ASME PTC 19.2-2010

[Revision of ASME/ANSI PTC 19.2-1987 (R2004)]

Pressure Measurement

Instruments and Apparatus Supplement

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

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Three Park Avenue • New York, NY • 10016 USA

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This Code will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to PTC 19.2–2010.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Code. Periodically certain actions of the ASME PTC Committee may be published as Code Cases. Code Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

The American Society of Mechanical Engineers
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NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Supplement. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Supplement.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

This Instruments and Apparatus Supplement to The American Society of Mechanical Engineers (ASME) Performance Test Codes (PTC) 19 Series provides information on instrumentation and associated procedures for tests involving measurement of pressure. It is intended to promote results consistent with the best engineering knowledge and practice in industry.

The object and scope of any test should be agreed upon in writing by all parties to the test prior to the test.

ASME PTC 2, *Definitions and Values Code* and ASME PTC 19.1, *Test Uncertainty* may be especially useful references when using this Supplement.

The previous Supplement replaced an older version published in 1964. The previous edition was approved by the Board on Performance Test Codes on September 23, 1986, and adopted by the American National Standard Institute (ANSI) as an American National Standard on August 25, 1987.

Subsequent to the 1987 revision, the PTC 19.2 Committee was reactivated to work on the current revision. This revision uses updated pressure-measurement technologies. Obsolete or rarely used pressure-measuring devices were deleted, resulting in a substantially reduced number of pressure-measurement devices. Some of the less frequently used field devices, such as manometers and piston gauges, were moved to the two appendices.

This edition of PTC 19.2, *Pressure Measurement* was approved by the PTC Standards Committee on December 18, 2009, and approved and adopted as a Standard practice of the Society by action of the Board on Standardization and Testing on January 19, 2010. It was also approved as an American National Standard, by the ANSI Board of Standards Review, on April 22, 2010.

ACKNOWLEDGMENTS

The Committee gratefully acknowledges the contribution and leadership role of Charles Doran.

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Performance Test Codes

(The following is the roster of the Committee at the time of approval of this Code.)

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Proposing Revisions. Revisions are made periodically to the Supplement to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Supplement. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Supplement. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME PTC Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code and the paragraph, figure, or table number(s), and be written as a Question and a Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable Code edition(s) to which the proposed Case applies.

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The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his request in the following format:

Subject: Cite the applicable paragraph number(s) and the topic of the inquiry.

Edition: Cite the applicable edition of the Supplement for which the interpretation is being requested.

Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC 19.2 Standards Committee holds meetings, which are open to the public. Persons wishing to attend any meeting or telephone conference should contact the Secretary of the PTC 19.2 Standards Committee.

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Section 1
Object and Scope

1-1 OBJECT

The object of this Supplement is to give instructions and guidance for the accurate determination of pressure values in support of the ASME Performance Test Codes. The choice of method, instruments, required calculations, and corrections to be applied depends on the purpose of the measurement, the allowable uncertainty, and the characteristics of the equipment being tested.

1-2 SCOPE

The methods for pressure measurement and the protocols used for data transmission are provided in this Supplement. Guidance is given for setting up the instrumentation and determining the uncertainty of the measurement. Information regarding the instrument type, design, applicable pressure range, accuracy, output, and relative cost is provided.

Information on pressure-measuring devices that are not normally used in field environments is given in the Nonmandatory Appendices A (Piston Gauges), B (Manometers), and C [Low-Absolute-Pressure (Vacuum) Instruments].

1-3 UNCERTAINTY

The methods provided in this Supplement are designed to assist in the evaluation of measurement uncertainty based on current technology and engineering knowledge, taking into account published instrumentation specifications and measurement and application techniques. This Supplement provides guidance in the use of methods to establish the pressure-measurement uncertainty.

Section 2
Definitions and Terms

2-1 INTRODUCTION

The thermodynamic state of a simple fluid is specified by two independent properties. In experiments involving fluids, pressure is customarily selected as one of the properties to be measured. Pressure measurements are also important in systems involving flowing fluids as an indirect means of measuring velocity and flow rate.

Relevant static pressures span a large range of values. Because of associated dynamic-pressure measurement problems, pressure-measurement systems vary greatly in complexity and include a large number of different devices.

Section 2 covers the definitions of pressure, fundamental thermodynamic and fluid-mechanic concepts of pressure, pressure units and conversion among different units, pressure considerations in and pressure relations for flowing fluids, and the use of existing installed instrumentation in equipment tests.

2-2 DEFINITIONS

accuracy: the closeness of agreement between a measured value and the true value. Since accuracy varies with measurement device type and the manufacturer, the manufacturer should be consulted for their precise definition.

energy relationships: the steady-state microscopic one-dimensional conservation of energy equation (along a streamline in an inviscid, irrotational steady flow) is

$$\frac{1}{2}(V_2^2 - V_1^2) + \int_{P_1}^{P_2} \frac{dP}{\rho} + g(Z_2 - Z_1) = 0 \qquad (2\text{-}2\text{-}1)$$

where

dP = differential pressure
g = constant gravitational acceleration
V = velocity
Z = elevation
ρ = density

The subscript number denotes a position and corresponding fluid state.

Equation (2-2-1) applies to the steady flow of a frictionless fluid with no mechanical work performed on or by the surroundings, uniform velocities, and a constant gravitational acceleration.

For the special case of an incompressible fluid, eq. (2-2-1) reduces to the Bernoulli equation

$$\frac{1}{2}(V_2^2 - V_1^2) + \frac{1}{\rho}(P_2 - P_1) + g(Z_2 - Z_1) = 0 \qquad (2\text{-}2\text{-}2)$$

In manometry, the fluid is static and the kinetic energy term vanishes. Then the sum of the second term, pressure head, and the third term, elevation head, is zero.

In a flowing fluid, an increase in the first term in eq. (2-2-2), velocity head, involves a corresponding decrease in either elevation head, the static-pressure head, or both. Thus, after a flow-area contraction, the velocity head is necessarily increased to accommodate the constant mass flow, and consequently the static pressure is reduced. After a flow expansion at subsonic flow velocities, the static pressure is increased. In each case, the total pressure is the same before and after the area change, except for frictional losses, which would increase temperature and internal energy at the expense of mechanical energy.

pressure: normal force per unit area exerted by a fluid on a containing wall with respect to a reference.

pressure, absolute: normal force per unit area exerted by a fluid on a containing wall with respect to zero absolute pressure. Absolute pressure can be positive only (see Fig. 2-2-1).

pressure, ambient: normal force per unit area exerted by the atmosphere at a location (usually local barometric pressure; see Fig. 2-2-1).

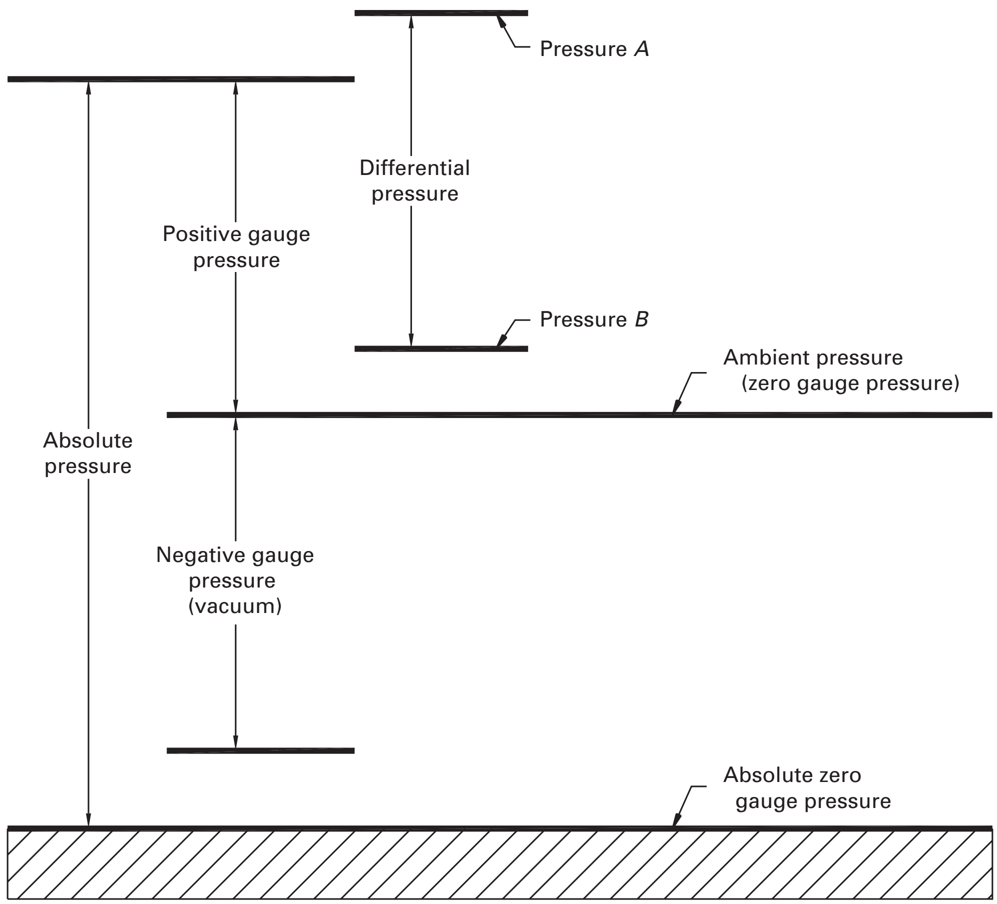
pressure, differential: difference between any two pressures (see Fig. 2-2-1).

pressure, gauge: normal force per unit area exerted by a fluid on a containing wall with respect to local ambient pressure. Gauge pressure can be either positive or negative. Common practice is to refer to negative gauge pressure as vacuum (see Fig. 2-2-1).

pressure, static: pressure at a point where a fluid element is in equilibrium. Static pressure would be indicated by an instrument at rest with respect to the fluid.

pressure, total: pressure on a plane normal to local flow direction. It is the maximum value of pressure as function of direction at a point. It is equal to the summation of static pressure and velocity pressure. Total pressure is indicated when a moving fluid is brought to rest at the instrument.

Fig. 2-2-1 Pressure Terminology



pressure, velocity (for a flowing fluid): expressed as ρV^2 where ρ is the fluid density and V is the fluid velocity; also called dynamic pressure. Velocity pressure (or head) is the net pressure increase that can be derived from complete conversion of the velocity (or dynamic energy) to pressure in a reversible process.

2-3 UNITS

The International System of Units (SI) and the corresponding U.S. Customary units are used in this Supplement.

Pressure is expressed in units of Pascal, Pa, which is equivalent to newtons/square meter. Conversion factors for commonly used pressure units are given in Table 2-3-1 [1].

The International Standard Atmosphere is 760 mmHg (29.921 in. Hg) at 0°C (32°F). In SI units, this is 101.325 kPa (14.69595 lbf/in.^{2}) at the standard gravitational acceleration of 9.806650 m/s^2 (32.17406 ft/sec^2).

2-4 DYNAMIC MEASUREMENTS

2-4.1 Fluctuating Pressure

In many situations in conducting tests, flows are unsteady; that is, velocity and pressure vary with time, either cyclically or as random fluctuations. It is usually necessary to determine the true average pressure to evaluate the time average energy of the stream. The best way to do this is to reduce the causes of pressure fluctuation to negligible proportions.

Where this cannot be done, two methods of obtaining an average are possible. First, the pressure instrument may be damped sufficiently to give a value that is fluctuating only slightly and is therefore easily readable. This gives a true average only if the instrument response is linearly proportional to the pressure signal and if the damping forces are linearly proportional to pressure and the damping is equally applied to both rising and falling pressures. This linearity

Table 2-3-1 Pressure Conversion Factors

Units	Conversion Factor to Pascal (Pa)
Atmosphere (normal = 76 cm Hg)	1.013 25 E + 05
Atmosphere (technical = 1 kg_f/cm^2)	9.806 650 E + 04 [Note (1)]
Bar	1.000 000 E + 05 [Note (1)]
cm Hg (0°C)	1.333 22 E + 03
cm H_2O (4°C)	9.806 38 E + 01
Decibar	1.000000 E + 04 [Note (1)]
Dyne/cm^2	1.000000 E − 01
ft H_2O (39.2°F)	2.98898 E + 03
Gram-force/cm^2	9.806650 E + 01 [Note (1)]
in. Hg (32°F)	3.386389 E + 03
in. Hg (60°F)	3.37685 E + 03
in. H_2O (39.2°F)	2.49082 E + 02
in. H_2O (60°F)	2.4884 E + 02
in. H_2O (68°F)	2.4864 E + 02
Kilogram-force/cm^2	9.806650 E + 04 [Note (1)]
Kilogram-force/m^2	9.806650 E + 00 [Note (1)]
Kilogram-force/mm^2	9.806650 E + 06 [Note (1)]
Kip/$in.^2$ (ksi)	6.894757 E + 06
Millibar	1.000000 E + 02 [Note (1)]
mmHg (0°C)	1.333224 E + 02
Poundal/ft^2	1.488164 E + 00
Pounds-force/ft^2	4.788026 E + 01
Pounds-force/$in.^2$ (psi)	6.894757 E + 03
Torr [mmHg (0°C)]	1.333224 E + 02

GENERAL NOTE: For other conversions, refer to ASME PTC 2, *Definitions and Values*, and ASME B40.100, *Pressure Gauges and Gauge Attachments*.

NOTE:
(1) Relationships are exact in terms of the base units.

may be closely approximated by a porous-plug type of damper in the instrument leg or pipe.

Second, a graphing instrument or digital storage and processing unit capable of responding to frequencies greater than the maximum frequency of pressure fluctuation may be selected. The graphic or digital record of pressure as a function of time can then be analyzed to yield a true average.

Alternatively, digital data-processing systems may be directly employed to yield a true average.

2-4.2 Fluctuating Flow

When pressure measurements are taken for the purpose of evaluating flow rate, such as with flowmeters, it should be realized that average pressure does not correspond to average flow rate (this is due to the power-law relation between velocity and velocity pressure). To obtain a true average flow rate, it may be necessary to obtain a graphic record of velocity pressure with a high-frequency-response instrument, derive from this a curve of the square root of velocity pressure, and use the average of this square-root curve to calculate velocity. It is possible to carry out this process automatically by electronic methods when an electronic pressure transducer is used. However, the error encountered may be shown to be negligibly small under some conditions and thus ignored.

2-5 USE OF CONTROL AND OPERATING INSTRUMENTATION

Equipment to be tested may be provided with pressure instrumentation, pressure connections, and gauges for either control or operating information. It may be necessary or desirable for the test engineer to utilize this instrumentation. The precision and accuracy of the installed instrumentation should be considered in designing a test, and the installed pressure-measurement systems should be calibrated separately. When doubts exist about the accuracy and precision of installed instrumentation or when the measurement-system analysis identifies deficiencies, alternate test instrumentation should be provided.

2-6 TWO-PHASE FLUID SYSTEMS

Many applications require pressure measurement in two-phase fluid systems [2]. In these applications, care shall be exercised to avoid problems due to pumping of multiphase fluid into instrument lines, static-liquid head-pressure contributions, and vapor-pressure interference. Although such problems are more difficult with differential-pressure measurement, they are mitigated by keeping the instrument lines full of single-phase fluid (e.g., the liquid phase) or by employing pressure transducers directly mounted to the measurement port. Techniques of liquid purging, or, in the case of single-component systems, cooling the instrument lines to cause condensation of entering vapor, should be used to maintain a liquid phase in the lines. Continuous or periodic purging should also be used to maintain air or other suitable gas in the lines for some two-phase measurements.

Section 3
Measurement Devices

3-1 TYPES OF DEVICES

This section deals with the devices commonly used in industry to measure pressure. It does not deal deeply with the design details but rather is intended to present a brief description on the principle of operation of pressure-measuring instruments. Since there are many different pressure-measurement devices to choose from, an informed decision should be made only after research and consultation about which device is most suitable for a given application.

Usually the first considerations involved in selection of a pressure-measurement device are the magnitude and type of the pressure to be measured and the accuracy of devices available to operate at the desired pressure. Other considerations include the chemical aggressiveness of the process media, phase, temperature, environmental conditions, vibration, and pulsation.

The types of devices are generally considered either mechanical or electronic.

3-1.1 Mechanical Devices

A mechanical device converts pressure to a mechanical analog of that pressure. For example, a Bourdon tube will deflect under pressure and the motion is transmitted to a pointer that indicates the measurement on a circular dial for local indication. The majority of mechanical devices employ elastic elements such as Bourdon tubes, bellows, or diaphragms that move in response to pressure change (see Fig. 3-1.1-1). Elastic gauges are discussed further in subsection 3-3.

Other mechanical devices employing nonelastic elements, such as piston gauges and manometers, are covered in Nonmandatory Appendices A and B. Low-pressure measurement devices are covered in Appendix C.

3-1.2 Electronic Devices

An electronic device converts an applied pressure to some form of measurable electrical quantity. The term "pressure sensor" refers to the basic device that converts mechanical energy to an electrical output proportional to the mechanical stimulus. For example, pressure sensors often employ elastic elements such as diaphragms that deflect with changes in pressure. These deflections cause a change in some electrical quantity such as resistance or capacitance.

Pressure transmitters or transducers translate the low-level electrical outputs from sensors to higher-level signals that are suitable for transmission and processing. Thus a complete device may include circuitry for temperature compensation and signal conditioning. The applications of these devices are further discussed in subsection 3-2.

The types of electronic devices are categorized by the principles used by the pressure sensor. The most common types are described in paras. 3-1.2.1 through 3-1.2.9.

3-1.2.1 Bonded Strain Gauge. Strain-gauge technology involves the four-resistor network of a Wheatstone bridge as shown in Fig. 3-1.2.1-1. A voltage source is connected (across A and C) so that current will flow through each leg. If the strain-gauge elements are strained such that R1 and R3 increase in resistance and R2 and R4 decrease in resistance, there will be a potential difference between B and D. Strain-gauge elements consist of fine wires or foils. By bonding them to a pressure-sensitive element such as a diaphragm, the strain gauge may be elastically deformed in a manner proportional to pressure. If the resistors are set up in such a manner that deformation will cause two of the resistors to be put in tension and two in compression, then the net effect is an output voltage change 4 times greater than if only one resistor were used.

A typical bonded strain-gauge configuration is shown in Fig 3-1.2.1-2.

3-1.2.2 Deposited-Thin-Film Strain Gauge. The most recent strain-gauge production process is based on thin-film technology. Thin-film gauges employ Wheatstone-bridge circuitry and have eliminated the need for bonding elements by depositing the bridge circuit directly on an elastic member by vacuum deposition or sputtering. A typical deposited-thin-film construction is shown in Fig. 3-1.2.2-1.

3-1.2.3 Piezoresistive Pressure Sensor. Silicon pressure sensors manufactured with semiconductor technology also operate on a resistive principle. The resistance change in a semiconductor changes with geometrical changes in the structure and is called the piezoresistive effect. The resistance changes are substantially greater than those in standard strain gauges. Thus, conductivity

Fig. 3-1.1-1 Typical Pressure Devices

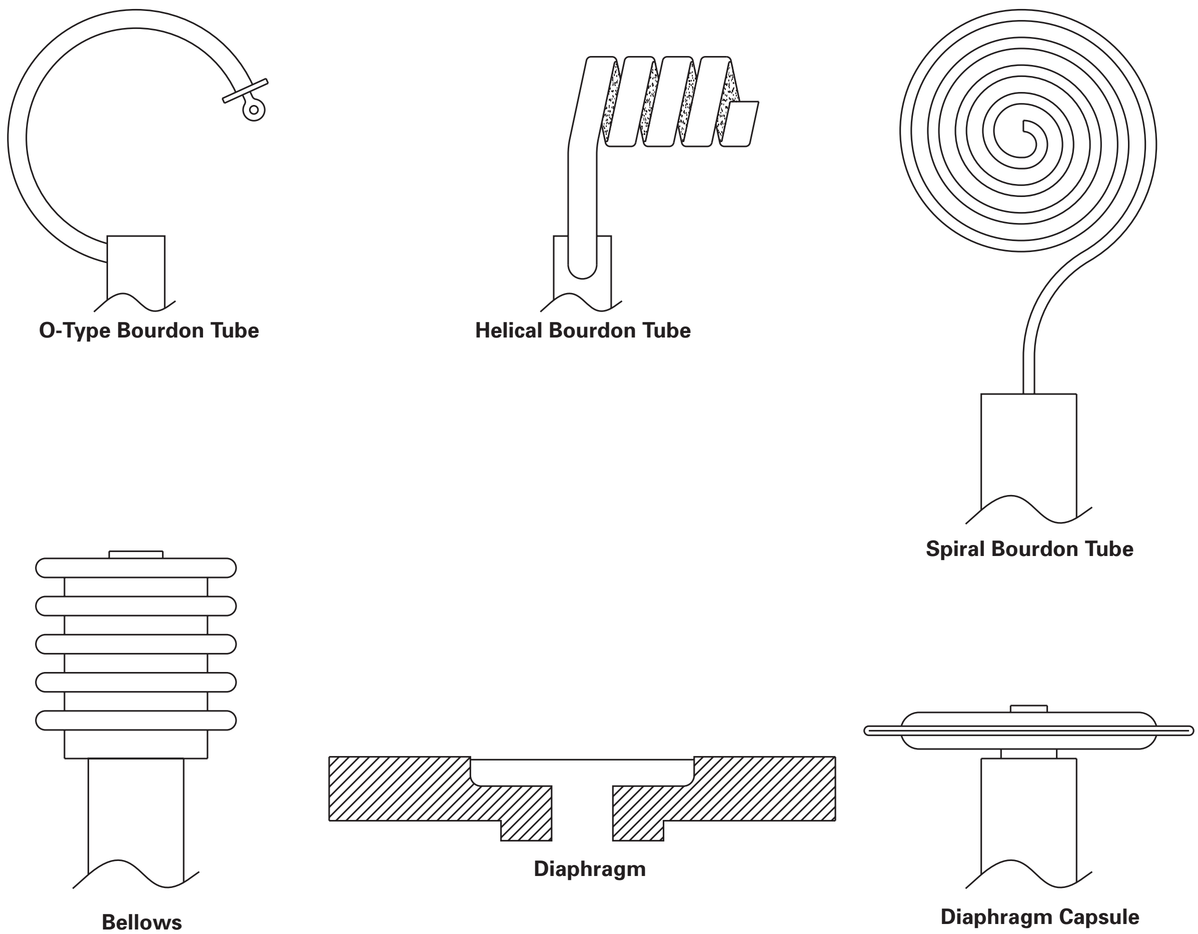


Fig. 3-1.2.1-1 Wheatstone Bridge

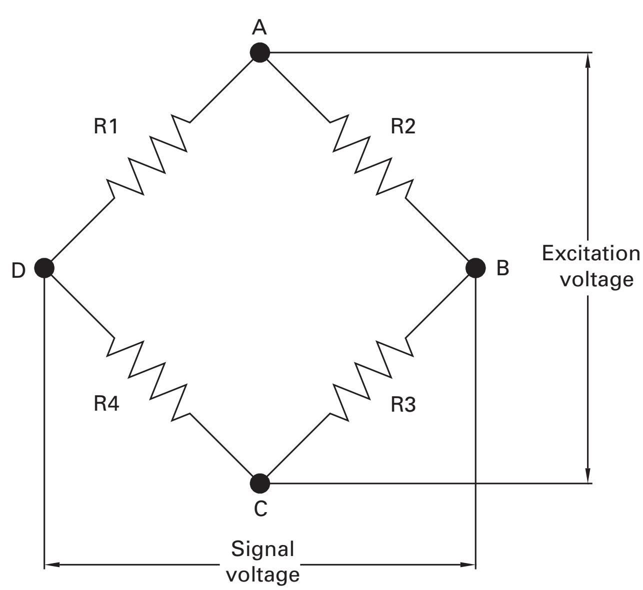


Fig. 3-1.2.1-2 Bonded Strain Gauge

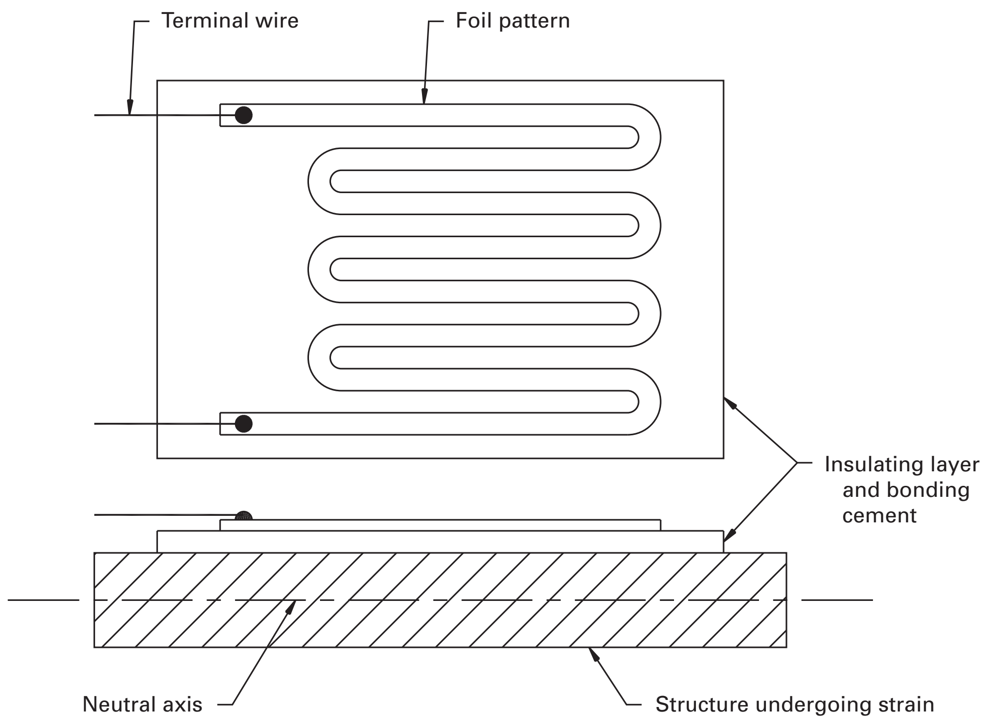


Fig. 3-1.2.2-1 Typical Deposited-Thin-Film Strain Gauge

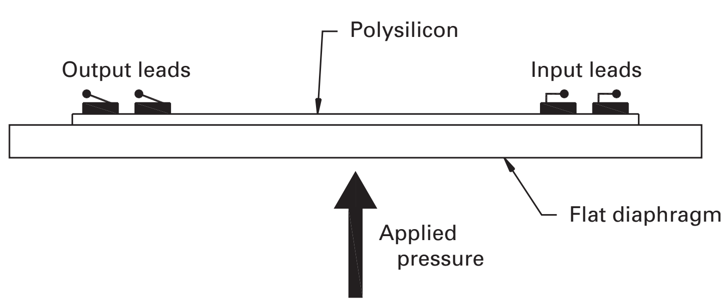
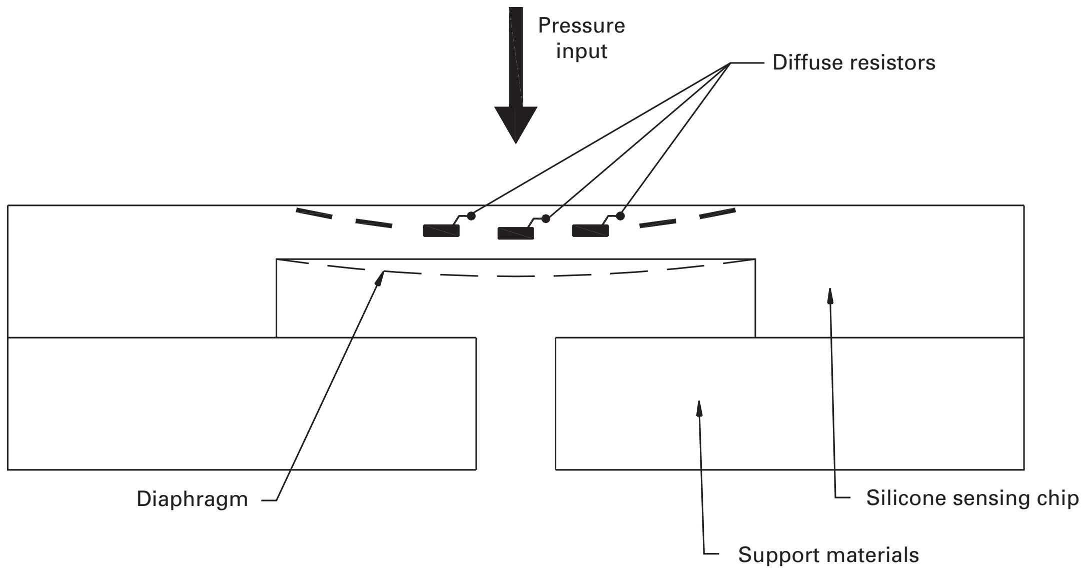


Fig. 3-1.2.3-1 Typical Piezoresistive Pressure Sensor



in a diffused semiconductor is influenced by a change (tension or compression of the crystal structure) that can be produced by an extremely small mechanical deformation. A typical construction is shown in Fig. 3-1.2.3-1.

3-1.2.4 Capacitive Pressure Sensor. A simple variable capacitance device may be made by positioning a diaphragm between two fixed electrode plates separated by a dielectric material. A change in pressure causes the distance between the plates to change, resulting in a change in capacitance. A typical construction is shown in Fig. 3-1.2.4-1.

3-1.2.5 Photoelectric Pressure Sensor. The basic technology uses a light source and a photoelectric element. A displacement member modulates the amount of light incident on the photosensitive element. The photoemissive properties will be changed at a rate linear to displacement. The displacement member is often connected to an elastic element (diaphragm, bellows, or Bourdon tube). A typical construction is shown in Fig. 3-1.2.5-1.

3-1.2.6 Inductive Pressure Sensor. In this type of sensor, two coils are wired in opposition to form two legs of an alternating current (AC) bridge. A diaphragm made of a magnetic material is placed between the two coils. Changes in pressure will cause the diaphragm to move toward one of the coils and away from the other. As the diaphragm moves, the relative inductance of the coils will change [3]. A typical construction is shown in Fig. 3-1.2.6-1.

3-1.2.7 Linear Variable Differential Transformer. The linear variable differential transformer (LVDT) is an electromechanical sensor that produces an electrical output proportional to the displacement of a separate movable core. As shown schematically in Fig. 3-1.2.7-1, three coils are equally spaced on a cylindrical coil form. A rod-shaped magnetic core positioned axially inside this coil assembly provides a path for magnetic flux, linking the coils. When the primary or center coil is energized, AC voltages are induced in the two outer coils. When the core moves, the voltage induced in the coil toward which the core is moved increases, while the voltage induced in the opposite coil decreases. The LVDT is used to measure the displacement of an elastic element such as a diaphragm, bellows, or Bourdon tube.

3-1.2.8 Piezoelectric Pressure Sensor. When pressure or strain is applied to crystals such as quartz, Rochelle salt, and barium titanate, the crystals produce a measurable voltage. The quartz piezoelectric gauge consists of one or more quartz crystals stacked between appropriate insulators, connectors, and load-distribution plates. As pressure changes, the strain is transmitted to the crystals. This will cause a measurable charge or voltage to appear across the crystal. A typical construction is shown in Fig 3-1.2.8-1.

Fig. 3-1.2.4-1 Typical Variable Capacitive Pressure Sensor

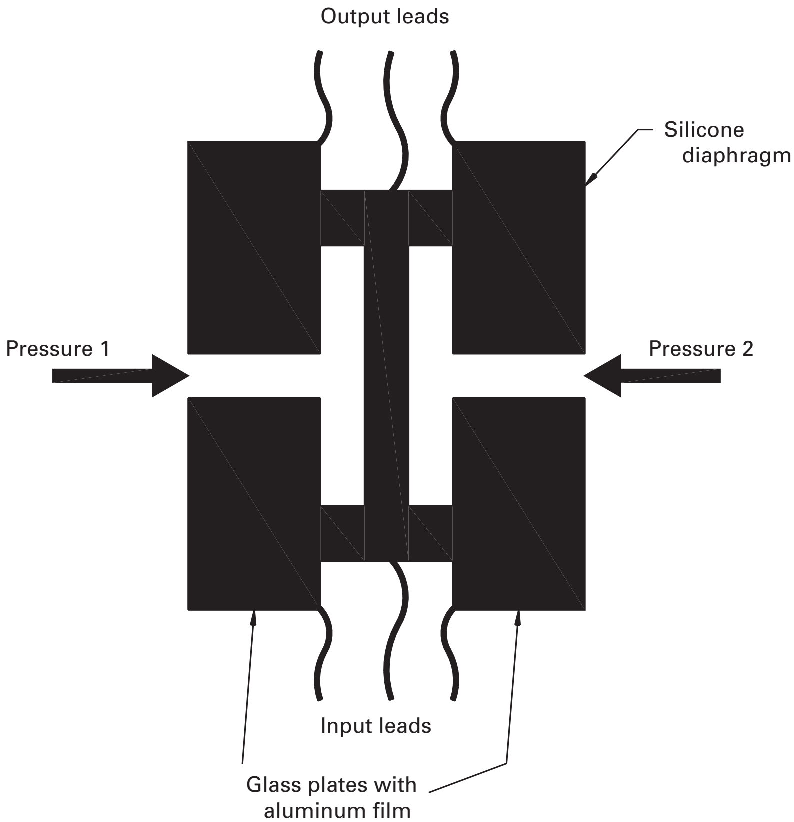


Fig. 3-1.2.5-1 Photoelectric Pressure Sensor

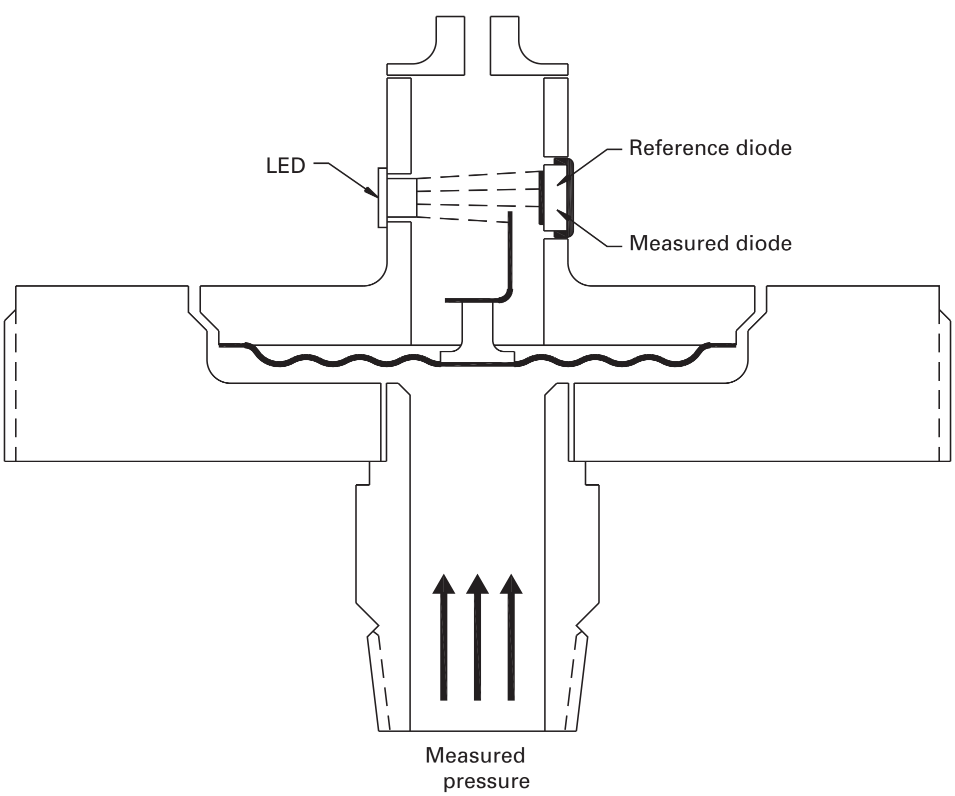


Fig. 3-1.2.6-1 Inductive Pressure Sensor

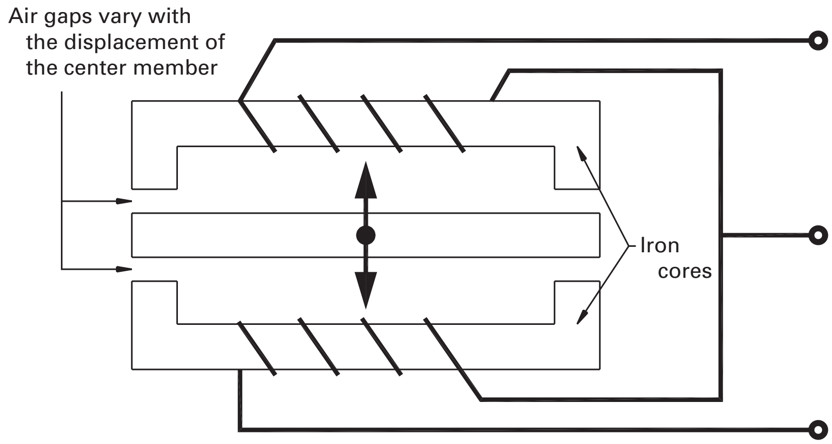


Fig. 3-1.2.7-1 Preferred Schematic Representation of the Linear Variable Differential Transformer (LVDT)

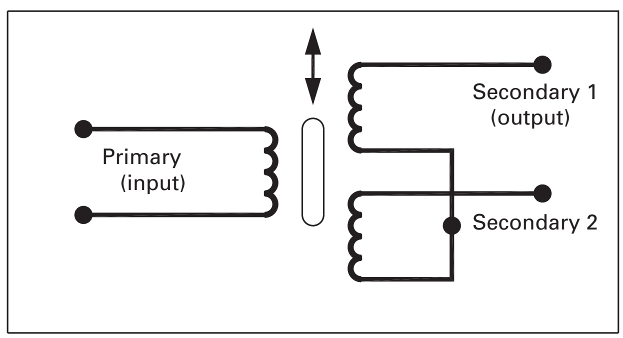


Fig. 3-1.2.8-1 Piezoelectric Pressure Sensor

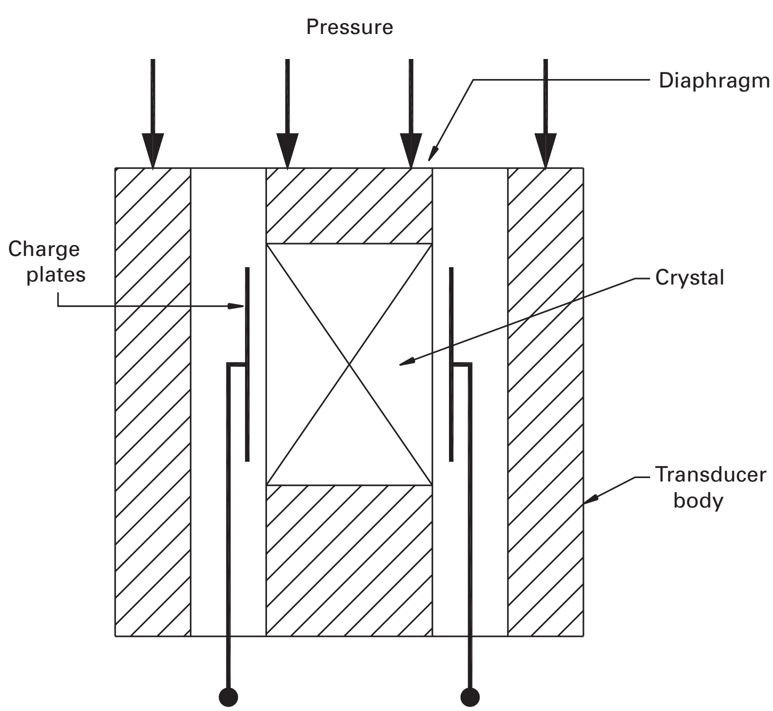
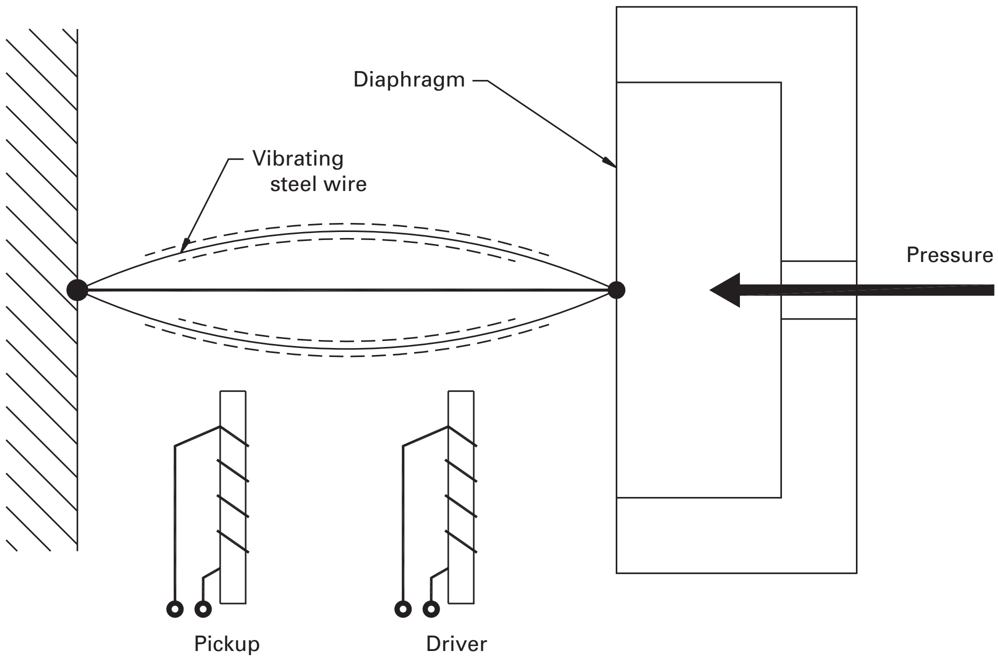


Fig. 3-1.2.9-1 Pressure Transducer With Vibrating Element



3-1.2.9 Pressure Transducer With Vibrating Element. In this type of sensor, the applied pressure varies the resonant frequency of a vibrating element. Devices usually employ fine wires, diaphragms, or cylinders. A simple example is shown in Fig. 3-1.2.9-1. A steel wire is stretched between a diaphragm and a fixed reference point. The wire is excited to its fundamental resonant frequency with the aid of a magnetic driver and a pickup coil. When pressure is applied to the membrane, the tension on the wire is reduced and the resonance frequency is reduced.

3-1.3 Pressure Instrument Summary

Table 3-1.3-1 is intended to guide the user in the selection of the appropriate pressure-measurement technology. This table is a guide only. A particular manufacturer may offer devices of a particular type that would perform satisfactorily outside these limits. Each offering shall be evaluated for the particular application. Exclusion from the table does not indicate inferior performance with respect to the listed devices. Here again, manufacturers should be consulted to provide assistance in selection.

3-2 PRESSURE TRANSMITTERS AND THEIR APPLICATIONS

A pressure transmitter senses a pressure and outputs a proportional current signal. The working principle varies. Some pressure transmitters are resistive or crystal-silicon-resonant sensors; others are capacitive or piezoelectric. All of them include attached amplifiers and filtering circuits. For details, consult the manufacturer's documentation to check what type it is and how it works.

Extensive functionality enables the pressure transmitter to be precisely adapted to the plant's requirements. Various versions of pressure transmitters are available to measure gauge pressure, absolute pressure, or differential pressure. Typically, applications with proper parameterization are liquid-level, process-flow, or other pressure-related measurement types.

Pressure transmitters can be used in a number of different system configurations. One such system is a stand-alone version, supplied with the necessary auxiliary power. Another is part of a complex system environment such as one using bus technologies (e.g., fieldbus protocol).

The pressure is transmitted through the isolation diaphragms. Resistive, crystal-silicon-resonant, capacitive, or piezoelectric sensors register the signal, and a built-in amplifier and filtering circuit produces a usable signal. An overload diaphragm is installed to provide protection from pressure overloads, if the measuring limits are exceeded. Typically, pressure ranges are available starting as low as 10 in. H_2O up to several thousand psi. All transmitters have a turn-down capability to overlap several pressure ranges, making inventory and replacement decisions easier.

The highly accurate and stable sensor technology in combination with dP integrated temperature-sensing

Table 3-1.3-1 Pressure Instrument Summary

Device Type	Applicable Pressure Ranges	Accuracy [Note (1)]	Output [Note (2)]	Relative Cost [Note (3)]
Mechanical				
Bourdon-tube gauge	−14.7 psi to 100,000 psi	0.1% to 5%	A, B	L, M
Bellows gauge	−14.7 psi to 10 psi	1% to 2%	A, B	L, M
Diaphragm gauge	−14.7 psi to 600 psi	1% to 5%	A, B	L
Electronic				
Bonded-strain gauge	Depends on sensing element used	1% to 5%	C	L, M
Deposited-strain gauge	15 psi to 50,000 psi	0.2% to 1%	C, D	L, M
Piezoresistive pressure sensor	−14.7 psi to 10,000 psi	0.1% to 1%	C, D	L, M
Capacitive pressure sensor	−14.7 psi to 500 psi	0.02% to 1%	C, D	M
Photoelectric pressure sensor	−14.7 psi to 10,000 psi	0.02% to 1%	C, D	M
Inductive pressure sensor	0 psi to 10,000 psi	0.2% to 1%	C, D	M
Linear Variable Differential Transformer (LVDT)	Depends on sensing element used	1% to 5%	C	M
Piezoelectric pressure sensor	3 psi to 15,000 psi	0.2% to 1%	C, D	M, H
Pressure transducer with vibrating element	0 psi to 50 psi	0.1% to 1%	C, D	M, H

NOTES:
(1) For consistency, accuracy is defined as the difference between the true value and the gauge indication as expressed as a percentage of gauge span (algebraic difference between the limits of the scale). This would include the effect of linearity, hysteresis, and repeatability. Contact manufacturers for specifications of these individual effects.
(2) The following code is used:
A = analog indicator
B = digital indicator
C = voltage output
D = current output
(3) For comparison, the following code is used for relative instrument costs:
H = high costs
L = low cost
M = medium cost

elements can also measure static pressure. All values can be shown on the integral indicator or remotely monitored through communications software or communication protocols.

Typical performance specifications include the following:

– zero-based calibrated span
– linear output
– terminal-based accuracy (linearity, hysteresis, and repeatability)
– static-pressure effects
– span effects
– power-supply effects
– vibration effects
– mounting-position effects
– response time
– failure alarm
– zero-adjustment limits
– external zero adjustment
– burst-pressure limits
– self-diagnostics
– advanced diagnostics (optional)
– ambient temperature limits
– process temperature limits
– ambient humidity limits
– working pressure limits
– maximum pressure limits
– maximum working pressure (MWP)
– minimum pressure limits
– remote setup using communications, diagnostics, and optional status output for pressure high-low alarm
– multisensing technology to detect abnormalities

Fieldbus-protocol connectivity or other bus system is also available.

3-2.1 Special Applications of Differential-Pressure (ΔP) Transmitters

Important applications of pressure and of differential-pressure (ΔP) transmitters include flow, liquid-level, and density measurements. These applications are described in paras. 3-2.1.1 through 3-2.1.3.

3-2.1.1 Flow. This measurement method utilizes the pressure drop across a metering restriction, such as an orifice plate, a flow nozzle, or a Venturi tube, as a function of fluid flow. A differential-pressure transmitter is commonly used to measure this pressure drop and send information to a central control room. See Fig. 3-2.1.1-1 for typical flow installations.

The differential-pressure span is often very small relative to the static pressure inside the pipe. For example, the differential pressure may be on the order of 25 kPa (100 in. H_2O), with a static pressure of 40 MPa (5,800 psi), a ratio of 1 part in 1,600. This limits the choice of transmitters to those that have been specifically designed for operation up to high static-pressure levels with minimum effect of static-pressure variation on the measurement of the pressure differential.

Associated with high static-pressure operation is the over-range characteristic of the flow transmitter. The ability to withstand full static pressure applied independently to either process port (high-side or low-side over-range) during startup or in the event of a system malfunction is essential. Over-range protection of the diaphragms is provided by mechanical support from a contoured backup profile in the body block. There are other designs in which the diaphragms are supported hydraulically by closing a valve to prevent complete volume transfer. A suitable transmitter shall maintain its calibrated accuracy.

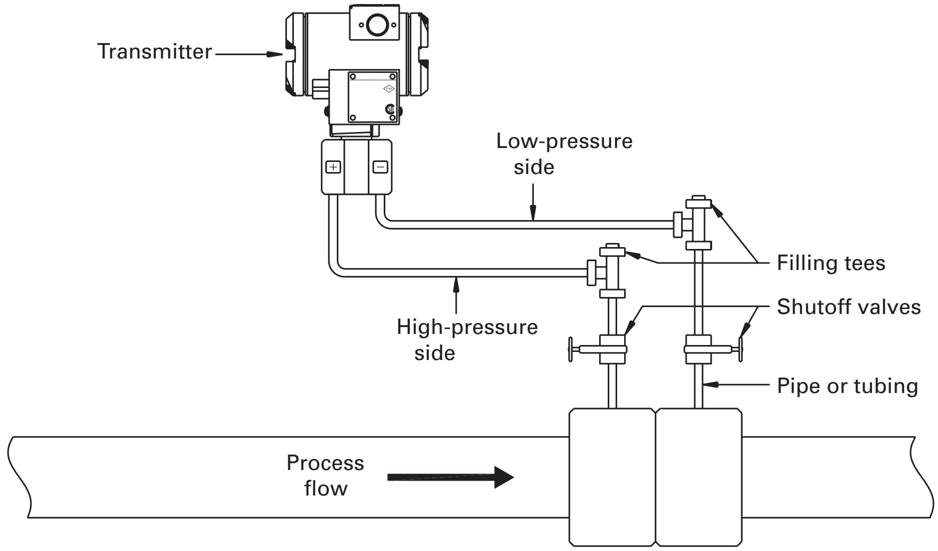
Figure 3-2.1.1-2 shows an exploded view of a differential-pressure transmitter that can be used for flow measurement. The sensor diaphragms, process-cavity flanges, gaskets, and flange fittings (such as vent or drain valves and process adaptors) are selected from a choice of corrosion-resistant materials offered by the manufacturer. These are usually the only parts that come into direct contact with the process fluid.

The central body contains the actual sensor and is hermetically sealed to enable long-term, full-vacuum operation and maintain full operability. The center cavity of the sensor is filled with silicone oil or other suitable liquid to support the high static pressure of the process. Another function of the filling liquid is to provide damping (in combination with a suitable internal resistance restriction and volume transfer). Flow signals are often noisy, and without this damping, would cause noisy output signals. In addition, adjustable electronic damping is usually available. Excessive damping, however, should be avoided because of the square-law relationship between flow velocity and differential pressure that will lead to erroneous flow measurements. Most instrument manufacturers, therefore, place an upper limit on the adjustment they provide.

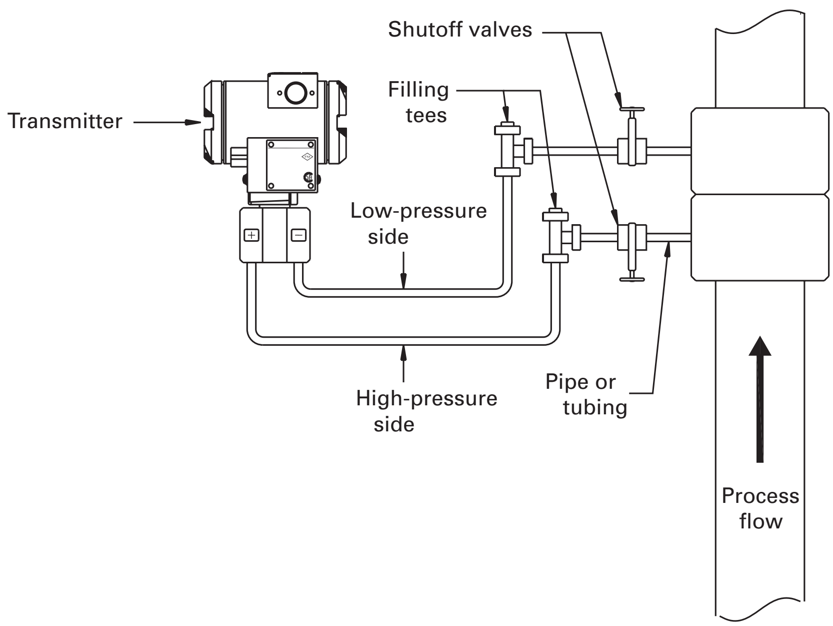
Other requirements relate to, and vary substantially with, the operating environment. They include, but are not limited to, compensation for variations in outdoor ambient temperature and process temperature, immunity to vibration and mechanical shock, the need to maintain calibrated accuracy with power-supply variations and environmental interferences (radio frequency and magnetic), and sometimes the need to operate safely in explosive atmospheres (dust, hydrocarbons, etc.). The adjustments of concern to the user are for zero, span, and elevation or suppression.

3-2.1.1.1 Adjustment for Zero. Zero is adjusted with the input at the lower-range value of the pressure differential (usually zero) by first closing the valve to the low-pressure impulse line and then opening the equalizing valve to ensure that the process cavities are at the same pressure (see Fig. 3-2.1.1-1). This procedure shall be performed after installing the transmitter, to correct

Fig. 3-2.1.1-1 Typical Flow Installations

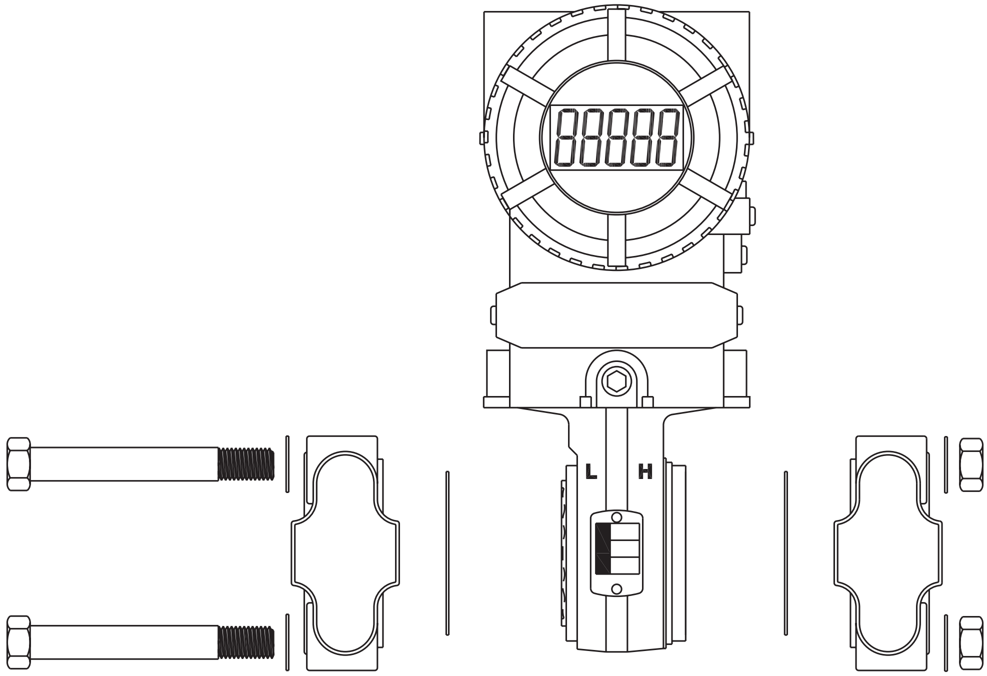


(a) Horizontal Flow



(b) Vertical Flow

Fig. 3-2.1.1-2 Exploded View of Differential-Pressure Transmitter



GENERAL NOTE:
H = high-pressure side
L = low-pressure side

installation effects, and after the process cavities have been properly filled or drained (depending upon the type of installation).

3-2.1.1.2 Adjustment for Span. Adjustment for span is normally made by the factory or instrument shop. It requires an application of a known pressure differential, usually equal to the upper-range value, in addition to zero. An exception is when the transmitter is being returned to a previously calibrated span setting.

3-2.1.1.3 Adjustment for Elevation and Suppression. Suppression is the condition in which an instrument's measurement range is entirely above zero, as in an instrument calibrated for 25 kPa (100 in. H_2O) to 50 kPa (200 in. H_2O). Elevation is the condition in which an instrument's measurement range starts below zero, say –25 kPa (–100 in. H_2O) to 25 kPa (100 in. H_2O).

The elevation-suppression adjustment operates like a coarse zero adjustment and is used only to achieve ranges that are not zero based. With many modern instruments, this adjustment is done with a configuration tool that does not require external calibration equipment.

The differential-pressure transmitter ranges used for flow measurements are almost never elevated or suppressed because most flow primary elements are not symmetrical with regard to flow in both directions.

3-2.1.2 Liquid Level. Many of the liquid-level measuring devices used by industry for accuracies to about 0.1% of span depend upon the fundamental equation

$$\text{Pressure} = \text{Density} \times \text{Height}$$

Pressure and fluid height bear a direct relationship if density remains constant, and for most applications this is a valid assumption. Density compensation is discussed in para. 3-2.1.2.4.

The same differential-pressure transmitters as were described in para. 3-2.1.1 may also be used to measure liquid level. An impulse line from below the minimum liquid level in the tank is connected to the high-side transmitter connection and, following the manufacturer's instructions, air is purged from this line and from the process cavity of the transmitter, allowing liquid from the tank to enter. The low-side transmitter connection is vented to

Fig. 3-2.1.2.1-1 Flange-Mounted Transmitters (Courtesy of The Foxboro Company)

(a) Flush Diaphragm

(b) Extended Diaphragm

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atmosphere in an open-tank application or connected to the vapor space above the maximum liquid level in closed tanks, as indicated for the direct-mounted installations described in paras. 3-2.1.2.1 through 3-2.1.2.3. Using a differential-pressure transmitter with impulse-line process connections is generally the less-expensive approach if process fluid can be tolerated in these lines and in the process cavities of the transmitter.

3-2.1.2.1 Open-Tank Installations. Examples of direct flange-mounted liquid-level transmitters are shown in Fig. 3-2.1.2.1-1, and its application, mounted to a tank nozzle, is shown in Fig. 3-2.1.2.1-2. The flush diaphragm is suitable for applications where the process liquid is free from suspended solids. An extended-diaphragm version eliminates the pocket at the transmitter connection and should be used for slurries and viscous liquids. Figure 3-2.1.2.1-3 shows a variation of the transmitter with the extended diaphragm and a remote-seal element.

3-2.1.2.2 Closed-Tank Installations. Closed-tank liquid-level applications differ from open-tank applications in that the pressure over the liquid may differ from atmospheric pressure. Figure 3-2.1.2.2-1 is a schematic diagram of a level transmitter for closed-tank service, and Figs. 3-2.1.2.2-2 through 3-2.1.2.2-8 show examples of closed-tank installations, using both integral and remote-seal transmitter forms. These are differential-pressure transmitters with one side connected through a compensating leg to measure pressure above the liquid. The compensating leg can be either wet or dry depending on the characteristics of the process vapor. Any change in liquid level in the compensating leg, however, will cause measurement error. Also, changes in the ambient temperature can result in excessive errors due to changing specific gravities in the wet leg. A dry leg should be used when the process vapor is not readily condensible or when the compensating leg is at a higher temperature than the tank interior (see Figs. 3-2.1.2.2-2, 3-2.1.2.2-3, and 3-2.1.2.2-4). A trap installed at the bottom of the leg minimizes the possibility of condensate collecting in the compensating-diaphragm cavity. When the process vapor is condensible, a wet leg should be used (see Figs. 3-2.1.2.2-5, 3-2.1.2.2-6, and 3-2.1.2.2-7). The leg should be filled with process liquid or a suitable seal fluid (see Table 3-2.1.2.2-1), using a filling tee installed at the top of the leg. The wet leg can be avoided if the transmitter can be installed near the top of the tank (see Fig. 3-2.1.2.2-8) so that the condensate drains back into the tank.

In all of the installations shown, the minimum measured level shall be at or above the datum line. Also, when the installation is to be used on vacuum service, the transmitter should usually be mounted at or below the datum line (see Figs. 3-2.1.2.2-2, 3-2.1.2.2-4, 3-2.1.2.2-5, and 3-2.1.2.2-7) to keep the filling liquid pressurized above its vapor pressure. However, this requirement varies somewhat among manufacturers, depending upon their filling pressure, so the manufacturer's recommendations should be followed closely.

To determine the span and range values for a specific application, use the following equations:

Fig. 3-2.1.2.1-2 Flange Transmitter Mounted Directly to Tank Nozzle

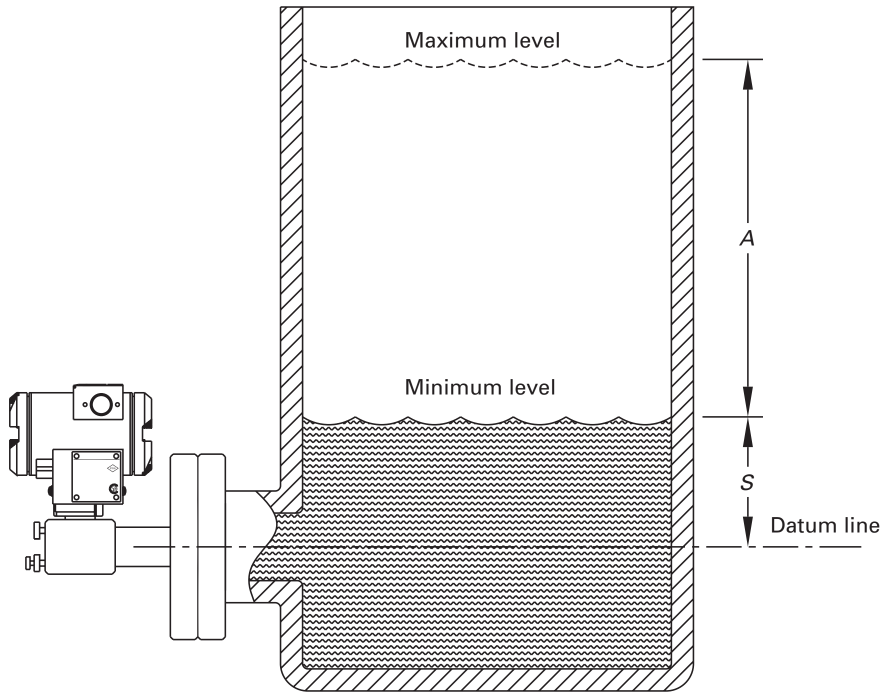

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Fig. 3-2.1.2.1-3 Open-Tank Installation With Remote-Seal Type of Transmitter

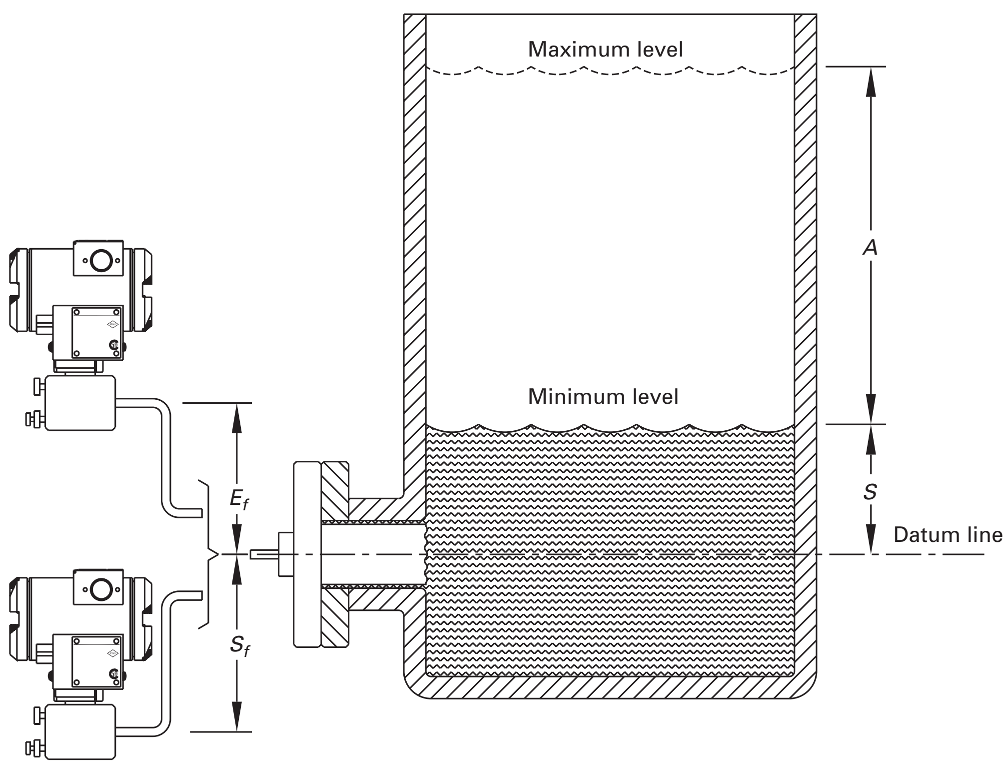

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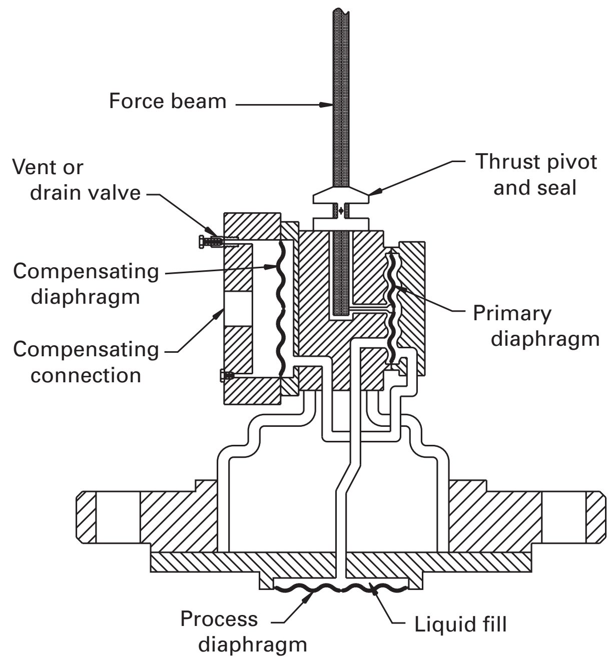
Fig. 3-2.1.2.2-1 Schematic Diagram of Closed-Tank Transmitter Primary



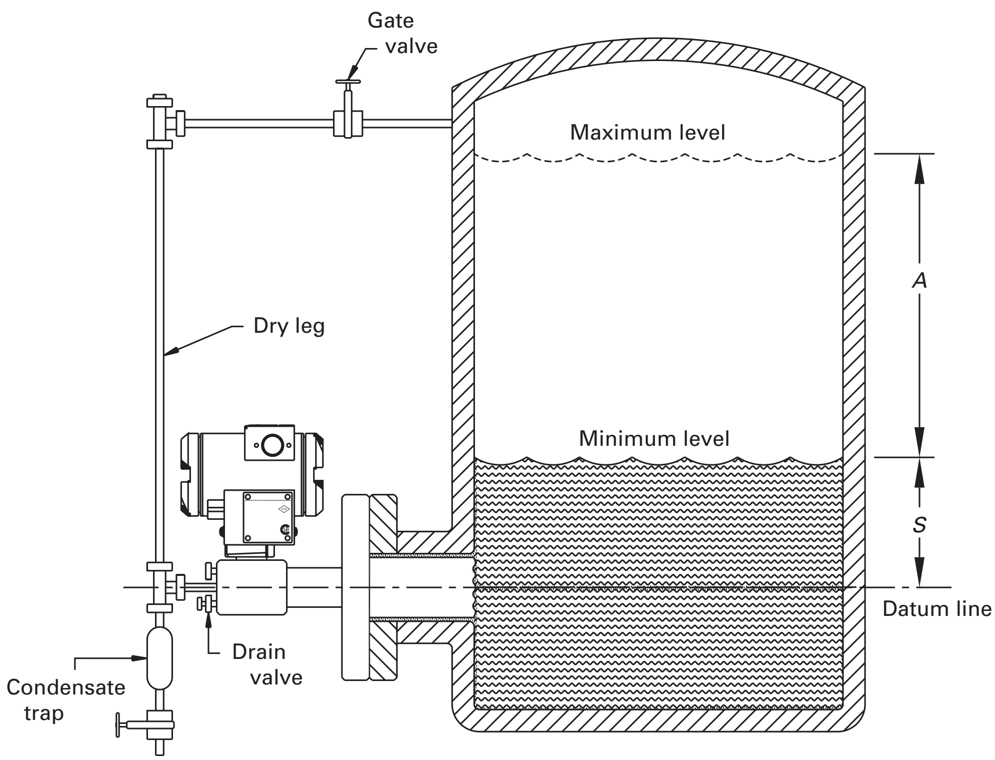
GENERAL NOTE: This figure has been adapted from the Invensys Foxboro FoxDoc 2006 CD, by permission of The Foxboro Company.

Table 3-2.1.2.2-1 Seal-Fluid Selection Chart

Liquid	Freezing Point/ High-Temperature Limit, °C	Specific Gravity [Note (1)]	Recommended Service
Water	0/+93	1.00	General usage
Mixture of 50% water and 50% glycerin	−28/+96	1.14	Antifreeze for hydrocarbon service
Mixture of 50% water and 50% ethylene glycol	−36/+149	1.07	Antifreeze for other than hydrocarbon service
Fluorinated hydrocarbon (generally high viscosity)	−18/+260	1.90	Acids, alkalies, strong salts
Silicone (high temperature)	+21/+316	. . .	. . .
Silicone (low temperature)	+51/+149	. . .	. . .

NOTE:
(1) Changes greatly with temperature, affecting measurement accuracy.

Fig. 3-2.1.2.2-2 Closed-Tank Installation, Dry Leg



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$$\text{Span} = AC_t \tag{3-2-1}$$

$$\text{Lower-range value} = SC_t + S_fC_f - EC_s - E_fC_f \tag{3-2-2}$$

$$\text{Upper-range value} = (A + 5)\,C_t + S_fC_f - EC_s - E_fC_f \tag{3-2-3}$$

where

A, E, E_f, S, and S_f = length as shown in Figs. 3-2.1.2.1-2, 3-2.1.2.1-3, and 3-2.1.2.2-2 through 3-2.1.2.2-8

C_f = specific gravity of the liquid in the tube system

C_s = specific gravity of the liquid in the wet leg

C_t = specific gravity of the liquid in the tank

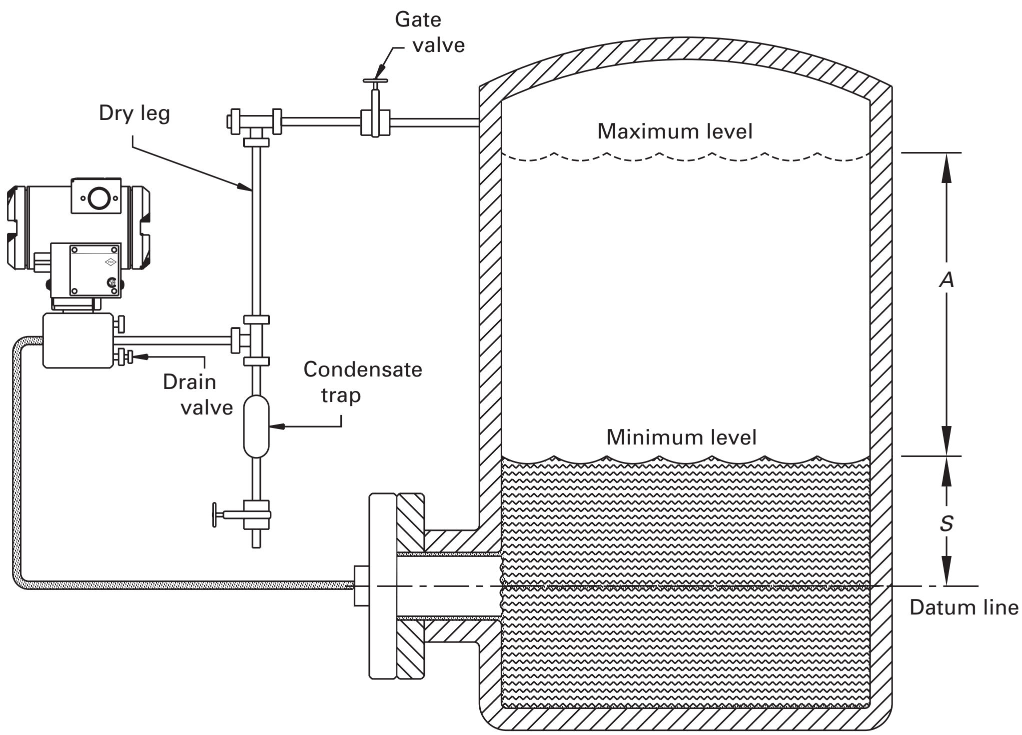
A negative upper- or lower-range value indicates that positive pressure must be applied to the compensating side of the measuring element when calibrating a transmitter for this range. Refer to Table 3-2.1.2.2-2 for the type of calibration required. Note that specific gravity terms have been used as a convenience in the preceding equations rather than density, causing the span values to be in terms of height of an equivalent column of water. This is because of the extensive use of water and its role as a reference standard for many pressure measurements.

3-2.1.2.3 Repeaters. Another device often used for level measurement is a direct-mounted pneumatic force-balance transmitter that reproduces a process pressure on a one-to-one basis (see Fig. 3-2.1.2.3-1). Sometimes called a repeater, it has no particular range or calibration inherent in its construction.

The useful working range is determined entirely by the air supply and the required output pressure, which can be biased relative to the measured pressure using a zeroing adjustment. A sensing diaphragm contacts the process liquid on a nearly flat surface. There is no filling liquid, which simplifies maintenance. Linearity varies somewhat with the choice of supply pressure and with the transmitter design, but it is usually best at midrange. The manufacturer should be consulted for details of operation, application, associated equipment, and accuracy.

3-2.1.2.4 Density Compensation. It may be important to accurately know the level under conditions of varying specific gravity. The differential-pressure type of level meter measures the product of height and a specific gravity. If a second instrument is added that meas-

Fig. 3-2.1.2.2-3 Closed-Tank Installation, Dry Leg Transmitter Above Datum Line



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ures specific gravity, and the reading on the level meter is divided by the gravity reading, the actual level of the liquid is the result. A small computer (pneumatic or electronic) should be used to perform the division and provide a compensated level signal.

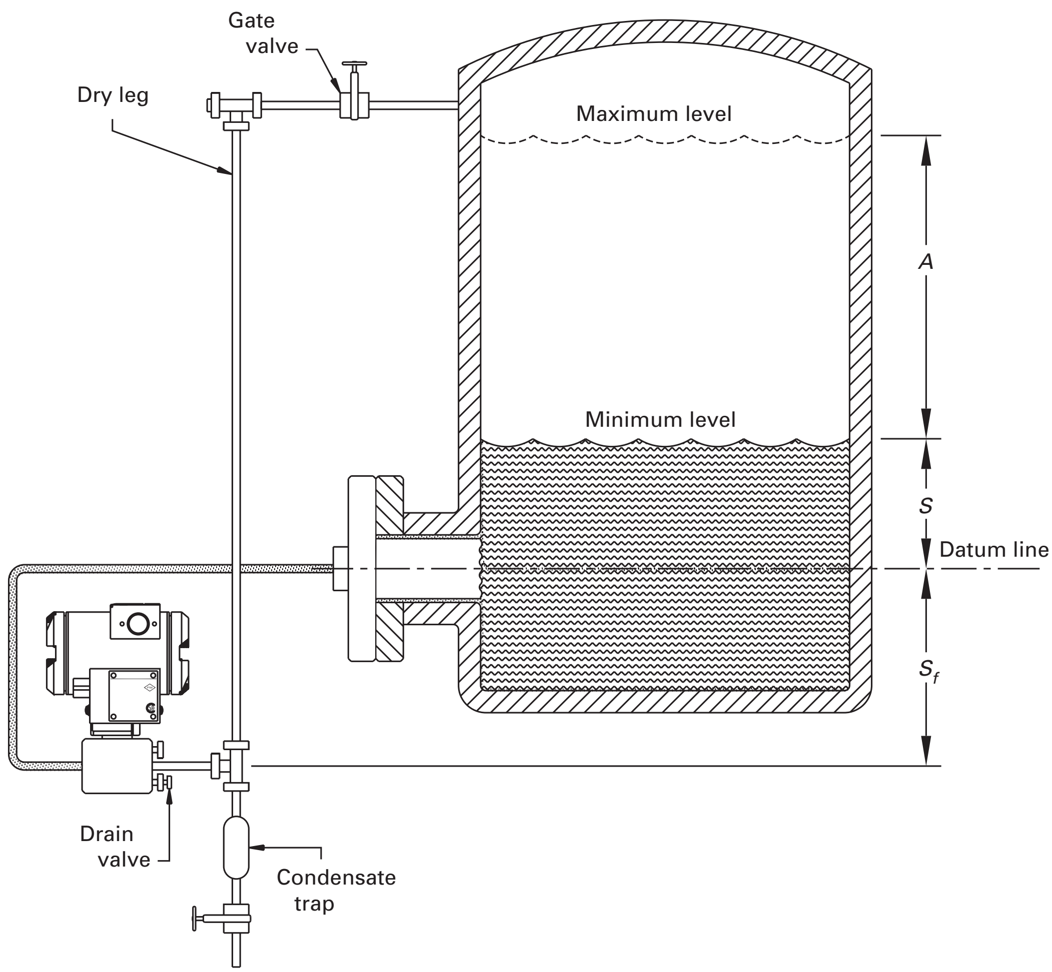
3-2.1.3 Liquid Density (Specific Gravity). Density is mass per unit volume and is usually expressed as kilograms per cubic meter (kg/m^3). Specific gravity is just one of many numerical scales that may be applied to density-measuring instruments. It is the ratio of the density of a liquid to the density of water, the temperature of both liquids being stated. Thus, specific gravity of 0.904 20°C/4°C means that the density of the liquid sample at 20°C divided by the density of water at 4°C is 0.904. Since specific gravity is a ratio, it is dimensionless.

3-2.1.3.1 Basic Concepts. The application of a differential-pressure instrument to density measurement develops from the fact that pressure at the bottom of a vertical column of liquid is the product of liquid density multiplied by the height of the column. It is readily seen, however, that a simple hookup such as is shown in Fig. 3-2.1.3.1-1 would be unsatisfactory for most applications because of insufficient sensitivity. A more useful differential arrangement, loading one side of the instrument with a constant known pressure (see Fig. 3-2.1.3.1-2), would allow the pressure span to be shortened. Its readability is increased by a factor of 10 by reducing its span one-tenth that of the instrument in Fig. 3-2.1.3.1-1.

If the instrument was provided with a suppression adjustment (usually available in differential-pressure transmitters), the constant pressure to the low-pressure side of the differential instrument (represented by the reference water column of Fig. 3-2.1.3.1-2) could be eliminated. The low-side pressure connection would simply be vented to the atmosphere.

3-2.1.3.2 Sample-Column Method. A common method of measuring the density of a process liquid is by means of a sample column, shown schematically in Fig. 3-2.1.3.2-1. The sample enters the column at the bottom and overflows into a return line to establish a constant sampling height. A bubbler tube connected to the differential-pressure instrument makes possible the measurement of pressure at the bottom of this column without bringing the process liquid into contact with the instrument. The resulting back pressure is related to the liquid level measured vertically from the base of the dip tube to the liquid surface. This arrangement makes it easy to measure or adjust the head.

Fig. 3-2.1.2.2-4 Closed-Tank Installation, Dry Leg Transmitter Below Datum Line



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The required height of the sample column is determined by dividing the differential-pressure span of the instrument (height of water) by the density span. Here, the temptation is to use a short instrument pressure span to make the sample column short; however, the air-pressure change in the tube is about 3 mm H_2O (0.01 in. H_2O) during the formation of every bubble, thereby placing a practical minimum length on the column for signal stability. The diameter of the sample column is also important. For good speed of response, the sample should be changed at least once per minute.

However, one must remember that flow is always accompanied by pressure drop; also, fluctuations in flow will change the liquid head above the overflow weir, which is the perimeter of the top of the sample-column pipe. A good approach to the problem is to pick a pipe size and then calculate its performance using the sample flow rate, its variation, and the volume and top perimeter of the proposed pipe.

The variables to be determined are the rate of change of the sample, the pressure change due to flow variation, and the head change of liquid above the crest of the weir (Francis formula[1]) due to flow variation.

[1] Francis formula

$$h = \left(\frac{Q}{1.84L}\right)^{2/3}$$

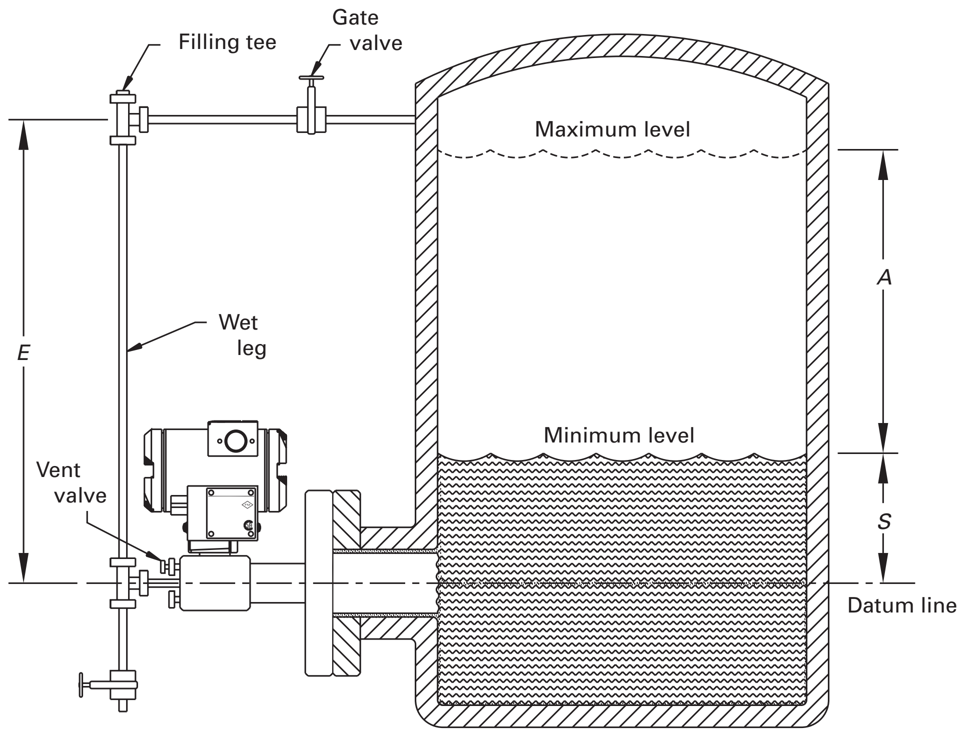
where
h = head of liquid above crest of weir, m
L = perimeter of top of sample column, m
Q = flow rate over weir, m^3/s

or

$$h = \left(\frac{Q}{3.33L}\right)^{2/3}$$

where
h = head of liquid above crest of weir, ft
L = perimeter of top of sample column, ft
Q = flow rate over weir, ft^3/sec

Fig. 3-2.1.2.2-5 Closed-Tank Installation, Wet Leg



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A negative upper- or lower-range value indicates that positive pressure must be applied to the compensating side of the measuring element when calibrating a transmitter for this range. Refer to Table 3-2.1.2.2-2 for the type of calibration required. Note that specific gravity terms have been used as a convenience in eqs. (3-2-1), (3-2-2), and (3-2-3) rather than density, causing the span values to be in terms of height of an equivalent column of water. This is because of the extensive use of water and its role as a reference standard for many pressure measurements.

If a bubble tube is used, pressure on the bubbles shall be held constant. This requires a good quality air regulator upstream from the adjustable restriction. Temperature fluctuation is by far the greatest source of error in density measurements. This is apparent from a few examples shown in Table 3-2.1.3.2-1. For petroleum products and organic solvents, the temperature effects are much greater than for aqueous liquids, and range from 0.0007/°C to 0.0014/°C. Therefore, it may be necessary to apply a heat-exchanger and temperature controller to the incoming sample.

3-2.2 Use of Differential-Pressure Instruments for Boiler Control

Differential-pressure instruments are not used only to measure the pressure drop across various in-line components such as filters, screens, and so on; their most frequent application is in the inferential measurement of water level and flow rate. Almost all differential-pressure gauges or indicators are so-called motion-balance sensors that employ two bellows. The basic components of the sensor are the high- and low-pressure chambers, the range spring, and the drive assembly, which transfers bellows motion to the readout pointer.

3-2.2.1 Boiler-Drum Water Level. A typical arrangement for controlling the water level in the boiler drum is shown in the Fig. 3-2.2.1-1. The water level in the drum is measured by a transmitter that is a differential-pressure device. The output signal from the transmitter increases as the differential pressure decreases, which in turn indicates an increase in drum water level.

Fig. 3-2.1.2.2-6 Closed-Tank Installation, Wet Leg Transmitter Above Datum Line

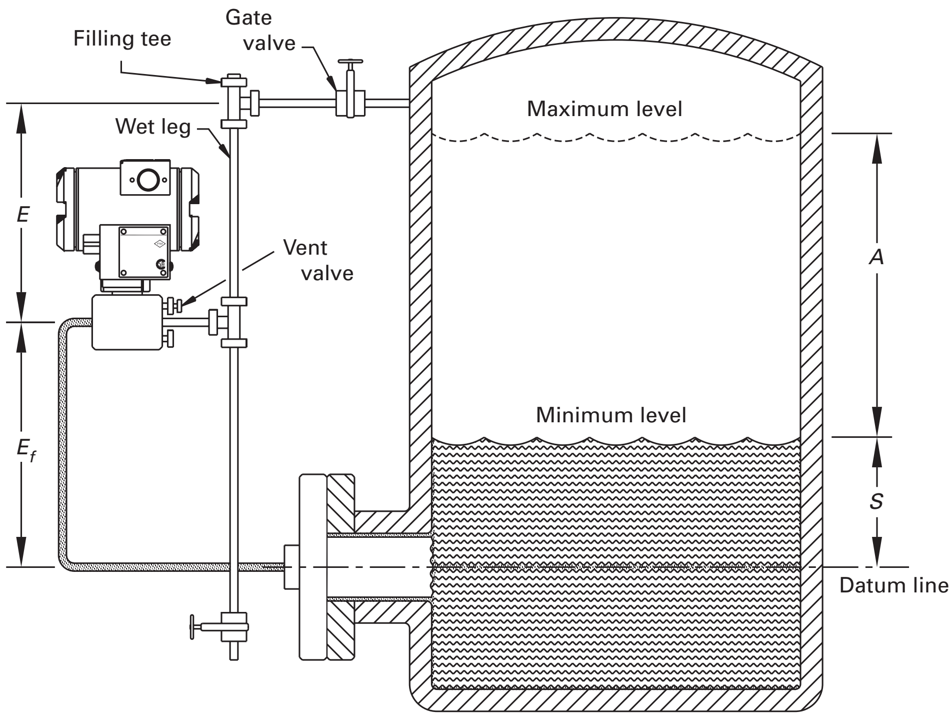

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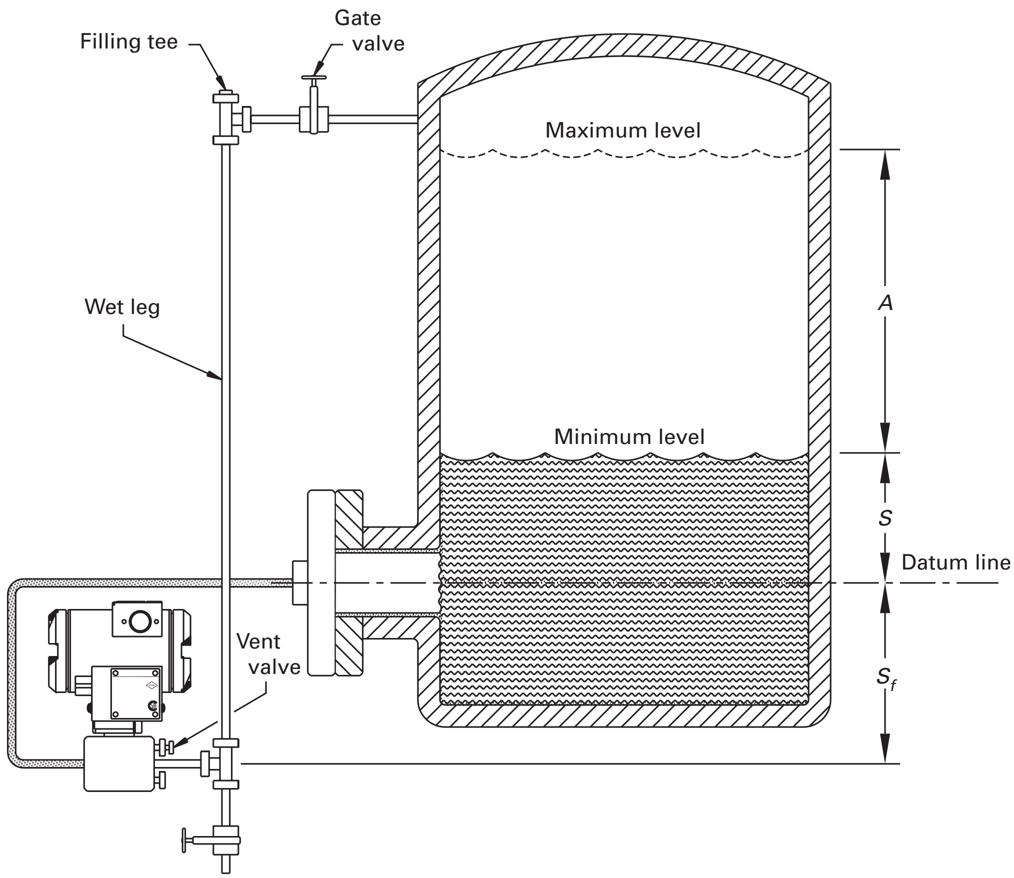
Table 3-2.1.2.2-2 Type of Calibration Required for Various Transmitter Applications

Service	Initial Level Condition of Transmitter Application	Transmitter Elevation	Type of Calibration
Open tank, or closed tank with dry leg	Minimum level at datum line	At datum line	Zero based
		Above datum line	Elevated zero
		Below datum line	Suppressed zero
	Minimum level above datum line	Above datum line	Elevated zero [Note (1)]
		At or below datum line	Suppressed zero
Closed tank with wet leg	Minimum level or above datum line	Any transmitter elevation	Elevated zero

NOTE:
(1) Can be suppressed zero depending on relative head pressures.

Fig. 3-2.1.2.2-7 Closed-Tank Installation, Wet Leg Transmitter Below Datum Line

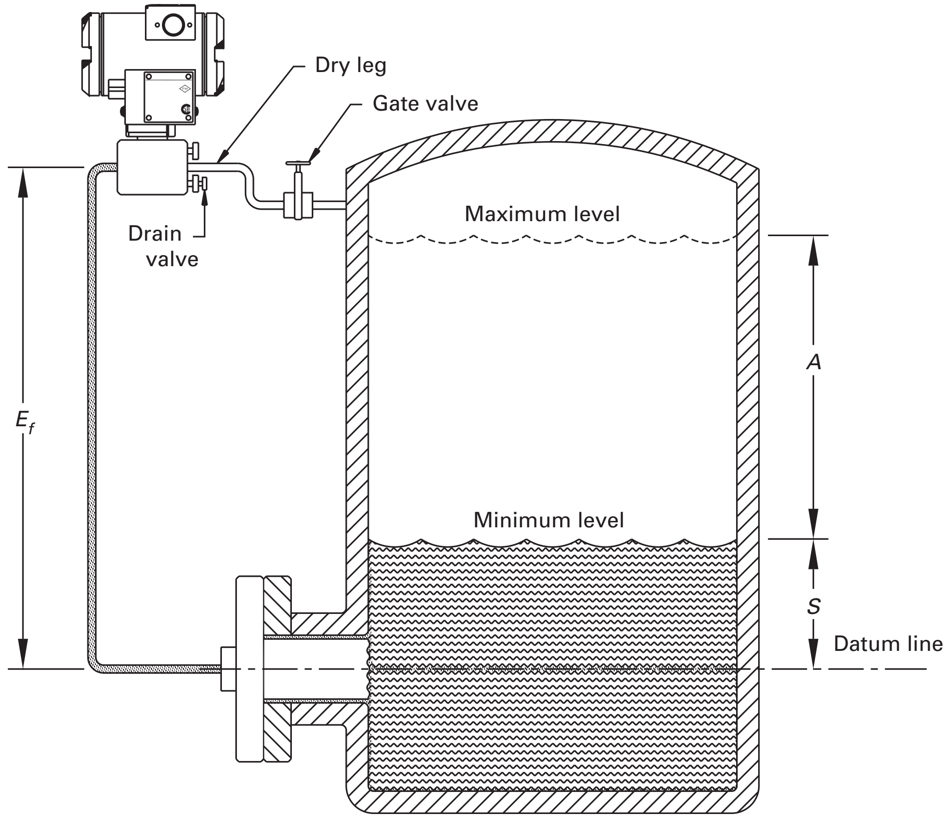


GENERAL NOTE: This figure has been adapted from the Invensys Foxboro FoxDoc 2006 CD, by permission of The Foxboro Company.

Table 3-2.1.3.2-1 Variations in Density for Different Fluids

	Change in Density	
Liquid	Per °C	Per °F
Water at 15°C (59°F)	0.00016	0.00009
Water at 31°C (88°F)	0.00032	0.00018
Water at 80°C (176°F)	0.00062	0.00034
Sugar, 50% solution at 20°C (68°F)	0.00036	0.00020
Caustic soda (NaOH), 50% solution at 20°C (68°F)	0.00073	0.00041

Fig. 3-2.1.2.2-8 Closed-Tank Installation, Dry Leg Transmitter Above Upper Process Tap



GENERAL NOTE: This figure has been adapted from the Invensys Foxboro FoxDoc 2006 CD, by permission of The Foxboro Company.

Fig. 3-2.1.2.3-1 Repeater-Type Level-Measurement Device

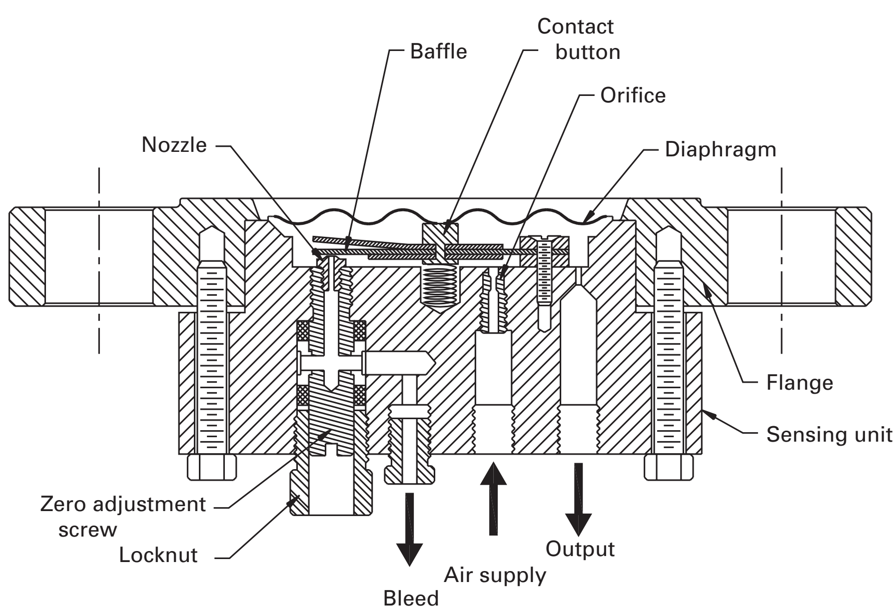


Fig. 3-2.1.3.1-1 Hydrostatic Head Provides One Method of Density Measurement

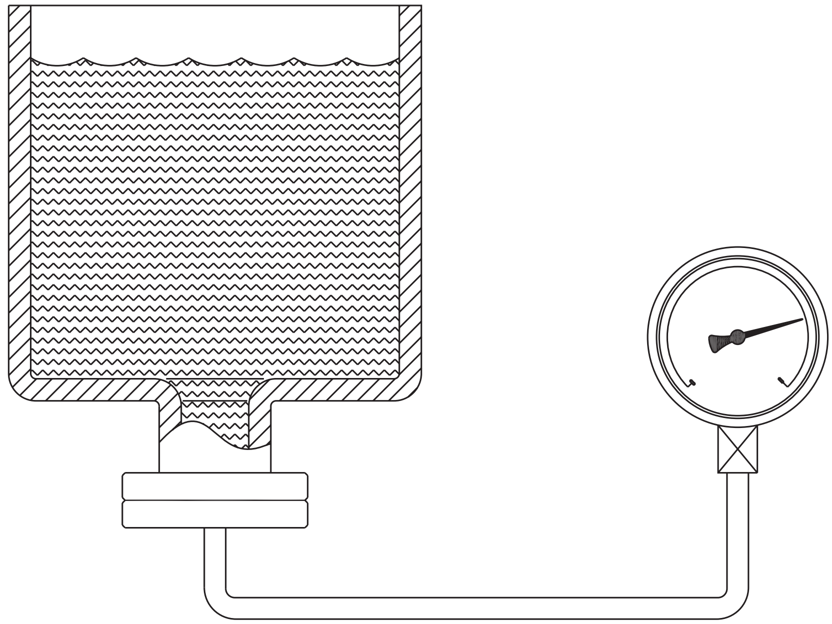


Fig. 3-2.1.3.1-2 Differential Hydrostatic Head Increases Sensitivity of Density Measurement

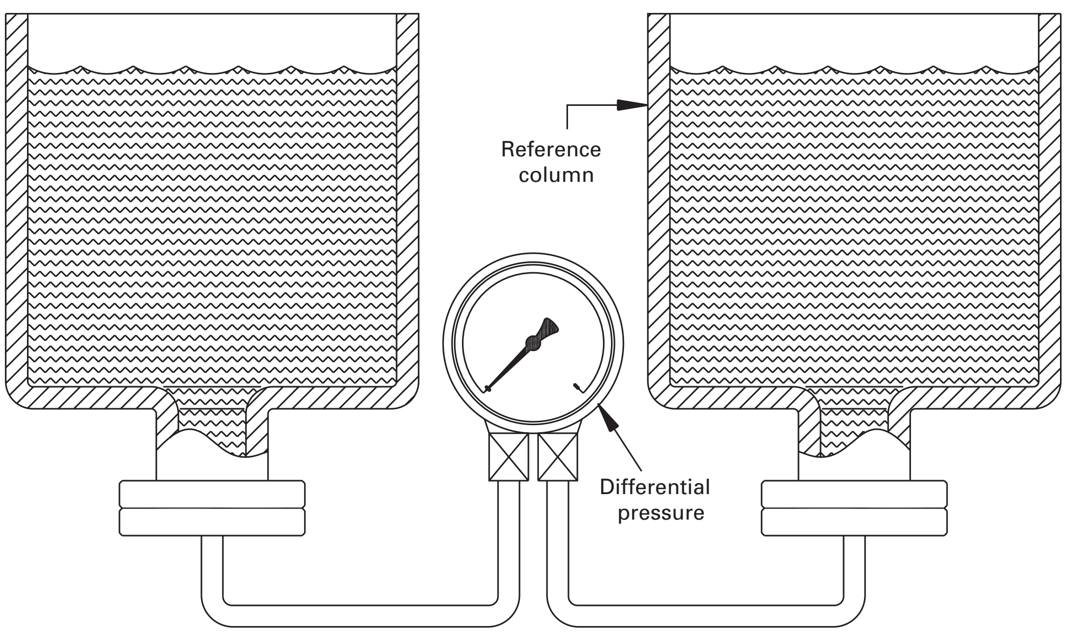


Fig. 3-2.1.3.2-1 Common Method of Measuring Density of a Process Liquid

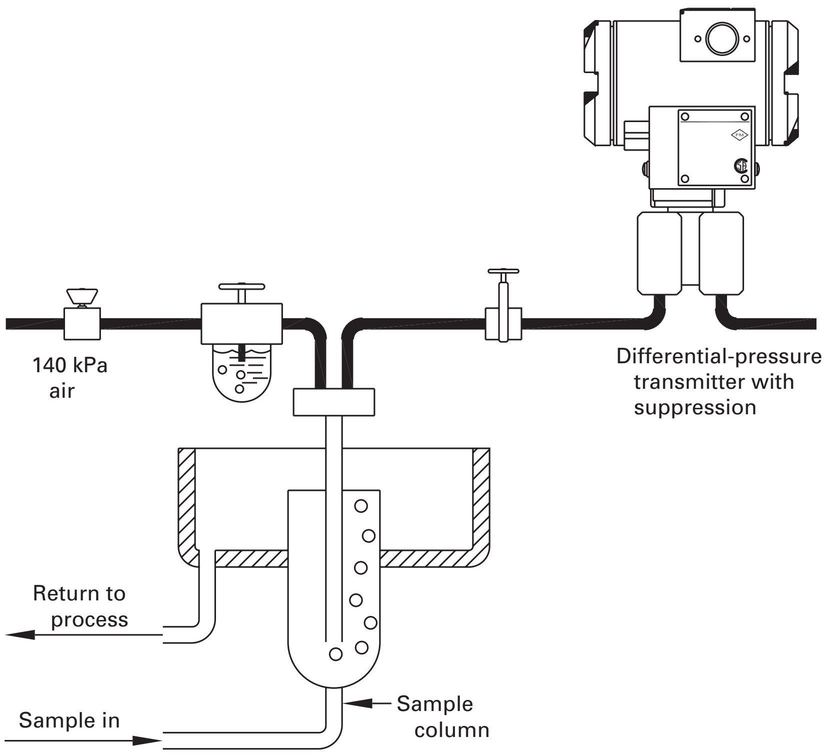
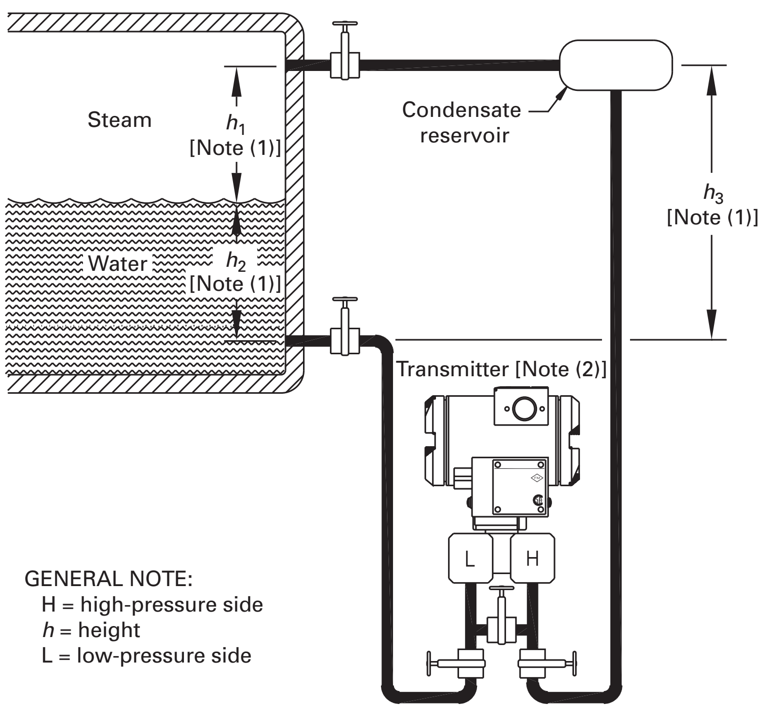


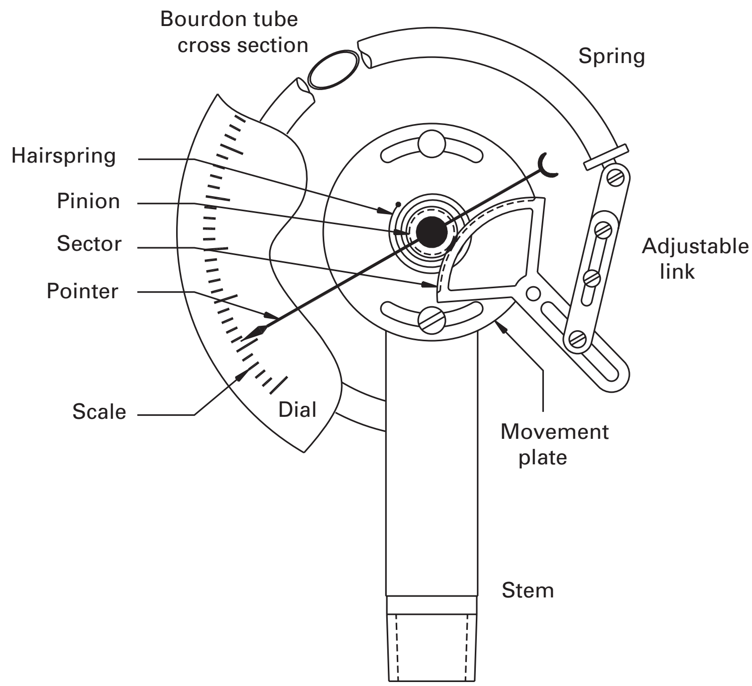
Fig. 3-2.2.1-1 Typical Drum Water Level



GENERAL NOTE:
H = high-pressure side
h = height
L = low-pressure side

NOTES:
(1) 70° F water-column equivalent
(2) Net transmitter pressure differential = $h_3 - (h_2 + h_1)$

Fig. 3-3.1.1-1 Bourdon Gauge



On the high-pressure side of the transmitter, the effective pressure equals boiler-drum pressure plus the weight of a water column at ambient temperature. The height of this water column is the distance between the two drum-pressure connections.

On the low-pressure side, the effective pressure equals the boiler-drum pressure plus the weight of a column of saturated steam (with column height from the upper drum-pressure connection to the water level) plus the weight of a column of water at saturation temperature (with column height from water level to the lower drum-pressure connection).

Since the density of saturated steam and water at saturation temperature changes with drum pressure, the level calibration data will be accurate at only a single drum pressure. Therefore, the signal from the transmitter must be pressure compensated to be accurate for all pressures.

3-2.2.2 Feedwater Flow and Steam Flow. The drum level is the basic measurement used for controlling feedwater flow to the drum. This is called the single-element control. On the other hand, two-element control (seldom used) uses the two measurements of steam flow and boiler-drum level, and three-element control includes the feedwater flow measurement in the control strategy. The most widely used method of controlling boiler-drum levels in the power-generation industry utilizes a single-element control at low loads with transfer to three-element control at higher loads. The three-element control is used to minimize the cycling effect created by shrink and swell of the water level in the drum.

The measurement of both steam flow and feedwater flow utilizes head-loss meters such as the flow nozzle, venturi tube, or the orifice meter. The pressure taps on such meters are generally connected to a differential-pressure measuring device. This device provides the flow by using the pressure-flow square-root relationship and can be calibrated for accuracy using a pressure-temperature compensation factor.

Similar arrangements with head-loss meters are also used for measuring the flow of fuel oil and fuel gas to the boiler.

3-2.2.3 Furnace Draft. The furnace draft (or furnace pressure) is measured by a pressure tap in the furnace wall. The pressure tap connection is made large enough (e.g., a 2-in. NPS connection with 1-in. piping) to ensure that slight changes in the furnace draft are sensed without delay by the measuring instrument. The measuring instrument can be a differential-pressure cell with one end sensing the furnace draft and the other end sensing the atmospheric pressure.

The control arrangement in balanced draft furnaces is such that the air flow demand is met by modulating the control device of the forced-draft fan. The change in forced-draft flow affects the furnace draft, which is in turn controlled by the induced-draft fan. This is a series action with inherent delay. For improved control, the signal to the forced-draft control device should also be added to a summer at the output of the furnace-draft controller, thus eliminating the time lag between the control device of the forced-draft fan and that for the induced-draft fan.

Fig. 3-3.1.1-2 Bourdon Tubes

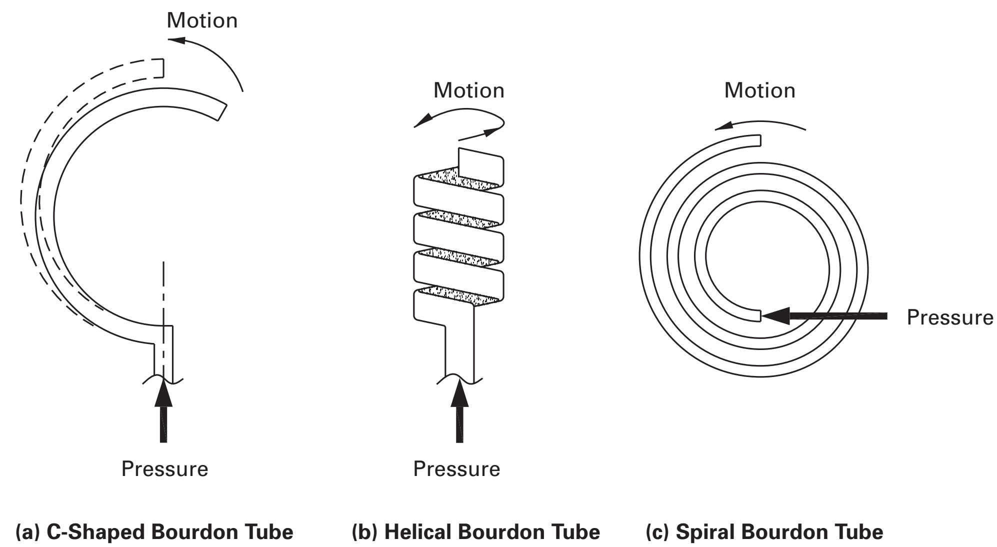


Fig. 3-3.1.2-1 Bellows Gauge

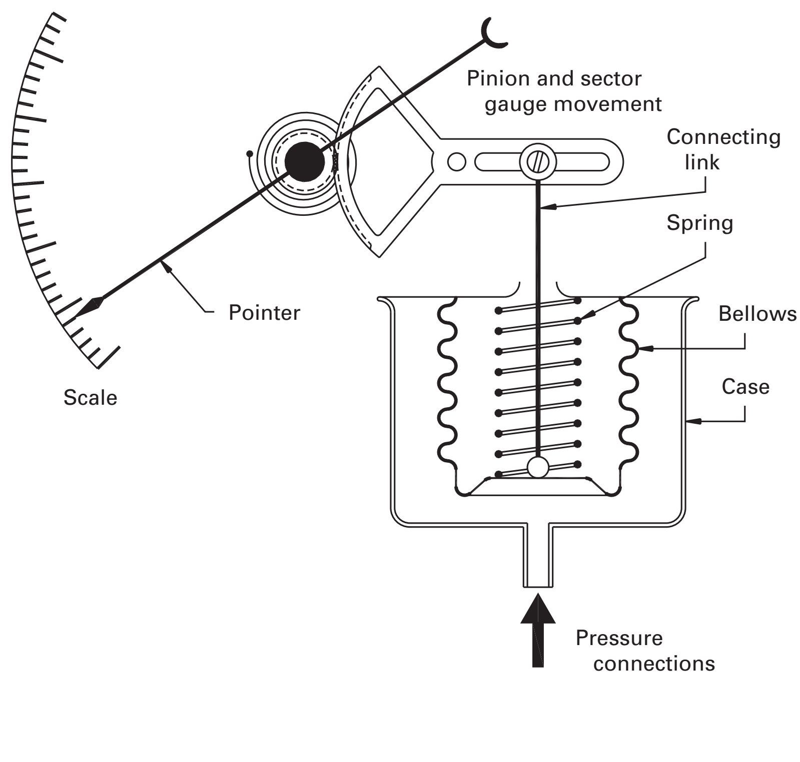
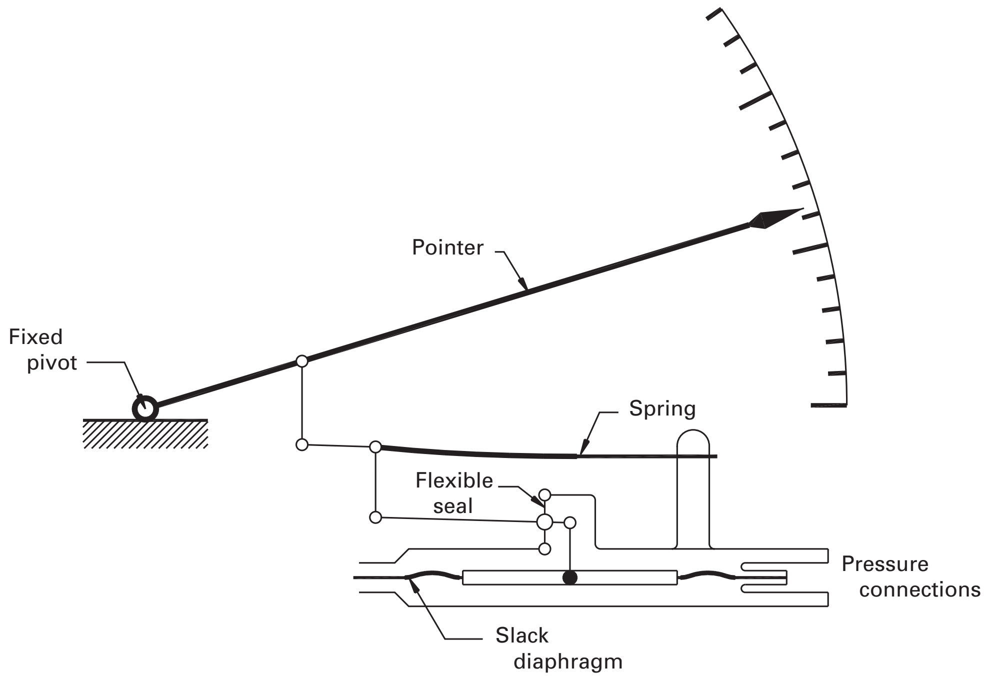


Fig. 3-3.1.3-1 Slack Diaphragm Gauge



3-2.2.4 Combustion Air. Combustion air flow measurement generally utilizes low-range dP cells in conjunction with a flow element in the duct. Typical flow elements for this service are pitot tube arrays in either the suction or discharge side of the forced-draft fans depending upon available ductwork straight lengths. The pitot tube measures the pressure differential between the static pressure and the velocity head pressure in the duct.

3-3 ELASTIC GAUGES AND THEIR APPLICATIONS

Elastic gauges are devices that use an elastic component that moves in response to pressure changes. Positive and negative (vacuum) pressure gauges, as ordinarily used, are instruments for measuring the difference between ambient pressure (atmospheric pressure) and the pressure in a pipe or vessel. The pressure to be measured is transmitted to the interior of an elastic component and results in an output motion or deflection. Elastic components most often consist of Bourdon tubes, bellows, or diaphragm capsules.

The output motion of the elastic component under pressure usually requires a mechanical mechanism to amplify and translate this motion into a detectable circular rotation of a pointer. In addition, some pressure-indicating gauges are designed without amplification mechanisms and are considered direct drive. The circular rotation of the pointer over a calibrated scale (dial) provides an indication of the applied pressure. Ambient pressure exterior to the elastic chamber is usually atmospheric pressure. The pressure relationships are shown in Fig. 2-2.1.

NOTE: More details on elastic gauges may be found in ASME B40.100, chapter titled "Gauges: Pressure Indicating Dial Type – Elastic Element" [4].

3-3.1 Types of Gauges

Gauges are classified by sensing-element type described in paras. 3-3.1.1 through 3-3.1.3.

3-3.1.1 Bourdon Tube Gauge. The Bourdon tube gauge illustrated in Fig. 3-3.1.1-1 involves a curved elastic tube, closed at one end. The tendency of the tube is to straighten out when pressure is applied. This deflection of the closed end is proportional to the pressure input, and the tube acts as a spring. Fig. 3-3.1.1-1 illustrates the motion amplified by the mechanical mechanism, called a movement. The movement components include a sector gear, pinion, and hairspring.

In indicating-dial gauges, the usual Bourdon tube is curved through an arc of 200 deg to 300 deg. In other types, the Bourdon tube may be in the form of a spiral or helix having a number of complete turns, as illustrated in Fig. 3-3.1.1-2. Combinations of these forms may be used with or without a motion-amplifying movement.

Bourdon tube gauges are made for both positive and negative (vacuum) pressure, compound and differential pressure measurement.

3-3.1.2 Bellows Gauge. The bellows gauge illustrated in Fig. 3-3.1.2-1 utilizes a thin-walled convoluted pressure-sensing component. This construction is used for measuring low pressures up to 350 kPa (50 psi).

3-3.1.3 Diaphragm Gauge. A slack diaphragm gauge, illustrated in Fig. 3-3.1.3-1, utilizes a flexible diaphragm. The motion of the diaphragm is transmitted and amplified by a suitable linkage and gears to operate a pointer. The diaphragm gauge is suitable for measuring low pressures.

3-3.2 Gauge Selection

Gauges shall be selected on the basis of their respective accuracy classification, size, case type, compatibility with the process fluid, and connections. These are discussed in paras. 3-3.2.1 through 3-3.2.5.

3-3.2.1 Accuracy. Dial-gauge accuracy is expressed as the difference between the true value and the gauge indication expressed as a percentage of the gauge span (algebraic difference between the limits of the scale). Gauges are available from manufacturers graded by accuracy limits. The following accuracy limits are defined in ASME B40.100 [4] for common gauges used for industrial and laboratory applications:

– Grade 4A: ±0.10% of span
– Grade 3A: ±0.25% of span
– Grade 2A: ±0.50% of span
– Grade 1A: ±1.0% of span
– Grade A: ±1.0% of span for the middle 50% of span and 2.0% for the balance
– Grade B: ±2.0% of span for the middle 50% of span and 3.0% for the balance
– Grade C: ±3.0% of span for the middle 50% of span and 4.0% for the balance

Grade 3A and Grade 4A are usually considered where accurate pressure measurements are required for evaluating critical processes and for test panels used to evaluate plant equipment.

3-3.2.2 Size. Since accuracy and readability are closely associated, the size of a gauge selected should be determined by the value trying to be resolved. Thus, more accurate gauges generally should have larger dials to increase resolution.

If a gauge is remote from the reader, a larger, more legible dial should be required than if the gauge were mounted on a panel in front of the reader.

3-3.2.3 Case Type. Case type is determined by several factors, including the size, method of mounting (stem, panel, or surface), material required to withstand the environment, and location of the pressure connection. In addition, cases may or may not have a solid wall between the pressure-sensing component and the observer. It is generally accepted that a solid front case will reduce the possibility of parts being projected forward in the event of a pressure-retaining component failure.

3-3.2.4 Process Media. Elastic components of gauges are generally thin-walled members that of necessity operate under high-stress conditions and shall, therefore, be carefully selected for compatibility with the medium being measured. The potential for corrosive attack is established by many factors, including the concentration, temperature, and the chemical aggressiveness of the media.

3-3.2.5 Connections. Pressure gauge connections are generally taper pipe threads. Common sizes are ¼-18 NPT and ½-14 NPT and are used up through 20,000 psi or 160 000 kPa. Above this pressure, ¼-in. high-pressure tubing connections, or equal, should be used. Other appropriately sized connections employing sealing means other than tapered threads shall be acceptable.

3-3.3 Operating Conditions

The operating conditions to be considered include the range, installation, temperature, pressure pulsation, and vibration. These are discussed in paras. 3-3.3.1 through 3-3.3.5.

3-3.3.1 Range. The range of a gauge should be selected so that the full-scale pressure is approximately twice the intended operating pressure. The maximum pressure at which the gauge is continuously operated should not exceed 75% of the full-scale pressure.

The use of gauges near zero pressure is not recommended because the accuracy tolerance of the gauge may be a large percentage of the applied pressure. For this reason, gauges should not be used for the purpose of indicating residual pressure in a tank, autoclave, or other device that has been seemingly exhausted.

3-3.3.2 Installation. Gauges should be installed in the same position and the same orientation as when calibrated. The normal position is the dial in a vertical plane and midscale at the twelve o'clock position. If gauges are to be mounted in other than normal position, it may be necessary to recalibrate the gauge in the intended mounting position.

When gauges are installed in a system where a liquid head exists, it may be necessary to compensate for this static head. The compensation may be negative or positive depending on the location of the gauge above or below the pressure tap in the system. Gauge users shall ensure the sensor tubing is completely filled with the process fluid.

3-3.3.3 Temperature. Using a pressure gauge in an environment or with media that cause the temperature of the elastic element to be different from that at which it was calibrated will increase the indication error. The error caused by temperature will be approximately the percentage values given by the following formula:

$$\frac{0.04\% \text{ of span}}{°\text{C}} \times (t_1 - t_2)°\text{C}$$

where

t_1 = temperature at calibration, °C

t_2 = temperature of the gauge in service, °C

For example, a change of 1% at full-scale pressure occurs for each 25°C change in temperature. This error is approximately proportional to the applied pressure.

Gauges represented as being compensated for service at various temperatures generally have components of special materials and design to compensate not only for the temperature effects on the elastic element but also for similar effects on the gauge mechanism. Consult the manufacturer or supplier for specific temperature ratings.

A siphon should be used to provide a seal against steam or other high-temperature condensable vapors. See para. 3-3.4.3.

3-3.3.4 Pressure Pulsation. Pressure pulsations, particularly those that are high frequency, can quickly produce abnormal wear on gauge mechanisms and can result in fatigue failure of the elastic pressure components.

3-3.3.5 Vibration. Severe vibration may cause premature wear on the mechanisms of pressure gauges. This is characterized by a gradual loss of accuracy. The effects of severe vibration may be reduced or eliminated by mounting the gauge remotely using flexible piping.

3-3.4 Gauge Attachments

When added to a pressure gauge, special accessories improve the gauge's ability to withstand adverse conditions and broaden its usefulness by performing functions not normally required of a pressure gauge alone. Some of these accessories include diaphragm seals, pulsation dampeners, siphons, pressure limiter valves, and other attachments. These are discussed in paras. 3-3.4.1 through 3-3.4.5.

3-3.4.1 Diaphragm Seals. A diaphragm seal is a mechanical separator using a diaphragm or bladder together with a fill-fluid to transmit pressure from the medium to the pressure element assembly. Other terms used are "chemical seal" and "gauge isolator." This device is intended to keep the medium out of the pressure element assembly. The purpose of the device is to prevent damage from corrosion or clogging, to maintain sanitary requirements of the medium, or to reduce the process temperature to which the pressure element assembly is exposed. See subsection 5-4 and ASME B40.100, chapter on "Diaphragm Seals" [4] for more information on the use of diaphragm seals.

3-3.4.2 Pulsation Dampeners. A pulsation dampener is a device installed between the pressure source and the pressure-sensing element that is used to minimize the effect of pressure surges. These devices are also known as snubbers, pressure equalizers, gauge protectors, and gauge savers.

See the chapter on "Snubbers" in ASME B40.100 [4] for more information on the use of pressure dampners.

3-3.4.3 Siphons. A siphon is a device installed between the pressure source and the pressure-sensing element that is used to seal against steam or other condensable vapors. The device is designed to permit cooling of condensable vapors and retention of condensate when installed in series between the gauge and the pressurized fluid. There are several devices, including pigtail siphons, coil siphons, vapor traps, and mechanical siphons. One of the more commonly used, the pigtail siphon, is a coiled tube that provides a large cooling surface. The trap created by the coil prevents the condensate from draining away. Incoming vapor passes through this liquid seal and is cooled. Condensate may be added at installation or condensation induced by cooling the siphon.

3-3.4.4 Pressure Limiter Valves. Pressure limiter valves are devices that protect pressure-sensing instruments from pressure sources in the event of system pressure rising above the adjusted closing pressure of the device. Pressure limiter valves are used to protect pressure-sensing instruments against damage, loss of accuracy, and/or rupture in the event of excessive system pressure. See the chapter on "Pressure Limiter Valves" in ASME B40.100 [4] for more information.

3-3.4.5 Other Gauge Attachments. A wide variety of pressure-gauge options and attachments are available by contacting the manufacturers. Included are

(a) bleeding devices to allow flushing of the pressure component

(b) maximum reading pointers that indicate the maximum pressure

(c) gauge cocks to shut off the gauge from the pressure system

(d) heaters to protect gauge elements from solidification of fluids

(e) electric contacts so that a circuit could be closed or opened at a desired pressure

(f) liquid-filled gauge cases to dampen pointer motion and increase the life of gauge mechanisms

3-3.5 Gauge Safety

Adequate safety results from intelligent planning and installation of gauges into a pressure system. The pressure-sensing component in most gauges is subject to high internal stresses, and some applications are subject to the possibility of catastrophic failure. The following systems are considered potentially hazardous and shall be carefully evaluated:

(a) compressed gas systems
(b) oxygen systems
(c) systems containing hydrogen or free hydrogen atoms
(d) corrosive fluid systems (gas and liquid)
(e) pressure systems containing any explosive or flammable mixture
(f) steam systems
(g) nonsteady pressure systems
(h) systems where high overpressure could be accidentally applied
(i) syste ms containing radioactive or toxic fluids (gas and liquid)

Refer to ASME B40.100 [4] or contact gauge manufactures for guidance toward minimizing the hazards that could result from misuse or misapplication of pressure gauges with elastic elements.

3-3.6 Gauge Testing

Gauge testing and accuracy verification are covered in ASME B40.100 [4]. Gauges used for transfer standards should be tested for accuracy regularly. The frequency of such testing shall depend on their demonstrated ability to retain accuracy over long periods and after repeated use.

A wide variety of mechanical and electronic standards are available to test gauges. Some of these are

(a) piston gauges (see Nonmandatory Appendix A)
(b) manometers (see Nonmandatory Appendix B)
(c) pressure transducers

Selection of a standard shall be determined by the accuracy and pressure range of the gauge being tested, suitability of the pressure medium, and convenience of use.

Gauges with higher accuracy ratings are frequently provided with adjustment means. These include rotating dials, adjustable pointers, and span adjustments. The first two are readily available to the user and should be used to adjust for zero, and also to set the pointer or dial at a known pressure. Contact the gauge manufacturer for instructions on other adjusts involving span or linearity. The record of calibration verification should be made on some suitable form such as that shown in Form 3-3.6-1.

Form 3-3.6-1 Recording of Gauge-Test Data Sample

DESIGNATION OF GAUGE NO. ________ OWNER ________

Make and type: ________

Size and range: ________

CONDITIONS DURING TESTS

	Before Use	During Use	After Use
Date and hour of test	________	________	________
Temperature of gauge	________	________	________
Pressure standard used	________	________	________

TEST DATA (All in lb/in.^{2})									Average Correction of Before and After Tests	Variance Difference Between Before and After Corrections
Standard Pressure	Gauge Reading Before Use. Rap Gauge Before Reading.				Gauge Reading After Use. Rap Gauge Before Reading.					
	Up	Down	Average	Correction	Up	Down	Average	Correction		

REMARKS:

(1) Range of pressure during test: ________

(2) Pressure characteristics during use:

(a) *Steady* – Less than 1% per second and 5% per minute, the percentage referring to the full range of the gauge.

(b) *Fluctuating* – Changes faster than for “steady” – not regular in occurrence.

(c) *Pulsating* – Changes faster than for “steady” and characterized by cyclic regularity.

(3) Equipment and location where gauge was used: ________

____

(4) Operator making tests: ________

(5) Other remarks: ________

____

Section 4
Calibration and Standards

All pressure measurements are ultimately referred to devices that serve as primary standards of pressure measurements. These, in turn, can be calibrated in terms of the basic units of mass, length, and time. The most important primary pressure standards are the piston gauge and the manometer. From these devices, pressure values are transferred to the point of use, often through long calibration chains, using various types of gauges and transducers. Most of the uncertainty of pressure measurements at the point of use comes from errors accumulated in the transfer of the measurement along a calibration chain and not from the primary standard.

To demonstrate traceability of measurements to the National Institute of Standards and Technology (NIST), other recognized international standard organizations, or recognized physical constants, it is necessary to establish calibration hierarchies. Each level in the hierarchy, including that corresponding to NIST, constitutes an error source that contributes to the error in the final measurement. Figure 4-1 is a typical pressure-measuring instrumental hierarchy.

Calibration of measurement instruments at NIST is possible; however, such calibrations can be time-consuming, inconvenient, and expensive. Most industrial working standards are referred to interlaboratory or transfer standards.

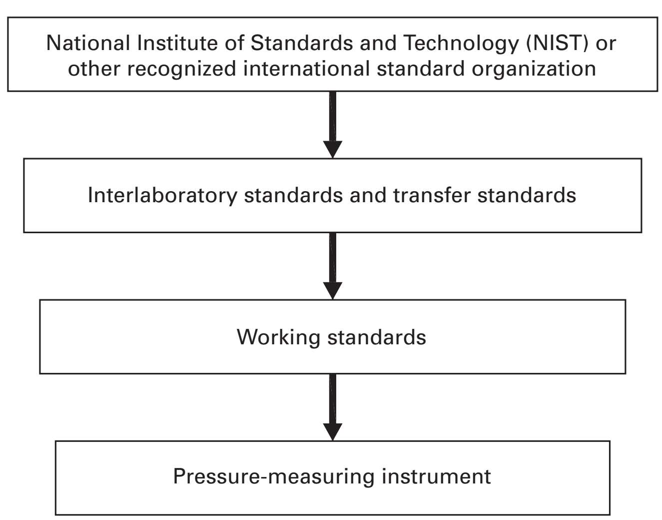
Nonmandatory Appendices A and B contain brief descriptions of the operating principles of piston gauges and manometers, which serve as interlaboratory and transfer standards.

Primary and/or secondary pressure standards are utilized for interlaboratory standards and transfer standards and have direct traceability to NIST or to other recognized national standard organizations, which provide the highest level of standards for calibration. A primary pressure standard is a pressure-measuring instrument that can reduce pressure measurements into measurements of mass, length, temperature, and gravity. Examples are piston gauges and manometers. On the other hand, a secondary standard is an instrument that must be calibrated to relate the output directly to pressure. The output from a secondary standard can be sensed mechanically or electrically utilizing principles of inductance, capacitance, or resistance.

Primary and secondary pressure standards are typically used and maintained by a calibration laboratory, which could be internal or external to an organization. The calibration laboratory provides measurements with traceability to stated references such as the National Bureau of Standards. Such pressure standards can then be used to calibrate working standards or used directly to calibrate measuring instruments in the field such as pressure gauges or pressure transmitters and pressure transducers.

Uncertainty of the pressure measurement at the point of use should include the errors accumulated and propagated in the transfer of the measurement along a calibration chain.

Fig. 4-1 Pressure-Measurement Calibration Hierarchy



Section 5
Measurement Installations

5-1 PRESSURE TAPS

The basic pressure sensor is the pressure tap or piezometer. A pressure tap usually takes the form of a hole drilled in the side of a flow passage and is assumed to sense the true static pressure. See Fig. 5-1-1. When the fluid is moving past the tap, which is usually the case, the tap will not indicate the true static pressure. The streamlines are deflected into the hole as shown in Fig. 5-1-2, setting up a system of eddies. The streamline curvature results in a pressure at the tap mouth different from the true fluid pressure. These factors in combination result in a higher pressure at the tap mouth than the true fluid pressure, a positive pressure error.

5-1.1 Velocity-Induced Errors

The magnitude of the pressure error of a carefully made square-edged pressure tap is a function of the Reynolds number, R_d^*, based on the shear velocity, v^*, and the tap diameter, d. The shear velocity equals the square root of the ratio of the local wall shear stress, τ_o, to the fluid density at the wall, ρ:

$$v^* = \sqrt{\frac{\tau_o}{\rho}}$$

The data of Shaw [5], Rainbird [6], and Franklin and Wallace [7] for taps with geometry as shown in Fig. 5-1-1 are correlated by the following expressions [8]:

$$\frac{\Delta P}{\tau_o} = 0.000157\ (R_d^*)^{1.604} \text{ for } R_d^* = v^* d/v \leq 385$$

$$\frac{\Delta P}{\tau_o} = 0.269\ (R_d^*)^{0.353} \text{ for } R_d^* > 385$$

(Extrapolation beyond $R_d^* = 1{,}000$ may be unreliable.)

Figure 5-1.1-1 shows the errors for different-size taps in fully developed flow in a smooth pipe of diameter, D. The errors are nondimensionalized by the dynamic pressure $q = ½\ (\rho V^2)$ and are a function of the pipe Reynolds number. Larger tap diameters and higher velocities give larger errors. Similar calculations have been carried out for throat taps in an ASME nozzle [9, 10].

The above information represents a correlation of available experimental data for a limited Reynolds number range. Other correlations have been found to be more representative at higher Reynolds numbers, such as those encountered in throat tap nozzles (see reference [11]).

5-1.2 Other Sources of Errors

The effect of compressibility on tap errors is not understood well nor demonstrated, even though correlations for this effect have been suggested [6, 12]. The only conclusion that can be reached is that at Mach numbers near unity, the tap error is greatly magnified and measurements in this region should be avoided if possible.

When a pressure tap is located in an accelerating flow field, the external pressure gradient is the significant parameter for correlating tap error. It has been found [6, 13, 14, and 15] that the effect of the pressure gradient is to move the effective location of the tap upstream from 0.30 tap diameters to 0.37 tap diameters. The lower number corresponds to incompressible flow while the higher number corresponds to nearly sonic flow.

In most cases, it is possible to reduce the pressure-tap error by using taps of smaller diameter. The limitation is, however, that it is more difficult to make a smaller tap that is free from burrs. The presence of burrs of a height greater than about 0.008 times the tap diameter will greatly magnify the tap error [16]. Similarly, rounding of the tap or locating the tap at positions other than normal to the surface will also affect the tap error, as shown in Fig. 5-1.2-1 [16], where relative errors are shown as percentages of the dynamic pressure.

5-2 PRESSURE PROBES

5-2.1 Total Pressure Probes

Total pressure probes are used to determine the total pressure at a specific location. Total pressure is used to determine head-loss data and to establish velocities, state points, and flow rates. By definition, total pressure can be sensed only by stagnating the flow isentropically.

5-2.1.1 Impact Tube. An impact tube or pitot tube is an open-end tube placed in the flow field pointing directly upstream (see Fig. 5-2.1.1-1). The pressure

Fig. 5-1-1 Tap Geometry

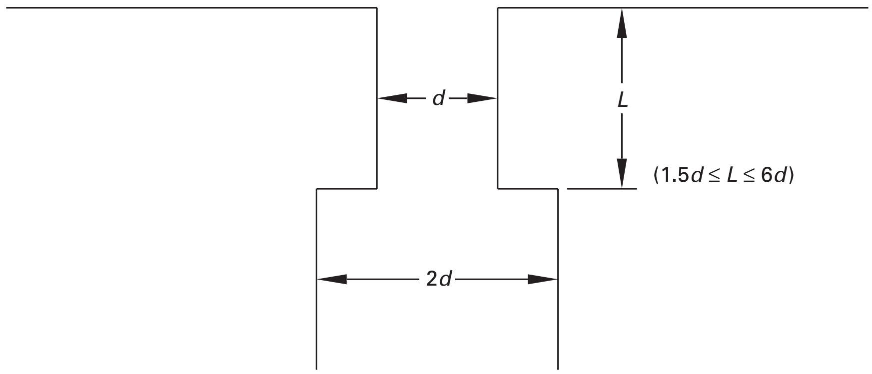


Fig. 5-1-2 Pressure-Tap Flow Field

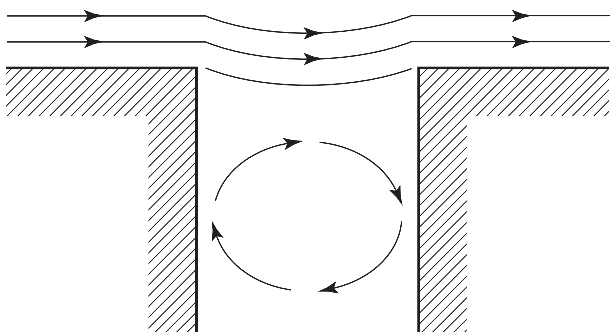
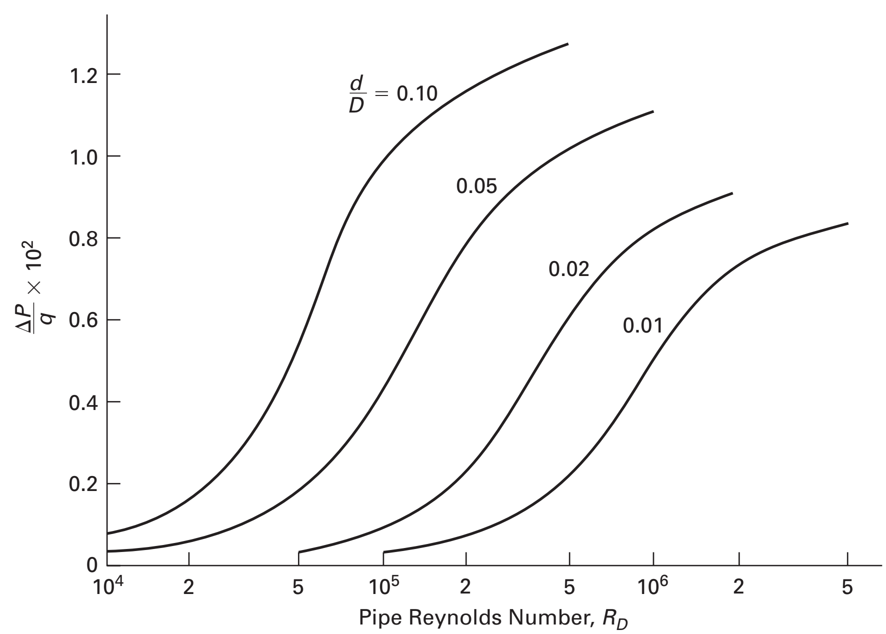
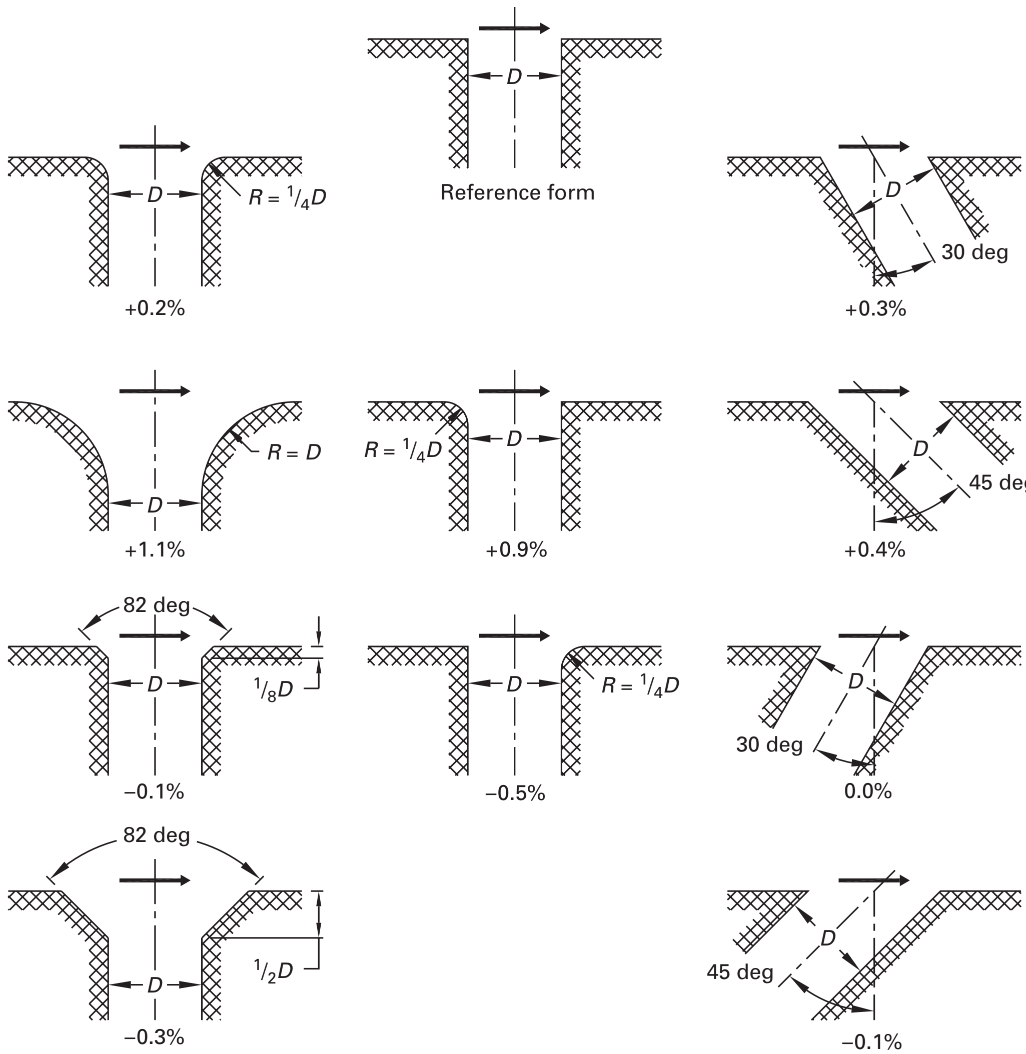


Fig. 5-1.1-1 Errors for Different Size Taps in Fully Developed Pipe Flow



GENERAL NOTE:
D = diameter of pipe
d = diameter of tap
P = absolute pressure
q = dynamic pressure

Fig. 5-1.2-1 Relative Tap Errors as Percent of Dynamic Pressure



in the tube is total pressure, P_t. The maximum velocity can be determined by changing the orientation of the pitot tube until a maximum total pressure is observed. If the static pressure, P_s, is known and the fluid is incompressible, the velocity pressure, P_v, can be calculated as the differential between the total and static pressure. This can be used to calculate the velocity, V, of the fluid at the impact tube's location. For incompressible flow of density, ρ

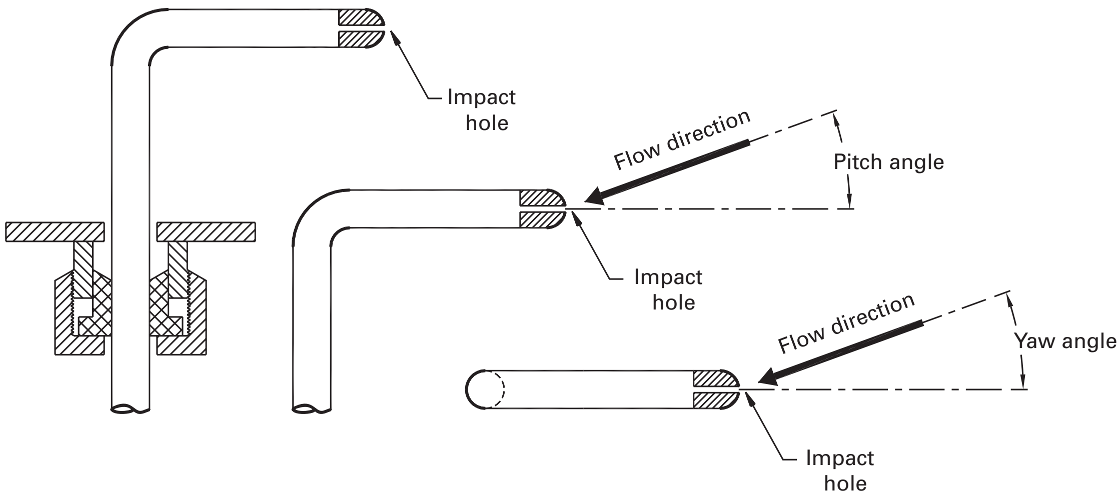
$$V = \sqrt{\frac{2(P_t - P_s)}{\rho}}$$

The impact tube can be traversed across a duct to determine the velocity profile. The shape of the tip determines the sensitivity of the probe to flow angularity (flow not parallel to the head). Figure 5-2.1.1-2 gives the variation of total pressure indication with angle of attack and geometry for pitot tubes, where ΔP_t is the change in total pressure and P_v is the velocity pressure [17].

5-2.1.2 Kiel Probe. A Kiel probe resembles an impact tube surrounded by a cylindrical shroud to direct the flow parallel to the head of the impact tube (see Fig. 5-2.1.2-1). Kiel probes are used because they are relatively insensitive to pitch-and-yaw angles up to angles of 40 deg or more measured from the axis of the head. They should be used to measure total pressure in cases where the exact flow direction is unknown or varies with operating conditions.

Other types of probes are also used to measure total pressure. All of these probes operate on the principle of stagnating the flow isentropically (as occurs at the

Fig. 5-2.1.1-1 Impact Tube



upstream side of a cylinder oriented perpendicular to the flow field) (see Fig. 5-2.1.2-2).

5-2.2 Static Pressure Probes

Static pressure probes sense the static pressure of a fluid field whether the fluid is in motion or at rest. Static pressure is required to determine fluid velocity and is useful in obtaining flow direction (as used on sphere, cylinder, wedge, and cone-type probes).

5-2.2.1 Static Tube. A static tube, similar to an impact tube, is used to determine the static pressure in a fluid stream (see Fig. 5-2.2.1-1). The accuracy of static-pressure measurement with a static tube depends mainly on the location of the sensing taps. The nose of the probe tends to accelerate the flow, which lowers the tap pressure, while the stem tends to stagnate the flow, raising the static pressure. Both effects should be compensated when constructing this type of probe. The static tube shall be calibrated before use. The static tube can be combined with an impact tube to give a pitot-static tube, which samples both the static and total pressure (see Fig. 5-2.2.1-2).

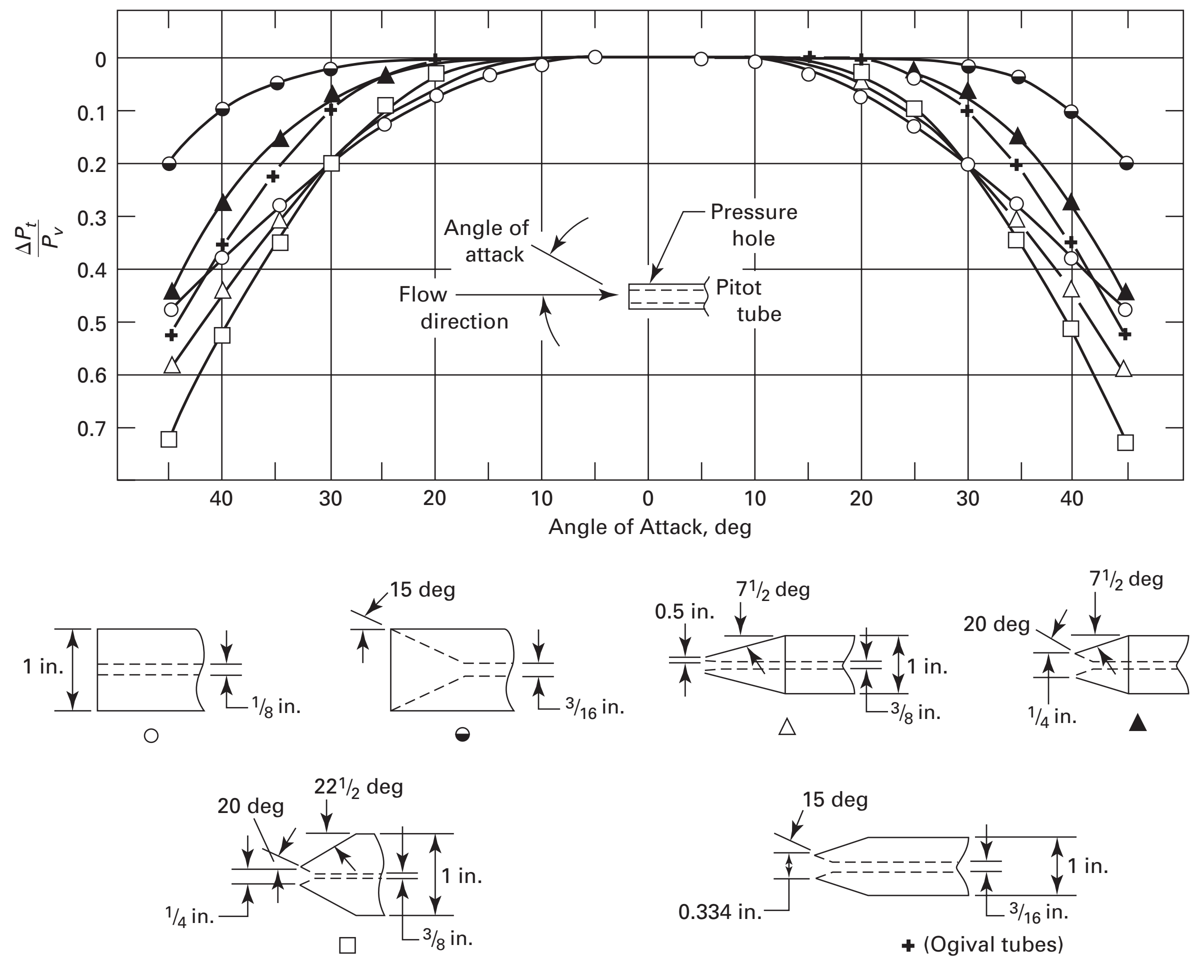
5-2.2.2 Aerodynamic Probes. Accuracy of static-pressure measurement using static-pressure taps in aerodynamic probes depends on the tap location, tap size, Mach number, and direction and change of direction of the flow field [18, 19]. Many probe configurations fall under the general title of "aerodynamic probes." Among these are the spherical, cylindrical, wedge, and cone-type probes. To exemplify their principle of operation, consider the cylindrical probe, sometimes referred to as a Fechheimer probe, in a flow field as shown in Fig. 5-2.2.2-1. Two taps are located on the cylinder in a plane perpendicular to the cylinder's center line but separated by a certain angle. Calibration of the cylindrical probe depends on the tap location with respect to the flow direction. As the probe is rotated in a flow field, an orientation can be obtained where the pressures sensed at both taps are equal. This can be done, for example, by connecting the taps to opposite legs of a manometer. The pressure sensed at these taps can then be determined and calibrated with respect to static pressure. In this way, a probe that senses static pressure and two-dimensional flow direction can be obtained.

Using the same principle as described above, static pressure can be measured by wedge-type probes, which similarly give a two-dimensional flow direction (see Fig. 5.2.2.2-2).

Three-dimensional flow directions can be determined using five-hole spherical and cone-type probes (see Fig. 5-2.2.2-3). These probes use the same principle but in two perpendicular planes. Therefore, a static pressure-balance between two holes in each of the two perpendicular planes is required. A yaw-and-pitch angle is then determined.

5-2.2.3 Basket Tip Probes. A static-pressure measurement can be quite cumbersome using an aerodynamic probe, and it is often not feasible. If only the static pressure is of interest, a basket probe can be used. This probe measures the static pressure independent of the exhaust-flow direction and mitigates the effects of a wet-steam two-phase flow for low-to-moderate fluid velocities. The basket tip probe should be used for static-pressure measurements in the condenser of a steam turbine where the flow direction is not well defined and in locations within the exhaust neck that are closer to the steam turbine. The latter constitutes the measurement

Fig. 5-2.1.1-2 Variation of Total Pressure Indication With Angle of Attack and Geometry for Pitot Tubes



GENERAL NOTE:
P_t = total pressure
P_v = velocity pressure

of the exhaust pressure of the turbine. There are two designs of basket tips currently in use. Figure 5-2.2.3-1 shows the design historically used in ASME PTC 6, *Steam Turbines*. The second one was developed and used in ASME PTC 12.2, *Steam Surface Condensers* (see Fig. 5-2.2.3-2) [20, 21].

5-2.2.4 Probe-Blockage Effects. Standard pressure probes such as cylinders and spheres are commonly used to measure total and static pressures as part of performance tests of flow elements. It is usually assumed that the probe's presence in the flow field does not change the characteristics of the flow. If the probe is small compared to the flow area, its effect on the flow is usually small and can be neglected. However, larger probes will influence the flow characteristics noticeably such that the measurements will no longer indicate the correct flow parameters. This phenomenon is generally called probe-blockage effect.

The blockage should be looked upon as a perturbation of the velocity in the vicinity of the probe. These perturbations are important both when the probe is calibrated and when it is used to make pressure measurements. If the significant blockage is due to the probe stem, Figs. 5-2.2.4-1 and 5-2.2.4-2 should be used to estimate the magnitude of the probe-blockage effect [22]. These figures are based on a cylinder of diameter, d immersed midway into the circular free-jet or pipe of diameter, D. Note that in a free-jet, the effect of blockage is to increase the static pressure while in a pipe, the opposite is true.

Fig. 5-2.1.2-1 Keil Probe

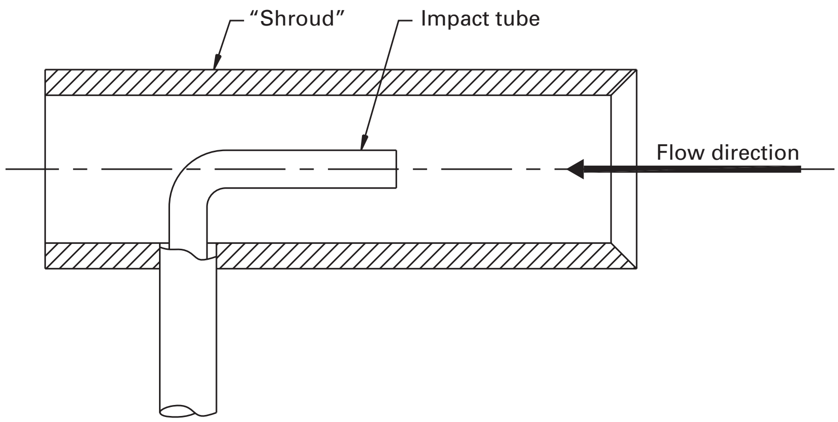


Fig. 5-2.1.2-2 Total Pressure Location on a Cylinder in a Flow Field

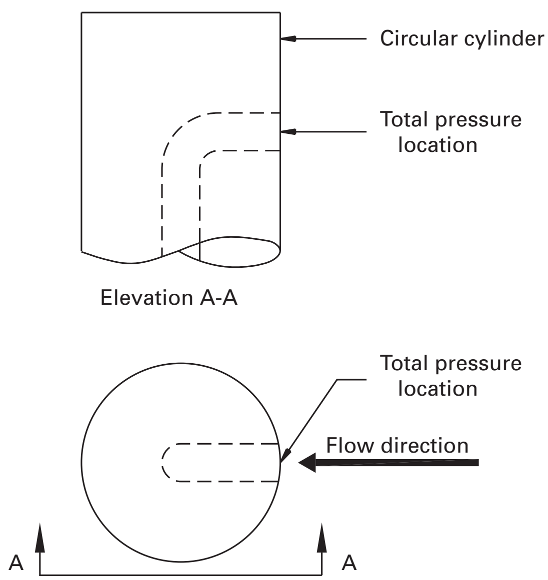


Fig. 5-2.2.1-1 Static Tube

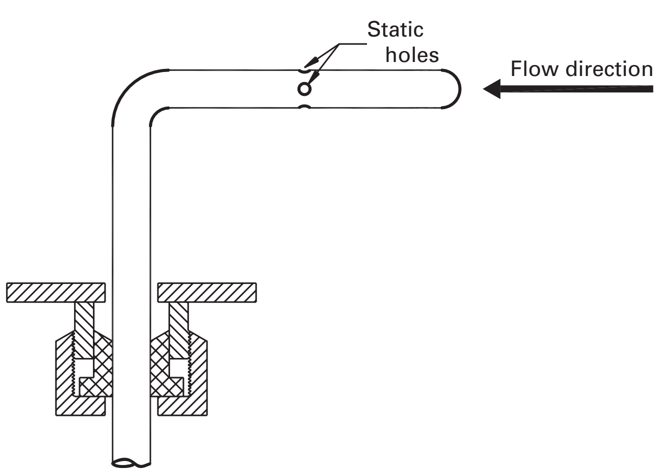


Fig. 5-2.2.1-2 Pitot-Static Tube

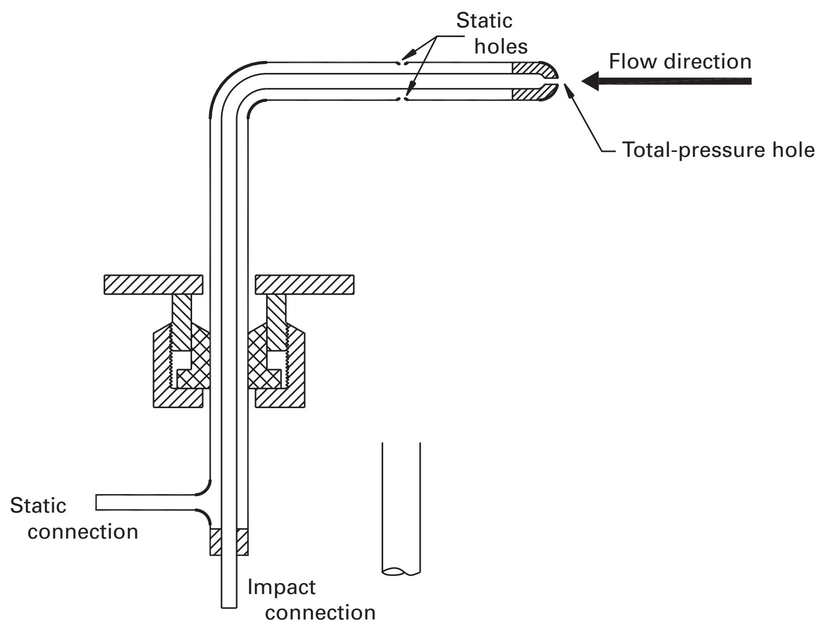


Fig. 5-2.2.2-1 Cylindrical Probe, Principle of Operation

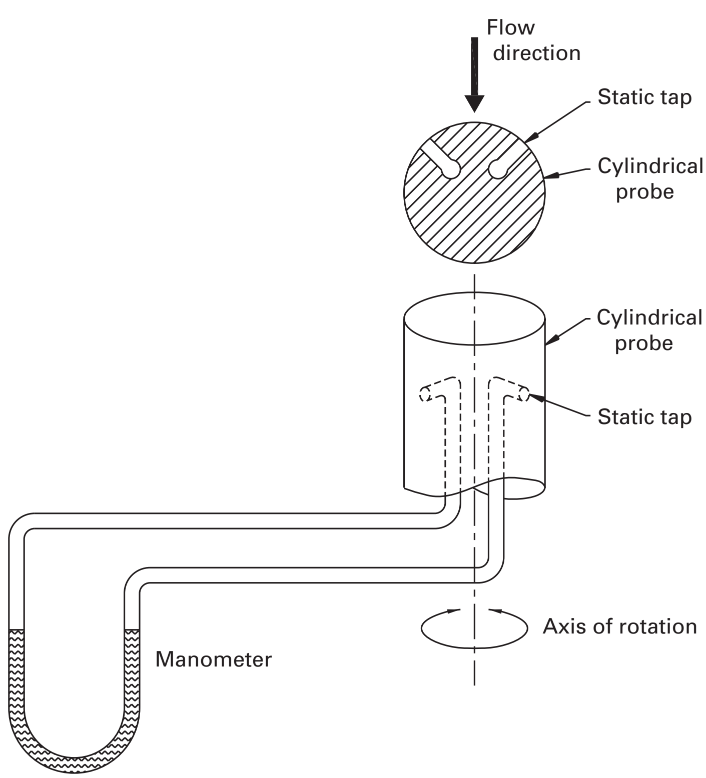


Fig. 5-2.2.2-2 Wedge-Type Probe

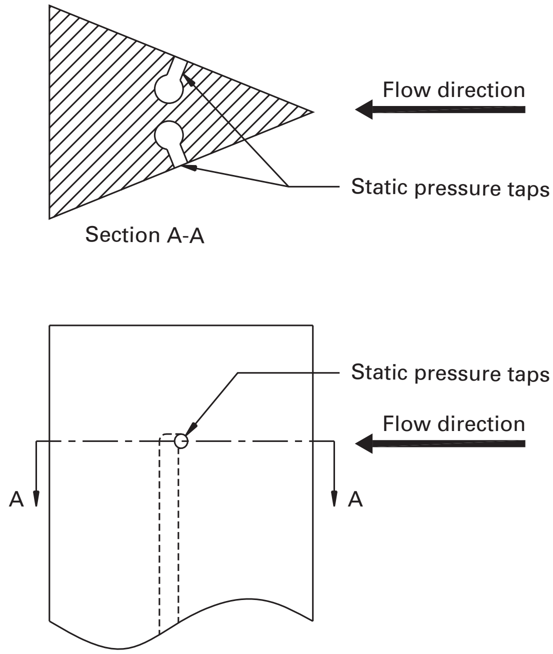
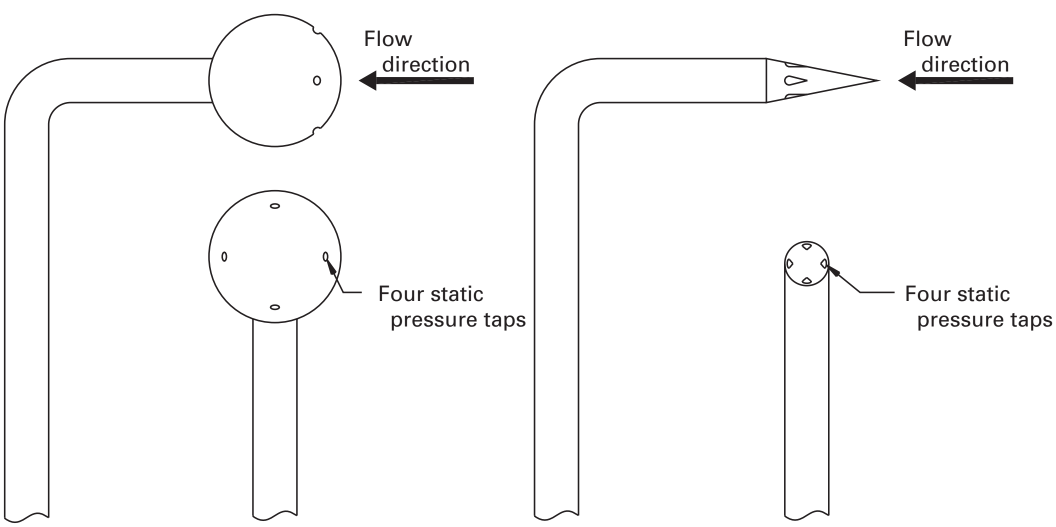


Fig. 5-2.2.2-3 Spherical- and Cone-Type Probes



(a) Spherical-Type Probe

(b) Cone-Type Probe

Fig. 5-2.2.3-1 Basket Probe

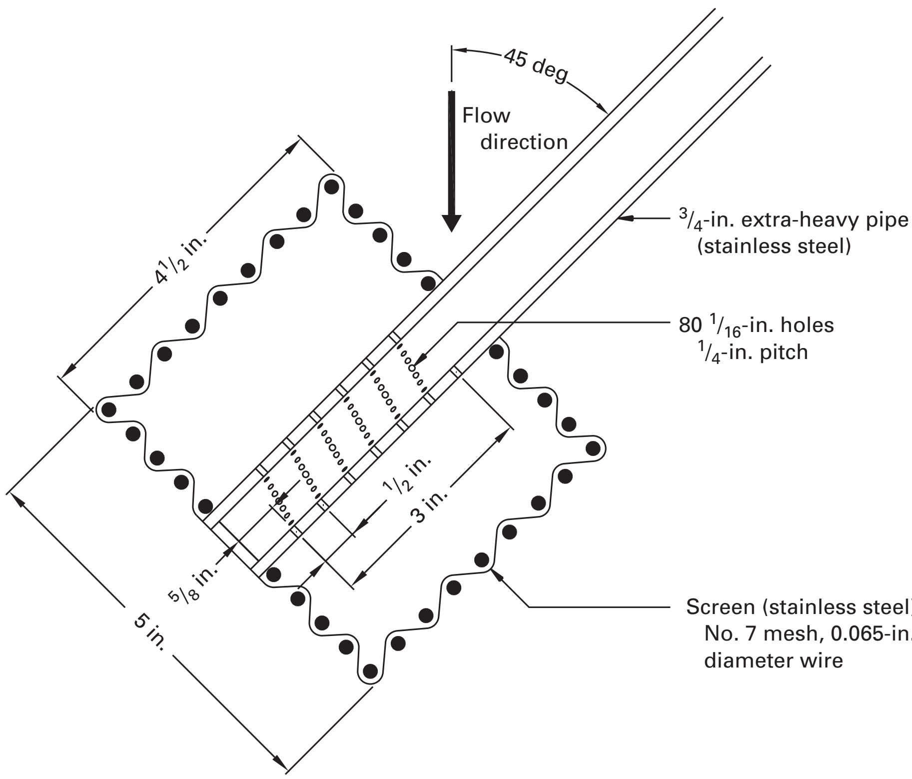


Fig. 5-2.2.3-2 Alternate Basket Probe

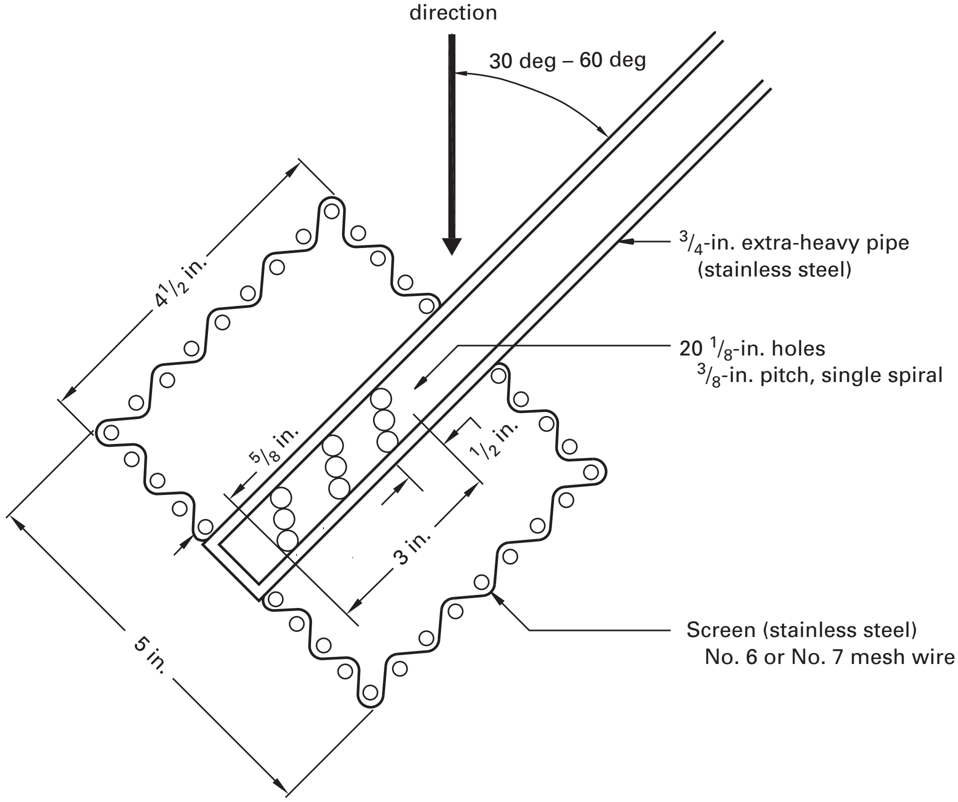
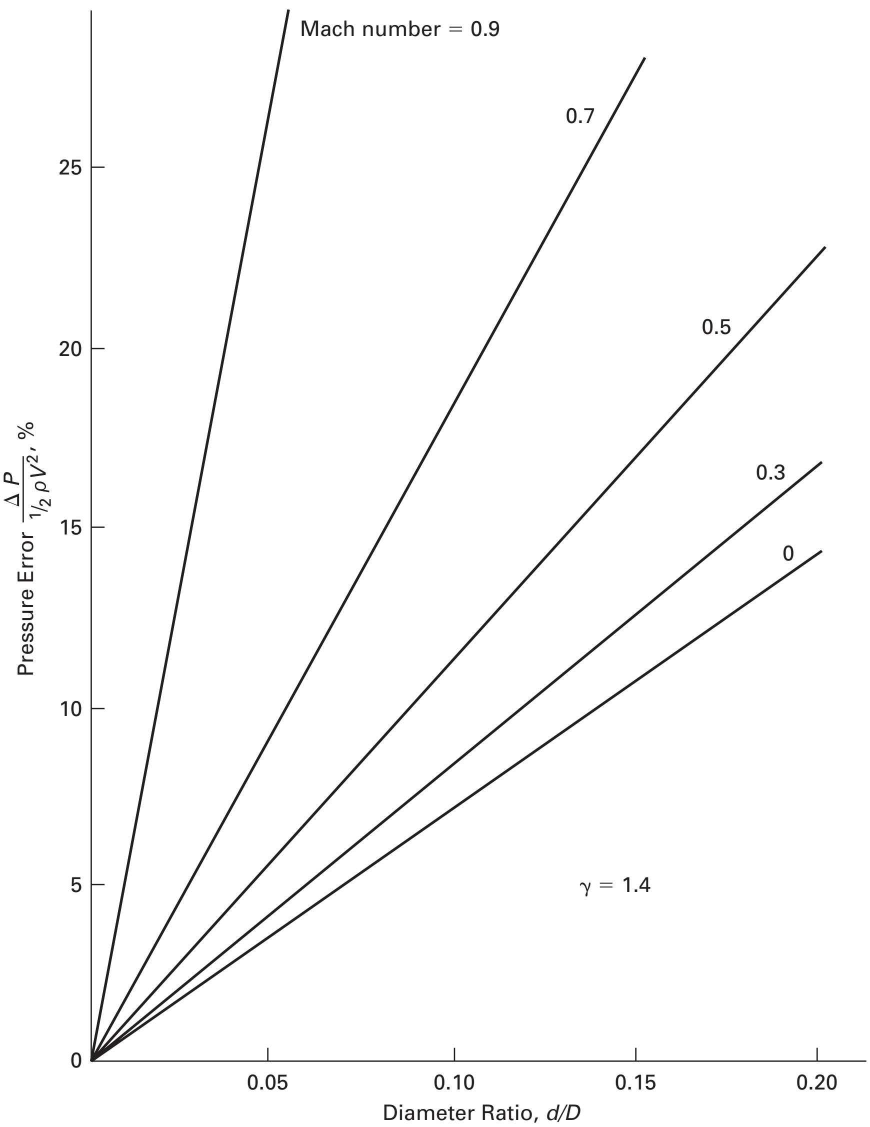
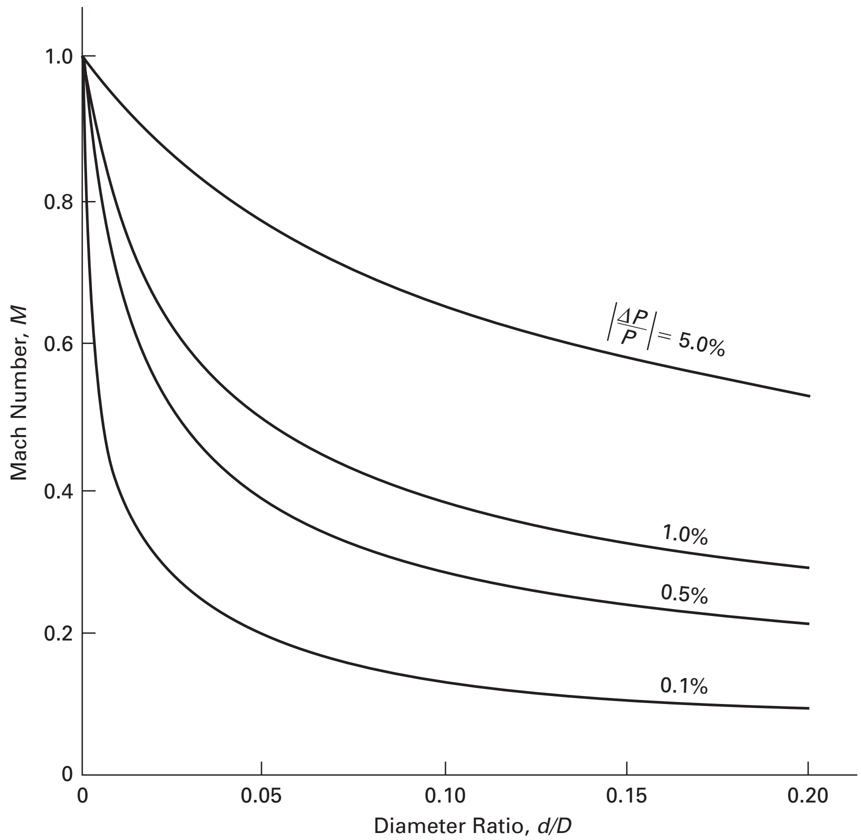


Fig. 5-2.2.4-1 Magnitude of Probe-Blockage Effects, Pressure Error



GENERAL NOTE:
D = diameter of pipe
d = diameter of cylinder
P = absolute pressure
V = fluid velocity
ρ = fluid density

Fig. 5-2.2.4-2 Magnitude of Probe-Blockage Effects, Mach Number



GENERAL NOTE:
D = diameter of pipe
d = diameter of cylinder
P = absolute pressure

5-3 CONNECTING PIPING

5-3.1 Pressure Gauges or Elastic Gauges

Pressure gauges (sensors) use a Bourdon tube, a diaphragm, or bellows as connecting piping. One end of the Bourdon tube is connected to the process pressure side and the other end to the pointer or transmitter. Bourdon tubes can be extended into spirals or helical coils to improve the resolution of the gauge or sensor.

The connecting piping includes a shutoff valve between the gauge and the process side. A second valve is often added either to drain condensate in a vapor service or to allow calibration. Other accessories include a siphon to protect the gauge from any damage due to temperature.

5-3.2 Strain Gauge

The gauges are bonded onto a beam or a structural member without any connecting requirement. A new sensor development is the fiber-optic load sensor. A fiber-optic strain gauge is installed by drilling a very small hole into a stud or bolt and inserting the gauge into the hole. Due to the variety of strain gauges, manufacturers' manuals should be followed closely.

5-3.3 Capacitance Manometer

The transducer is often mounted horizontally on a vibration isolation pad. A flexible bellows connection should be used to minimize vibration. For a differential transducer, the two ports shall be connected together through a piping to set the zero point. In vacuum application, an isolation valve shall be used. The sensor inlet shall be connected to the isolation valve through bellows tubing.

5-3.4 Piston Gauge

The connecting pipe shall have one shutoff valve in case of absolute measurement and two valves for differential-pressure measurements.

5-3.5 Pressure Transducer or Transmitter

The pressure transducer can be mounted directly onto the wall of a vessel or through an adaptor to piping or tubing.

The process inlet is connected to the transmitter via a pipe. The pipe includes a valve. In the case of differential transmitter, a three-way manifold (T-piece) connection with three valves shall be used. The valve at the center functions as an equalizing valve. The valves at the two other ends are at low-pressure and high-pressure sides.

5-3.6 DP Cells

Straight pipe is required both upstream and downstream of the dP cell for the velocity profile to develop fully. The size and orientation of the pressure taps are a function of both the pipe size and the process fluid.

Recommendations on connecting piping include the following:

(a) If the process fluid can plug the pressure taps or may gel or freeze, chemical seal protectors should be used.

(b) In steam application, the lead line should be tilted toward the pressure tap to drain condensate back to the pipe.

5-4 DIAPHRAGM SEALS

5-4.1 Typical Diaphragm Seals

Diaphragm seals are designed to separate the pressure instrument from the process while allowing pressure variations to be transmitted to the instrument's sensing element. The pressure applied on the diaphragm of the diaphragm seal is transmitted to the pressure-sensing element by filling it with suitable system fluid.

The upper and lower housings of the diaphragm seal and the diaphragm itself are made from a wide selection of materials that are suitable to handle almost any exotic process. (Seek advice on materials compatibility before choosing materials of construction.)

All diaphragm seals are designed to be used in combination with conventional pressure gauges as well as with transmitters or pressure switches. Pressure ranges from 5 in. H_2O to 20,000 psi can be handled with temperatures up to 750°F.

Parameters that influence accuracy and performance of a diaphragm seal assembly can be very complex, requiring thorough calculations and simulation under all anticipated conditions of operation.

Diaphragm seals are used most extensively in the process industry such as petrochemical, chemical, and gas plants; oil refineries; pulp and paper mills; food and dairy processes; and water and sewage treatment plants.

5-4.2 Factors That Shall Be Considered for Various Applications

If the process is corrosive, highly viscous, or heterogeneous, or contains suspended matter, the fluid shall not enter the interior of a regular pressure element. The temperature may be beyond the capability of existing pressure instruments, or the effect of the temperature may cause unacceptable inaccuracies. A diaphragm seal with capillary will facilitate relocation for easy observation of the instrument. Sanitary conditions shall be maintained. A flush-mounted diaphragm seal avoids cavities and dead volume. A suitably designed diaphragm seal will provide protection.

5-4.3 Theory of Operation

Figures 5-4.3-1 through 5-4.3-11 highlight operating principles of a diaphragm seal assembly: diaphragm seals, the pressure instrument, and capillary. The pressure instrument may be a conventional pressure gauge, per Fig. 5-4.3-1, or a pressure transmitter, pressure switch, or pressure transducer. The diaphragm seal assembly shall be carefully filled with a suitable liquid. Any pressure applied to the diaphragm is hydraulically transmitted to the pressure-sensitive element of the measuring instrument.

The pressure instrument should be either directly assembled or connected to the diaphragm seal by means of a capillary. The capillary isolates the instrument from hot processes. Effects of location, temperature, viscosity, and length of capillary on response time and accuracy shall be considered.

Once filled and calibrated, the hermetically sealed diaphragm seal assembly shall not be disassembled.

Where applicable, diaphragm seal parts (diaphragm, lower housing, and gaskets) that are exposed to the process shall be made of materials that resist pressure, temperature, and possible chemical corrosion.

The system fill-fluid may leak if the diaphragm is damaged or subjected to abnormal wear. Therefore, the fill-fluid should be carefully selected to be compatible with the process. This is especially true when the diaphragm seal is used in food and beverage processing. A variety of fill-fluids are available to handle almost any application.

5-4.4 Basic Designs

There are three basic designs of diaphragm seals that are suitable for virtually all applications. These are diaphragm, in-line, and probe seals.

Selection of diaphragm, in-line, or probe seals shall depend on the most convenient means of installation and on pressure conditions and accuracy requirements.

See Figures 5-4.3-2 and 5-4.3-3 for examples of these seals.

Fig. 5-4.3-1 Seal Assembled With Capillary

Fig. 5-4.3-2 Diaphragm Seals and In-Line Diaphragm Seals Installed

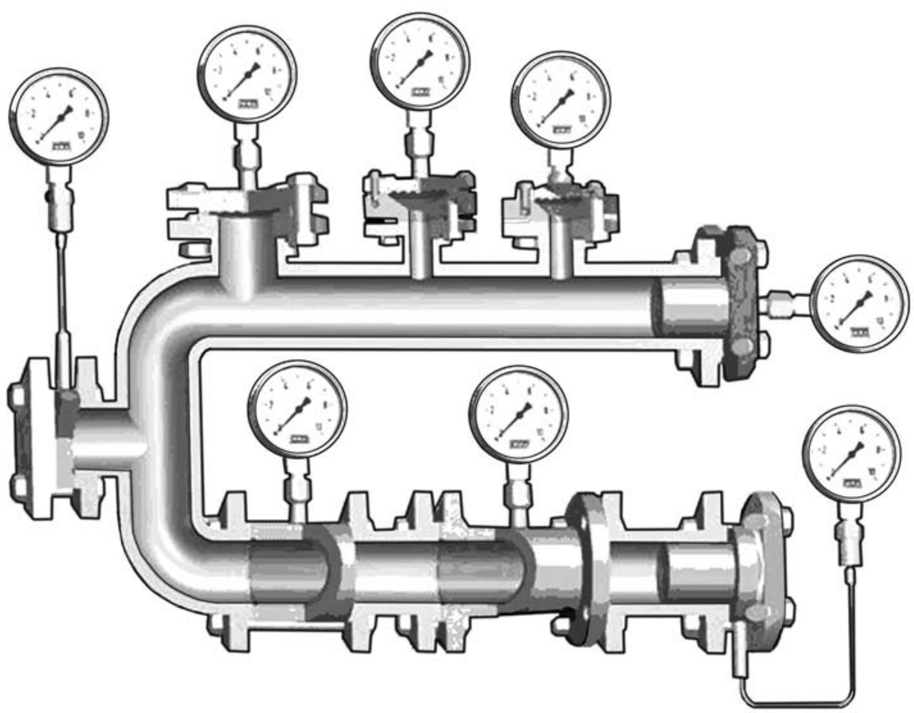


Fig. 5-4.3-3 Diaphragm Seals and Probe Seal Installed

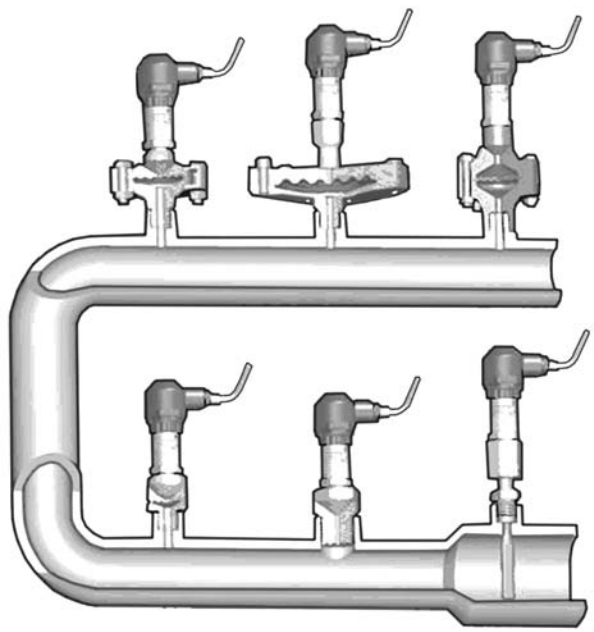


Fig. 5-4.3-4 Threaded Diaphragm Seal

Fig. 5-4.3-5 Flanged Diaphragm Seals

(a) $^1/_2$-in. to $1^1/_2$-in. Tapered Bolt Holes

(b) $^1/_2$-in. to $1^1/_2$-in. Through Bolt Holes

Fig. 5-4.3-6 Integral Flange and Diaphragm Seal

Fig. 5-4.3-7 Separate Flange and Diaphragm Seal

Fig. 5-4.3-8 Pancake Diaphragm Seal With Capillary Connection

Fig. 5-4.3-9 Pancake Diaphragm Seal Installed

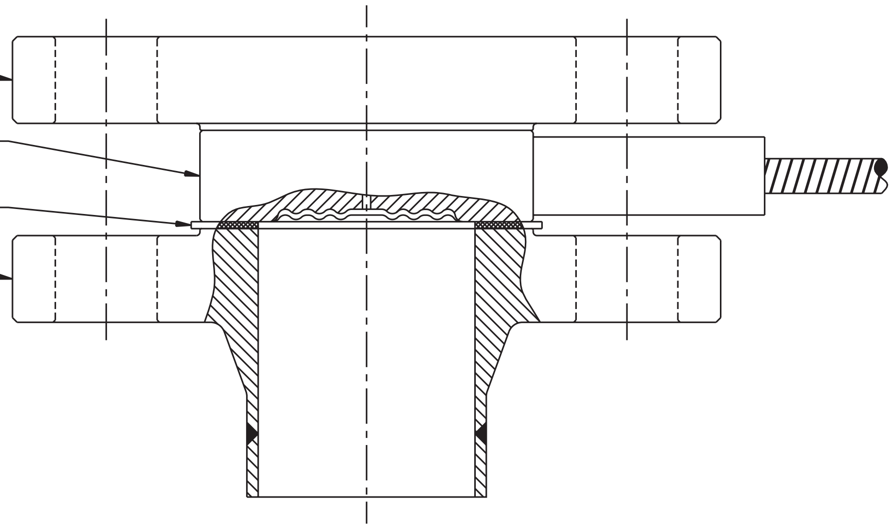
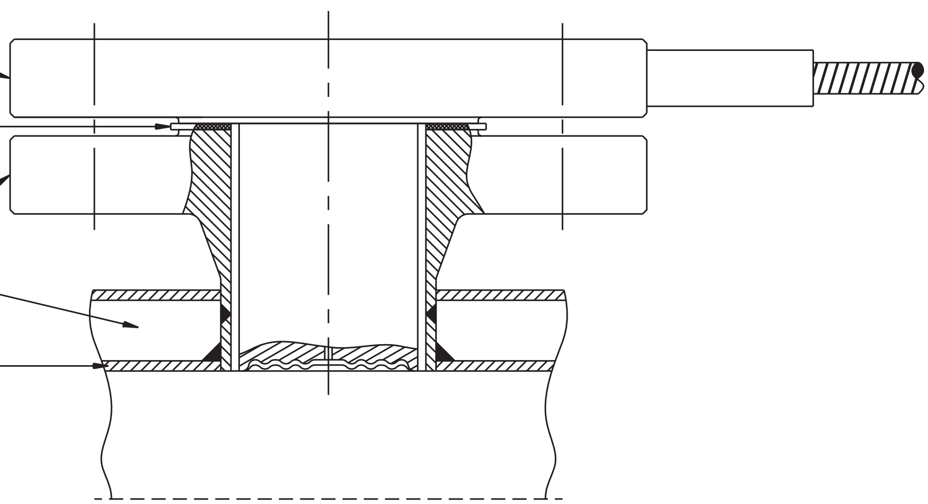


Fig. 5-4.3-10 Flange Extension



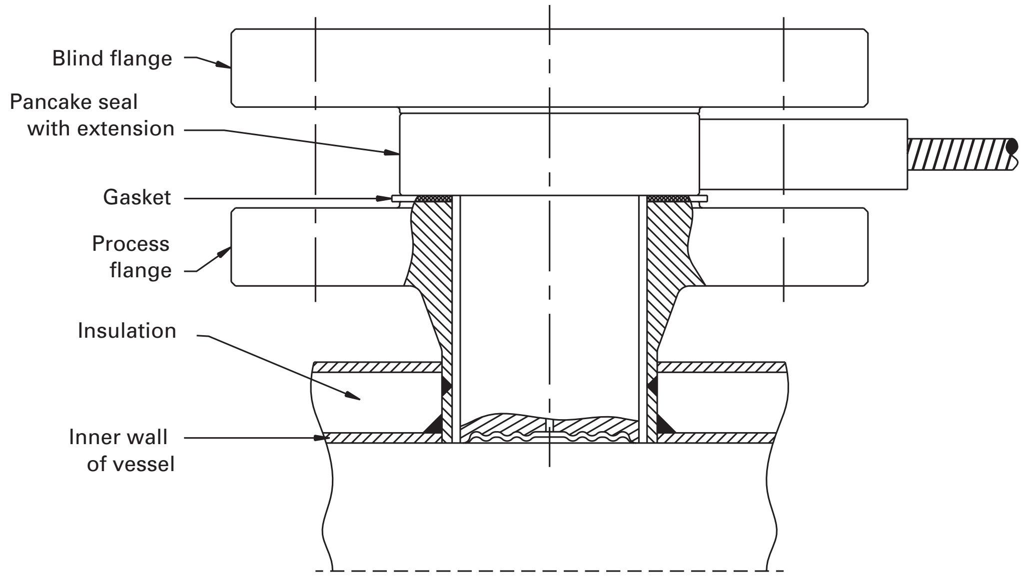
5-4.5 General Application for Diaphragm Seals

The three types of general-application seals include diaphragm seals (threaded, flanged, flush or extended, pancake), in-line seals, and probe seals. Diaphragm seals are available with pressure ratings of up to a 10,000 psi and temperature ratings of up to 750°F; these designs are universally suitable for corrosive, hot, and viscous processes.

5-4.5.1 Threaded Seals. Threaded diaphragm seals (see Fig. 5-4.3-4) provide lower housings with ¼-in. to 1½-in. NPT (female and male) sizes. The lower housing screws onto a pipe, and a mounting ring bolted to the lower housing holds the upper housing with diaphragm in place. Threaded seals are available in a large variety of materials with or without flushing connections. Lower housings are available that meet all existing national and international standards.

5-4.5.2 Flanged Seals. Flanged diaphragm seals (see Fig. 5-4.3-5) include a mounting flange to be used when aligning the diaphragm with the process connection. The ½-in. to 1½-in. versions of this seal are available in a large variety of materials (including Teflon linings and coatings) and with or without flushing connections. Smaller welded sizes are available including welding adapters that enable a larger diaphragm diameter to be used with the smaller connections.

Fig. 5-4.3-11 Pancake Extension



5-4.5.3 Flush Flanged Diaphragm Seals

(a) Integral Flange and Diaphragm Seals. Flanged diaphragm seals (see Figs. 5-4.3-6 and 5-4.3-7) include a mounting flange that assists when aligning the diaphragm with the process connection. The 2-in. to 5-in. (50-mm to 125-mm) versions of this seal should be used with the diaphragm surface flush with the process or with a flushing ring. Versions of this seal are available in a large variety of materials (including Teflon linings and coatings). The diaphragm is an integral part of a standard flange and installed to be flush with the flange gasket face. Both types enable simple installation while the diaphragm is fully exposed to the process medium.

(b) Separate Flange and Diaphragm Seals. The upper housing with its welded diaphragm is separate from the retainer flange. This design allows the use of different flange materials.

(c) Pancake Seals. Pancake diaphragm seals (see Figs. 5-4.3-8 and 5-4.3-9) provide a basic 2-in. to 5-in. (50-mm to 125-mm) process connection. Available with or without a flushing ring, this seal has a flush or recessed diaphragm surface. Versions of this seal are available in a large variety of materials (including Teflon linings and coatings). The capillary connection is on the side of the seal, enabling use in areas where space is limited or restricted on the outside of the vessel. Because the flange is not a permanent part of this seal, it provides more flexibility in plants where flanges with different pressure ratings are required.

The diaphragm housing corresponds to the size of the sealing face of a standard flange. Upon installation, the diaphragm seal is sandwiched between the process flange and a standard blind flange.

(d) Flanged Seal With Extended Diaphragm. Extended flanged seals (see Figs. 5-4.3-10 and 5-4.3-11) in 2-in. to 5-in. versions are available in a large variety of materials (including Teflon coatings) and provide a choice of extension lengths (2 in., 4 in., 6 in., and 8 in. are standard). These mount on a pipe flange and extend through insulation to the tank wall.

Versions of the extended flange that incorporate a full flange are available. There are also versions to be sandwiched in a manner similar to the pancake type.

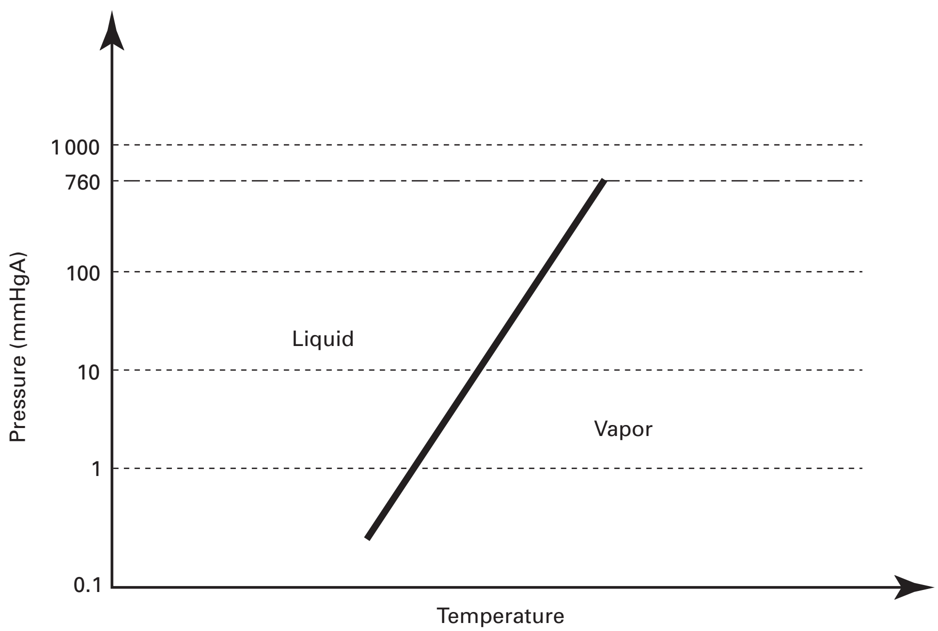
5-4.6 Materials

The proper selection of materials at the purchase stage insures long service life and reduced maintenance cost. Literature or other available information shall be consulted to ensure selection of the best possible material for a given application. The effects of corrosion shall be considered when selecting materials for pressure-containing parts. The process pressure and temperature requirements shall be reviewed to ensure selection of the proper wetted part material.

5-4.6.1 Corrosion. All metals and alloys are susceptible to corrosion, which is the progressive dissolving or wearing away caused by chemical attack. For example, gold is highly corrosion resistant to the atmosphere, but it will corrode if exposed to mercury at ambient temperature. On the other hand, iron is not corroded by mercury but corrodes when exposed to atmosphere. The two basic types of corrosion are uniform and localized.

5-4.6.2 Uniform Corrosion. Uniform corrosion, the most common form type, attacks over large surface areas. It is also the easiest to control through selection

Fig. 5-4.7-1 Vapor Pressure Curve of a Fill-Fluid



of appropriate materials or protection methods, such as zinc, chromium, or nickel plating. To protect against external corrosion, special paints or plating shall be used.

5-4.6.3 Localized Corrosion. The various forms of localized corrosion are galvanic, crevice or gap, pitting, selective leaching, intergranular, and stress corrosion.

5-4.6.4 Material Selection. Material selection is the responsibility of the user. The manufacturer should be contacted for assistance in material selection.

5-4.7 Fill-Fluids

Generally, the primary criteria for fill-fluid selection are temperature limits and compatibility with the process.

Ideally, any fill-fluid should work in any application. Therefore, selecting the fill-fluid should be a matter of checking its compatibility with the process fluid and the process temperatures. Unfortunately, the fluid's characteristics change with temperature, and this can affect the overall performance of a fill-fluid in a remote-seal system. In addition, the temperature limits set for a fluid will depend upon how that fluid is to be used, so merely reading the manufacturer's product data sheet for a fluid will not always be a good indicator that it will work well in a specific filled system. Experience is extremely important here.

The requirements of a fill-fluid for a remote-seal system depend upon a variety of characteristics, including the fluid's

(a) safety and handling needs
(b) process compatibility with the remote-seal system
(c) viscosity
(d) coefficient of thermal expansion
(e) specific gravity
(f) potential operating-temperature range

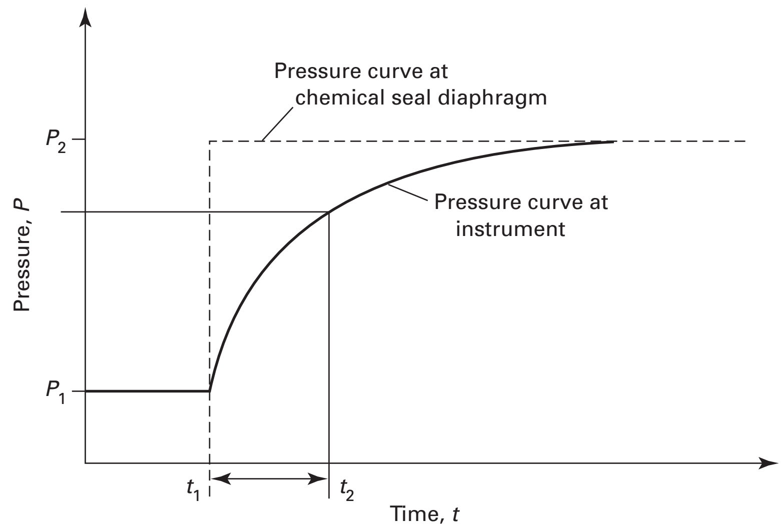
Many manufactures offer a variety of fluids that will meet most customer requirements, but it is important to understand how the fluid's characteristics interact with the seal system and how it will affect its performance in a given application before the final selection is made.

The fill-fluid chosen for a vacuum application shall be able to meet the conditions of the application. In particular, the key parameter of the fluid is its vapor pressure. The vapor pressure curve of a fluid represents the pressure and temperature conditions when it changes from the liquid state into the vapor state. The fluid chosen shall be one that remains in the liquid state throughout all combinations of pressure and temperature to which it may be exposed. The fluid will remain in the liquid state if the conditions on the upper left side of the curve are met on the vapor pressure curves shown in Fig. 5-4.7-1. If the application is one where the temperature and pressure are on the lower right side of the line, then the vapor pressure limit is exceeded and vaporization will occur. When vaporization occurs, the seal will be damaged.

5-4.8 Capillaries

Capillaries transmit pressure from the seal to the pressure-measurement device. When choosing capillaries, length and inside diameter should be considered.

Fig. 5-4.9-1 Response Time



Both of these can have an effect on overall performance in the area of temperature and time response.

5-4.9 Response Time

The response time of the measuring system (diaphragm seal, capillary, and pressure instrument) is the time it takes for the instrument to indicate 63.2%, 90%, or 95% of the value of a sudden pressure variation (see Fig. 5-4.9-1).

The response time is a function of volume displacement in the measuring system. The change of the volume of the fill-fluid is proportional to the volume of the system; the response time can be improved if the volume is reduced. The intent should be to optimize the volume of the pressure element and diaphragm seal by varying the length and internal diameter of the capillary. The viscosity of the fill-fluid will also affect response time. However, coefficient of expansion and operating-temperature range shall also be considered as they affect accuracy. The objective is to balance these conflicting effects to provide the most important parameters of indication, accuracy, or response time.

5-4.10 Installation

The level difference between pressure instrument and diaphragm seal (in particular with attached capillary) causes a shift in zero point. This is a result of the hydrostatic pressure of the capillary fill-fluid. The reading is lower if the instrument is above the level of the diaphragm seal, but higher if the instrument is below this level. The level difference should be specified to enable compensation when designing and calibrating the diaphragm seal-assembly (see Fig. 5-4.10-1).

5-4.11 Performance of Diaphragm Seals

The quality of a measuring system (diaphragm seal, capillary, and pressure instrument) is largely influenced by the interaction of various parameters, such as displacement volume, control volume, volume changes due to temperature and pressure, geometrical data of the complete assembly, the characteristics of fill-fluid, and the stiffness curve of the diaphragm under varying operating conditions. The manufacturer shall be consulted for assistance in selecting the components of the measuring system.

5-5 INSTALLATION EFFECTS

Most pressure indicators are located remote from the pressure sensor, often at a different elevation. This difference in height introduces a bias in the pressure measurement for which a correction factor shall be introduced.

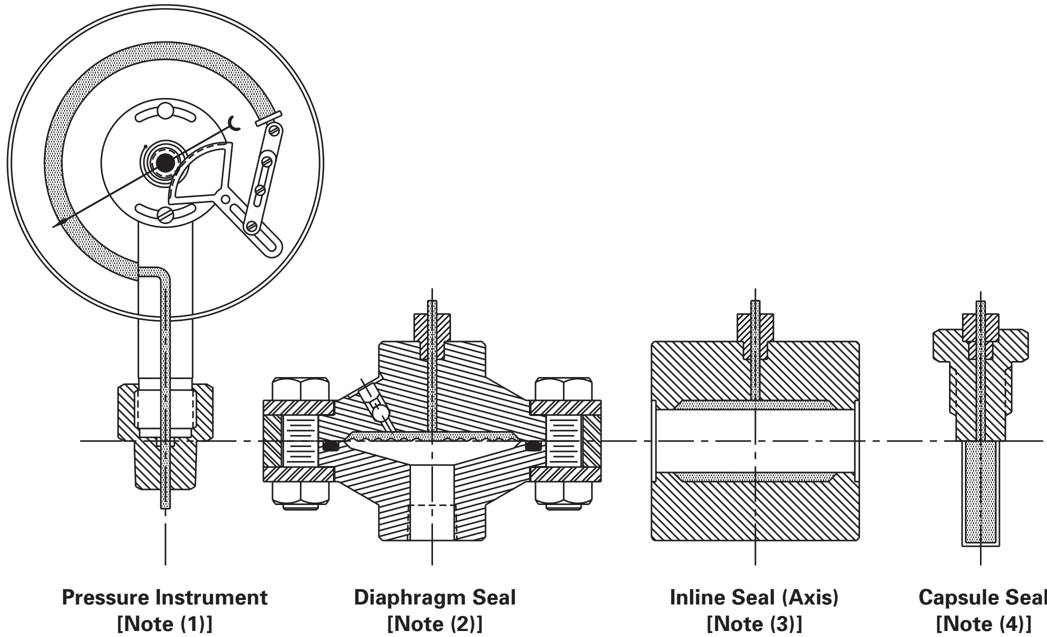
5-5.1 Gauge Pressure Measurement

In the case of gauge pressure measurements, the reference is the atmospheric pressure. However, the sensor indication can change not because of a change in process pressure but because of change in atmospheric pressure.

5-5.2 Strain Gauges

When selecting a strain gauge, one shall consider not only the strain characteristics of the sensor, but also its temperature sensitivity and change in resistance due to time. Strain gauges, when mounted at a distance from the measuring point, increase the possibility of errors due to temperature variations and wire resistance changes.

Fig. 5-4.10-1 Installation Consideration of Pressure Instrument and Diaphragm Seals



NOTES:
(1) Installs at the sealing face of the pressure connection
(2) Installs at the level of the diaphragm or at the sealing face of the flange (flange seals and pancake seals)
(3) Installs at the diaphragm horizontal
(4) Installs at the sealing face of the pressure connection

5-5.3 Calibration

Regular calibration of sensors shall be performed as time causes drift and loss of calibration.

5-5.4 Temperature Compensator

Variations in ambient and process temperatures can cause error in pressure measurements. In such cases, a temperature compensator should be used.

5-5.5 Vibration Dampers

To prevent fluctuation in measurement, vibration dampers should be installed between the process and the instrument.

5-5.6 Transmitter Housing

The transmitter should be located in an area where the ambient temperatures do not have a negative effect on its capabilities. If that is not possible, then the transmitter should be housed in a temperature-controlled case.

5-5.7 Transmitter

Location transducers and transmitters shall be mounted as far away as practical from sources of electromagnetic or radio-frequency interference.

Section 6
Uncertainties in Pressure Measurement

6-1 INTRODUCTION

There is an inherent uncertainty in the use of any measurement (pressure, temperature, etc.) to represent a true value. The total uncertainty in a measurement is the combination of uncertainty due to random error and uncertainty due to systematic error.

6-2 COMBINED STANDARD UNCERTAINTY AND EXPANDED UNCERTAINTY

The combined standard uncertainty, $u_{\bar{x}}$, of the measurement mean, which is the total uncertainty at plus or minus one standard deviation level, is calculated as follows:

$$u_{\bar{x}} = \sqrt{\left(b_{\bar{x}}\right)^2 + \left(s_{\bar{x}}\right)^2} \tag{6-2-1}$$

where

$b_{\bar{x}}$ = systematic standard uncertainty

$= \frac{B_{\bar{x}}}{2}$, where $B_{\bar{x}}$ represents the 95% confidence limit

$s_{\bar{x}}$ = random standard uncertainty of the mean

The expanded uncertainty of the measurement mean is the total uncertainty at a defined level of confidence. For applications in which a 95% confidence level is required, the expanded uncertainty, $U_{\bar{x}}$, is calculated as follows:

$$\begin{aligned} U_{\bar{x}} &= 2u_{\bar{x}} \\ &= 2\sqrt{\left(b_{\bar{x}}\right)^2 + \left(s_{\bar{x}}\right)^2} \end{aligned} \tag{6-2-2}$$

Expanded uncertainty is used to establish a confidence interval about the measurement mean, which is expected to contain the true value. Thus, the interval $\bar{X} \pm U_{\bar{x}}$ is expected to contain the true value with 95% confidence.

6-3 RANDOM STANDARD UNCERTAINTY

Since only a finite number of measurements are acquired during a test, the true population mean and population standard deviation are unknown but can be estimated from sample statistics. The sample mean, X, is given by

$$\bar{X} = \sum_{j=1}^{N} X_j \tag{6-3-1}$$

where

N = number of measurements in the sample

X_j = value of each individual measurement in the sample

The sample standard deviation, s_x, is given by

$$s_x = \sqrt{\sum_{j=1}^{N} \frac{(X_j - \bar{X})^2}{N-1}} \tag{6-3-2}$$

Since the sample mean is only an estimate of the population mean, there is an inherent error in the use of the sample mean to estimate the population mean. For a defined frequency distribution, the random standard uncertainty of the sample mean, s_x, can be used to define the probable interval about the sample mean that is expected to contain the population mean with a defined level of confidence. The random standard uncertainty of the sample mean is related to the sample standard deviation as follows:

$$s_{\bar{x}} = \frac{s_x}{\sqrt{N}} \tag{6-3-3}$$

For a normally distributed population and a large sample size ($N > 30$), the interval $\bar{X} \pm 2s_{\bar{x}}$ is expected to contain the true population mean with 95% confidence (where the value 2 represents the Student's t value for 95% confidence).

6-4 USING ELEMENTAL RANDOM ERROR SOURCES

Another method of estimating the random standard uncertainty of the mean for a measurement uses information about the elemental random error sources in the entire measurement process. If all the random standard uncertainties are expressed in terms of their contribution to the measurement, then the random standard uncertainty for the measurement mean is the root-sum-square of the elemental random standard uncertainties of the mean from all sources divided by the square root of the number of readings, N, averaged to determine the mean value, $\bar{X}$. This can be expressed as follows:

$$s_{\bar{x}} = \frac{1}{\sqrt{N}} \sqrt{\sum_{k=1}^{K} (s_{\bar{x}_k})^2} \tag{6-4-1}$$

where

K = total number of systematic error sources

As an example, consider the pressure data-acquisition system consisting of

— pressure transducer
— excitation voltage
— signal conditioning process
— recording device
— probe errors
— environmental effects

Each of the elemental random standard uncertainties of the mean, $s_{\bar{x}_k}$, is calculated from the sample standard deviation, s_x.

6-5 SYSTEMATIC STANDARD UNCERTAINTY

The systematic standard uncertainty, $b_{\bar{x}}$, is defined as a value that quantifies the dispersion of the systematic error associated with the mean. The true systematic error, β, is unknown, but $b_{\bar{x}}$ is evaluated so that it represents an estimate of the standard deviation of the distribution for the possible β values.

The systematic standard uncertainty of the measurement is the root-sum-square of the elemental systematic standard uncertainties, $b_{\bar{x}}$, for all sources.

$$b_{\bar{x}} = \sqrt{\sum_{k=1}^{K} (b_{\bar{x}_k})^2} \qquad (6\text{-}5\text{-}1)$$

where

$b_{\bar{x}_k}$ = an estimate of the standard deviation of the k^{th} elemental error source

There can be many sources of systematic error in a measurement, such as the calibration process, instrument systematic errors, transducer errors, and fixed error of methods (including spatial variation).

As an example, the elemental systematic uncertainties due to calibration and spatial variation can be combined as follows:

$$b_{\bar{x}} = \sqrt{(b_{\bar{x}-calib})^2 + (b_{\bar{x}-spatial})^2} \qquad (6\text{-}5\text{-}2)$$

6-6 PROPAGATION OF MEASUREMENT UNCERTAINTIES INTO A RESULT

Calculated results are not usually measured directly. Instead, more basic parameters such as temperature and pressure are either measured or assigned and the required result is calculated as a function of these parameters. The magnitude of uncertainty in a test result can be quantified by combining the uncertainties of the individual parameters that constitute the result along with the absolute sensitivity of these parameters on the result.

For example, consider the elemental systematic uncertainty in a measurement loop consisting of a differential pressure, ΔP, measured across a flow nozzle measured by means of a digital differential-pressure indicator and converted to flow rate, w, using the simplified equation

$$w = C\sqrt{\Delta P} \qquad (6\text{-}6\text{-}1)$$

where

C = any constant for converting the square root of differential pressure to flow rate

The relative sensitivity coefficient (dimensionless) for flow rate with respect to differential pressure is

$$\theta' = \frac{\delta w / w}{\delta \Delta P / \Delta P} = \tfrac{1}{2} \qquad (6\text{-}6\text{-}2)$$

The relative sensitivity coefficient can also be established numerically by making a small change in the differential pressure and noting the change in the flow rate.

The differential pressure indicator is calibrated in place and zeroed at line pressure immediately prior to the test. In-place calibration and zeroing at line pressure minimizes uncertainties due to mounting position, ambient-temperature effects, and static-pressure effects. The uncertainty of the differential pressure transducer is characterized by ±0.1% of span. The span is 0 in. H_2O to 800 in. H_2O. At test conditions the differential pressure is 200 in. H_2O. The relative uncertainty, U, of the pressure transducer is

$$\frac{U_{\Delta P}}{\Delta P} = \frac{(\pm 0.001) \times 800}{200} \pm 0.4\% \text{ of the pressure reading}$$

The resulting uncertainty in terms of flow is

$$\frac{U_w}{w} = \theta'\left(\frac{U_{\Delta P}}{\Delta P}\right) = \frac{1}{2}(\pm 0.004) = \pm 0.002 \text{ or } 0.2\% \text{ of the reading}$$

The flow could similarly be affected by other elemental systematic uncertainties such as the basic orifice calibration, upstream flow disturbances, downstream flow disturbances, and uncertainty due to beta ratio.

6-7 UNCERTAINTY OF MEASUREMENTS (EXAMPLE)

Consider the test data given below for the following three measurements in the power-plant cycle:

(a) throttle pressure, P_1
(b) exhaust pressure, P_2
(c) condensate flow, w, using a differential-pressure transmitter

The uncertainty due to random error using the standard deviation of the sample mean $S_{\bar{x}}$ are given in Table 6-7-1.

The throttle-pressure elemental uncertainties are illustrated in Table 6-7-2.

The exhaust-pressure elemental uncertainties are illustrated in Table 6-7-3.

The condensate-flow elemental uncertainties are given in Table 6-7-4.

Table 6-7-1 Uncertainty Due to Random Error

Parameter	Mean Value, $\bar{X}$	Number of Samples, N	Sample Standard Deviation, s_x	Standard Deviation of the Mean Value, $s_{\bar{x}}$
Throttle pressure, P_1, psia	813.7	60	5.2	0.67
Exhaust pressure, P_2, in. Hg	3.38	60	0.23	0.03
Condensate flow, w, lb/hr	892,766	60	5,000	645

Table 6-7-2 Throttle-Pressure Uncertainties

Elemental Uncertainty Source	Systematic Uncertainty, b_x, psia	Random Uncertainty, $s_{\bar{x}}$, psia	Degrees of Freedom, $v = N - 1$
Spatial variation	0	. . .	. . .
Calibration	1	. . .	. . .
Mounting effect	0	. . .	. . .
Ambient-temperature effect	1	. . .	. . .
Random error	. . .	0.67	59
Total error	1.4	0.67	59

Table 6-7-3 Exhaust-Pressure Uncertainties

Elemental Uncertainty Source	Systematic Uncertainty, b_x, in. Hg	Random Uncertainty, $s_{\bar{x}}$, in. Hg	Degrees of Freedom, $v = N - 1$
Spatial variation	0.08	. . .	. . .
Calibration	0.03	. . .	. . .
Mounting effect	0	. . .	. . .
Ambient-temperature effect	10.03	. . .	. . .
Random error	. . .	0.03	59
Total error	0.09	0.03	59

Table 6-7-4 Condensate-Flow Uncertainties

Elemental Uncertainty Source	Systematic Uncertainty, b_x, lb/hr	Random Uncertainty, $s_{\bar{x}}$, lb/hr	Degrees of Freedom, v
Base calibration	22,000 (2.5%)	. . .	. . .
Upstream flow disturbance	11,000 (1.25%)	. . .	. . .
Downstream flow disturbance	6,200 (0.7%)	. . .	. . .
Beta ratio	0 (0%)	. . .	. . .
Measurement loop	1,800 (0.2%)	. . .	. . .
Random	. . .	645 (0.072%)	59
Total error	25,000 (2.99%)	645 (0.072%)	59

The uncertainty of test result is established by propagating the uncertainty of each measured parameter using the sensitivity coefficients and calculating ${b_R}^2 = \sum \left(\theta_i b_{\bar{x}}\right)^2$ for the systematic standard uncertainty contribution and ${S_R}^2 = \sum \left(\theta_i s_{\bar{x}}\right)^2$ for the random standard uncertainty contribution to the result. The combined standard uncertainty of the result, R, is then

$$u_R = \sqrt{(b_R)^2 + (S_R)^2} \tag{6-7-1}$$

while the expanded uncertainty in the result at 95% confidence is given by

$$U_{R,95} = 2u_R \tag{6-7-2}$$

NONMANDATORY APPENDIX A
PISTON GAUGES

A-1 PISTON GAUGES

The piston gauge is one of the few measuring devices that measures pressure in terms of the fundamental units of force and area. Because it can also generate a pressure through applying a weight across a known area, its use is frequently associated with a device known as a deadweight tester. While such use is an important application, it is not the one that falls within the scope of this section. The basic equation for the piston gauge is

$$P = \frac{F}{A}$$

where
A = area
F = force
P = pressure

Measurement of pressure to an accuracy of 1 part in 10,000 or better can be made with certain types of piston gauges. To achieve this accuracy, the environment in which the gauge is to be used and certain parameters of the instrument itself shall be considered. Failure to consider these can introduce a considerable error. Acceleration due to gravity, air buoyancy, temperature, surface tension of the fluid, weight of the fluid, and elastic deformation of the cylinder shall be evaluated and corrections made to reduce the error in measurement.

Piston-gauge designs commonly incorporate the following three designs of cylinders:

(a) simple cylinder
(b) re-entrant cylinder
(c) controlled-clearance cylinder

A platform with calibrated weights is balanced on a piston, which is floated on the fluid within a cylinder. A connection to the cylinder transmits the fluid pressure from the process connection in which pressure is to be measured.

A-1.1 Simple Cylinder Piston Gauge

The simple cylinder gauge is the most often used and is available with a range up to 83 000 kPa (12,000 psig).

In use, the piston gauge is connected to the system under test as shown in Fig. A-1.1-1.

Pressure is connected to the inlet line, which must in general be filled with a hydraulic oil. This oil is necessary to provide for proper operation of the piston and cylinder. It also serves to keep corrosive or contaminating fluids from reaching the internal parts of the measuring system. If very large displacements of hydraulic fluid are required for a particular piston gauge (e.g., one with a large piston diameter), an oil reservoir should be added to the system. This would be an expanded area of the inlet pipe arranged so that large *volumetric* changes would result in small *height* changes within the inlet column. This is important because head effects can contribute to reading errors.

In use, calibration weights are added to or taken from the weight platform until the piston rests somewhere in its midposition; usually a fiduciary mark or scale is available to properly position the piston. It is also common practice to rotate the weights and piston while taking a final reading to minimize piston-to-cylinder friction effects.

Note that the total weight of piston, weight table, and calibration weights is used to calculate the pressure being measured. The manufacturer's literature will give the net weight of the table and piston. This shall be added to the calibration weights for pressure measurement. Frequently, the calibration weights are corrected or calibrated for a particular piston gauge and, therefore, may not be interchangeable between gauges of the same model or type. Manufacturer's literature should again be consulted for this information.

Because the force of gravity varies with location and altitude, some manufacturers will provide correction factors for this phenomenon. Generally, however, this not a factor where accuracies $\geq$ 0.5% are involved.

The optional auxiliary gauge (see Fig. A-1.1-1) is useful for estimating the total weight to be used, but may be omitted for reasons of economy.

A-1.2 Re-Entrant Cylinder Piston Gauge

The re-entrant cylinder gauge is usually used for higher pressure measurements; however, it can be used for lower pressures as well. The lower limit is usually determined by the weight of the platform. Commercially available re-entrant cylinder gauges are available with range of approximately 552 kPa to 276 MPa (80 psi to 40,000 psi).

Figure A-1.2-1 is a schematic representation of a re-entrant cylinder piston gauge. Note that a cavity is

Fig. A-1.1-1 Simple Cylinder Piston Gauge

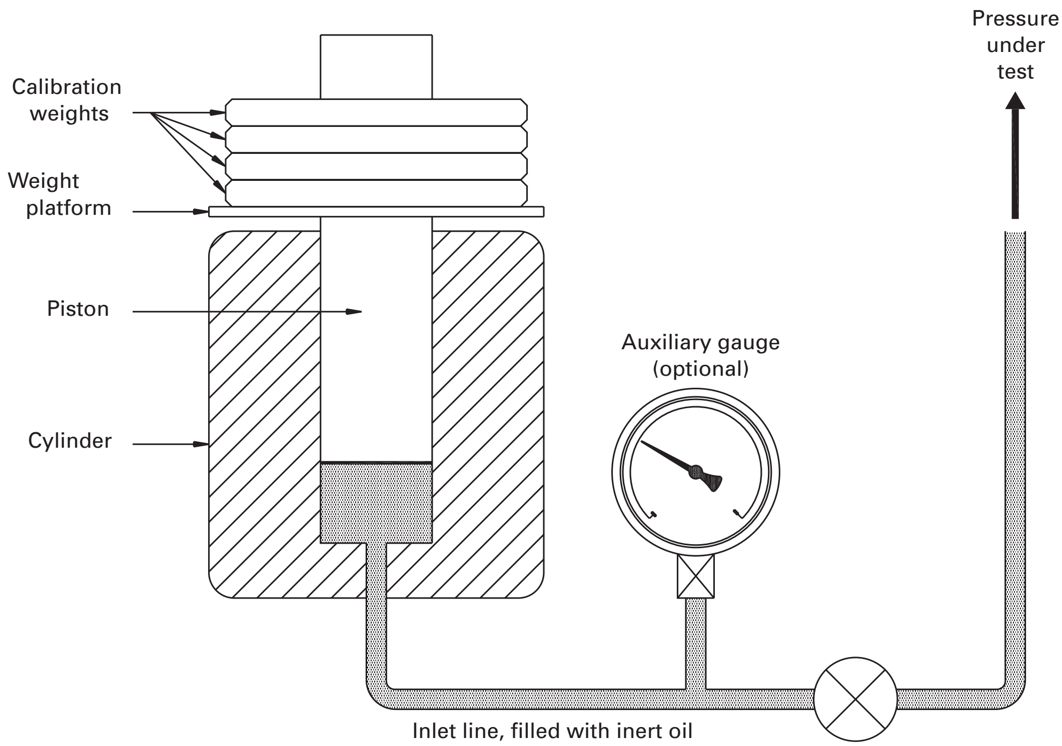


Fig. A-1.2-1 Re-Entrant Cylinder Piston Gauge

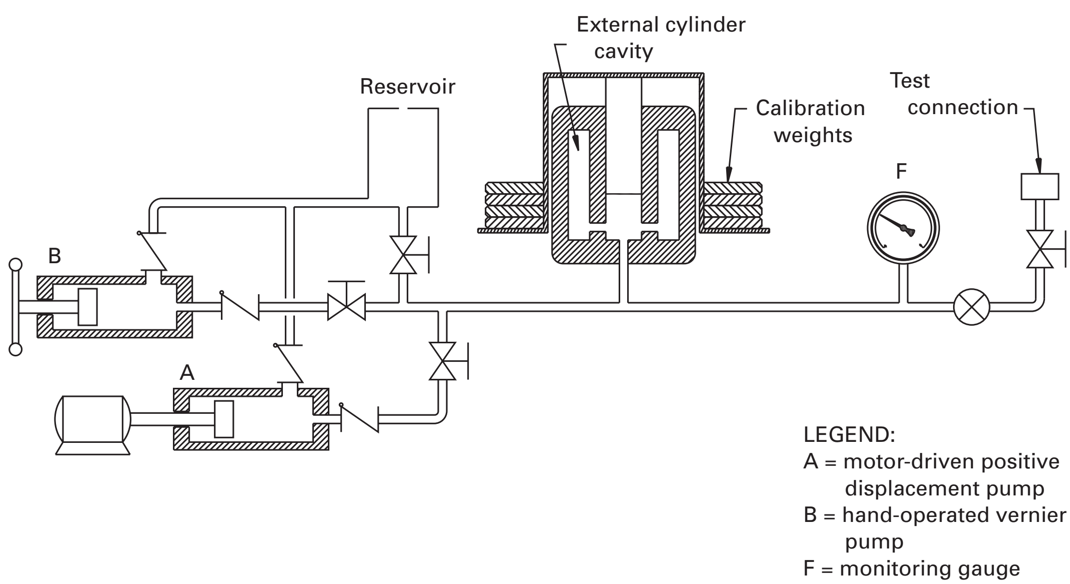
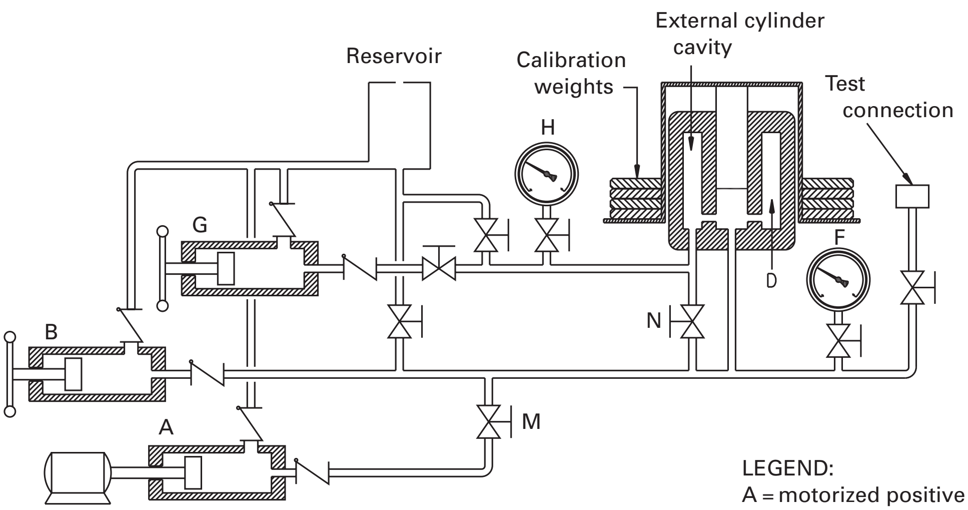


Fig. A-1.3-1 Controlled-Clearance Cylinder Piston Gauge



LEGEND:
A = motorized positive displacement pump
B = hand pump
D = cylinder
F = pressure gauge
G = hand pump
H = pressure gauge
M = valve
N = valve

provided around the outside of the cylinder so that the fluid pressure is exerted on the outside as well as the in side of the cylinder. This design reduces the clearance between piston and cylinder at higher pressures and thereby reduces the otherwise excessive leakage of pressure fluid to tolerable levels.

The operation of this piston gauge is similar to that of the simple cylinder gauge. Because of the higher pressures being measured, a motor-driven positive displacement pump (see A in Fig. A-1.2-1) is sometimes provided. This pump is used to increase the system pressure to near the measurement value. A second hand-operated vernier pump B is used for the final adjustment. A monitoring gauge F is provided to allow tracking of the system pressure as it increases.

A-1.3 Controlled-Clearance Cylinder Piston Gauge

The controlled-clearance cylinder gauge is usually used for higher-pressure measurement. However, as mentioned in Section 2, NIST maintains a group of controlled-clearance piston gauges covering the range from 35 kPa to 2.5 GPa (5 psi to 370,000 psi).

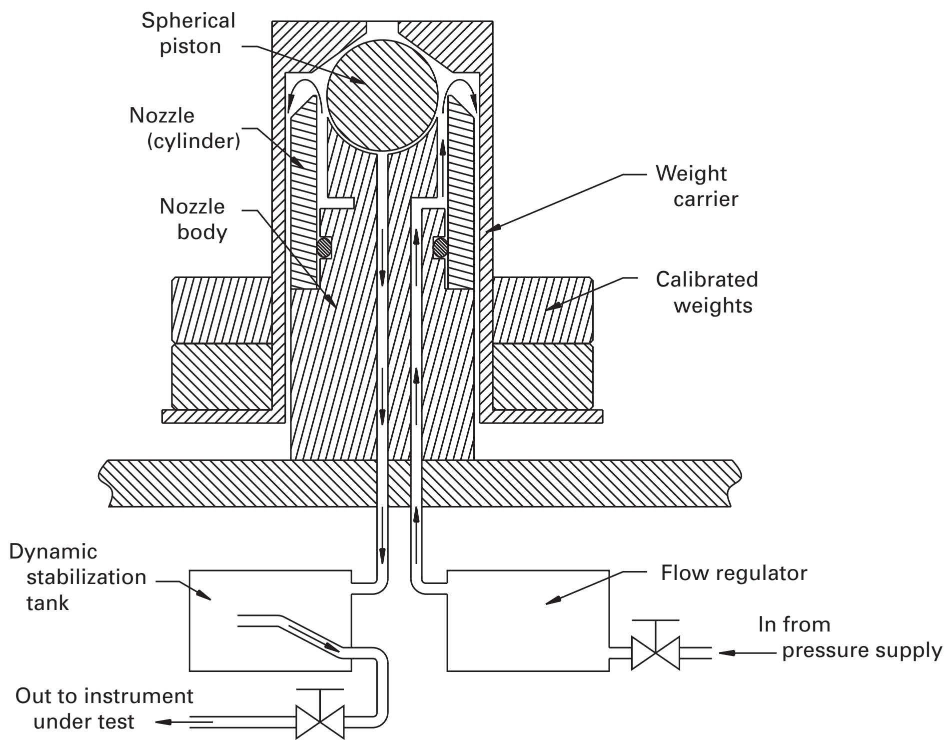
Figure A-1.3-1 is a schematic representation of a controlled-clearance piston gauge. It is similar to the re-entrant type with the exception of the source of pressure for the external cylinder cavity. The motorized positive displacement pump A can be used to pressurize the system to near the measurement point. By opening valve N, this pressure is exerted in cylinder D as well as the external cavity. When the pressure is near the measurement value, valves N and M are closed and pump A stopped. The pressure in cylinder D is then adjusted by use of hand pump B. Similarly, the pressure in the external cylinder cavity is adjusted by use of hand pump G. The internal and external cylinder pressures are monitored by gauges F and H, respectively. The external pressure is usually reduced to just below the pressure in cylinder D. Care shall be taken to not allow the differential pressure between the cylinder D and external cavity to increase to a point where the cylinder is damaged.

A-1.4 Pneumatic Deadweight Ball Gauge

Ball gauges using air or gas as the fluid are available with range capability of up to 7000 kPa (1,000 psi). The use of such a gauge is usually limited by the available source of dry compressed gas, the pressure of which must be about 50% higher than the pressure to be measured. Pneumatic ball gauges are easily operated and can be used to measure down to about 1.0 kPa (4 in. H_2O). A major advantage of these gauges is insensitivity to contamination.

Figure A-1.4-1 is a schematic diagram of the pneumatic tester. In this type of construction, a precision ceramic ball is floated within a tapered stainless steel nozzle. A flow regulator introduces pressure under the ball, lifting it toward the annulus between the ball

Fig. A-1.4-1 Pneumatic Deadweight Ball Gauge



and nozzle. Equilibrium is reached when the vented flow equals the fixed flow from the supply regulator, and the ball floats. The pressure, which is also the output pressure, is proportional to the load. During operation, the ball is centered by a dynamic film of air, eliminating physical contact between the ball and nozzle.

When weights are added or removed from the weight carrier, the ball rises or lowers, affecting the air flow. The regulator senses the change in flow and adjusts the pressure under the ball to bring the system into equilibrium, changing the output pressure accordingly. Thus, regulation of output pressure is automatic with changes in load on the spherical piston (ball).

A-1.5 Absolute-Pressure Piston Gauge

By enclosing the calibration-weight platform and evacuating the chamber, the piston gauge can be used to measure absolute pressure (see Fig. A-1.5-1). When testing in the region below atmospheric pressure, the pressure source is shut off and the vacuum pump is used. The vacuum created allows the fluid (usually air or gas) in the piston to expand and lift the weight platform. The platform is rotated by a motor drive within the enclosure to reduce piston drag.

The accuracy of measurement is the same as for the tester used in atmosphere, with the exception that the air buoyancy becomes a variable and introduces less error as absolute zero pressure is approached.

A-1.6 Vacuum Piston Gauge

The vacuum piston gauge (Fig. A-1.6-1) is similar in design to the simple cylinder gauge used for measuring above-atmospheric pressure, with the exception that the weights are hung from the piston. The vacuum range is dependent on the vacuum pump used. Piston gauges for commercial use are available to measure down to 25 mmHg absolute (1 in. Hg absolute). The highest vacuum that can be measured is dependent on the barometric pressure at the time and place of use. Accuracies of 3 parts in 10,000 can be achieved if the piston gauge reading is corrected for the environment in which it is used.

Control of the unit is by use of a valve to shutoff the vacuum source and a second valve to bleed air into the cylinder. The weight carrier shall be rotated during evacuation of the cylinder and at the time of measurement reading.

A-1.7 Piston Gauge With a Diaphragm Separator

A piston gauge equipped with a diaphragm separator can be used to measure pressure in processes where the process fluid is not compatible with the gauge (see Fig. A-1.7-1).

Fig. A-1.5-1 Absolute-Pressure Piston Gauge

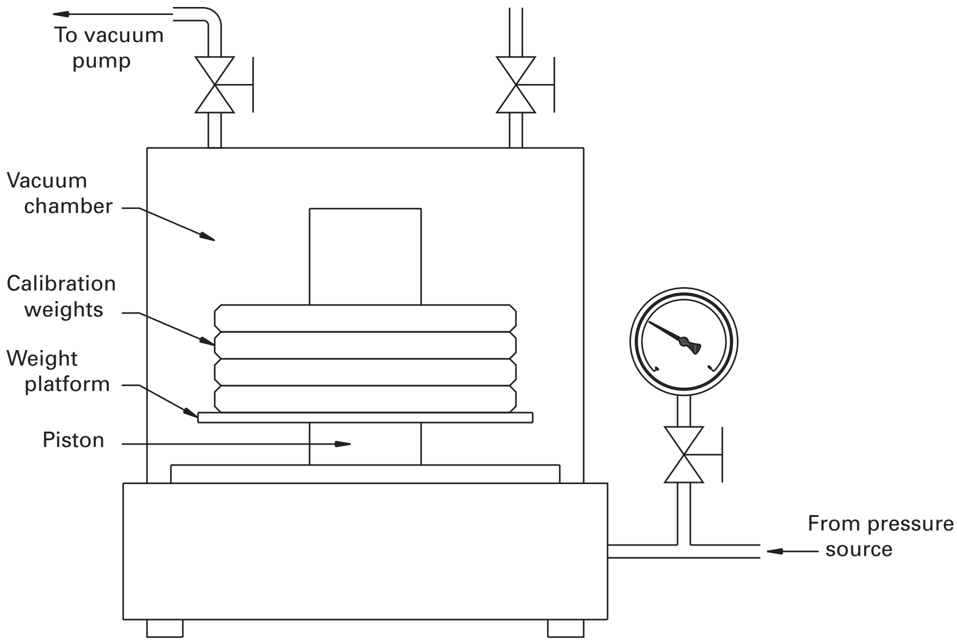


Fig. A-1.6-1 Vacuum Piston Gauge

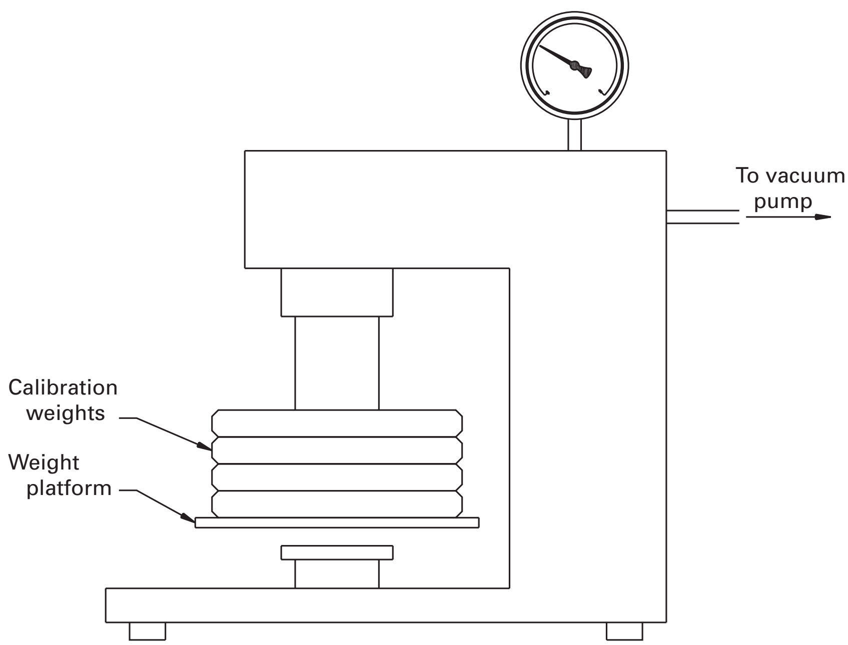
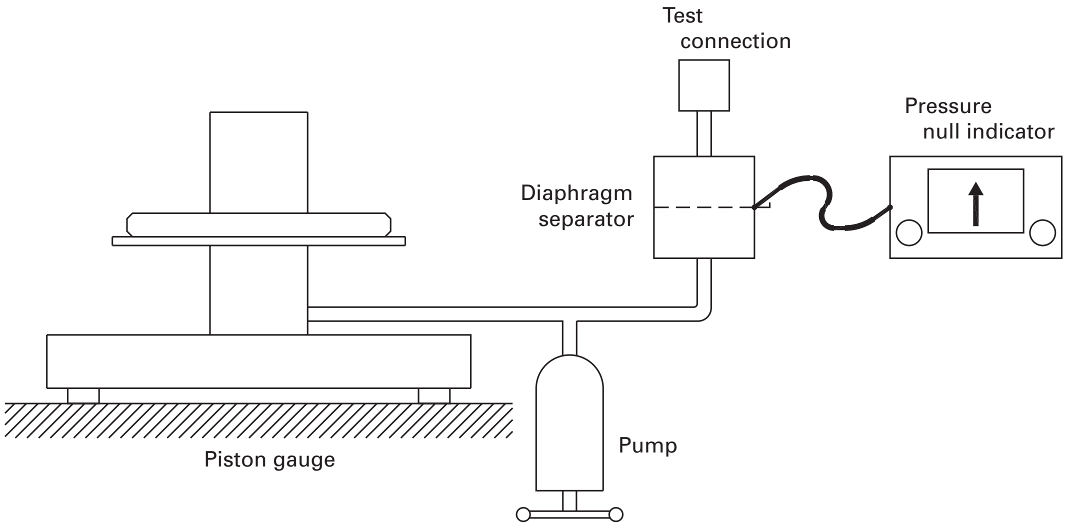


Fig. A-1.7-1 Piston Gauge With a Diaphragm Separator



The diaphragm separator can be one of a number of devices, such as those discussed in para. 5-3.5, for measurement of differential pressure, or the separator can be integral to the piston gauge.

When using these devices, the weight applied to the piston gauge must bring the separator element to its null or zero-differential point. The diaphragm device should be capable of measuring a low differential pressure compared to the pressure measurement to be made. The accuracy of these devices is usually stated as a percentage of the range. Therefore, if the range is low in comparison to the pressure being measured, the error is less. Care shall be exercised when applying pressure to the diaphragm separator to avoid over-ranging the instrument, causing damage, and introducing error in the measurement.

NONMANDATORY APPENDIX B
MANOMETERS

B-1 MANOMETERS

The use of manometers, particularly in a field environment, has lessened as transducers have become more accurate and accepted. However, the simplicity of construction and close approximation of many specialized designs to primary standards helps maintain their place in certain applications. A few of these designs are described here. For others, including special versions such for low absolute pressure (vacuum measurements) and for their respective details of operation, the literature should be consulted.

B-1.1 U-Tube Manometer

The basic form of the manometer is a U-shaped tube with the vertical legs. Fig. B-1.1-1 shows the manometer being used to measure absolute pressure in a pipe, and Fig. B-1.1-2 shows its use with a flowmeter element measuring differential pressure. The liquid in the U-tube shall be denser than the fluid in the pipe and immiscible with it.

B-1.2 Cistern Manometer

In the cistern manometer (see Fig. B-1.2-1), the area of one leg is made substantially larger than the other, in the form of a cistern into which the narrow leg dips. The advantage of the cistern is that the liquid level inside it will vary only slightly while substantial changes of level will occur in the narrow leg. This facilitates applying a scale to only the narrow leg and correcting the graduations on this scale for variations of level in the cistern. Reading accuracy is increased, relative to a U-tube with the same filling liquid, by the fact that one does not have to add two readings to obtain the pressure. The manometer can be configured to read pressures below atmospheric pressure by leaving the cistern open to the atmosphere and making the test-pressure connection to the top of the narrow tube.

A refinement of the cistern manometer, which enables the construction to be mostly from nontransparent materials, is to add a floating scale with suitable low-friction bearings to the narrow leg. A small window with a fixed hairline index allows an operator to take all readings at a convenient elevation. The addition of a vibrator to the outside of the narrow leg will eliminate errors due to bearing friction, but not those due to surface tension on the float.

B-1.3 Inclined Manometer

If a manometer is inclined at an angle with the vertical, the vertical displacement is still the same, but the movement of liquid along the tube is greater in proportion to the secant of the angle. The common form of inclined manometer is made with a cistern, as shown in Fig. B-1.3-1.

The scale is graduated to take account of the liquid density, inclination, and cistern level shift so that readings will be in convenient pressure units such as equivalent vertical centimeters or inches of water. A spirit level and leveling screws are usually provided so that the designed angle can be reproduced in installation.

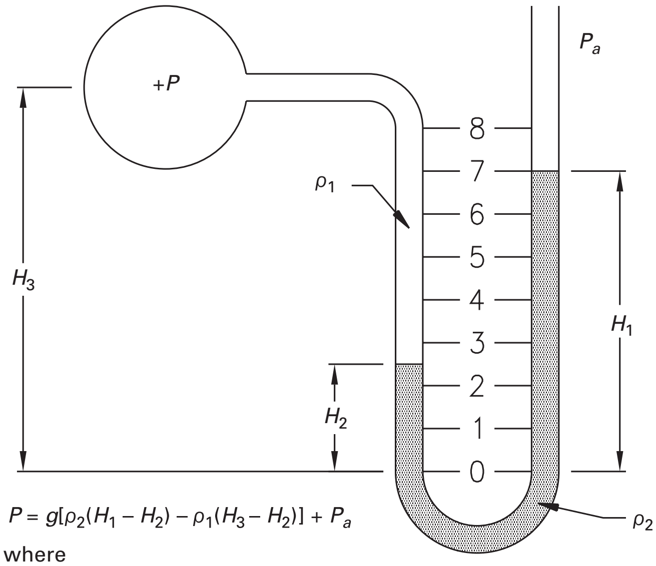
This form of manometer is usually used for gas pressures, as for draft gauges. The graduation intervals are commonly 0.25 mm H_2O (0.01 in. H_2O) with spans up to about 250 mm (10 in.).

B-1.4 Micromanometer

A micromanometer is a precision device for measuring very small differential pressures. Depending on the reference pressure, it can also be used to measure absolute pressure or near-atmospheric pressure.

It consists of an inclined tube with a vertically moveable well (see Fig. B-1.4-1). The inclined tube is short and set on a nearly flat slope for high sensitivity. This tube is not graduated but is merely provided with a fixed index. The well is moved by means of a micrometer screw and is connected to the inclined tube indicator with a flexible hose. To operate it, the instrument is first zeroed by adjusting the height of the well, independently of the micrometer, so that the meniscus in the inclined tube coincides with the index when the micrometer reads zero. With a differential pressure applied between the well and the upper end of the inclined tube, the meniscus moves away from the index. It is brought back to coincidence by raising the well with the micrometer screw. The micromanometer reading then measures the differential pressure in terms of head of the manometer liquid. Since this is a null method, it is capable of refinement to high precision.

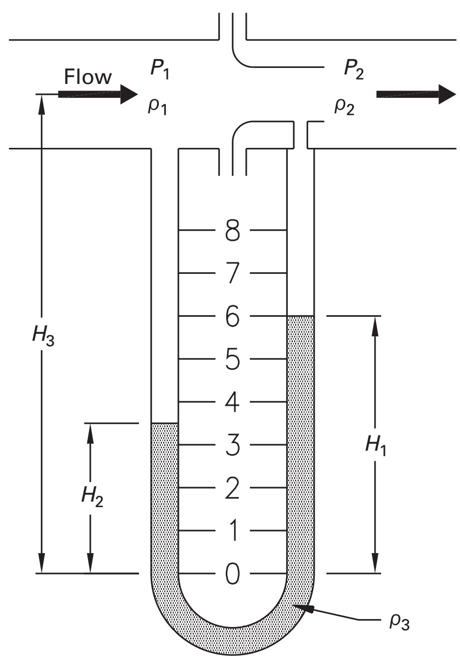
Fig. B-1.1-1 U-Tube Manometer for Absolute Pressure



$$P = g[\rho_2(H_1 - H_2) - \rho_1(H_3 - H_2)] + P_a$$

where
g = magnitude of local acceleration due to gravity
H = height
P = absolute pressure
P_a = atmospheric pressure
ρ = density

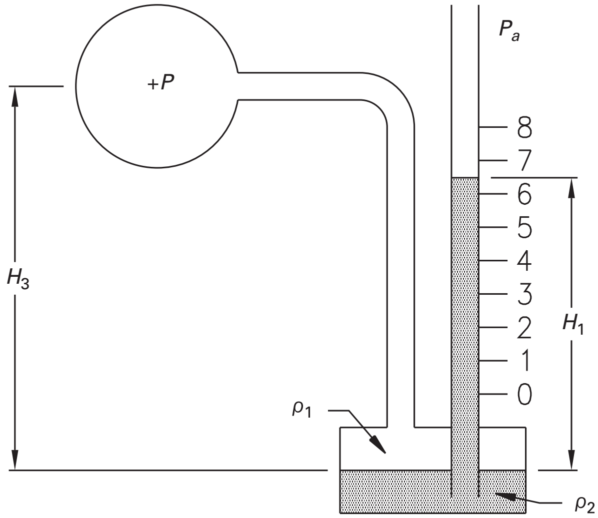
Fig. B-1.1-2 U-Tube Manometer for Differential Pressure



$$P_1 - P_2 = g[\rho_3(H_1 - H_2) - \rho_2(H_3 - H_1) - \rho_1(H_3 - H_2)]$$

where
g = magnitude of local acceleration due to gravity
H = height
P = absolute pressure
ρ = density

Fig. B-1.2-1 Cistern Manometer



$P = g(\rho_2 H_1 - \rho_1 H_3) + P_a$

where

g = magnitude of local acceleration due to gravity
H = height
P = absolute pressure
P_a = atmospheric pressure
ρ = density

Fig. B-1.3-1 Inclined Manometer

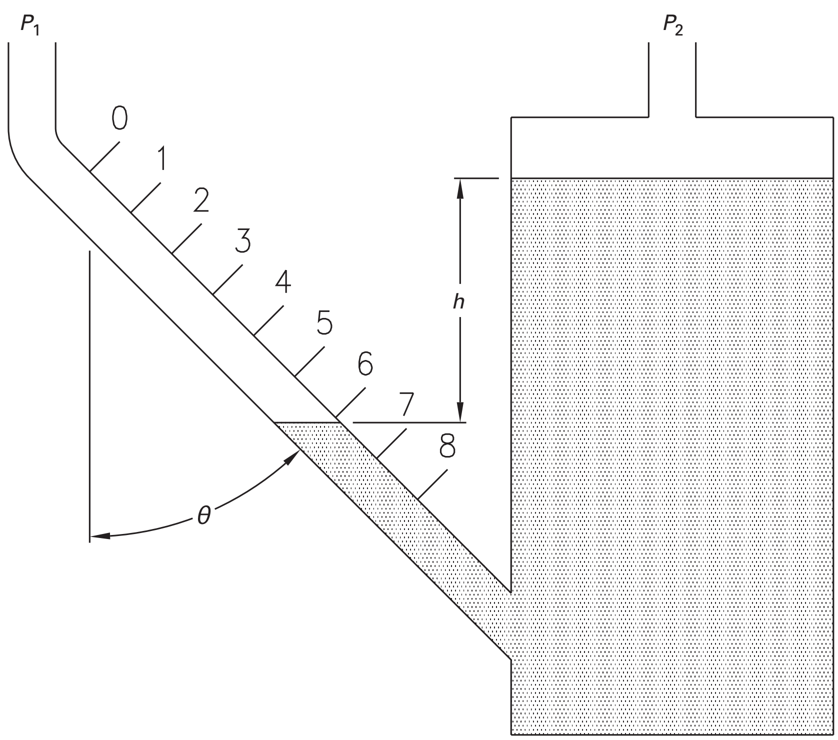
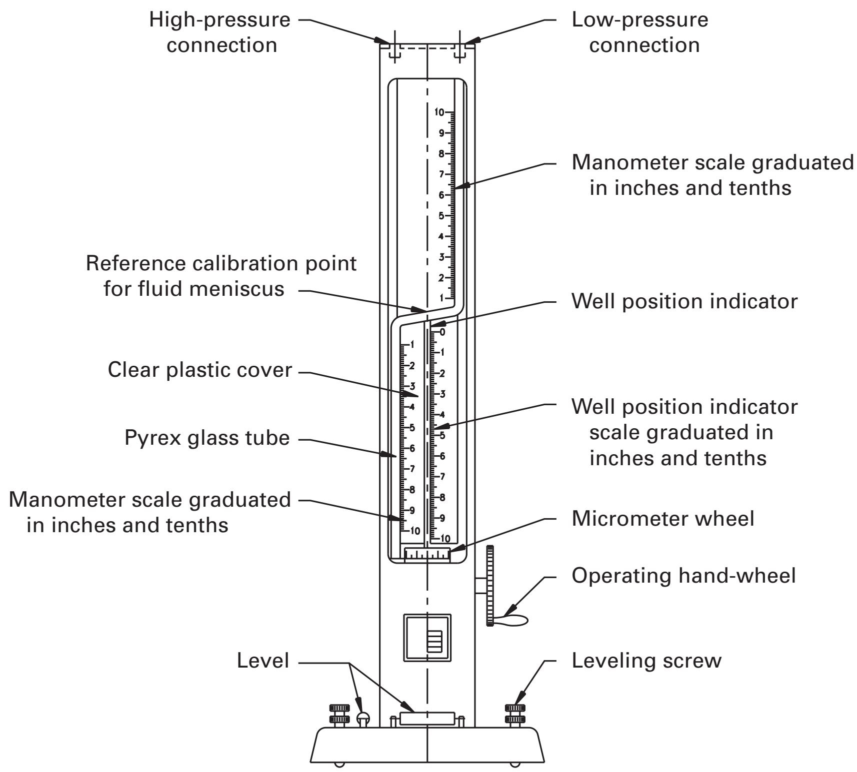


Fig. B-1.4-1 Micromanometer (Null Reading)

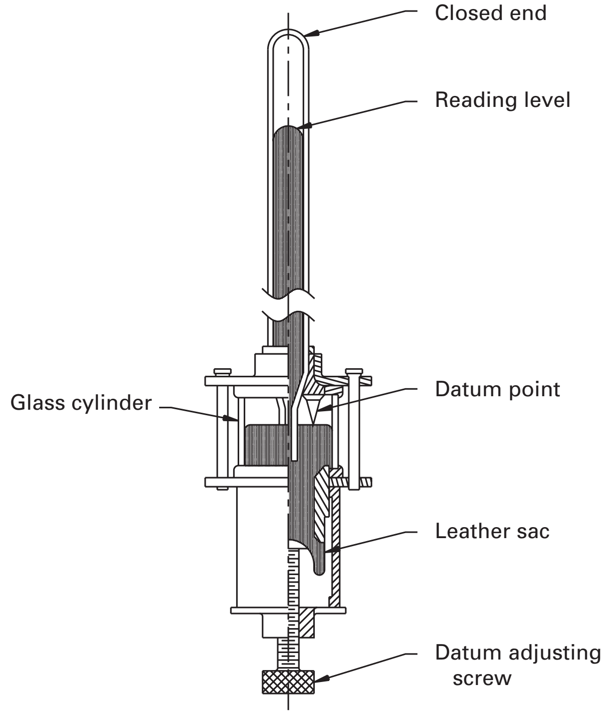


B-1.5 Fortin Barometer

A Fortin-type barometer (see Fig. B-1.5-1) is an absolute-pressure mercury manometer specifically designed for the purpose of measuring atmospheric pressure. It comprises a vertical glass tube of 6.35-mm (0.25 in.) bore or larger for more precise instruments, sealed at its upper end, and with its lower end immersed in a cistern of mercury. The upper end of the tube is evacuated, and the surface of the cistern mercury is exposed to ambient atmospheric pressure, which forces mercury to rise in the tube to a height corresponding to the atmospheric pressure. The level of the mercury meniscus in the tube is measured by a vernier index moveable relative to a fixed graduated scale.

The level of mercury in the cistern is adjusted to a fixed reference point of ivory by means of a displacer screw operating against the flexible bottom of the cistern. The tip of the ivory point corresponds to the zero of the reading scale. Readings shall be corrected for nonstandard temperature, gravity, and capillary depression, which should be computed, and also for instrument imperfections, which can be detected only by comparison calibration.

Fig. B-1.5-1 Fortin Barometer



NONMANDATORY APPENDIX C
LOW-ABSOLUTE-PRESSURE (VACUUM) INSTRUMENTS

C-1 UNITS AND TERMINOLOGY

Historically, two meanings of the term "vacuum" have evolved. Both meanings refer to absolute pressures below normal atmospheric pressure, but differ in their reference points. For example, when an automechanic describes a "20-in. vacuum," he is discussing a negative gauge pressure equivalent to 20 in. Hg. A vacuum technologist speaks of a "hard" vacuum of 10^{-13} Torr. Here, the technologist means an extremely low absolute pressure. To add to the confusion, note that different units are used. Each area of usage has its own set of "customary" terms to quantify vacuum measurements. Table C-1-1 lists the more common units, conversion factors, and area of usage. Note particularly the term "Torr" (= 1 mmHg). This unit is in common use, but such use is being discouraged. Ultimately, the Pascal should displace all other units and its use is being encouraged.

C-2 TECHNOLOGY

The choice of measuring devices becomes progressively more restricted as the absolute pressure level decreases. Indicating gauges should measure down to about 10 kPa (3 in. Hg) absolute. By careful and innovative design, other direct-measuring devices should be able to measure down to 0.1 Pa (0.75 μm). To measure pressures lower than this limit, inferential measurements are available that can be related to pressure for a known gas or mixture of gases. Devices used to measure vacuum referenced to atmosphere (sometimes called suction vacuum) are not discussed here. Instead, only devices intended for low absolute pressures are covered.

C-3 DIRECT MEASURING DEVICES

The gauges that measure pressure directly include the mercury micromanometer, butyl-phthalate manometer, diaphragm comparator, and McLeod gauge.

C-3.1 Mercury Micromanometer

If a mercury manometer is refined for the best possible precision, it is possible to read levels accurately to about 1 Pa (0.01 mmHg). This requires tubes of at least 16 mm (0.63 in.) to minimize capillary effects, precision-scale engraving, vernier reading, sighting edges arranged to eliminate parallax, and adequate illumination. Such an instrument could therefore be used to determine pressure difference of 130 Pa (1 mmHg) to 1% precision, and 1.3 kPa (10 mmHg) to 0.1% precision. Instruments of this grade are available commercially as well-type manometers or barometers with a span of 100 kPa (30 in. Hg) or on special order up to 340 kPa (100 in. Hg) span. This is, of course, not a convenient test instrument but is useful for calibration purposes. If the reference leg of the manometer is carefully filled, the reference pressure will be the vapor pressure of mercury of about 0.5 Pa (0.004 mmHg) at atmospheric temperature, which is less than the reading limit of the gauge.

C-3.2 Butyl-Phthalate Manometer

Water is not useful as a manometric liquid for low absolute pressure because of its high vapor pressure. However, butyl phthalate, as used in the Hickman vacuum gauge shown in Fig. C-3.2-1, is a liquid with vapor pressure much less than that of mercury and density of the same order as water. With a manometer arrangement of similar precision, butyl phthalate can measure absolute pressures about one order of magnitude lower than mercury. It has the disadvantages that its temperature coefficient of expansion is high and many gases and liquids are highly soluble in it, so that the low-pressure reference side of the manometer must be continuously pumped. This also means that the liquid is easily contaminated, with a consequent change in density.

C-3.3 Diaphragm Comparator

A special modification of the diaphragm pressure gauge is commercially available for the measurement of very low pressure differentials, with a sensitivity of about 0.1 Pa (1 μm) (see Fig. C-3.3-1). The reference pressure, usually a high vacuum, is applied to one side of a diaphragm and the unknown higher pressure to the other side. The diaphragm forms one plate of an electrical capacitor. An adjustable direct-current (DC) voltage is applied to bring the diaphragm back to its original position by electrostatic attraction. The balance point is indicated by a capacitance bridge circuit. The value of the balancing DC voltage is read from a potentiometer, and is the measure of pressure difference. The span of the instrument is 20 Pa (150 μm). The reference base should be a high vacuum or atmospheric pressure. The instrument is a true pressure gauge, but it is affected by the dielectric constant of the gas and, of course, by temperature. These effects become more important at higher pressure levels.

Table C-1-1 Vacuum Measurement Units

Units	Where Used [Note (1)]	Conversion Factors [Note (2)]					
		psi	kPa	in. H_2O	in. Hg	mmHg	Bar
in. H_2O(4°C) (39.2°F)	GP	0.0361	0.249	1	0.0736	1.87	0.00249
in. Hg(0°C) (32°F)	GP/LA	0.491	3.39	13.6	1	25.4	0.00339
psi	GP/LA	1	6.89	27.7	2.04	51.7	0.0689
mm (of Hg)(0°C) (32°F)	LA	0.0193	0.133	0.535	0.0394	1	0.00133
micron of Hg (μ)	LA	1.93×10^{-5}	1.33×10^{-5}	5.35×10^{-5}	3.94×10^{-5}	10^{-3}	1.33×10^{-6}
Torr (sec mm of Hg)	LA	0.0193	0.133	0.535	0.0394	1	0.00133
Pascal	LA	1.45×10^{-4}	10^{-3}	4.01×10^{-3}	2.95×10^{-4}	7.50×10^{-3}	10^{-5}
Millibar	LA	0.0145	0.100	0.401	0.0295	0.750	10^{-3}
Bar	GP/LA	14.5	100	40.1	29.5	750	1

NOTES:
(1) GP = measurement referenced to atmospheric pressure; LA = low absolute.
(2) Rounded to three places.

Fig. C-3.2-1 Hickman Vacuum Gauge

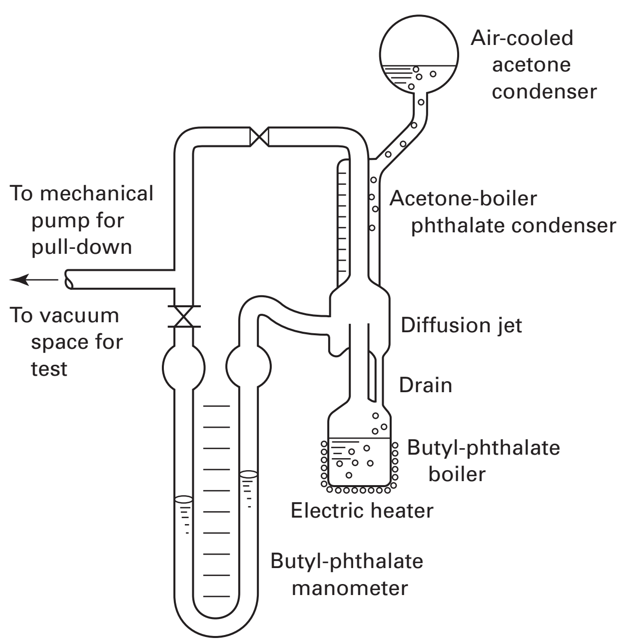
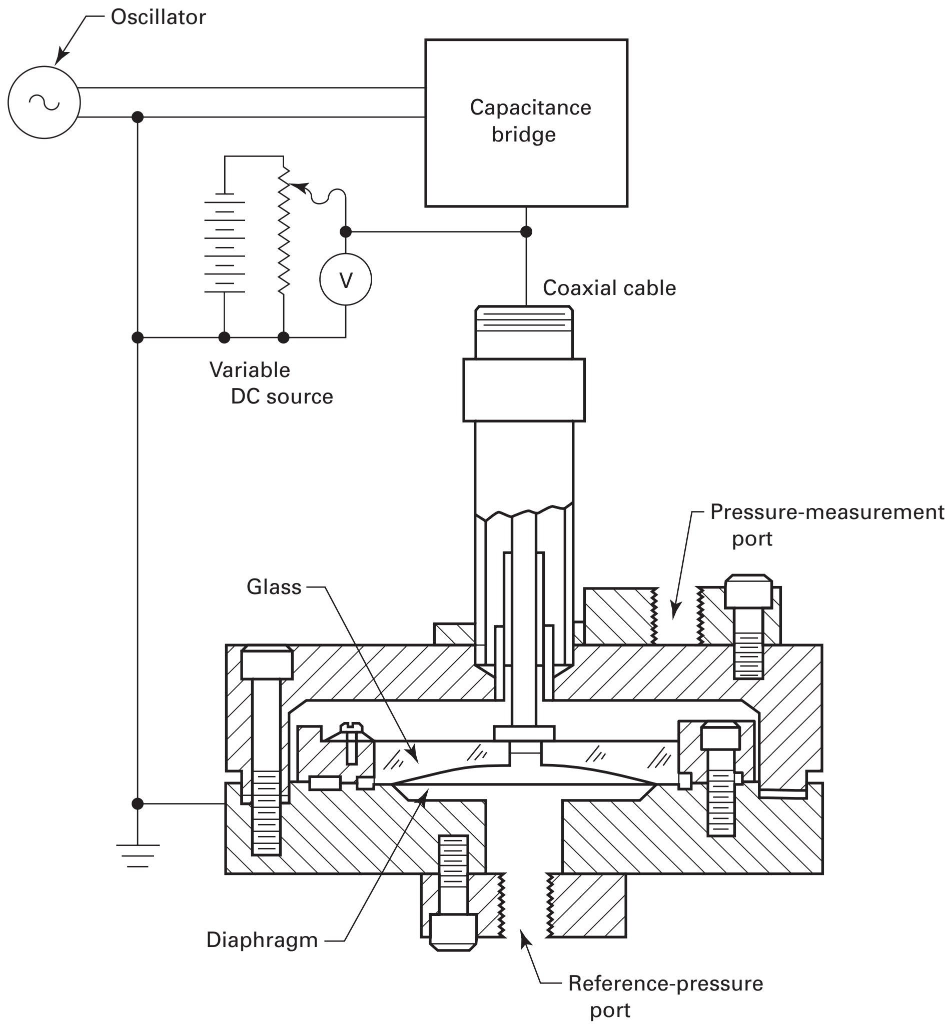


Fig. C-3.3-1 Diaphragm Pressure Comparator



C-3.4 McLeod Gauge

This gauge is used to compress a volume of the rarefied gas into a much smaller volume. From the dimensions of the apparatus, and a reading of a substantial mercury-level difference, the pressure of the original sample in terms of a height of a mercury column is calculated. The arrangement is shown in Fig. C-3.4-1. The compression is essentially isothermal because of the time involved and the large surface-to-volume ratio. The measurement starts with mercury drained out of the instrument and the gauge filled with the gas to be measured. The mercury is raised by any of a number of possible methods cutting off the volume, V, in the measuring bulb. As the mercury continues to rise, this gas is compressed into the measuring capillary extension, until the level in the exactly similar reference capillary reaches a zero point corresponding to zero volume in the measuring capillary. The mercury level in the measuring capillary will be lower because of the trapped gas. The level reference, h, is related to the original pressure, P, (both in linear units) in the following way:

$$P_1V_1 = P_2V_2, \text{ for isothermal compression}$$

where

$$P_1 = \frac{Ah^2}{V_1 - hA}$$

$$P_2 = P_1 + h$$

$$V_2 = hA$$

and

A = area

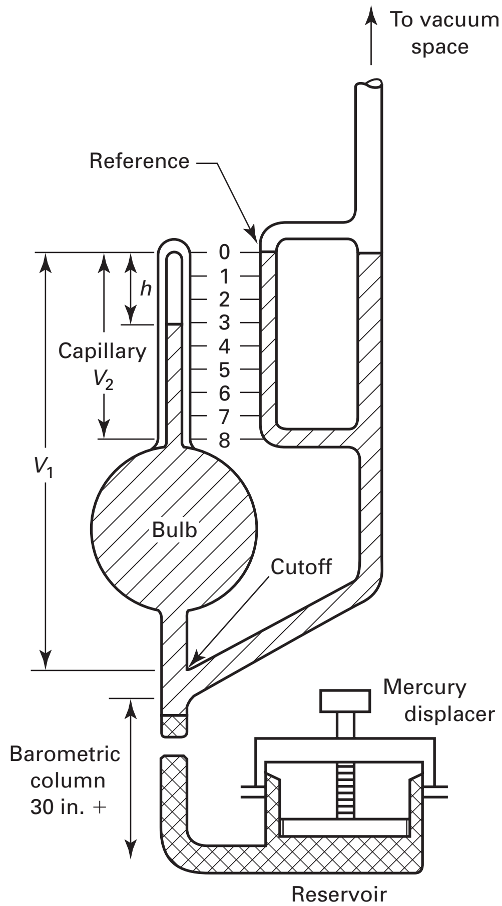
which reduces to, approximately

$$P_1 = \frac{Ah^2}{V_1}$$

since $hA < V_1$

Alternatively, the gauge may be arranged to compress the gas only to a fixed volume, V_2, identified by a reference zero mark at the base of the measuring capillary. Then the mercury will stand higher in the reference capillary by the height, h. The original pressure is then

Fig. C-3.4-1 McLeod Gauge



$$P_1 = P_2\left(\frac{V_2}{V_1}\right)$$

where

$$P_1 = h\left(\frac{V_2}{V_1 - V_2}\right)$$

$$P_2 = P_1 + h$$

Since $\frac{V_2}{V_1 - V_2}$ is a constant of the measurement, P_1 is a direct linear function of h.

Combining these two methods provides a double range in one instrument for high and low pressures.

If condensible components are present in the original sample, they will be partially condensed by the compression and will not contribute to the final gas volume. The McLeod gauge measures essentially only the fixed gases in the original sample. The range of the usual commercial forms of McLeod gauge covers from 0.001 Pa to 7 kPa (0.01 μm to 50 000 μm), not, of course, in the same gauge. At the lower end of this range, it is necessary to provide a cold trap between the gauge and the system to prevent contamination of the system by the mercury vapor from the gauge.

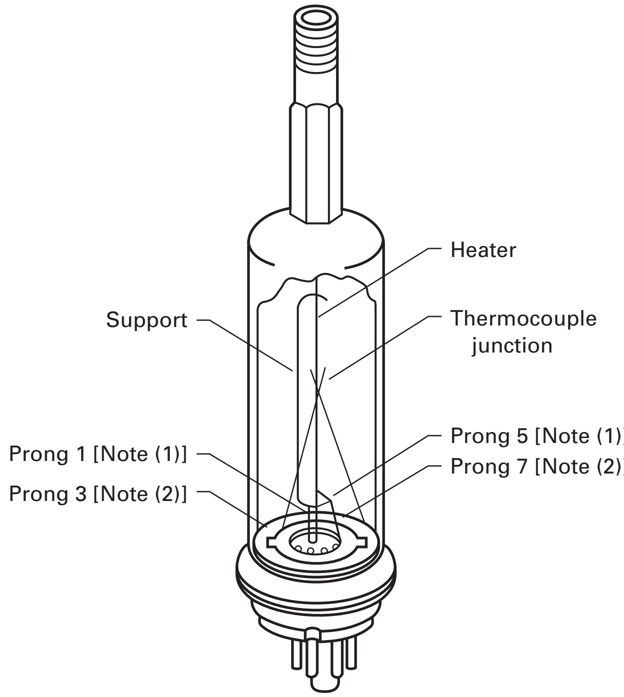
C-4 INFERENTIAL MEASURING DEVICES

When the pressure to be measured falls below that covered by the previous devices, it is necessary to use detectors that respond to a pressure-related property. Two such properties are thermal conductivity and ionization.

Thermal-conductivity devices rely upon the fact that, for several decades of pressure in the region of interest, the heat loss from a thin wire is nearly linear with pressure. Thermocouple and Pirani gauges are two devices using this phenomenon.

The principal advantages of the thermocouple and Pirani vacuum gauges are their simplicity and low cost. Improvements in their performance are being constantly made. Their principal disadvantages are the shift in calibration caused by contaminating vapors from the vacuum system and slow response. The shift in calibration is more severe near the low-pressure end of the scale. This is caused primarily by the change in emissivities of the heating element, thermocouple junctions, and surrounding walls of the container. Response of the thermal-conductivity gauges is relatively slow, because

Fig. C-4.1-1 Thermocouple Gauge



NOTES:
(1) Prongs 1 and 5 = heater inputs
(2) Prongs 3 and 7 = thermocouple output

of thermal inertia. These gauges must be calibrated for the gas mixture to be encountered.

C-4.1 Thermocouple Gauge

In the usual form of construction of a thermocouple gauge, a short length of resistance wire is heated to perhaps 200°C. At the midpoint of this heater wire, a thermocouple is spot-welded. A sensitive microammeter (of the order of 200 microamperes) and low internal resistance (of the order of 50 Ω) is used to measure the current produced by the voltage at the thermocouple. The assembly of the thermocouple and heater element is usually mounted in a metal or glass envelope, as shown in Fig. C-4.1-1. A short connection of tubing is provided for connection to the vacuum system.

For a given gauge, the reading of the microammeter is constant for a constant heater input and constant pressure. The reading depends upon the gas composition. At pressures higher than 30 Pa (225 μm), the microammeter reading is very low and may correspond to about 10% of full-scale value. The reason for this effect is that the thermal conductivity through the gas is high and essentially independent of pressure above 130 Pa (1 mmHg). However, as the pressure is reduced below 130 Pa, the gas conductivity begins to decrease with pressure down to about 1.3 Pa (10 μm). Since the thermal conductance of the gas decreases for decreasing pressures, the temperature of the heating element (and thus the thermocouple junction as well) increases.

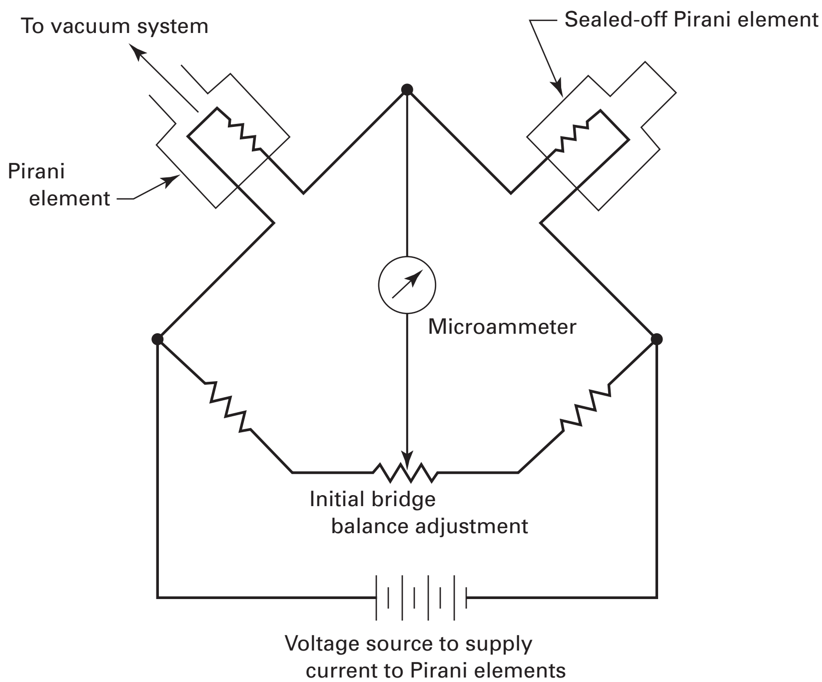
This increase in temperature of the thermocouple junction with decreasing pressure results in an increase in the voltage output of the thermocouple. Thus, the deflection of the microammeter is greatest for the lower pressures. In some thermocouple gauges, the microammeter reading is about 80% of the full scale at 1.3 Pa (10 μm).

As pressure is reduced below 1.3 Pa, the temperature change at the thermocouple junction is comparatively small. Thus the microammeter reading approaches an asymptote for decreasing pressures. This asymptote is due to two major factors: thermal radiation and thermal conduction through the supporting leads of the heater and thermocouple elements. At pressures below 1.3 Pa, the thermal radiation and heat conduction through the leads are essentially constant and are considerably greater in magnitude than the effect of thermal conduction through the gas. For these reasons, pressure measurements less than 1 Pa (7.7 μm) are not attempted with the thermocouple gauge.

C-4.2 Pirani Gauge

The Pirani gauge is similar in operation to the thermocouple gauge. The same factors that limit the performance of the thermocouple gauge at pressures above 130 Pa (1 mmHg) and at pressures below 1 Pa (10^{-2} mmHg) also limit the measurable pressure range of the Pirani gauge. In the Pirani gauge, however, only a heating element is used and the change in resistance

Fig. C-4.2-1 Pirani Vacuum Gauge



of this element is measured as a function of pressure. The usual detecting-circuit arrangement for a Pirani gauge is to use the heating element in one arm of an electrical bridge network (see Fig. C-4.2-1). To compensate for ambient effects, including supply-voltage variations, another Pirani element is enclosed in a sealed and evacuated chamber and used as the balancing element in the bridge circuit. The power is supplied to two opposite corners of the bridge, and an indicator, typically a DC microammeter, is connected to the remaining corners. Initial bridge zero balance is obtained at an absolute pressure no greater than 0.01 Pa (10^{-4} mmHg). As the pressure increases from about 1 Pa to about 100 Pa, resistance of the sensing Pirani element decreases. This unbalances the bridge and causes indication on the microammeter corresponding to pressure.

C-4.3 Ionization Gauges

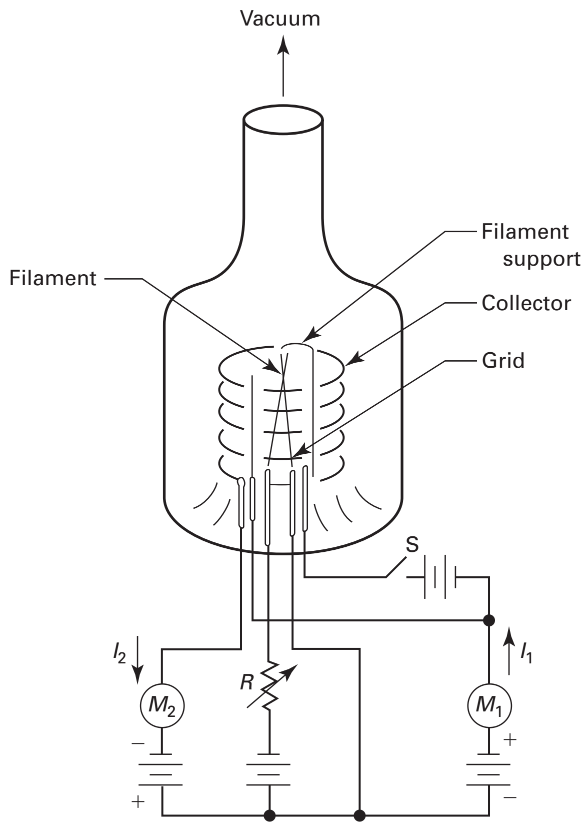
Ionization gauges measure the frequency of collection and discharge of ions at an electrode. They include a means for producing ions and a means for collecting them. Associated instrumentation is then used to measure the ion current. This current is, for constant conditions, proportional to gas density, which is in turn related by the ideal gas law to gas pressure. Several types of gauges exist. Their function is similar; only the details of operation differ.

C-4.3.1 Bayard-Alpert Cage. The hot-filament or Bayard-Alpert gauge generates ions by collision of energetic electrons with the gas molecules. Thermionic emission, as employed in an electron vacuum tube, is used. Bias of the individual elements within the gauge determine proper operation. Refer to Fig. C-4.3.1-1. The filament is heated by voltage supplied through R. R is adjusted until current *I*, through the grid circuit, is equal to a value dependent upon physical dimensions of the gauge. The voltage between the grid and filament acts to accelerate the electrons toward the grid. Collisions with gas molecules in this area produce positively charged ions. They are, in turn, attracted to the collector. M measures the ion current *I*, and is calibrated in pressure units. If the voltage between filament and collector is not set high enough, electrons that escape the grid would impinge upon the collector, subtracting from the ion current in an unknown manner.

Due to exposure to dirty atmospheres or other factors, it is possible during operation or storage for the gauge to become contaminated, and therefore require cleaning. To ensure proper operation, the other voltages are turned off and the switch (S) closed. An electric current is passed through the grid, heating the entire gauge, thus causing accelerated outgassing of the gauge, thereby in effect cleaning it.

During normal operation, the gauge is heated by the filament and some material is also evaporated from the filament. This combination of outgassing and pumping (gettering) at elevated temperatures can cause the indicated pressure to be in error if the gauge is not coupled closely to the gas volume whose pressure is of inter-

Fig. C-4.3.1-1 Bayard-Alpert Ionization Gauge



GENERAL NOTE:
I = current
M = measurement
R = resistance
S = switch

est. The reading obtained will be valid for the pressure inside the gauge, but will be inaccurate for the vacuum system if this caution is not observed.

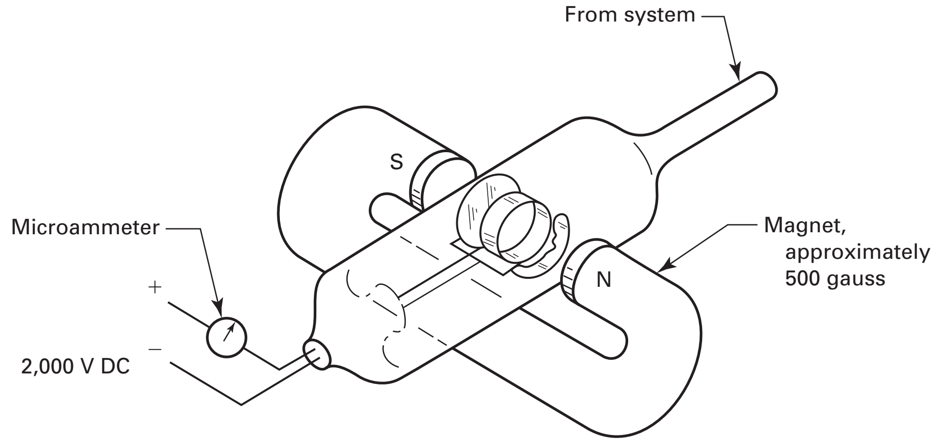
A pressure and atmosphere limitation exists for the hot filament gauge. Too high pressure or an atmosphere excessively rich in oxygen, water, or carbon dioxide, or other gases that can react with the hot filament will destroy the filament. Generally these conditions are avoided for pressures below 0.1 Pa to 0.01 Pa (10^{-3} mmHg to 10^{-4} mmHg). Frequently, emission or collector current is automatically monitored for evidence of excessive pressure, and provision is made to automatically shut off the filament when excess pressure exists.

As indicated before, the upper pressure range for the hot-filament gauge is generally 0.1 Pa (10^{-3} mmHg). The lower limit is influenced by design of the gauge, but generally corresponds to about 10^{-5} Pa to 10^{-6} Pa (10^{-7} mmHg to 10^{-8} mmHg). One order-of-magnitude decrease below this level is possible through careful design and selection of materials.

C-4.3.2 Phillips-Penning Gauge. This gauge is a commercially available ionization gauge. Ionization of the gas in this gauge is caused by the electrons and ions created in a glow discharge. To achieve even greater efficiency of ionization of the gas molecules, the electrons created in the glow discharge are constrained to move in helical paths by the proper application of electric and magnetic fields (see Fig. C-4.3.2-1). The amount of ionization produced in a given gas by this method is a function of the number of molecules per unit volume.

The ions thus formed are collected at the cathode. An electronic current flow is thereby set up in the external circuit. A microammeter is used to measure this current flow. For pressures below 0.1 Pa (1 μm), the microammeter reading is closely proportional to pressure. However,

Fig. C-4.3.2-1 Phillips-Penning Gauge



at pressures above 0.1 Pa (1 μm) and up to about 60 Pa (5 mmHg), the relation between the microammeter reading and pressure departs widely from linearity. The current commercially available Phillips-Penning-type ionization gauges do not read pressures of air much above 60 Pa (0.5 mmHg).

The Phillips-Penning type of ionization gauge is not too costly or complicated, and there is no danger of destruction if the gauge is accidentally exposed to atmospheric pressure. It has the following principal disadvantages:

(a) Its sensitivity to pressure changes above 13 Pa (100 μm) is low.

(b) The glow-discharge phenomena involved in its operation are dependent on the condition of the anode and cathode surfaces. This latter effect results in errors in calibration when contaminants cover the cathode and anode surfaces.

However, for pressure readings below 13 Pa, the Phillips-Penning ionization gauge performs quite satisfactorily.

C-4.3.3 Alphatron Gauge. This ionization gauge measures gas pressures from 0.01 Pa (0.1 μm) up to atmospheric pressure. The alphatron vacuum gauge uses a small quantity of radium as an alpha source (see Fig. C-4.3.3-1). The alpha particles emitted from this source ionize the gas molecules. The positive ions thus produced are accelerated by an electric field to a negatively charged collector probe. The accumulated positive charge on this probe causes an electronic current flow, which is measured by an electrometer amplifier. The output of this amplifier operates a microammeter or a strip-chart recorder.

Six pressure scales are available on the alphatron gauge. The lowest full-scale range is 13 Pa (10 μm). The other five scales increase in factors of 10 up to the highest full-scale pressure reading of 130 kPa (1 000 mmHg). The output indications of this gauge are quite linear as a function of pressure over this entire range. This gauge is calibrated to read pressure correctly for dry air at normal room temperatures. As is the case with all ionization types of pressure-reading gauges, corrections shall be made if the gas composition is different from that of dry air, or the temperature of the gases being measured is different from that for which the gauge is calibrated. For gases other than air, the scale factors are provided for making the necessary conversion. Since the alphatron is linear over most of its pressure range for gases heavier than air, and linear over the entire range for air, and gases lighter than air, the application of these correction factors is simple.

Although great care has gone into making the alphatron gauge as free as possible from the effects of contamination in the vacuum system, reasonable precautions should be taken to keep the vacuum system from depositing vapors on the radium source and the probe insulators. If a gauge becomes contaminated by vapors from the vacuum system, a simple cleaning with a solvent and a few minutes' drying time will restore the original calibration of the gauge.

C-4.3.4 Molecular Gauge. Another very useful vacuum pressure gauge is the molecular vacuum gauge. One model of this gauge is calibrated to read pressures from 0.26 Pa (2 μm) up to 26 kPa (20 mmHg). Its operation depends on the transfer of molecular momentum transmitted from a moving surface to another surface in close proximity (see Fig. C-4.3.4-1). At pressures below 130 Pa (1 000 μm), the angular deflection of the dial indicator is almost linearly proportional to pressure. This is because the mean free path of a molecule at pressures below 130 Pa is larger than the distance between the two surfaces. To extend the range of the gauge above 130 Pa up to 2.6 kPa (20 mmHg) of air, the designers have included vanes on one of the surfaces to produce

Fig. C-4.3.3-1 Ionization Chambers of an Alphatron Gauge

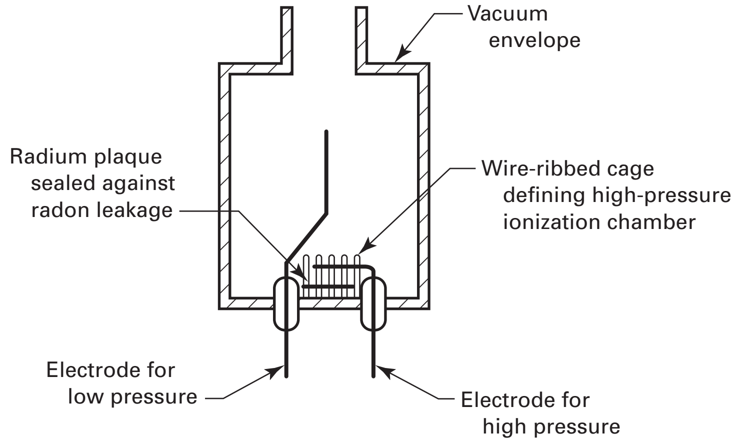
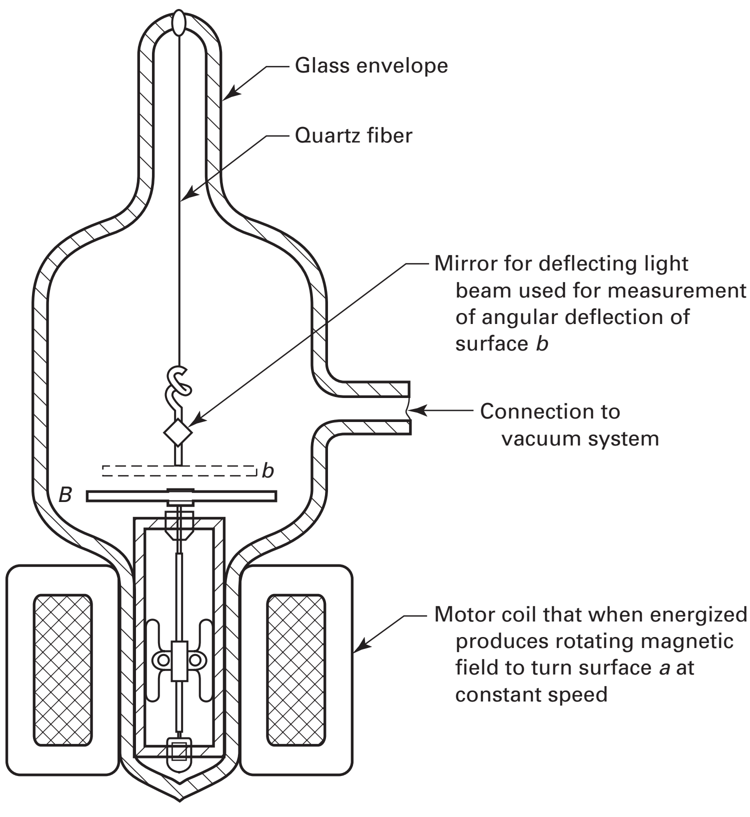


Fig. C-4.3.4-1 Langmuir-Dushman Molecular Gauge



$$B = KuP\sqrt{\frac{M}{T}}$$

where

B = rate of momentum transfer per unit area between the rotating surface a and the suspended surface b
K = constant for a given gas
M = molecular weight
P = absolute pressure
T = Kelvin temperature
u = angular velocity of the surface a

windage effects. If it were not for these vanes, the response of the gauge to pressures above 130 Pa would be very small because of the very low rate of momentum transfer when the mean free path is less than the separation between the surfaces.

Since this vacuum gauge depends for its operation on the transfer of momentum of the gas molecules, its deflection will be a function of the molecular weight of the gas as well as the temperature. The gauge is customarily furnished to be direct reading for dry air. For gases heavier than air, the deflection will be greater for a given pressure. The reverse is true for gases lighter than air. Correction factors are available for some of the more common gases. The gauge is also available with a linear scale of arbitrary units so that the user may calibrate the gauge more conveniently when it is to be used for measurement of other gases. In addition to being dependent for its calibration on the gas mass and temperature, it is also dependent on the power-line frequency. This is because a small synchronous motor is used to drive the driver surface at a constant speed. The equation in Fig. C-4.3.5-1 readily illustrates that the molecular momentum transfer between the surfaces is a function of the speed of the driver surface.

For some installations, it may not be convenient to use a gauge of this type because the dial indicator has to be located in close proximity to the system under measurement. Figure C-4.3.5-1 is a sketch of the early Langmuir-Dushman molecular vacuum gauge. It is limited to about 130 Pa (1 000 μm) maximum pressure. However, recent improvements have extended the pressure range up to 2.6 kPa (20 mmHg) by adding vanes on the moving surface to produce windage effects.

C-5 APPLICATIONS CONSIDERATIONS

Even if the precision of a vacuum gauge is high, the readings obtained will be in error if certain precautions and corrections are not made. If a leak exists at the vacuum-gauge connection to the vacuum system, a pressure drop could easily result in the direction of molecular flow in the vacuum system under measurement. If the molecular conductance between the vacuum gauge and the point at which the pressure measurement desired is high, then it is quite likely that a correction in the reading is not necessary. However, if the molecular conductance of the pipe or tubing connecting the vacuum gauge to the vacuum system is very low, then serious errors could be obtained. For these reasons, the vacuum gauge should be placed as close as possible to the point in the vacuum system for which the pressure information is desired. In this regard, due consideration shall be given to the possibility of contaminants such as oil vapors from back-streaming vacuum pumps. These contaminants could result in large errors in the gauge readings. In many cases, a simple, right-angle elbow-pipe connection from the gauge to the vacuum system helps considerably in reducing gauge contamination. Another point that is often overlooked when using vacuum gauges in systems occurs when there is a large difference in temperature between the vacuum gauge and the point in the system for which pressure information is required. As mentioned earlier, this can be a subtle source of error in the hot-filament ionization gauge. In the case of high-vacuum furnaces, temperatures may be elevated by several hundred degrees Celsius. Elementary considerations of the gas laws clearly indicate the correction factors involved.

In addition to accuracy and the application of correct scale factors in the use of the vacuum gauges, those operating the gauge should be aware of the speed of response of the vacuum gauge to sudden changes in pressure. In the case of the thermal-conductivity gauges, the time constants involved are of the order of seconds. Most composition-dependent gauges are considerably more rapid in responding to a pressure change, and their response is usually limited by the recording device used to measure the output signal of the vacuum gauge. In many applications, however, it is usually found that the speed of response of even the slow thermal-conductivity gauges is entirely adequate since the time constants of the vacuum system itself are considerably larger.

In general, the measurement problem should be carefully considered before a vacuum gauge is selected for any particular application. Careful consideration shall be given to the particular kind of gas variable being measured. In many cases, pressure is the most important quantity. In other cases, the gas density is a much more important factor than the pressure. From economic considerations it may be found that the thermal-conductivity vacuum gauges have more than adequate accuracy and speed of response to satisfy the measurement requirement. Where high accuracy is required, it may be necessary to use some of the more expensive vacuum gauges. However, expensive vacuum gauges do not necessarily mean more accurate measurements if the gauge is improperly applied and necessary correction factors are not made.

NONMANDATORY APPENDIX D
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