

INTRODUCTION TO PRESSURE

Atmosphere is composed of the gases and liquids that surround the earth and make it livable. These gases and liquids have weight and exert a pressure on the surface of the earth. The measurement and control of pressure is a primary consideration in the design, construction, and maintenance of process systems.

Pressure is defined as force exerted over a unit area. Force may be exerted by liquids, gases, and solids. Mathematically, pressure is expressed as:

$$P = F/A$$

where:

- P = pressure
- F = force
- A = area

Therefore, the amount of force exerted by a substance directly affects the amount of pressure.

Force Exerted by Liquids

When a liquid is poured into a tank or vessel, it will conform to the shape of the tank or vessel. The force that the liquid exerts on the sides and bottom of the tank

or vessel must be determined in order to measure pressure. The amount of force a specific volume of liquid in an open tank exerts over a specific area depends on three factors: the height of the liquid above the measurement point, the specific gravity, or weight, of the liquid, and the temperature of the liquid.

Water at 60°F is the standard liquid to which other liquids are compared. It can be used to demonstrate the effect of the height of the liquid above the measurement point. The weight of water at 60°F is 62.34 pounds per cubic foot. To determine the force of a specific volume of water at 60°F over a specific area, the height of the water above the measurement point must be determined and multiplied by 62.34 pounds per square foot. If the measurement is taken at the bottom of the tank, the force produced will depend on the total height of the water in the tank. For example, if the level of water in the tank is 1 foot, the water is exerting a force of 62.34 pounds on every square foot of the bottom of the tank. If the level of water in the tank is raised to three feet, the force on each square foot is 62.34 x 3, or 187.02 pounds per square foot.

If force is measured on the side of the tank, the measurable force the water exerts on the side of the tank will depend on the height of water above the measuring instrument. For example, if the level of water in the tank is three feet and the measuring instrument is placed one foot above the bottom of the tank, there are two feet of

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water above the instrument. Therefore, the force exerted by the water at that point would be 62.34×2 , or 124.68 pounds per square foot.

In addition to height, the weight of the liquid must also be determined in order to determine the force exerted by a liquid in an open tank. Specific gravity is a reference number that compares the weight of a specific volume of liquid to the same volume of water at 60°F, and a specific volume of gas at a specific temperature to the same volume of air at the same temperature. Water and air are assigned specific gravity constants of 1. These values serve as the reference for determining the specific gravity of other liquids and gases.

Figure 1-1 compares the weight or mass of a specific volume of mercury to the same volume of water at 60°F. A cubic foot of mercury weighs 845.95 pounds while a cubic foot of water weighs 62.34 pounds. Since mercury weighs 13.57 times as much as water at 60°F ($845.95/62.34 = 13.57$), the specific gravity of mercury is 13.57 (13.57×1). Table 1-1 shows the specific gravities of liquids and gases commonly used in industrial processes.

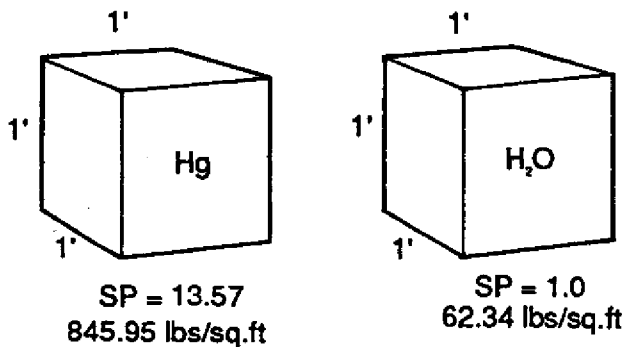


Figure 1-1. Comparison of Specific Gravities of Water and Mercury

The third factor that influences the pressure of a liquid in an open tank or vessel is temperature. Temperature is a measurement of how hot or cold a substance is. The specific gravity, or mass density, of most liquids is calculated at a standard temperature. Table 1-2 lists the standard temperatures of some common liquids and gases. If the temperature of the liquid changes, its specific gravity may also change. This is because changes in temperature will cause the liquid to

expand or contract, depending on whether the temperature rises above or falls below the specific standard temperature.

Changes in temperature will have an inverse effect on the force a liquid exerts. For example, as the temperature of a liquid increases, the liquid expands and becomes lighter per volume. Consequently, the force per unit of area will decrease. On the other hand, as the temperature of a liquid decreases, the liquid contracts and becomes heavier per volume. This causes the force per unit of area to increase. Figure 1-2 demonstrates the effects of changes in temperature on the weight of a cubic foot of water. At 60°F, water weighs 62.34 pounds per cubic foot. However, at 100°F, water weighs 61.99 pounds per cubic foot, and at 32°F, it weighs 62.46 pounds per cubic foot.

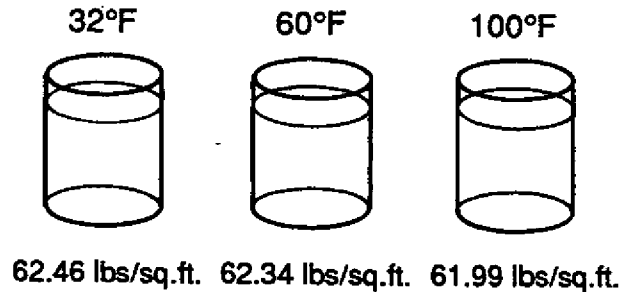


Figure 1-2. Effect of Temperature Changes on Water

In many process systems, liquids are not contained in open vessels, but are confined in closed vessels or piping. In a closed vessel, a liquid will be subject to any forces that may be exerted on it by an external source. Therefore, in addition to the height of the liquid above the measurement point, the specific gravity of the liquid, and its temperature, the force exerted by any external source must also be identified to determine the force exerted by a liquid in a closed vessel.

Pascal's Law states that when a force is applied to a confined fluid, the force will be transferred undiminished throughout the fluid to all surfaces of the containing vessel. This means that for liquids in closed vessels, the force exerted on the fluid by an external force will be consistently indicated, regardless of where the measurement is taken.

Table 1-1. Specific Gravity of Various Liquids

Liquid	Specific Gravity
Ethyl Alcohol, C_2H_5O	0.7939
Kerosene, 41 API at 60 F	0.8200
Ellison Gage Oil	0.8340
Benzene (Benzol), C_6H_6	0.8794
Butyl Cellosolve, $C_8H_{14}O_2$ (Ethylene Glycol Monobutyl Ether)	0.9019
Water	1.000
Alcohol Glycol	1.000
Carbitol, $C_8H_{14}O_3$ (Diethylene Glycol Monoethyl Ether)	1.024
n-Butyl Phthalate, $C_{16}H_{22}O_4$	1.0477
Ethylene Glycol (Glycol), $C_2H_6O_2$	1.1155
Halowax Oil	1.19-1
Glycerine (Glycerol), $C_3H_8O_3$	1.260
o-Dibromobenzene, $C_6H_4Br_2$	1.956
1, 1-Dibromoethane, $C_2H_4Br_2$	2.089
Acetylene tetrabromide (Tetrabromoethane), $C_2H_2Br_4$	2.964
Mercury	13.570

Force Exerted by Gases

While liquids conform to the shape of the vessel they are contained in, gases have no definite shape. Gases expand to fill the entire area that contains them. As a result, a gas will exert an equal amount of pressure on all surfaces of the vessel that contains it. Two factors that affect the force a gas exerts are the volume of the vessel and the temperature of the gas.

The relationship between the force exerted by the gas and the volume of the vessel is expressed in Boyle's

Law. Boyle's Law states that if temperature is held at a constant, the force exerted by the gas on the walls of a containing vessel varies inversely with the volume of the vessel, provided the mass remains unchanged. This means that if the volume of the vessel increases, force exerted by the gas decreases, and if the volume of the vessel decreases, the force exerted by the gas increases.

The relationship between temperature and the force a gas exerts is expressed in Charles' Law. This law states that if the volume of the vessel holding a gas is constant, the force exerted by the gas on the walls of the

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Table 1-2. Standard Temperatures

Name or Description	Temp F	Name or Description	Temp F
Acetic Acid	68	Kerosene	68
Acetone	68	Linseed Oil	68
Allyl Alcohol	68	Methyl Acetate	68
n-Amyl Alcohol	73.4	Methyl Iodide	68
Ammonia	-28.3	Naphthalene	m.p.
Alcohol-ethyl	68	Nitric Acid	68
Alcohol-methyl	68	Nitrobenzene	68
Aniline	68	Octane	68
Benzene	68	Petroleum	68
Bromine	68	n-Pentane	68
n-Butyl Alcohol	68	Propionic Acid	68
n-Butyric Acid	68	Sodium Chloride Brine	
Calcium Chloride Brine (20% by wt.)	68	20% by wt.	68
Carbon Disulfide	68	10% by wt.	68
Carbon Tetrachloride	68	Sulfuric Acid and Water	
Chloroform	68	100% by wt.	68
Ethyl Ether	68	95% by wt.	68
Ethyl Acetate	68	90% by wt.	68
Ethyl Iodide	68	Toluene (C ₆ H ₅ CH ₃)	68
Ethylene Bromide	68	Turpentine	68
Ethylene Chloride	68	Water	68
Formic Acid	68	Xylene C ₆ H ₄ (CH ₃) ₂	
Glycerine (glycerol)	68	Ortho	68
Heptane	68	Meta	68
Hexane	68	Para	68
Isobutyl Alcohol	68	Zinc Sulfate and Water	
		10% by wt.	68
		1% by wt.	68

vessel will vary directly with the temperature of the gas. This means that an increase in temperature will cause a gas to exert a greater force, and a decrease in temperature will decrease the amount of force.

PRESSURE MEASUREMENT

Units of Measurement

There are several different scales used to quantify force over area or pressure. Table 2-1 lists several pressure unit conversion factors. The standard unit of pressure in the English or foot-pounds-second (FPS) system is pounds per square inch, or PSI. In the meter-kilogram-second (MKS) system, pressure is expressed as kilograms per square meter. In the standard international (SI) units, pressure is measured as Newtons per square meter, or as Pascals. In the United States, pounds per square inch (PSI) is the term most widely used to quantify pressure.

Once force has been accurately measured, pressure can be determined by dividing the force by the area it is exerted over ($P = F/A$). For example, water at 60°F weighs 62.34 pounds per cubic foot and exerts a force of 62.34 pounds per square foot. Since there are 144 square inches in a square foot, the amount of pressure a cubic foot of water exerts on a square inch is calculated as follows:

$$\begin{aligned}
 P &= \frac{62.34 \text{ pounds}}{144 \text{ square inches}} \\
 &= .433 \text{ pounds per square inch}
 \end{aligned}$$

The pressure formula can also be used to determine how force is multiplied if a given pressure is applied over a given area. According to Pascal's Law, whenever an external pressure is applied to any confined fluid at rest, the pressure is increased at every point in the fluid by the amount of the external pressure. The practical consequences of Pascal's Law are apparent in hydraulic presses and jacks, hydraulic brakes, and instruments used for measurement and calibration.

Figure 2-1 illustrates how force can be multiplied in a hydraulic press. If a force of 100 pounds (F_1) is applied over an area of one square inch (A_1), the pressure is 100 pounds per square inch. This pressure will be transmitted throughout the liquid to all surfaces of the container. To determine the pressure of a force of 100 pounds per square inch (F_2) over an area of eight square inches (A_2), F_2 would be multiplied by A_2 (100 x 8). Therefore, there would be a total of 800 pounds of force at A_2 .

Pressure will be slightly affected by the point on the earth's surface where it is measured. For example, at sea level, the gases and liquids that make up the atmosphere exert a pressure of approximately 14.696 pounds per square inch. Atmospheric pressure will decrease by about .036 PSI for each 1000 feet of elevation. At an elevation of 3000 feet, the atmosphere exerts a pressure of approximately 14.588 pounds per square inch.

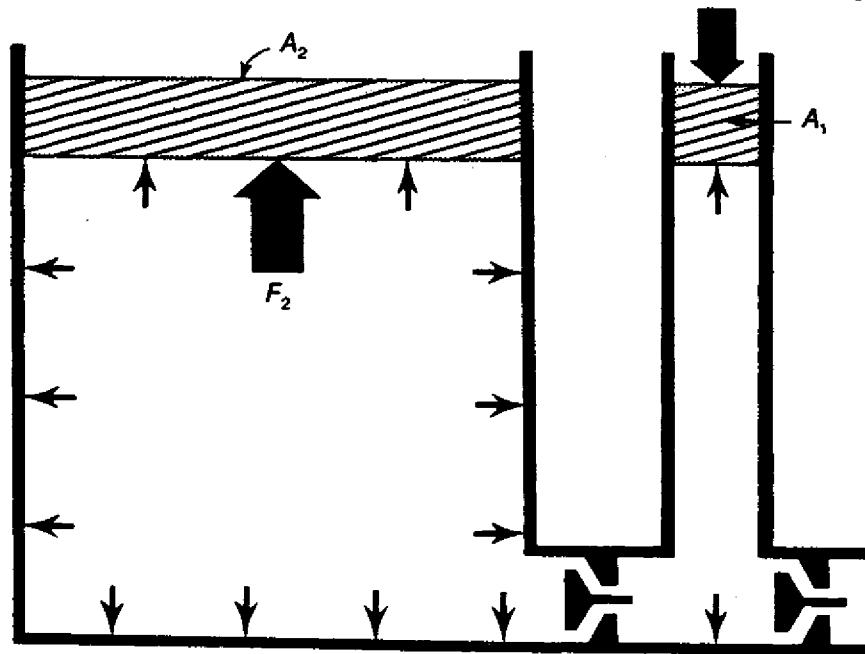
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Table 2-1. Pressure Conversion Factors

PRESSURE UNIT CONVERSION FACTORS	
All fluids at a temperature of 71.6°F (22°C)	
<p><i>1 inch of water equals</i></p> <p>.0360 lb/sq in. .5760 oz/sq in. .0737 in. mercury .3373 in. #3 fluid 1.2131 in. Red Oil</p>	<p><i>1 inch of Red Oil equals</i></p> <p>.0297 lb/sq in. .4752 oz/sq in. .0607 in. mercury .2781 in. #3 fluid .8243 in. water</p>
<p><i>1 foot of water equals</i></p> <p>.4320 lb/sq in. 6.9120 oz/sq in. .8844 in. mercury 4.0476 in. #3 fluid 14.5572 in. Red Oil 62.208 lbs/sq ft</p>	<p><i>1 inch of #3 fluid equals</i></p> <p>.1068 lb/sq in. 1.7088 oz/sq in. .2184 in. mercury 2.9643 in. water 3.5961 in. Red Oil</p>
<p><i>1 inch of mercury equals</i></p> <p>.4892 lb/sq in. 7.8272 oz/sq in. 4.5782 in. #3 fluid 13.5712 in. water 1.1309 ft water 16.4636 in. Red Oil</p>	<p><i>1 ounce/sq in. equals</i></p> <p>.1228 in. mercury .5849 in. #3 fluid 2.1034 in. Red Oil 1.7336 in. water</p> <p><i>1 pound/sq in. equals</i></p> <p>2.0441 in. mercury 27.7417 in. water 9.3586 in. #3 fluid 2.3118 ft water 33.6542 in. Red Oil</p>
<p>1 kg per sq cm = 14.22 psi 1 kg per sq cm = 98.067 kilopascals 1 kilopascal = .1450 psi</p>	

In some process systems, it may be necessary to know if an indicated pressure includes or excludes atmospheric pressure. To distinguish this, two specific pressure units are used — pounds per square inch gage, or PSIG, and pounds per square inch absolute, or PSIA. PSIG is a reference to atmospheric pressure. This

means that a PSIG measuring instrument will indicate zero when it is not connected to a process pressure, and the sensing element is exposed to atmospheric pressure. On the other hand, PSIA is referenced to absolute zero. Absolute zero is the pressure measurement when all the pressure exerted by the atmosphere has been removed.



$$P_1 = P_2$$

$$P_1 = \frac{F_1}{A_1}$$

$$P_2 = \frac{F_2}{A_2}$$

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$F_2 = \frac{A_2}{A_1} F_1$$

$$F_2 = \frac{A_2}{A_1} F_1$$

$$F_2 = \frac{8 \text{ sq. in.}}{1 \text{ sq. in.}} 100$$

$$F_2 = 800 \text{ lbs.}$$

Figure 2-1. Force Multiplied in a Hydraulic Press

Since this is a theoretical value, it cannot be completely obtained. A pressure measuring instrument designed to indicate PSIA will read 14.696 pounds per square inch at sea level, when it is not connected to a process pressure, and the sensing element is exposed to atmospheric pressure.

In some cases, pressure measurement below atmospheric pressure is expressed as a vacuum. A common term used to express vacuum is inches of liquid. Vacuum is often measured in inches of water (In H₂O) or mercury (In Hg). A practically perfect vacuum would be indicated as 407.513 In H₂O or 29.9213 In

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Hg. Inches of liquid can be used to indicate either gage pressure or absolute pressure, depending on the method of measurement.

Converting Measurement Units

Pressure measurements may be converted from one unit to another by using charts or by using mathematical formulas. Figure 2-2 lists some common conversions between units of measurement.

In the H₂O and Hg columns on the Pressure Unit Reference Chart, there are two values shown at the atmospheric pressure reference line. The number immediately below the atmospheric pressure reference line is the value that would be indicated by a manometer

that has its measuring tube closed at the top and the tube evacuated. This type of manometer measures absolute and would indicate the values listed at atmospheric pressure. The zero value listed immediately above the atmospheric reference line would be the value indicated by an open tube manometer measuring gage pressure.

The last column on the chart is for vacuum. Vacuum is the unit used to measure pressure below atmospheric and has atmospheric pressure as the reference. When vacuum is zero, the process being measured is at atmospheric pressure. However, if the vacuum is 15 In Hg, for example, then the process pressure is below atmospheric. When a process is exposed to pressures below atmospheric pressure, the term "vacuum" is commonly used to indicate the measurement. Vacuum

	PSIG	PSIA	In Hg	In H ₂ O	Vac
	5	19.696	10.18	138.42	
	1	15.696	2.036	27.684	
Atmospheric Pressure	0	14.696	0	0	0
Absolute 0		0	29.9213	407.518	29.95

Figure 2-2. Pressure Unit Reference Chart

measurements are frequently used in steam systems.

In order to convert measurements between PSIG and PSIA, the value for atmospheric pressure at sea level is added or subtracted to a given measurement.

$$\text{PSIA} = \text{PSIG} + 14.7$$

$$\text{PSIG} = \text{PSIA} - 14.7$$

For example, a measurement of 75 PSIA could be converted to PSIG as follows:

$$\begin{aligned} \text{PSIG} &= 75 - 14.7 \\ &= 60.3 \end{aligned}$$

A gage reading of 90 PSIG would be converted to PSIA as follows:

$$\begin{aligned} \text{PSIA} &= 90 + 14.7 \\ &= 104.7 \end{aligned}$$

In addition, PSIG and PSIA measurements can be converted to inches of mercury and inches of water. These conversions are accomplished by using the following formulas.

$$\text{In Hg} = \text{PSIG} \times 2.036$$

$$\text{In Hg} = \text{PSIA} \times 2.036$$

$$\text{In H}_2\text{O} = \text{PSIG} \times 27.684$$

$$\text{In H}_2\text{O} = \text{PSIA} \times 27.684$$

When converting absolute pressure units, the solution must indicate that the measurement value is in absolute units. Therefore, a gage reading of 17 PSIA would be converted to In Hg as follows:

$$\begin{aligned} \text{In Hg} &= 17 \times 2.036 \\ &= 34.612 \text{ absolute} \end{aligned}$$

Similarly, a reading of 138.42 In H₂O would be converted to PSIG as follows:

$$\begin{aligned} \text{PSIG} &= 138.42 \div 27.684 \\ &= 5 \end{aligned}$$

Differential Pressure

Differential pressure (ΔP) is the difference in pressure measurements taken at two related points. It is calculated by subtracting the higher pressure reading from the lower pressure reading. Differential pressure may be either absolute or gage pressure, as long as both points are measured in the same units. Differential pressure transmitters are often used with flow and level measuring systems.

MANOMETERS

Manometers are simple and accurate pressure measuring devices. While there are several different types of manometers, all manometers operate on the principle that changes in pressure will cause a liquid to rise or fall in a tube.

Basic Manometers

A basic manometer (see Figure 3-1) includes a reservoir that is filled with a liquid. The reservoir is

usually enclosed with a connection point that can be attached to a source in order to measure its pressure. A transparent tube, or column, is attached to the reservoir. The top of the column may be open, exposing it to atmospheric pressure. Or, the column may be sealed and evacuated. Manometers that have open columns are usually used to measure gage pressure, or pressure in reference to atmospheric pressure. Manometers with sealed columns are used to measure absolute pressure, or pressure in reference to absolute zero. Manometers

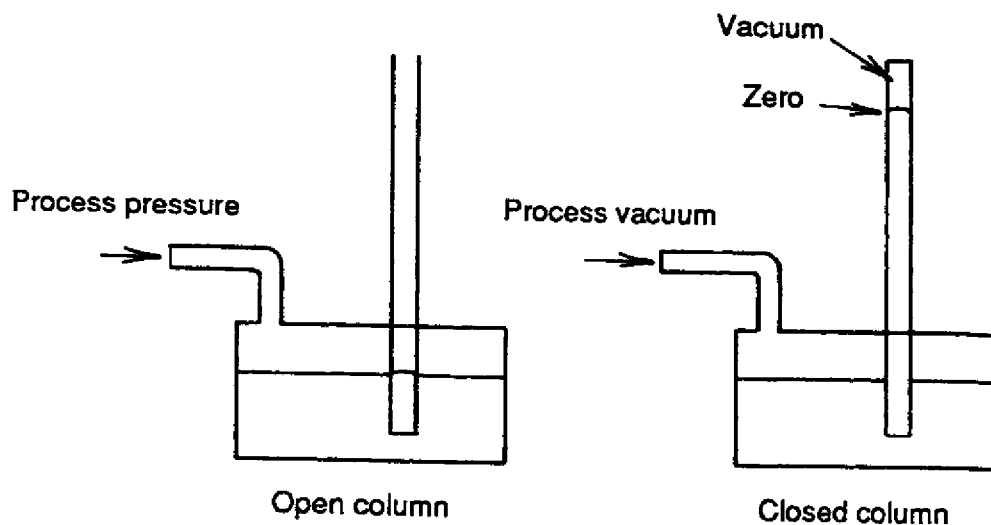


Figure 3-1. Basic Manometers

with sealed columns are also used to measure vacuum.

When a manometer is connected to a process, the liquid in the column will rise or fall according to the pressure of the source it is measuring. In order to identify the amount of pressure, it is necessary to identify the type of liquid in the column, and the height of the liquid.

The type of liquid in the column of a manometer will affect how much it rises or falls in response to pressure. Any liquid may be used to indicate pressure in a manometer. The most widely used liquids are

water, mercury, and red oil. Water and mercury are used because much is known about their specific gravities, thermal expansion, and mass. Red oil is often used because, unlike mercury, it is not toxic and will not contaminate the environment. Red oil can be obtained with various specific gravities that will be compatible with the measuring system.

Regardless of the type of liquid used in the manometer, its specific gravity must be known in order to accurately measure pressure. As shown in Table 3-1, water has a specific gravity of 1 and mercury has a

Table 3-1. Specific Gravity Chart

Liquid	Specific Gravity
Ethyl Alcohol, C_2H_5O	0.7939
Kerosene, 41 API at 60 F	0.8200
Ellison Gage Oil	0.8340
Benzene (Benzol), C_6H_6	0.8794
Butyl Cellosolve, $C_6H_4O_2$	0.9019
(Ethylene Glycol Monobutyl Ether)	
Water	1.000
Alcohol Glycol	1.000
Carbitol, $C_6H_4O_3$	1.024
(Diethylene Glycol Monoethyl Ether)	
n-Butyl Phthalate, $C_{16}H_{22}O_4$	1.0477
Ethylene Glycol (Glycol), $C_2H_6O_2$	1.1155
Halowax Oil	1.19-1
Glycerine (Glycerol), $C_3H_8O_3$	1.260
o-Dibromobenzene, $C_6H_4Br_2$	1.956
1, 1-Dibromoethane, $C_2H_4Br_2$	2.089
Acetylene tetrabromide	2.964
(Tetrabromoethane), $C_2H_2Br_4$	
Mercury	13.570

specific gravity of 13.6. This means that it takes 13.6 times as much pressure to raise mercury one inch in a column as it takes to raise water one inch. A pressure of one PSI will support water in a column at a height of 27.684 inches and mercury in a column at a height of 2.036 inches. For general pressure measurement, one PSI can be rounded off to 27.7 In H₂O and 2 In Hg.

To understand how the type of liquid in the reservoir affects the amount it rises or falls in a column, compare the amount of pressure required to cause liquid to rise one inch. For example, water exerts a force of .036 PSI. Since water has a specific gravity of 1, a pressure of .036 PSI applied to the reservoir of a water manometer will cause the water to rise one inch in the column. Any pressure measured by a water manometer can be determined by measuring the height of water in the column and multiplying the number of inches by .036 PSI. For example, if the level of water in the column is two inches, it indicates a pressure of .072 PSI.

This procedure can also be used to determine pressure measured by a mercury, or any other liquid, manometer. To do this, multiply the number of inches of liquid in the column by .036 PSI times the specific gravity of the liquid. For example, if the level of liquid in a mercury manometer is three inches, the pressure could be calculated as follows:

$$3(.036 \text{ PSI} \times 13.6) = 1.4688 \text{ PSI}$$

The type of liquid used in a manometer, along with the length of the column, will also affect the range of pressure that the manometer can measure. Mercury manometers are typically used to detect and indicate higher pressures because it takes a greater amount of pressure to move mercury one inch than it takes to move water one inch. However, while water manometers do not usually have the range of mercury manometers, they are more sensitive to low pressure. Therefore, water manometers are often used to measure very low pressures.

In order to indicate the height, or level, of liquid in the column, a manometer will typically have a scale mounted near the column or etched directly on the column. The scale can be graduated to read In H₂O, In Hg, or PSI. In some cases, both inches of liquid and PSI are included on the same scale. The type of column used will determine whether the pressure value indi-

cated is gage pressure or absolute pressure. If the column is open, it will indicate gage pressure. If the column is sealed and evacuated, it will indicate absolute pressure.

Manometers with sealed and evacuated columns are also used to detect and indicate vacuum. When the reservoir of a mercury manometer with a sealed column is open and exposed to the atmosphere, the mercury in the column will be 29.9213 inches high. For manometers used to detect and indicate vacuum, this point is usually marked zero. As vacuum in the process changes, the height of the mercury changes. When the mercury in the column has fallen 29.9 inches, it will be at the same level as the mercury in the reservoir. This vacuum measurement of 29.9 In Hg indicates a perfect, or complete, vacuum.

Since manometers are accurate pressure measuring instruments, they are often used as calibration standards. However, there are a number of factors that can affect the accuracy of manometers. For example, the method used to attach the scale to the column can affect its position and therefore the accuracy of the level reading. The type of graduation on the scale will also affect the accuracy of the reading. A scale that is graduated at every inch will provide a less accurate reading than a scale graduated at every eighth of an inch. In addition, accuracy will also be affected by the tolerance, or degree of accuracy, that the manufacturer sets when making the scale. When the manometer is used for calibration purposes, this tolerance will be more critical than it would be for a shop standard.

Another factor that will affect the accuracy of a manometer is the shape of the liquid at the interface between the liquid and air in the column. This level is called the meniscus (see Figure 3-2). The shape of the meniscus is determined by the type of liquid used. For water-air-glass combinations, adhesive forces dominate, causing an elevation of water at the glass surface. This produces a concave meniscus. For mercury-air-glass combinations, cohesive forces dominate, causing the meniscus to be convex. In order to minimize the errors that result from the shape of the meniscus, the reading must be taken at the surface of the liquid in the center of the column. Also, the capillary effect produced by the adhesive and cohesive forces can be compensated for by using columns with larger diameters.

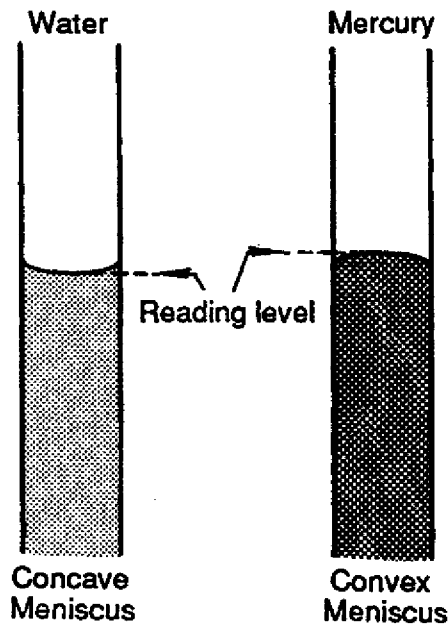


Figure 3-2. Meniscus

The quality of the fill liquid will also affect the accuracy of pressure measurements. The fill liquid must be clean and have a known specific gravity.

Types of Manometers

There are several different types of manometers. These include well manometers, inclined manometers, McLeod gages, and capacitance manometers. Figure 3-3 shows a well manometer. On this type of manometer, the reservoir is referred to as the well. The glass column that contains the liquid extends from the well. To measure pressure with this type of manometer, the process is connected to a fitting on the well. The measured pressure is then determined by reading the liquid level in the scale of the column. The scale may be graduated to read pounds per square inch or inches of water or mercury.

One common type of well manometer is a barometer. A barometer has a seal and an evacuated measuring column. This type of manometer detects and measures changes in atmospheric pressure.

A variation of the well manometer is the inclined manometer, shown in Figure 3-4. This manometer also

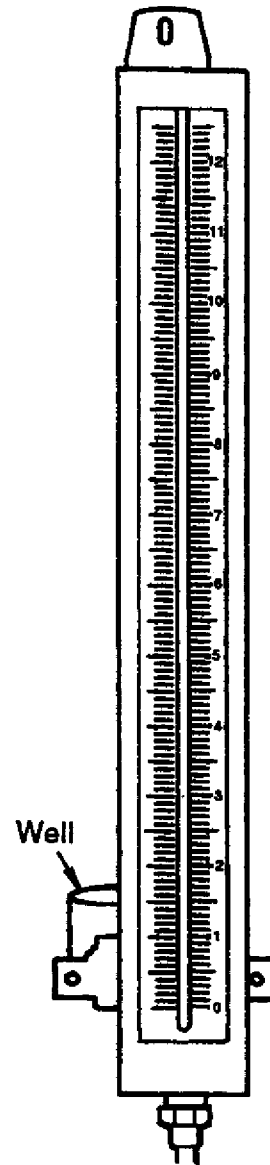


Figure 3-3. Well Manometer

has a well that contains the liquid and a transparent column. However, on an inclined manometer, the tube is mounted at an angle. Pressure is indicated by the vertical amount the liquid rises or falls in the column. The advantage of this structure is that a small change in pressure will cause greater movement of the liquid in the column, as shown in Figure 3-5. For example, an increase of .036 PSI will cause water to rise one inch in the tube of a well manometer. However, because the column of an inclined manometer is angled, the water must move a greater distance in this column in order to

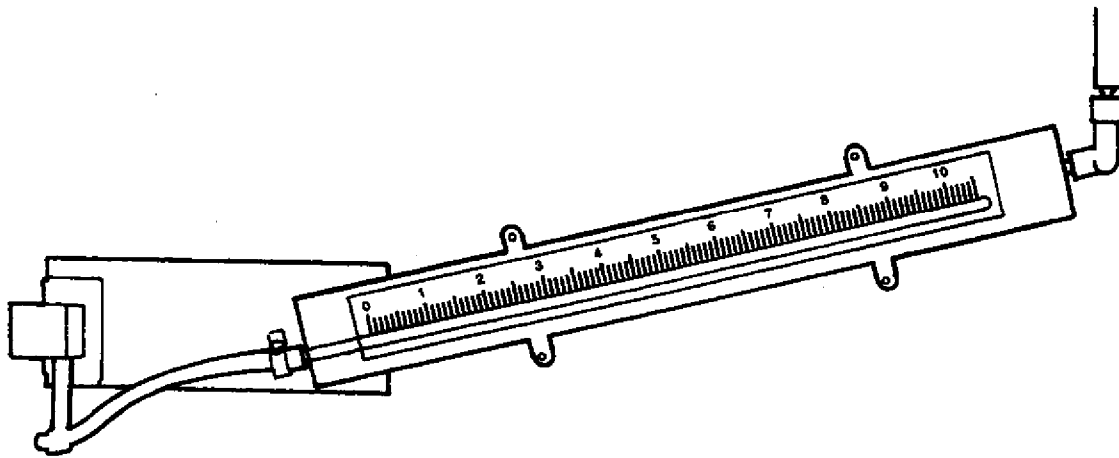


Figure 3-4. Inclined Manometer

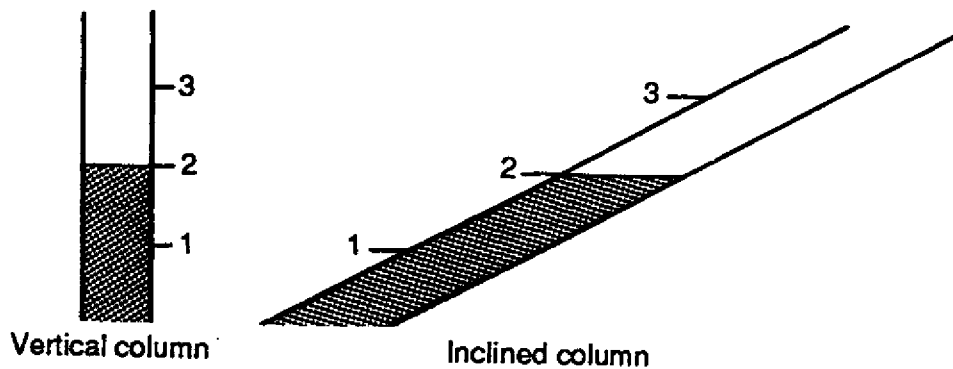


Figure 3-5. Liquid Column

accomplish a one inch vertical rise. This makes it possible to measure very small changes in pressure.

Another widely used type of manometer is the U-tube manometer (see Figure 3-6). With this type of manometer, the tube is bent into the shape of a U and is not connected to a well. Instead, the tube itself is the reservoir. Usually, the tube is filled until both sides are approximately half full. When pressure is equal, the column of liquid in each side will be at the same height. This is usually marked as zero on the scale. To measure pressure, one leg of the tube is connected to the process and the other leg is left open and exposed to the

atmosphere. In this way, a U-tube manometer provides a PSIG measurement. Pressure is indicated by the amount the liquid falls in one leg and rises in the other leg. The total movement of the liquid in both legs is the pressure measured by the U-tube manometer. For example, if the liquid level in the leg connected to the process pressure decreased five inches, and the level in the other leg rose five inches, the pressure measured by the U-tube manometer would be ten inches of liquid. U-tube manometers can also be used for vacuum measurements. This requires that one leg be sealed and the other leg connected to the process.

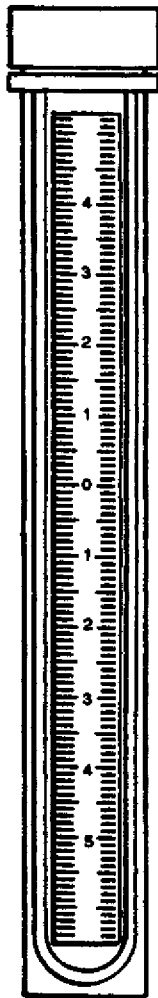


Figure 3-6. U-tube Manometer

Another type of manometer is the McLeod gage. This instrument is used as a fundamental standard for measuring vacuum. The McLeod gage measures vacuum by trapping and compressing a volume of gas (see Figure 3-7). A specific volume of mercury is contained in the gage reservoir and the connection point is connected to the vacuum source. When the connection is securely made, the gage is rotated 90 degrees. When the gage is rotated, the mercury closes one of the lines, compressing the trapped gas in the column.

Boyle's Law states that if the volume of the container holding a gas changes, the pressure of the gas changes. Therefore, as the mercury rises in the column of the McLeod gage, the volume of the container holding the gas decreases, and the pressure of the gas

increases. When the pressure of the gas equals the pressure exerted by the mercury, the mercury will stop rising in the tube. When this happens, the measured vacuum is determined by reading the level of the mercury on the scale.

The capacitance manometer (see Figure 3-8) uses the electrical characteristic of a capacitor to measure pressure. The capacitance manometer is in effect a U-tube with innovations. The U-tube is replaced by two cisterns, and capacitor plates are provided for equilibrium definition. One cistern is fixed; the other movable cistern is elevated via the lead screw until capacitor plate equilibrium is attained.

Pressure is applied to the fixed cistern while the movable cistern is at some reference pressure such as atmospheric pressure. When pressure changes, mercury will flow through the connecting line to the other cistern. This changes the amount of mercury in both cisterns and also changes the distance between the mercury and the capacitor plate in that cistern. This change in distance between the mercury, which acts as one capacitor plate, and the other capacitor plate changes the capacitance of the capacitors in both cisterns. This change in capacitance can be measured as pressure using an electrical circuit.

Table 3-2 provides information on the range and accuracy of various types of manometers.

Safety

Some types of liquids used in manometers are toxic and can be damaging to the environment. Therefore, when using manometers to measure or indicate pressure, do not connect any manometer to a pressure that has the potential to exceed the range of the manometer. This could cause the liquid to be forced out of the tube.

In addition, since the tubes in many manometers are made of glass and can be easily broken, it is important to use care in handling these manometers. If the liquid is accidentally spilled from a manometer, follow your facility's procedures for containing and cleaning hazardous materials.

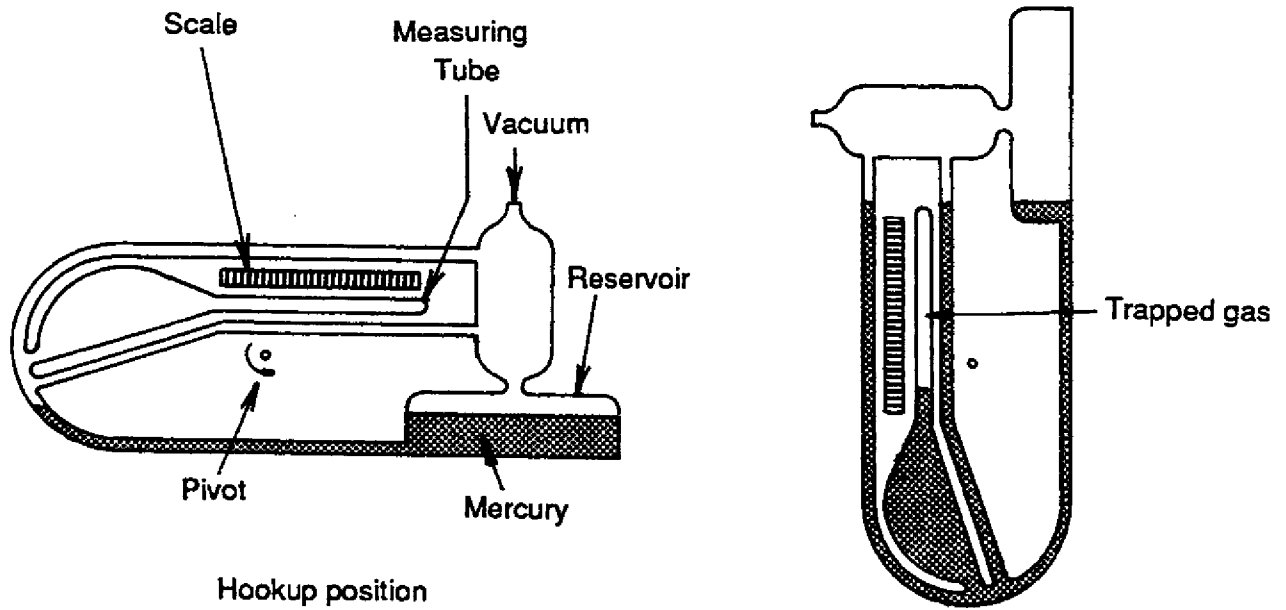


Figure 3-7. McLeod Gage

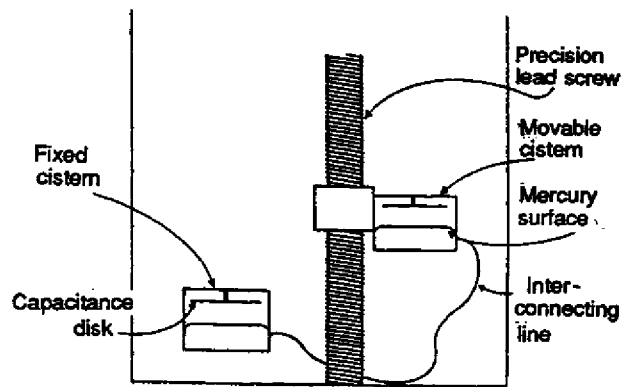


Figure 3-8. Capacitance Manometer

Table 3-2. Manometer Reference Chart

Class	Type	Optimum range	Accuracy
U-tube	Glass - mercury	0.5 - 50" Hg	0.02"
	Glass - water	0.5 - 100" H ₂ O	0.02"
	Glass - two-liquid	0.01 - 1" H ₂ O	0.5%
	Float, electric, etc.	0.5 - 50" Hg	0.05"
	Multiple-tube	0 - 100" Hg	0.5%
Single tube	Vertical - open top	2-100" Hg	0.02"
	Compression manom.	vac. - 200 PSI	1%
	Open-cistern, vac. gage	0 - 30" Hg	0.02"
	Mercurial barometer	Atmospheric	0.01"
	do., photocell servo	Atmospheric	0.005"
	Abs. pressure gage	0 - 100" Hg abs.	0.005"
Inclined-tube	0 - 4" H ₂ O	0.005"	
Micromanometer	Null method, etc.	0.001 - 20" H ₂ O	0.05%
Liquid col. & plunger	Mercury	50 - 5000 PSI	
	Vacuum	Microns	
Liquid column (compression manom.)	Laboratory McLeod	0.01 - 2000	2%
	Industrial McLeod	0.1 - 100,000	

MECHANICAL PRESSURE TRANSDUCERS

Mechanical pressure transducers are devices that convert force exerted by fluids into motion that can be measured to indicate the amount of pressure. Some mechanical transducer elements serve as sensing elements in gages or transmitters. Table 4-1 provides a quick reference of mechanical transducers commonly used in mechanical pressure elements. It includes different types of Bourdon tubes, bellows, and diaphragms. The instruments are listed by class, along with their optimum range and their accuracy percentage.

Bourdon Tubes

One type of mechanical pressure transducer is the Bourdon tube. There are three common types of Bourdon tubes — the C tube, the helical tube, and the spiral tube.

The simplest and one of the most common types of Bourdon tubes is the C type, shown in Figure 4-1. This instrument is an oval tube, shaped to resemble the letter C. One end of the tube is open while the other end is sealed and free to move. The open end is attached to the frame or case of the transducer. Then, the pressure to be measured is applied through the open end. As pressure is applied, the tube will start to straighten slightly. This mechanical response is related to the pressure formula ($P = F/A$). Since the outside surface of the C tube is

longer than the inside, the outside has a greater area. Consequently, the force exerted on the outside surface is greater than the force exerted on the inside, causing the tube to straighten. As the tube straightens, the sealed tip will move, providing an indication of pressure changes.

C tubes are commonly used inside pressure gages. Figure 4-2 shows the inside assembly of a pressure gage mounted in the gage case. It includes the components that convert the movement of the tip of the C tube into motion that moves the pointer around the dial (see Figure 4-3). A linkage is attached to the movable tip of the C tube. The other end of the linkage is attached to a sector gear. The sector gear meshes with a pinion that turns a shaft that is connected to the pointer. The motion of the shaft causes the pointer to move on the dial. In this way, when pressure is applied to a pressure gage, the position of the pointer on the dial will indicate the amount of pressure.

The scale on the dial of a pressure gage is graduated in pressure units, such as PSI, PSIG, or PSIA. The movement of the pointer on the dial is controlled by a hair spring. This spring reduces hysteresis by returning the pointer to its original position when the pressure is removed from the transducer.

The scales on the dials of some pressure gages include readings below zero. These gages are referred to as compound gages and are often used to indicate

Table 4-1. Pressure Elements

Class	Type	Optimum range	Accuracy
Tube-spring	Single Bourdon	10-30,000 psi	2%
	do., elec. trans.	10-3000 psi	2%
	do., pneu. trans.	10-3000 psi	2%
	do. "Inspector's"	10-5000 psi	0.5%
	Double Bourdon	50-800 psi	2%
	Helical	5-500 psi	1.5%
Diaphragm (Metallic)	Spiral	10-1000 psi	1.5%
	Unloaded, flat	1-200 psi	1.5%
	Unloaded, corrugated	0.5-50 psi	2%
	Spring-loaded	2-200 psi	1%
	do., strain-ga. trans.	50-1500 psi	1%
Membrane (leather, fabric, plastic, etc.)	do., pneu. trans.	vac.-300 psi	0.5%
	Spring-loaded	0.2-100" H ₂ O	1.5%
	do., elec. trans.	0.1-50" H ₂ O	1.5%
Bellows	do., pneu. trans.	0.1-40" H ₂ O	1.5%
	Unloaded	1-100" H ₂ O	2%
	Spring-loaded	0.5-200 psi	2%
	do., elec. trans.	0.5-50 psi	1%
	do., pneu. trans.	0.1-100 psi	1%
	Pendulum-loaded	10-200" H ₂ O	2%

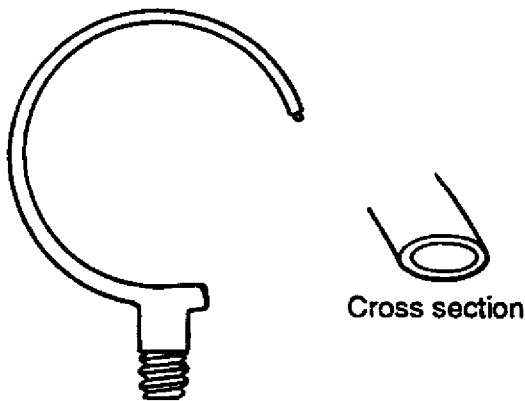


Figure 4-1. Bourdon Tube

vacuum (see Figure 4-4). Therefore, on a compound gage the portion of the scale below zero is usually graduated in inches of mercury.

Another type of Bourdon tube is the helical tube, shown in Figure 4-5. This is an oval tube that is wound into a helix. Its shape resembles a coil. A helical tube pressure element operates on the same principle as the C tube. One end of the tube is closed and is free to move while the other end is open and firmly attached to the transducer case or frame. The pressure to be measured is applied through the open end, causing the tube to try to uncoil. Like the C tube, the tip of the tube moves in response to the movement of the coil caused by the pressure. However, the advantage of the helical tube is that it produces more tip movement than the C tube.

A third type of Bourdon tube is the spiral tube, shown in Figure 4-6. In this transducer, the oval tube is wound in a spiral. The major advantage of this type of

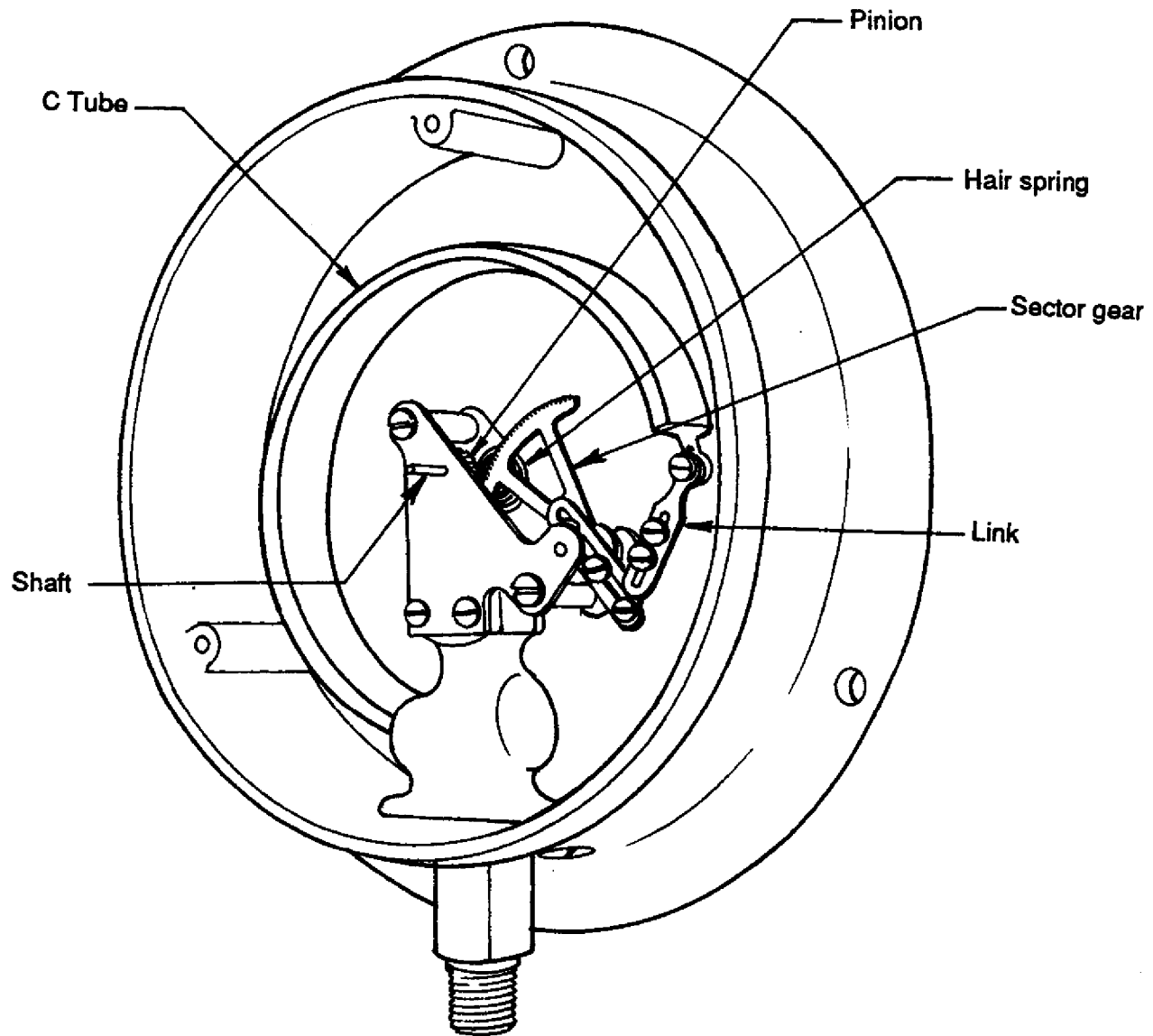


Figure 4-2. Inside Assembly of Pressure Gage

Bourdon tube is that the tip produces more motion than both C tubes and helical tubes.

All Bourdon tubes have similar capabilities. The type of Bourdon tube chosen for an application is primarily determined by the range required and the characteristics of the process. Generally, the C tube is the stiffest or least sensitive, and the spiral is the most sensitive. The C tube Bourdon element can have a

useful range from 30 In Hg vacuum to 100,000 PSIG. The spiral Bourdon element can have a range up to 40,000 PSIG. All Bourdon tubes have an accuracy of $\pm 1/2\%$ to $\pm 1\%$ of span. Therefore, a Bourdon element calibrated to measure the pressure between 200 and 500 PSIG can be expected to indicate 400 PSIG, with an accuracy of ± 1.5 PSI, which is $1/2\%$ of the 300 PSI pressure interval. An element calibrated 0 to 5000

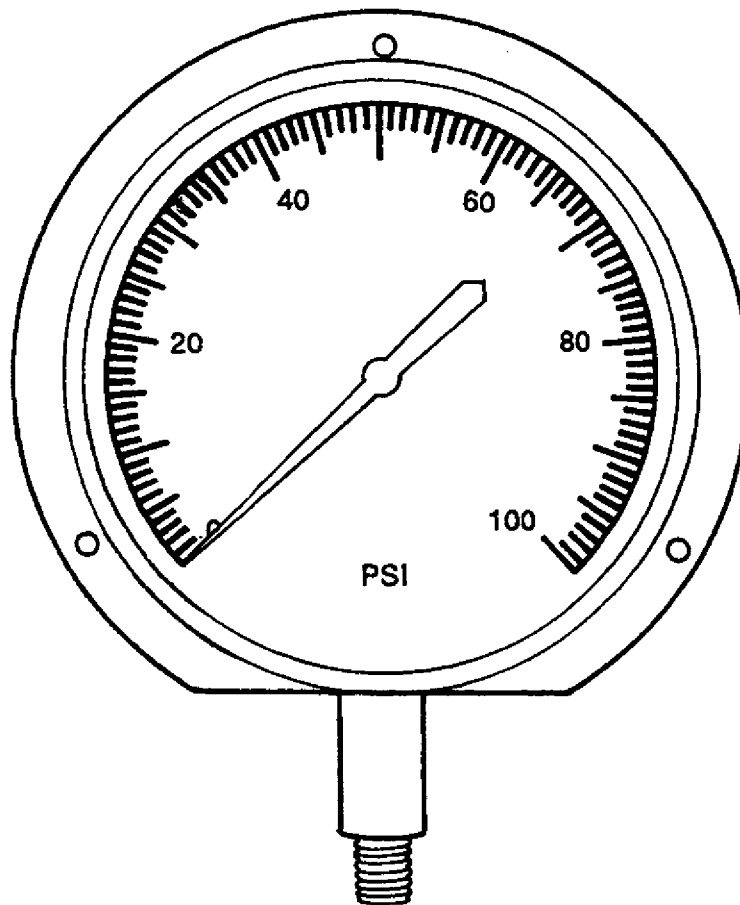


Figure 4-3. Pressure Gage Dial

would indicate true pressure with an accuracy of $\pm 2 \frac{1}{2}$ PSI.

The usual materials of construction for Bourdon tubes are brass, phosphor, bronze, steel, and 304 and 316 stainless steel. For some applications, fused quartz is used as Bourdon tube material. In the fused quartz gage (see Figure 4-7), the rotation of the multi-turn Bourdon tube is sensed by a mirror suspended on the end of the tube. An optic transducer and servo system measure rotation and provide an output that is proportional to pressure.

Bellows

Another type of mechanical pressure element is a bellows (see Figure 4-8). A bellows is a cylindrical

device that is usually ribbed and very flexible. Bellows are usually made of phosphor, bronze, or brass. A pair of matched bellows can be used to measure absolute pressure or differential pressure. Usually one end of the bellows is attached to the transducer case and the other end is free to move. When pressure is applied to the inside of the bellows, it will expand, causing the free end to move. The movement of the movable end is measured in order to identify the amount of pressure.

A bellows will also respond if pressure is applied to its outer surface. The arrangement (see Figure 4-9) is frequently called a bellows in a can. The process is connected to the can and the pressure is applied outside the bellows. The bellows sensing element will respond to changes in pressure in the can by expanding or contracting. The movement can be measured and the

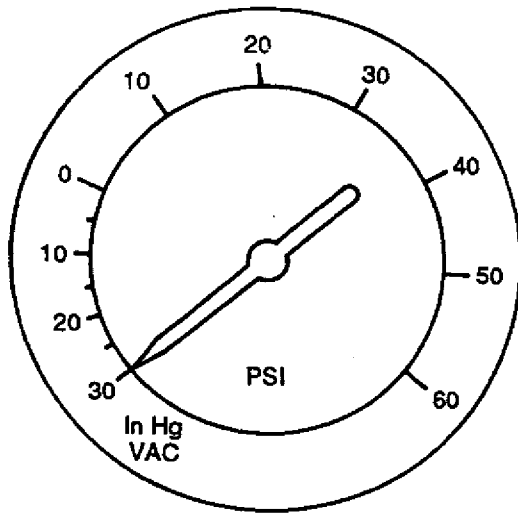


Figure 4-4. Compound Gage

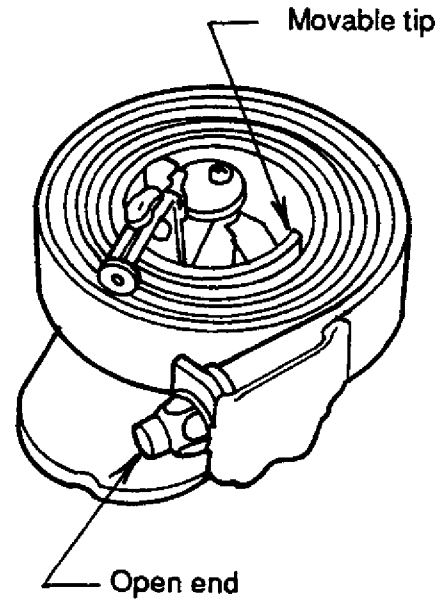


Figure 4-6. Spiral Tube

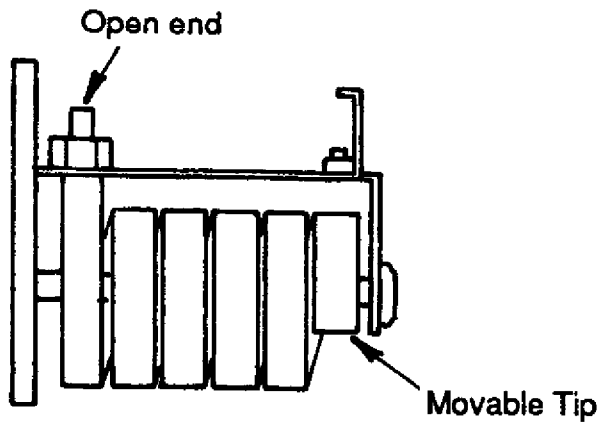


Figure 4-5. Helical Tube

measurement can indicate pressure. An advantage of the bellows in the can arrangement is that the can will protect the bellows, which is usually constructed from a soft flexible material, from impact damage. Since the can is not designed to produce movement, it can be constructed from a sturdy material that can offer the bellows protection from physical damage.

Bellows elements are more sensitive than Bourdon elements and can be used at relatively low pressure levels (0 PSIA to 30 PSIG). The accuracy of a bellows element is about the same as that of a Bourdon tube

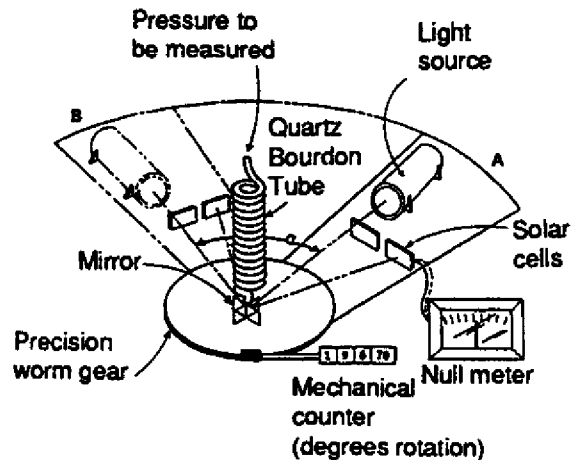


Figure 4-7. Fused Quartz Gage

element: $\pm 1/2\%$ to $\pm 1\%$ of calibrated span. Their calibrated spans can be as narrow as 5 In H_2O .

Since pressure elements are very sensitive to small pressure changes, they can be easily overranged and damaged. To protect the sensing element from damage, many bellows transducers will have mechanical over-range or under-range stops that prevent the bellows from excessive expansion or contraction (see Figure 4-10). In addition, bellows also include springs that resist the expansion or contraction of the bellows. These springs are usually attached to the bellows element with a screw

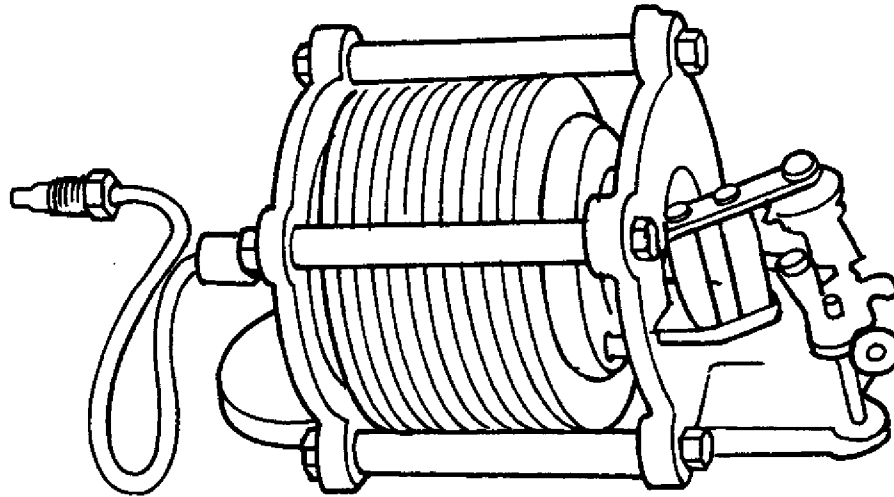


Figure 4-8. Bellows

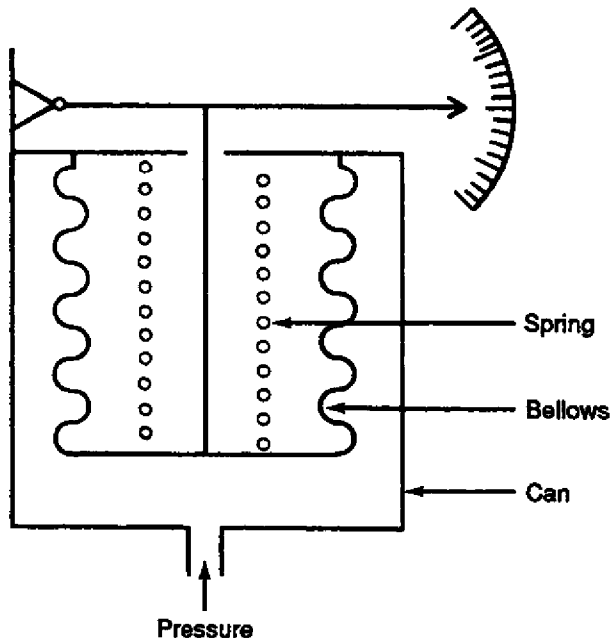


Figure 4-9. Bellows in a Can

that allows the spring tension to be adjusted. These springs are used to zero the bellows pressure element.

The bellows element is available in configurations suitable for gage, absolute, differential, or vacuum measurements. Figure 4-11 shows two bellows used to form a gage. Both bellows are connected to a balance beam which is connected to a pointer that moves on a scale. One of the bellows is evacuated and sealed. This

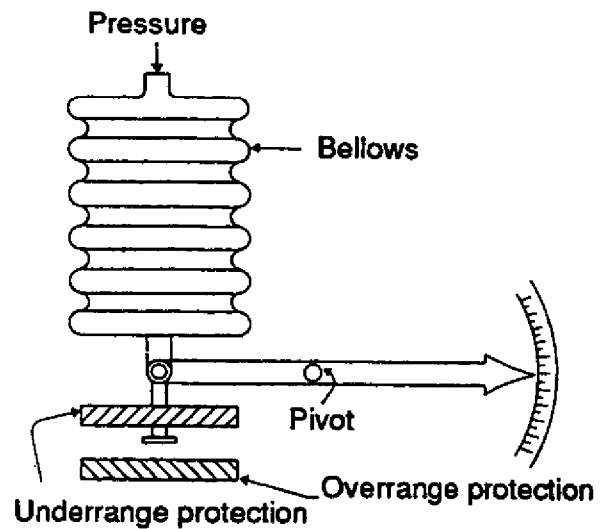


Figure 4-10. Bellows with Stops

bellows serves as a reference and is set at, or as close as possible to, absolute zero. Process pressure, or the pressure to be measured, is applied to the other bellows. As the process pressure is applied to this bellows, the movement produced in response to changes in process pressure is transferred to the balance beam. This causes the pointer on the scale to move. The distance the pointer moves is based on the amount of process

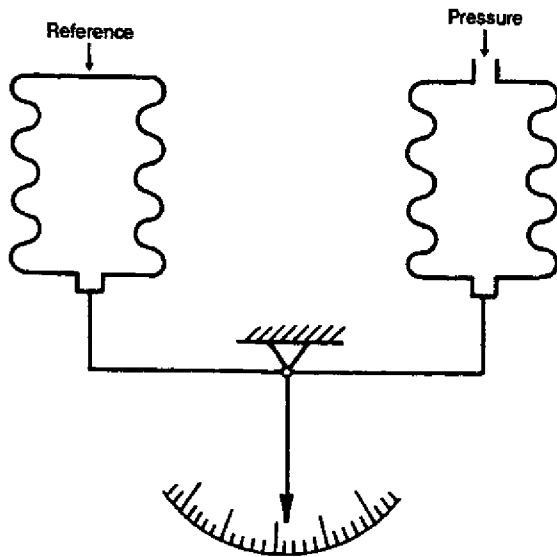


Figure 4-11. Bellows Pressure Sensors in Balance Beam Gage

pressure compared to the reference bellows. Since the reference bellow is set at absolute zero, the movement of the pointer provides a PSIA indication of pressure. This method can also be used to provide a measure of differential pressure.

Diaphragms

A diaphragm is a mechanical pressure transducer that is used to detect slight changes in pressure. A diaphragm is a single disk that is exposed to a process (see Figure 4-12). Since process pressure is exerted over a relatively large area, this instrument is more sensitive to small changes in pressure. This principle is based on the basic pressure equation, $P = F/A$. If a small pressure is exerted over a large area, the force will be relatively large, and will cause the diaphragm to flex. A mechanical device, such as a pin, rod, or bar, is usually connected to the diaphragm so that the amount of flex can be measured in order to determine the amount of pressure exerted.

Diaphragms may be composed of a number of materials. Metal diaphragms are frequently used in gages and control devices. Metal diaphragms, or stiff diaphragms, are made of phosphor, bronze, beryllium, copper, trumpet brass, stainless steel, or monel.

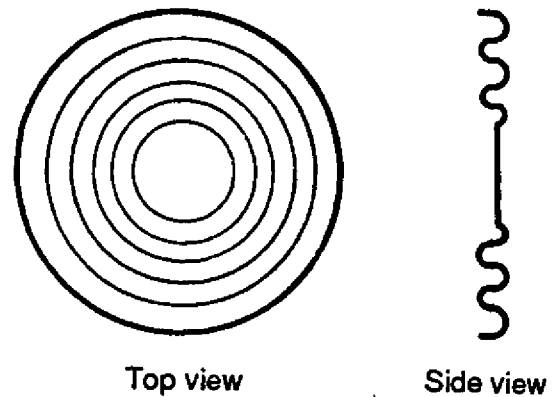


Figure 4-12. Basic Diaphragm

Nonmetal diaphragms are made of neoprene, polyethylene, silk, leather, teflon, koroseal, and silicone. These diaphragms are flexible, but are limited to use on low pressure systems. Large, very flexible diaphragms, called slack diaphragms, are used in control valve actuators (see Figure 4-13).

The diaphragm most often used in pressure transducers is a diaphragm capsule, shown in Figure 4-14. This type of diaphragm is actually two metal diaphragms that are connected at the edges. The area between the two diaphragms is filled with a fluid that has a low freezing point, a high boiling point, low viscosity, and a low coefficient of thermal expansion. For process temperatures between 0°F and 400°F, conventional fill liquids, such as those listed in Table 7-1 (Chapter 7) are typically used. For process temperatures below 0°F special fill liquids such as kerosene, and toluene are usually used. According to Pascal's Law, since fluid is noncompressible, any movement produced by the side of the diaphragm that is exposed to the process will be transmitted undiminished to the other diaphragm. The rod or pin that is attached to the diaphragm will move in response to changes in pressure. This motion can be measured to determine pressure.

Diaphragm capsules are frequently used as

isolation devices. (Isolation devices are discussed in Chapter 7). In addition, diaphragm capsules are commonly used in control transmitters, pressure gages, and differential pressure transmitters.

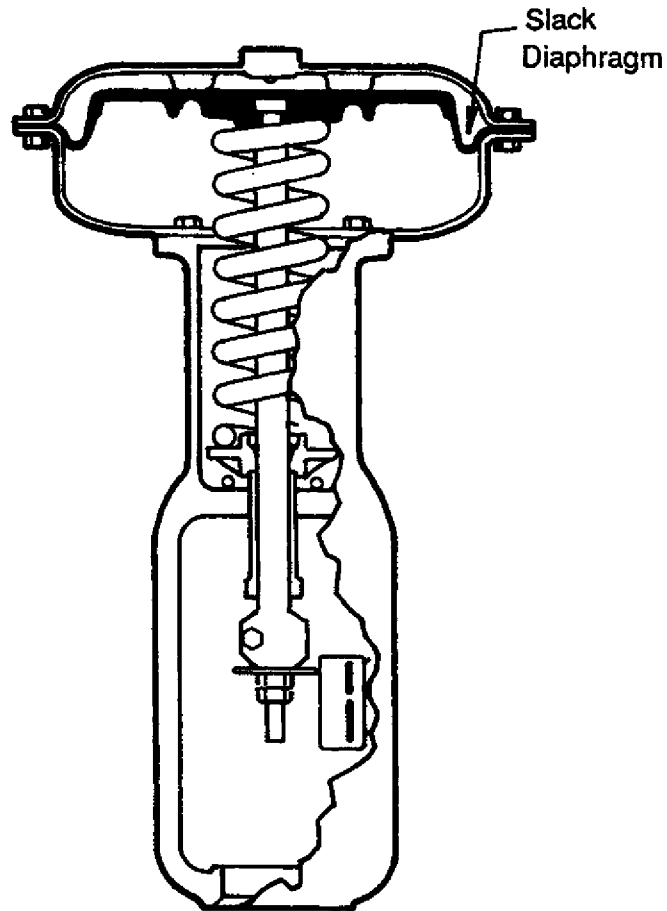


Figure 4-13. Control Valve with Slack Diaphragm

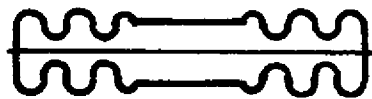


Figure 4-14. Diaphragm Capsule

ELECTRICAL PRESSURE ELEMENTS

Electro-mechanical pressure transducers convert the motion produced by mechanical sensing elements into changes in electrical signals. There are many different designs of electrical pressure transducers. These devices are widely used to monitor and control process pressure.

The Wheatstone Bridge

One common design of an electrical pressure transducer circuit is the Wheatstone bridge. Figure 5-1 illustrates a simple Wheatstone bridge circuit configuration. This configuration has two parallel legs that form a bridge. A voltage source is connected to the bridge so that current will flow through each leg. A typical Wheatstone bridge also has a measuring circuit installed across the bridge. This circuit provides a path for current flow if the bridge is not balanced. The bridge circuit includes four resistors. It is designed so that when the resistance of all four resistors is exactly equal, the current flow through each leg is equal and there is no current flow through the circuit across the bridge. At this point the bridge is balanced.

With the design of this Wheatstone bridge, if the resistance of one of the resistors changes, the current flow through each leg will no longer be equal. For example, if the resistance of Resistor 2 in Figure 5-1 is decreased, but the voltage remains the same, there will

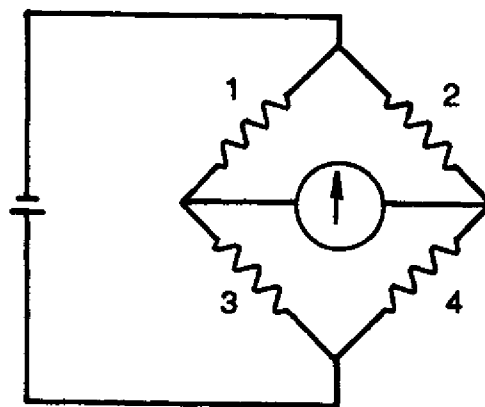


Figure 5-1. Simple Wheatstone Bridge

be more current flow through the leg that has Resistor 2 than through the leg that has Resistor 1. However, if the resistances of Resistors 3 and 4 remain the same, the current flow through the part of the circuit that has these two resistors will not change. This situation creates an imbalance in the bridge. Current will flow through the measuring circuit connected across the bridge. The amount of current flow is directly proportional to the amount of imbalance in the Wheatstone bridge. Therefore, in order to monitor the imbalance in the bridge, a meter may be installed in the measuring circuit across the bridge.

When a Wheatstone bridge is used as a pressure measuring instrument, one of the resistors in the bridge circuit is replaced with a resistance that is connected to a pressure sensing element. The pressure sensing element is exposed to the changes in process pressure. When there is no process pressure, the resistance of Resistors 1, 2, 3, and 4 is equal and the bridge is balanced. Therefore, there will be no current flow through the circuit across the bridge and the instrument will indicate zero pressure.

However, if pressure changes, the pressure sensing element will respond to the change in pressure and will change the resistance in the bridge. The change in resistance will cause an imbalance in the bridge circuit. When this happens, the measuring instrument will indicate the pressure change.

Potentiometric Transducers

Another type of electrical transducer is the potentiometric transducer. This transducer usually utilizes a Wheatstone bridge circuit in which one of the bridge resistors is replaced by a potentiometer. A potentiometer is a wire-wound resistor with a movable slide on it (see Figure 5-2). The slide is usually connected to some type of mechanical pressure sensing element. As the mechanical pressure sensing element moves in response to pressure changes, it moves the slide on the potentiometer. When the slide moves, the resistance value of the potentiometer changes. This changes the resistance in the bridge circuit.

When a potentiometer that is attached to a mechanical pressure sensing element is connected to a typical Wheatstone bridge circuit, the circuit can be used to measure pressure. For example, Figure 5-3 shows a

Wheatstone bridge with Resistor 2 replaced by a potentiometer. In this case, when the pressure of the measured variable is at zero, the potentiometer has the same resistance as Resistors 1, 3, and 4. Therefore, the current flow through the two legs would be equal, and there will be no measurable difference in potential across the bridge. Since there will be no current flow across the bridge, the meter will indicate zero pressure.

If the pressure changes, the slide on the potentiometer will be moved by the mechanical pressure sensing element. This will change the resistance of the potentiometer, creating an imbalance in the bridge circuit. For example, if the change in pressure causes the potentiometer resistance to decrease, its resistance will be less than the resistance of Resistor 1, while the values of Resistors 3 and 4 will remain equal. Consequently, a current will flow across the measuring circuit. This current will be proportional to the change in pressure that caused the slide on the potentiometer to move. A meter or control circuit connected across the bridge will measure this current flow and provide an indication of process pressure.

A potentiometric pressure transducer has a limited response to pressure changes. In addition, pulsating pressures can easily wear and damage the windings of the potentiometric transducer. For these reasons, it is important to consider the characteristics of the process pressure being measured with this type of transducer and to exercise care when using it.

Linear Variable Capacitor Transducers

A linear variable capacitor is another type of electrical pressure transducer. A capacitor is a device that

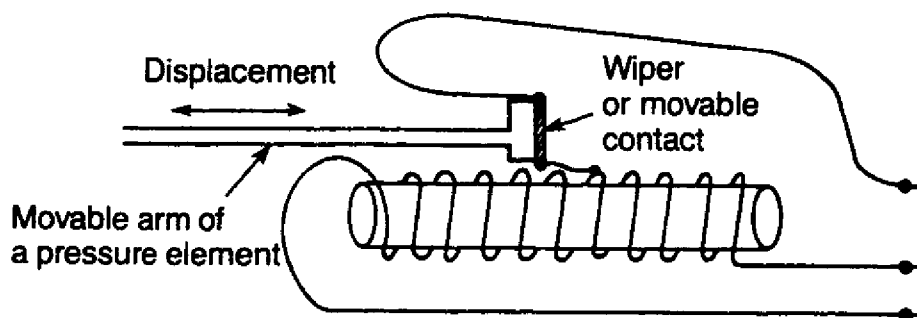


Figure 5-2. Potentiometer

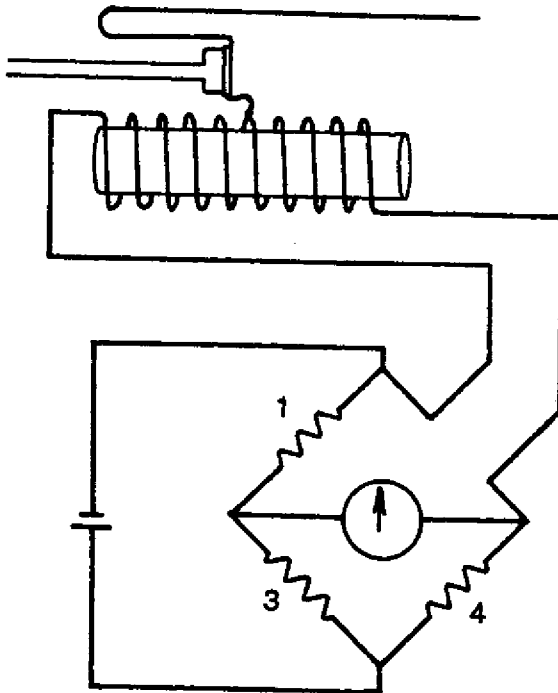


Figure 5-3. Wheatstone Bridge with Potentiometer

opposes current flow in an AC circuit. It consists of two metal plates that are separated from each other by an insulating material called a dielectric. The amount of opposition to current flow that a specific capacitor provides will depend on the area of the plates, the

distance between the plates, and the type of dielectric that separates them. If any or all of these elements change, the amount of opposition to current provided by the capacitor will also change.

On a linear variable capacitor electric transducer, the distance between the plates is adjusted to detect and indicate changes in process pressure (see Figure 5-4). In this case, the capacitor is connected in a circuit. A meter or system control device is connected to the circuit output to measure the changes in current flow that result from changes in capacitance. One plate of the capacitor remains stationary. The other plate is movable and is connected to a mechanical pressure element, such as a diaphragm.

When pressure is applied to the mechanical pressure element, it moves the movable plate of the capacitor. Since the other plate is fixed, this movement changes the distance between the two plates. When the distance between the plates changes, the capacitance of the capacitor changes. Changes in capacitance change the opposition to current flow that a capacitor inserts in an AC circuit. Therefore, by measuring the current flow in the circuit, changes in pressure can be detected and indicated. If the output of the capacitor circuit is connected to a process control system, changes in process pressure can be used to control a process variable.

The linear variable capacitor transducer has several characteristics that make it ideal for measuring low input levels. These characteristics include:

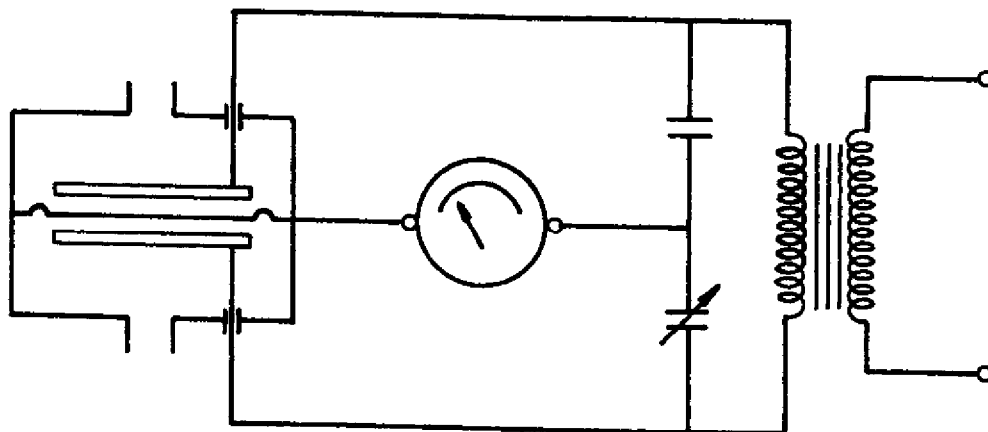


Figure 5-4. Linear Variable Capacitor

- production of large changes in capacitance with small movement
- minimum hysteresis due to internal friction
- fast response
- minimum self-heating effects
- resistance to difficult environments

Linear Variable Differential Transformer Transducers

Another widely used electrical pressure transducer is the linear variable differential transformer or LVDT (see Figure 5-5). When this device is used to measure pressure, an AC voltage is connected to the primary (P) winding of the transformer. The secondary winding consists of two windings (S1 and S2) that are connected so that their outputs are at opposite polarities. A movable core is attached to a mechanical pressure sensing device, such as a bellows or diaphragm. When the core is in the center position, the outputs of S1 and S2 will be equal and of opposite polarity. At this point, the output is zero and the transducer indicates zero pressure.

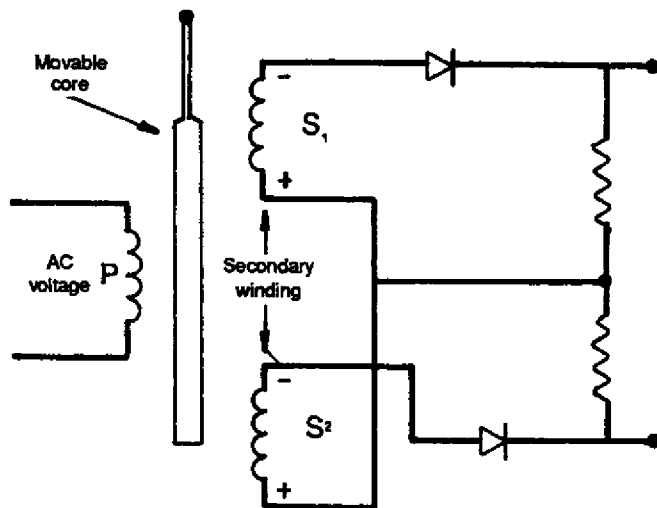


Figure 5-5. Linear Variable Differential Transformer

If process pressure changes, the mechanical sensing element will move, causing the movable core to move. For example, in Figure 5-6 the core has moved almost completely out of secondary winding S2 and covers the entire surface of secondary winding S1. Therefore, the voltage induced into S1 will be greater than the voltage induced into S2. Consequently, the output of S1 will be greater than the output of S2. If an instrument is connected to the output of the transformer, it will indicate that S1 is predominant. If the transducer is designed so that increased output from S2 indicates an increase in pressure, the instrument will indicate an increase in pressure. In this case, if the core moved out of winding S1 and covered almost all of S2, the instrument would indicate a decrease in pressure.

One advantage of an LVDT is that it is rugged, and therefore will not be easily damaged. Also, since the movable core does not have to touch the transformer windings, there is no need to compensate for friction.

Variable Inductor Pressure Sensors

A variable inductor pressure sensor is another device used to detect pressure (see Figure 5-7). In this type of sensor, two coils are wired in opposition to form two legs of an AC bridge. A diaphragm made of a

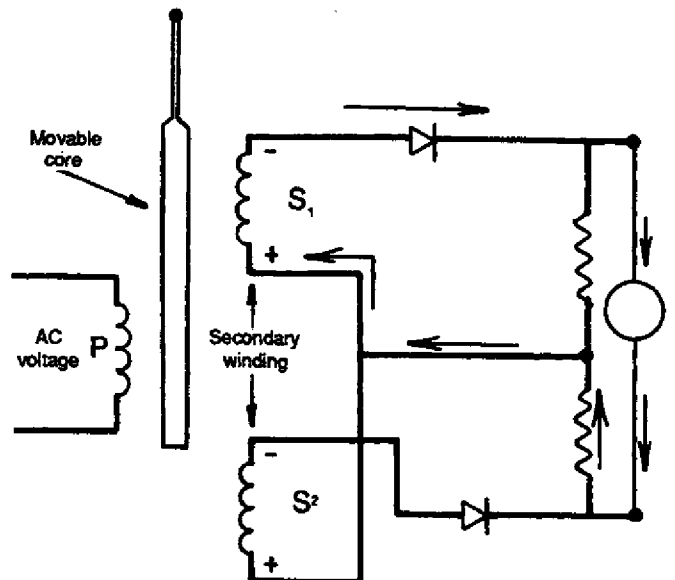


Figure 5-6. Linear Variable Differential Transformer With Core Moved

magnetic material is placed between the two coils. Pressure from the measured process is applied to one side of the diaphragm while the other side of the diaphragm is exposed to a reference pressure, such as atmospheric pressure. Changes in process pressure will cause the diaphragm to flex and move toward one of the coils and away from the other. This creates a small air gap between the diaphragm and the coils. The gap allows the diaphragm to touch the core face and protects it from damage caused by overloads. As the diaphragm moves, the relative inductance of the coils changes. These changes in relative inductance change the circuit output. Therefore, the circuit output can be measured as pressure.

The construction of the variable inductor pressure sensor makes them extremely rugged and stable in performance. Other advantages of this type of sensor include a high output and dependable overload protection. However, two disadvantages of variable inductor pressure sensors are that their frequency response is limited and they sometimes produce nonlinear output.

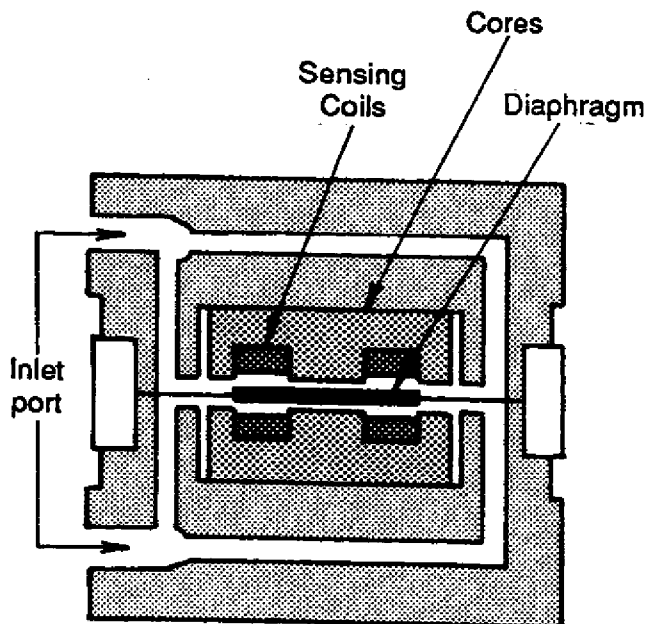


Figure 5-7. Variable Inductor Pressure Sensor

ELECTRONIC PRESSURE ELEMENTS

Strain Gage Transducers

Many of the smaller electronic pressure transducers use strain gages to vary the resistance in an electric circuit. Strain gages consist of a series of wires that are supported by some type of insulation.

The basic principle of a strain gage is that the cross sectional area of the wire will affect its resistance. If the cross sectional area is changed, the wire's resistance will also change. A wire's resistance can be manually adjusted by stretching or straining the wire. The resulting changes in resistance allow strain gages to indicate changes in process pressure.

There are two types of strain gages — unbonded strain gages and bonded strain gages. Figure 6-1 is an illustration of an unbonded strain gage. It consists of a stationary member and a movable armature. Both the stationary member and the movable armature have insulated pins that support a series of small wires. These wires are connected so that they will respond to changes in pressure. The movable armature of an unbonded strain gage is connected to a mechanical sensing element, such as a bellows or a diaphragm. When pressure changes, the mechanical pressure element will move the movable armature to change the tension on the wires in the strain gage. Changing the tension on the wires will change the resistance. In this way, the gage indicates changes in pressure.

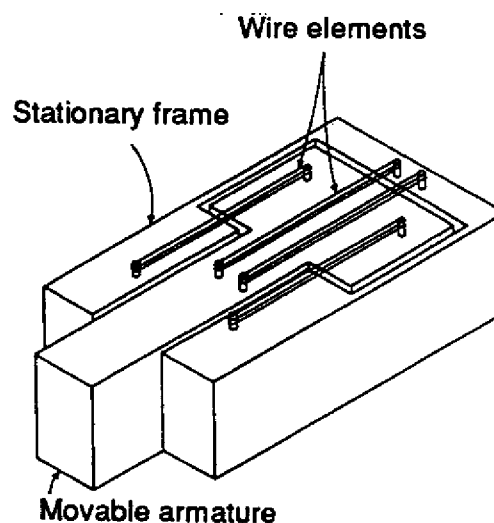


Figure 6-1. Unbonded Strain Gage

Unbonded installations offer high sensitivity and moderate accuracy (short term accuracy of 1%). However, due to creep and hysteresis, unbonded gages must be frequently recalibrated. Also, with unbonded gages, zero tends to shift because of long term changes in wire resistivity and stress relief.

While bonded strain gages suffer less from long term instability, they are only half as sensitive as

unbonded gages. In bonded strain gages (see Figure 6-2), small wires or pieces of foil are bonded to a piece of insulating material with adhesive. Usually, bonded strain gages have two sets of wires or foil. One set is called the active strain gage element and will be subjected to strain. The other set is the slip, or dummy, element and will not be strained.

When used to measure pressure, a bonded strain gage is fastened to some movable part of a mechanical pressure sensing element. For example, bonded gages are often glued to diaphragms or force beams that will bend or flex when pressure changes. The slip, or dummy, is glued to some part of the pressure element that does not move. The active strain gage element is connected in a way that allows it to bend or strain in response to the movement of the pressure sensing element. As the active strain gage element bends or strains, the wires or foil in the bonded strain gage will be strained. The tension of the wires or foil will change their resistance.

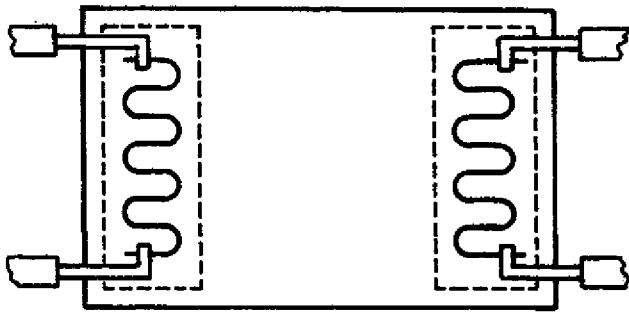


Figure 6-2. Bonded Strain Gage

Typically, in strain gage transducers, a wire, foil, or semiconductor resistor element is bonded to a diaphragm. The deflection of the diaphragm alters the gage resistance and unbalances an associated bridge. Strain gage transducers are usually part of a bridge circuit, such as the Wheatstone bridge shown in Figure 6-3. In this example, G_1 and G_2 represent strain gage elements. G_1 is an active strain gage element and is connected to the pressure sensing element so that it will tension the wires. G_2 is a dummy because it is connected to a part of the pressure element that will not cause it to be tensioned. When the resistances of G_1 and G_2 are equal and resistors R_1 and R_2 are equal, the

bridge is balanced; there is no current flow across the bridge and through the measuring instrument. In an installed and calibrated instrument, this condition should always exist when process pressure is at zero.

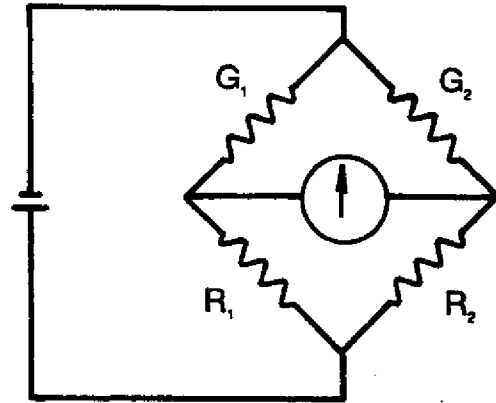


Figure 6-3. Wheatstone Bridge with Strain Gage

When a voltage is applied to the bridge, current flow through both branches in the bridge will be equal as long as there is no process pressure. This means that there will be no current flow across the bridge and the instrument will indicate zero pressure. However, as system pressure increases, the mechanical sensing element will move, increasing the tension on the wires of the active strain gage (G_1). The increased tension on the wires will increase the resistance of strain gage G_1 . Therefore, the resistances of G_1 and G_2 are no longer equal. To compensate for the increase in resistance of G_1 , more current will flow through the leg of the bridge to which G_2 is connected. Meanwhile, resistors R_1 and R_2 will still be equal. To balance the current flow through these two resistors, some current will flow from the leg connected to strain gage G_2 through the instrument and into the leg of resistor R_1 . The specific amount of this current flow will depend on the resistance of strain gage G_1 . Since the resistance of G_1 depends on the pressure of the process, this circuit configuration can be used to detect and indicate pressure.

Strain gage elements are ideal for taking dynamic[†] measurements. They offer fast response, low source impedance, and minimum mechanical motion, as well

as, small size and weight. In addition, the device works equally well with AC or DC power. However, the disadvantages of the instrument include a loss of accuracy in use due to hysteresis, and rather costly output measurement devices.

A fairly recent development in the field of strain gage sensors is the use of a silicon diaphragm on which N and P type semiconductor gages are diffused. These sensors are very useful for specialized applications. They can be designed with diaphragms with 0.1 inch diameters and still produce an output of several hundred millivolts. In addition, with these sensors, repeatability, hysteresis, and drift have been virtually eliminated.

Piezoelectric Transducers

When pressure or strain is applied to crystals such as quartz, rochelle salt, and barium-titanate, the crystals will produce a measurable voltage. This voltage can be monitored to measure pressure.

The quartz piezoelectric gage (see Figure 6-4) is one of the oldest forms of pressure transducers. It consists of one or more quartz crystals stacked between appropriate insulators, connectors, and load distribution plates. These plates are usually exposed to a mechanical sensing element that moves in response to pressure. As the pressure element moves, it applies pressure to the crystals through the load distribution

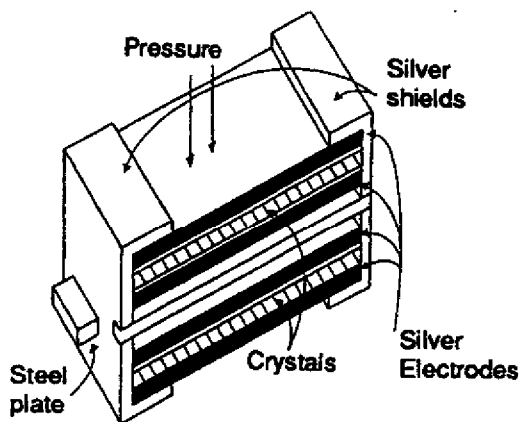


Figure 6-4. Piezoelectric Pressure Transducer

plate. This will cause a measurable charge or voltage to appear across the crystal. The amount of voltage is directly proportional to the amount of pressure or strain on the crystal. The power of the output from the crystal is extremely small and will not apply any load to the low powered miniaturized electronic circuits in the transducer. However, because the power output is so small, the signal must be amplified to be usable in pressure control circuits or measuring instruments.

Two types of thermal transfer gages are in wide usage. The simplest is the thermocouple gage (see Figure 6-5). The element in this type of gage is a fine wire or ribbon heated electrically and immersed in a gas whose pressure is to be measured. The steady-state temperature attained by the heated wire depends, among other things, on the loss of heat by conduction through the surrounding gas. The thermal conductivity of the gas varies with pressure in a range of vacuum conditions. Thus, the temperature of the ribbon will vary with gas pressure. The thermocouple gage measures the temperature of the strip with a thermocouple. Since thermal conductivity varies among gases, the gage must be individually calibrated to the gas for good accuracy.

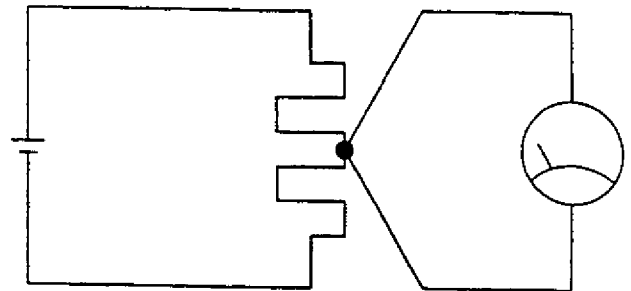


Figure 6-5. Thermocouple Gage

The other type of thermal transfer gage is the Pirani gage (Figure 6-6). In the Pirani gage, the wire element is made into an electrical resistance with two wire elements, one of which is sealed in a vacuum as a reference. The two elements are two electrical resistances forming two legs of a Wheatstone bridge. The cooling effect on the element exposed to the system unbalances the bridge to provide an output signal. Sensitivity is higher than with a thermocouple gage,

and accuracy is some ± 5 percent. Individual calibration is again required. Thermal transfer gages are universally used because they are simple, inexpensive, and easy to use.

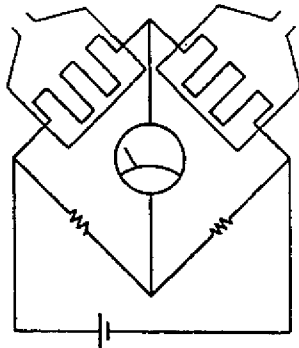


Figure 6-6. Pirani Gage

One type of ionization gage is the hot-cathode ionization gage (see Figure 6-7). In hot-cathode ionization gages, electrons emitted from a cathode move towards a grid. Some of the electrons collide with molecules of the gas whose pressure is to be measured. The gas molecules lose electrons as a result of the collisions, producing positive ions. The remaining electrons are collected on the grid. The positive ions, however, are attracted to the negatively charged collec-

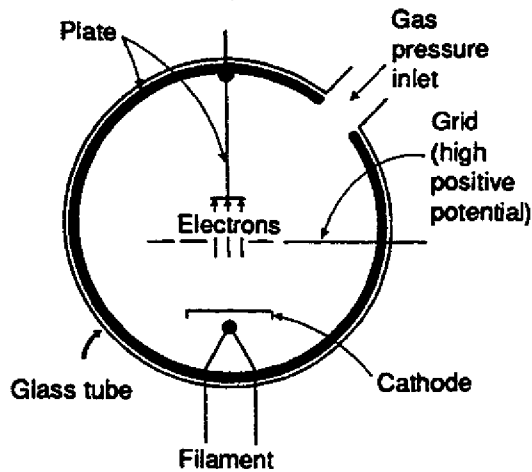


Figure 6-7. Hot-cathode Gage

tor. Each ion so collected causes a pulse of current to flow in the collector circuit. The number of ions produced depends on the molecular density of the gas. This means that collector current is proportional to gas molecular density, or pressure.

Another type of ionization gage is the cold-cathode gage (see Figure 6-8). The cold-cathode gage consists of an open anode loop between two cathode surfaces with a high voltage impressed between them. A magnetic field deflects electrons from traveling directly to the anode and causes them to oscillate among the magnetic lines of flux. With the increased mean free path, a significant number of ionizing collisions with gas molecules occur. The charge on the field builds up to an equilibrium, where each ion leaving the field causes an ion to enter. This current is then a measure of molecular density, or pressure. The cold-cathode gage accounts for half the ionization gages used.

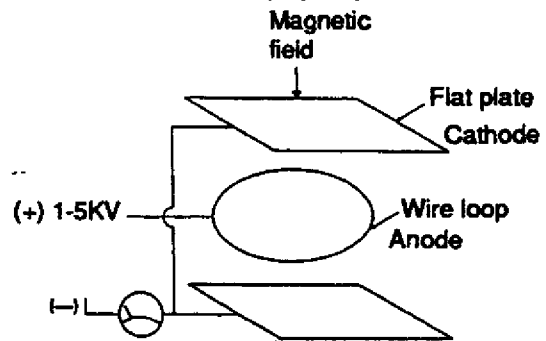


Figure 6-8. Cold-cathode Gage

The Knudsen gage consists of a very light vane and mirror supported on a delicate torsion suspension. Adjacent to the suspended vane are two fixed vanes heated electrically. A rarefied gas in the regions between the vanes produces a force whereby the suspended vane is repelled against the torsion of its suspension. The resulting deflection is read on a calibrated scale. The Knudsen gage finds little industrial application because of its mechanical awkwardness and lack of convenient remote indication.

Mass spectrometers of the magnetic deflection type are used in the measurement of ultrahigh vacuums. High sensitivity is provided in one model by a nine-stage electron multiplier, with magnesium-silver

dynodes, which gives a gain of 10^3 to 10^6 electrons per ion. This sensitivity permits partial gas pressure measurement to 10^{12} mm Hg.

7

INSTALLATION CONSIDERATIONS

The manner in which a pressure measuring instrument is installed in a process is an important factor in achieving accurate and reliable operation. While pressure measurement is usually accomplished by placing the measuring device in direct contact with the process, some process conditions can damage the sensing element. For example, high temperatures may melt the solder or otherwise deform a sensing element; a corrosive fluid may cause the sensor to deteriorate or disintegrate; vibration can cause excessive wear or mechanical shock; and a highly viscous fluid can plug a measuring instrument and render it useless. When potentially damaging conditions such as these exist in a process, special installation precautions must be taken to protect the measuring instrument.

In addition to process conditions, the method of mounting a measuring instrument will affect its accuracy. For example, the position of the instrument in relation to the process may require that zero adjustments be made to the instruments. Therefore, planning the installation of a pressure instrument requires consideration of the accuracy as well as the protection of the instrument.

Protection Devices

A variety of techniques and devices are used to protect pressure measuring instruments from damage

that can be caused by process conditions. Some of the most common devices include seal pots, mechanical pressure seals, and pulsation dampers.

Seal pots are often used when measuring steam pressure or in processes in which a vapor will condense into liquid at ambient temperatures. A seal pot acts as a condensate chamber, and provides a large area of liquid contact between the process and measuring instrument. Figure 7-1 shows a typical seal pot installation.

When a seal pot is installed in liquid and vapor applications, the lead lines to the measuring instrument should be full of liquid to protect the instrument from high temperatures. In steam service applications, the seal pots may be cooled with water or some other coolant to reduce the time required for the vapor to form condensate. In some cases, the seal pot, lines, and instrument are filled with a sealing fluid to prevent freezing. When a sealing fluid is used, the measuring instrument should be zeroed with the lines full of the seal fluid.

In systems where the process fluid is corrosive or highly viscous, mechanical pressure seals are typically used to protect pressure measuring instruments from damage. Mechanical seals are installed between the measuring instrument and the process and serve to isolate the instrument from the corrosive or plugging effects of the process.

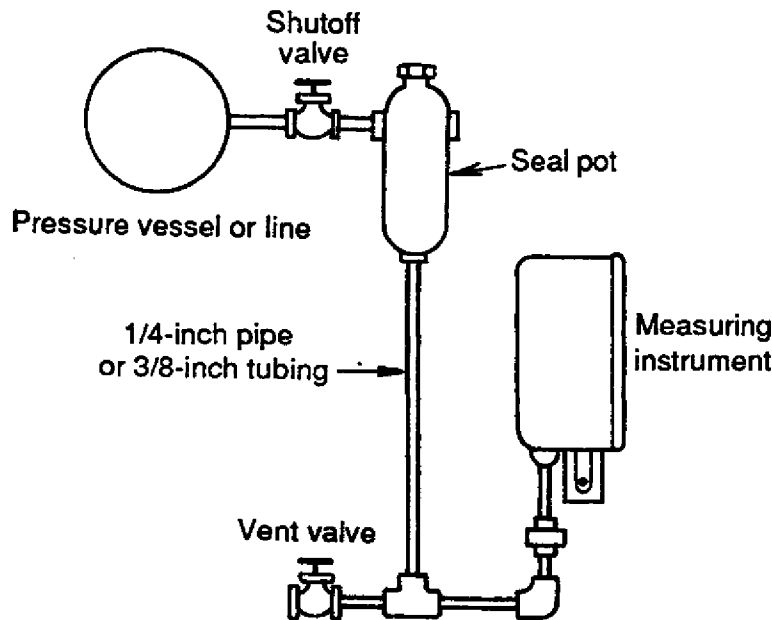


Figure 7-1. Typical Seal Pot Installation

An exploded view of a standard mechanical seal is shown in Figure 7-2. It consists of a bottom housing that is connected to the process, a diaphragm capsule that is filled with oil, and a top housing to which the measuring instrument is connected. The top housing connection lines and sensing element contain a fill liquid which is added under vacuum to ensure that there are no air bubbles that could adversely affect the accuracy of the measurement. The bottom housing contains a flushing connection through which process fluid can be drained when maintenance is required.

The operation of a mechanical seal is based on Pascal's Law that states that force applied to a liquid in a confined area is transmitted undiminished throughout the liquid. A mechanical seal is designed so that process pressure exerts a force on the diaphragm, which is transferred via the fill liquid to the measuring instrument.

The type of fill liquid used in a mechanical seal will depend on the particular application. However, in all cases, the liquid should have a low freezing point, a high boiling point, low viscosity, and a low coefficient of thermal expansion. For process temperatures between 0°F and 400°F, conventional fill liquids are typically used. Table 7-1 shows some of the commonly used

conventional liquids. For process temperatures below 0°F, special fill liquids, such as kerosene and toluene are usually required. For high temperature applications, special volumetric elements with a sodium-potassium liquid are commonly used.

A variety of diaphragm designs can be used in mechanical pressure seals. Some seals have a single diaphragm that is welded to the top housing. The diaphragm capsule design shown in Figure 7-2 consists of a thin lower diaphragm that is bonded to a strong corrugated backup plate. The oil filled capsule is threaded into the top housing. Since seal diaphragms are exposed to the process fluid, they are generally constructed of a corrosion resistant metal or a metal coated with a material such as teflon. Standard seals are designed to withstand rupture up to 2500 PSIG.

The seal shown in Figure 7-2 is designed for use with small displacement sensing elements such as Bourdon tubes, force balance diaphragms, helical and spiral elements, and small bellows. If the measuring instrument contains a bellows with a diameter greater than three-quarters of an inch, a large capacity seal is needed to match the displacement of the pressure element. Figure 7-3 shows one type of large displacement seal. In this design, a rolling diaphragm is used to

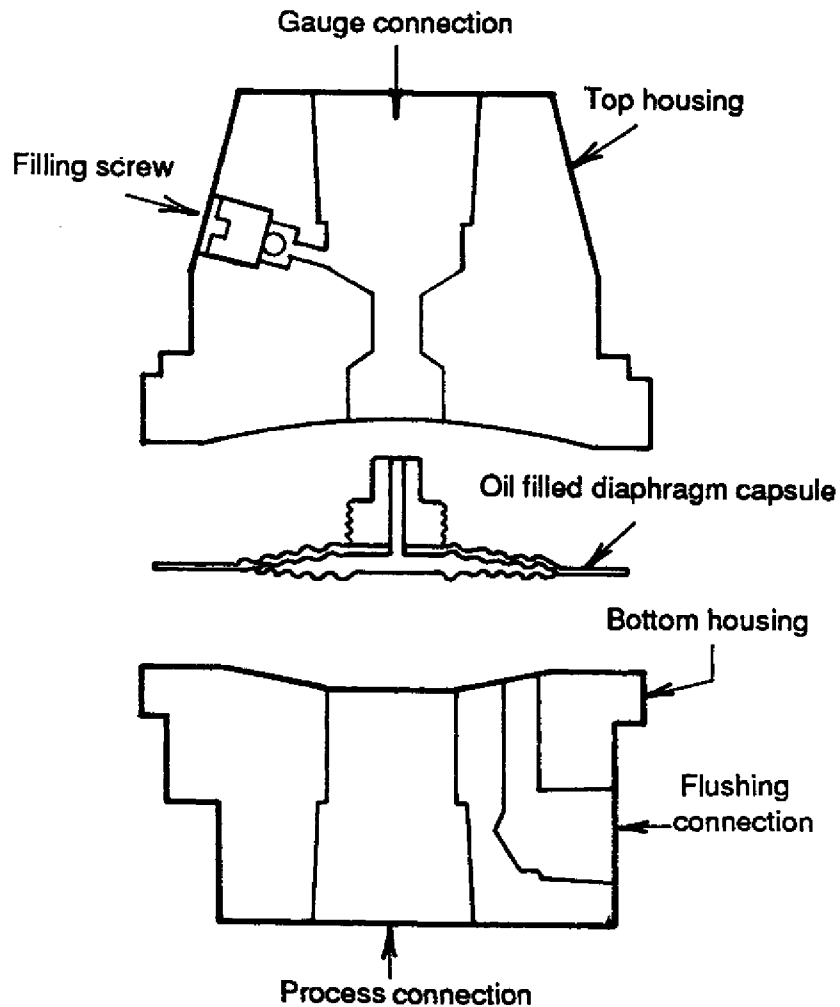


Figure 7-2. Standard Mechanical Seal (Exploded View)

increase the capacity of the seal.

In applications in which solids buildup is a concern, in-line pressure seals may be used to protect the measuring instrument. In-line seals are available in a variety of designs. For example, the spool shaped full stream design shown in Figure 7-4 does not contain cavities in which material can accumulate. This type of seal is designed for pressure applications up to 200 PSIG. The basic components of this seal include a flexible cylinder, a cast iron housing, and end flanges. The space between the cylinder and housing contains the fill liquid. The measuring instrument is threaded through a port that opens to the fill liquid. The force of

the process is exerted against the flexible cylinder and transmitted by the fill liquid to the measuring instrument. One disadvantage of in-line seals is that the process line must be drained before they can be removed for maintenance.

A pig tail is another commonly used mechanical seal (see Figure 7-5). This device consists of a complete turn in a section of tubing or pipe (usually 1/4 inch ID) and is used to connect the pressure instrument to the process. A pig tail is used to protect pressure gages from thermal shock in high process temperatures. Steam and other vapors condense and form a liquid trap in the lower portion of the pig tail. When the process is

Table 7-1. Commonly Used Fill Liquids

Fill Liquid	Temperature Range (°F)
Toluene	-40 to 200
Kerosene	-30 to 350
Dibutyl Phthalate	20 to 300
70% Glycerin/30% Water	30 to 300
Instrument Oil	35 to 300
Light Turbine Oil	40 to 300
96.5% Glycerin	70 to 450
Mercury	-30 to 700
22% Sodium/78% Potassium	20 to 1400
56% Sodium/44% Potassium	70 to 1500

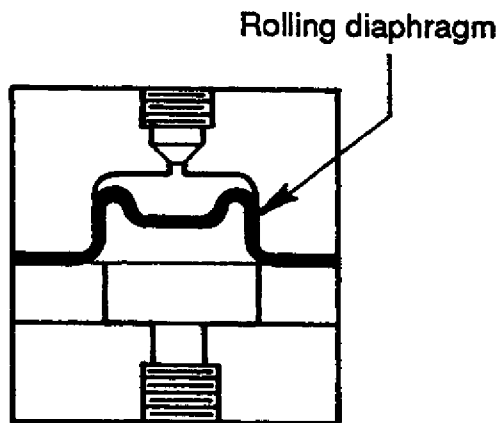


Figure 7-3. Large Capacity Seal

not under pressure, the liquid forms a seal between the process and the measuring instrument. When the process is started up, the liquid in the loop helps to protect the element from pressure and temperature shock.

Most pig tails are mounted vertically to prevent thermal shock. When mounted horizontally, the pig tail will absorb some mechanical shock and vibration, protecting the measuring instrument from possible

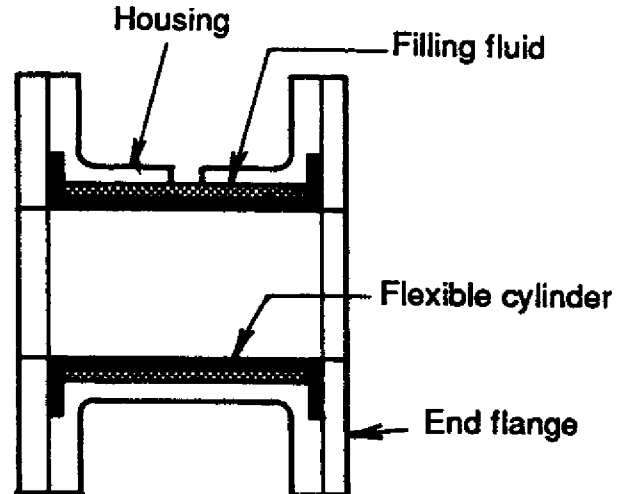


Figure 7-4. Full Stream Mechanical Seal

damage and excessive wear.

Another commonly used protection device is a pulsation damper, or snubber. This device is typically used in applications where there is rapid fluctuation of process pressure. Sudden changes in pressure make it difficult to read the actual value of the pressure measurement and cause unnecessary wear on the instrument. The effect of pressure fluctuation can be

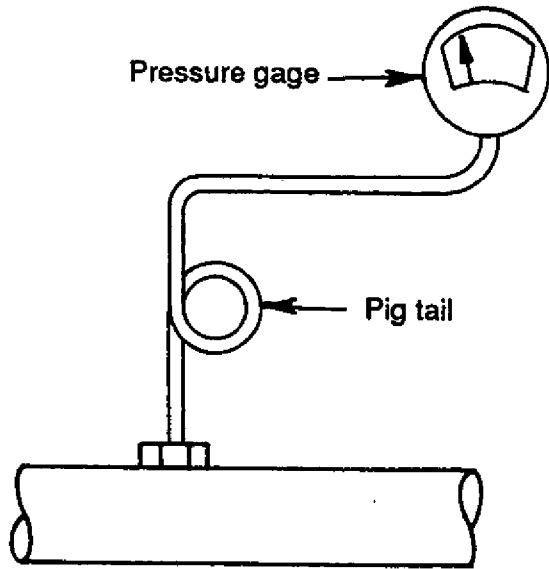


Figure 7-5. Pig Tail

minimized by placing a restriction in the impulse line to reduce the response rate of the instrument. Since it is desirable to instantly measure process response, the installation of a restriction that slows the measuring instrument's rate of response must be carefully planned to prevent overdamping.

In some applications, capillary tubing can be installed as a restriction. In this case, the amount of restriction can only be adjusted by changing the tubing length. Another disadvantage is that capillary tubing is likely to become plugged with foreign matter.

Pulsation dampers are available in a variety of designs (see Figure 7-6). The snubber design shown in Figure 7-6A contains a porous filter disc at the inlet to the restriction. With this type of snubber, the rate of response is delayed by a fixed time of about 10 seconds. The snubber shown in Figure 7-6B contains a small piston that absorbs shock and surge by rising and falling with pressure impulses. Figures 7-6C and 7-6D show two snubber designs that provide a means for adjusting the amount of restriction to obtain the best damped response.

The snubber shown in Figure 7-6C has an adjustable needle valve with a filter to prevent plugging of the

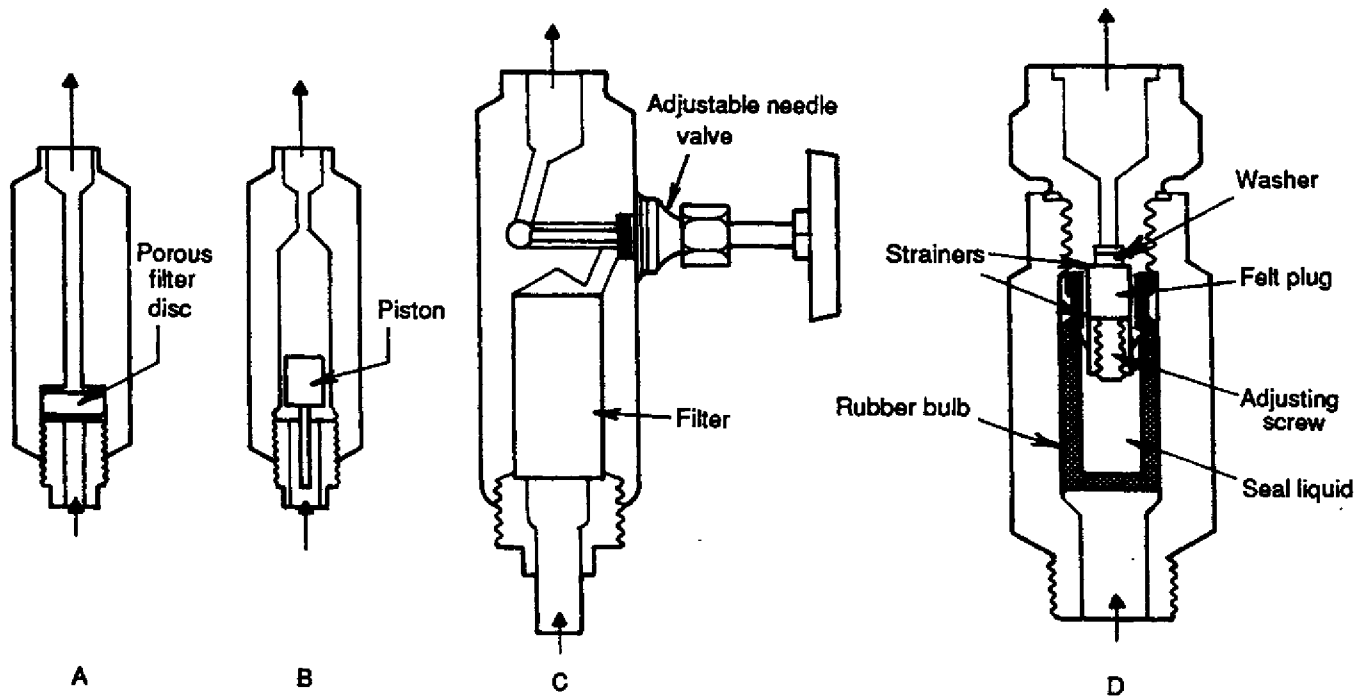


Figure 7-6. Pulsation Dampers

needle valve restriction. The snubber shown in Figure 7-6D contains a bulb made of rubber, or some other pliable material, that is filled with an inert seal liquid such as oil or glycerine. The seal liquid acts as a buffer between the process and the measuring instrument. The transfer of fluid between the bulb measuring instrument and the process is slowed by an internal adjustable restrictor. Since the restrictor adjusting screw is internally located, it is more difficult to make changes to the restriction in this snubber than in the needle valve snubber.

Zero Suppression and Elevation

When measuring the pressure of a vapor or liquid process, the impulse line connecting the process to the instrument will usually be full of liquid. In the case of a vapor process, this is due to the likelihood of the vapor in the impulse line condensing into liquid at ambient temperatures. In the case of a liquid process, this is due to the process liquid entering and being trapped in the line.

The weight of the liquid in the impulse line creates a hydrostatic head which exerts pressure on the measuring instrument. As a result, the total pressure on the measuring instrument includes both the process pressure and the head pressure. Therefore, accurate measurement of process pressure requires nullifying the head pressure in the impulse line to zero.

The manner in which head pressure is nullified depends on whether the measuring instrument is mounted above or below the process. When the measuring instrument is mounted below the process, the total pressure exerted on the instrument will be the process pressure plus the weight, or head pressure, of the liquid in the line. Therefore, accurate measurement of the process pressure involves subtracting the head pressure from the total pressure.

Head pressure is determined by multiplying the height of the liquid by the specific gravity of the liquid. For example, assume that a measuring instrument is mounted 10 feet below a steam drum and the impulse line has an inner diameter of one inch. The head pressure exerted by the water in the line would be calculated as follows:

$$10\text{ft} \times 0.433 \text{ PSIG/ft} = 4.33 \text{ PSIG}$$

Therefore, if the gage reading indicates 50 PSIG, the actual process pressure can be determined by subtracting 4.33 PSIG from the reading. In most cases, the head pressure is compensated by a correction called zero suppression. This involves adjusting the gage indicator to read zero when the process pressure is zero, and only head pressure is exerted on the instrument. In effect, zero suppression automatically subtracts the effect of head pressure, so the instrument reading indicates only process pressure.

Mounting the measuring instrument above the process has the opposite effect. In this case, process pressure must overcome the downward force exerted by the column of liquid in the impulse line before process pressure can be measured. The liquid is held in the impulse line by a seal installed at the connection to the process. To compensate for the pressure of the liquid in the impulse line, an elevated zero adjustment is made to the gage. With an elevated zero, the gage is adjusted to indicate the head pressure when there is no process pressure. When the process is under pressure, the instrument will indicate the actual process pressure.

Zero suppression and elevation corrections may be accomplished by adjusting pointer position or by using special suppression and elevation kits supplied by the manufacturer. These kits vary with the particular design of the instrument, but typically consist of a spring arrangement that is used to add a bias effect to the zero adjustment. Essentially, it serves to allow a greater zero adjustment of the instrument.

QUIZ

QUIZ

1. An open tank has a bottom area of 9 square feet and contains 36 cubic feet of water at a temperature of 60°F. How much force will the water exert on each square foot of the bottom of the tank?
 - a. 516.4 lbs./sq ft.
 - b. 62.34 lbs./sq.ft.
 - c. 249.36 lbs./sq.ft.
 - d. 433.0 lbs./sq ft.

2. If the level in the open tank used in Question #1 is lowered two feet, how much force per square inch will the water exert at a point one foot from the bottom?
 - a. .036 lbs./sq. in.
 - b. .866 lbs./sq. in.
 - c. .433 lbs./sq. in.
 - d. none of the above

3. Assuming that atmospheric pressure is 14.7 PSI, convert 6 PSI to In H₂O absolute.
 - a. 166.66 In H₂O absolute
 - b. 573.39 In H₂O absolute
 - c. 241.66 In H₂O absolute
 - d. 166.2 In H₂O absolute

4. An open tube manometer indicates 7.108 In Hg. What is the pressure measurement?
 - a. 2 PSI
 - b. 3 PSIA
 - c. 17.684 PSIA
 - d. 3 PSIG

5. What law does the McLeod gage employ to measure vacuum?
 - a. Pascal's Law
 - b. Boyle's Law
 - c. Charles' Law
 - d. Ideal Gas Law

50 Pressure