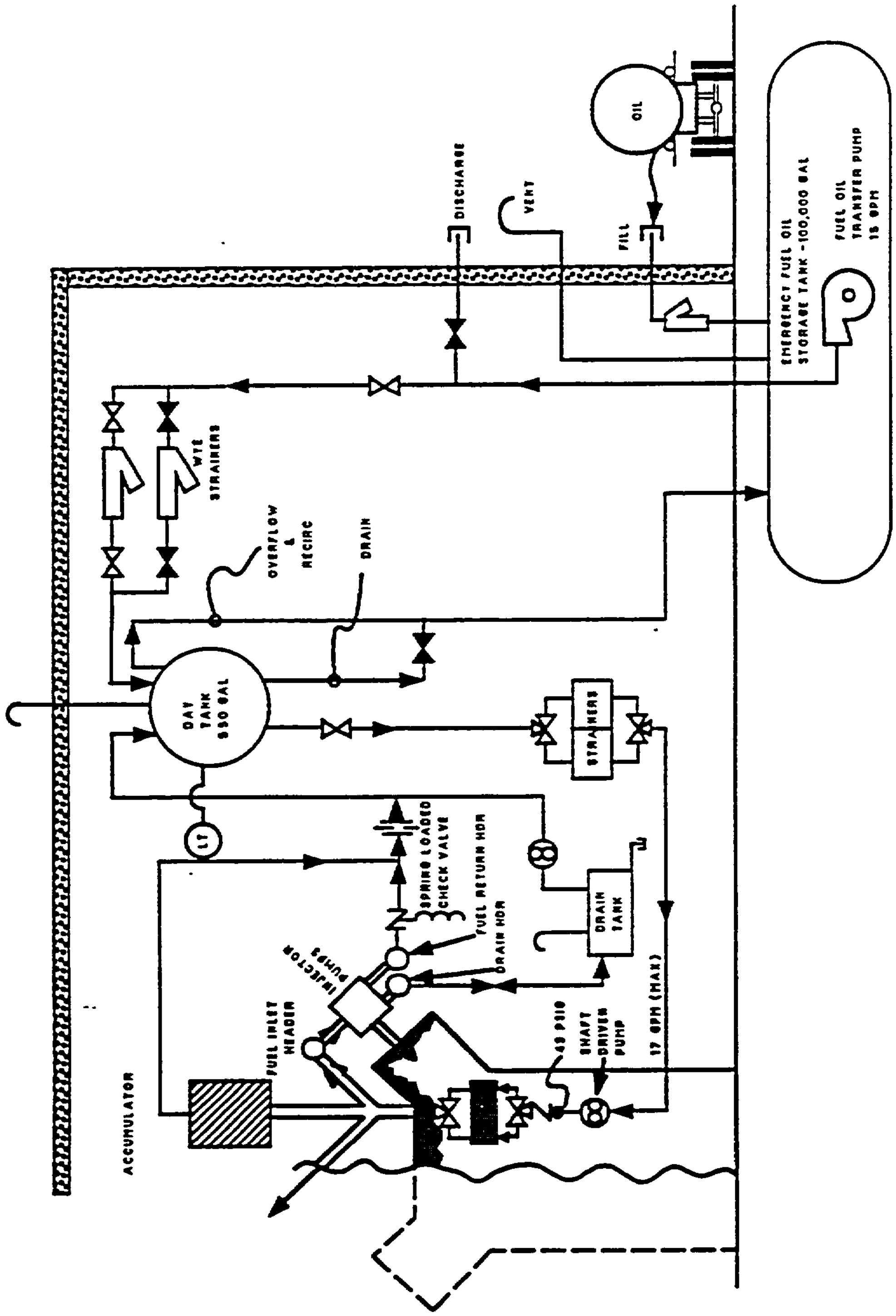


Figure 13 - 5. Diesel Fuel Oil System

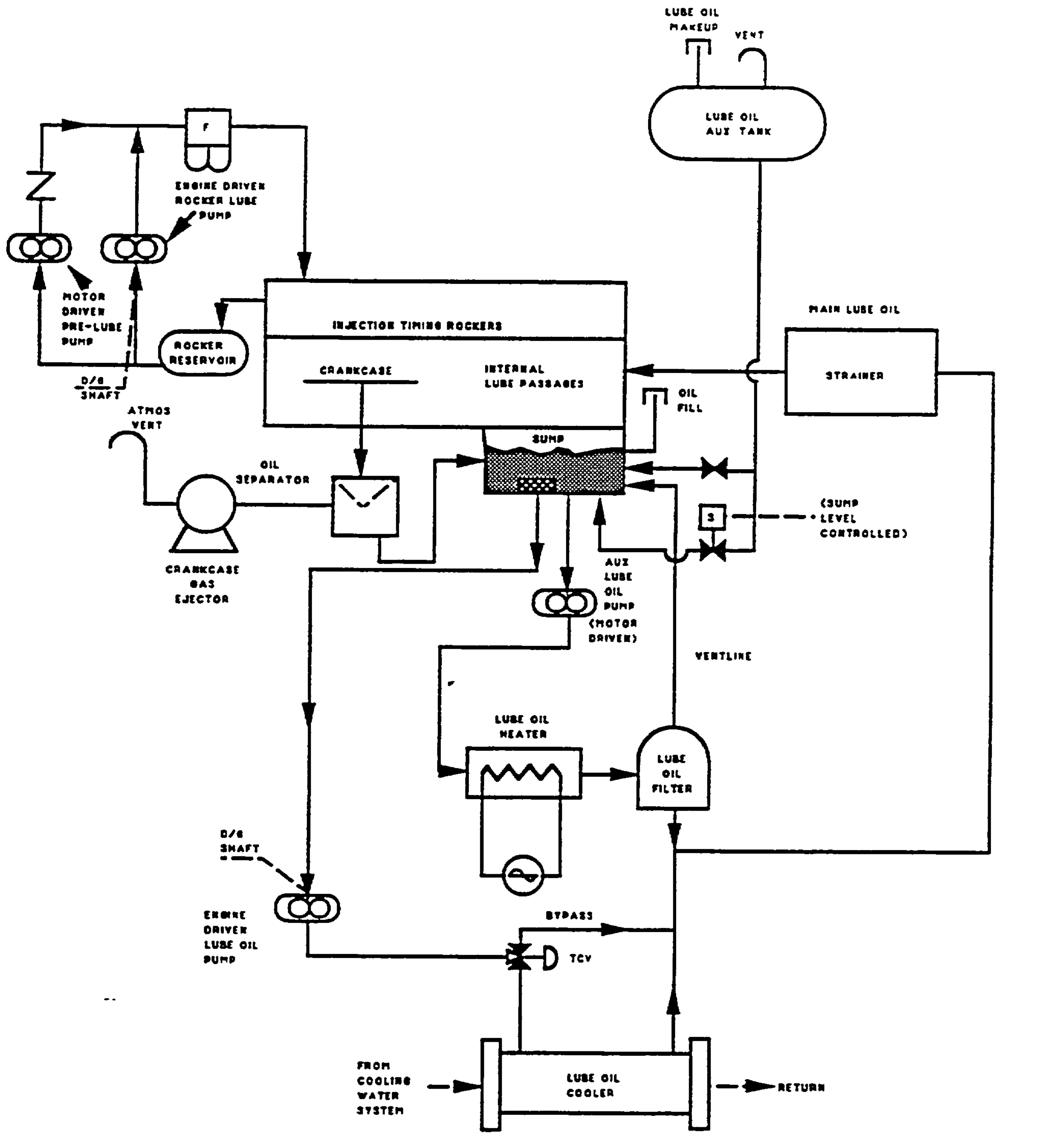


Figure 13 - 6. Diesel Generator Lube Oil System

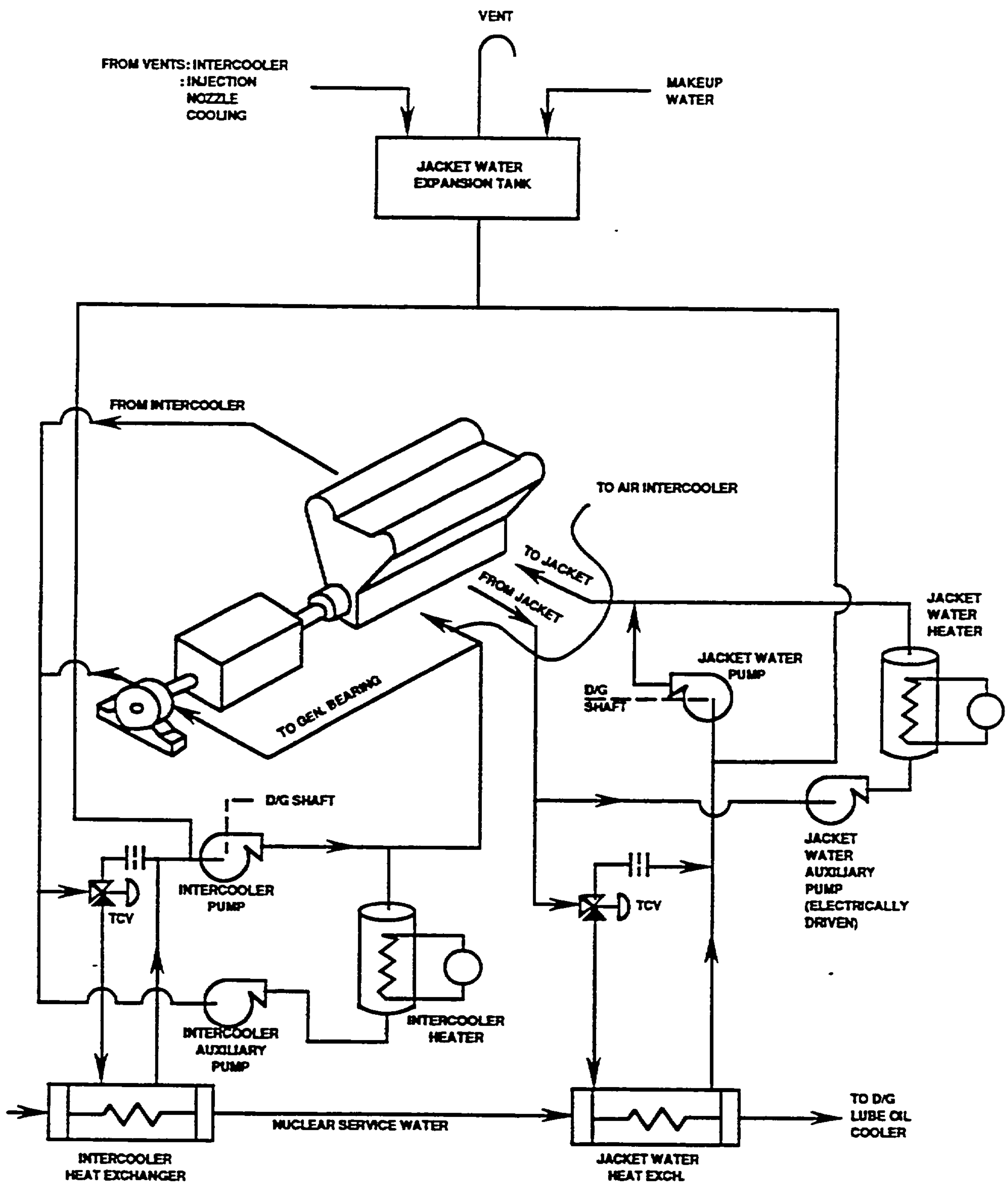


Figure 13 - 7. Diesel Cooling System

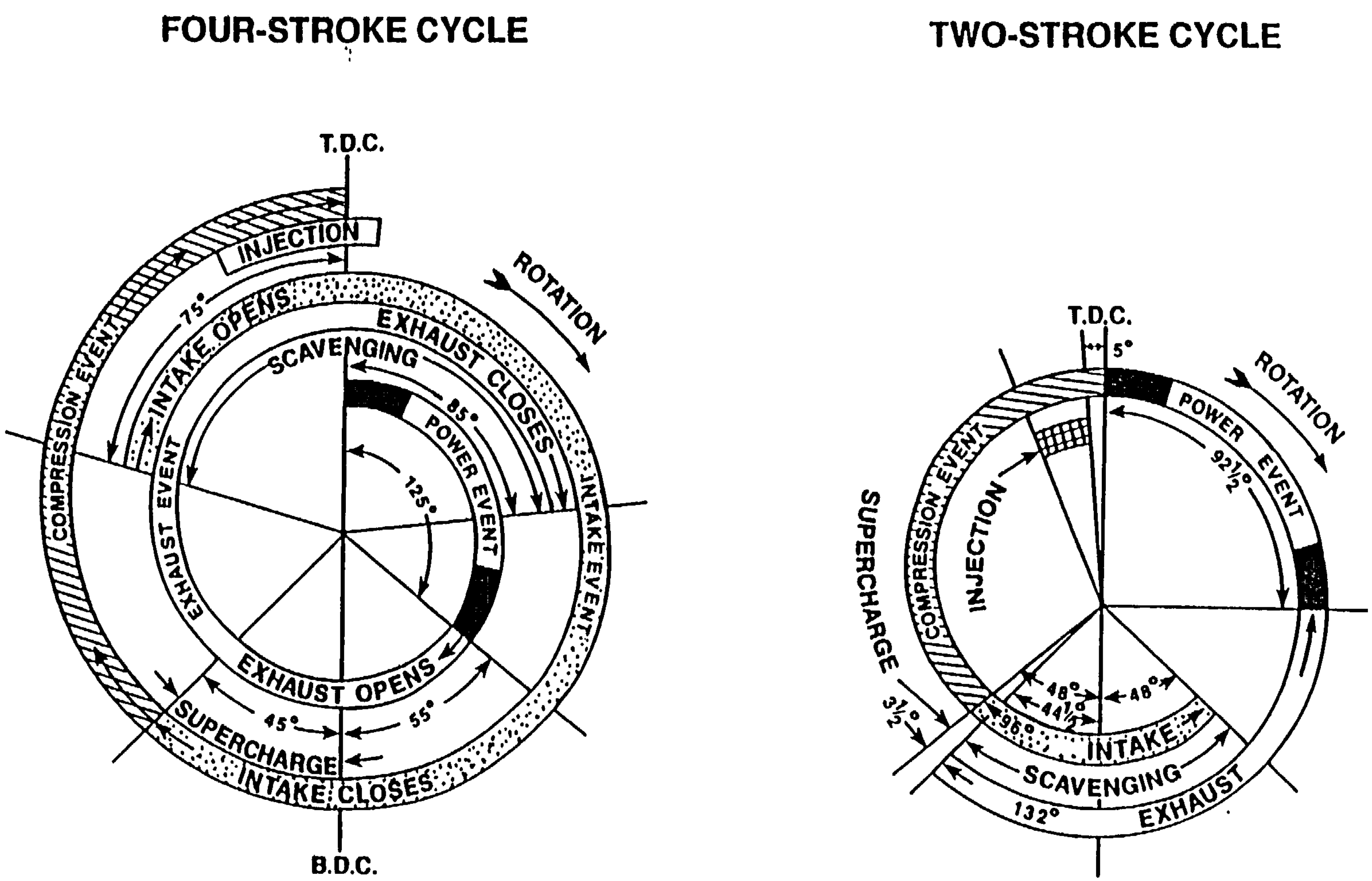


Figure 13-8. Diesel Cycle Timing

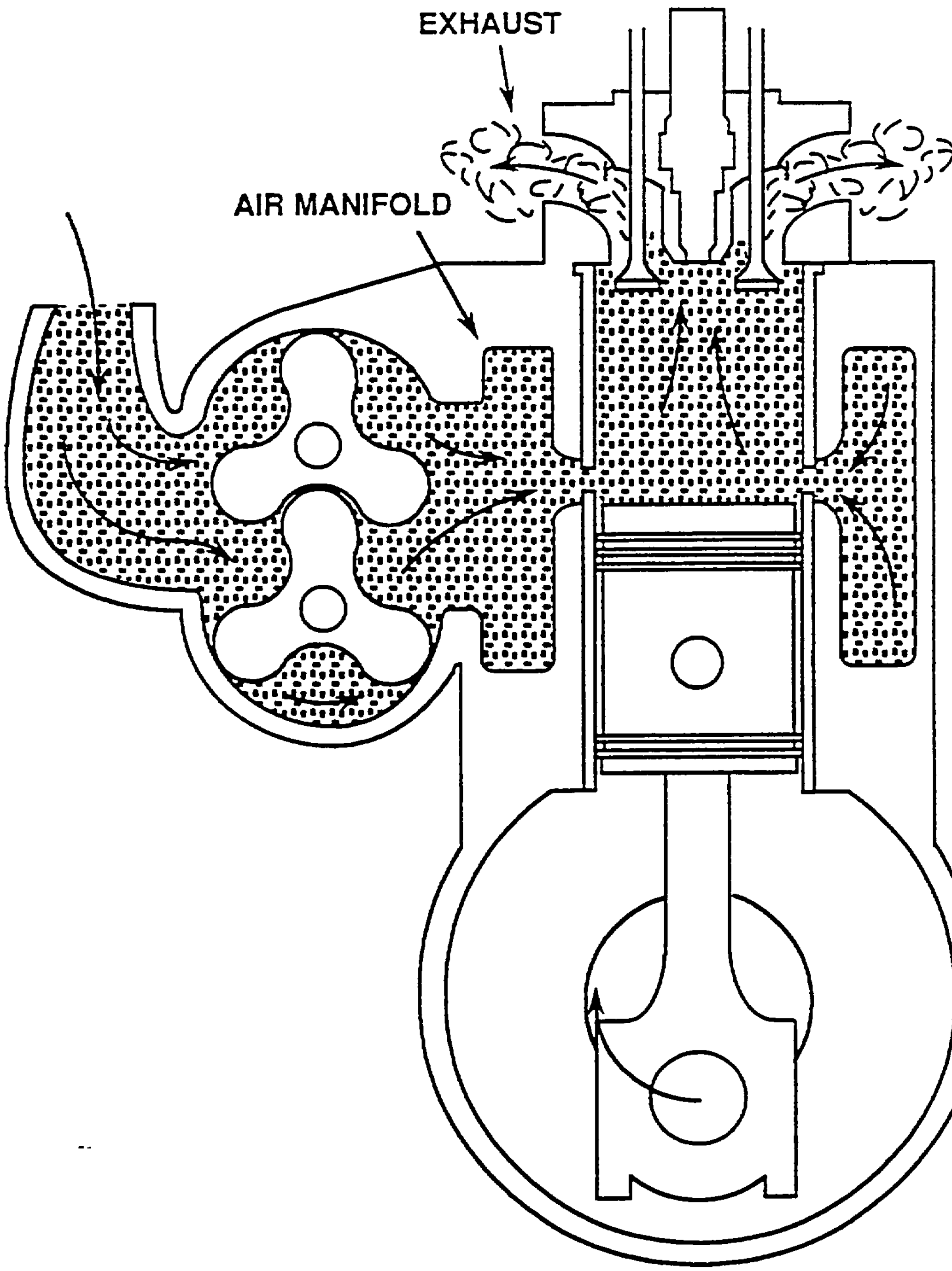


Figure 13 - 9. Roots Blower Scavenging System

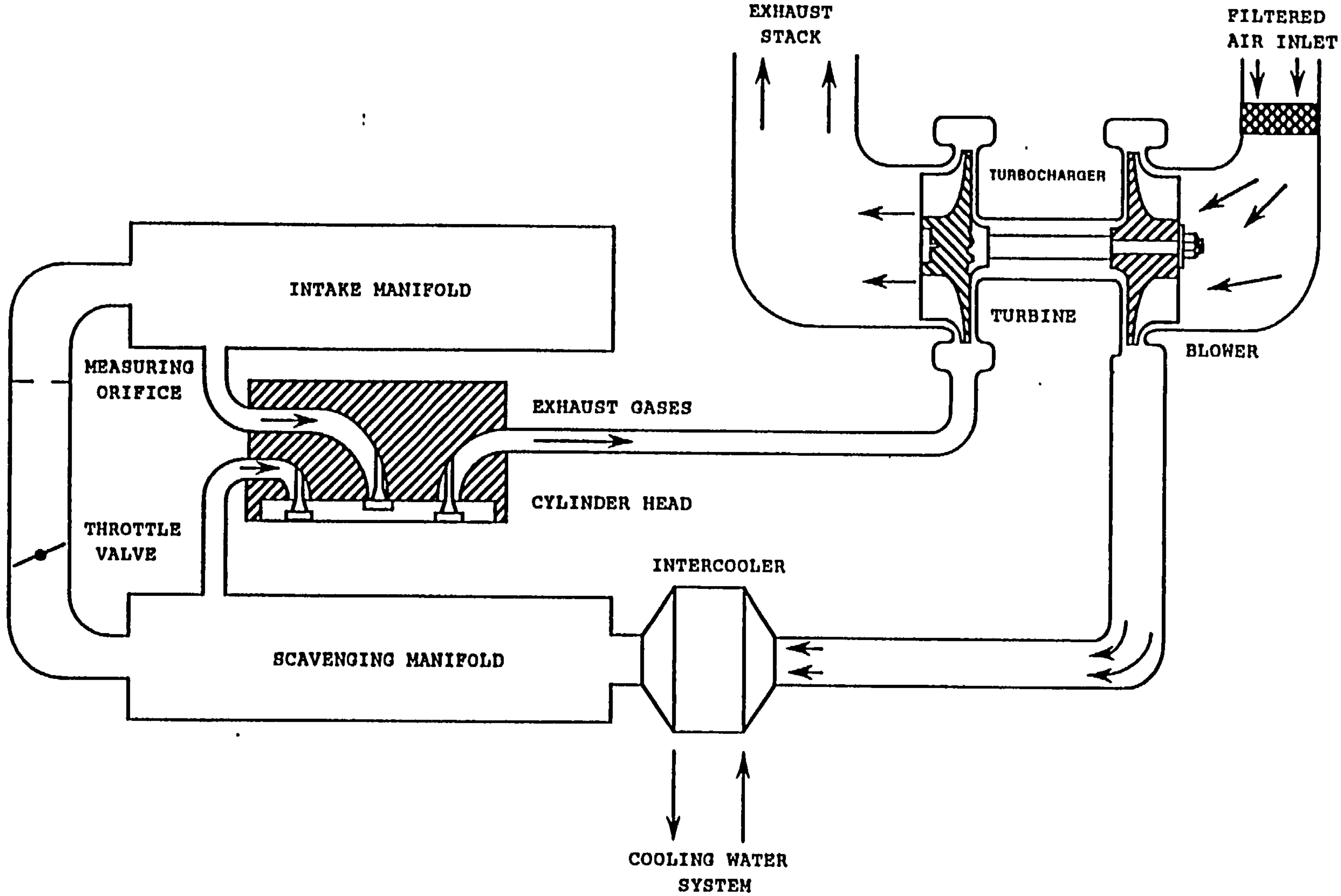


Figure 13 - 10. Turbocharger System

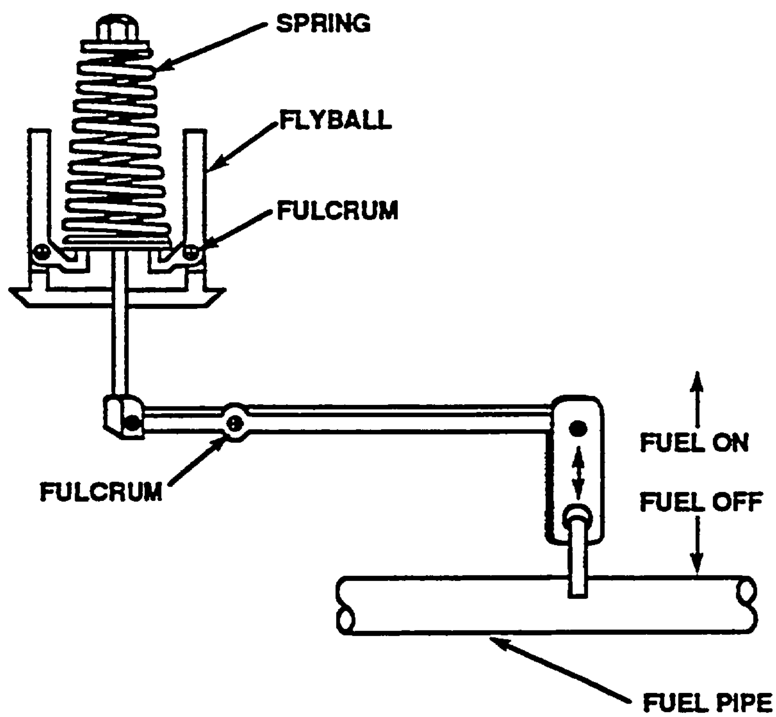


Figure 13 - 11. Simple Mechanical Governor

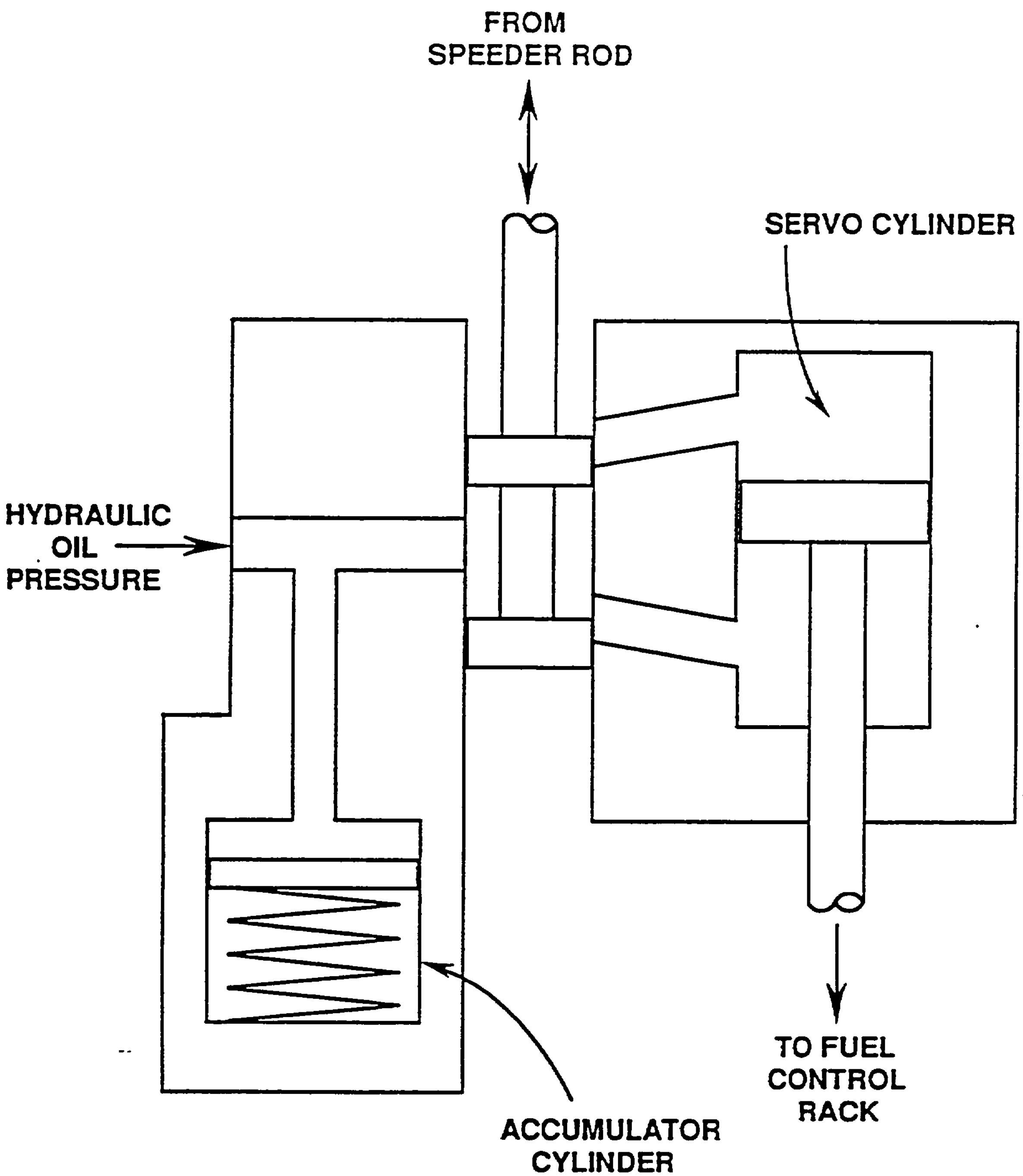


Figure 13-12. Hydraulic Governor

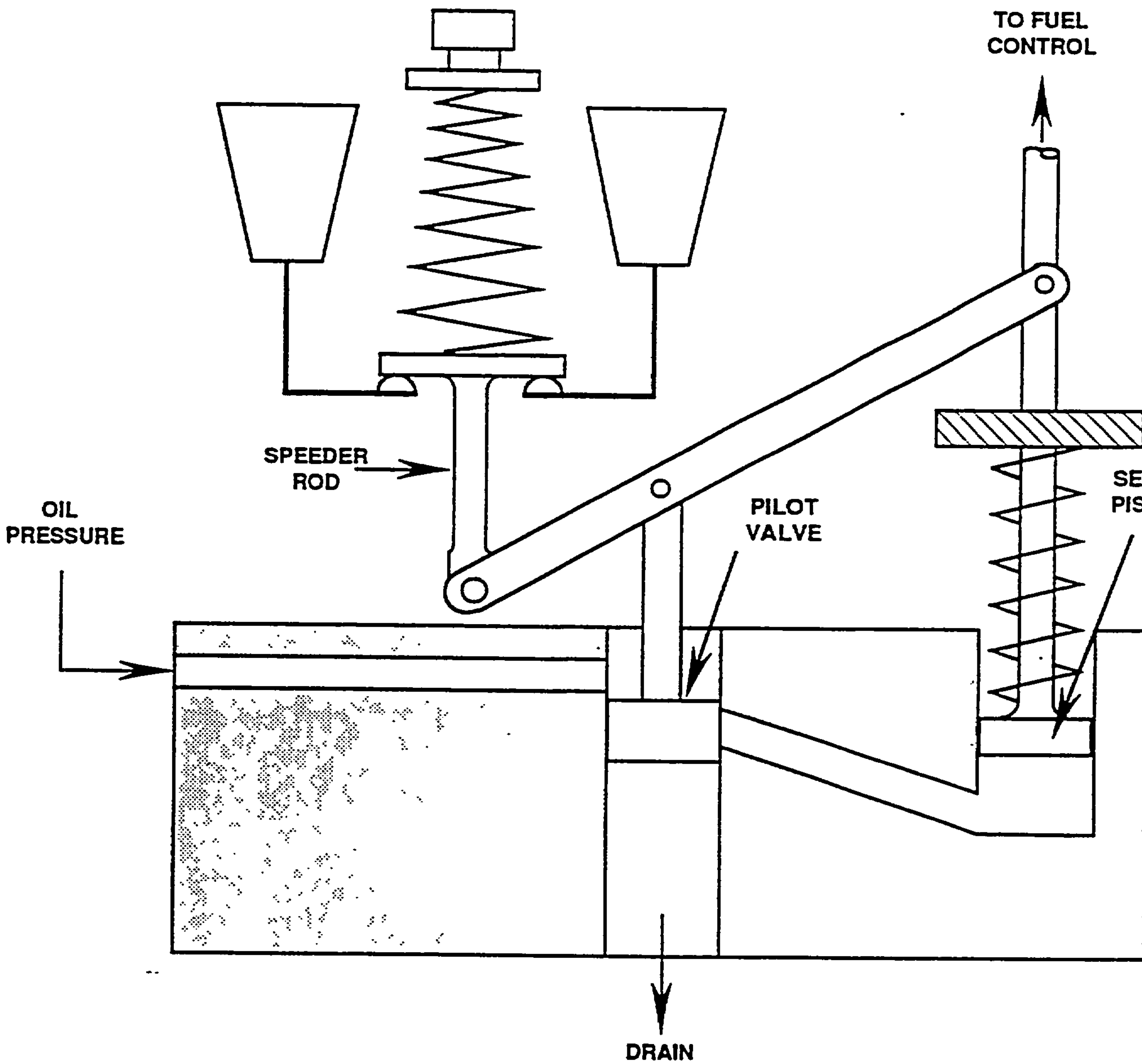


Figure 13-13. Hydraulic Governor With Feedback

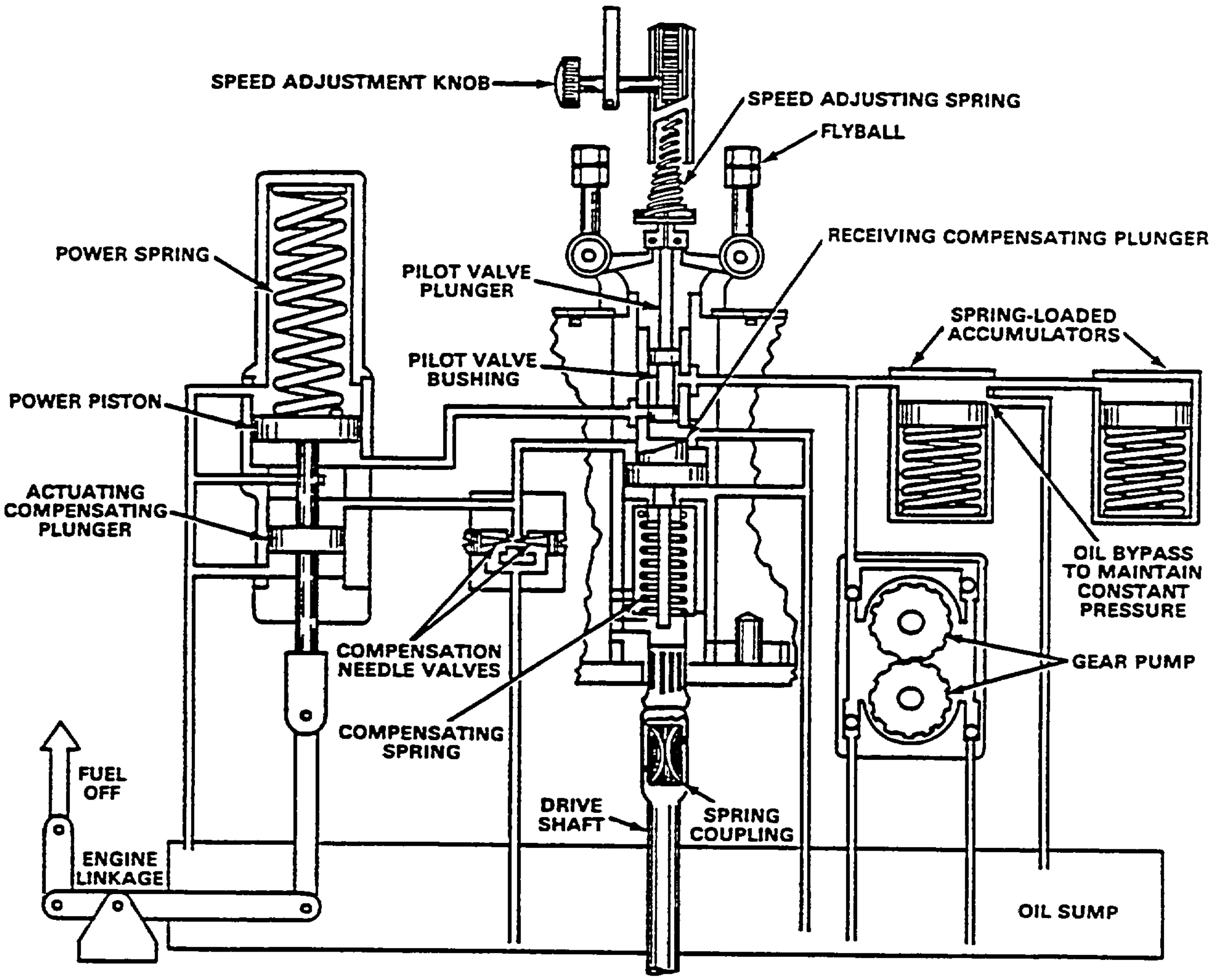


Figure 13-14. Hydraulic Governor with Compensating Device

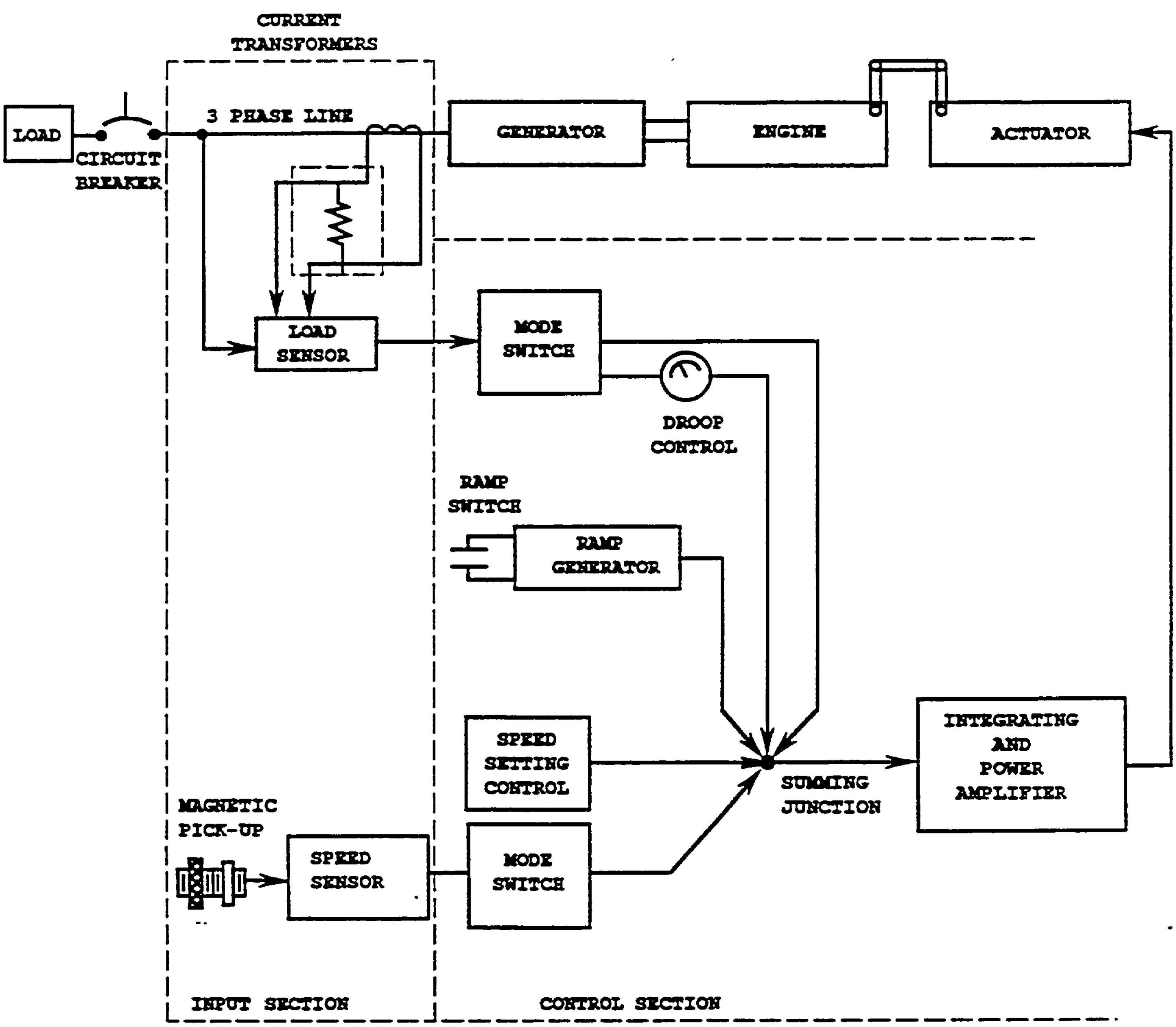


Figure 13 - 15. Electric Governor

14.0 PROCESS INSTRUMENTATION

Learning Objectives

After studying this chapter, you should be able to:

1. List and state the functions of the 4 major components in a basic instrument channel.
2. Regarding the temperature indication from a resistance temperature detector (RTD) or thermocouple, state the effect caused by:
   a. Open circuits
   b. Short circuits
3. List and explain the basic operation of the detectors used to sense:
   a. Pressure
   b. Level
   c. Temperature
   d. Flow
4. Regarding the level indication of a differential pressure (D/P) cell, explain the effect caused by:
   a. Opening the equalizing valve
   b. A change in reference leg level
   c. A change in reference leg density
   d. A change in monitored water level
   e. A change in monitored water density
5. Regarding the flow indication of a D/P cell, explain the effect caused by:
   a. Opening the D/P equalizing valve
   b. Erosion or obstruction of the primary element
6. Describe the purpose of environmental qualification.
7. Describe the methods used to compensate for instrument inaccuracies during accident conditions.

14.1 Introduction

The complexity of a nuclear power plant requires that process parameters throughout the station be sensed and displayed to the operators in a central location (control room). In addition to keeping operators informed, the instruments provide information to control equipment, protective devices, alarms, and recorders. This chapter addresses the detection of process variables and the conversion of these measured values into electrical signals. Nuclear instrumentation systems will be covered in Chapter 16.

14.2 Basic Instrument Channels

There are two basic types of parameter measurement: direct and indirect. A gauge glass on the side of a tank is an example of direct water level measurement. If a pressure instrument measures the pressure of the water at the bottom of a tank and then converts that pressure to an equivalent water level, the measurement is indirect. Most plant parameters are measured indirectly. An instrument channel is used for indirect measurements. All instrument channels follow the same simple pattern. First, the parameter must be detected. Next, the detector output must be converted to an easily used signal, usually an electric signal. This signal must then be amplified and then sent to an indicator for display of the parameter value. Figure 14-1 is a basic instrument channel.

The function of each block of the instrument channel is as follows:

- Detector senses the parameter monitored and converts the magnitude of the parameter to a mechanical or electrical signal.
- Transducer converts the output signal of the detector to a signal that can easily be used. (If the detector signal can be used directly, this "conversion" step is not needed.)

- Amplifier increases the process signal to a usable magnitude. (In many cases, signal conditioning occurs in the amplifier section.)

- Indicator displays the process variable signal being monitored.

14.3 Temperature

Unlike most measured variables, temperature is difficult to define because the term "temperature" refers to a thermal state (heat content) of molecules of matter that cannot be measured directly. Temperature is thus an indirect measure of a thermal condition of molecules within a body. It is related to heat but it is not heat, and so must be measured in a relative manner using scales which tell us only whether one object is hotter or colder than some reference value.

Temperature is a measurement of the average kinetic energy of the molecules or atoms contained in a system. It is the property of a body which determines the flow of heat. Uses of temperature measurements range from inputs into the reactor protection system to measurement and control of the chilled water temperature from the station air conditioning system. The two basic types of temperature detectors that will be discussed are the thermocouple and the resistance temperature detector.

14.3.1 Thermocouples

When one end of a metal rod is heated, a voltage potential is developed from the warm end of the rod to the cold end. Thermocouples operate on the principle that when two dissimilar metals are joined or welded together, a voltage potential is developed across the junction if the junction temperature differs from the temperature at the metal ends.

To form a simple thermocouple, dissimilar metals X and Y are joined (normally welded) together to form a measuring junction as shown in Figure 14-2A. If the junction is heated or cooled, a voltage potential will be developed across the junction. The voltage can be measured across the other ends of the metals. The size and polarity of the voltage will depend on the two metals that are used, and the temperature difference between the junction and the ends of the metals. The metals are selected so that the voltage difference is directly proportional to the temperature difference over the temperature range of interest.

The voltages produced by common thermocouples are very small, normally in the millivolt range. Therefore, a very accurate voltage measuring device (normally a potentiometer) must be used for the measurement, and care must be taken to minimize the effect of the measuring device on the thermocouple circuit. Just the connection of the voltage measuring device adds new junctions of dissimilar metals to the thermocouple circuit as shown in Figure 14-2B. Because the leads of the potentiometer are normally made from a different metal from the thermocouple metals, two new dissimilar-metal junctions (A and B) are formed. Each of these new junctions also produces a temperature-dependent voltage output that will interfere with the output indication of the thermocouple circuit unless some compensation is provided.

One common method of compensation in a thermocouple circuit is to maintain junctions A and B at a constant, or reference, temperature. Then, any change in the voltage output of the thermocouple circuit is due solely to changes in the temperature of the measuring junction. In this compensation method, junctions A and B are often called the reference, or cold, junctions (or just reference junction because they are normally collocated), and the measuring junction is often called the hot junction. Other thermocouple circuits may add a temperature compensation circuit to offset the effects of any temperature change at the reference junction(s).

Figure 14-3 illustrates a thermocouple circuit in which M_1 and M_2 are dissimilar metals connected to form junction "J". This junction is the hot junction and is in contact with the medium to be monitored for temperature. Because the metals used in thermocouples are normally expensive, lead wires are often used to carry the signal from the measuring location to the indication location. However, the lead wires add two new junctions that must be temperature-compensated or kept at a constant reference temperature.

In Figure 14-3, the lead wires, L_1 and L_2 (frequently made of copper), connect the thermocouple to the potentiometer (or other voltage measuring device). The L_1 and L_2 connections are made at terminals A and B of the thermocouple, the cold or reference junction.

The net voltage developed between terminals A and B depends on the materials used for M_1 and M_2 and the temperature differential (ΔT) between the hot and cold junctions.

For a given set of dissimilar metals, the voltage output of the thermocouple is proportional to the temperature differential between the hot and cold junctions. If the temperature of the cold or reference junction (T_{REF}) is held constant, the net voltage in the thermocouple circuit will be affected only by a change in temperature of the hot or measuring junction (T_H). It is possible then to calibrate the scale of the potentiometer in units of temperature so that T_H can be read directly, instead of voltage. Because the cold junction temperature does not change, the calibrated thermocouple will generate a voltage proportional to the temperature of the hot junction.

$$\text{Voltage}_{(C\text{-}D)} \propto T_H - T_{REF}$$

$$\text{Voltage}_{(C\text{-}D)} \propto T_H .$$

Depending on the type of reference junction enclosure used, changes in ambient temperature may cause a temperature change of the reference junction. If this occurs, the net voltage in the thermocouple circuit will be affected and will no longer be proportional to the temperature at the hot junction. Some thermocouple applications monitor the temperature of the reference junction and provide automatic compensation or correction of the temperature reading on the potentiometer.

The indications resulting from thermocouple failures are not always straightforward. In most power plant applications, the measuring junction temperature is much hotter than the reference junction temperature. Under these conditions, an open measuring junction or open thermocouple lead will result in a failed low indication because the thermocouple voltage is blocked from reaching the measurement circuitry.

A shorted thermocouple circuit can produce a number of indications, depending on the location of the short. If the short occurs between the two thermocouple metals, the instrumentation will read the temperature at the location of the short if that temperature is on-scale, or at the nearest scale-end. The short location acts like a new thermocouple.

Thermocouples are used in plant applications where rugged instrumentation is required. They are normally installed in reactor vessels at the top of the reactor core to measure the temperature of the coolant exiting the fuel assemblies. Because the thermocouples used in reactor vessels may be required to indicate accurately at temperatures up to 2300°F, the common metal combination used for these thermocouples is chromel/alumel, two alloys of nickel.

A special application of thermocouples (dual junction thermocouples) is sometimes used in the reactor vessel to monitor vessel water level. A dual junction thermocouple includes one junction that is heated by electrical current and one normal unheated measuring junction. The dual thermocouple output varies widely depending on whether the thermocouple is immersed or uncovered. Reactor vessel level can be determined based on the installed height of the uncovered thermocouples.

14.3.2 Resistance Temperature Detector

The resistance temperature detector (RTD) operates on the principle that a metal's resistance to current flow will change with temperature. This change in resistance is proportional to temperature and can be measured with simple electronic circuits.

Industrial RTDs are usually made of platinum, nickel, or copper. The selection of a metal for use as an RTD depends on several factors, the most important being the ease of obtaining a pure metal and the capability of drawing it into a fine wire. Additional requirements are the metal's ability to follow rapidly changing temperatures, linearity, and a relatively high rate of resistance change.

The fractional change in electrical resistance of a material per unit change in temperature is the temperature coefficient of resistance for the material. The coefficient is expressed as the fractional change in resistance (ohms per ohm) per degree of temperature change at specific temperature and is given the symbol α. For most metals, the temperature coefficient is positive.

Pure platinum has a linear and stable resistance-to-temperature relationship. For this reason, pure platinum is the international standard of temperature measurement usually used in power plants. As the standard, it serves as a reference for checking the calibration of other temperature-indicating devices in the plant.

Figure 14-4 shows the relationship between the resistance of different metals to applied temperature. The vertical axis plots the ratio of the resistance at the applied temperature to the resistance of the reference temperature. The reference temperature in this case is 0°C. The horizontal axis plots the temperature applied to the metals.

As indicated by Figure 14-4, the response of platinum is nearly linear over the entire range of the applied temperature. Recently, sensors made of very thin platinum films deposited on a substrate have come into use. The substrate is usually made of ceramic. This method of constructing RTDs leads to small sensing elements with high resistance values.

Copper is inexpensive and has the closest linear relationship of known metals over a rather wide temperature range. Copper has low resistance to oxidation above moderate temperatures but has much poorer stability and reproducibility than platinum in most applications. The low resistance of copper is a disadvantage when a high resistance element is desired.

Nickel has been widely used as a temperature sensing element over the range from about -100° to +300°C (-150° to +570°F), principally because of its low cost and the high value of its temperature coefficient. Above 300°C (570°F), the resistance-temperature relationship for nickel changes. Nickel is very susceptible to contamination by certain materials, and the relationship of resistance to temperature is not as well known nor as reproducible as that of platinum.

The resistance versus temperature relationship of tungsten is not as well known as that of platinum. Full annealing of tungsten is impractical; therefore, tungsten sensors are less stable than well-made platinum sensors.

14.3.2.1 RTD Construction

The elements of RTDs can be constructed in a variety of ways, varying from a cage-like open array of resistance wires within a guard screen to a coil wound on a mandrel and encased in a rugged well (see Figure 14-5). The choice of structure depends on such factors as: compatibility of the resistance material with the environment, requirements for speed of response, extent of immersion permitted, and the expected mechanical stresses to be experienced.

Although some laboratory resistance temperature detectors are constructed with the resistive element exposed, most are constructed so that the fine wire element is coiled and loosely supported on a mica form. The coil is annealed, heated until the stresses caused by the coiling procedure are relieved, and then installed in a protective sheath or well. Industrial-grade RTDs are formed in a similar manner. Extra care is taken to fabricate the element so that the effects of mechanical shock are minimized.

Typical sheathed RTDs contain coils wrapped around a support that evenly distributes the resistance while maintaining good thermal contact and electrical insulation from the protective sheath.

The element is annealed and stretched lightly over the support to give firm sealing. After its end wires are connected, the RTD element is fixed in place with varnish or some other sealing material. The sheath is filled with a material such as magnesium oxide or aluminum oxide, and then the entire sheath is hermetically sealed. The completed sheath is attached to a mechanical fitting that allows the RTDs to be installed in a thermowell. A loading spring is used to give the tip of the sheath positive contact with its thermowell. This prevents vibration and improves the response time of the detector.

14.3.2.2 Wheatstone Bridge

A type of circuit that is widely used for precision measurements of resistance is the Wheatstone bridge. The circuit diagram of a Wheatstone bridge is shown in Figure 14-6. R_1, R_2, and R_3 are precision resistors and R_x is the resistor (RTD) whose unknown value of resistance is to be determined. R_1 and R_2 have equal resistance values, and R_3 is a variable resistor. When the bridge is balanced (R_3 equals R_x), there is no difference in voltage across terminals **b** and **d**, and the galvanometer deflection will be zero when the switch is closed.

When the switch to the battery is closed, current flows from the battery to point a. Here the current divides, as it would in any parallel circuit, part of it passing through R_1 and R_3, and the remainder passing through R_2 and R_x. The two currents, labeled I_1 and I_2, unite at point **c** and return to the battery. The value of I_1 depends on the sum of resistances R_1 and R_3, and the value of I_2 depends on the sum of resistances R_2 and R_x.

When the sum of resistances R_1 and R_3 are equal to the sum of resistances R_2 and R_x, equal currents will flow and the galvanometer will indicate zero when its switch is closed. In this case, R_3 and R_x have equal resistance values. If R_x resistance changes (due to a temperature change), then the bridge will become unbalanced and the galvanometer will deflect. If the galvanometer is calibrated to indicate in degrees, the meter deflection would indicate the temperature being sensed by R_x.

Some RTD circuit applications require a balanced bridge circuit at all times. These applications require R_3 to be adjusted either manually or automatically to balance the bridge. With the bridge balanced, the resistance of R_x is equal to R_3. Because R_3 resistance is known, the temperature sensed by the RTD (R_x) can be determined by applying the proper resistance - temperature correlation for the RTD.

14.3.2.3 Remote RTD Connections

Two methods of making electrical connections from a remote RTD to the measuring instrument are commonly used, namely the two-lead connection and the three-lead connection (see Figure 14-7). Both methods employ a bridge circuit to measure the resistance of the remote RTD element.

The two-lead connection shown in Figure 14-7(A) is the simplest, consisting of two relatively low-resistance leads, **k** and **l**, connecting the RTD element with the measuring instrument. The leg R_x comprises the resistance of the element plus the resistance of the leads **k** and **l**. Unless leads **k** and **l** are of <u>very</u> low resistance, they can add a measurable amount of resistance in the R_x leg. Even if the resistance of the leads is known at one temperature and allowed for in the measurement, the leads are subject to ambient temperature changes and can add an unknown resistance to the circuit. Therefore, the two-lead connection should be used only where leadwire resistance can be kept to a minimum and where only a moderate degree of accuracy is required.

The three-lead connection shown in Figure 14-7(B) is used to compensate for leadwire resistance changes due to temperature changes along the wiring path. In this circuit, leads **l** and **m** are connected in close proximity to the RTD thermometer element at a common node. The third lead, **k**, is connected to the opposite resistance leg of the element. The resistance of lead **l** is added to bridge arm R_3 , while the resistance of lead **k** remains with R_x , thereby dividing the lead resistance and retaining a balance in the bridge circuit. Although this method compensates for the effect of lead resistance, the ultimate accuracy of the circuit depends upon leads **k** and **l** being of equal resistance. Special matching techniques are used on leads **k** and **l**, particularly when the distance between the RTD element and the measuring equipment is relatively long.

Loss of power to an RTD circuit causes the indication to fail to zero or off-scale low. If an RTD element develops an open circuit, the temperature indication will fail off-scale high because an open circuit gives infinite resistance. Conversely, a shorted RTD element represents zero resistance and will cause the indication to fail off-scale low.

14.4 Pressure

Pressure, defined as force per unit area, is one of the most commonly measured parameters in the plant. The application of any force, or pressure, will always produce a deflection, a distortion, or some change in volume or dimension, no matter how small or large the force. Pressure measurements range from that of the high pressure reactor coolant system (RCS) measured in pounds per square inch (psi) down to the vacuum in the main condenser measured in inches of mercury (in Hg). The devices listed in this section are used for measurement of system pressure.

All common types of mechanical pressure detectors are fundamentally differential pressure detectors; that is, they are designed to measure the difference of two pressures — the pressure to be measured and the reference pressure.

A great deal of confusion arises from the fact that the zero point on most pressure gauges represents atmospheric pressure; whereas, absolute pressure is required for some engineering calculations. To clarify the numerous meanings of the word pressure, we examine the relationships among gauge pressure, atmospheric pressure, vacuum and absolute pressure, as shown in Figure 14-8.

Atmospheric pressure is the force exerted on an area of earth's surface due to the weight of the atmosphere. Standard atmospheric pressure at sea level is 14.7 psi — equivalent to the pressure required to support a column of mercury (Hg) 29.92 in or 760 mm in height.

If the measured pressure is greater than that of the atmosphere, the difference shown is known as gauge pressure. If the gauge pressure reading is added to the atmospheric pressure reading, the result is absolute pressure.

Pressures below atmospheric are expressed as vacuum or absolute pressure. If expressed as vacuum, the equivalent absolute pressure can be determined by subtracting the vacuum reading from the atmospheric pressure.

Vacuum pressure may commonly be discussed in one of three unit systems. Probably the most common units are inches of mercury vacuum (in Hg). This is the difference in pressure as measured by the height of a column of mercury. Another unit often seen is feet of water vacuum (ft H_2O) or inches of water vacuum (in H_2O).

14.4.1 Bourdon Tube

A Bourdon tube gauge is often used to measure pressure. One type of Bourdon tube gauge (see Figure 14-9) consists of a flattened C-shaped metal tube that is sealed at one end. As pressure is applied to the tube, the tube tends to straighten. Further pressure makes the tube straighten even more. This effect is caused by the application of pressure to differential areas. Recall that $P = F/A$; therefore, $F = PA$. Because the tube is curved (C-shaped), the inside curve of the tube has less area than the outside curve of the tube. This unbalanced force tends to straighten the tube, causing deflection of the sealed end. (If the pressure is removed, the elasticity of the tube will return it to its original shape.) The movement of the sealed end of the tube is transmitted through a linkage to a pointer or transmitter. The pointer indicates the pressure being measured on a scale. There are many types of Bourdon tube gauges. The tube can have a spiral or a helix shape, which causes a degree of magnification to tube movement.

14.4.2 Bellows

The need for a pressure-sensing element more sensitive to low pressures than the Bourdon tube and providing greater power for actuating recording and indicating mechanisms resulted in the development of the metallic bellows.

The use of metallic bellows has been most successful on pressures ranging from 0.5 to 75 psig. Figure 14-10(A) illustrates a basic bellows-sensing element.

The bellows-type pressure gauge is usually built as a one-piece, collapsible, seamless metallic unit with deep folds formed from very thin-walled tubing. The moving end of the bellows is usually connected with a simple linkage to an indicator pointer. The flexibility of a metallic bellows is similar to that of a helical, coiled compression spring. The relationship between increments of load and deflection is linear up to the elastic limit. However, this linear relationship exists only when the travel of the bellows occurs under the influence of a minimum compressive force. The arrangement of the detector should allow bellows travel to be measured on the compressive side of the point of pressure equilibrium. For this reason, the spring in Figure 14-10(A) is exerting a compressive force on the bellows that the movement or measuring action of the bellows must overcome. In practice, the bellows is always opposed by a spring, and the deflection characteristics of the unit is the net result of the spring and the bellows.

14.4.3 Diaphragm

The diaphragm gauge is similar to the bellows gage, but it has a diaphragm instead of bellows (see Figure 14-10B). The diaphragm gauge works the same way as the bellows gauge. The diaphragm gauge is less rugged than the bellows gauge, but it is very accurate at low pressures. The diaphragm gauge can measure pressure or vacuum.

The diaphragm is usually opposed by a light spring. The amount of deflection of the diaphragm is proportional to the applied pressure. If a vacuum is applied that allows the spring to contract, the amount of contraction should be proportional to the amount of vacuum.

14.5 Mechanical - Electrical Conversion

In the sensors described above, the application of pressure results in mechanical movement or motive. Two devices are available for the conversion of this mechanical movement into an electrical signal that can be used in the plant control or protection systems. The use of one device, the force balance transmitter, results in a current (milliampere, mA) output. The use of the other device, the movable core transformer transmitter, results in a voltage output.

14.5.1 Force Balance Transmitter

Force balance refers to the system whereby the free motion of the sensor is limited and actively opposed by some mechanical or electrical means.

In Figure 14-11 a simplified force balance transmitter is shown. As pressure increases, the diaphragm is moved to the left. This motion, in turn, causes movement of the force bar (the force bar is pivoted at the sealed flexure). The force bar motion causes movement of the reference arm, which closes the gap of the error detector. The position error detector works on the principle of a varying magnetic gap which varies the coupling between the primary and secondary windings of a transformer. When the gap of the error detector becomes smaller, the output of the error detector increases. The output of the error detector is amplified and applied to the force feedback coil. The increased current in the force feedback coil exerts a greater pull on its armature moving the reference arm in the opposite direction, thus restoring the system balance. The amount of current required to maintain the system in balance is proportional to pressure and, therefore, can be used in the indicating and control loops. Two current ranges, 4 to 20 mA or 10 to 50 mA, are generally used for this transmitter's output circuitry.

14.5.2 Movable Core Transmitter

In the movable core transmitter, shown in Figure 14-12, the pressure sensor's mechanical linkage is connected to the core of a linear variable differential transformer (LVDT). The LVDT consists of a primary coil and two secondary coils. The movement of the core changes the magnetic flux coupling between the primary coil and the secondary coils which, in turn, causes a change in the voltage output of the secondary coils.

Normally the two secondaries are connected series opposing as shown in Figure 14-12. For this configuration, when the iron core is centered the output voltage, e_{out}, is zero. This point is referred to as the LVDT's null position. As the core is moved above the null, the output is in phase with the primary voltage. Conversely, as the core moves below its null position, the output is 180 degrees out of phase with the primary voltage. These phase relationships are caused by the series opposed connection of the secondaries. The LVDT will produce an output voltage that is a linear function of core position for a considerable range either side of null. Further, if the direction of displacement from the null is needed, this can be determined by use of a phase sensitive network that is referenced to the excitation voltage.

14.5.3 Variable Capacitance Transmitter

A relatively new type of transmitter is being installed in nuclear plants. This new transmitter is called a variable capacitance transmitter (see Figure 14-13) and consists of a set of parallel capacitor plates with a sensing diaphragm placed between the plates. The capacitor is filled with silicon oil. The need for a pressure-sensing element, such as a bellows or bourdon tube, and its mechanical linkage has been eliminated by connecting the process fluid to a separate isolating diaphragm. One side of the isolation diaphragm is in contact with the process stream, while the other side is in contact with the silicon fill oil. When pressure is applied to the isolating diaphragm, its force is transmitted through the silicon oil to the sensing diaphragm causing it to deflect. The deflection of the sensing diaphragm is detected by the capacitor plates. The change in capacitance, because of sensing diaphragm deflection, is converted to a 4 to 20-mA output that is transmitted to the plant protection and/or control systems.

14.5.4 Strain Gauge

A strain gauge (see Figure 14-14) is manufactured by bonding a semiconductor resistor to a diaphragm and sealing it. It is then placed in a protective casing. When pressure is applied to the diaphragm, the strain gauge is distorted by elastic deformation causing its length to increase and its cross-sectional area to decrease. These changes cause the resistance of the strain gauge wire to increase.

The gauge is attached to a meter through a balanced Wheatstone bridge. The added resistance unbalances the bridge allowing a signal to pass to the meter deflecting the needle producing a reading on the meter. If desired, a second semiconductor resistor can be installed on the opposite side of the diaphragm so that it now can read either pressure or vacuum. The meter used with this set up would be a center zeroing type that will read pressure when the needle deflects in one direction; and vacuum, when it deflects in the opposite direction.

14.6 Flow Rate Measurement

Flow rate is a measurement of the amount of fluid that passes a point during a given time interval, expressed as volume per unit time or mass per unit time. Flow rate is difficult to measure directly so common fluid flow relationships are used to allow other parameters to be measured and converted to flow rate.

The fluid flow Continuity Equation (see PPE Course Pre-Study Text Section 1.5) can be used to show that if a sudden pipe diameter reduction is placed in the path of a steady flowing incompressible fluid, the fluid velocity within the diameter reduction must increase significantly to maintain constant flow. Bernoulli's Equation can then be used to show that the velocity increase is acccompanied by a corresponding drop in pressure within the diameter reduction. The following simplification of Bernoulli's Equation describes the relationship of the fluid velocity and pressure conditions existing at the entrance(e) to the reduction and within (w) the reduction.

$$(v_w)^2 - (v_e)^2 \propto P_e - P_w \text{ (or } \Delta P_{ew})$$

where

- v_w = velocity within the diameter reduction (ft/sec),
- v_e = velocity at entrance to the reduction (ft/sec),
- P_e = pressure at entrance to the reduction (lbf/ft^2),
- P_w = pressure within the diameter reduction (lbf/ft^2), and
- ΔP_{ew} = differential pressure from entrance to within the diameter reduction (lbf/ft^2).

To measure flow using these relationships, a differential pressure (ΔP or D/P) is created by some type of diameter reduction or primary device such as an orifice plate, a flow nozzle, or a flow venturi (see Figure 14-15). Because flow rate is proportional to the square root of the ΔP, the ΔP is sensed and converted from a mechanical movement to an electrical signal for flow rate measurement. A specific primary device in a specific pipe location must initially be calibrated using known flow rates to obtain a reliable indication.

A disadvantage of using a pipe diameter reduction device to measure flow rate is that some of the pressure reduction caused by the device is not regained when the pipe diameter returns to full size. The cause of this non-recovery of pressure, or head loss, is fluid friction as described in Section 1.5 of the PPE Course Self-Study Text. The more fluid friction caused by the pipe reduction device, the more head loss or non-recovery of pressure that occurs in the device.

14.6.1 Orifice Plate

The orifice plate is merely a circular hole in a thin, flat plate that is clamped between the flanges at a joint in the system piping. One side of a D/P detector is connected upstream of the plate and the other side just downstream of the plate. The reduction in the flow area causes a pressure drop that is proportional to the square of the flow passing through the orifice. The orifice plate is inexpensive and accurate, but this device causes significant head loss (see Figure 14-15). In addition, orifice plates are susceptible to flow erosion, which makes the output inaccurate.

14.6.2 Flow Nozzle

The flow nozzle consists of a rounded inlet core and an outlet nozzle. The flow nozzle lends itself very well to the measurement of wet gases such as saturated steam with moisture in suspension. If the steam is dry or possesses superheat, then the nozzle is not necessary unless other conditions require it. Droplets carried in suspension in a gas stream can exert a considerable erosive effect, and the curved surface on the nozzle face guards this device against such action, thus contributing to a long, useful life that makes it more desirable for some installations than the orifice plate. Nozzles have somewhat better pressure recovery than the orifice plates and cause less head loss.

14.6.3 Flow Venturi

The flow venturi has a lower head loss than an orifice plate or flow nozzle, and is used in systems where a high pressure drop across the primary element is undesirable. The venturi consists of rounded inlet and outlet cones connected by a constricted middle section. As the velocity increases in the constriction, the pressure decreases. A pressure tap is provided in this low pressure area.

14.6.4 Elbow Flow Measuring Device

Elbow flow measuring devices (see Figure 14-16) operate on the principle that when liquid travels in a circular path, centrifugal force is exerted along the outer edges. Thus, when liquid flows through a pipe elbow, the force on the elbow's outer radius is greater than the force on the elbow's inner radius. Pressure taps are taken off the inside of the elbow (low pressure) and off the outside of the elbow (high pressure). The elbow-type flow device accuracy is poor at low flow rates. However, because the head loss across these devices is minimal, they are used in systems where maximum flow rates are essential (e.g., reactor coolant systems and main steam systems).

14.6.5 Pitometer

The main advantage of the pitometer is that the head loss is nearly undetectable. This is extremely important in the RCS when natural circulation flow is used as emergency cooling for the reactor. The use of the pitometer provides virtually no resistance to natural circulation flow.

Refer to Figure 14-17 during the following discussion of the operational theory of the pitometer. Although this cross-section view looks very much like a venturi, the actual pitometer tube more closely resembles a piece of pipe with eight fins on the inside circumference. The figure shows a cross section that happens to cut through the center of two opposite fins. The fins are equally spaced radially and are oriented axially around one circumference with two different types of fins in the cross section. The bottom one has its pressure nozzle pointed into the flow stream while the top one has its pressure nozzle pointed away from the flow stream. These two types of fins alternate around the inside of the tube.

The pitometer is reversible. It makes absolutely no difference which way the tube is installed in the piping. There will be four fins pointing in each direction no matter which way the tube is installed. However, the D/P detector must be connected properly (high-pressure and low-pressure taps) to provide accurate indication.

For this example, assume that flow is from left to right. The top fin's pressure nozzle faces downstream. Therefore, it will sense system pressure and transmit that pressure to the left piezometer ring (or chamber). All four of the nozzles that point downstream are connected to the same piezometer ring.

The bottom fin in our example faces upstream. It also is exposed to system pressure and will transmit that pressure to the right piezometer ring. The bottom fin and its nozzle are also exposed to the impact pressure on the fluid flowing by it. This impact pressure is proportional to the square of the flow rate.

Both piezometer rings run the full circumference of the insert. Each ring has five ports connected to it. Four come from the fins and the fifth connects to an access tap. The access tap is the point where a D/P transmitter will be connected. The purpose of sending the input from four fins to a common piezometer rings is to average those inputs. Because turbulence exists in the piping, it is conceivable that all four of the nozzles connected to each ring would see slightly different pressures. The rings will negate the effects of any turbulence through averaging and yield a much more stable pressure output to the D/P transmitter.

Both piezometer rings are exposed to system pressure; therefore, a D/P transmitter connected to each will cancel system pressure. The output of the transmitter will be proportional to only the impact (dynamic) pressure sensed by the upstream nozzles. This signal is then used to compute RCS flow rate.

14.7 Flow Sensors

14.7.1 Bellows Flow Sensor

The bellows flow sensor (see Figure 14-18) consists of two bellows: one that senses the high side (inlet) pressure of the primary device and another that senses the low side (outlet) pressure of the primary device. The difference in force exerted by the two bellows is proportional to the ΔP developed by the primary element. A mechanical connection is made to the force bar of the force balance transmitter or to the core of the movable core transformer to convert the differential pressure signal to an electrical signal. Since the flowrate is proportional to the square root of the ΔP, a square root extractor is again required.

14.7.2 Diaphragm Flow Sensor

The majority of the flow transmitters in the plant use diaphragm flow sensors. Again, the principle of opposing forces created by the ΔP across the primary device is used to sense flow with the diaphragm flow sensor (see Figure 14-19). The displacement of the diaphragm causes motion of the force bar of the force balance transmitter or the core of the movable core transformer and converts the D/P signal to an electrical signal. A square root extractor is again required.

14.7.3 Magnetic Flow Sensor

Unlike the previous flow sensors discussed in this section, the magnetic flow sensor (see Figure 14-20) does not require a primary element. The magnetic flow transmitter works on the principle that voltage can be generated if relative motion exists between a conductor and a magnetic field. The liquid is used as the conductor. The flow transmitter generates the magnetic field, and the flow of the liquid provides relative motion. Electrodes located in the piping detect the generated voltage.

14.8 Level

Accurate determination of water levels in a power plant is very important. Failure to maintain correct water levels in certain pieces of equipment can result in a quick failure or breakdown.

Most measurements of level are based on a pressure measurement of the liquid's hydrostatic head (see Figure 14-21). This hydrostatic head is the weight of the liquid above a reference or datum line. At any point, its force is exerted equally in all directions and is independent of the volume of liquid involved or the shape of the vessel. The measurement of pressure as a result of level head can be translated to level height above the datum line as follows:

$$z = P/\gamma,$$

where

z = height of liquid (ft),
P = pressure resulting from hydrostatic head (lbf/ft^2), and
γ = weight density of liquid (lbf/ft^3).

The relationship of the height of water above the gauge to the pressure is true if neither the atmospheric pressure above the water nor the water density (temperature) changes. A change in either of these parameters would necessitate a calibration change.

Bellows, diaphragm, or variable capacitance sensors can be used to provide a level indication signal. On tanks that are vented, the low side of the D/P sensor is open to atmospheric pressure.

Not all tanks are open to the atmosphere. Many are enclosed to prevent vapors from escaping or to allow pressurizing the tank contents. For these applications, a D/P detector is used (see Figure 14-22). To prevent any pressure on top of the liquid from being added to the hydrostatic pressure resulting from the liquid height, the pressure at the top of the tank is applied to the low pressure side of a D/P transmitter. The high pressure side is subjected to both the gas pressure on top of the liquid and the hydrostatic head of the liquid itself. The D/P transmitter's output is the pressure difference between the high pressure (hydrostatic + gas pressure) and the low pressure (gas pressure only) connections. With this D/P transmitter arrangement, level indication is not affected by changes in tank pressure. Any ΔP between the two sides of the detector is produced solely by the level in the tank.

A variation of the D/P system described above is the reference leg level detection system. A reference leg system is typically used in systems where the vapor produced by the liquid in the tank could condense in the low pressure leg and cause a ΔP variation. In the reference leg arrangement, a D/P transmitter is again attached to the bottom of a closed tank (see Figure 14-23). Note that the low pressure side is now the tank connection (variable leg) while the high pressure side is the reference leg side. The level (ΔP) is sensed in accordance with the following equation:

$$\Delta P = z_r \gamma_r - z_v \gamma_v$$

where

z_r = height of the reference leg,
γ_r = density of the reference leg,
z_v = height of the variable leg, and
γ_v = density of the variable leg.

Note from the above formula that a density change in either the reference or variable leg will affect the ΔP that is seen by the sensor. When the vessel is full, the ΔP is equal to zero if the density is the same in both legs. As the level goes below full, the ΔP in the reference leg system increases. Other phenomena that cause the ΔP to increase (cooling the reference leg or warming the tank contents) will cause the indicated tank level to decrease. Lowering the level in the reference leg would cause ΔP to decrease and the indicated tank level would increase above the actual level. Therefore, it is essential that the level in the reference leg is kept constant. This is usually accomplished by an external filling connection or by a condensing pot connected to the vapor space. Figure 14-24 depicts a typical pressurizer level detection system using a reference leg with a condensing pot.

Both flow and level sensors use D/P cells or transmitters. If the equalizing valve (bypass valve) for the D/P cell is opened, the high pressure and low pressure signals for the D/P cell would be equalized and a zero ΔP would be generated. This would correspond to an indication of a full vessel for a reference leg level detection system or no flow for a flow measuring system.

14.8.1 Level Error

A normal occurrence that will cause inaccurate level indication is the heating or cooling of the tank contents. During normal plant operation, a pressurizer temperature in excess of 600°F is normal. During a plant shutdown, the pressurizer (and the rest of the RCS) will be cooled to less than 200°F. As the pressurizer cools, the water will become more dense resulting in a lower level. However, although z_v decreases, γ_v increases, and the $z_v\gamma_v$ term remains essentially unchanged. Because the reference leg height (z_r) and density (γ_r) have not changed, the D/P detector senses no change in level. To compensate for this inaccuracy at lower temperatures, an additional D/P detector is installed that has been calibrated at a pressurizer temperature below 200°F. The cold calibrated D/P detector is only used at low pressurizer temperatures; it is inaccurate at high pressurizer temperatures. In some cases, the temperature of the tank contents is continuously measured to provide electronic density compensation of the level indication.

Errors in level indication from detector failure or electronic failures are not predictable to any amount of usefulness. Predictable failures that are of concern during transient or accident conditions relate to the loss of the reference leg. Two abnormal conditions for discussion are rapid depressurization, associated with steam generator level, and containment temperature increases affecting both the steam generator and the pressurizer.

The water in the reference leg is maintained at ambient temperature, except in the condensing pot where the water is near saturation temperature. During depressurization the water in the condensing pot can flash to steam. This would remove some of the water from the reference leg, thus lowering the reference pressure on the detector, thereby giving a higher than actual indicated level. This condition will correct itself as the condensing pot refills due to condensation. Some indications of this transient are bouncing level indications or unequal level indications between two level instruments.

One incident that increases the containment temperature would be a small line break that flashes to steam. The increase in the ambient temperature will affect the level indication by increasing the reference leg ambient temperature therefore decreasing the density in the leg; this again will decrease the reference pressure on the detector giving a higher than actual indicated level. To reduce the effects of changing reference leg temperature, a stable ambient temperature should be provided. Electrical and electronic equipment should also be maintained in a proper environment to prevent degradation of electrical circuitry.

14.9 Signal Processing

The output of the force balance transmitter and the variable capacitance transmitter is a current signal with a range of 4 to 20 mA or 10 to 50 mA for many different circuits. Figure 14-25 illustrates how the current output of one of these transmitters is used to supply input signals to several systems. If a 4-20 mA transmitter output and 250 ohm resistors are assumed, then by Ohms law, the input signal to each system will vary over a 1 to 5 volt range as the output of the transmitter varies from 4 to 20 mA. Since the resistors are in series, each system receives the same input signal. The arrangement in Figure 14-25 is known as a current loop.

14.10 Calibration

Calibration is a recurring and important activity related to plant instrumentation and control maintenance. Instruments are normally calibrated on a "loop basis." The instrument loop includes the components from the sensor or instrument element to any signal processing or conditioning equipment to the transmitter or actuator device and finally to any recording or indicating devices. Plant instrument calibration methods vary significantly between types of instruments, but some calibration procedure elements are similar. The instrument must be "zeroed" to ensure that the lowest response or indicating ranges are accurate. The instrument range must be verified with instrument accuracy determined over the entire operating range or span, and with linear responses over the entire range. The setpoints of the instrument, or the alarm readings, must be adjusted and properly set. And finally, the repeatability of the instrument must be verified. When the instrument is found to be out of tolerance, a determination must be made of the error impact on plant operation and safety. The equipment used in performing instrument calibrations are as diverse as the calibration methods. Typical equipment used in calibrations include power supplies for simulating electrical inputs when calibrating electronic equipment; manual loaders and dead weight testers for calibrating pressure indicating equipment; manometers; gauges; and decade boxes. In all of these cases the equipment must be the correct accuracy, the proper range, and must be utilized in accordance with the proper instructions and procedures.

14.11 Environmental Qualification

Although knowledge of how various primary and secondary transducers function is desirable from an operations standpoint, it is vital that the operator have a general idea of how the instrumentation responds under accident conditions. In some cases, the operator is relied on to mitigate the consequences of certain accidents. To take correct actions, the operator must be supplied with usable information upon which to base decisions.

In order for utility companies to operate a nuclear plant, the NRC requires instrumentation that is able to monitor certain specified parameters within specified ranges, and accuracy that has been environmentally qualified.

The basic aim of qualification of safety-related equipment is to reduce the potential for common mode failures due to environmental effects, and to demonstrate that safety electrical equipment is capable of performing its designated safety-related functions. To accomplish this, the equipment must be designed to perform with a certain degree of accuracy during normal operations, abnormal operating conditions (i.e., local heat up due to cooling equipment malfunction), accident conditions, and for a specified time after an accident.

Qualification may be accomplished in several ways: type testing, operating experience, or analysis. In type testing, the instrument is actually subjected to the various environments and operating conditions for which it was designed, and its performance is measured.

Although operating experience is very limited as a sole means of qualification, it can serve as a useful supplement to other tests in that it may show how materials and equipment change with time under actual service and maintenance conditions. Operating experience is of particular use in qualification of equipment outside the containment.

Qualification by analysis requires a mathematical model to predict the response of the instrument to environmental influences. The validity of the model must be justified by test data, operating experience, or physical laws. Because general mathematical models that accurately predict the overall response of an instrument to a variety of environmental inputs do not exist, the usual analysis case predicts the response of the instrument to a single input (i.e., seismic event) while holding all the other inputs constant. Then, other partial type tests are done and the results are combined to provide the necessary qualification data.

Of the three methods, by far the most preferred is type testing. In fact, NUREG-0588 states that the NRC will not accept analysis in lieu of test data unless testing of the component is impractical.

14.12 Compensating Measures for Adverse Environment

The results of environmental qualification reveal that, even with the best design and construction, instrument channel accuracy is still affected by adverse environmental conditions. However, because of environmental testing, these effects are predictable and the maximum expected inaccuracies can be determined. Once the maximum expected inaccuracy for an instrument is known, the instrument reading can be corrected to yield a conservative value for the monitored parameter.

Emergency operating procedures (EOPs) use a variety of process instrument indications to direct operator actions during an accident condition. Many instruments that are relied upon have components located inside containment. If an accident causes an adverse containment environment, then many instrument readings may become inaccurate. In this event, EOPs provide alternate, more conservative, parameter values for use in directing the operators. For example, a steam generator level of 50% may be acceptable under normal conditions. But, if the instrument is being subjected to adverse environment, it may be inaccurate. Therefore, the EOPs will require a higher indicated level (such as 60%) to ensure actual level is acceptable. These alternate parameter values are used whenever containment temperature, pressure, or radiation level exceeds a predetermined value. The values vary among vendors of nuclear reactor plants.

In other EOP applications where an accurate instrument reading is required from an instrument affected by adverse environment, graphs in the procedures provide a correction for indicated parameter values based on the value of the adverse parameter (temperature or pressure). The graphs provide a more accurate indication of the actual monitored parameter but are somewhat time consuming and are only used when accuracy of measurement is vital.

14.13 Summary

The measurement of process variables involves the conversion of these variables into a mechanical motion, and then into an electrical signal. The electrical signal is used as an input for indication, control, and protection systems. The process variables discussed in this chapter were temperature, pressure, flow, and level. Each process variable is monitored by an instrument channel to provide essential information to the operator. Instrument channel component operation was discussed including the effects of adverse environment and compensating measures. Remember that an operator controls the plant based on indications from process instrumentation. Therefore, knowledge of the operation of process instrumentation is essential to the safe operation of the plant.

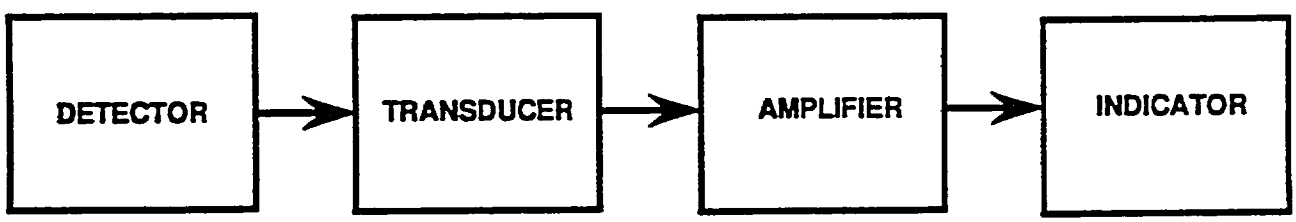
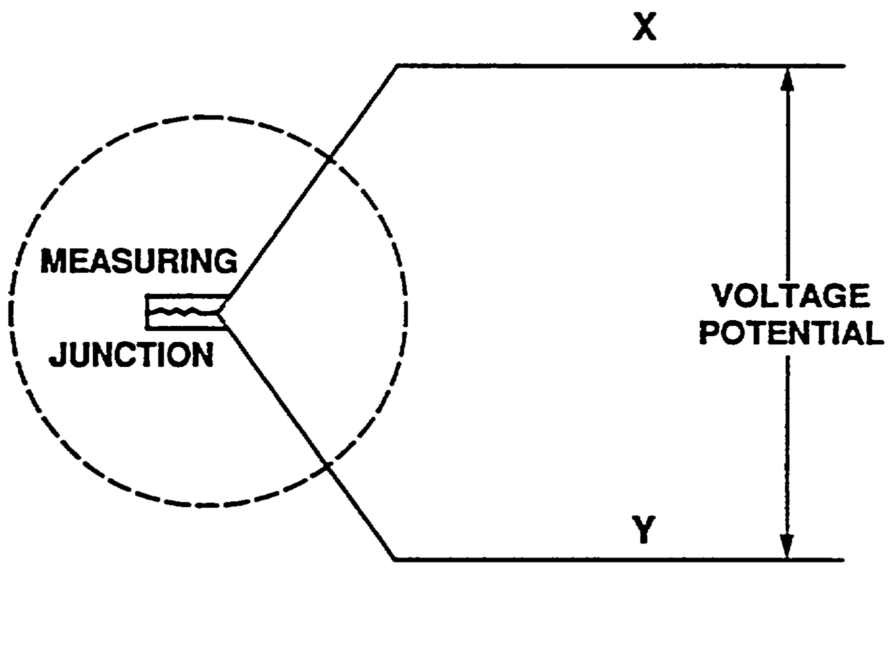
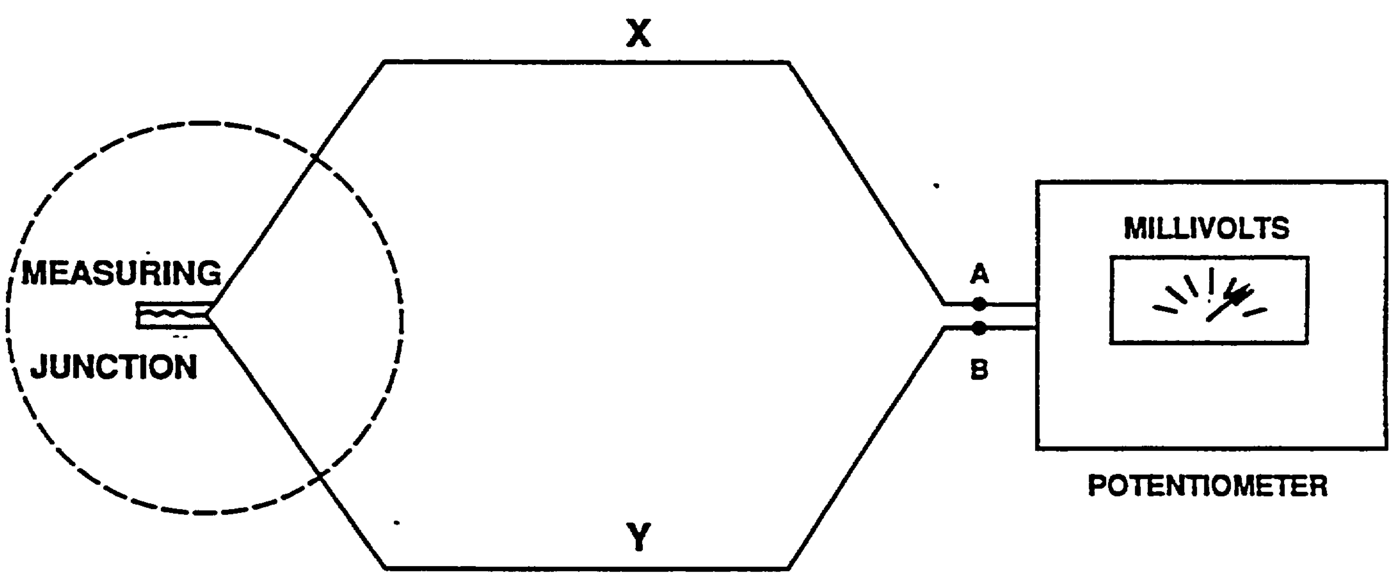


Figure 14-1. Basic Instrument Channel



A. Simple Thermocouple



B. Basic Thermocouple Circuit

Figure 14-2. Basic Thermocouple Diagrams

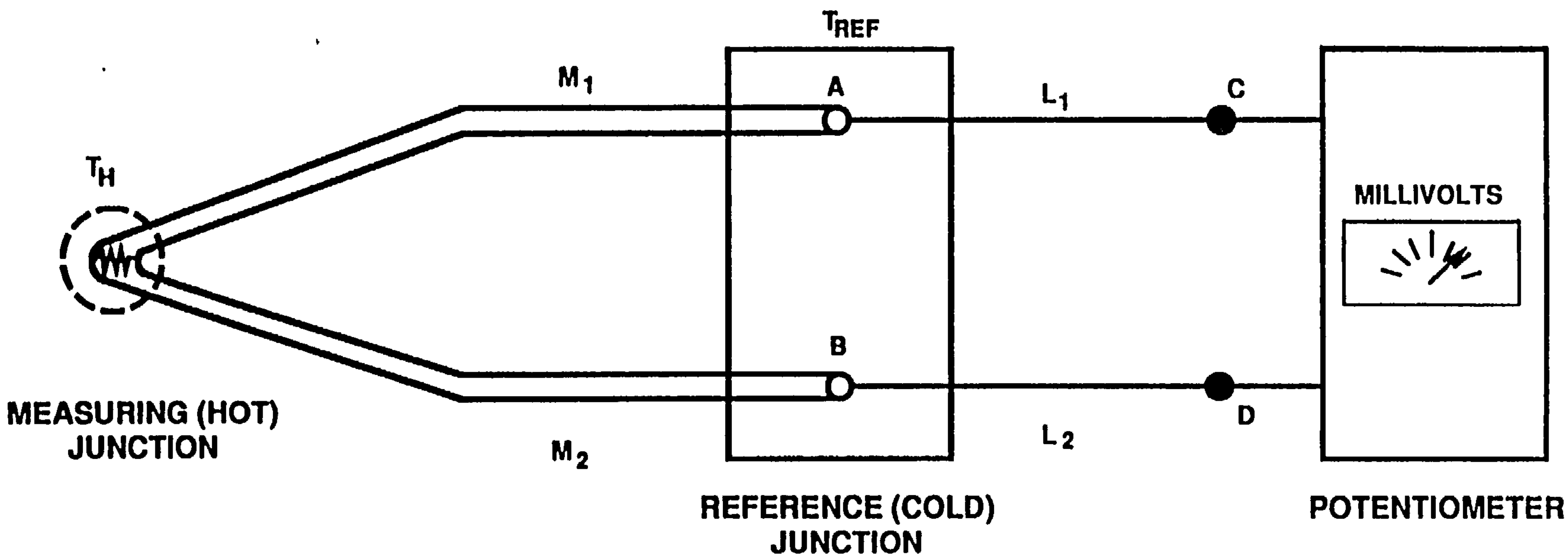


Figure 14-3. Detailed Thermocouple Circuit

Temperature Resistance Coefficients for Common Metals

Material	α (°F^{-1})
Aluminum	0.0025
Copper	0.0024
Gold	0.0022
Nickel	0.0037
Platinum	0.00217
Tungsten	0.0027

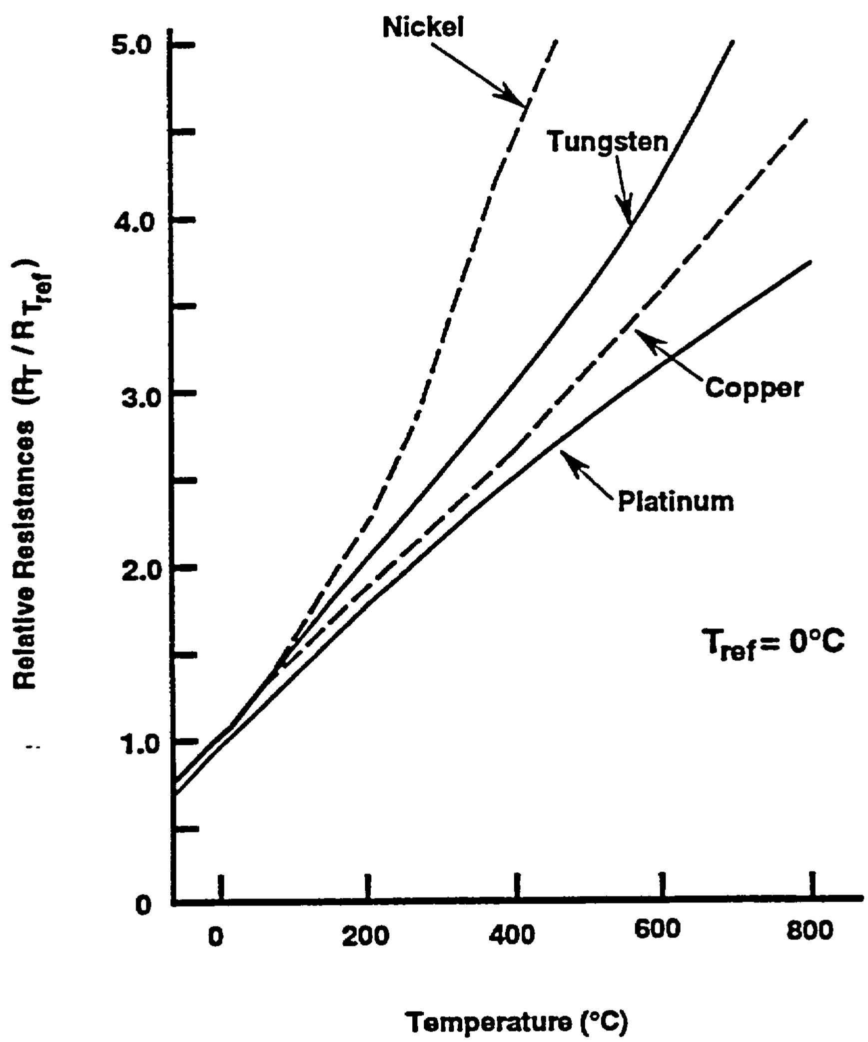


Figure 14-4. Resistance - Temperature Characteristics of Metals at Elevated Temperatures

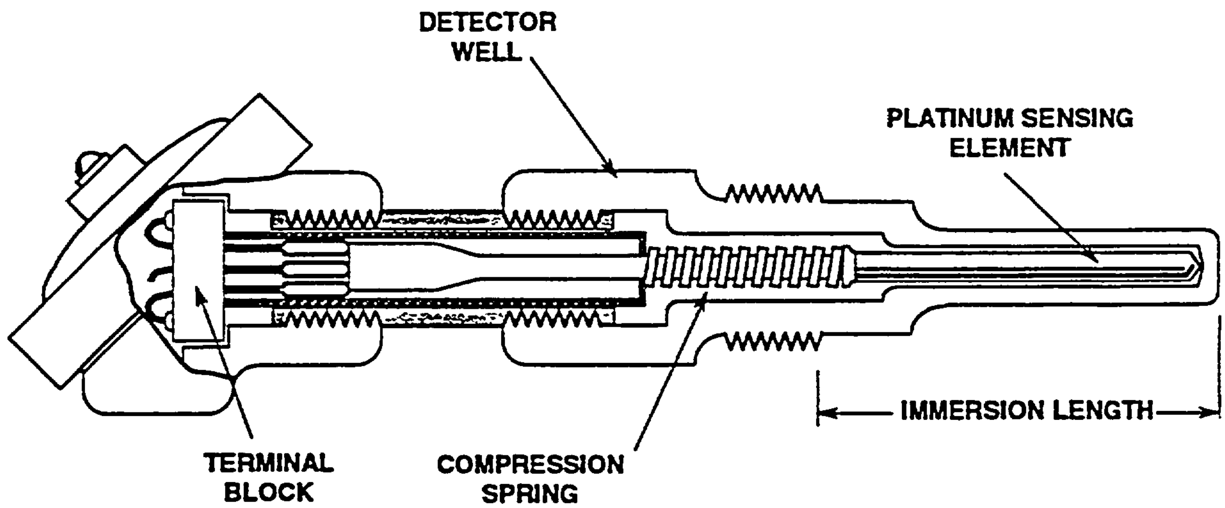
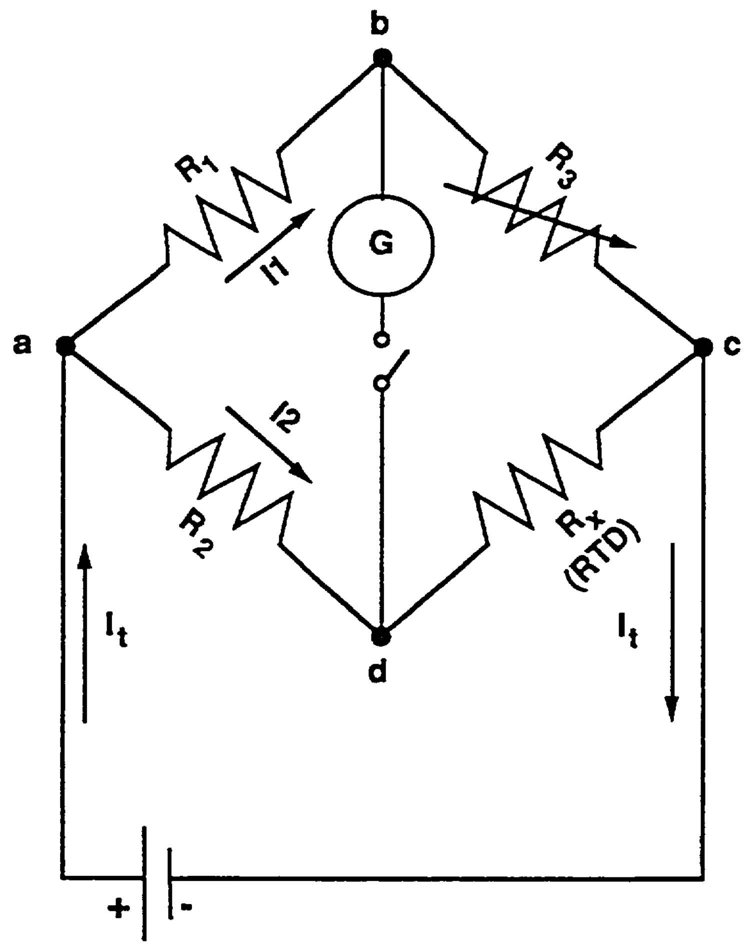


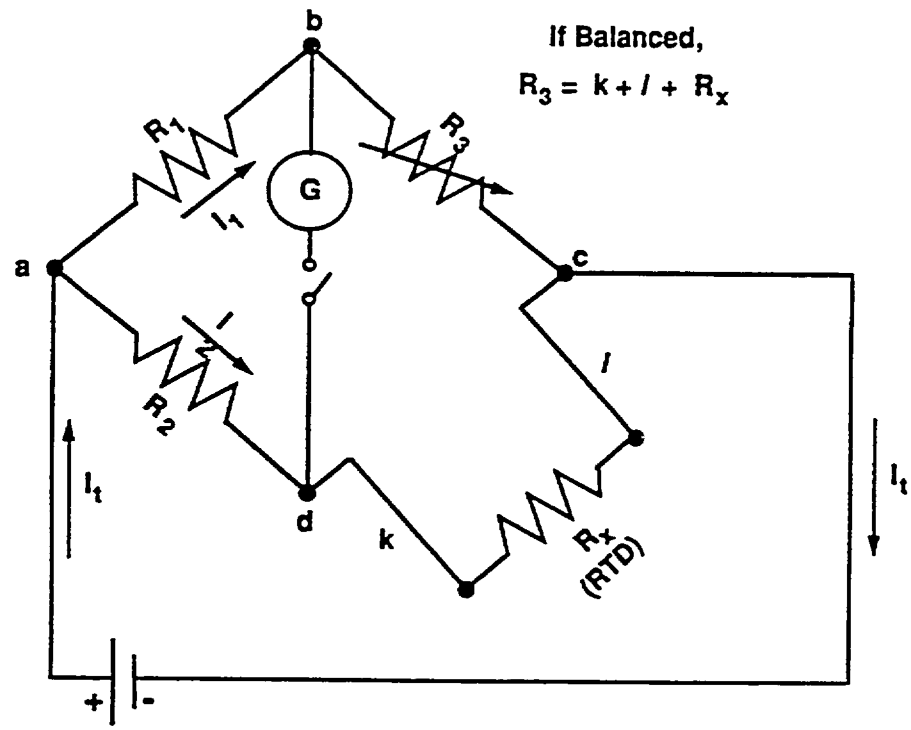
Figure 14-5. Resistance Temperature Detector



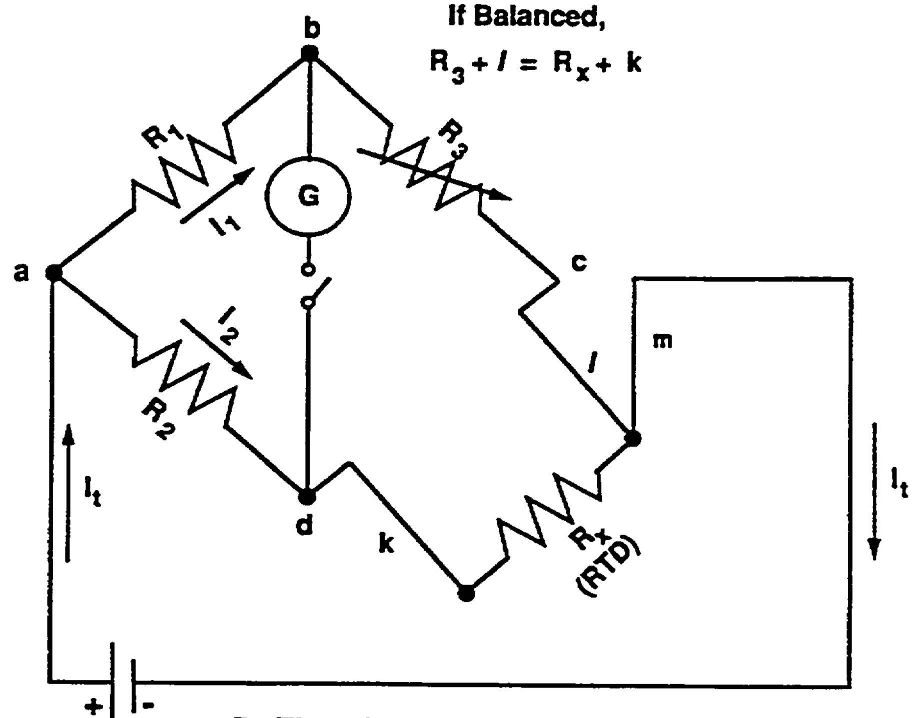
NOTE: $R_1 = R_2$

If the bridge is balanced, $R_3 = R_x$

Figure 14-6. Wheatstone-Bridge Circuit



A. Two-Lead Connection



B. Three-Lead Connection

Figure 14-7. Remote RTD Connections

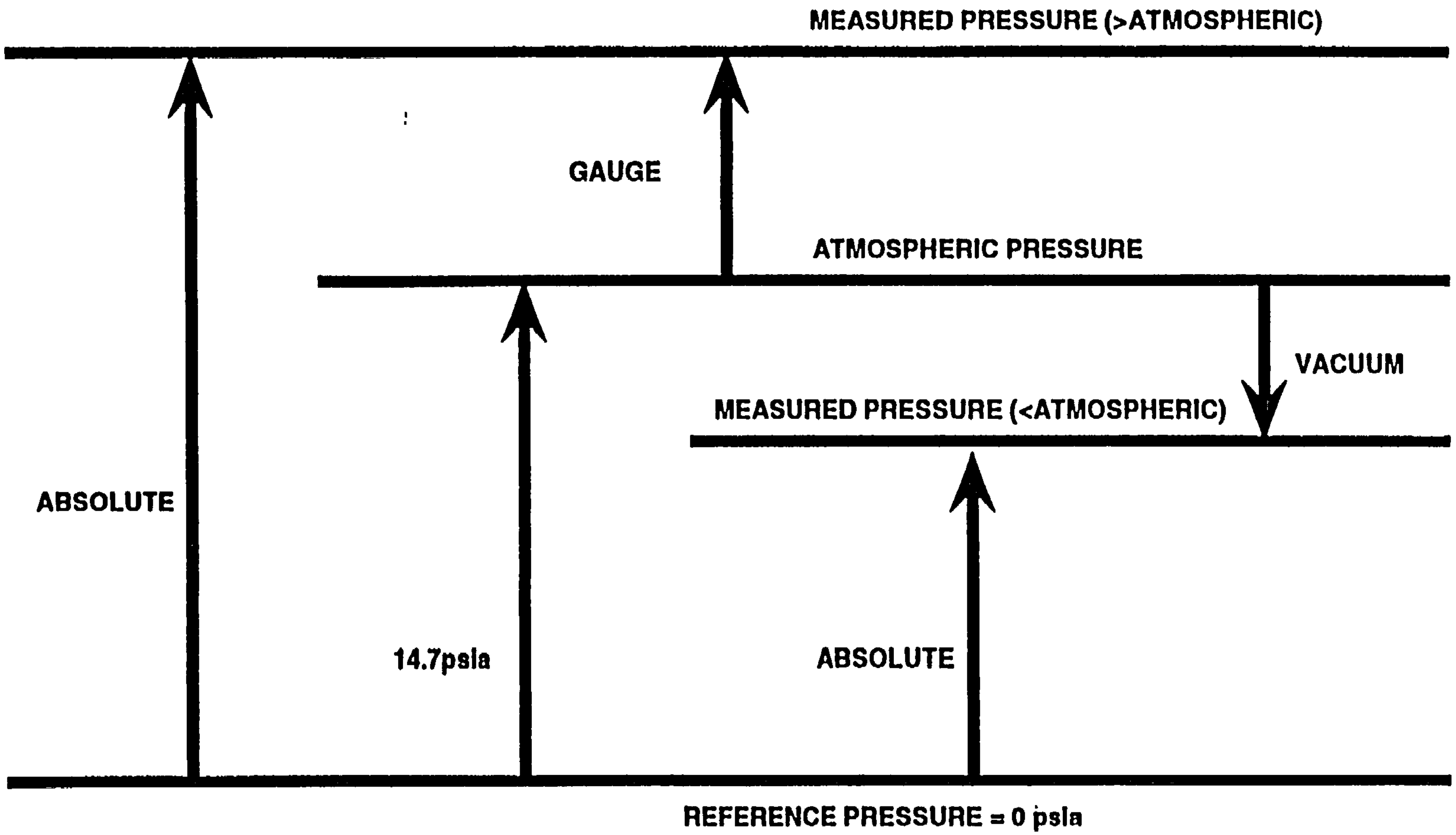


Figure 14-8. Pressure Units

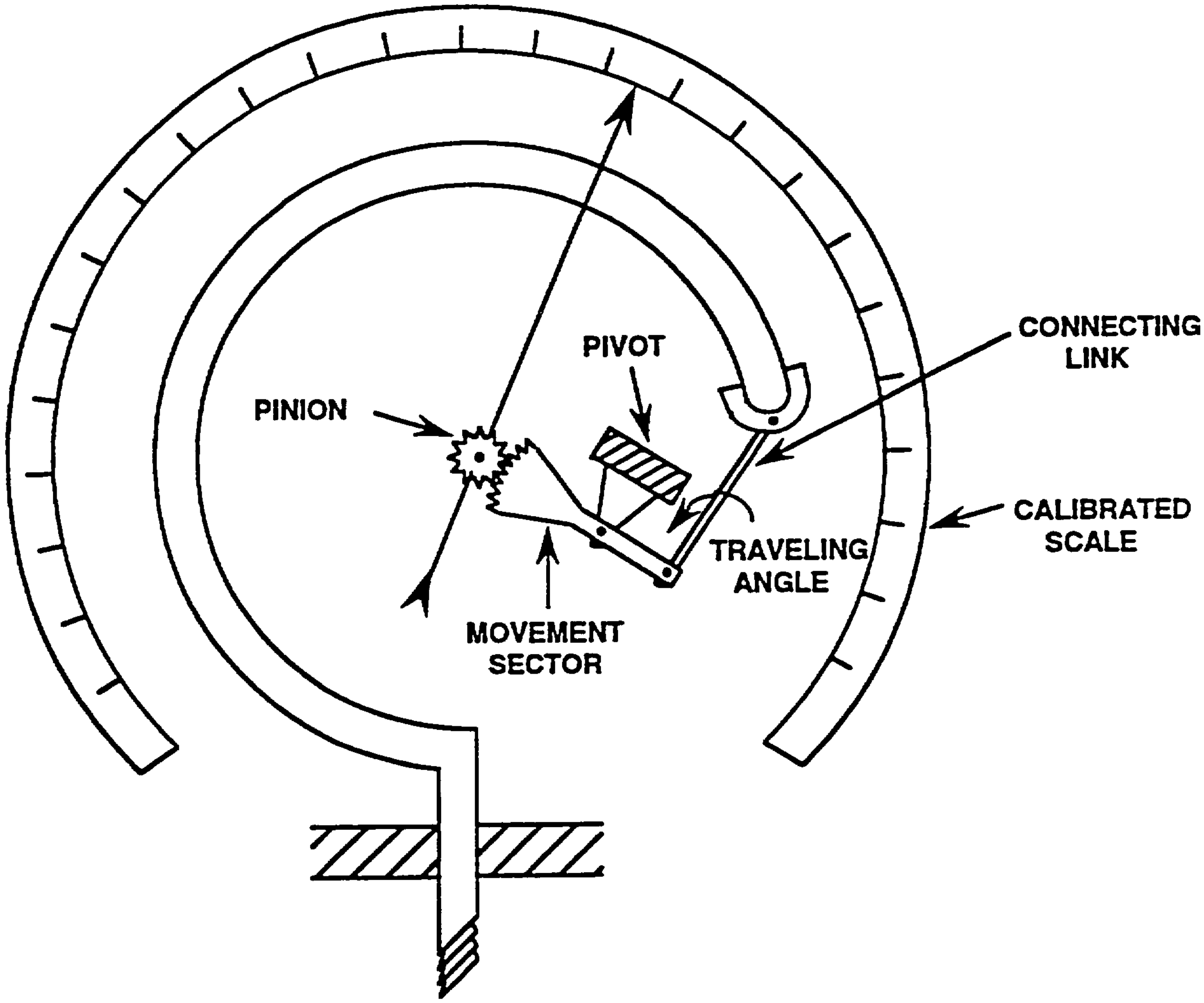


Figure 14 - 9. Bourdon Tube Pressure Gauge

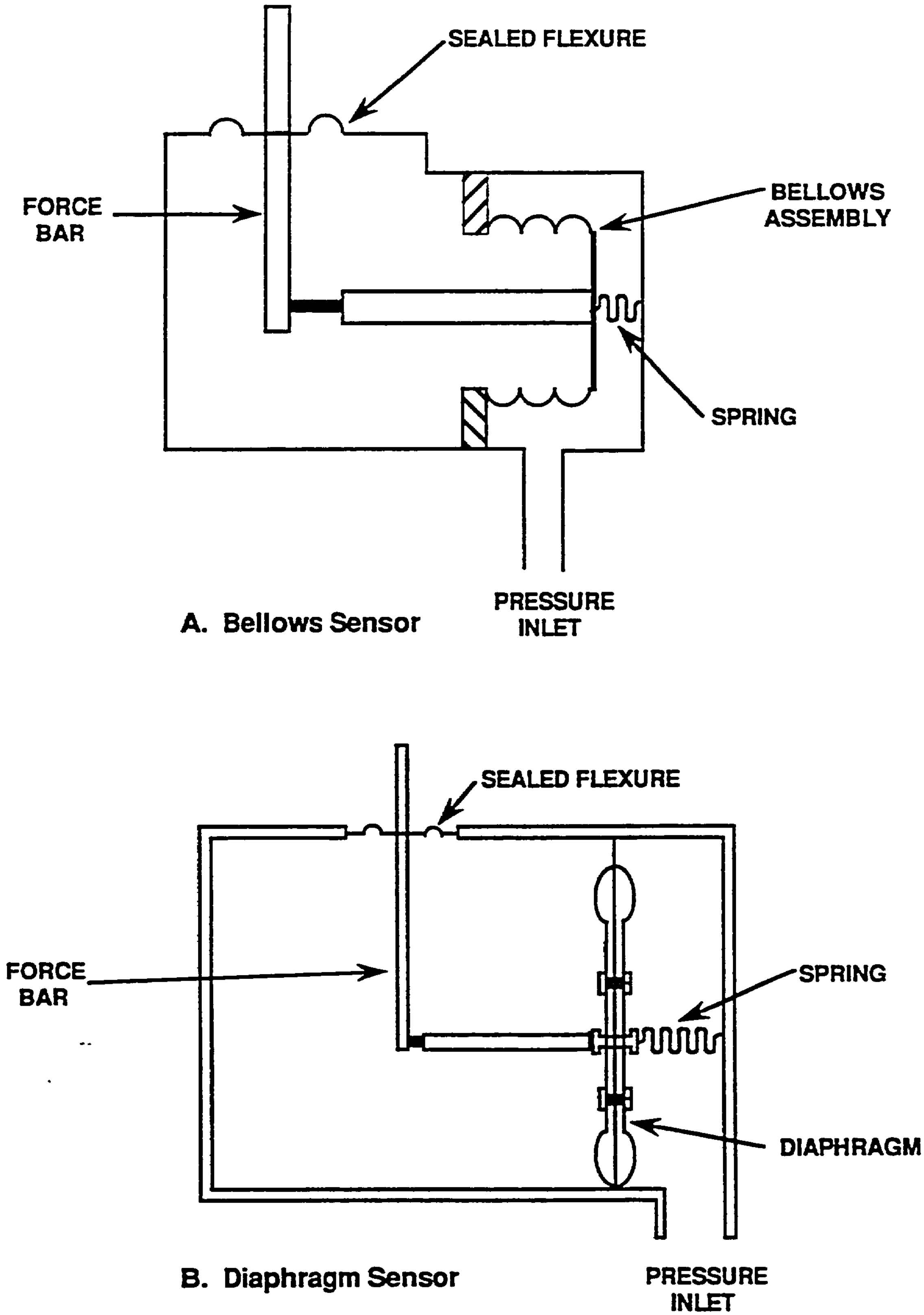


Figure 14-10. Diaphragm / Bellows Pressure Sensors

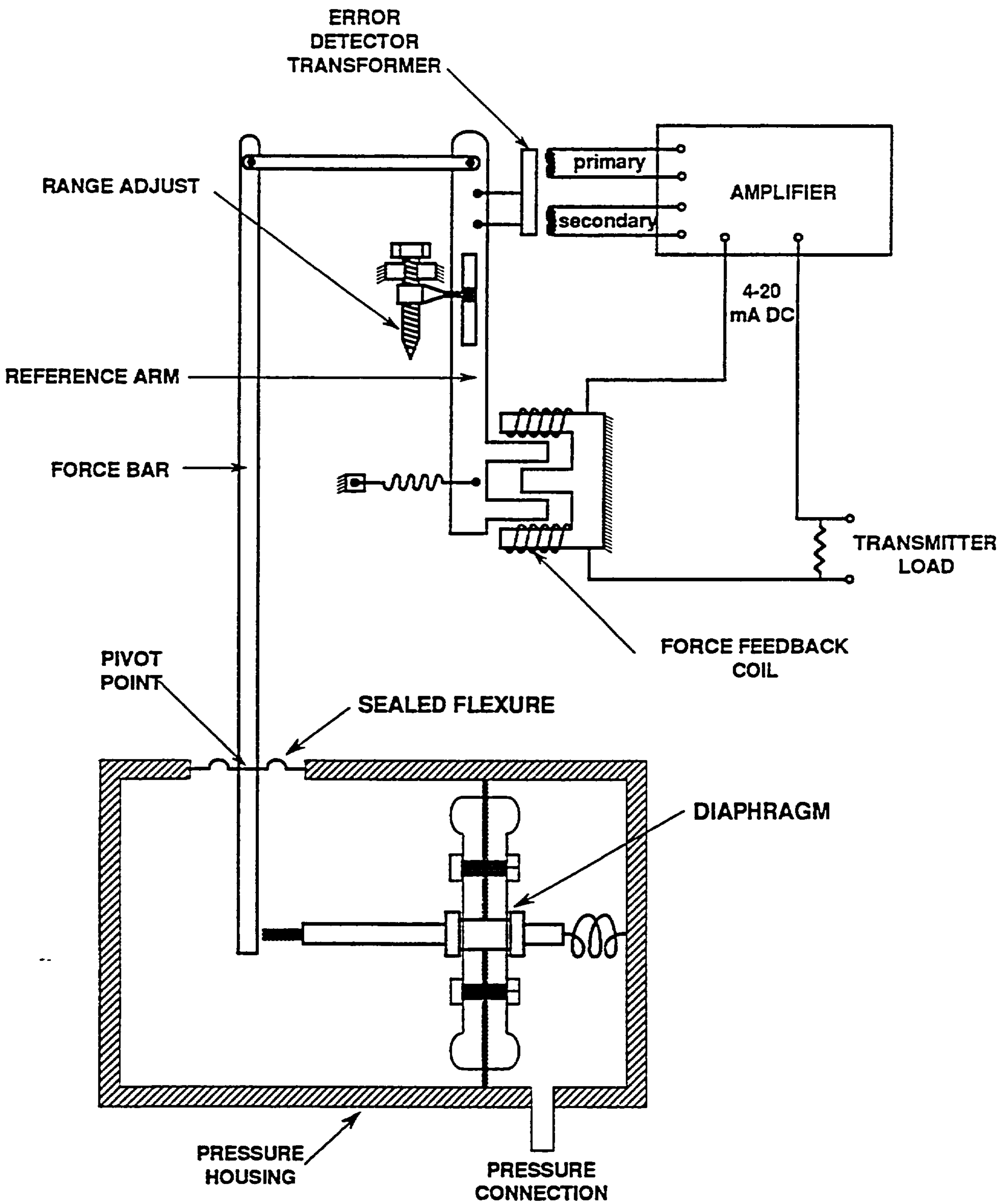


Figure 14-11. Force Balance Transmitter

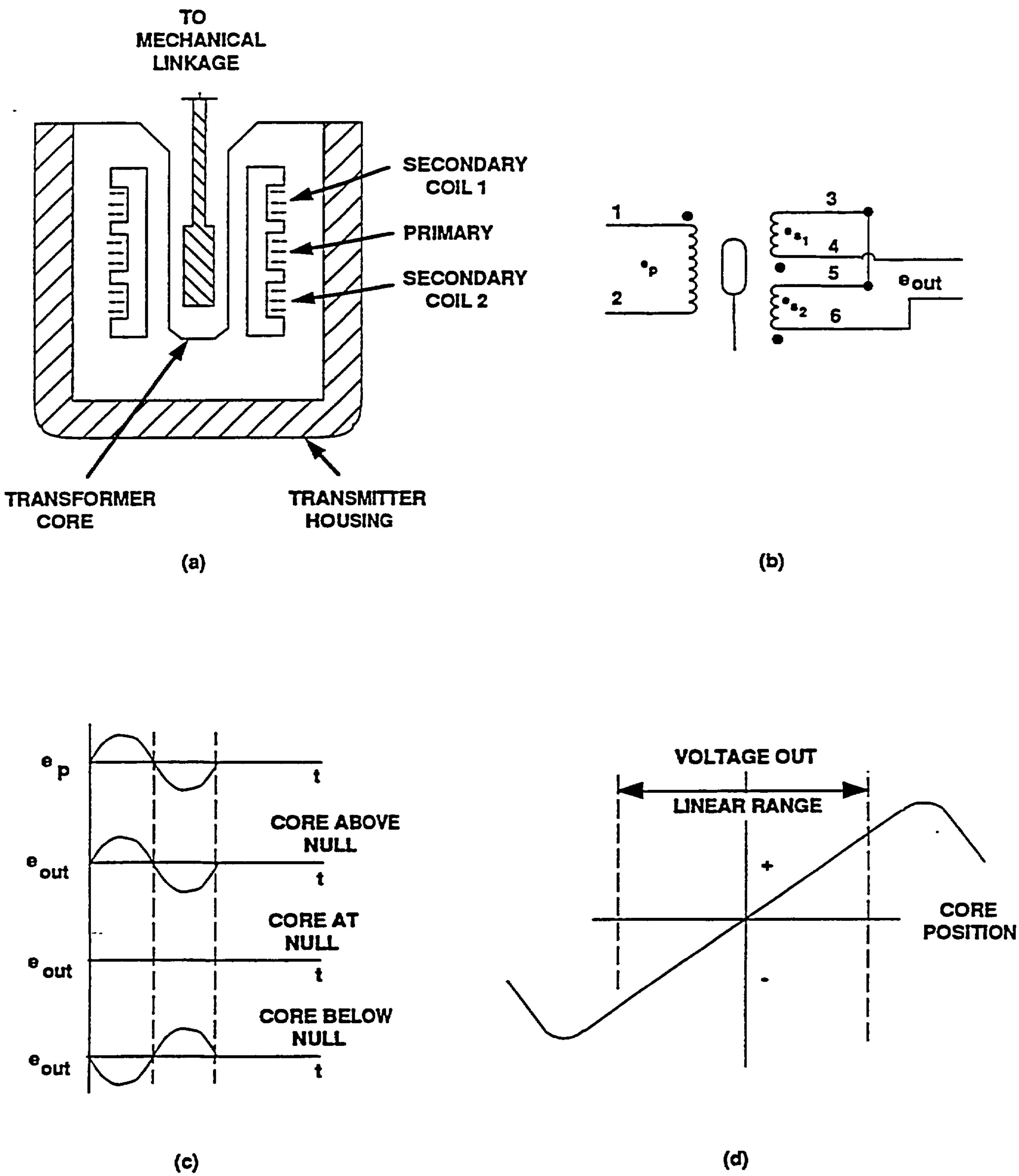


Figure 14-12. Movable Core Transmitter

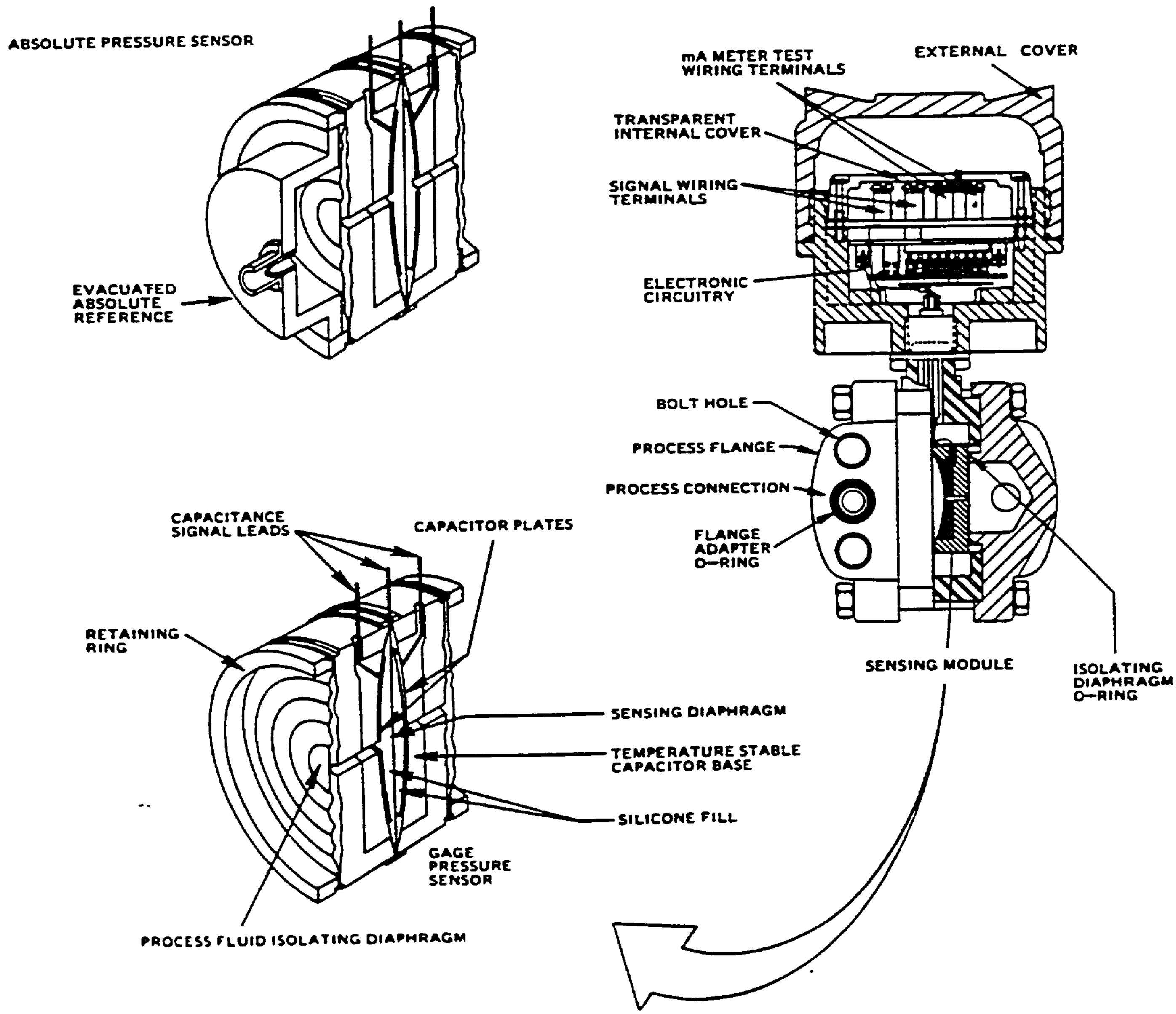


Figure 1.3-6 Variable Capacitance Transmitter

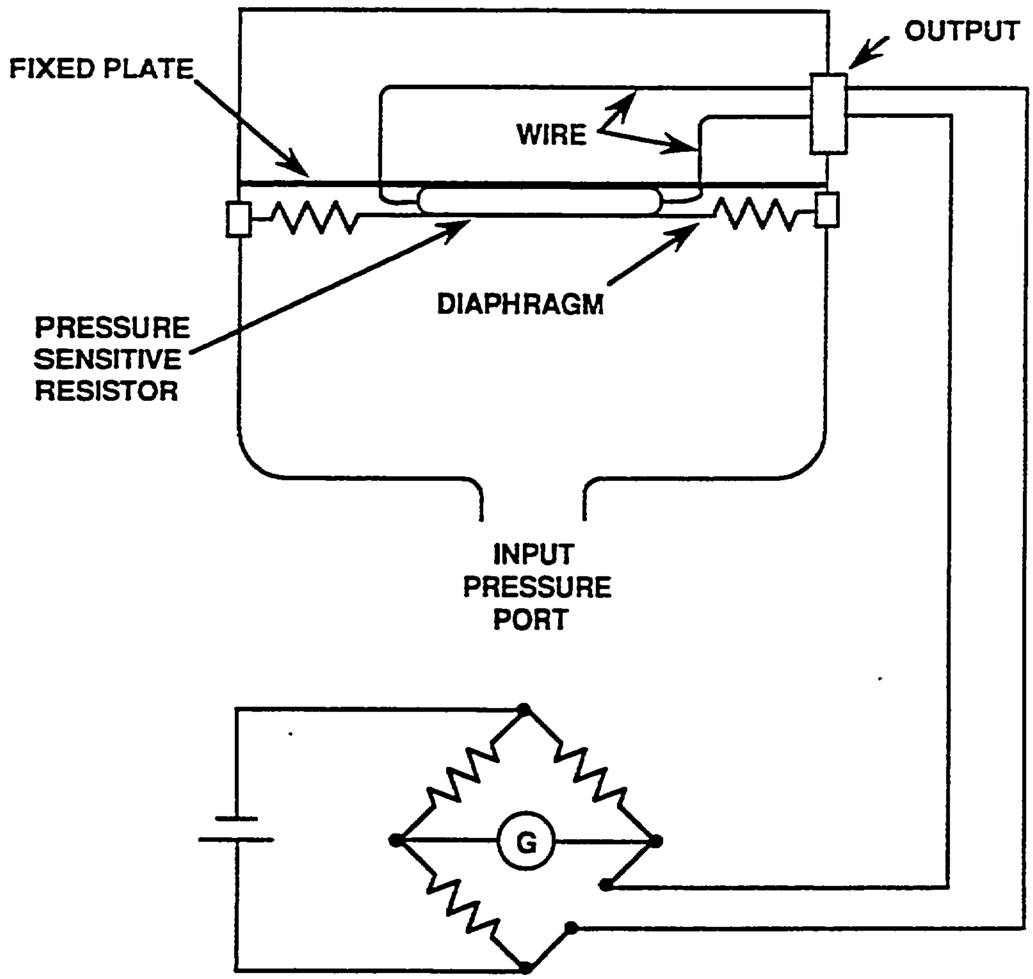


Figure 14 - 14. Strain Gauge

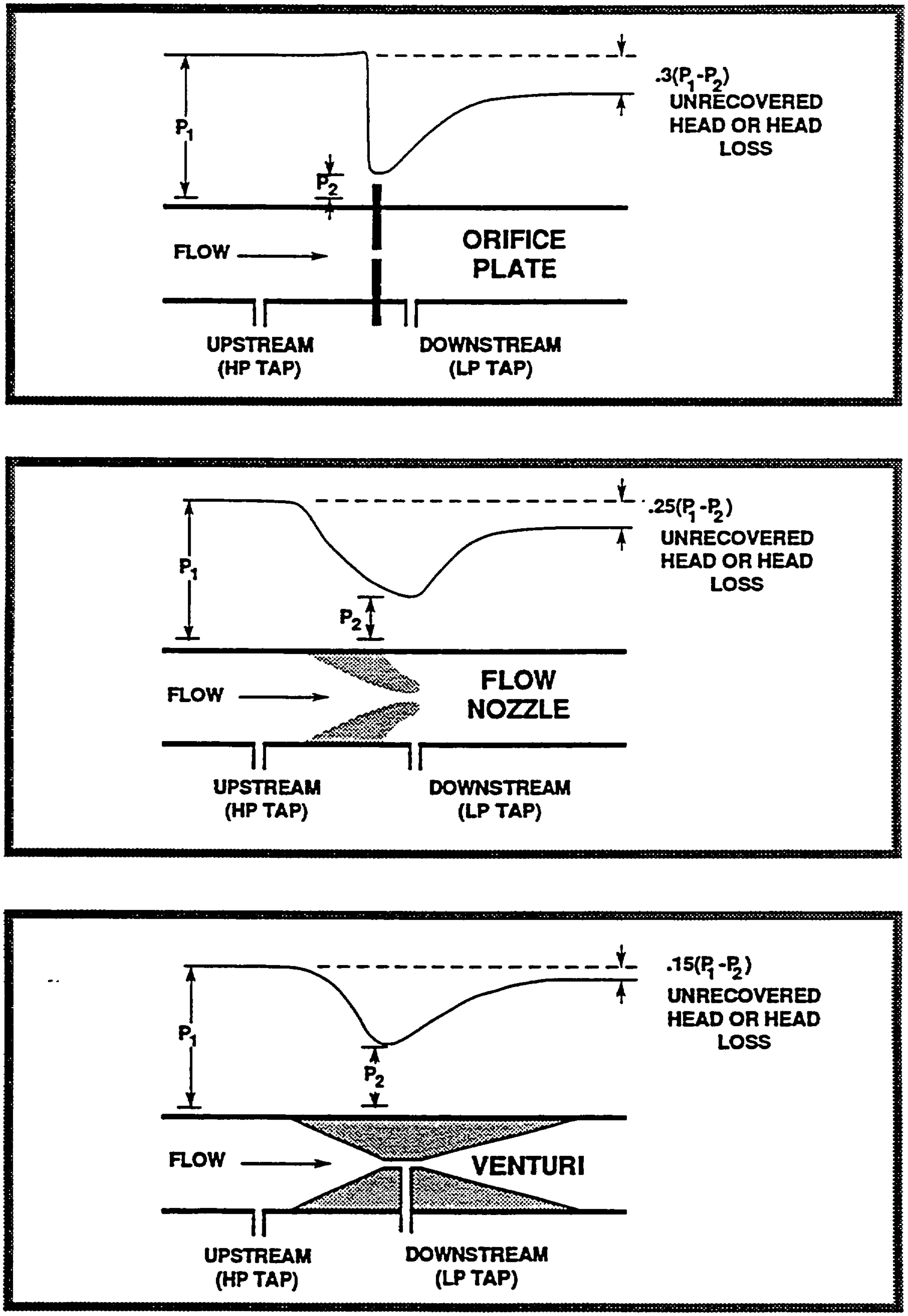


Figure 14-15. Primary Elements

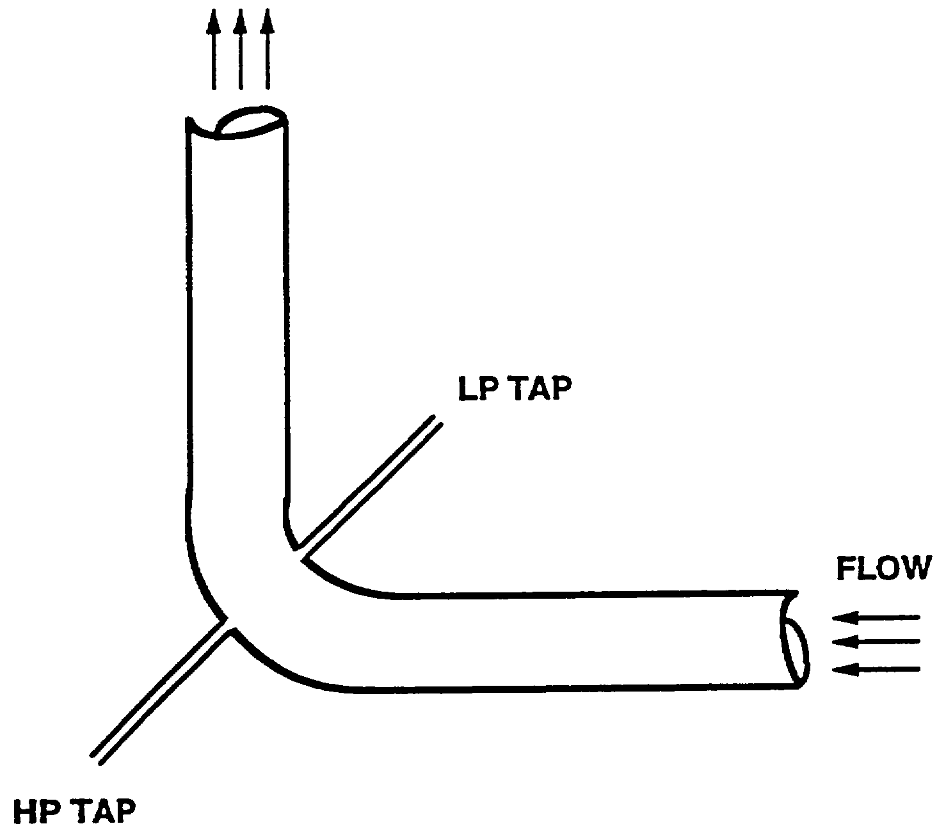


Figure 14-16. Elbow Flow Measuring Device

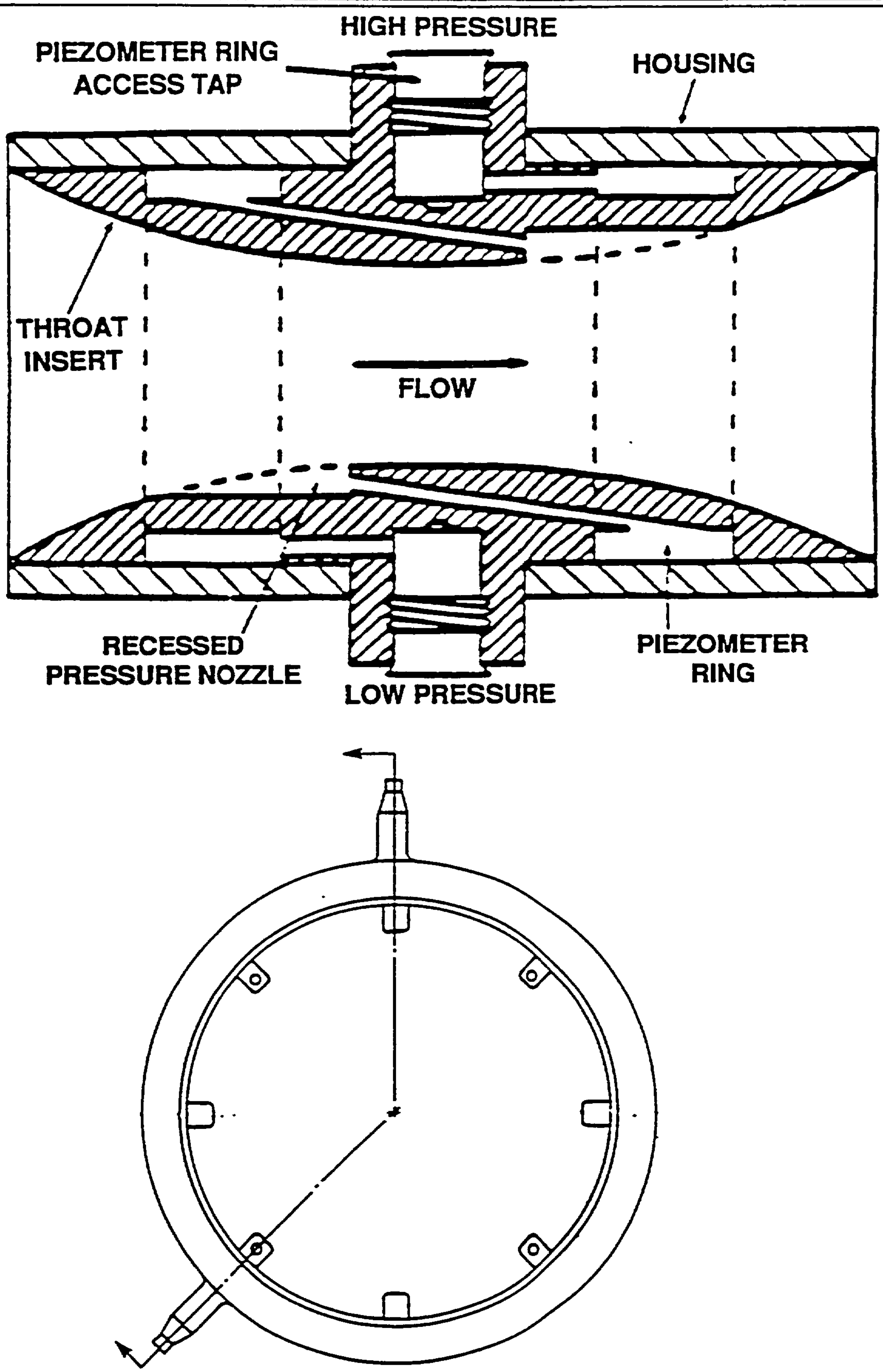


Figure 14 - 17. Pitometer Flow Tube

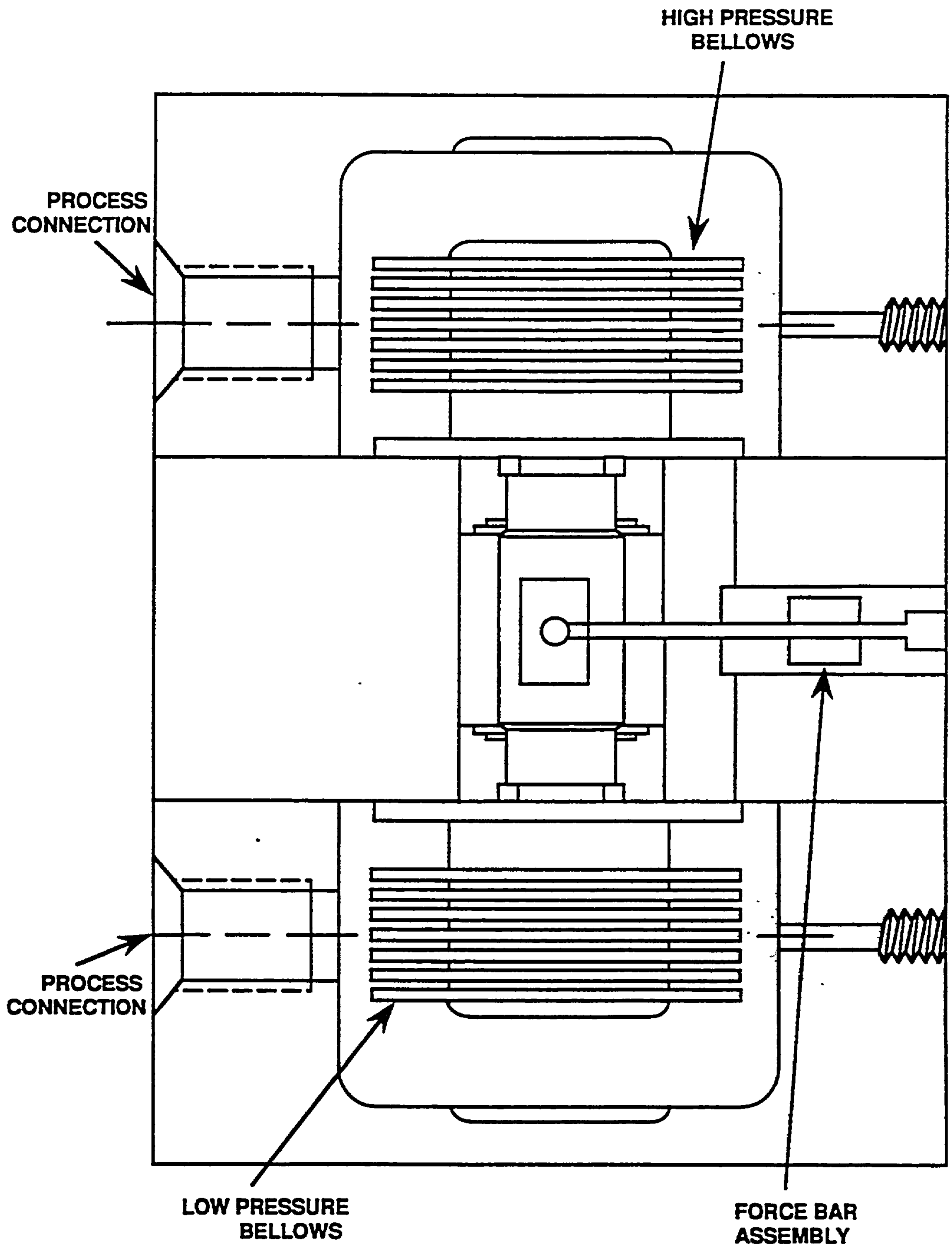


Figure 14 - 18. Bellows Flow Sensor

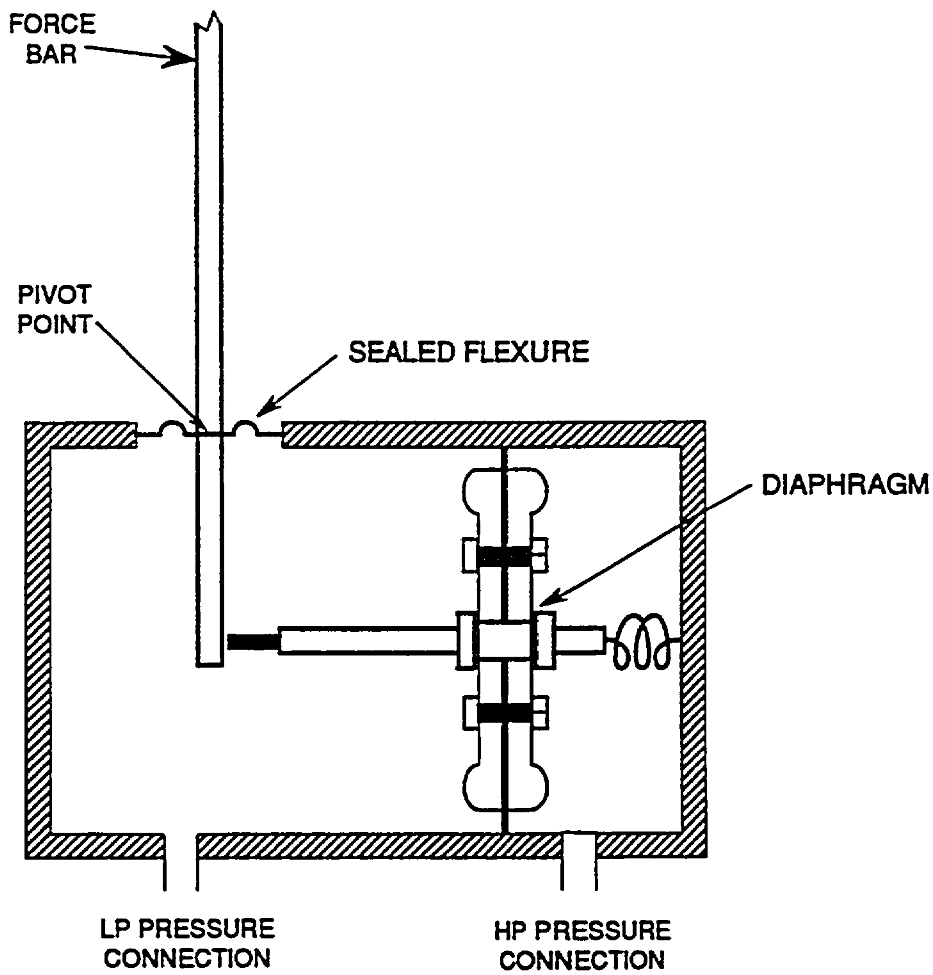


Figure 14 - 19. Diaphragm Flow Sensor

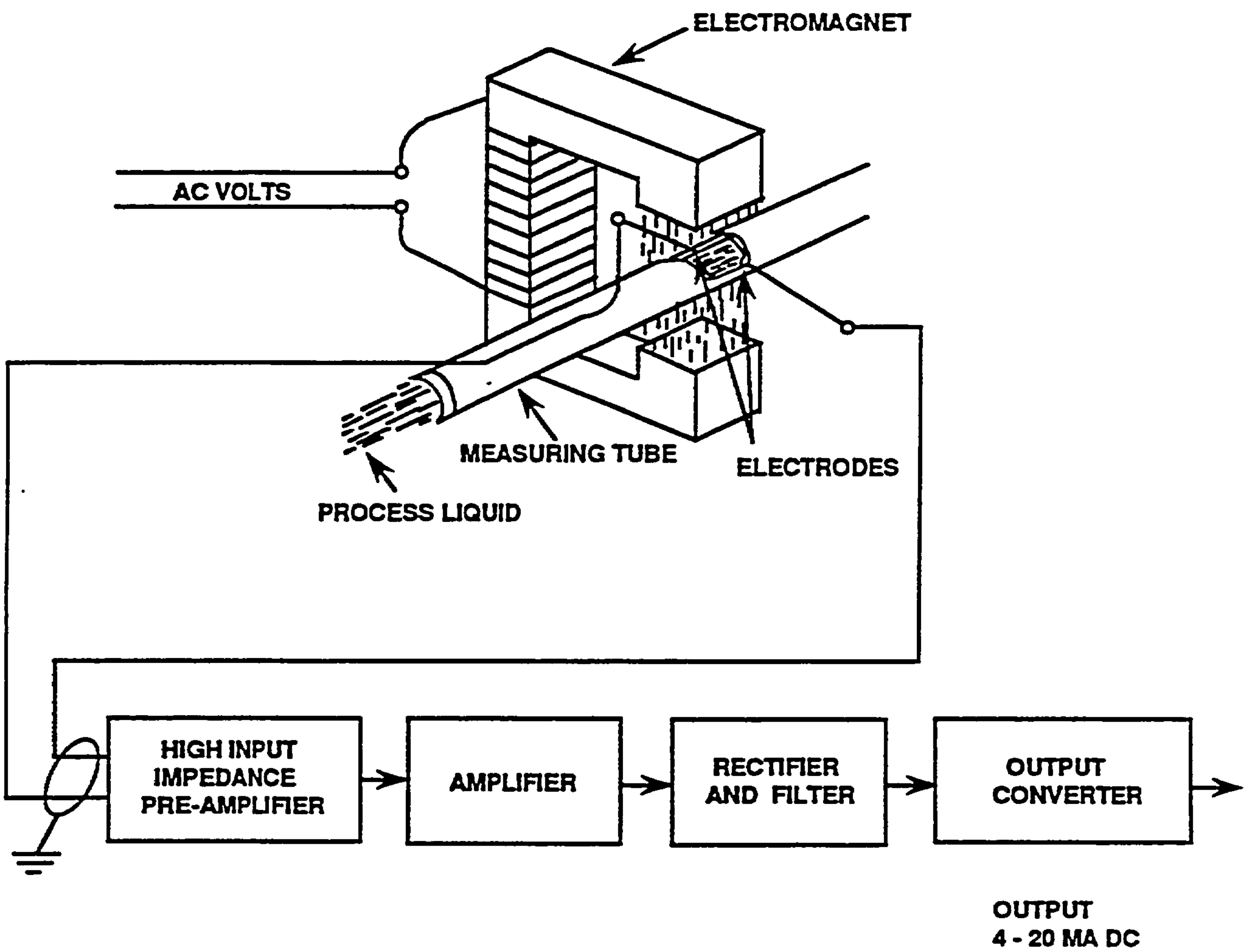


Figure 14-20. Magnetic Flow Sensor

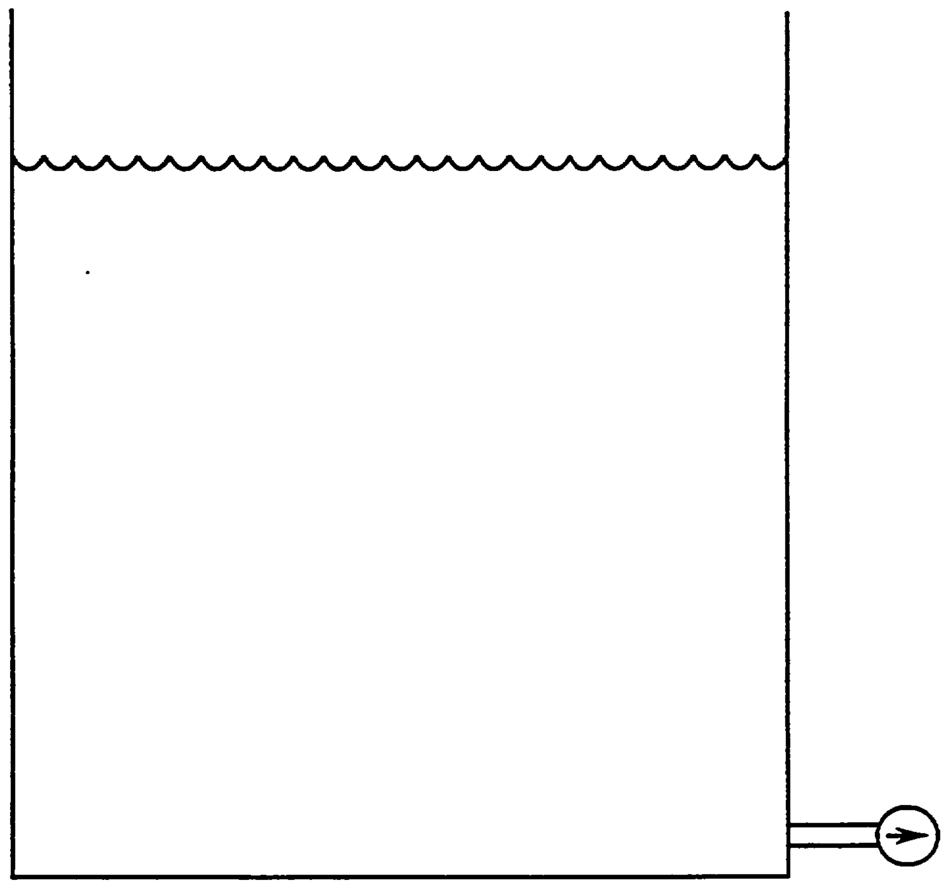


Figure 14 - 21. Level Measuring Device for Tank Open to Atmospheric Pressure

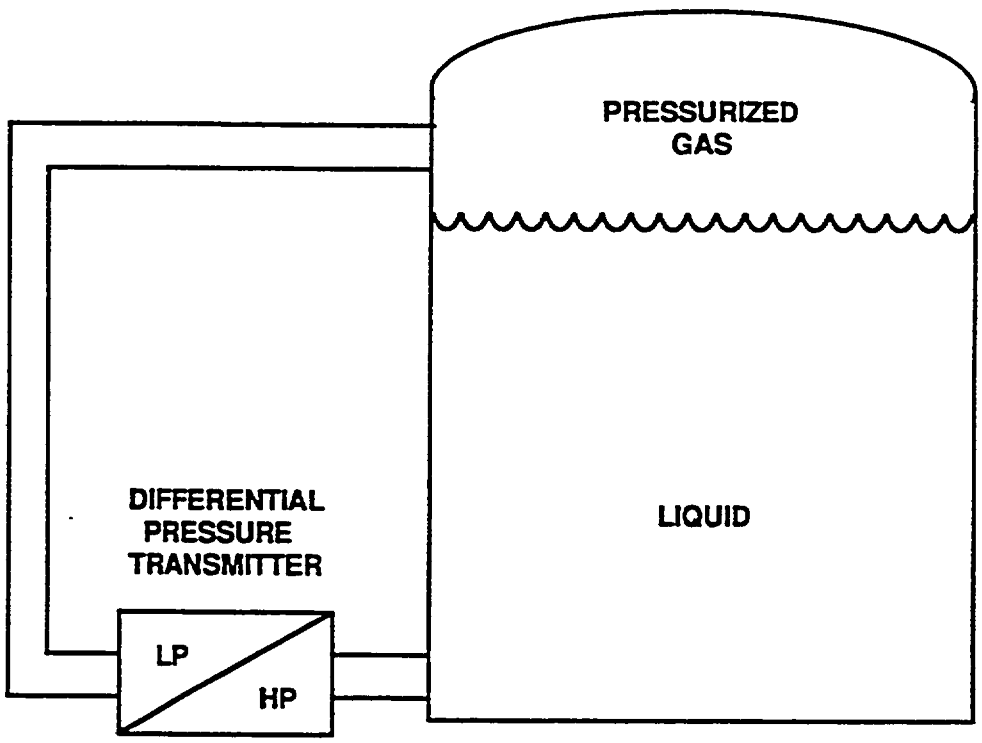


Figure 14-22. Differential Pressure Level Detector

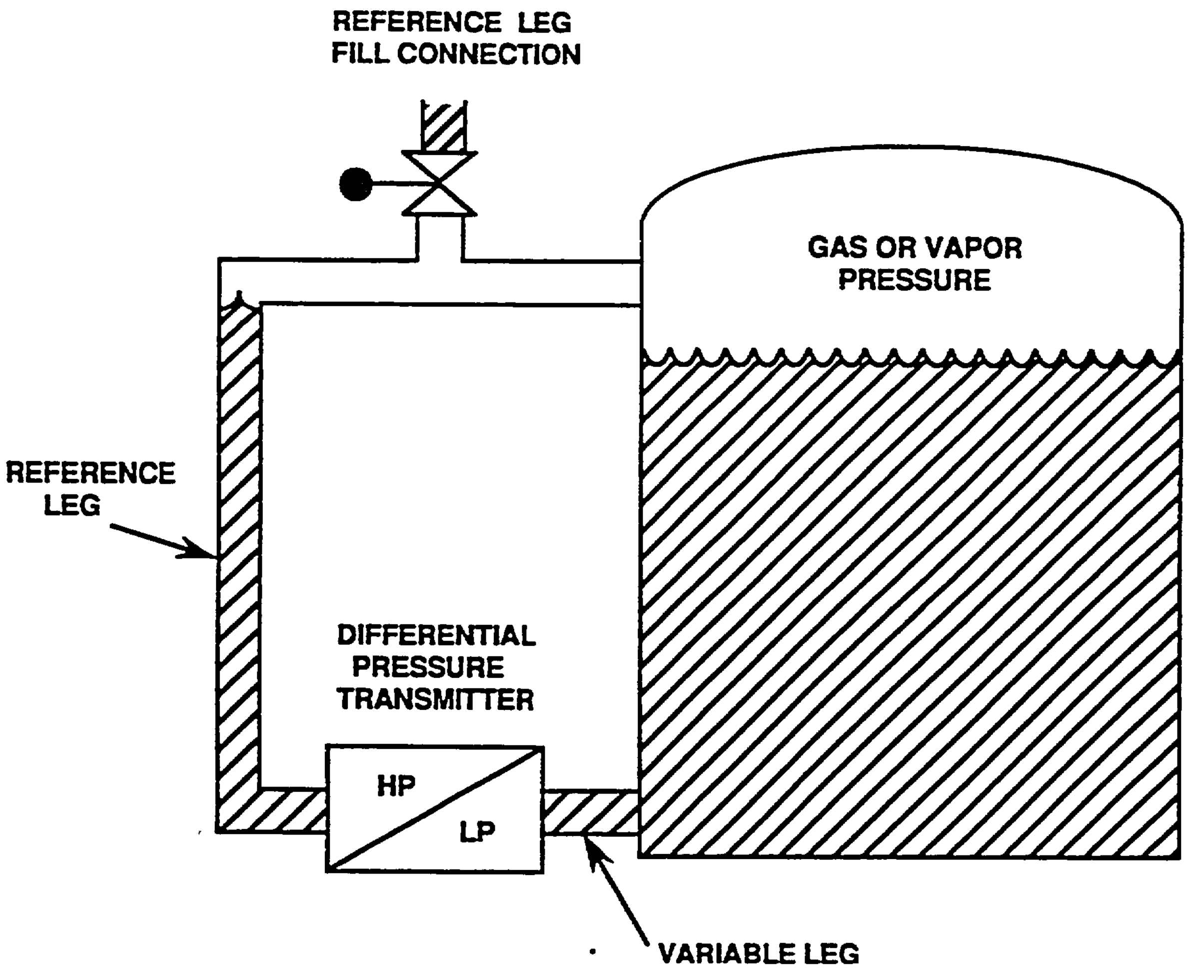


Figure 14-23. Reference Leg Differential Pressure System

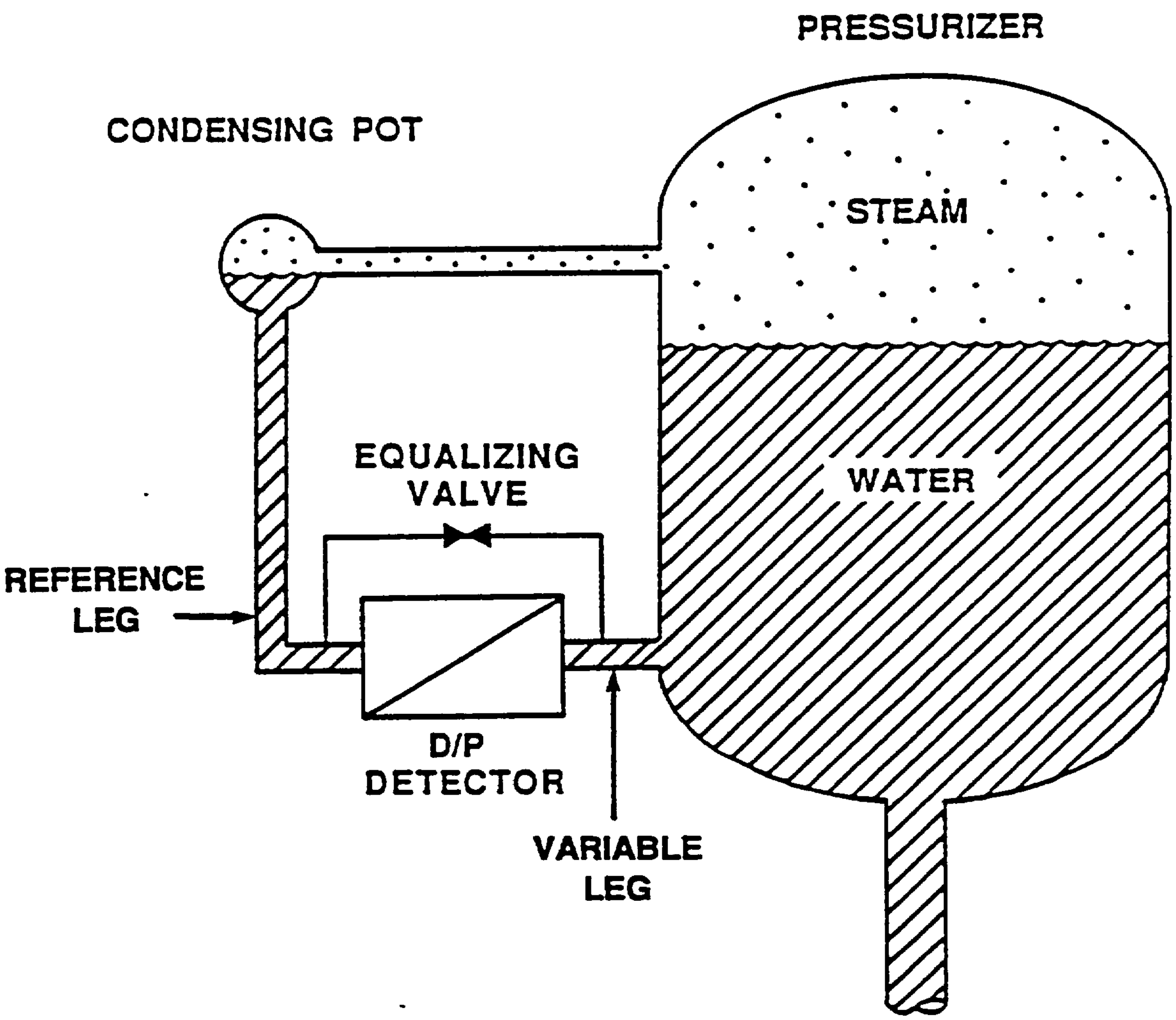


Figure 14-24. Pressurizer Differential Pressure Level Detector

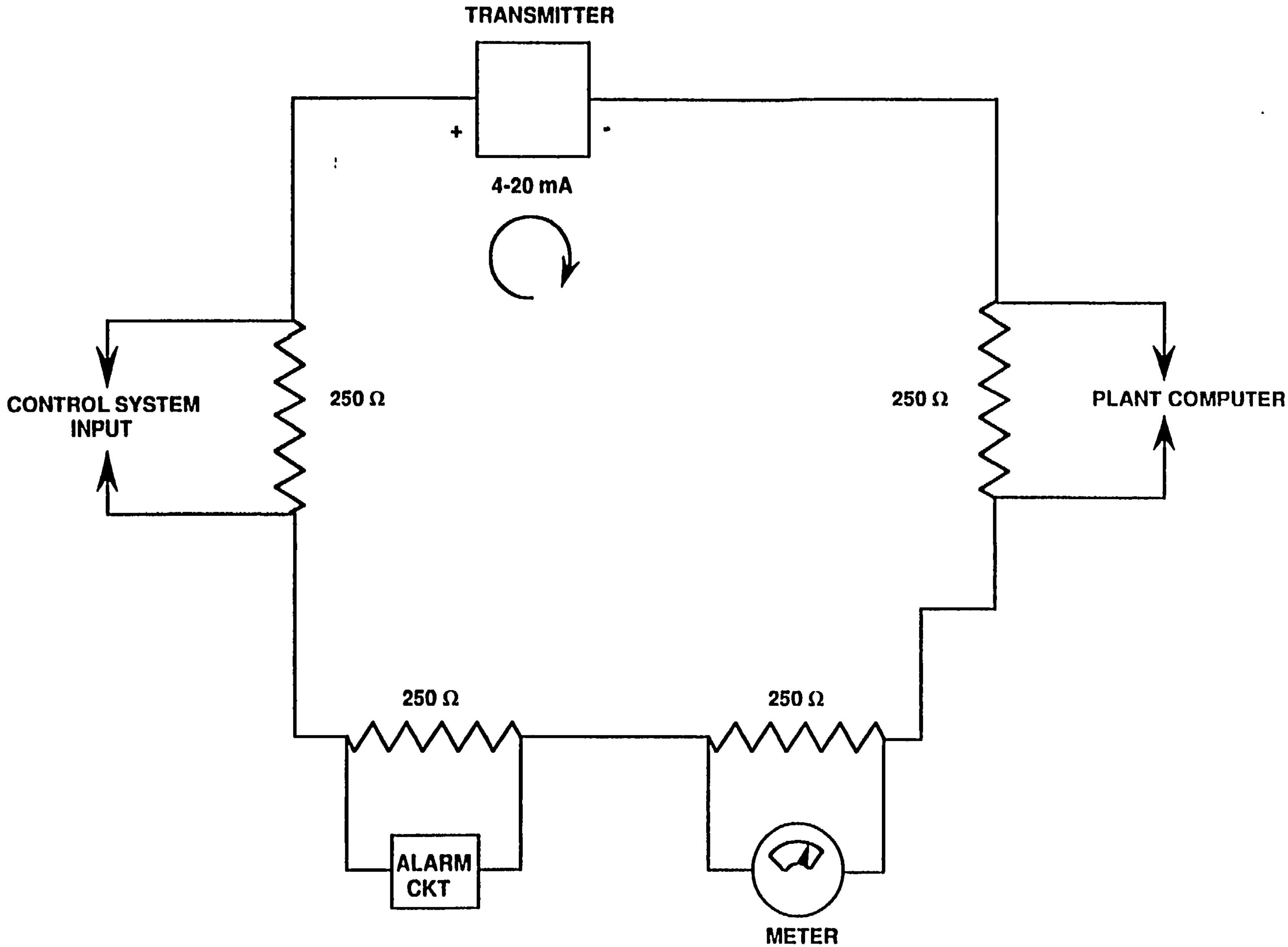


Figure 14-25. Current Loop

15.0 CONTROLLERS

Learning Objectives

After studying this chapter, you should be able to:

1. Explain the difference between open-loop and closed-loop control systems.
2. Explain the principles of operation and the relative advantages/disadvantages of the following types of controllers:
   a. Bistable
   b. Proportional
   c. Proportional integral
   d. Proportional derivative
   e. Proportional integral derivative
3. Define or explain various controller terms such as time constant, dead time, gain, reset rate, reset time, rate gain, and setpoint.
4. Explain the functions of bistable controllers, including the neutral zone and deadband.
5. Explain the change in output response to step and ramp changes in error signals for the following types of controllers:
   a. Proportional
   b. Proportional integral
   c. Proportional integral derivative

15.1 Introduction

In power plants, automatic control is essential in such operations as controlling tank levels, pressure, temperature, flow and chemistry. An automatic regulating system in which the controlled variable is a system process variable such as temperature, pressure, flow, or pH is often called a process control system.

Control systems naturally fall into two types, depending on the relationship between the controlled element and the controlling element. An open-loop or open-cycle control system is one in which the controlling element is unaware of the effect it is producing on the controlled element. A simple example of an open-loop system is an automobile that has no speedometer but does have a calibrated throttle. The driver can set the throttle for 40 mph, for example, and hope that the actual speed is in that vicinity. However, such a control system does not measure and cannot correct for errors caused by wind velocity, road slope and conditions, motor condition, or any of the many factors affecting car speed. The open-loop system has the inherent shortcoming of any system that does not sample the final product — the system does not know if it is doing what is expected. In other words, the system has no feedback.

Refinements could be built into the automobile throttle system; a slope-measuring device could correct for road slope, for example. Refinements of this nature, while requiring more complicated control mechanisms, would still not assure the desired speed under all conditions. A closer approach to the ideal can be made by a mechanism that measures the actual speed and makes correction for any deviation of speed from the desired value. Perhaps the most obvious means for measuring such a deviation is a speedometer visible to the eye of the driver. By reading the actual speed on the dial and mentally comparing this value with the desired speed, and then changing the throttle setting to reduce the error, the driver acts to close the loop or provide feedback between the output speed and input throttle setting. The use of a driver in this system results in a *closed-loop*, *closed-cycle*, or *feedback control* system. A cruise control system on an automobile is an automatic closed-loop speed control system.

15.2 Controller Terminology

Figure 15-1 is a block diagram identifying five elements common to all feedback control systems. The first of these is the input signal, or *setpoint*, which determines the desired value of the second element which is the output or *controlled or process variable*. The third element, *feedback*, involves measurement of the output and feeding it back to the input, either in a proportional or modified form. *Comparison*, or *summation*, is the fourth element; this function compares the input signal with the signal fed back from the output. The result of comparison is a *difference*, or *error signal* which in turn drives the fifth element, the *controller*. The function of the controller is to produce the output signal that is used in the controlling circuit. In general, the controlling circuit contains the system or device whose performance is to be controlled.

The measurement and feedback portion of the control system must measure the system output (in whatever form) and convert it into an electrical or pneumatic signal that can be compared with a signal corresponding to the setpoint. Typical process control variables include fluid system pressure, temperature, flow level, and electrical circuit voltage and current.

The combined effects of resistance and capacitance in a control system produce an initial time-dependent response (output) curve for most controllers. Because of this initial time dependence, one measurable characteristic representative of the output is the time constant, which is determined by the system resistance and capacitance. The time constant, shown in Figure 15-2, is defined as the time required for a system output to reach 63.2% of the total output change. In practical (stable) control systems, the time-dependent output dies away in a short period of time leaving the steady state output. Generally, response for a system reaches steady state after about five time constants have elapsed since the input was changed. The time constant is a measure of how long it takes the system to respond to an input change. The greater the time constant, the slower the system reaction will be. Most of the theoretical controller discussions in this section ignore the effects of the system time constant, which is normally relatively short for control systems used in nuclear power plants.

In addition to the delay due to system resistance and capacitance, another time quantity found in control circuits is dead time. Dead time is defined as the time difference between when an input change occurs in a process and when the system starts to respond (see Figure 15-2). The major effect of dead time is to introduce a delay into the control loop that allows the controlled variable to deviate slightly from the setpoint before control action is taken. A longer dead time allows more deviation from setpoint. Once the control action begins though, the speed of the response is determined by the system time constant.

Gain (K) describes how much a controller output changes for a given change input. The definition of gain that will be used for this section is the percent change in output divided by the percent change in input.

$$K = \frac{\%\text{ change in output}}{\%\text{ change in input}}$$

The use of percent change notation allows the comparison of gains for controllers with different input and output quanties (e.g., input = inches; output = flow) and different ranges of operation. The gain of a controller is a function of the physical parameters of the process and the controller design.

15.3 Examples of Feedback Control

A *closed-loop or feedback* control system is one in which the output has a direct effect upon the control action. The error signal, which is the difference between the setpoint signal and the measurement/feedback signal, is fed to the controller so as to reduce the output error and bring the output of the system to the desired value.

To illustrate the concept of a closed-loop control system, consider the thermal system shown in Figure 15-3A. In Figure 15-3A a human being acts as the controller and wants to maintain the temperature of the hot water at a given value. The thermometer installed in the hot water outlet pipe measures the outlet temperature. This temperature is the output of the control system. If the operator watches the thermometer and finds that the outlet temperature is higher than the desired value, then the operator reduces the amount of steam supply to lower this temperature. If the temperature becomes too low, the sequence of operations would need to be repeated in the opposite direction.

If an automatic controller is used to replace the human operator, as shown in Figure 15-3B, the control system becomes automatic (i.e., an automatic feedback or automatic closed-loop control system). The position of the dial on the automatic controller sets the desired temperature. The output, the actual temperature of the outlet water, which is measured by the temperature-measuring device, is compared with the desired temperature or setpoint to generate an actuating error signal. To do this, the output temperature must be converted to the same units as the setpoint. The error signal produced in the comparison circuit is used by the controller to produce an output signal. This signal is sent to the control valve actuator to change the valve position for steam supply so as to correct the actual water temperature. If there is no error, no change in the valve position is necessary.

The manual feedback and automatic feedback control system cited above operate in a similar fashion. The operator's eyes are the analog of the error-measuring device; his brain, the analog of the automatic controller; and his muscles, the analog of the actuator.

The control of a complex system by a human operator is not always effective because of the many interrelations among the various variables. Even in a simple system an automatic controller can overcome human shortcomings. If high precision control is necessary, control must be automatic.

In closed-loop systems, the closeness with which the actual output meets the setpoint depends more on the behavior of the feedback element than on the actual controller. A feedback control system is, in general, inherently more accurate than an open-loop system constructed of essentially the same elements. On the other hand, stability is always a problem in the closed-loop control system because it may tend to overcorrect errors, which may lead to oscillations of constant or changing amplitude.

For a feedback control system to operate in a stable fashion, negative feedback must be used. Negative feedback means that the feedback signal is opposite in sign to the measured variable. Negative feedback causes the error signal to approach zero when the measured variable approaches the setpoint value as shown by the following relationship:

Error = setpoint - measured variable

Thus, error is positive if the measured variable is smaller than the setpoint and negative, if larger than the setpoint. If the feedback is positive, the controlled variable increases and the actuating signal also increases. This causes an increased value of controlled variable, which results in a further increase in actuating signal, and so on. The result is an unbounded increase(unstable) in the controlled variable and loss of control by the controller.

15.4 Controller Operation

Five types of controller operations will be discussed:

1. bistable control,
2. proportional control,
3. proportional integral (PI) control,
4. proportional derivative (PD) control, and
5. proportional integral derivative (PID) control.

Each type of control relates the controller output to its input. For example, with proportional control, the controller output is proportional to its input (error signal). By far, the most common type of control is PID. As will be shown, PID controllers incorporate the advantages of proportional, integral, and derivative control.

Figure 15-4 shows a *simplified* steam generator water level control system and will be used to illustrate each type of control. To minimize the complexity of these examples, effects such as shrink and swell are ignored in these discussions and the associated illustrations. In this example, feedwater is supplied through a feedwater regulating valve, and steam is drawn out the top of the steam generator. Assume that with the valve 50% open and with steam demand at 50%, feed flow will match steam flow and the steam generator will be in steady state. Similarly, 100% steam flow will equal feed flow with the valve 100% open. The function of the controller is to control the feed regulator valve to maintain steam generator level. The controlled variable in this case is the steam generator level. The feed regulating valve is the final control element. A feedback signal is provided by a level transmitter. Assume the level setpoint is 100 inches of water. At that level, the error signal is zero and the feed regulating valve is 50% open.

For each type of control, the system response to a change in steam demand and a step change in input (such as would occur if the level transmitter failed or the setpoint was instantaneously changed) are examined.

15.4.1 Bistable Control

A bistable contoller is a device that has two operating conditions — either completely on or completely off. Bistable control can be achieved by using very high gain. For example, for any positive error, the output is a maximum (on); for any negative error, the output is a minimum (off). The magnitude of the error is of no concern to the simple bistable controller, only the sign (positive or negative) of the error signal is important.

Bistable controllers are often used in protective systems when a control function is fully actuated if a process variable exceeds a limiting setpoint. Bistable controllers are not typically used to control a process variable around a setpoint because of the bistable's oscillatory (on versus off) output characteristic. This characteristic is demonstrated in the following paragraph.

Simple bistable control is illustrated in Figure 15-5 for the steam generator water level control system shown in Figure 15-4. Assume the level is at the setpoint of 100 inches and the steam generator is in steady state with the feed flow matching the steam flow. If a decrease in steam flow occurs at time zero, a mismatch between feed flow and steam flow occurs, and the steam generator level begins to rise. As soon as the level rises above the setpoint, the bistable controller causes the regulating valve to fully shut. The level then drops below the setpoint, which causes the valve to fully open. These alternating reversals will continue indefinitely. The frequency of these oscillations can be very high and can cause rapid wear on the final control element (regulating valve).

The simplest means of reducing the oscillation frequency is to operate the bistable controller with a dead band or neutral zone (see Figure 15-6). In this case the valve does not shut until the level increases to 120 inches, and the valve stays fully shut until the level falls to 80 inches, where it fully opens. The region *between* 80 inches and 120 inches in this example is referred to as the dead band or neutral zone. Nothing happens to the regulating valve when the level is in this band. Note that the reduction in oscillation frequency results in larger deviation from the setpoint.

The response of a bistable controller to a step input or error signal is illustrated in Figure 15-7. Assume the level indicator fails high causing a negative error signal (100 inches setpoint minus 200 inches "measured"). This would cause the regulating valve to shut, and the steam generator would rapidly boil dry.

15.4.2 Proportional Control

The example steam generator system with proportional control is illustrated in Figure 15-4. With proportional control, the output of the controller is proportional to the input or error signal. Therefore, the gain of a proportional controller (k) is the constant of proportionality. In the simplest case, if the error is small, the output is small, and if the error is large, the output is large. Proportional controllers give an output to input relationship that is linear (proportional). The magnitude of the linear input/output relationship is a function of the controller gain. With proportional control, the final control element has a definite position for each value of the measured variable.

The input band (error signal range) over which the proportional controller provides a proportional output is called the proportional band. It is defined as the change in input required to produce a 100% change in output:

$$\text{Proportional Band} = \frac{\%\ \text{Change in Input}}{\%\ \text{Change in Output}} \times 100\%$$

The gain of a proportional controller and the proportional band are reciprocals, as shown in the following equations:

$$\text{Gain} = \frac{100\%}{\text{Proportional Band}} \quad \text{and}$$

$$\text{Proportional Band} = \frac{100\%}{\text{Gain}}.$$

This inverse relationship shows that specifying the proportional band is simply another way of specifying the gain for a proportional controller. Some manufacturers of proportional controllers specify gain adjustments in units of gain, whereas other proportional controller manufacturers use adjustments expressed in units of percent proportional band. Regardless of the units used, the adjustment performs the function of determining the input-to-output proportional relationship:

$$P = K_p E + P_0,$$

where

- P = controller output,
- E = error (setpoint minus measured variable),
- K_p = gain of proportional controller, and
- P_0 = controller output with no error.

Rearranging terms, we can see that in steady state,

$$P - P_0 = K_p E,$$

which implies that the error signal must offset the difference in controller output.

For any value of the measured variable, there is a corresponding controller output. The input/output characteristics for various proportional bands (gains) are shown in Figure 15-8.

Assume that a proportional controller with a gain of 1 is used in the steam generator water level control system. Now consider the response to a decrease in steam flow from 50% to 25% as shown in Figure 15-9. The level immediately rises due to the mismatch between steam flow and feed flow. The regulator responds by closing the regulating valve proportionately as the level rises above the setpoint. The higher above the setpoint the level rises, the more the valve will close. The response can be determined by observing that when the level reaches 120 inches, the level error will be

$$E = 100 - 120 = -20 \text{ inches}$$

Because the definition of gain is on a percentage change basis, the percent level change must be determined. This can be done by dividing the error by the steam generator level range of 200 inches. The percent level change is

$$\frac{-20}{200} = -10\%$$

In this example, the controller output with no error is 50%. The controller output for the -10% level change can then be determined. With a gain of 1,

$$P = (1)(-10\%) + 50\% = 40\%$$

Because 40% feed flow is greater than the 25% steam flow, the level will rise, causing an even greater level error. Eventually, the level will rise to a point where the controller output produces a 25% feed flow. At this point, the level will stop changing. The final level corresponding to a 25% feed flow is

$$25\% = (1)(\%E) + 50\%$$

$$\%E = -25\% = \frac{E}{200 \text{ inches}}$$

$$E = -50 \text{ inches}$$

$$-50 = 100 - \text{measured variable}$$
$$\text{measured variable} = 150 \text{ inches.}$$

In other words, the level will finally increase to 150 inches to accommodate the reduced feed flow.

If the gain is increased to 2 for the same example, the steam generator will again reach steady state when steam flow matches feed flow and the regulating valve is 25% open. However, the level error required to produce this change in flow with a gain of 2 is -25 inches, which corresponds to a level of 125 inches. Therefore, the controller with the higher gain (smaller proportional band) will control closer to the setpoint (100 inches) when a constant error is present.

Note that in both of these examples and in all cases, *the proportional controller will not control at the initial setpoint in steady state* if a constant error is present. In both examples, the feed flow change from the initial 50% introduced a resultant error or offset in the measured variable. Also note that as steady state is approached, some oscillation occurs in the controlled variable (steam generator level). System time constant and dead time combine to cause the reaction of the valve to be delayed compared to the error signal that initiates its movement. This delay together with the feedback signal causes initial overshoot as well as oscillation about the eventual steady state value. Increasing the gain (decreasing the proportional band) of a proportional controller will cause it to control closer to the initial setpoint, but at the expense of increasing overshoot and oscillation.

The response of a proportional controller to a step change input is illustrated in Figure 15-10. Again, assume the steam generator level is initially at 100 inches and that feed flow and steam flow are equal with the actuator valve 50% open. Now, assume that steam flow remains constant and the setpoint is instantaneously increased to 125 inches. The percent level error change is

$$E = 125 - 100 = 25 \text{ inches}$$

$$\%E = \left(\frac{25}{200}\right)100\% = 12.5\%$$

With a gain of one and because the controller output with no error (P_0) remains at 50%

$$P = (1)(12.5\%) + 50\% = 62.5\%$$

The actuator valve will open to 62.5% and increase flow. Because steam flow remains at 50%, the level will increase. As the level approaches 125 inches, the resulting level error signal will approach zero. After some oscillations around the new 125 inch setpoint, the valve will return to 50% open (zero error) when the actual level settles at 125 inches.

15.4.3 Proportional Integral Control

The example steam generator system is illustrated in Figure 15-11 with proportional integral control. In this type of controller, the output is a function of not only how large the error signal is (proportional control), but also how long the error signal has existed (integral control). Therefore, the longer steam generator level is above the setpoint, the more the regulator valve is shut. This integral action eventually eliminates the steady state error offset inherent in simple proportional control and *causes the controller to control at the initial setpoint.*

Prior to examining the operation of integral action, two terms need to be defined. The reset rate, K_i, refers to the number of times that the proportional output amplitude is added by the integrator to the output (or repeated) each minute (rpm). The term reset time, T_i, refers to the time needed for the proportional output amplitude to be added to the total output (or repeated) once.

The terms K_i and T_i are reciprocals of each other so that:

$$K_i = \frac{1}{T_i}.$$

To illustrate these terms, assume a proportional integral controller has a proportional band of 200% (gain = 0.5) and a reset rate of 2 rpm. If a step change of 20% occurs in the error signal, the magnitude of the change in the controller output due to proportional action is 10% (gain = 0.5). A reset rate of 2 rpm will cause an addition of another 20% every minute the error exists. (A reset rate of 2 rpm corresponds to a reset time of 30 seconds; therefore, the output of the controller will be increased an additional 10% every 30 seconds by the integrator.)

(As a general note, the quantitative analysis of combination controller responses involves the use of calculus or higher level mathematical techniques such as Laplace transforms. Therefore, the responses provided in the associated figures are not "solved" mathematically. The general shapes of the responses are provided for illustrative purposes only.)

The actions of a proportional integral control system in response to a decrease in steam flow are shown in Figure 15-12. Note that the integral action results in control at the setpoint of 100 inches after a change in steam flow.

Figure 15-13 illustrates the response of a proportional integral controller to a step change in the setpoint from 100 inches to 125 inches (an immediate 12.5% error signal). Immediately the error signal causes the valve to open, which causes the level to increase and the error to begin to decrease. After some oscillation, steady state is reached with steam flow matching feed flow (valve at 50%) and the level matching the new setpoint.

15.4.4 Proportional Derivative Control

The installation of a derivative function into the proportional control scheme gives the system the ability to "anticipate" a change in the process variable. A device, called a differentiator, produces an output that is proportional to the rate of change of the input.

$$P_d = K_d \left(\frac{di}{dt}\right),$$

where

P_d = derivative controller output,

K_d = derivative constant, and

$\frac{di}{dt}$ = rate of change of the input, i.

In Figure 15-14, derivative action has been added to the steam generator proportional control system. The derivative constant K_d, specifies the function of differentiation and is called the rate gain. A rate gain or derivative constant of 5%/%/second means that the output is equal to 5% for each 1% per second of input rate of change. Notice that the input to the derivative function is the output of the proportional function. Therefore, the gain of the proportional section affects the rate of change of the input to the derivative function, but the shape of the derivative input is similar to the shape of the original error input.

Assume a derivative controller is added to a proportional controller. If a step change of 10% causes the proportional controller output to change by 5% (proportional gain of 0.5), then the addition of the derivative action with a rate gain of 5 would cause an additional 25% increase in the controller output for a total output change of 30%.

Figure 15-15 illustrates the response of a proportional derivative controller to a decrease in steam flow from 50% to 25%. As in the case of the proportional controller alone, steady state steam generator level is controlled above the setpoint. With a gain of 1, steady state is eventually reached with a constant -50 inch level error to match the change in valve position required to match the decreased steam flow.

A close examination of the proportional control output graph and the proportional plus derivative graph shows that the time required to reach a particular controller output is decreased by the derivative action. Note that the more rapid response of the proportional plus derivative controller allows steady state conditions to be reached more quickly with fewer oscillations.

Another level transient is shown on Figure 15-16. This transient involves a step change in setpoint to 125 inches. The step change causes an increased controller output due to the derivative action.

Note that since steam flow did not change, the valve will initially open in response to the step change and then return to the 50% open position in the steady state as before. This implies the steady state level error will be zero, which in turn means that the steady-state level must equal the new setpoint. This is shown by the following equation:

$$\begin{aligned} E &= \text{setpoint - measured value} \\ &= 125'' - 125'' = 0'' \\ P - P_0 &= K_pE \\ 50\% - 50\% &= K_p(0'') = 0 \end{aligned}$$

Also note that a step change input would theoretically produce an infinite differentiator output. This is based on the fact that a step change has an infinitely high rate of change. In reality, no device can produce an infinite output. Therefore, real devices rapidly saturate to their maximum output value when a step change is applied to the input and then decay to zero output according to the time constant of the differentiator.

15.4.5 Proportional Integral Derivative Control

The proportional integral derivative (PID) controller is the most common type controller used in the nuclear power plants. The PID controller combines the actions of the three types of control modes discussed above and is shown in Figure 15-17.

First, the proportional component of the PID provides an output that is proportional to the error signal. To correct the inherent offset problem in a proportional controller, an integral function is added. Finally, the derivative action adds an anticipatory feature to the controller.

Figure 15-18 illustrates how the proportional, integral, and derivative actions of the PID controller combine to generate the PID controller output. The response to four different types of error signals are examined. Note that the proportional response to step error signals are also steps, and the proportional response to ramp error signals are ramps. Recall that the size of the step or ramp response is a function of the proportional gain.

In figure 15-18, the integral response to step errors is a ramp. The integral response increases linearly with time for a constant error. On the other hand, the integral response to a ramp error is not linear. It increases both with time and also in response to the increasing error signal.

The derivative response to step error signals is a spike that decays back to zero. Because the rate of the change of the step error signal is (by definition) infinite, the spike should be infinitely great;

however, it is limited by the maximum response of the electrical and mechanical components of the controller. For ramp error signals, the derivative response is an exponential buildup to a steady state value that is a function of the slope (rate of change) of the error signal.

At the bottom of Figure 15-18, the PID output is simply the sum of the proportional, integral, and derivative responses.

15.5 Comparison of Control Modes

Figure 15-19 shows the effects of an increase in steam flow above the original steady-state feed flow in the example system and compares the results obtained using the four different control modes.

Trace (a) shows the proportional control mode, which is characterized by several cycles before stabilization is reached. A steady state offset error exists at the new operating point.

Trace (b) shows the proportional plus integral mode, which is characterized by a zero offset error, a higher initial overshoot amplitude, and a longer period until stabilization is reached.

Trace (c) shows the proportional plus derivative mode, which is characterized by a shorter period until stabilization is reached, but a steady state offset error also exists at the new operating point.

Trace (d) shows the proportional plus integral plus derivative mode, which is characterized by the advantages shown in both trace (b) with its zero offset error, and trace (c) with its rapid stabilization. Notice that the addition of the integral function caused some decrease in stability from trace (c) due to the integral-derivative interaction, but in terms of overall system response, trace (d) is the best.

In general, the addition of the derivative function allows adjusting the controller for a higher gain (i.e. a smaller proportional band). The higher gain is desirable to help ensure that the controller is sensitive to smaller error signals. The added stability resulting from the derivative action compensates for the lower stability resulting from the higher gain.

Also, the addition of the derivative function allows adjusting the integral function for a smaller reset time, which equates to a greater number of repeats per minute. This is desirable to enable a return of the control variable to the setpoint in a shorter time.

Again, the added stability resulting from the derivative action compensates for the lower stability resulting from the increased integral action.

15.6 Summary

The simplified steam generator water level control system used in this chapter is but one of many uses of automatic control systems in use in commercial power plants as well as industry. Most of these systems, including actual steam generator level control systems that utilize steam flow measurements and programmed levels rather than a single setpoint, are much more complex than the system shown. However, all of these systems operate with the same basic principles. Negative feedback is used to create an error signal, which is in turn amplified, differentiated, and/or integrated to produce an output.

Chapter 15 Definitions

TIME CONSTANT	- The time required for a controller output to reach 63.2% of the total output change after an input change.
DEAD TIME	- The time difference between when an input change occurs and when the controller starts to respond.
GAIN	- The measure of how much a proportional controller output changes for a given input change.
RESET RATE	- In a proportional integral controller, the number of times each minute that the proportional component output amplitude is added to the total output by the integrator.
RESET TIME	- In a proportional integral controller, the time needed for the proportional component output amplitude to be added to the total output once (i.e., the inverse of the reset rate.)
RATE GAIN	- The measure of how much a derivative controller output changes for a given rate of input change; also called the derivative constant.
SETPOINT	- The process value at which a controller is attempting to maintain a process.

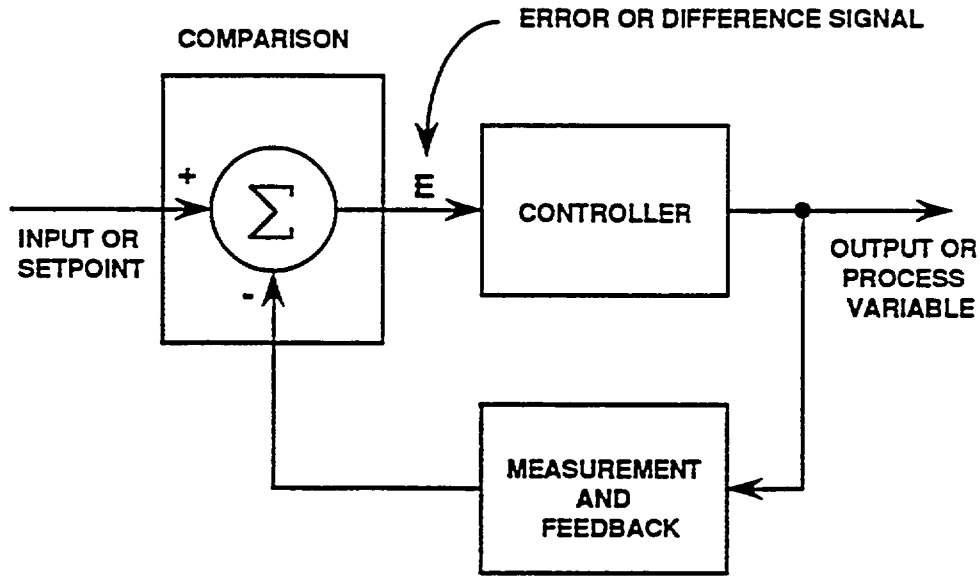


Figure 15 - 1. Block Diagram of Feedback Control System

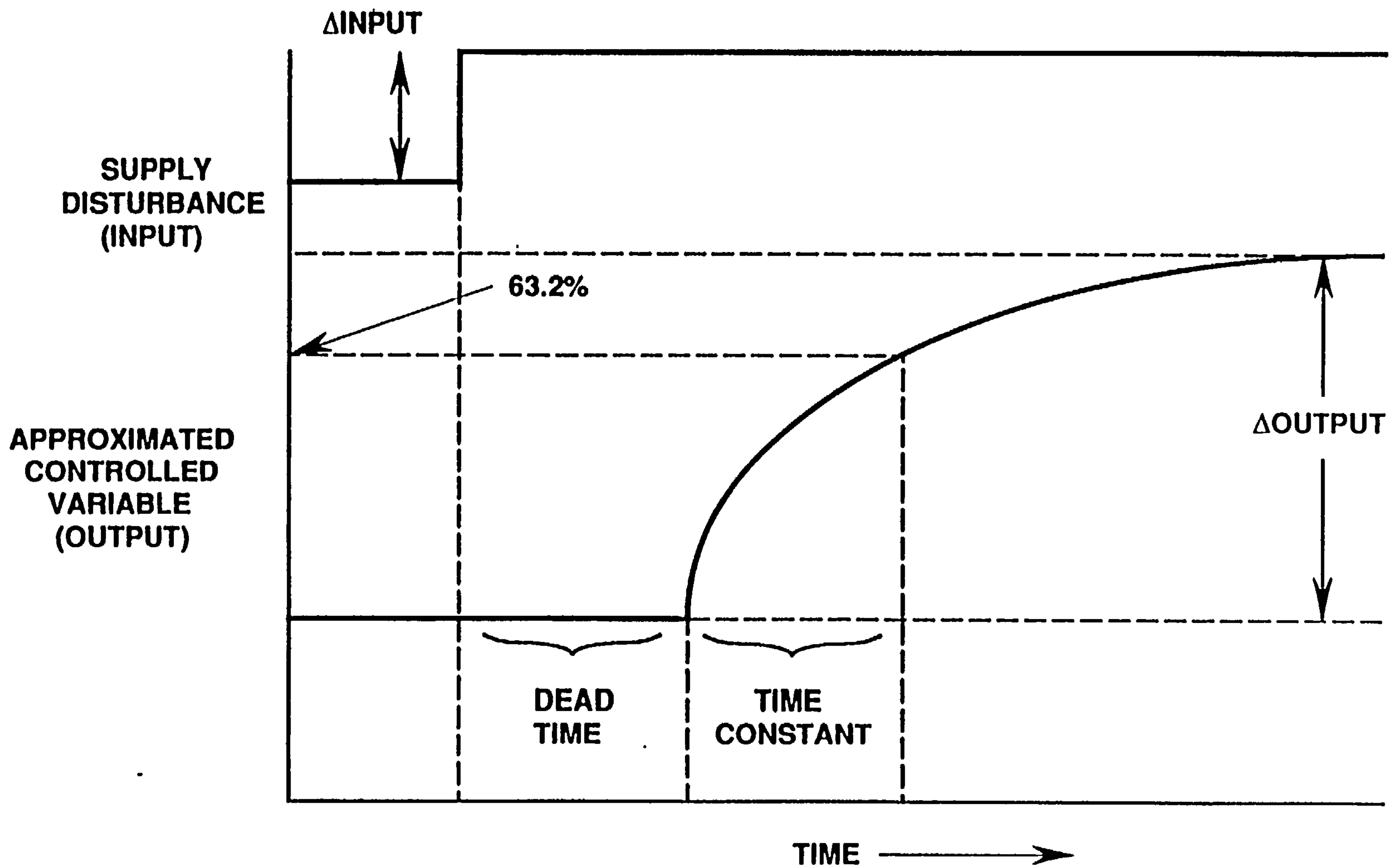
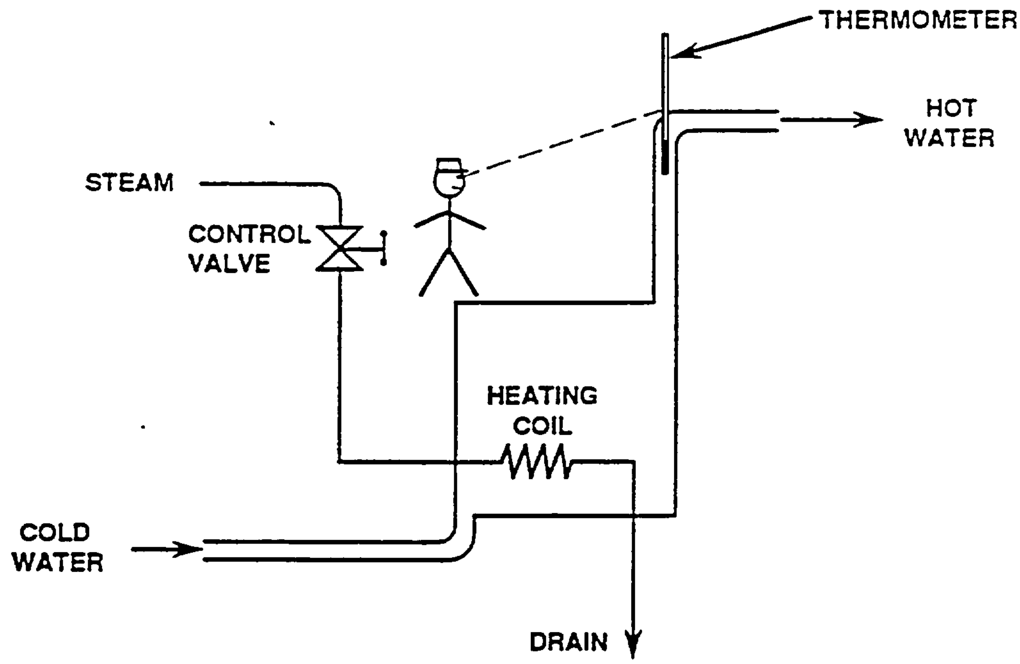
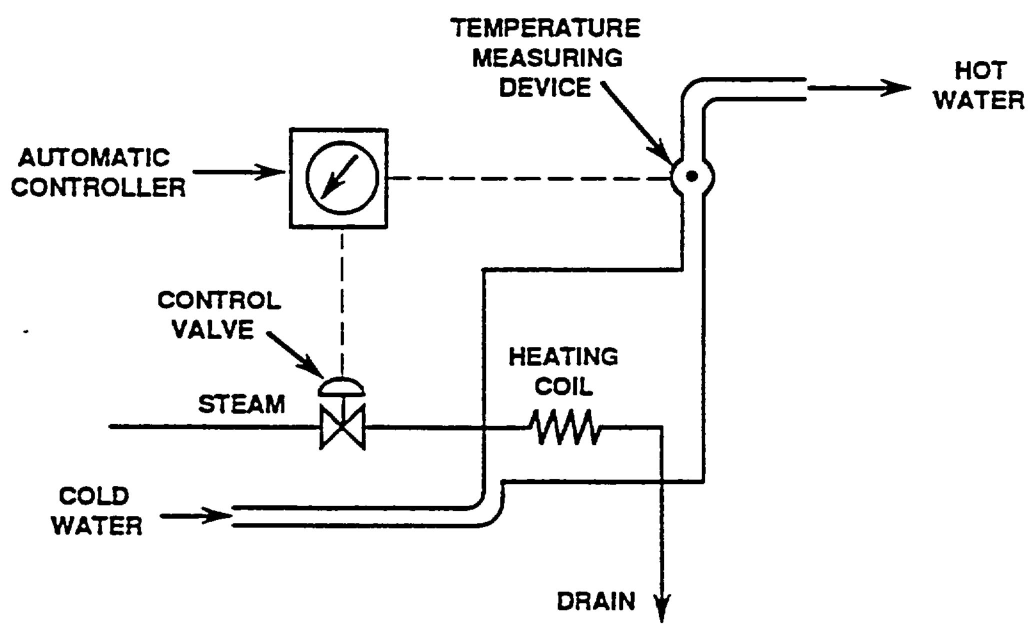


Figure 15 - 2. Control System Response



A. Manual feedback control of a thermal system



B. Automatic feedback control of a thermal system

Figure 15-3. Manual and Automatic Feedback Controls for Thermal Systems

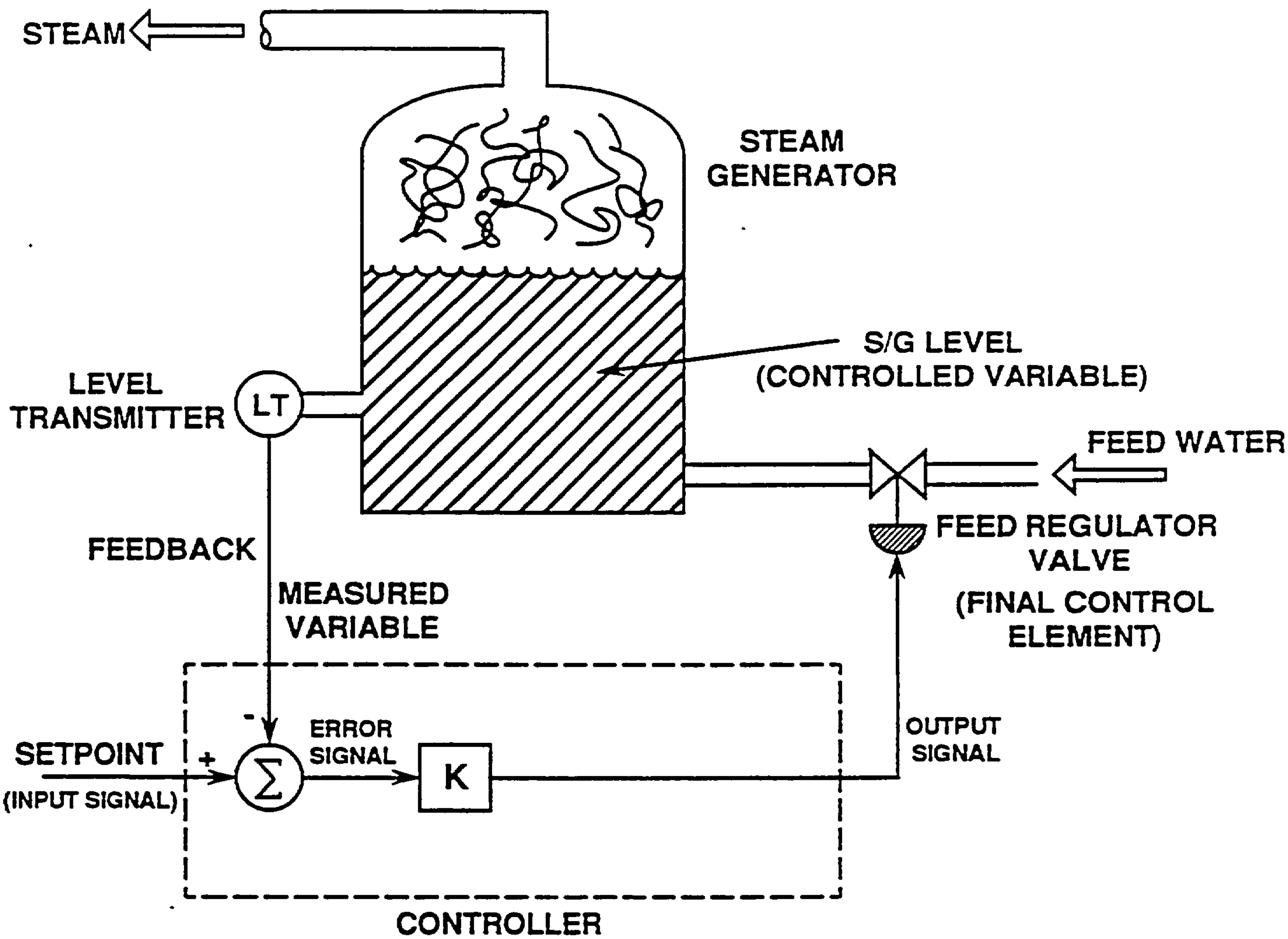


Figure 15-4. Steam Generator Water Level Control System

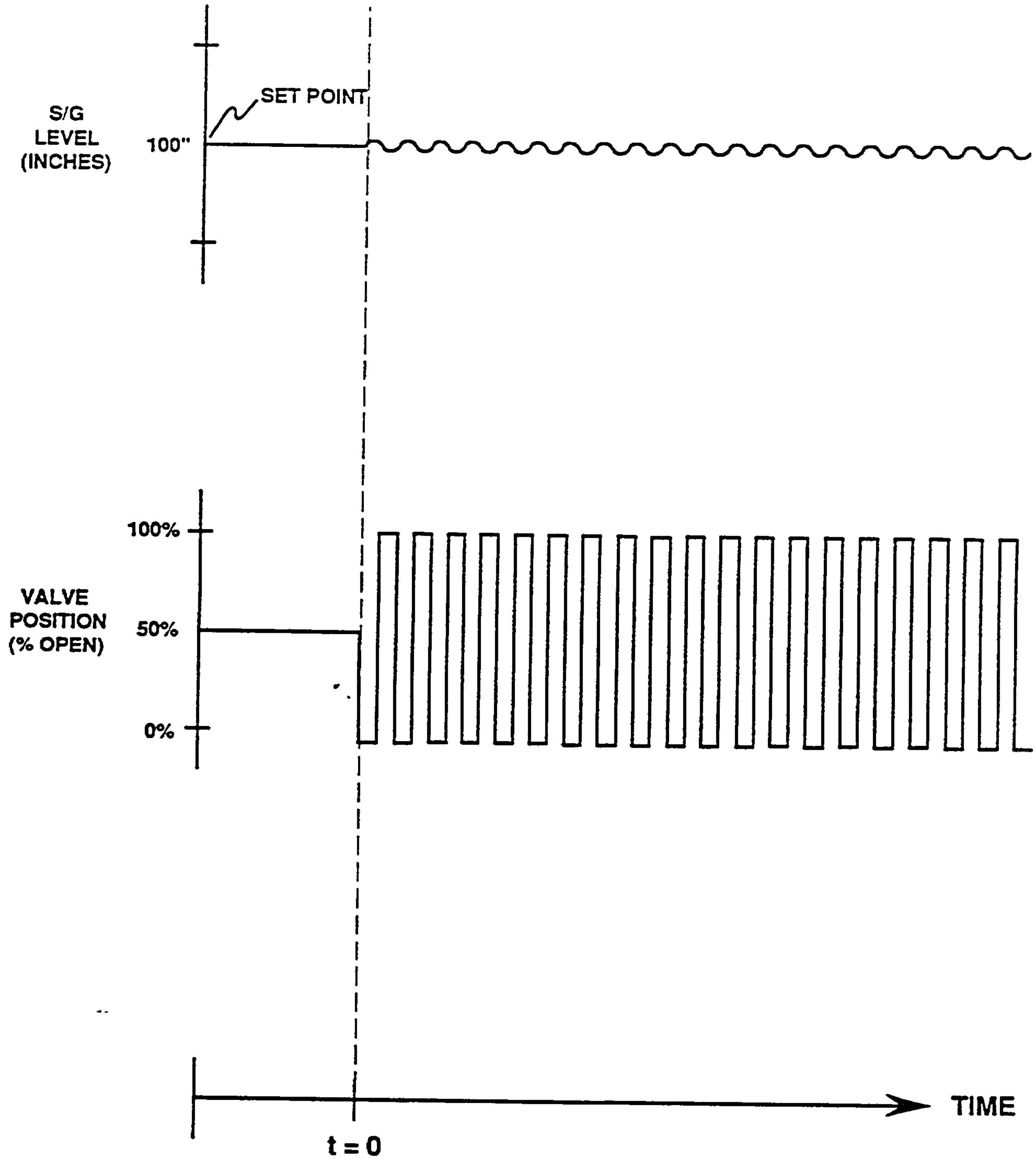


Figure 15-5. Simple Bistable Control

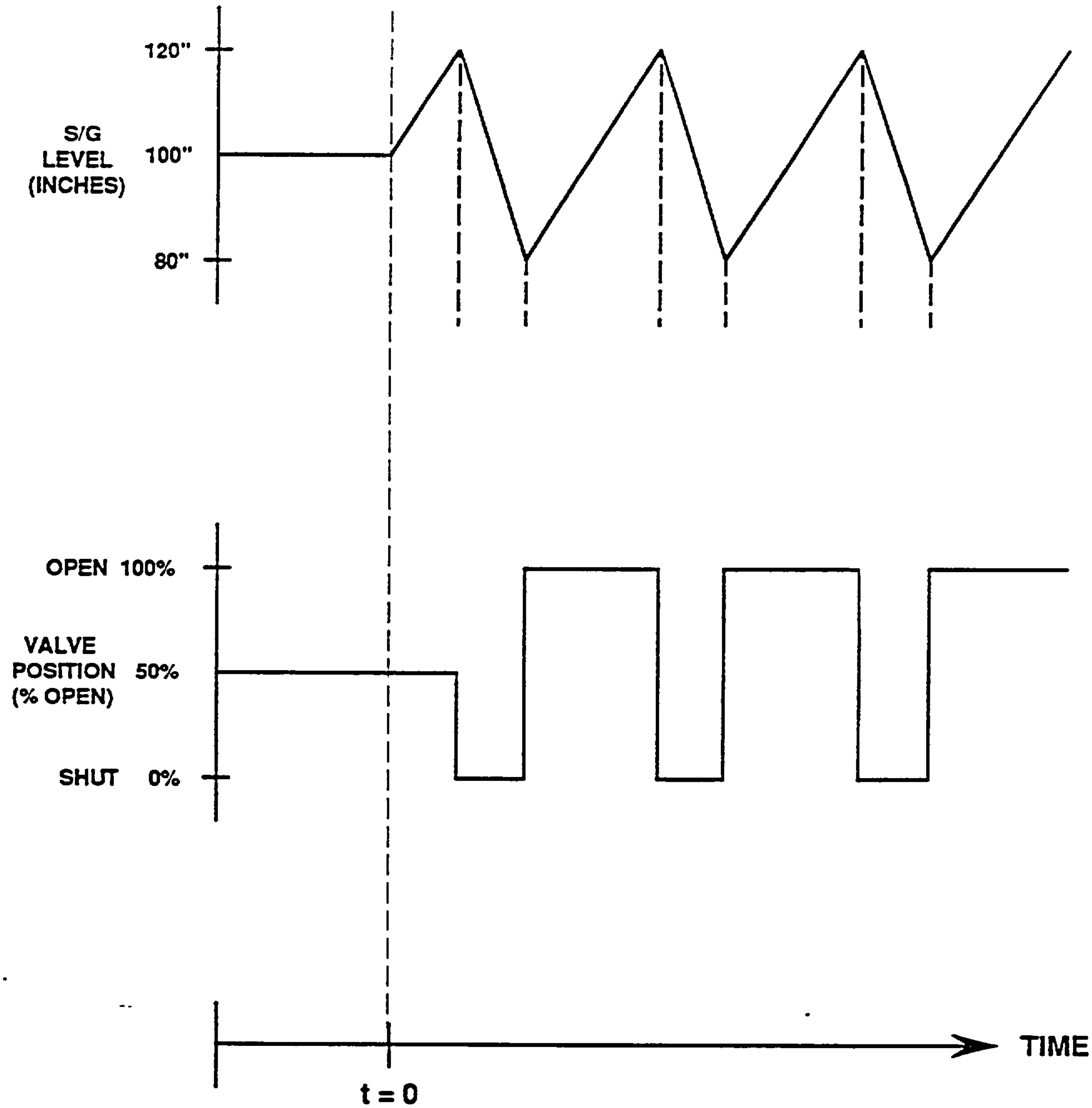


Figure 15 - 6. Bistable Control with Deadband Reaction to Decrease in Steam Demand

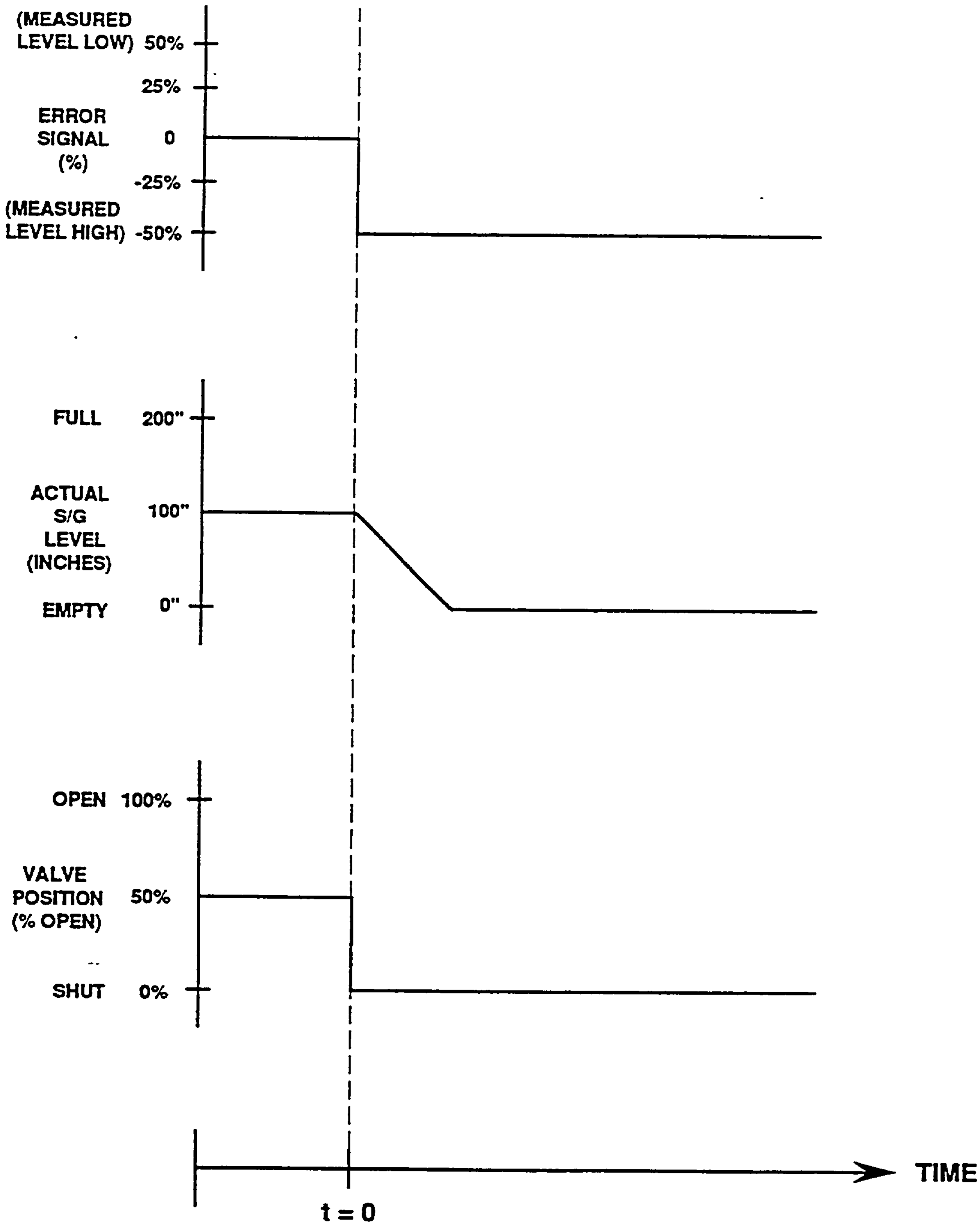


Figure 15-7. Bistable Response to Step Change in Input

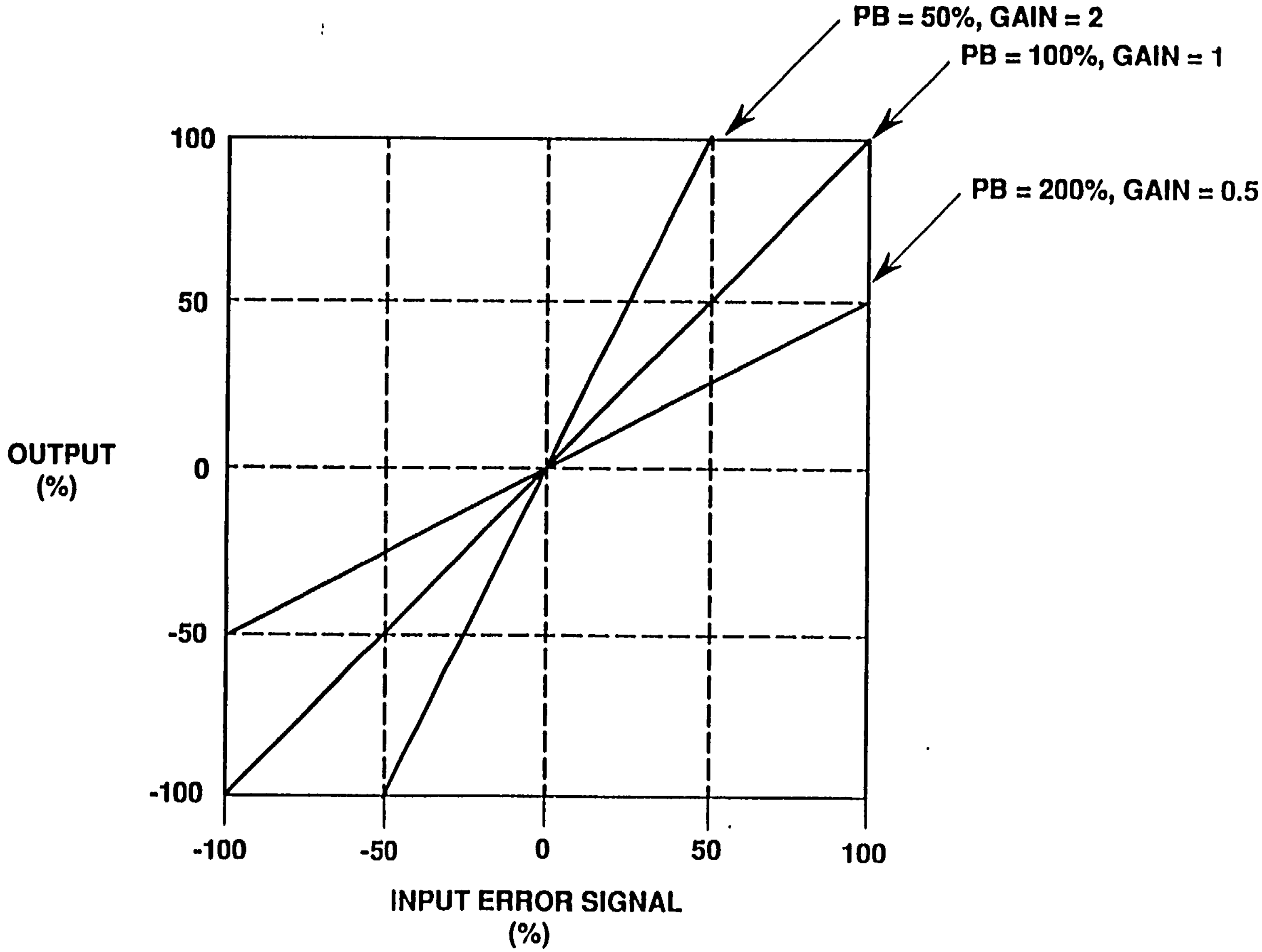


Figure 15-8. Proportional Band

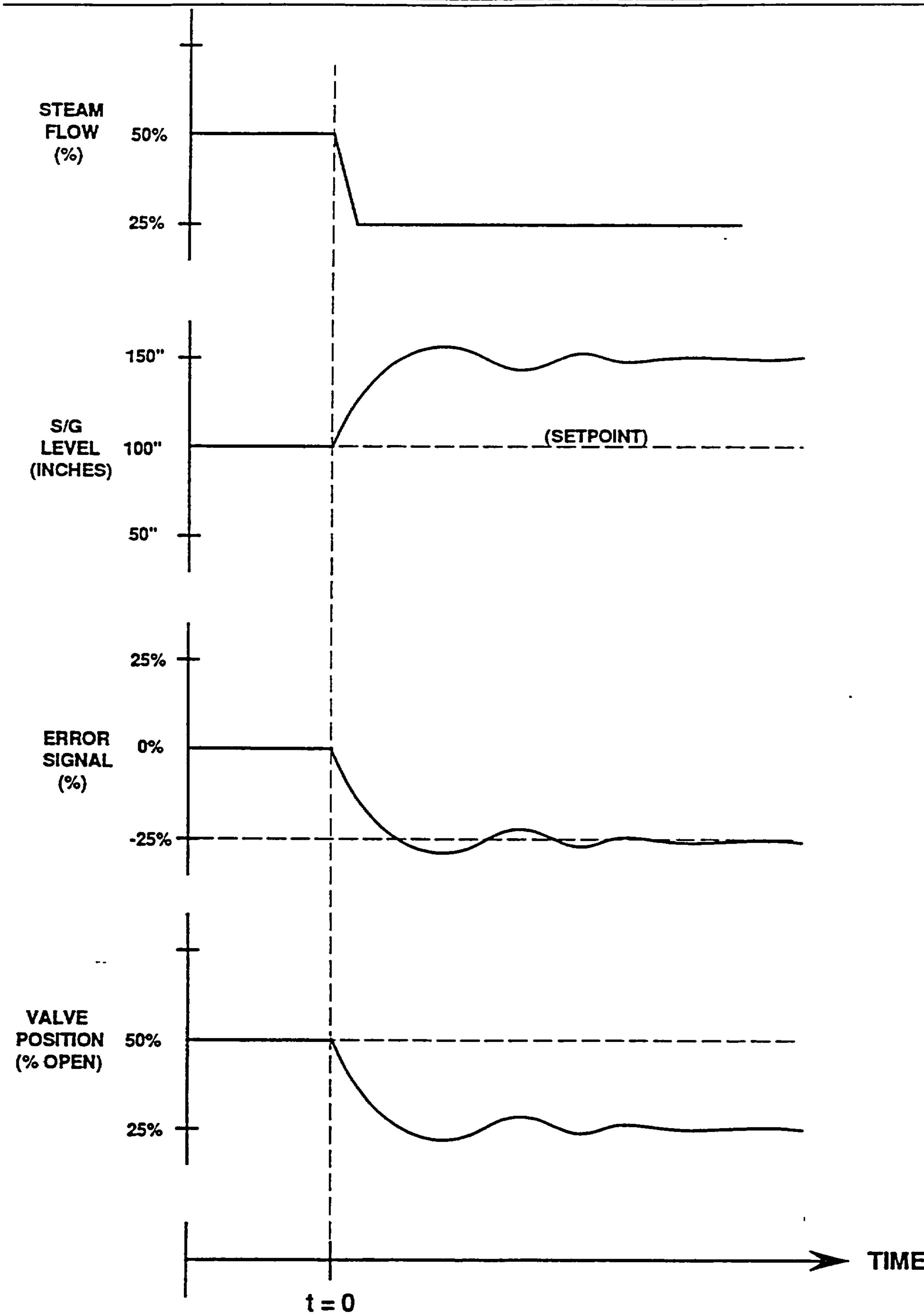


Figure 15-9. Response of Proportional Controller to Decrease in Steam Demand

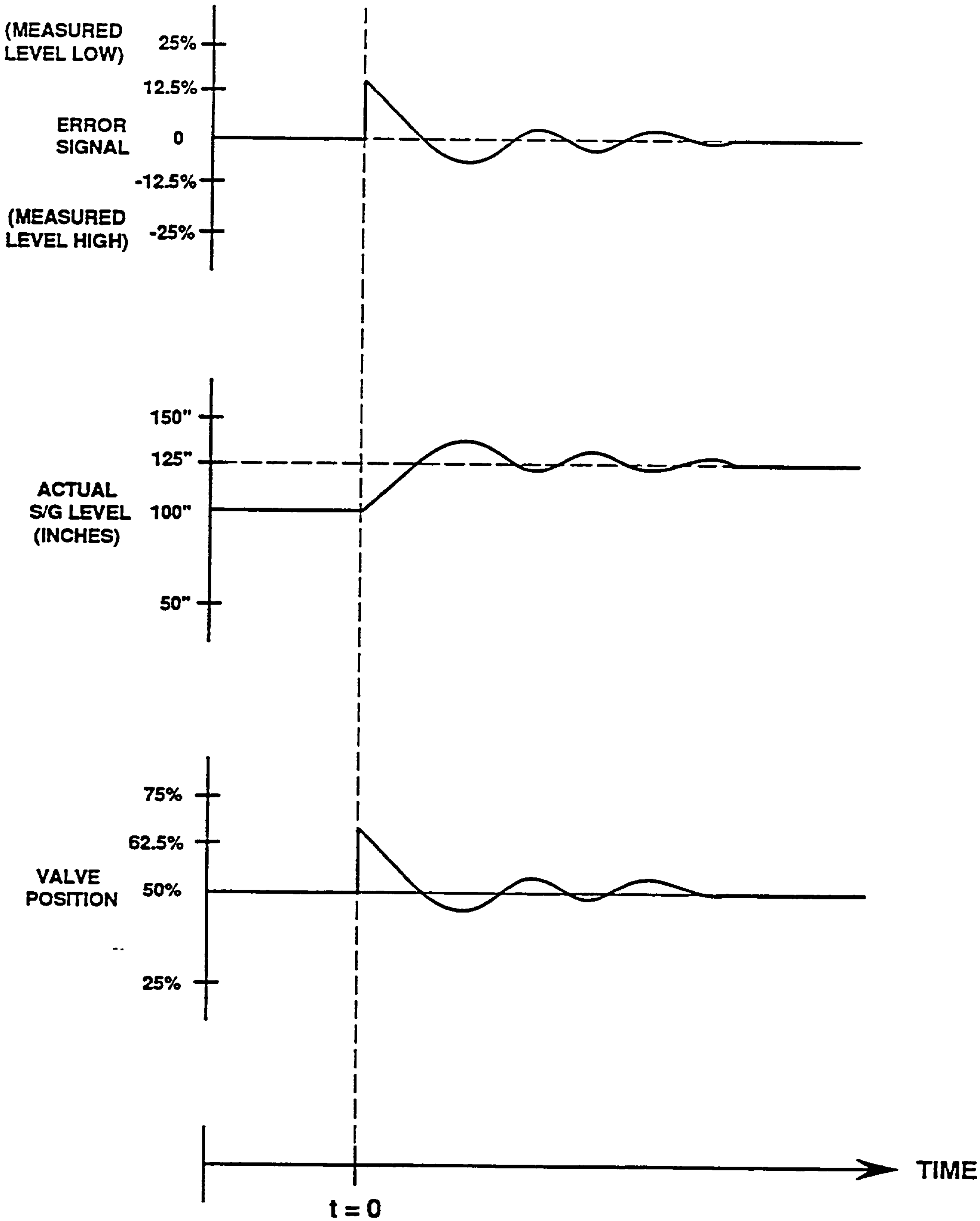


Figure 15-10. Proportional Controller Response to Step Change in Input (Gain = 1)

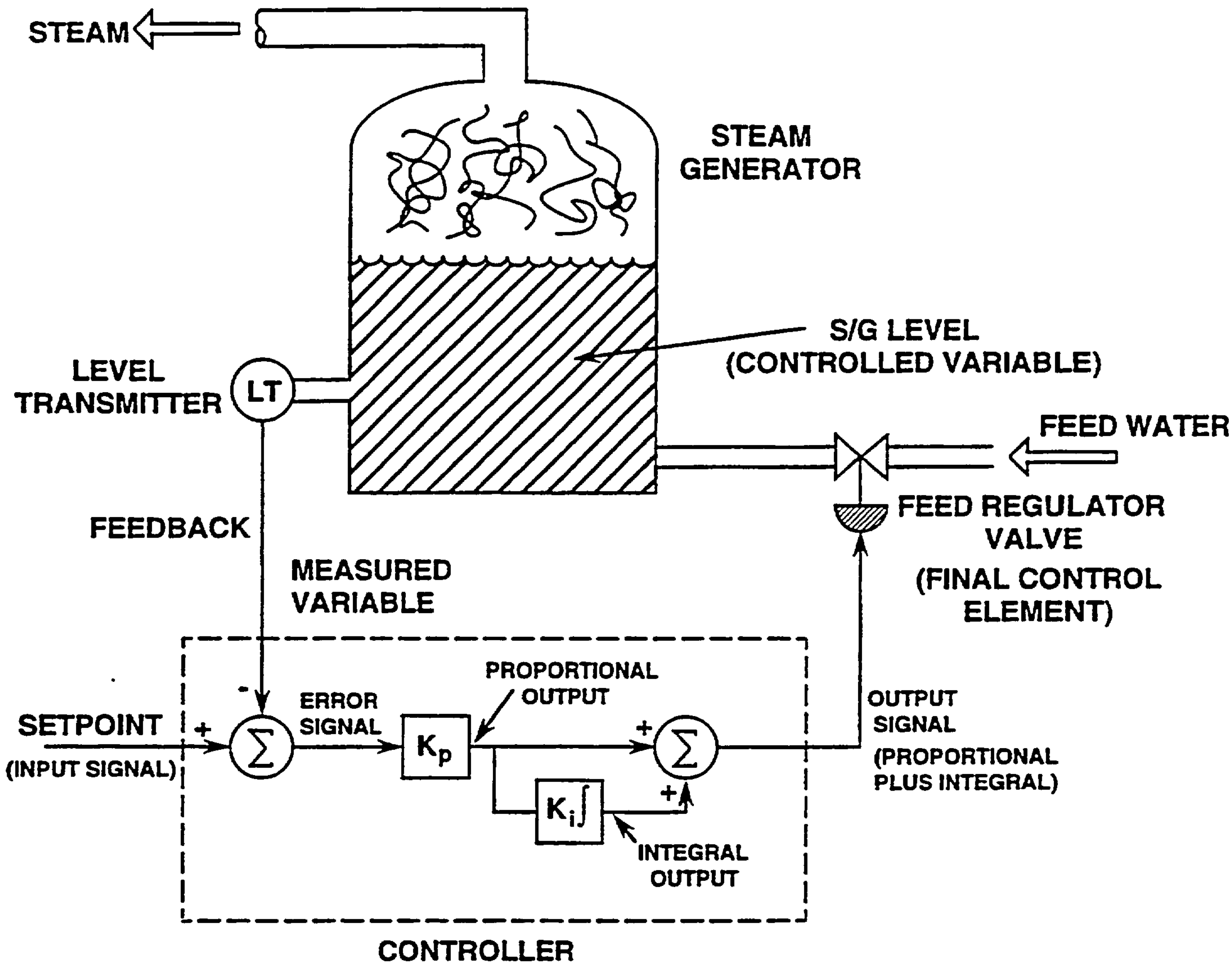


Figure 15-11. Proportional Integral Control

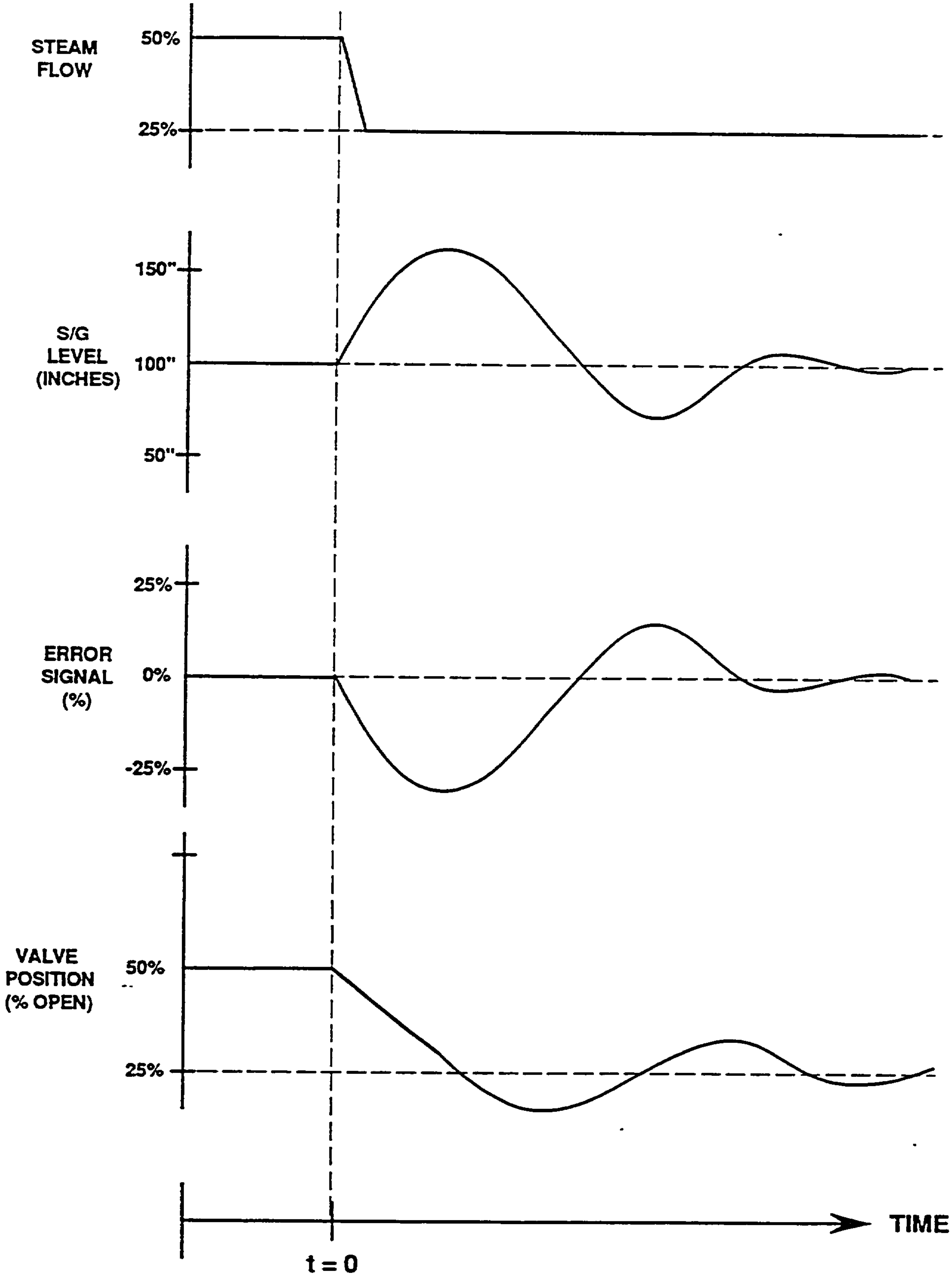


Figure 15-12. Response of Proportional Integral Controller to Decrease in Steam Demand

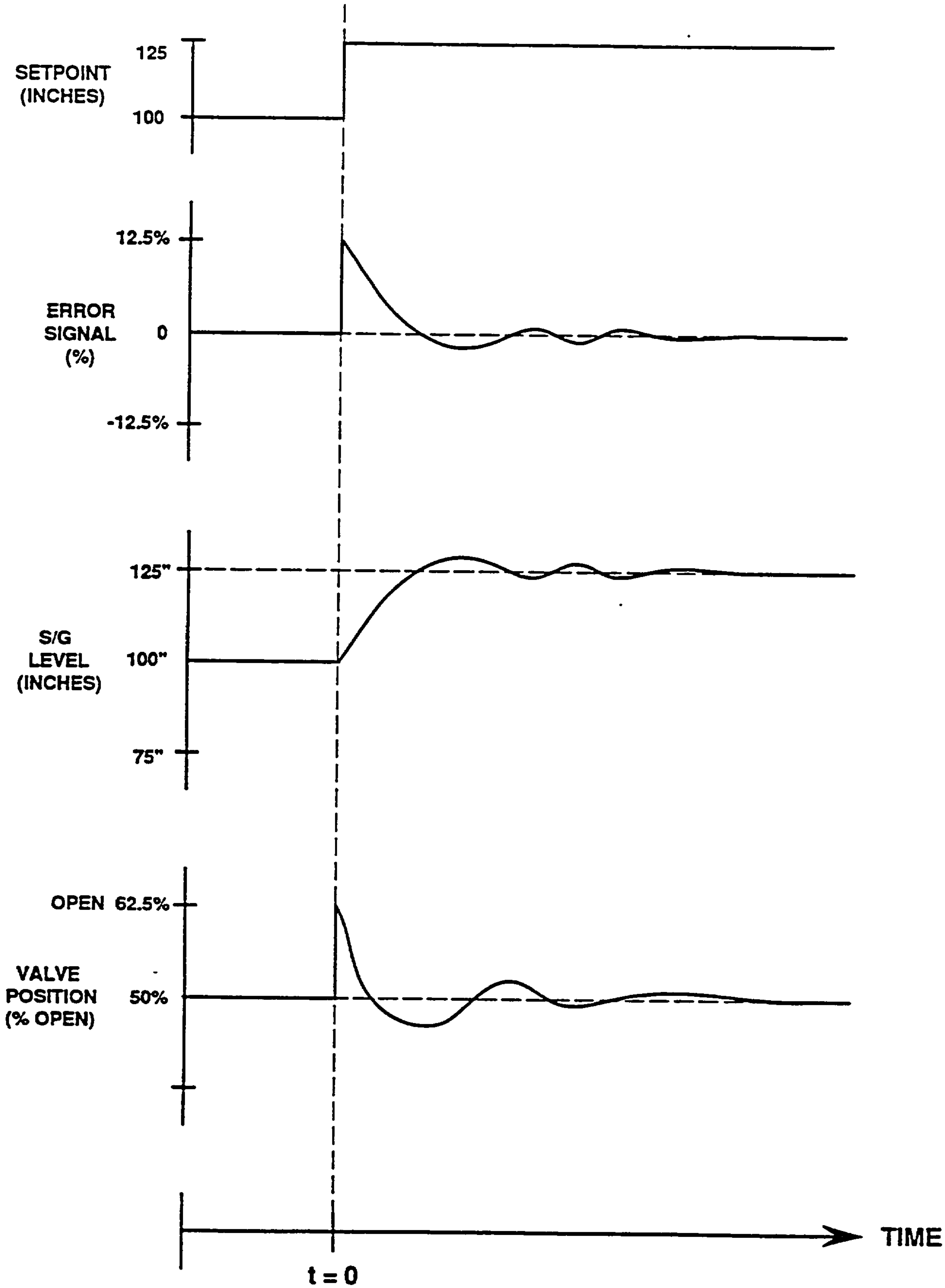


Figure 15-13. Proportional Integral Controller Response to Step Change in Level Setpoint

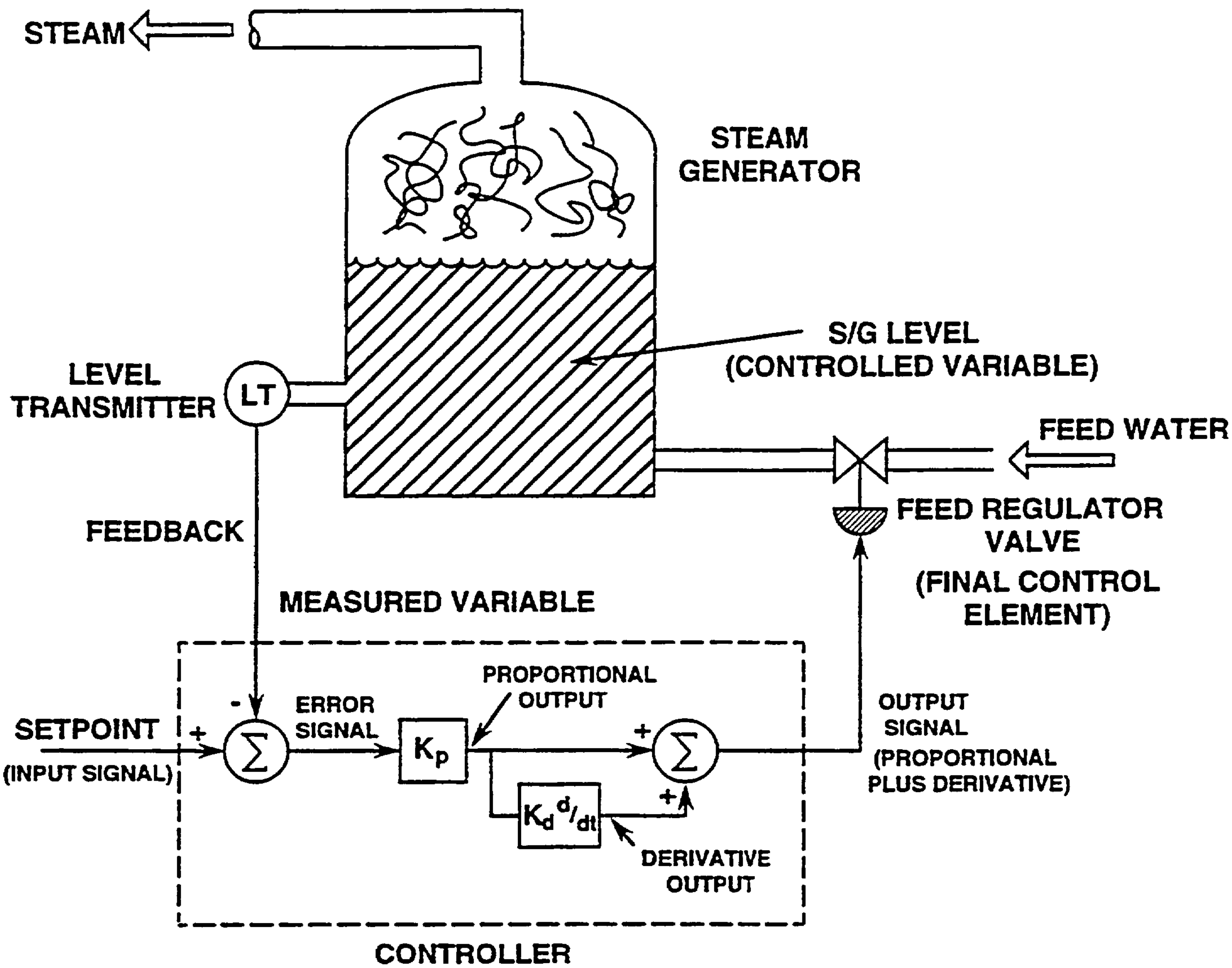


Figure 15-14. Proportional Derivative Control

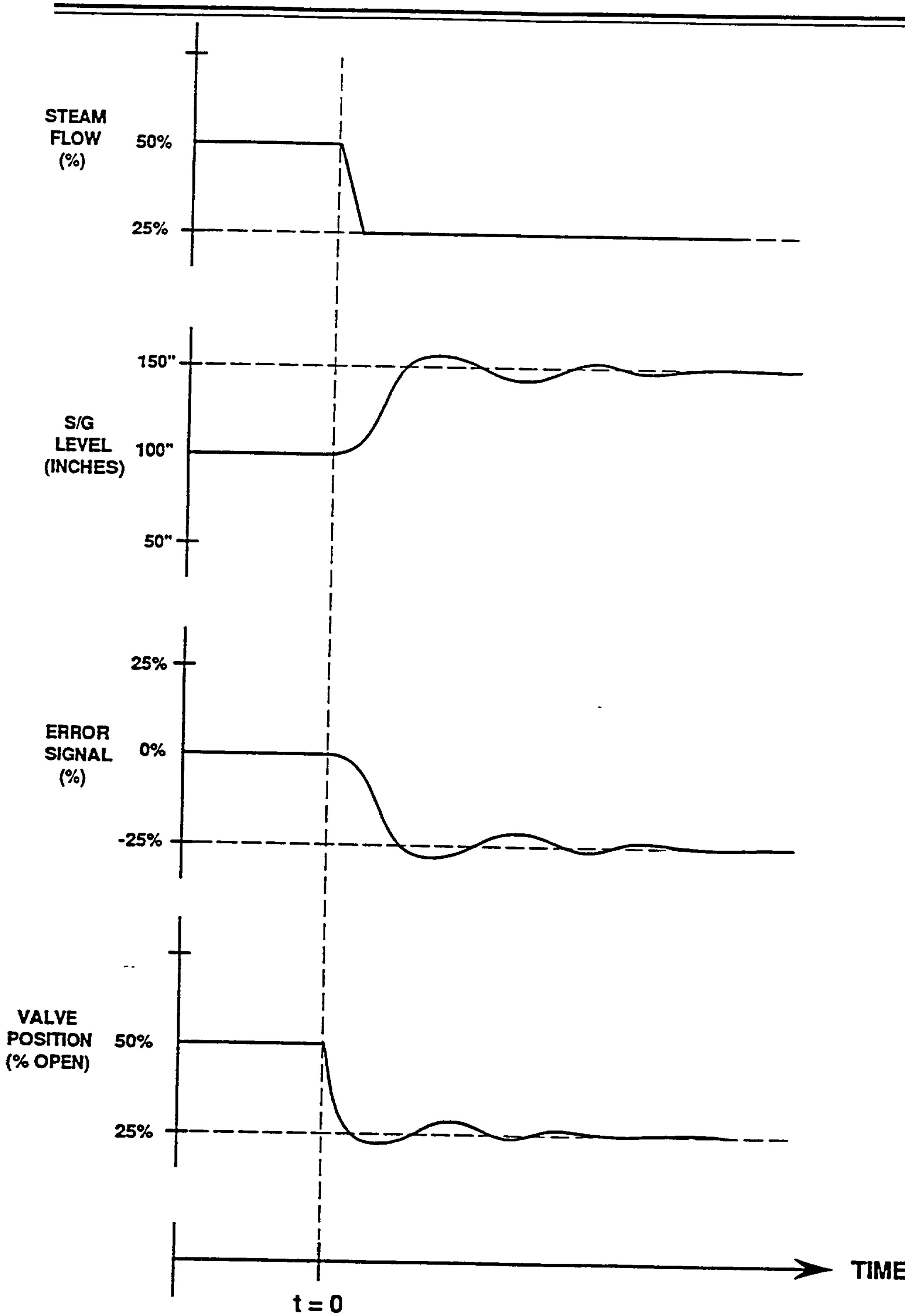


Figure 15-15. Response of Proportional Derivative Controller to Decrease in Steam Demand

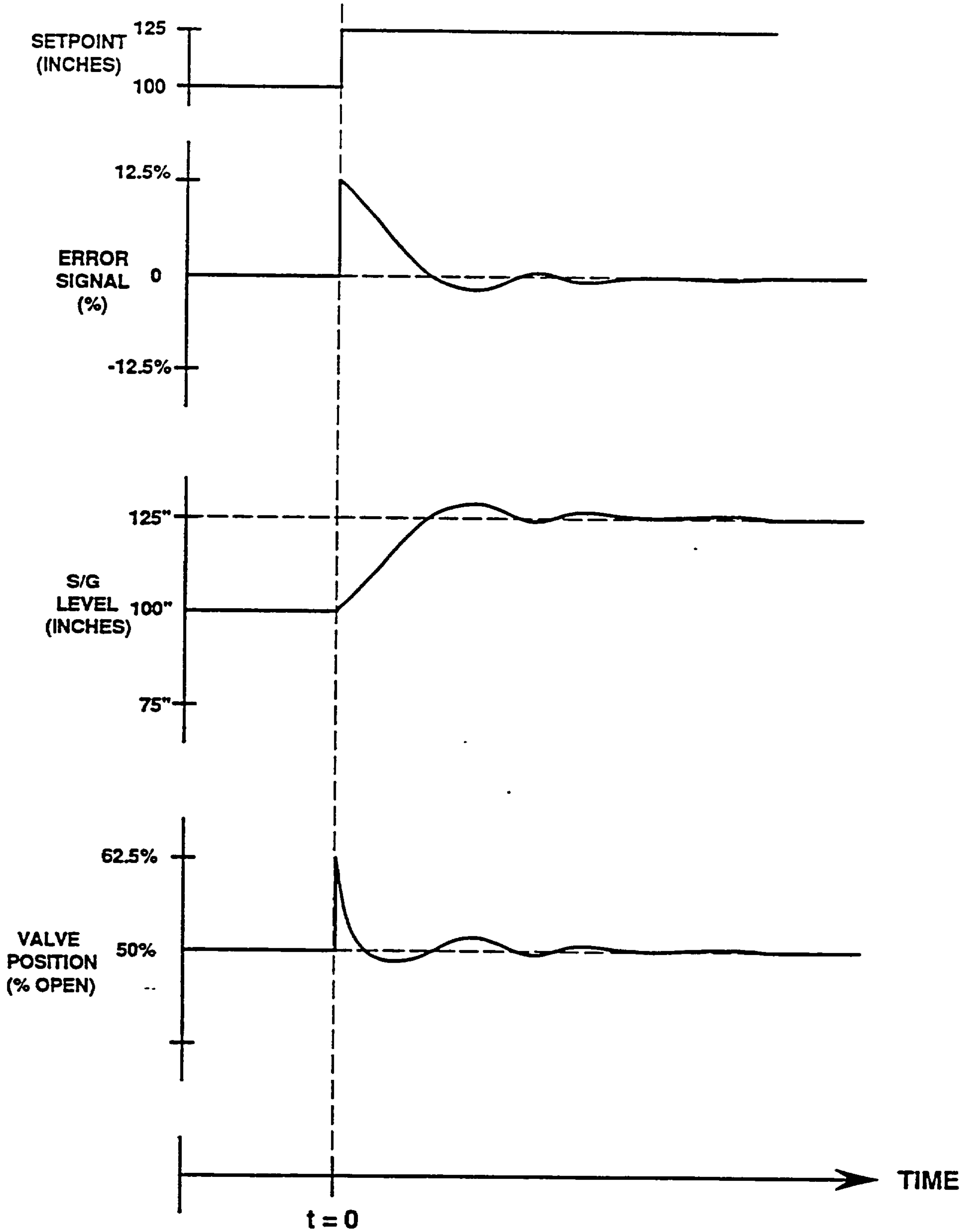


Figure 15-16. Response of Proportional Derivative Controller to Step Change in Setpoint

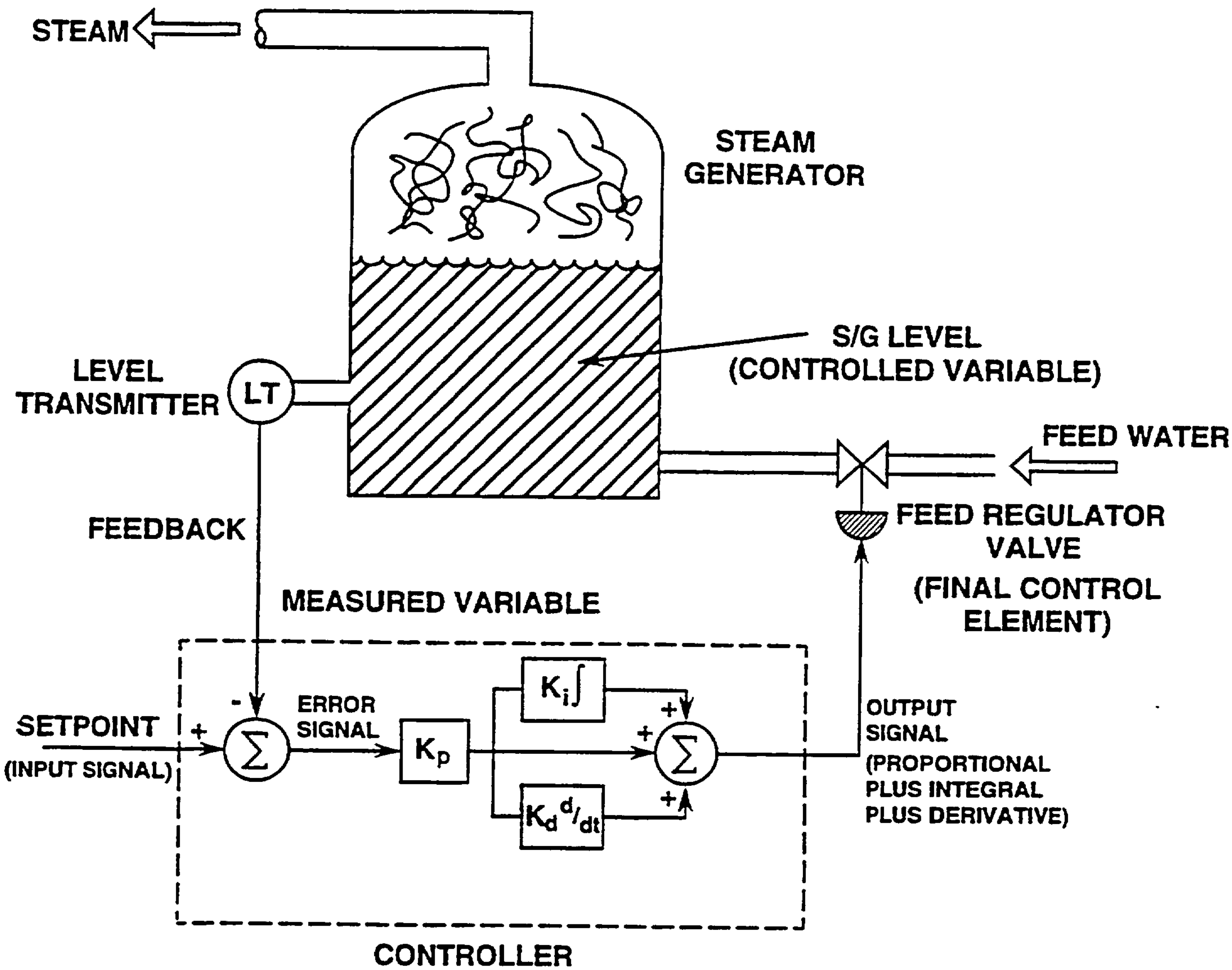


Figure 15-17. Proportional Integral Derivative Control

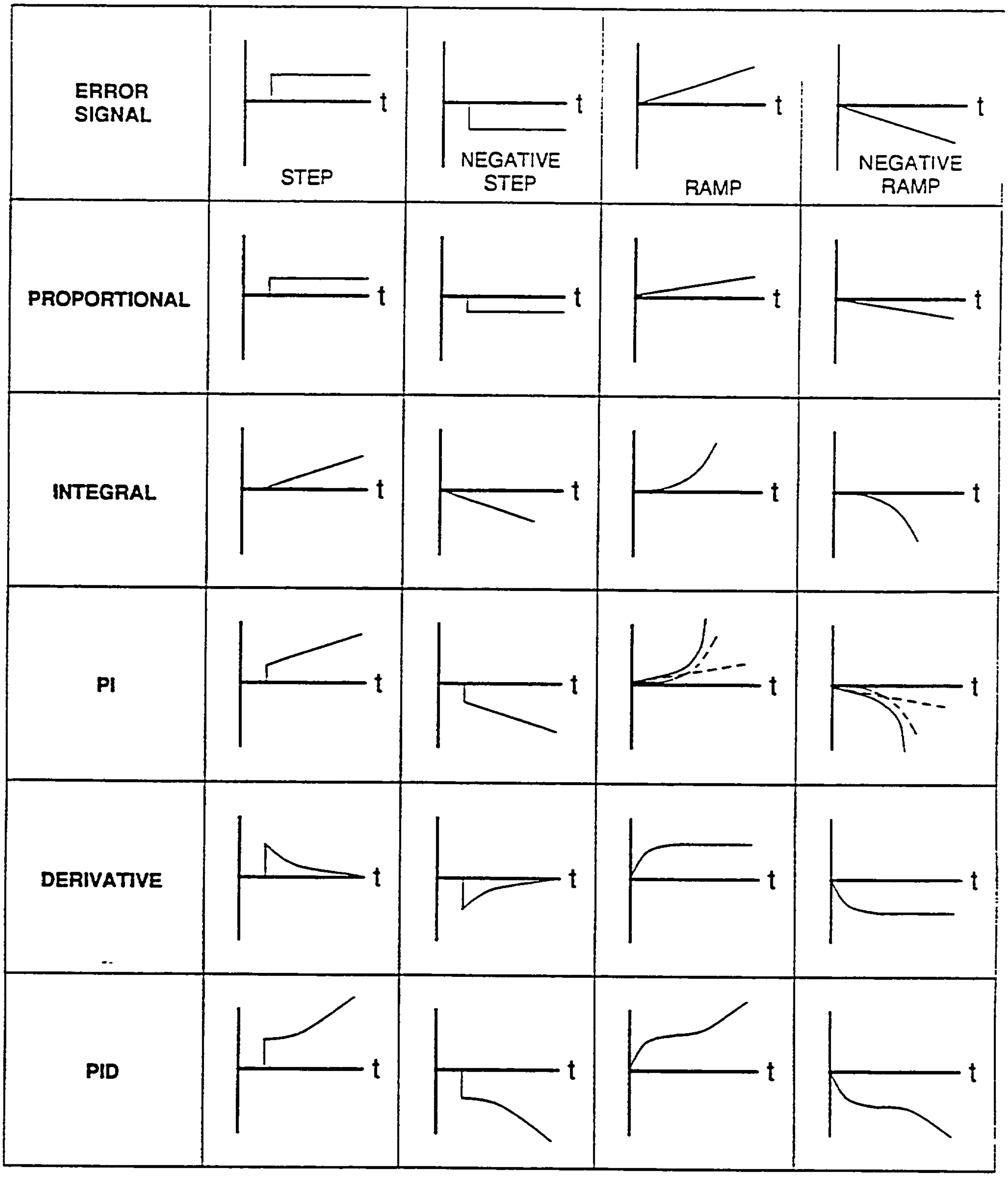


Figure 15-18. PID Controller Characteristics

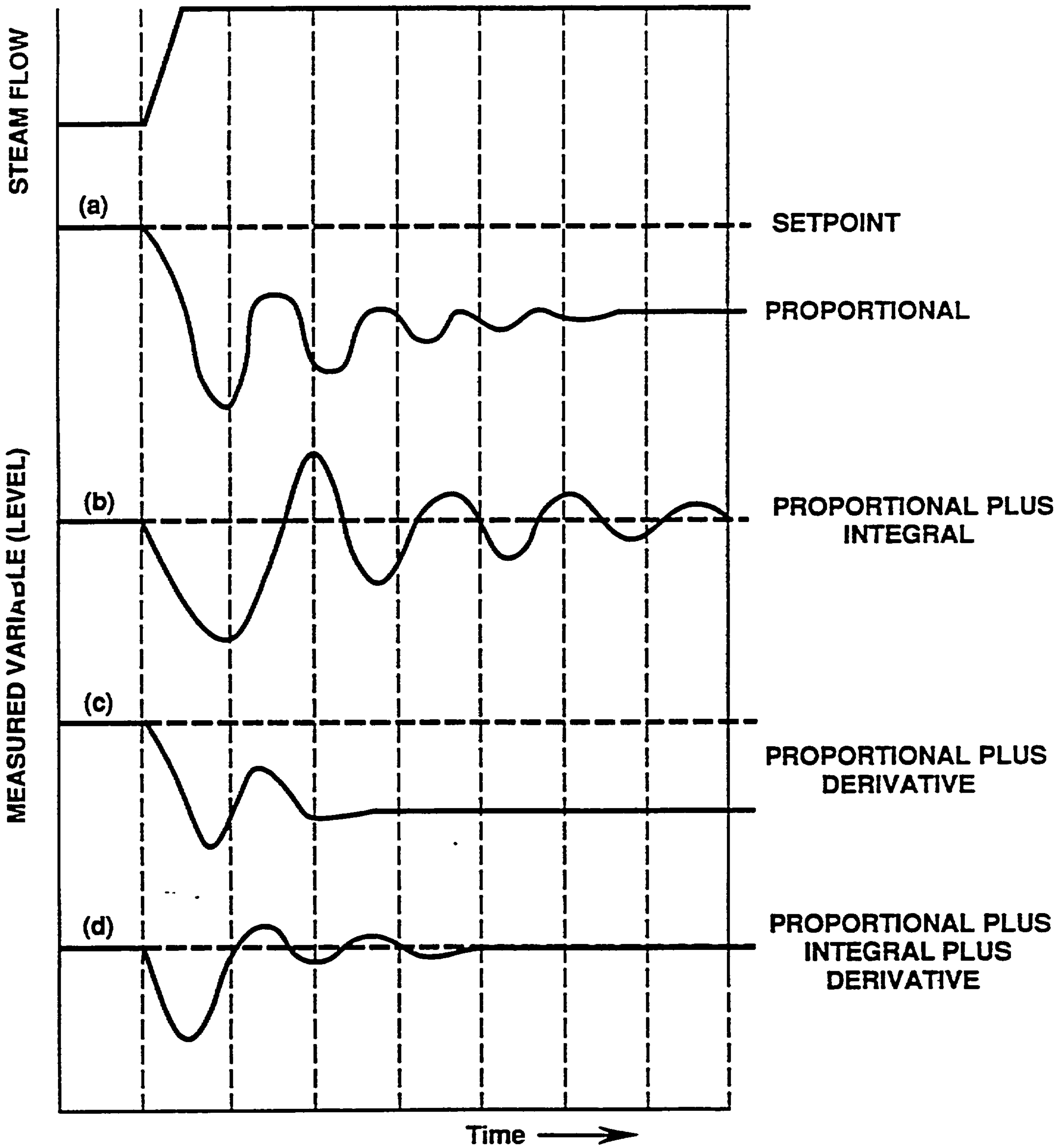


Figure 15-19. Effects of Change in Demand

16.0 NUCLEAR INSTRUMENTATION

Learning Objectives

After studying this chapter, you should be able to:

1. Describe the characteristics of a gas-filled detector operating in each region of the gas ionization curve.

2. Explain the three types of neutron reactions used to create charged particles.

3. State the region of the gas ionization curve in which each of the following detectors operate:
   a. BF_3 detector
   b. Compensated ion chamber (CIC)
   c. Uncompensated ion chamber (UIC)
   d. Fission chamber

4. Explain how each of the following detectors provide a signal proportional to reactor power:
   a. BF_3 detector
   b. CIC
   c. UIC
   d. Fission chamber
   e. Self-powered neutron detector (SPND)

5. Explain how gamma compensation is provided for each of the following:
   a. BF_3 detector
   b. CIC
   c. Fission chamber
   d. SPND

16.1 Introduction

The safe operation of a nuclear reactor requires instruments that can continuously monitor the nuclear reaction rate and accurately measure the thermal power output of the reactor. As described in Chapter 3, the thermal power output of a reactor can be accurately measured by multiplying the enthalpy rise of the reactor coolant in the reactor core times the coolant mass flow rate through the core. For nuclear reaction control purposes, however, the determination of power output in this manner may be too slow. If the nuclear reaction rate or reactor fission rate can be measured in a timely fashion, a timely measurement of thermal power output will also be obtained because the thermal power output of a nuclear reactor is proportional to the fission rate.

As discussed in Chapter 2, at normal operating conditions, reactor thermal power is essentially directly proportional to the rate of fissions occurring in the core. Each fission produces kinetic energy, gamma rays, and neutrons. Because the average number of neutrons given off in each fission is constant, reactor power is also proportional to the number of neutrons present in the core at any time, or to the neutron flux. Instruments are available that can measure the neutron flux with an almost instantaneous response. These instruments are particularly well suited for indicating the nuclear reaction rate and for providing associated signals to the plant's automatic control and safety systems. These instruments can also be appropriately calibrated to provide an accurate indication of the reactor thermal power output.

The Nuclear Instrumentation (NI) System measures the neutron flux in the reactor. The NI system must be able to measure the neutron flux that exists in a shutdown reactor (about 100 neutrons per square meter per second) to the flux that exists in a reactor at maximum power output (about 10^{14} neutrons per square meter per second). This measurement range of about 12 decades, as shown in Figure 16-1, required the early NI systems to incorporate three separate ranges of sensitivity in the detectors: the source (lowest) range, the intermediate range, and the power range. Newer NI systems have incorporated wide-range detectors, either as an add-on to the three basic detector ranges, or as a replacement for the source and intermediate range detectors.

In PWR plants, the neutron flux detectors (called "excore" detectors) are commonly located outside the reactor vessel to minimize the amount of fast neutron flux exposure that the detectors receive. The excore detectors measure leakage neutron flux, which is proportional to the neutron flux inside the core. Because the excore detectors are shielded from the core by several inches of water, the intercepted leakage neutron flux is mostly thermal neutrons. The excore detectors are normally encased in a good neutron moderator like polypropylene to ensure that almost all of the neutrons reaching the detector are in the thermal energy range. Figure 16-2 shows a typical arrangement of excore detectors around a PWR reactor vessel.

BWR plants have traditionally used only incore detectors to measure actual neutron flux at numerous (40 or more) locations in the core. The outputs of all these detectors, which measure very localized conditions, are then electronically summed and averaged to obtain an average power level for the core. Most PWR plants also use incore detectors to measure the actual flux at specific locations in the core. These detectors do not have immediate readouts, however, and are normally used to ensure that localized conditions are being accurately represented by the excore detectors.

This chapter discusses some common detectors used in nuclear instrumentation systems. Before that discussion can begin, however, some background information on nuclear radiation interactions and nuclear ionization should be reviewed. Almost all nuclear instrumentation detectors rely on the effects of nuclear ionization to convert from nuclear radiation interactions to an electronic output that is useful in measurement and control systems. The following sections will provide some background information on nuclear ionization; background information on nuclear radiation interactions is provided in Section 2 of the PPE Course Pre-Study Text.

16.2 Nuclear Ionization

Direct nuclear ionization is normally caused by a fast-moving charged particle, such as an alpha or beta particle moving through some material. If the charged particle approaches closely enough to an orbital electron of one of the atoms or molecules of the material, it will create forces that will dislodge the electron from the atom or molecule. What is left of the atom, after the electron has been stripped from it, is a positively charged ion since it has lost the negative charge of one electron. In addition, there is now a free electron moving through the material. These two particles, the remains of the atom with one electron removed, and the free electron, are referred to as an ion-pair. The ability of a charged particle to produce this ionization is expressed by a number called its specific ionization, which is the number of ion-pairs formed per centimeter of path traveled in a given material.

Specific ionization will tend to increase with the charge of the particle because it will exert more force on the orbital electron. For particles with the same charge and the same kinetic energy, those with higher mass will move more slowly and will spend more time in the vicinity of a given orbital electron, enhancing the probability of electron removal. Therefore, the specific ionization produced by an alpha particle is considerably greater that that caused by a beta particle.

Because a neutron possesses no charge, it does not produce ionization in the manner of beta and alpha particles. Neutrons produce ionization indirectly. Various materials can absorb or capture neutrons in their nuclei, which leaves the nuclei in an "excited state," or a condition of excess energy. This energy is commonly released by the emission of a charged particle, which produces the direct ionization described above.

Gamma rays or photons resemble neutrons in that they possess no charge and do not produce direct ionization as described for alpha and beta particles. However, gamma rays can interact with matter to produce ions by three specific processes: the photoelectric effect, Compton scattering, and pair production. The details of these processes are described in Section 2 of the PPE Course Pre-Study Text; for this discussion the student should recognize that gamma radiation can also produce ion-pairs in intercepting substances.

A substantial fraction of the energy released from nuclear fission appears in the form of gamma radiation. Therefore, at high power levels the intensity of this radiation is proportional to the fission rate, and hence the reactor power level. It would seem possible to use a measurement of gamma radiation level in or near the reactor core to indicate reactor power level, and indeed it can be done. However, the measurement is complicated because in addition to the gamma radiation released instantaneously from fissions, many of the resulting fission products decay, at various rates, with the release of sizable amounts of gamma radiation. This component of the overall gamma radiation level is not proportional to the instantaneous fission rate or reactor power level, but instead is a complicated function of the previous operating history of the core. Because the overall gamma radiation level has this component that is not directly related to the current power level of the reactor, measurement of the gamma radiation field does not provide a good indication of current reactor power level at low power levels.

16.3 Nuclear Ionization Detectors

Most nuclear instruments for the detection of radiation depend on the production of ion-pairs by ionizing particles in their passage through a gas. Radiation detectors basically consist of two electrodes in a chamber of gas with an electric potential established between the electrodes. A basic radiation detector is shown in Figure 16-3. As a general rule, the center wire is the positive electrode (anode) and the outer cylinder is the negative electrode (cathode), so that (negative) electrons are attracted to the center wire and positive ions are attracted to the outer cylinder. The anode is at a positive voltage with respect to the detector wall.

As ionizing radiation enters the gas between the electrodes, a finite number of ion-pairs are formed. The behavior of the resultant ion-pairs is affected by the potential gradient of the electric field within the gas. Under the influence of the electric field, the positive ions will move toward the negatively charged electrode, and the negative ions (electrons) will migrate toward the positive electrode. The collection of these ions will produce a charge on the electrodes and an electrical pulse across the detection circuit.

When a radiation detector is held in a constant incident radiation field, the magnitude of the charge collected on the electrodes or the pulse size will depend on the magnitude of the applied voltage difference between the two electrodes. Figure 16-4 provides detector gas ionization curves for various types of constant incident radiation fields and illustrates the dependency of the pulse size on the magnitude of the voltage applied to the detector. The curves in Figure 16-4 are produced with the detector remaining in a constant incident radiation field of the indicated type while the voltage between the two electrodes is slowly increased. Gas ionization curves of the type shown in Figure 16-4 can be divided into six different regions to describe the predominant behavior of the ion-pairs produced by incident radiation.

16.3.1 Recombination Region

If the voltage between the two electrodes is set to zero, ions will not be attracted to either electrode. The ion-pairs will be produced, but will recombine within the gas chamber, so no charge will flow in the detection circuit. As the voltage is increased above zero, some of the free negative ions (electrons) will be attracted to the anode, and some of the positively charged ions will be attracted to the cathode. Thus, there will be some charge flowing through the circuit.

When the voltage is low, recombination can occur while ions are traveling toward the electrodes, so not all the ions produced will reach the electrodes. As the detector voltage is increased, however, an increasingly larger fraction of the ions produced will reach the electrodes. This increase continues until the "saturation" voltage is attained. At this point, all the ions being produced by the incident radiation are being collected by the electrodes. A chamber in which the applied voltage is less than the saturation voltage is said to be operating in the "recombination region." This region is shown graphically in Figure 16-4 as Region I of the six-region curve. Detectors are not operated in Region I because neither the number of recombinations nor the number of ion-pairs initially produced can be determined accurately.

16.3.2 Ionization Region

In the ionization region (Region II of Figure 16-4), an increase in voltage does not cause a substantial increase in the number of ion-pairs collected. Therefore, this portion of the curve is flat. The reason for this is that every ion-pair produced in the detector is collected by the electrodes. The voltage is high enough to prevent recombination, but is not high enough to cause gas amplification (ions moving toward the electrodes so fast that they cause secondary ionizations). In the ionization region, the number of ion-pairs collected by the electrodes is equal to the number of ion-pairs produced by the incident radiation, and is dependent on the type and energy of the particles or rays in the incident radiation.

In the ionization region, the number of ion-pairs produced and the number of ions collected do not vary with voltage. When the incident radiation field is strong enough, ionization chamber instruments are operated in the ionization region because a small variation in detector voltage will not affect the output current in the detection circuit.

16.3.3 Proportional Region

When the detector voltage is increased beyond the ionization region values, gas amplification begins to occur. Some of the positive ions that are moving rapidly toward the positive electrode collide with neutral atoms and ionize them, resulting in the production of additional ion-pairs. These new ion-pairs are attracted to the electrodes and are collected with the ion-pairs produced by the incident radiation. The collected charge is proportional to the charge produced in the ionization region, which is dependent on the type and energy of the particles or rays in the intercepted radiation field.

A detector whose applied voltage is large enough to cause gas amplification is said to be operating in the "proportional region" (Region III of Figure 16-4). The gas amplification that occurs in this region can increase the total amount of ionization to a measurable value. Gas amplification is needed when the ionizing radiation that enters a chamber does not produce enough primary ionization to be measured accurately.

When instruments are operated in the proportional region, the voltage must be kept constant. If it is, the number of ion-pairs collected in the proportional region is directly proportional to the number of ion-pairs originally produced in the detector by the radiation. Proportional counter-detection instruments are operated in the proportional region because the effect of gas amplification makes the instruments sensitive to low levels of radiation.

16.3.4 Limited Proportional Region

As the voltage is increased still further, other factors arise that limit the production of secondary ion-pairs, so the gas amplification factor does not continue to increase proportionally to the voltage. The negative ions (electrons) are much lighter than the positive ions; thus, they are drawn toward the positive central electrode much faster than the positive ions are drawn to the chamber wall.

The result is a "cloud" of excess positive ions, which forms a space charge around the positive center electrode. The space charge reduces the electric field intensity between the electrodes and prevents some negative ions from reaching the center electrode. Consequently, at sufficiently high voltage in Region IV, the amplification factor approaches a limit, and the charge collected is no longer proportional to the initial ionization. Region IV is, therefore, referred to as the limited proportional region. At the upper end of this region the space charge effect is essentially the only factor determining the amount of charge collected. The discharge in the tube has become space-charge limited, and the same charge is collected regardless of the number of primary ion-pairs formed. Note that the gas amplification factor no longer has a definite value under these conditions.

16.3.5 Geiger-Mueller Region

The space charge limitation is effective across the Geiger-Mueller (G-M) region (Region V). In this region, any particle that produces ionization in the detector will produce a large amount of secondary ionization, even though the original ionization may consist of only one ion-pair. This large discharge of secondary ionization occurs for gamma rays, which produce ionization by secondary processes, and for all types of charged particles. Therefore, detectors operating in the G-M region cannot distinguish between different types of radiation. G-M detectors register one event for each intercept of an incident particle or ray.

16.3.6 Continuous Discharge Region

If the applied voltage is increased beyond the Geiger-Mueller region, there is a rapid increase in the charge collected; this condition is represented by the Continuous Discharge region (Region VI). The potential is so high, then, that once secondary ionizations are initiated, others follow in such rapid succession that the instrument is effectively in a continuous discharge. This region is not used for detection or measurement of ionizing radiation.

16.4 Neutron Detection

Neutrons are not detected directly, like alpha or beta particles. Neutrons do not have an electrical charge to cause direct ionizations, but neutrons can interact with certain materials to create charged particles, and the ionization effects of these particles can be measured.

Three types of reactions are used to create particles with neutrons. The first is the neutron-alpha (n, α) reaction.

$${}_0n^1 + {}_5B^{10} \rightarrow {}_5B^{11} \rightarrow {}_3Li^7 + {}_2He^4$$

In this reaction, a neutron strikes a boron-10 atom and is absorbed into the nucleus of the atom. The result is boron-11, which promptly decays into a lithium nucleus and a helium nucleus. The decay reaction also releases significant energy, which is normally converted into the kinetic energy of the decay nuclei. The high velocity of the nuclei often causes some of their orbital electrons to be stripped away, causing the nuclei to become charged particles. The charged helium nucleus essentially becomes an alpha particle, hence the neutron-alpha designation for the reaction. The charged alpha particle (and the charged lithium nucleus) produce significant ionization that can be used for neutron detection.

The neutron- alpha reaction is useful for neutron detection because it has a large probability of occurrence with boron-10. (The microscopic cross section of boron-10 is a very large 3,840 barns.) It is also useful because of the energy released when the reaction takes place. If the boron-10 is arranged so that the (n, α) reaction takes place in a gas, the kinetic energy of the decay nuclei will be consumed by ionization of the gas. The resulting ionization can then be detected, and is an indirect detection of the neutron.

The second method of detecting neutrons is a neutron-fission (n, f) reaction. A neutron is absorbed into a uranium-235 nucleus and produces uranium-236, which immediately fissions and produces charged fission fragments that can be used in the neutron detection process.

$${}_0n^1 + {}_{92}U^{235} \rightarrow {}_{92}U^{236} \rightarrow \text{fission fragments} + \text{neutrons}$$

The (n, f) reaction is highly suitable for use in neutron detection for several reasons. The reaction probability is relatively large (the cross section of U-235 is 580 barns). A great deal of kinetic energy is released (about 160 Mev shared among the fission fragments) in the reaction, and the energy can be readily used to produce gas ionization.

The third reaction is a neutron activation reaction. A neutron is absorbed into the nucleus of a rhodium-103 atom and produces rhodium-104, which is radioactive.

$${}_{0}n^{1} + {}_{45}Rh^{103} \rightarrow {}_{45}Rh^{104} + \gamma$$

Because the rhodium-104 is radioactive and, therefore, unstable, it eventually decays into palladium-104 by emission of a beta particle.

$${}_{45}Rh^{104} \rightarrow {}_{46}Pd^{104} + {}_{-1}\beta^{0}$$

The beta particle from the rhodium is negatively charged and can be used for neutron detection. This reaction is not prompt, because rhodium-104 has a half-life of 42.5 seconds. This delay occurs between the time the neutron is absorbed into the nucleus and the time that the rhodium-104 changes into palladium-104 and emits a beta particle. The half-life of rhodium-104 causes a delay in the neutron detection process. This delay is an important consideration in self-powered neutron detectors, which use this activation reaction. Proportional counters and ion chambers use neutron-alpha or neutron-fission reactions to detect neutrons. In all cases, the number of charged particles produced is proportional to the number of neutrons and, hence, to reactor power.

16.5 Proportional Type Detectors

A proportional type neutron detector is normally used to measure source/startup range neutron flux in a PWR. This type of detector amplifies and collects the ion-pairs from a single ionizing event and creates one large "pulse" of electric current. A count of the number of pulses produced is a measure of the number of neutrons entering the detector. As previously stated, this number can be correlated to reactor power.

All proportional detectors have several common features. For example, they all operate in the proportional region of the six-region gas ionization curve. Because of the high applied voltage, all of the ion-pairs created by the charged particles and the additional ion-pairs created by gas amplification will be collected. The additional ion-pairs created by gas amplification help create an easily discernible electrical pulse for each ionizing event. The size of the pulse will vary with the type of neutron reaction that is used. (Different charged particles create different numbers of ion-pairs.)

16.5.1 BF_3 Proportional Counter

The boron trifluoride (BF_3) proportional counter (see Figure 16-5) is one of the simplest types of proportional neutron detectors. The walls of its aluminum body serve as the negative electrode, and a tungsten wire in the center of the detector acts as the positive electrode. A ceramic seal and insulator are used at each end of the wire. An instrument cable at one end is connected to the positive and negative electrodes. The cable supplies the voltage to the electrodes and carries away the current created by the collection of ion-pairs.

Boron trifluoride (BF_3) gas is added to the chamber inside the detector, and neutrons react with the boron in the gas to create neutron-alpha reactions. The charged particles created then cause ionization in the gas. The high voltages applied to the electrodes make the detector operate in the proportional region.

The operation of a BF_3 proportional counter is as follows:

1. A neutron enters the detector and reacts with the boron in the gas to produce positively charged ions and free electrons.

2. Because there is a voltage applied between the electrodes, the positive ions move to-

ward the outer electrode. The kinetic energy of the positive ions produces more ion-pairs, which in turn accelerate toward the electrodes. The speed at which these ions are drawn to the electrodes depends upon the voltage applied to the electrodes; as more voltage is applied, the ions travel faster.

3. As the negative ions are collected at the positive electrode, they produce a current pulse that flows through the circuit. As more negative ions are collected, the current pulse magnitude increases until it reaches a peak. After all of the negative ions have been collected and converted into output, the circuit current returns to zero.

4. Each rise and fall of the current is equivalent to one pulse of electrical current. Each pulse is an indication of one ionizing event, and the number of ionizing events, or neutrons, entering the detector is proportional to reactor power. Therefore, the number of pulses produced can be used as an indication of reactor power.

For each electron that is collected in the chamber, there is a positively charged gas ion left over. These gas ions are heavy compared to the electrons, and move much more slowly. These ions move away from the positively charged tungsten wire, toward the negatively charged wall, and are neutralized by gaining an electron. In the process some energy is given off which causes additional ionization of the gas atoms. The electrons produced by this ionization move toward the center wire, and are multiplied again. This secondary pulse of charge is unrelated to the incident radiation, and can set off a series of pulses that must be eliminated or "quenched."

One method for quenching these discharges is to add a small amount (10%) of an organic gas such as methane in the chamber. The quenching gas molecules have a lesser affinity for electrons then the chamber gas, and therefore, the ionized atoms of the chamber gas readily take electrons from the quenching gas molecules. Thus, it is always the ionized molecules of quenching gas that reach the chamber wall. These ionized molecules of the quenching gas are neutralized by gaining an electron, and the energy liberated will not cause further ionization, but causes dissociation of the quenching gas molecule. This dissociation quenches multiple discharges. The quenching gas molecules are consumed during this process; therefore, the lifetime of proportional counters is limited by the usage of the quenching gas.

In addition to neutrons, gamma rays also cause ionization events in a proportional counter. The electrical charges produced by gamma reactions are smaller in magnitude than those produced by neutron reactions; therefore, the secondary ionizations caused by the gamma will produce a smaller pulse. This fact will allow the discrimination or removal of the gamma pulses, which would interfere with the neutron signal at the low reactor power levels where proportional counters are used.

16.5.2 Source Range/Startup Channel Gamma Compensation

The source range/startup channel provides the operator with necessary information to monitor the shutdown neutron flux levels and determine criticality during a reactor startup. Because the operator is interested in detecting only neutrons at the low power levels where proportional counters are used, a method must be used to eliminate the signal due to gamma reactions within the detector. A block diagram of a startup channel is shown in Figure 16-6.

The detector output (pulses) caused by neutrons and/or gamma events is supplied to a preamplifier (preamp), which functions to increase the magnitude of the detector output pulses. The pulse counting circuit performs two functions. First, the pulse height discriminator eliminates the undesirable gamma signal by passing only the larger neutron pulses. The signal is then converted to a uniform rectangular square wave by a square wave pulse shaper. The log pulse integrator/amplifier converts the neutron pulses into a logarithmic signal, which is required for accurate resolution on the local or remote indication.

The output of the log circuit supplies instrumentation meters and an input to the startup rate circuit (SUR). The startup rate is used to provide indication to the operator on the rate at which reactor power is changing. The meter will be calibrated to read out in decades/min (SUR) or seconds (period) as discussed in Chapter 2.

16.6 Ionization Type Detectors

The principles of operation for ion chamber neutron detectors are similar to those of the proportional detectors. The ion chamber has a positive electrode and a negative electrode that collect ion-pairs like the electrodes in a proportional detector. The ion chambers are coated with boron-10 to produce charged particles from the neutrons entering the detector. The gas inside the chamber that is ionized by the charged particles is usually argon.

The major difference between proportional detectors and ion chambers is that they operate in different regions of the six-region gas ionization curve. The ion chamber operates in the ionization region. The voltage applied between the electrodes in an ionization chamber is less than that applied in a proportional chamber. The lower voltage in the ion chamber means that no gas amplification takes place. When an ionizing event occurs, only the ion-pairs that are initially created by the ionizing event will be collected for measurement by the electrodes.

Ion chambers are normally used in higher neutron flux ranges. A higher neutron flux results in many ionizing events making it impossible to count each individual pulse. Instead, an electric current is produced, and the magnitude of the current signal is proportional to the number of ionizing events. Ion chambers can be designed to provide a means of removing the current caused by gamma ionizations from the current caused by neutrons.

16.6.1 Fission Chamber

Because fissioning a uranium atom results in two very large charged particles with significant energy to cause extensive ionization, fission chambers are normally operated in the ionization region to detect neutrons. The fission chamber is coated on the inner surface with a uranium oxide compound (U_3O_8). Thermal neutrons entering the detector have a large probability of being absorbed by the U-235 in the U_3O_8 coating. Of the neutrons that are absorbed, a percentage cause U-235 atoms to fission. The result is that two or more high energy, charged fission fragments cause ionization of the argon gas within the detector (see Figure 16-7). The ions are collected, and an electrical charge pulse can be observed. Some ionization of the argon gas may also be caused by gamma radiation present in the detector. The amplitude of the charge-pulse is dependent on the number of ion-pairs produced, and is a function of the energy of the ionizing radiation producing the ion-pairs. The fission fragments resulting from the interaction of neutrons with the U_3O_8 coating cause a significantly larger amount of ionization within the fission chamber than the gamma radiation incident on the detector. This results in the neutron-generated charge pulses being significantly larger than the gamma charge pulses. Pulse size discrimination circuitry can then be used to block out the unwanted gamma pulses.

One advantage of using a U-235 coating rather than a boron compound is that fission fragments have a much higher energy level than the charged particles resulting from the boron reaction. The higher energy fission fragments produce many more ionizations in the detector per neutron interaction than do the boron reaction particles. The greater ionization enables fission chambers to be used in lower neutron flux levels and higher gamma fields than BF_3 proportional counters can handle.

Fission chambers can be operated with either current indicating circuits or pulse counting circuits, or both, depending on the neutron flux level. They are especially effective with pulse counters due to the very large pulse size difference between neutron and gamma interactions. Because of their dual capability, fission chambers are often used in "wide range" channels in nuclear instrumentation systems, where they are capable of accurate indication over the source and intermediate ranges of neutron flux levels.

When a fission chamber is used for the intermediate range or power range flux levels (or the heating range in BWRs), the detector output is sent to a mean square analog unit. The output of the analog unit is proportional to the square of the variance of the input signal. By Campbell's theorem, this output value is proportional to the neutron event frequency (reactor power). A measurement technique, commonly referred to as Campbelling, employs the theorem that the variance of the current pulses about an average value is proportional to the square root of the average pulse rate. To obtain neutron event rate, the variation signal is amplified and then processed through a squaring circuit. This measurement technique also tends to discount any gamma-induced pulses. (If we assume a gamma pulse is one-tenth as tall as a fission pulse, and this ratio is squared, the gamma contribution to the output signal becomes only 1% vice 10%.)

Most BWRs use fission chambers, operating in the ionization region to measure neutron flux in the source, intermediate, and power ranges. While reactor power is in the source range, gamma compensation is provided by pulse height discrimination. The Campbelling technique eliminates the gamma contribution when power is high in the intermediate range or in the power range. Circuitry employing a combination of the two techniques is used for the lower intermediate range.

16.6.2 Compensated Ion Chamber (CIC)

Figure 16-8 shows a compensated ion chamber. This detector is actually two detectors in one case. The outer chamber is coated on the inside with B-10 and produces an electron flow due to neutrons and gammas. The inner chamber is uncoated and produces an electron flow due to gamma only. By connecting the two chambers so that the electron flows are electrically opposed, the net electrical output from the detector will be the electron flow due to neutrons only. Mathematically this relationship could be written as:

$e^- (n + \gamma)$ = electron flow in outer chamber
$e^- (\gamma)$ = electron flow in inner chamber
$e^-_{net} = e^- (n + \gamma) - e^- (\gamma)$
$e^-_{net} = e^- (n)$.

The detector high voltage and the compensating voltage is supplied from the intermediate range circuitry drawers to each compensated ion chamber. The compensating voltage is adjusted to cancel the effects of the gamma flux at the detector so that the output is proportional only to the neutron flux.

To achieve the proper amount of gamma compensation, the voltages between the two sets of electrodes must be balanced. If the voltage in the compensation chamber is too high, the detector is overcompensated. Too much opposing electron flow due to gammas only will exist, and the meter will read less than the actual neutron flux. If the compensating voltage is too low, under compensation will occur. Too little opposing electron flow due to gammas only will exist, and the meter will indicate higher than actual neutron level.

Because the output of the compensated ion chamber is an electron flow rather than pulses, no signal conditioning is necessary prior to the log current amplifier. This device provides a logarithmic output, from which a startup rate or period indication can be obtained by using a differentiator circuit similar to that discussed in Section 16.4.2.

16.6.3 Uncompensated Ion Chamber

As neutron levels increase into the power range, gamma compensation is not a major concern because gammas do not contribute much to the total ionization (about 0.1% at 100% power). The power range detector is an uncompensated ion chamber, which is constructed similarly to the CIC. The main difference is that no compensating voltage is applied to the power range detectors. An uncompensated ion chamber is shown in Figure 16-9.

16.7 Self-Powered Neutron Detectors (SPND)

Self-powered neutron detectors do not require an external voltage source to create a voltage potential in the detector. Instead, a current is produced in the detector as the result of activation and decay of the detector itself. As an example, the beta-current type of self-powered detector uses the following activation reaction to produce a current that can be measured.

$$ {}_{0}n^{1} + {}_{45}Rh^{103} \rightarrow {}_{45}Rh^{104} \rightarrow {}_{46}Pd^{104} + {}_{-1}\beta^{0} $$

In this reaction, a neutron causes a rhodium-103 atom to become a radioactive rhodium-104 atom. The rhodium-104 then decays into palladium-104 plus a beta particle (electron). The rhodium-104 half-life of 42.5 seconds delays the emission of the charged particle. The beta-current detector uses this production of beta particles (electrons) to create a current that is proportional to the number of neutrons entering the detector.

Figure 16-10 shows a self-powered detector. The center of the detector is an emitter, which is usually made of rhodium and is used to produce electrons. The emitter is surrounded by insulation, which is usually made of aluminum oxide. The metal walls of the detector encase these parts and serve as a collector for the electrons that are produced. The collector is attached to ground potential, and the ground potential is also connected to the rhodium emitter. A current meter indicates the electron flow from the ground potential to the emitter.

A neutron that passes through the detector hits the emitter and activates a rhodium atom. The beta particle has enough energy to pass through the insulator and reach the collector. As neutrons cause activation reactions, the result is a loss of electrons in the emitter. Therefore, there is a flow of electrons from the collector to ground potential to the emitter to make up for this loss. The strength of the current is proportional to the number of neutrons entering the detector, which is also proportional to reactor power.

A background correction is necessary due to gamma reactions that occur in the rhodium detector and leadwire. These reactions cause beta emissions; therefore, a portion of the detector's current flow is due to gamma rays. To compensate for this erroneous signal, a background detector is installed at each detector location. The background detector consists of the same components as the detector, except the rhodium is removed. Because the background detector is the same size and located in the same assembly, it is subject to the same gamma flux; therefore, its output current represents the same gamma current that is present in the neutron detector signal. The plant computer receives the background signal and corrects the SPND output for gamma interactions.

Self-powered neutron detectors are fairly simple and provide an accurate measurement of neutron flux. The disadvantage of these detectors is that they do not have a fast response time because of the rhodium half-life delay. Therefore, self-powered neutron detectors are not used for real-time reactor control.

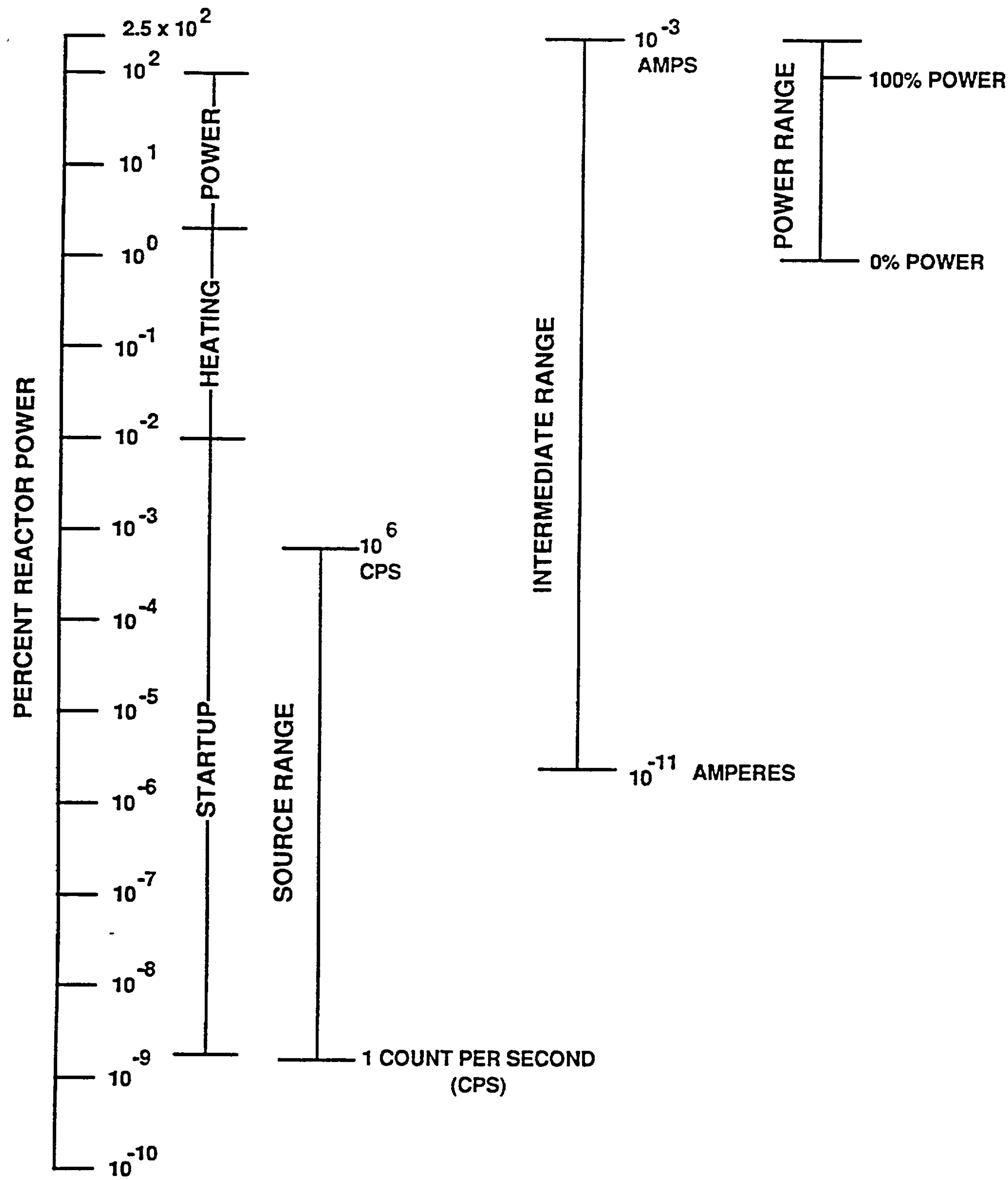


Figure 16-1. Neutron Detector Operational Ranges

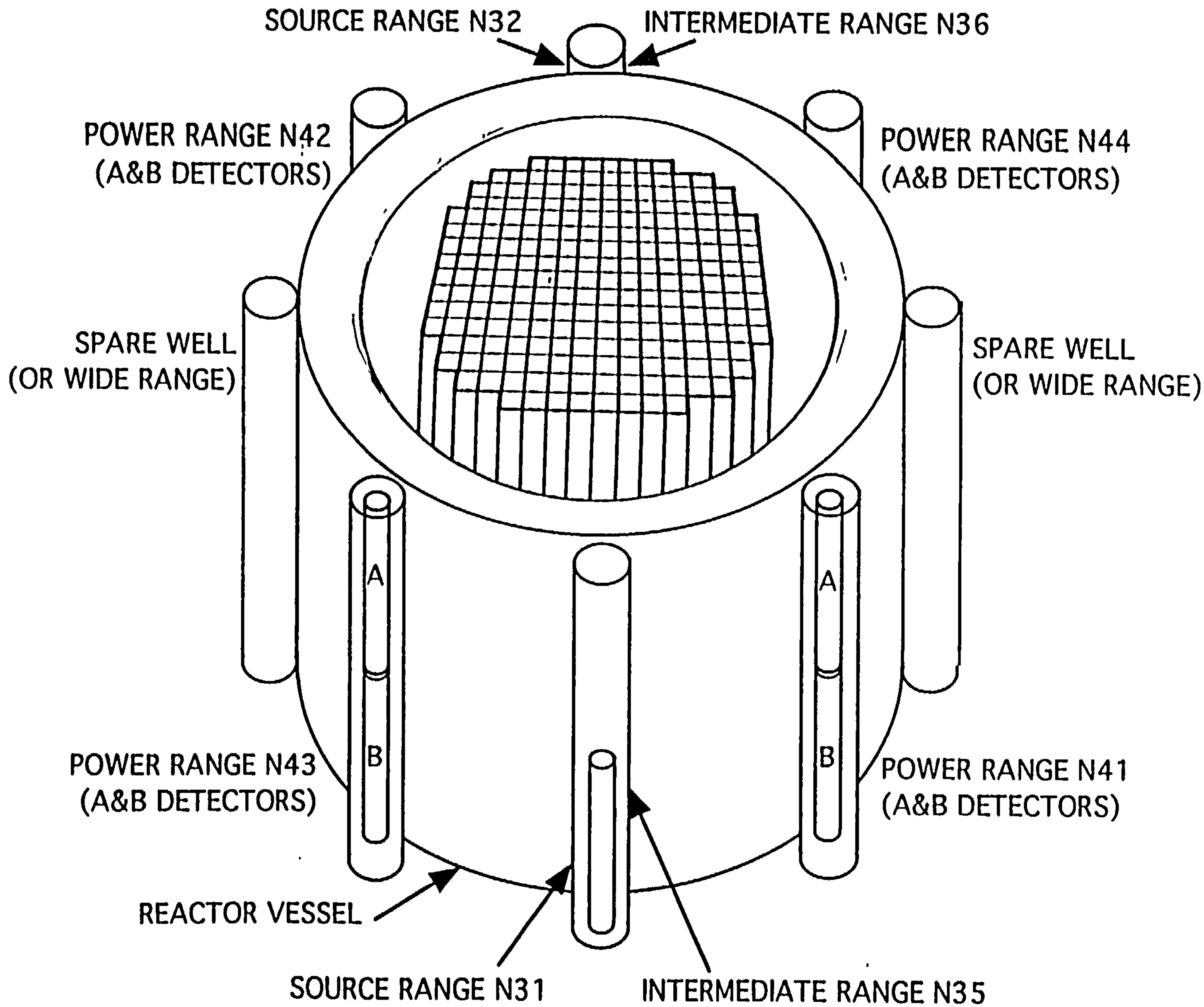


Figure 16-2. PWR Excore Neutron Detectors

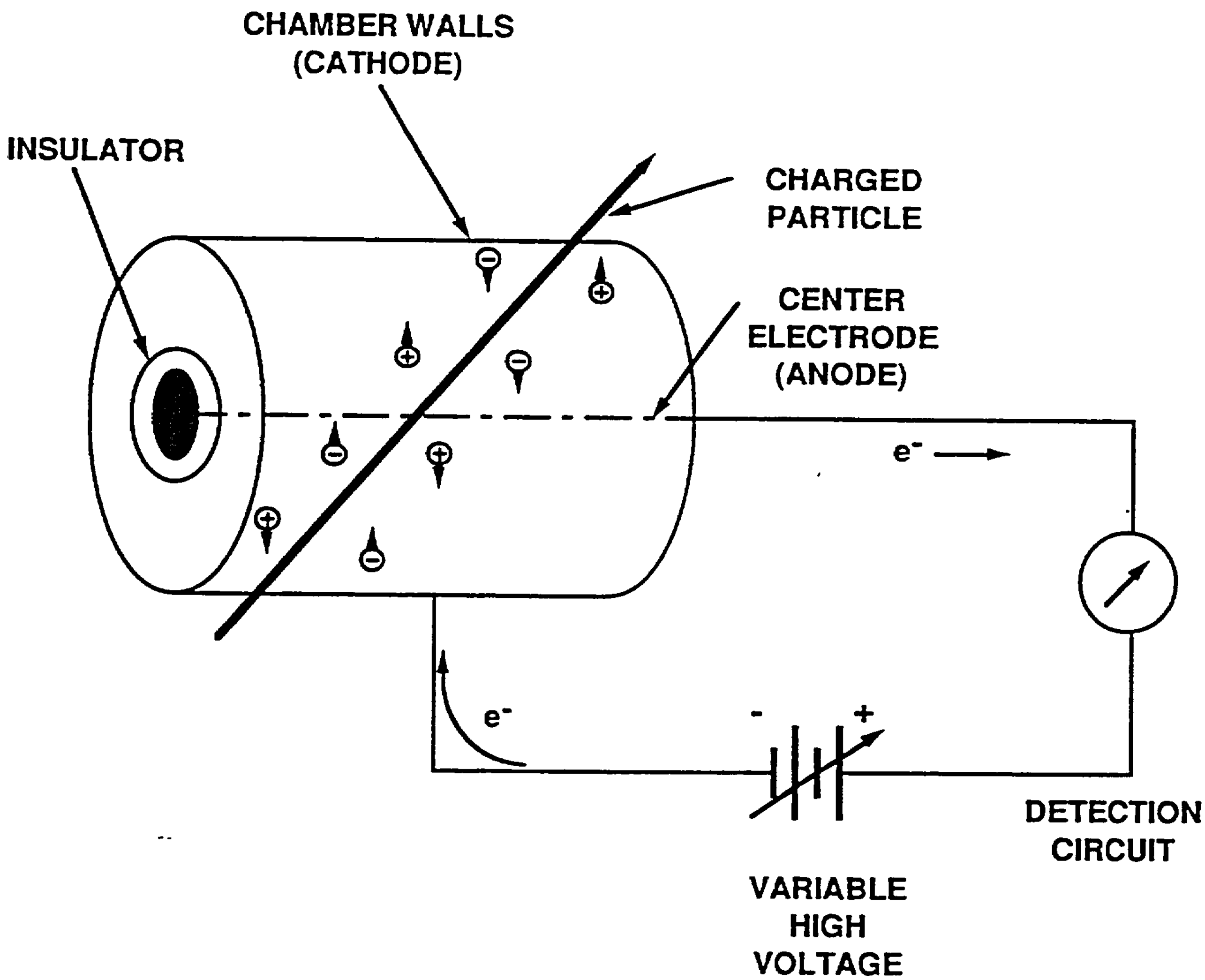


Figure 16-3. Gas-Filled Detector

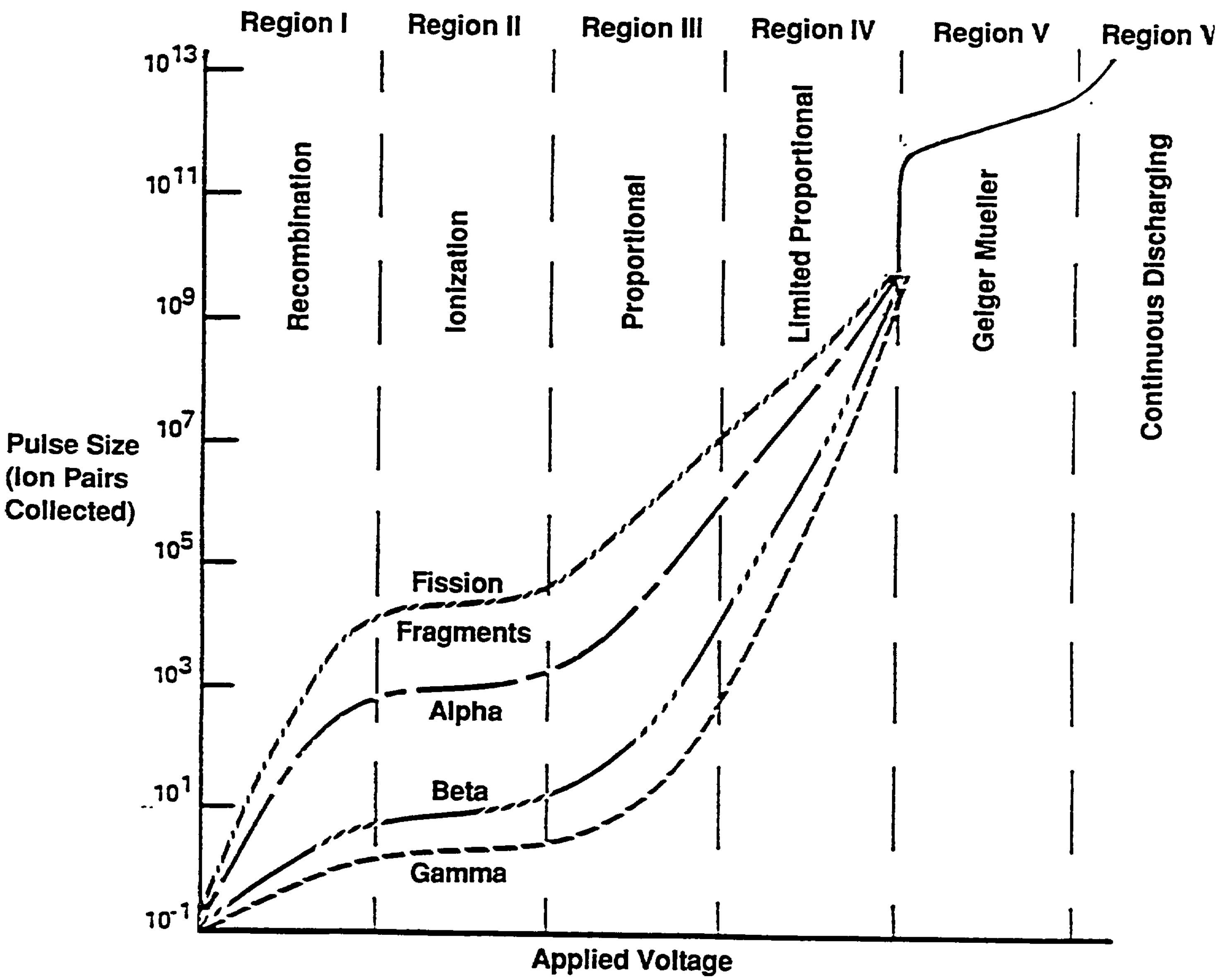
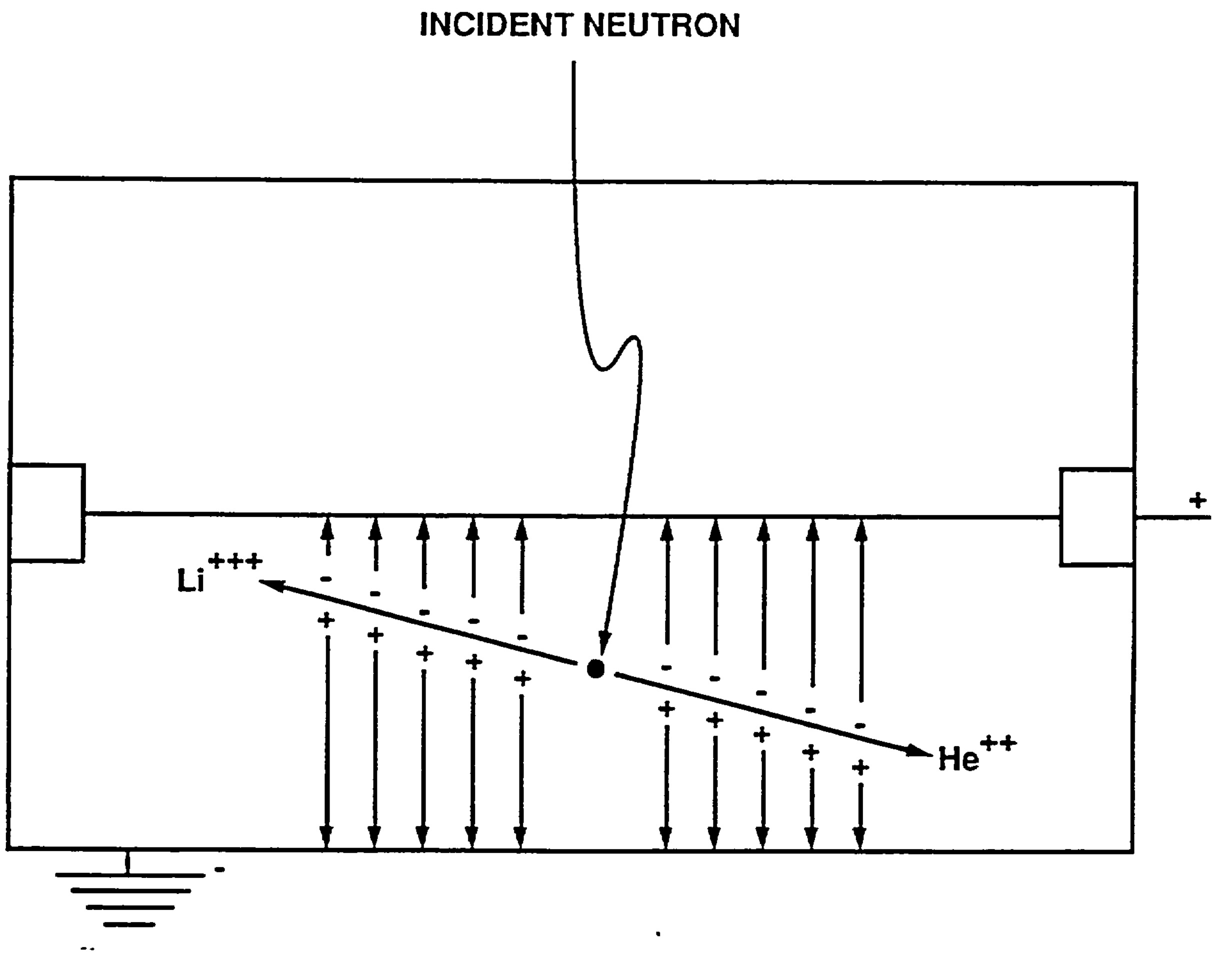


Figure 16-4. Gas Ionization Curves for Constant Incident Radiation Fields



$$^{1}_{0}n + ^{10}_{5}B \longrightarrow ^{7}_{3}Li^{+++} + ^{4}_{2}He^{++} + 5e^{-}$$

Figure 16-5. BF_3 Proportional Counter

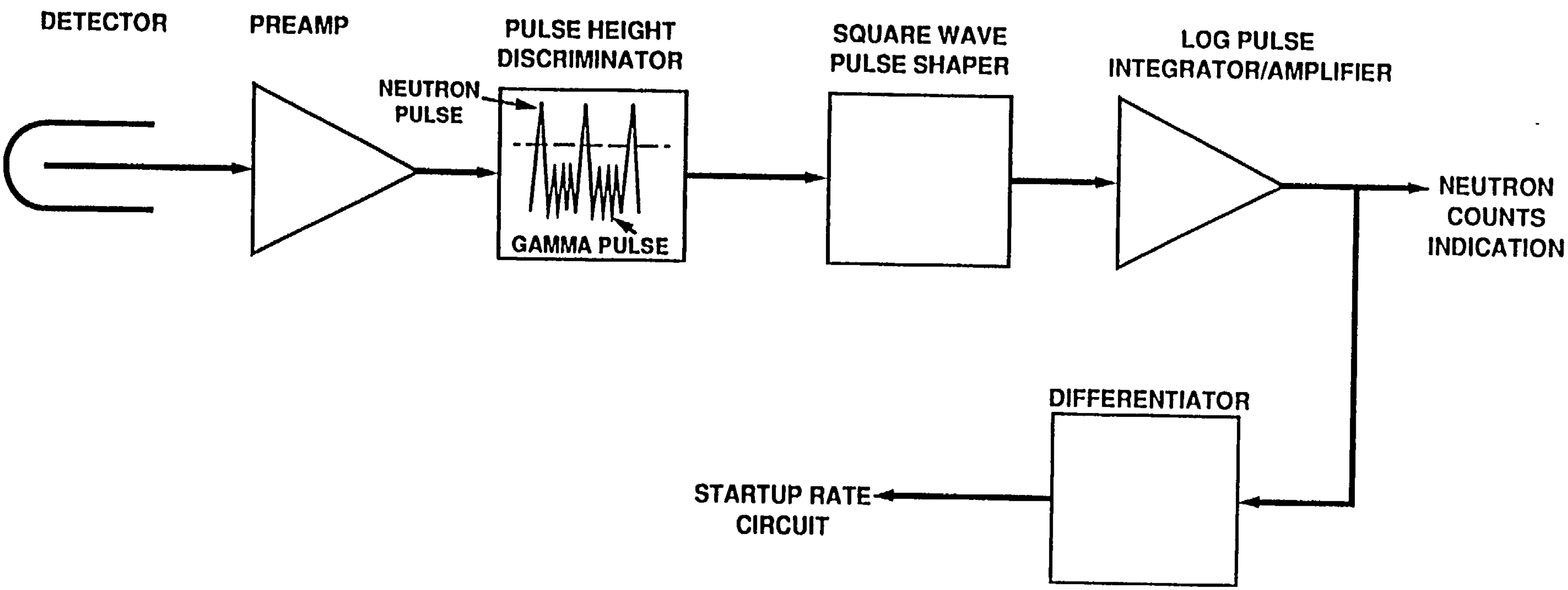
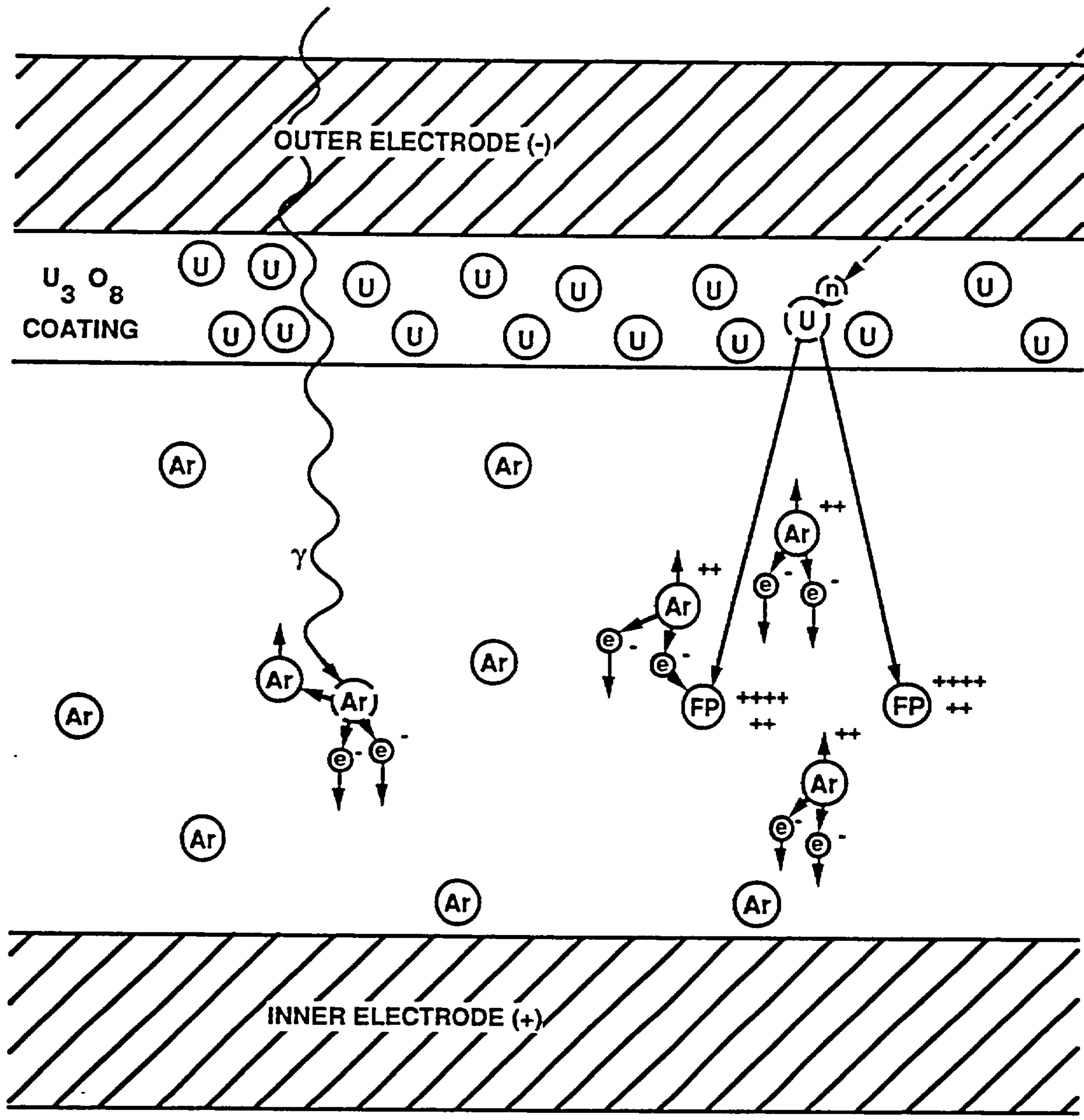


Figure 16-6. Startup Channel



DETECTOR DATA
90% ENRICHED IN U-235
INTERNAL PRESSURE 215 psi
LENGTH 1.6 INCHES
WIDTH 0.16 INCHES

Figure 16-7. Fission Chamber

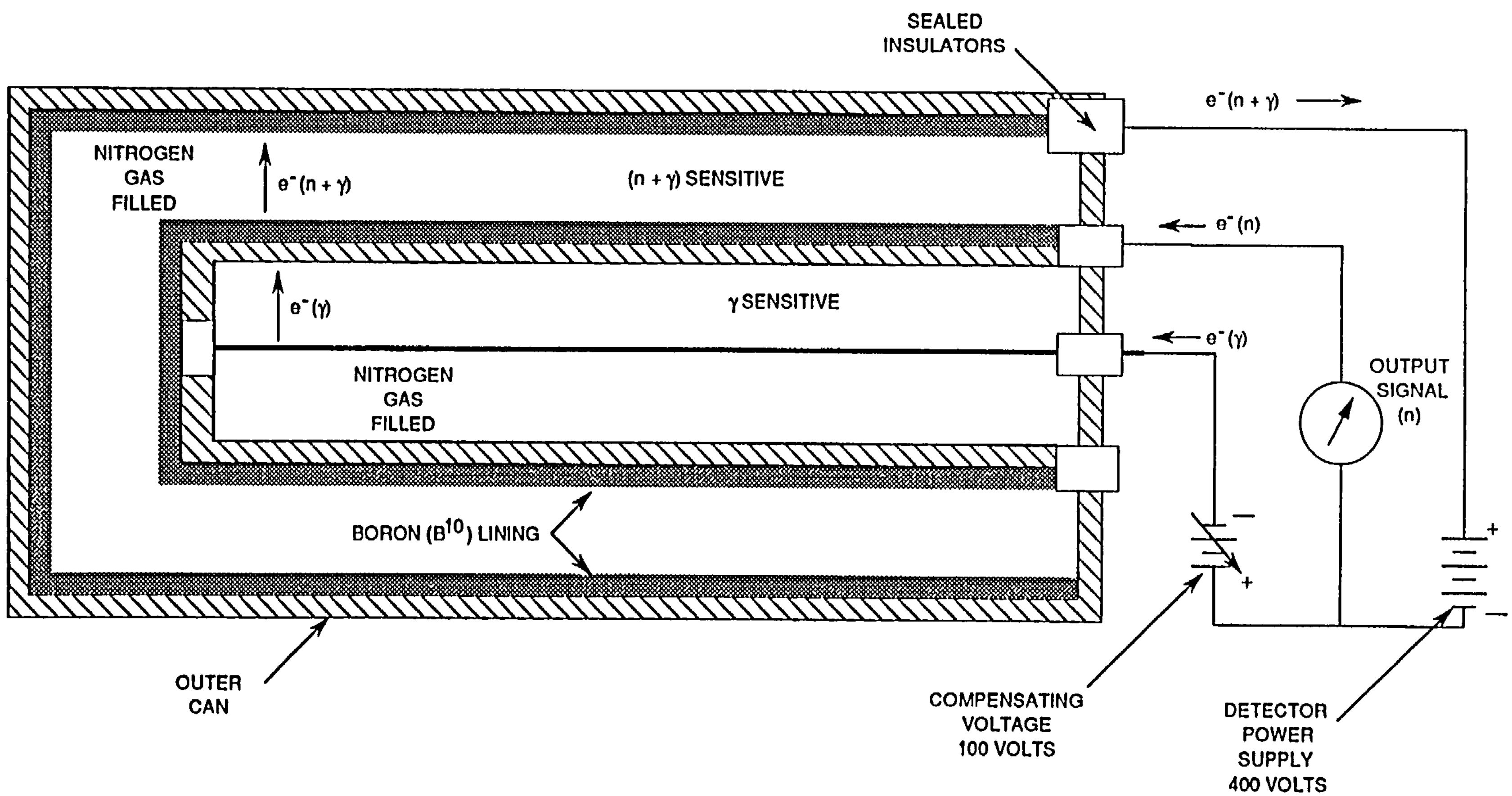


Figure 16-8. Compensated Ion Chamber

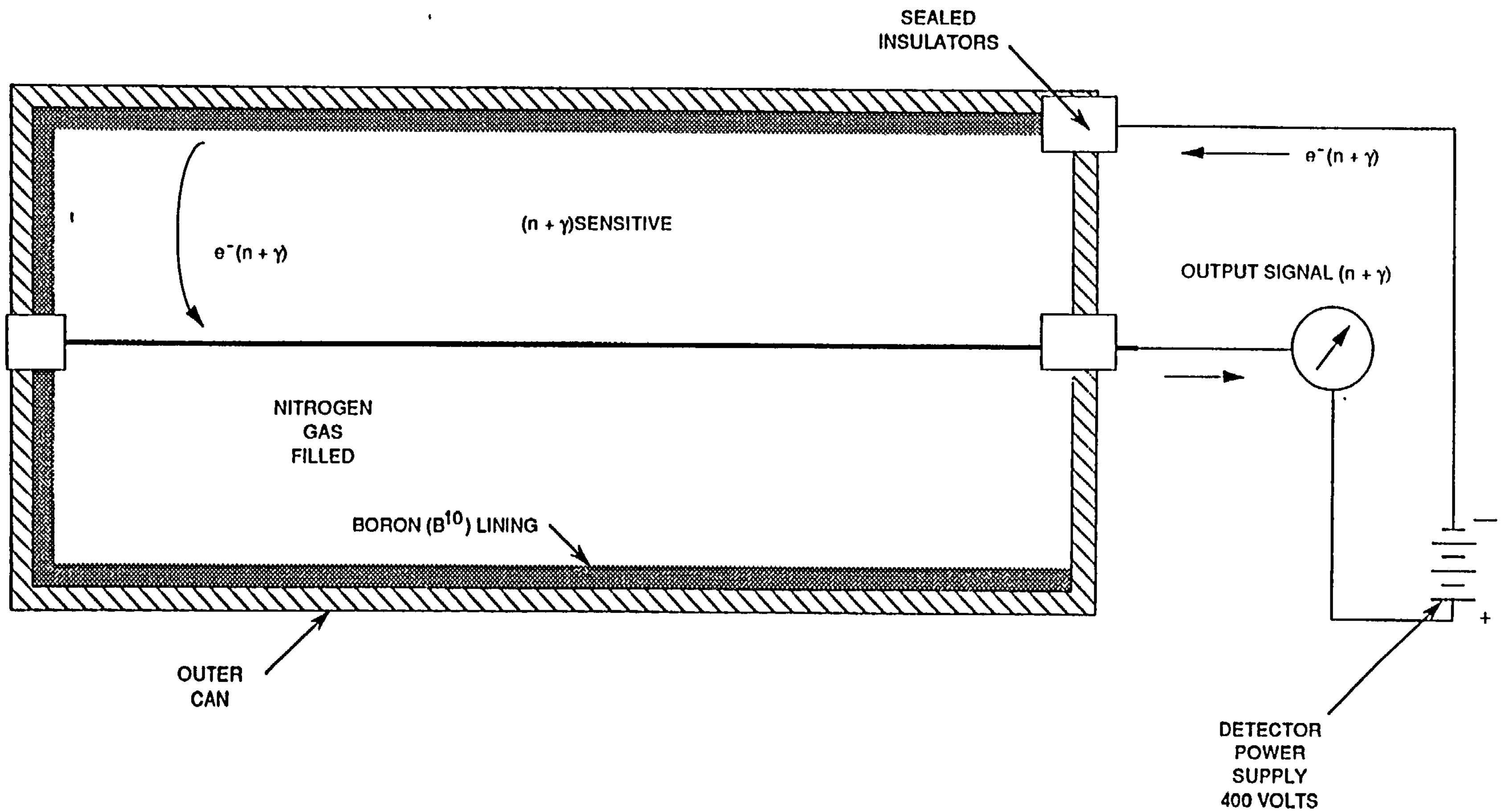


Figure 16-9. Uncompensated Ion Chamber

$$_{45}\mathrm{Rh}^{103} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{45}\mathrm{Rh}^{104} \rightarrow {}_{46}\mathrm{Pd}^{104} + {}_{-1}\beta^{0} + \mathrm{ENERGY}$$

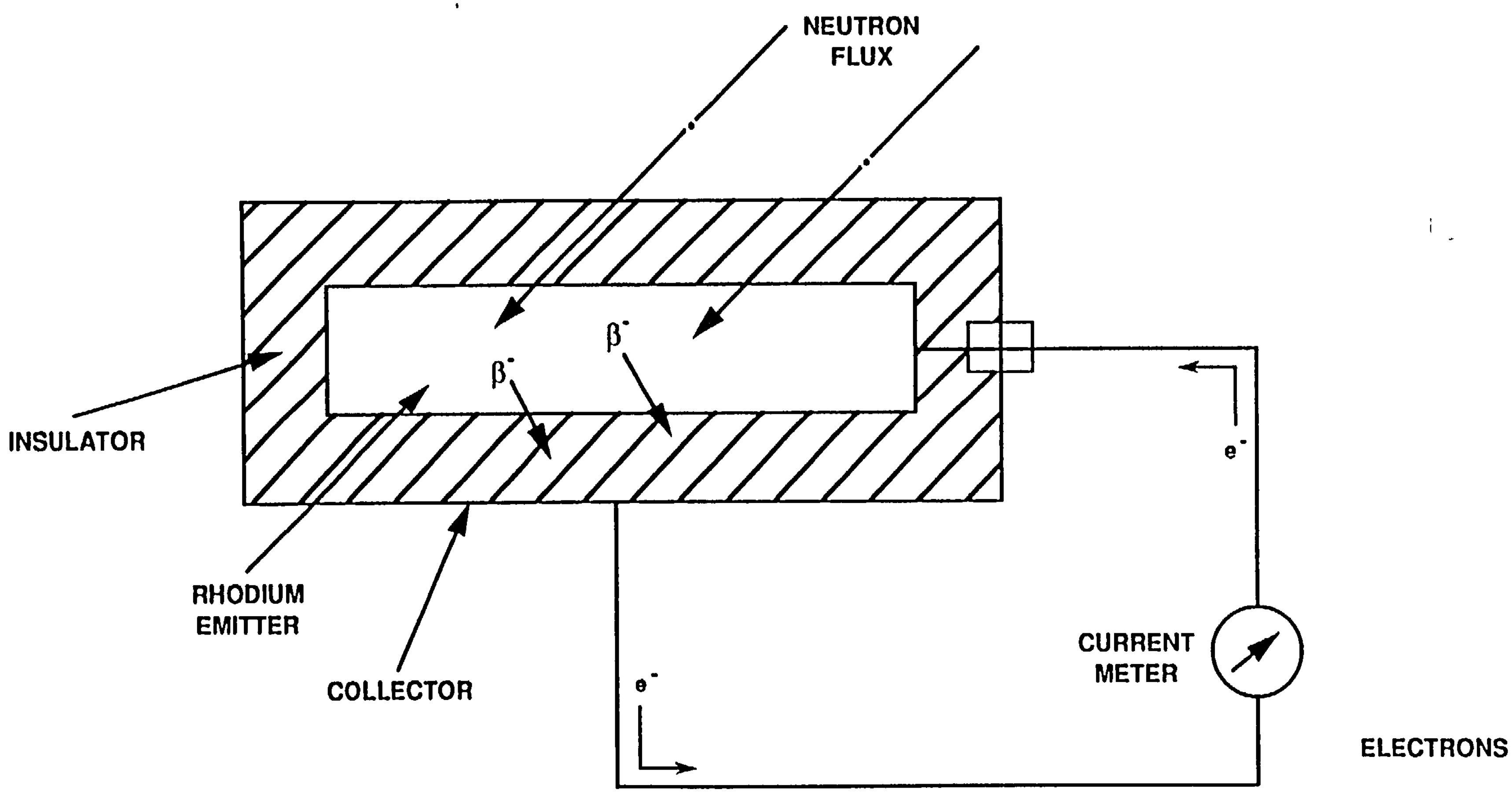


Figure 16-10. Self-Powered Neutron Detector