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PRASEODYMIUM, Pr. See Rare earth elements.

PRECIPITATION HARDENING. See Metal treatments.

PRESSURE MEASUREMENT

Knowledge of the pressure existing in a pipeline, tank, process tower, boiler, molding press, airplane cabin, space cabin, and many other units is an absolute necessity in most phases of industry, and in research and development. Knowledge of the pressure data enables the engineer to operate within safe design limits, and the researcher to establish the optimum conditions for product yield and product quality.

Pressure Terms

Pressure is defined as force per unit of area. It can be expressed in a wide range of units; Table 1 gives interconversion factors among lb/in.^{2} (psi), kg/cm^2, mm Hg (Torr), in. Hg, ft of water, and cm of water.

Table 1. Conversion Table of Pressure Units Based on Water at 60°F (62.367 lb/ft^3) and Hg at 60°F (846.32 lb/ft^3)[a]

	Required pressure unit					
Known pressure unit	lb/in.^{2} (psi)	kg/cm^2	mm head Hg (Torr)	in. head Hg	ft head of water	cm head of water
cm head of water	0.014209	0.00099902	0.73691	0.029012	0.032808	
ft head of water	0.43310	0.030451	22.461	0.88430		30.480
in. head Hg	0.48977	0.034434	25.400		1.1308	34.468
mm head Hg (Torr)	0.019282	0.0013557		0.039370	0.044521	1.3570
kg/cm^2	14.223		737.63	29.041	32.840	1001.0
lb/in.^{2} (psi)		0.070309	51.862	2.0418	2.3089	70.376

[a] Multiply known pressure units by factors given to obtain the required pressure units.

Atmospheric pressure (barometric pressure) is the pressure exerted by the column of air on the earth's surface, at a specified place and time. It varies with elevation above and below sea level and with weather conditions. To eliminate the normal ex-

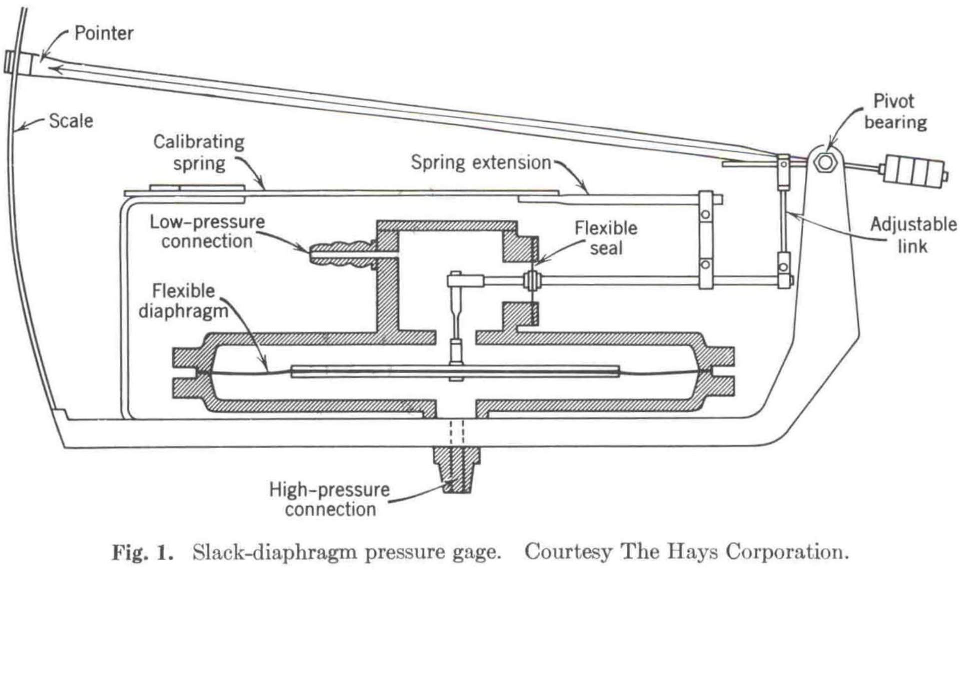

Fig. 1. Slack-diaphragm pressure gage. Courtesy The Hays Corporation.

isting variables, a *standard* or *normal atmosphere* having a pressure of 1,013,250 dyn/cm^2 has been established. This is equal to the pressure exerted by a column of mercury 760 mm high, at a temperature of 0°C, or 29.921 in. Hg, or 14.696 psi.

Absolute pressure is the pressure measured from zero pressure. But pressure gages frequently read in *gage pressure*, or *vacuum pressure* (see Vacuum technique). Gage pressure is equal to the absolute pressure minus the atmospheric pressure; this is convenient when a vessel is under a moderate pressure in excess of the ambient atmospheric pressure. It is often reported in $lb/in.^2$ *gage*, psig. The expression psia is often used when it is desired to emphasize that the measurement is absolute. A gage reading vacuum pressure reports the amount by which the pressure on it is less than atmospheric. A compound gage can register either gage or vacuum pressure.

Torr. This International Standard unit is now used for reporting less-than-atmospheric pressures on an absolute basis. It is equal to $\frac{1}{760}$ of a standard atmosphere, or 1 mm Hg.

Expressions such as "low," "medium," or "high," applied to pressure or vacuum, have come to designate ranges approximately as follows:

Pressure	*Gage pressure, psig*	*Vacuum*	*Vacuum pressure, Torr*
very high	over 5,000 (can be up to 100,000 or even higher)	low	25–760
		medium	10^{-3}–25
		high	10^{-6}–10^{-3}
high	500–5,000	very high	10^{-9}–10^{-6}
medium	50–500	ultra high	0–10^{-9}
low	0–50		

Elements for Pressure Measurement

Pressures and/or vacuums are generally measured by means of mechanical direct actuated elements. When measurement of very high pressures or vacuums between absolute zero and 25 Torr (25 mm Hg) are required, specialized elements are necessary. Most of the elements in use are described and many of them are illustrated in the subsequent sections.

The mechanical direct actuated pressure elements are the diaphragm, inverted bell, diaphragm capsule, bourdon tube including spirals and helixes, spring and bellows, and absolute pressure gage. The specialized units are the strain gage, electromagnetic, piezoelectric, thermoelectric, and ionization sensors.

Diaphragm Pressure Elements. A diaphragm is a pressure element which moves in a direction perpendicular to its flexible surface. Diaphragms may be fabricated from natural materials or from various synthetic materials including metals. They may be substantially flat or have one or many convolutions in their surfaces. The thinner the diaphragm material and the larger its effective area (pressure area) the lower the pressure range it can measure. In the design of this type of element, and in fact of all pressure elements, it is essential that the movement of the element always be less than the movement which would exceed the elastic limit of the diaphragm material. Exceeding the elastic limit would result in a permanent set or stretch of the diaphragm with resulting shift and error in the pressure measurement.

Figure 1 illustrates a typical arrangement for a direct-deflection type of diaphragm-actuated pressure gage. The process pressure produces a force which moves the diaphragm and its linkage into the cantilever spring to which is attached the pointer or pen arm to indicate or record the pressure. The pressure range can be changed by increasing or decreasing the gradient of the cantilever spring. This type of element is supplied for pressure ranges from 0–0.2 to 0–120 in. of water. To protect against overload pressures, the clearance between the diaphragm and its housing is small enough to prevent any excessive movement of the diaphragm.

Inverted-Bell-Type Pressure Element. Figure 2 shows a cross-sectional view of an inverted-bell-type pressure indicator. This unit is made up of two inverted bells, partly immersed in oil which acts as a liquid seal, supported at their upper ends on a balanced pivoted beam. The process pressure is introduced under the bell on the

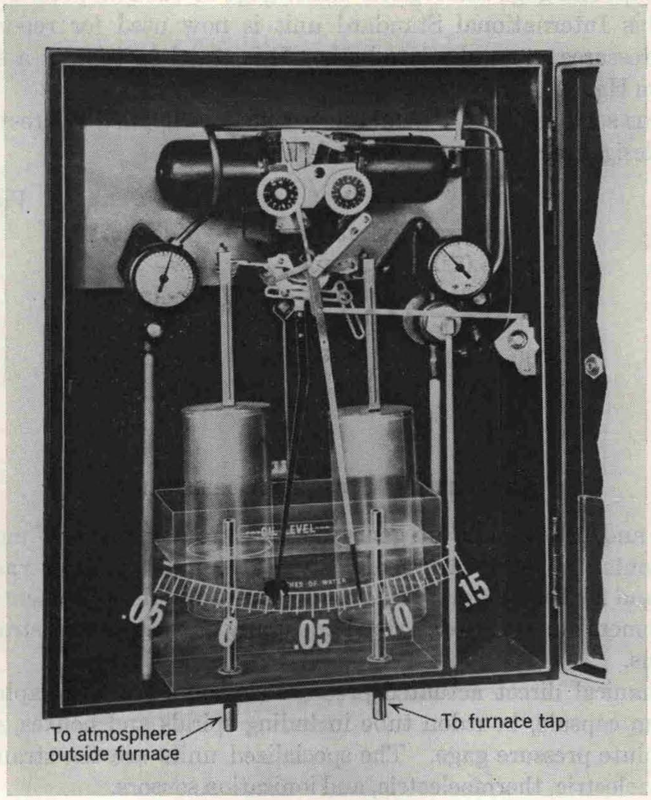

Fig. 2. Balanced-beam bell-type pressure gage.

right-hand side and atmospheric pressure is under the bell on the left-hand side. An increase in process pressure forces the right-hand bell to rise and, through a suitable linkage, connects to a pointer or pen arm to indicate or record the pressure. The two-bell arrangement permits lower pressure ranges and compensation for ambient pressure changes. The available ranges are from about 0–0.2 to 0–10 in. of water. A single-bell version can be supplied for ranges from about 0–0.6 to 0–10 in. of water. Both types of gage can be used on gage pressure, gage vacuum, or compound ranges. When subjected to overload pressures, these gages will lose their oil if a fast, large overload is applied, or if the overload is applied slowly, the bell will lift out of the oil seal and vent the process pressure.

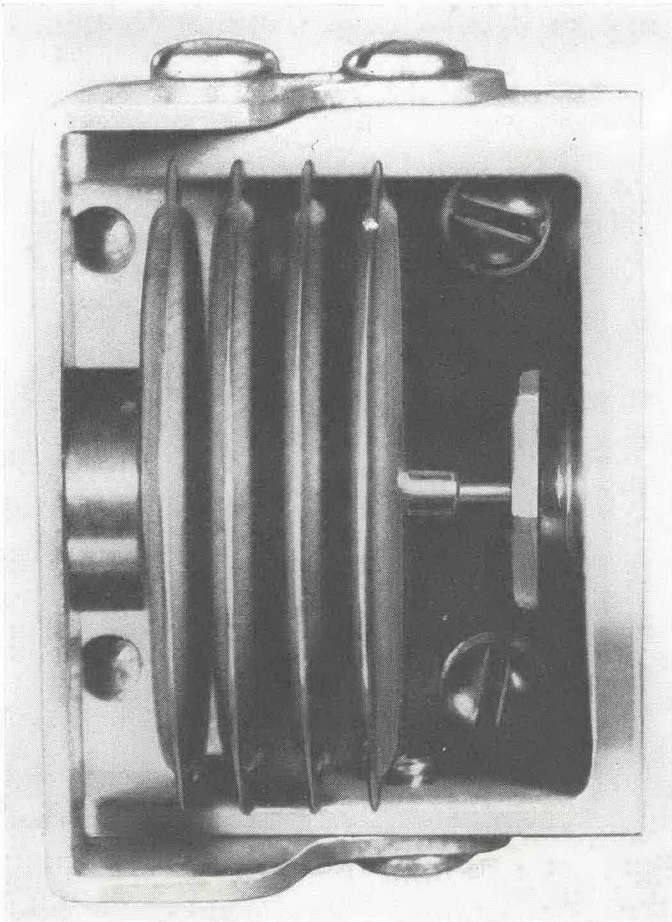

Fig. 3. Diaphragm capsule pressure element.

Diaphragm Capsule Pressure Element. This pressure element is made up of two or more circular formed metal diaphragms which are welded together at both their inner and outer edges around their complete periphery. Figure 3 shows a typical assembly. The fabricated unit becomes a flexible sac or container, sealed off at one end and open to a connecting tube at the other end for the process pressure connection. The diameter and number of diaphragms used to make up the complete unit depend on the material of the diaphragm and the pressure range desired. The process pressure is applied to the inside of the capsule through the connecting tube; it expands the capsule with a resulting movement at the closed end. The actuating linkage for the pointer or pen arm is attached to this closed end. Diaphragm capsules are used for pressure ranges from 0–10 in. of water to 0–100 psi. The materials may be phosphor bronze, stainless steel, or alloys of any type.

Bourdon Tube Pressure Elements. A bourdon tube is made from a flattened or elliptical tube, with one end sealed shut and the other end opened to the process pressure through a connecting tubing. The final shape of the tube along with the amount of flatness determines the trade name of the element and identifies the overall shape and form. There are spiral-, helix-, and "C"-type bourdon tubes.

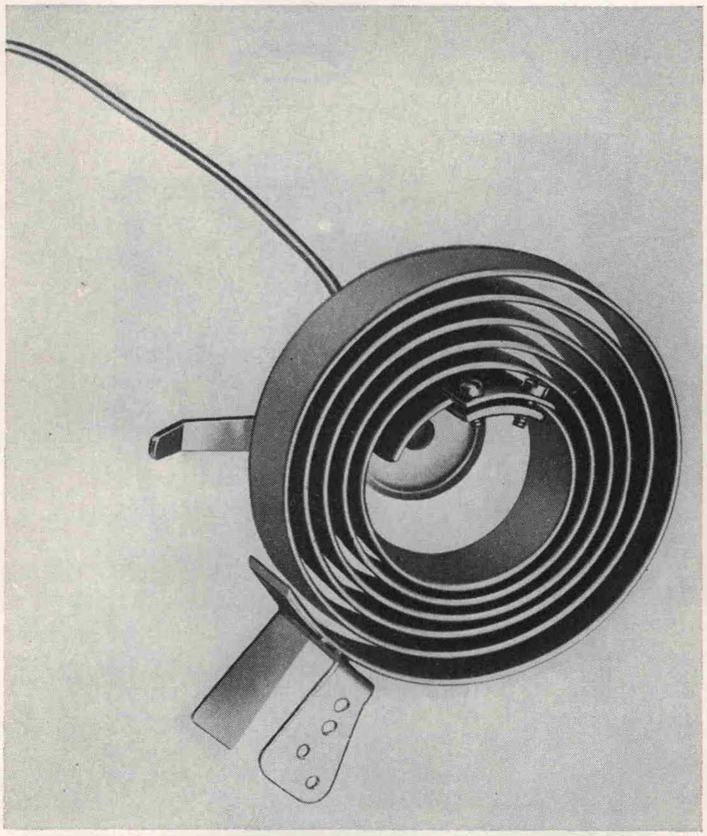

Fig. 4. Spiral pressure element.

Figure 4 shows a spiral and Figure 5 shows a helix. These elements are made from a thin-wall tube which is flattened to produce a long, narrow elliptical cross section. It is then formed into a spiral or helix as illustrated. When the process pressure is applied through the connecting tube, the resulting force tends to uncoil or straighten out the tubing. The rotating motion of the spiral or helix through a suitable linkage arrangement can be used to actuate a pointer or pen arm. The spiral is normally used for pressure ranges from 0–20 to 0–4000 psi, and the helix from 0–100 to 0–100,000 psi. The material used may be bronze, steel, stainless steel, or special alloys.

Figure 6 shows a "C"-type bourdon tube. This also is made from a thin-wall tube which may be flattened a small amount or a large amount, depending on the material and the pressure range. The tubing is formed into a "C" shape, with one end closed and free to move, and the other end fixed and opened to a connecting tube for the process pressure. The force from the applied pressure tends to straighten out the tube, thus producing tip travel. A suitable linkage will transfer this tip travel to a pointer or pen arm. These elements are used for pressures from 0–15 to 0–10,000 psi. The material used is bronze, steel, stainless steel, or special alloys.

Spring-and-Bellows Pressure Elements. Figure 7 shows a cross section of a spring-and-bellows pressure element. The bellows is formed from a length of thin-wall tubing by hydraulic extrusion in a die. This bellows is enclosed in a metal shell which

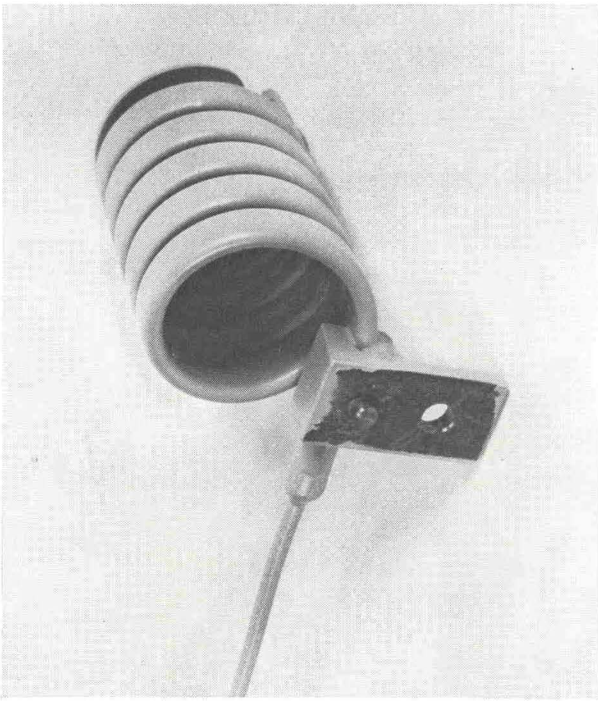

Fig. 5. Helix pressure element.

is connected by tubing to the process pressure. A compression-type spring is mounted inside the bellows resting against its bottom and restrained at the top by a form-fitted nut. A rod resting on the bottom of the bellows transmits any vertical motion of the bellows through a suitable linkage arrangement into a pointer or pen readout. As the process pressure inside the metal shell is increased, the bellows moves vertically upward and compresses the spring. The bellows-spring gradient is small compared to the spring gradient so that the pressure range is a function of the spring gradient only. A spring-and-bellows pressure element can be used on pressure ranges from about 0–5 in. of water to 0–50 psig. The lower pressures require bellows of a larger diameter than the higher pressures. The bellows is usually made of phosphor bronze or stainless steel but can also be supplied in many special metals.

Absolute Pressure Gage Element. When industrial process "low-vacuum" measurements are required, between 0–100 mm Hg and 0–30 in. Hg abs, it is frequently necessary to compensate for the normal variations in atmospheric or barometric pressure. Figure 8 shows a spring-and-bellows element which automatically compensates for the barometric pressure changes. The element includes a double bellows arrangement with both bellows fixed at the top and bottom and the adjacent end of each bellows attached to a movable plate, which transmits the bellows movement through a suitable linkage to a pointer or pen. The upper bellows is evacuated to a near perfect vacuum (absolute zero) and is then sealed off. The process vacuum is applied to the lower bellows, which then tends to collapse (close) the lower bellows, moving the center plate down. If the barometric or atmospheric pressure changes, the upper bellows will expand or contract, depending on any decrease or increase in the barometer. The bellows may be made of phosphor bronze or stainless steel.

Differential Pressure Gage Element (Meter Body). The formed bellows, diaphragm capsule, and single diaphragm are all used in the differential-pressure type of meter bodies. These units can be used to measure differences in pressure between two pipes, two stills, etc, from 0–1 in. of water up to 0–700 psi and with operating pressures as great as 10,000 psig. Figure 9 illustrates a formed-bellows-actuated meter body. The high-pressure and low-pressure bellows are joined together by means of the center stem assembly. The entire volume inside the bellows is filled with liquid and sealed off. When the process pressure at the high-pressure tap is greater than the process pressure at the low-pressure tap, the high-pressure bellows moves to the right and, through the center stem and liquid fill, moves the low-pressure bellows to the

Fig. 6. "C"-type bourdon tube pressure element.

right. Motion stops when the force on the range spring equals the force of the differential pressure (difference between the high-pressure and low-pressure process pressure). The cable and motion take-off arm translate the center stem movement to the torque tube and this connects to a linkage mechanism for positioning the pointer or pen arm.

Installation and Maintenance of Pressure Gages. The industrial pressure gages must be protected from excessive overload pressures, high process temperatures, and corrosive or solid entrained fluids which would deteriorate or clog up the pressure element. The instruction data supplied with the gage will outline exactly what precautions must be taken on the specific unit used.

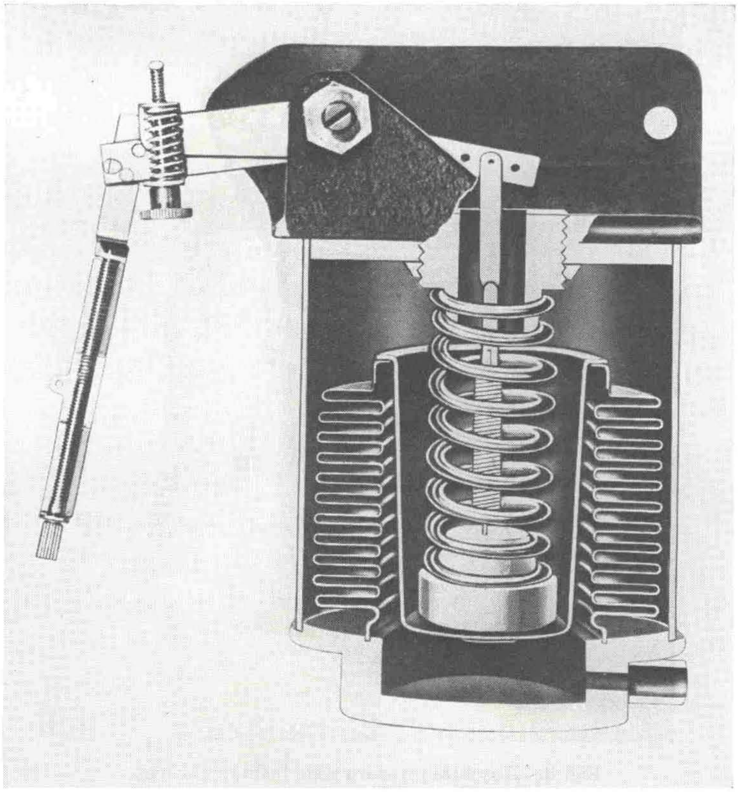

Fig. 7. Spring-and-bellows pressure element.

In checking the accuracy of a pressure gage, a primary standard or a certified secondary standard pressure unit must be employed. A primary standard would be a dead-weight tester for pressures of 20 psig and higher, and a "U"-tube manometer would be required for pressures of 1 in. of water to 20 psig. A secondary standard would be a high-precision bourdon tube pressure gage with certified accuracy of calibration and pressure ranges of 20 psig and higher, and a certified accuracy precision well-type manometer for pressures of 1 in. of water to 20 psig.

Specialized Types of Pressure Elements. All of the previously described pressure elements can be combined with various pneumatic and electrical devices to provide pressure transducers. The pneumatic transducers operate from a 20-psi pressure, clean air supply into a fixed nozzle, and a movable flapper system. The process pressure element, through a mechanism, sets the flapper in relation to the nozzle such that at minimum process pressure the space between the nozzle and flapper is maximum and the output pressure is minimum (3 psig). With maximum process pressure the space is minimum and the output is maximum (15 psig). A normal full-scale travel of the flapper is about 0.003 in.

In the electric transducers, some of the sensors used are strain gage, thermoelectric, and ionization. There are numerous other types which are somewhat specialized and will only be mentioned here. They are ultrasonic, electromagnetic, piezoelectric, capacitance, variable reluctance, variable permeability, vibrating wire, and photoelectric.

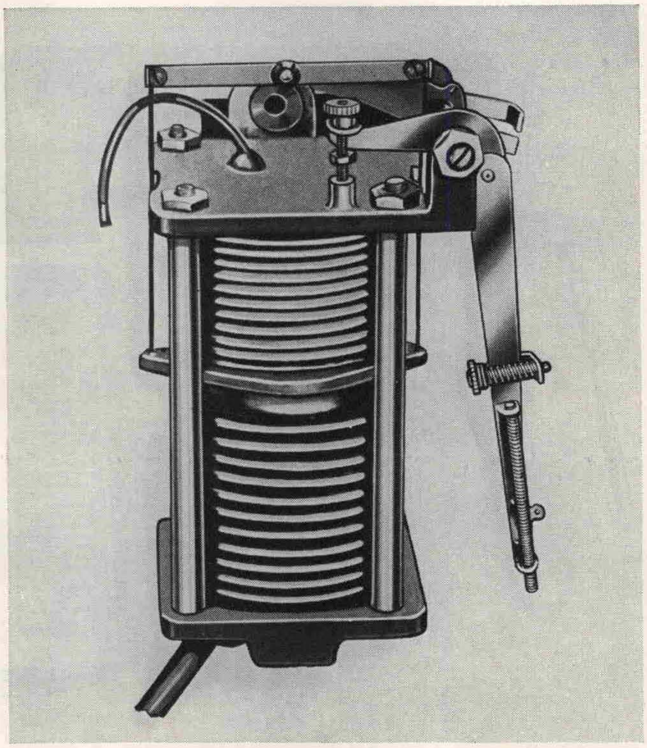

Fig. 8. Absolute pressure gage bellows element.

The *strain gage* consists of a small wire grid bonded to a plastic impregnated paper or cloth which is then cemented to the surface of the process pressure sensing device (usually a diaphragm). When the process pressure is applied, the resulting force moves the diaphragm, which produces a change in the length and diameter of the wire, changing its electrical resistance. This change in resistance is a measure of the force or pressure applied. A precision dc or ac resistance-bridge type of instrument must be used to measure this resistance change in equivalent pressure units. These sensors are used on pressures of 1 psi and greater.

The thermoelectric and ionization sensors are used primarily for the measurement of ultra high, very high, and high vacuums. The *thermoelectric* sensor operates on the principle that the heat loss from a hot wire varies as the pressure of the gas or vapor surrounding the hot wire varies. This variation in heat loss with pressure is relatively large in the high vacuum ranges for which it is used.

Figure 10 illustrates a resistance-bridge type of thermoelectric sensor where the heat lost by the coil of resistance wire in the measuring cell is indicated directly by resistance change in a leg of the bridge circuit. The compensating cell contains a second coil of resistance wire and this is sealed off at a pressure well below 1 Torr abs. This coil is designed so that changes in its resistance with temperature change will balance those changes in the measuring cell resistance and thus automatically compensates for temperature variations.

Figure 11 shows the diagram of a thermocouple type of thermoelectric sensor. The filaments are continuously and uniformly heated by means of the constant voltage

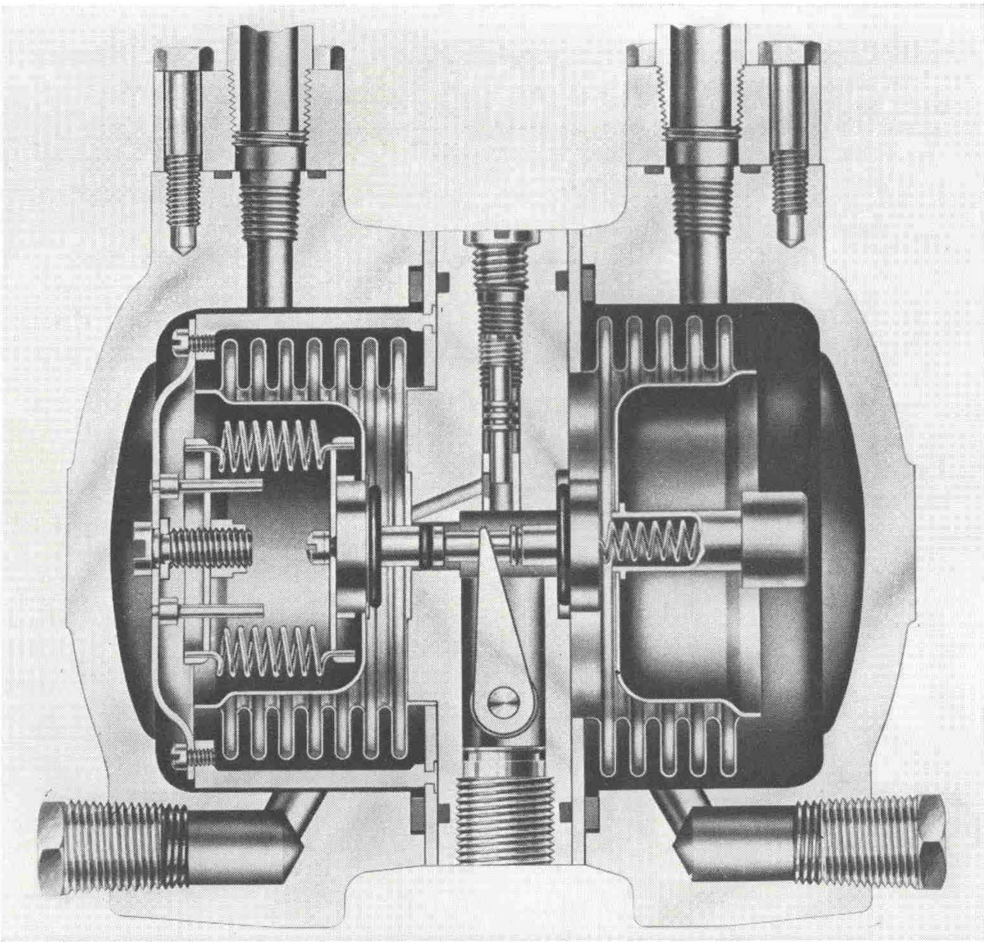

Fig. 9. Differential pressure gage element—bellows type.

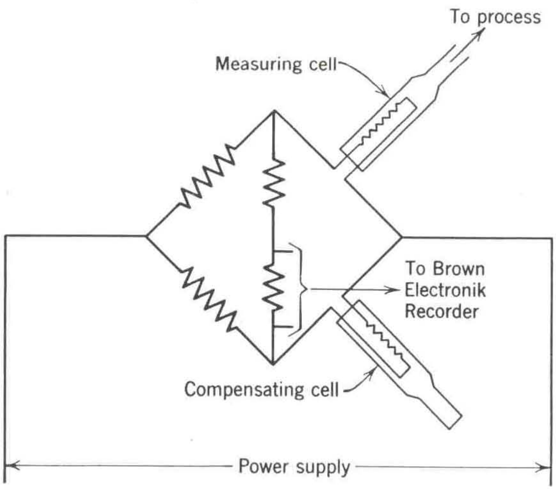

Fig. 10. Circuit of resistance-type thermal gage.

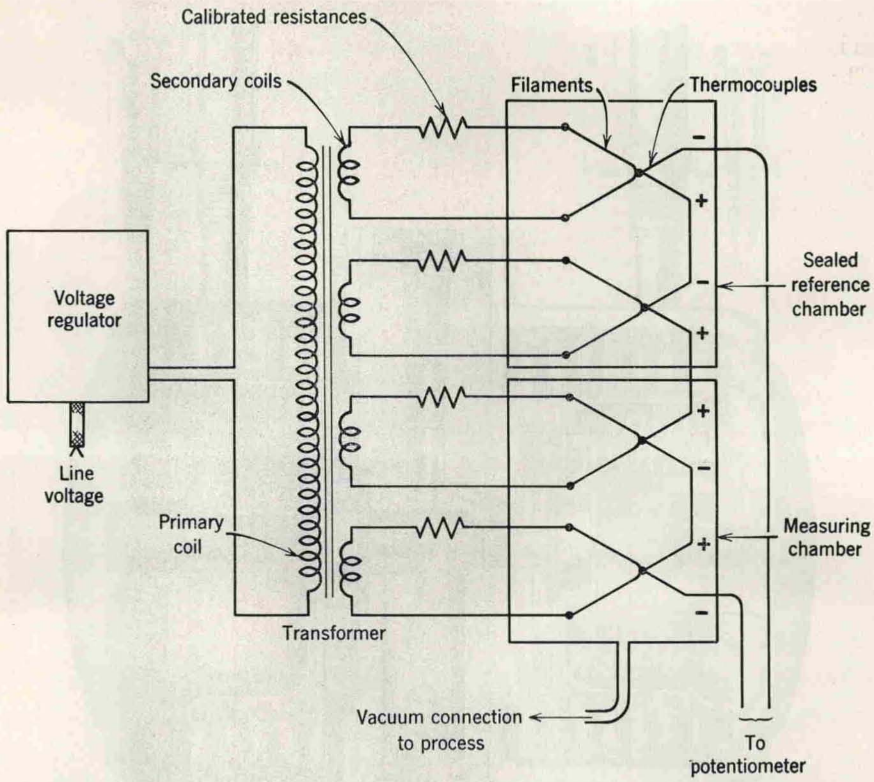

Fig. 11. Circuit of thermocouple-type thermal gage.

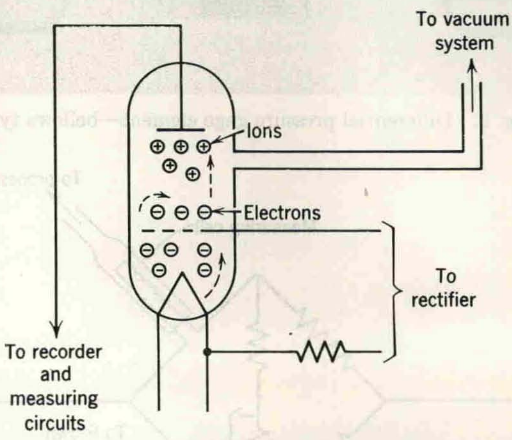

Fig. 12. Ionization gage.

regulator and transformer. There are two sections, a sealed one under high vacuum and a second one connected to the process pressure. A small sensitive thermocouple is located on each of the filaments and each pair of couples are connected in series to increase the generated emf. The two thermocouples in the reference chamber are connected in opposition to the two in the measuring chamber. Thus, their generated emf's oppose each other. This difference in emf is a measure of the difference in pressure between the reference chamber and the measuring chamber. This type of sensor is used in the high and medium vacuum ranges.

The *ionization* sensor is illustrated in Figure 12. The operation is based on the ability of electrons emitted from a hot filament to bombard the molecules of the residual gas in an evacuated system, forming an electric current flow from the resulting ions. The magnitude of the current flow is directly proportional to the number of ions formed. This is an indication of the amount of gas present, which is a measure of the vacuum pressure. The sensor is essentially a triode tube and the electron emission from the cathode is held constant by a precision bridge circuit. The electrons are attracted to the grid, which is at a high positive potential with respect to the cathode, and the momentum of the electrons carries them past the grid to the plate. The plate is held at a negative potential with respect to the grid and repels the electrons, driving them among the molecules of the gas. This bombardment of the gas causes ions to form and, with an existing potential difference, the ions are attracted to the plate, and the current flow is proportional to the number of ions formed. The current flow is proportional to the amount of gas present, actually the number of molecules present, and the magnitude of the current flow is a measure of the vacuum. Ionization sensors are used in ultra high and very high vacuums and must be protected against too high pressures, which would burn out their filaments.

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NOTE: In addition, all of the major instrument manufacturers have available descriptive and instructive data on their pressure gages and transducers.

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PRESSURE VESSELS

In chemical processing industries two factors among others are outstanding, namely, the yield of the product and the speed at which the desired yield is attained. Among the conditions which will influence these factors, the most important are temperature and pressure. While the temperature range in which the desired yield may be obtained at reasonable speed is comparatively moderate, approx −100 to 4500°C, the pressure range is enormously wider in industrial applications. For example, in the synthesis of acetylene from light hydrocarbon vapors, a pressure of less than 1 atm is preferred, while in the manufacture of synthetic diamonds a pressure of about 100,000 atm is required. Between these two extremes, the chemical processing industries have been using various pressures such as those given in Table 1.

Table 1. Pressures Used in Industrial Applications

Application	Pressure,[a] atm	Application	Pressure,[a] atm
nitric acid	1–10	methanol synthesis	50–350
synthetic ethanol	65–70	hydrogenation of coal	350–600
hydrogenation of vegetable oil	20–350	acetic acid synthesis	650–700
hydrogenation of petroleum distillates	200–350	ammonia synthesis	200–1,000
urea synthesis	200–400	polyethylene	50–2,000
oxo process	250–300	synthetic diamond	100,000–110,000

[a] Note that 1 atm = 14.7 psia.

There is no agreed-on dividing line between high and low pressures, but some authorities in the chemical processing industry consider any pressure above 50 atm (about 750 psia) is in the high-pressure field.

High-pressure technology concerns mainly (a) the production and maintenance of the pressure (see Pumps and compressors), (b) the design of vessels and other components of the system, and (c) provision for resistance to corrosion in a manner that is more precise than the practice used in dealing with ordinary pressures.

See also Pressure measurement.

Design and Fabrication of Pressure Vessels

With the advent of large capacity chemical plants, operating at high pressure levels, the size of individual vessels and accessories also increased in size to previously unknown regions, and the question of safety became extremely important. Even with normal-size vessels, safety should always be a mandatory consideration in designing, fabricating, testing, and operating a high-pressure vessel.

In designing a high-pressure vessel, the procedure may run as follows: The first step is to decide the size and shape of the vessel as required by functions which the vessel is to perform. Then comes the choice of materials of construction which will resist the attack by substances with which the vessel will come in contact. Next, provisions for heat transfer and temperature control should be worked out based on thermodynamics. The safe thicknesses of the vessel wall and other parts and attachments should then be calculated based on stresses in the vessel wall and the strength of the materials selected. The method of fabrication may be chosen according to the costs involved, but equally important considerations are those concerning transpor-