

# PRESSURE MEASUREMENT

## LIQUID MANOMETERS

Technically a manometer is any device used to measure pressure. However, the word manometer is commonly used to mean a pressure sensor which detects pressure change by means of liquid in a tube.

Manometers are differential pressure sensors. A differential pressure sensor measures the difference between a pressure being applied to it and a reference pressure (often atmospheric pressure).

**Differential pressure is a comparison of one pressure to another.**

There are many forms of flow meters. For flow in closed channels (such as pipes), the most commonly used, and the devices we shall consider here, are:

### U-tube manometer

The U-tube manometer is somewhat self-descriptive. In its basic form it consists of a clear glass or plastic tube shaped into the form of a 'U'. The tube is partially filled with a liquid, such as water, alcohol, or mercury (although for safety reasons mercury is no longer commonly used). The lower the density of the liquid, the higher the sensitivity of the manometer.

The diagram opposite shows a basic U-tube manometer. Both ends of the tube are open, and atmospheric pressure acts equally on the liquid through each end. Therefore the height of the liquid on each side of the U (in each limb) is equal.

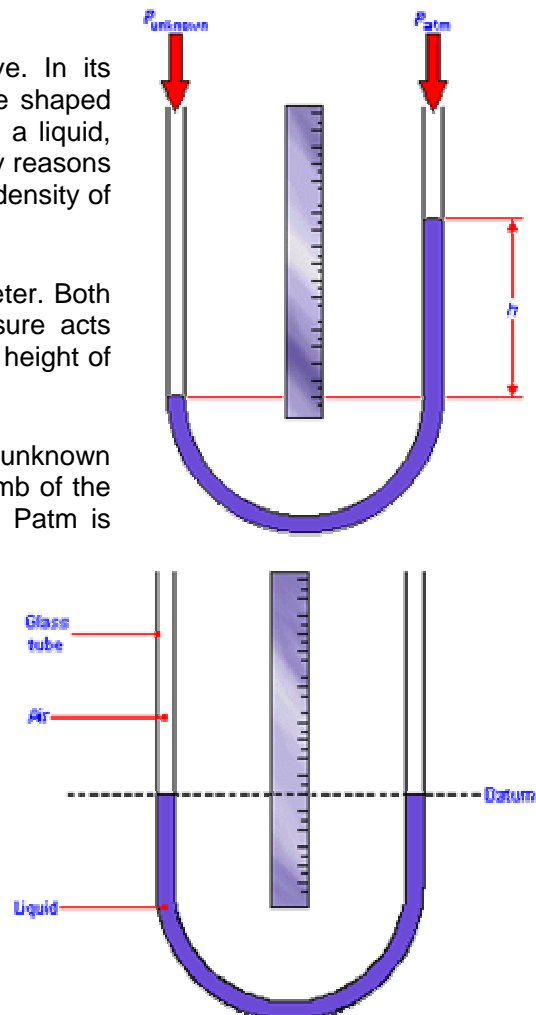
Now we show the U-tube manometer with an unknown pressure  $P_{\text{unknown}}$  applied to one limb. The other limb of the tube is left as it was, that is, atmospheric pressure  $P_{\text{atm}}$  is maintained at its open end. The unknown pressure acts on the liquid in the tube, forcing it down the limb it is applied to. Because the liquid is incompressible, it rises up the other limb. Hence the height of the liquid on either side of the tube is no longer equal. The difference between the height of the liquid in each limb,  $h$ , is proportional to the difference between the unknown pressure and atmospheric pressure.

In a U-tube manometer, the difference between the unknown pressure and atmospheric pressure is the gauge pressure. In a U-tube manometer,

$$P_{\text{gauge}} = P_{\text{unknown}} - P_{\text{atm}} = \rho gh$$

where,

$\rho$  is the density of the liquid in the tube, in  $\text{kg m}^{-3}$



$g$  is the acceleration due to gravity, that is,  $9.81 \text{ m.s}^{-2}$   
 $h$  is difference between the heights of the liquid in each limb, in m

If we know atmospheric pressure, or can accept the errors which occur using the standard value, then we can find  $P_{\text{unknown}}$  by rearranging the equation,

$$P_{\text{unknown}} = P_{\text{atm}} + \rho gh$$

The accuracy of U-tube manometers is largely dependant on the skill of the reader in judging the difference in height of the liquids in each limb. So that this can be made easier and the height difference  $h$  can be read from one limb, a half-scale is sometimes used. Because the increase in the fluid level in one limb is directly proportional to the decrease in level in the other limb, every 1 mm change in level in one limb represents a change in  $h$  of 2 mm. A half-scale will have, say, every 5 mm labelled on one limb as 10 mm, representing the change in  $h$ .

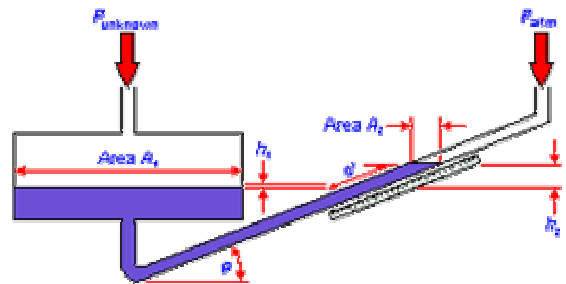
The U-tube manometer is not in wide use in industry, although it is sometimes used to calibrate other instruments. It is mainly used in laboratories for experimental work and demonstration purposes. It can be used to measure the pressure of flowing liquids as well as gases, but cannot be used remotely. If pressures fluctuate rapidly its response may be poor and reading difficult.



This picture shows manometers used in a piece of experimental apparatus for measuring flow of a liquid. As we shall see in the section on flow, the pressure of a liquid in a pipe relates to its flow rate. Here, a multi-limb manometer is used, which is effectively a series of inverted U-tube manometers.

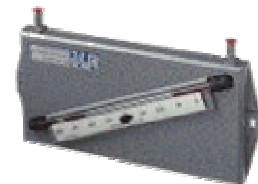
### Inclined Tube Manometer

The inclined tube manometer is a differential pressure sensor more sensitive than the U-tube manometer. Hence it is more suitable for use with smaller pressure measurements or where greater accuracy is required. This diagram shows its basic design.



One limb of the inclined tube manometer forms into a reservoir. The other limb of the manometer is inclined at a known angle  $\theta$ . The inclined limb is made from a transparent material such as glass or plastic. The reservoir is usually made of plastic, but does not need to be transparent.

The surface area of the fluid in the reservoir  $A_1$  is much larger than the surface area of the fluid in the inclined limb  $A_2$ . Both limbs are open ended and so subject to atmospheric pressure. If an unknown pressure  $P_{\text{unknown}}$  is applied to the reservoir limb, the change in height  $h_1$  will be relatively small compared to the change in height in the inclined limb  $h_2$ .



The gauge pressure is given by the equation

$$P_{\text{gauge}} = P_{\text{unknown}} - P_{\text{atm}} = \rho g d (A_2/A_1 + \sin\theta)$$

where,

$\rho$  is the density of the liquid in the tube, in  $\text{kg m}^{-3}$

$g$  is the acceleration due to gravity, that is,  $9.81 \text{ m.s}^{-2}$

$d$  is the distance the liquid has moved along the inclined limb, in m

$A_2$  is the cross-sectional area of the reservoir, in  $\text{m}^2$

$A_1$  is the cross-sectional area of the liquid in the inclined limb

$\theta$  is the angle of the inclined limb from the horizontal.

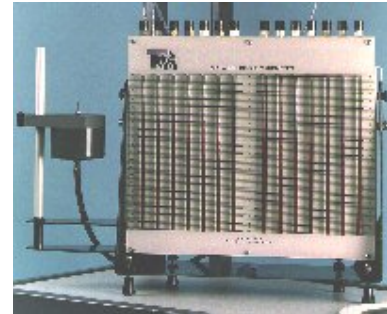
Because  $A_1$  is much larger than  $A_2$ , the ratio  $A_1/A_2$  can be considered negligible. Therefore

$$P_{\text{gauge}} = P_{\text{unknown}} - P_{\text{atm}} = \rho g d \sin\theta$$

If we know the atmospheric pressure, or can accept the errors which occur using the standard value, then we can find  $P_{\text{unknown}}$  by rearranging the equation,

$$P_{\text{unknown}} = P_{\text{atm}} + \rho g d \sin\theta$$

This picture shows a multi-limb inclined tube manometer used with experimental apparatus investigating air flow. Notice that the angle of inclination can be varied. This allows adjustment of the range and sensitivity to suit the pressure being measured.



The accuracy of inclined tube manometers relies less on the skill of the reader than U-tube manometers. They are more sensitive, but unless the inclined limb is relatively long they cannot be used over as wide a range of pressures.

Inclined tube manometers are used where higher sensitivity than a U-tube manometer is required. It cannot be read remotely, and it is usually used with gases.

## ELASTIC PRESSURE SENSORS

Elastic pressure sensors are so called because something flexes, stretches, or temporarily deforms when a pressure is applied.

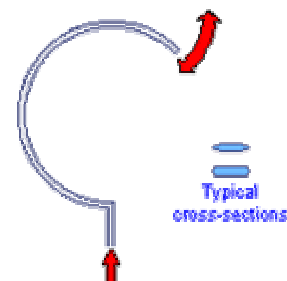
**Elastic pressure sensors initially convert pressure into a displacement.**

This allows displacement sensors to be used to condition the output signal from the pressure sensor. Some pressure sensors are referred to by the method they use to measure this displacement, such as piezoelectric and capacitive pressure sensors. Where electronic displacement sensors are used, the method of detecting pressure change is usually by means of a diaphragm. Elastic pressure sensors measure pressure differentially.

The elastic pressure sensors we will be studying are:

### Bourdon tube pressure gauge

The Bourdon tube pressure gauge, named after Eugène Bourdon, is probably the most popular pressure sensor.



Basic Bourdon tubes are made from metal alloys such as stainless steel or brass. They consist of a tube of elliptical or oval cross-section, sealed at one end. There are various shapes of Bourdon tube, including helical, spiral and twisted. A common design is the C-shape, as shown to the right. Here the tube is at atmospheric pressure. When increased pressure is applied to the open end, it deflects outwards (tries to straighten) in proportion to the pressure inside the tube (the outside of the tube remains at atmospheric pressure).

As the pressure is decreased, the tube starts to return to its atmospheric pressure position. The amount by which the tube moves in relation to the pressure applied to it depends on factors including its material, shape, thickness, and length. Compared to other elastic pressure sensors the deflection produced by Bourdon tubes is large.

The Bourdon tube pressure gauge, shown here, consists of a Bourdon tube connected to a pointer. The pointer moves over a calibrated scale. When pressure is applied, the movement of the tube is fairly small, so to increase the movement of the pointer it is mechanically amplified. This is usually by a connecting mechanism consisting of a lever, quadrant and pinion arrangement.

Bourdon tubes need some form of compensation for temperature, as temperature changes affect their accuracy. For remote sensing, the displacement of the Bourdon tube caused by pressure changes can be detected by a suitable displacement sensor.

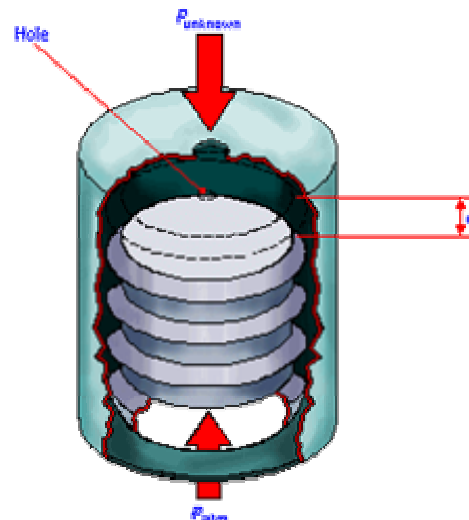
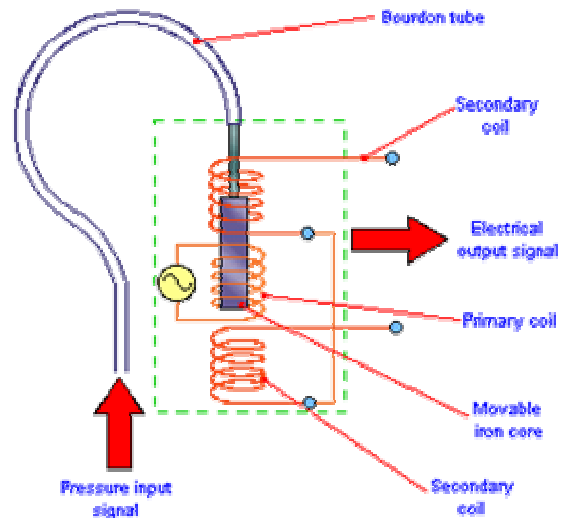
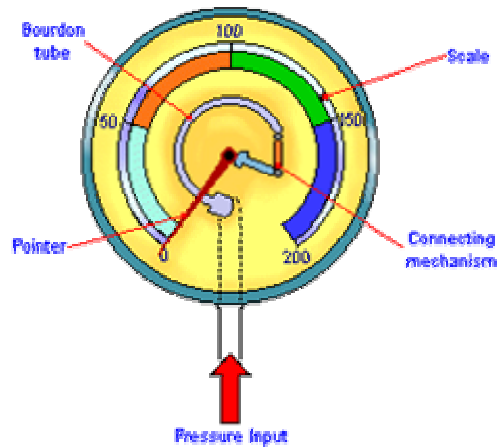
Here we show an LVDT connected to a Bourdon tube. This converts the displacement at the end of the tube into an electrical signal. This signal can then be displayed or recorded on an electrical device calibrated in terms of pressure.

Some designs of Bourdon tube pressure gauge tend to be fairly inexpensive because they are mass produced (which reduces costs). They are suitable for use with both liquids and gases, are used in a wide variety of applications, both industrial and domestic. Applications range from tyre pressure gauges, measuring the pressure in pneumatically controlled tools and machines, to pipeline pressure in chemical plants.

## Bellows

Bellows are differential pressure sensing devices mainly used in low pressure ranges of about 0 to 1000 pascals.

Here we show a set of metallic bellows, held inside a protective casing. The bellows are made of a thin copper alloy tube pressed into a corrugated shape. This is sealed at one end, with a small hole at the other end. When pressure is applied via the hole, the bellows expand a distance  $d$ . This displacement can be calibrated



in terms of pressure.

The pressure applied to the bellows  $P_{\text{unknown}}$  is given by the equation

$$P_{\text{unknown}} = (d/A)\lambda$$

where,

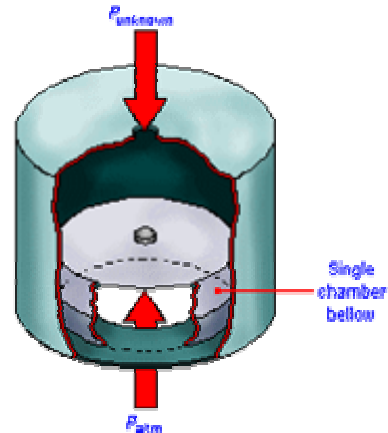
$d$  is the distance moved by the bellows in m

$A$  is the cross sectional area of the bellows in  $\text{m}^2$

$\lambda$  is the stiffness of the bellows in  $\text{N}\cdot\text{m}^{-1}$

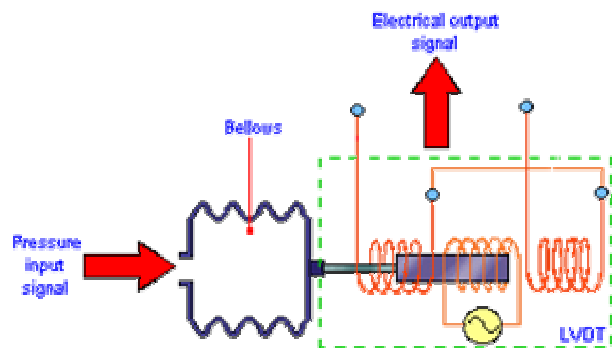
Here is a single chamber 'bellow'. It consists of two circular metal diaphragms connected back to back. These devices, commonly referred to as capsules, give smaller displacements than multi-chamber bellows.

Bellows usually produce small displacements. These need to be amplified, and displacement sensors such as LVDTs and potentiometers are often used to convert the displacement into an electrical signal.



Here is a bellows sensor used with an LVDT. The LVDT produces an electrical output signal directly related to the displacement input signal. This can then be displayed or recorded on a device calibrated in terms of pressure.

Bellows should not be used in an environment where they may be subjected to vibration or shock. Their accuracy is also affected by temperature changes.

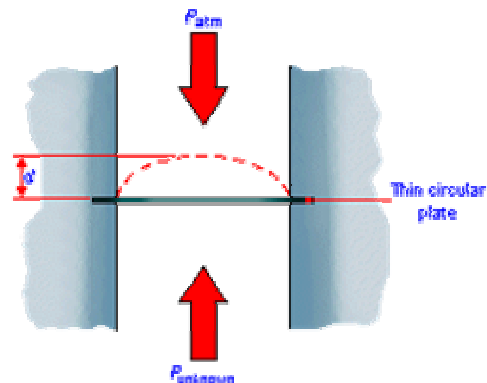


An example of the use of bellows is in control applications, for closing valves in a pipe when a critical pressure is reached.

## Capacitive pressure sensors

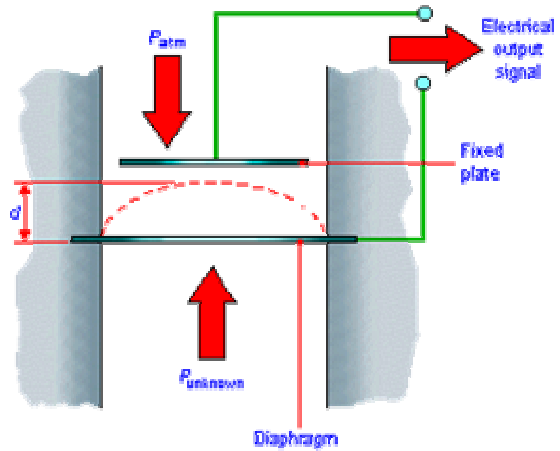
Capacitive pressure sensors use the electrical property of capacitance to measure the displacement of a diaphragm. The diaphragm is an elastic pressure sensor displaced in proportion to changes in pressure. It acts as one plate of a capacitor.

The diaphragm consists of a thin plate of metal alloy, such as stainless steel or brass. It is circular and fixed continuously around its edges to a cylinder. This diagram shows how it displaces when a pressure is applied to it. It is a differential pressure sensor, because it is subject to atmospheric pressure. The amount by which the diaphragm moves with respect to the unknown pressure applied to it depends on its shape and construction, size, thickness, and material. Therefore the precise relationship between pressure and displacement varies with each design. However, the displacement is small, rarely more than a few millimetres, often fractions of a millimetre. Because of this, these devices are often individually calibrated (against an accurate inclined tube manometer, for example).



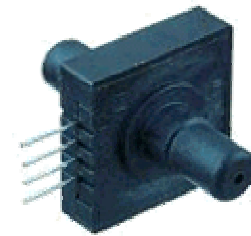
Because the displacement of the diaphragm is small, a displacement sensing device with high resolution, sensitivity and accuracy is required. Also, a non-contact device is required as any mechanical resistance will reduce the displacement even more. Using the diaphragm as one plate of a capacitor is a non-contact displacement sensing method, providing an electrical output with infinite resolution particularly suited to small displacements.

This diagram shows a diaphragm and capacitor combination. One plate of the capacitor is fixed, the other plate is the diaphragm. The dielectric is usually air. Notice that it does not use the variable area technique like the capacitive displacement sensor. Instead, the distance between the plates is varied. When there is a change in pressure, the diaphragm deflects in proportion to it, and this causes the distance  $d$  between the plates of the capacitor to change. The capacitance  $c$  of the capacitor is (approximately) inversely proportional to the distance  $d$  between the plates. That is,  $c \propto 1/d$



An electrical signal is connected to the two plates of the capacitor. The change in value of the capacitance causes this electrical signal to vary. This is then conditioned and displayed on a device calibrated in terms of pressure.

There are techniques other than change in capacitance used to measure the displacement of a diaphragm. For example, another design of pressure sensor uses a diaphragm made from silicon. Semiconductor strain gauges are diffused into the diaphragm. They are arranged in a form similar to the Wheatstone bridge. A stable electrical output is produced, and the arrangement of the strain gauges compensates for temperature changes. However, these types of pressure sensor are relatively expensive.



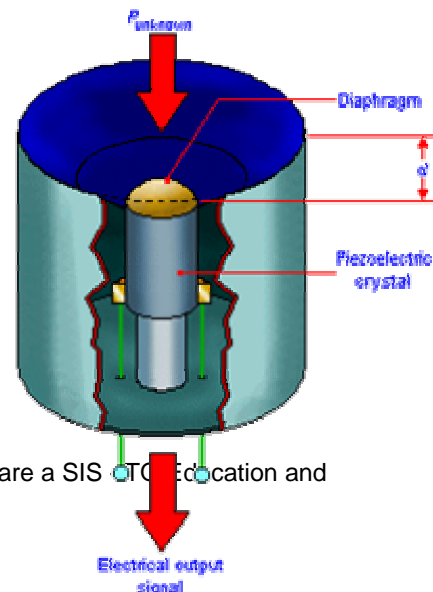
Because of the sensitivity of diaphragm based pressure sensors, they are used to measure small changes in pressure. An example application is small changes in pressure in liquid or gas pipelines so that the flow rate can be measured. See the flow section for how this achieved

## Piezoelectric pressure sensor

This diagram shows the principle of a piezoelectric pressure sensor. These sensors are similar to capacitive pressure sensors in that they detect pressure changes by the displacement of a thin metal or semiconductor diaphragm. In a pressure sensor using the piezoelectric effect, the diaphragm causes a strain on the piezoelectric crystal when flexing due to pressure changes. The electric charges of opposite polarity appearing on the faces of the crystal are proportional to this strain.

The piezoelectric crystal is usually quartz. This type of pressure sensor often incorporates signal conditioning circuitry in a sealed unit, using integrated circuit technology.

Piezoelectric pressure sensors operate at high temperatures and can be made small in size. Their main advantage is that they have a fast response and fairly wide operating range. Hence they can be used in applications such as measuring



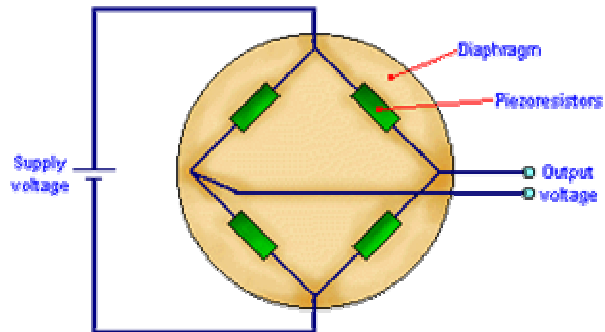
the pressure in a gun barrel when it is fired. They have very high sensitivity and also good accuracy, repeatability and low hysteresis.

## Piezoresistive and strain gauge pressure sensors

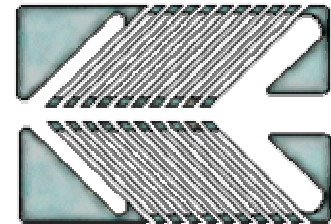
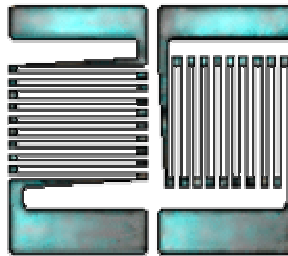
A pressure sensor similar to the piezoelectric pressure sensor is the piezoresistive pressure sensor. These devices use silicon diaphragms, which form part of a semiconductor integrated circuit chip.

**Piezoresistivity is a strain dependent resistivity in single crystal semiconductors.**

Four piezoresistors on the diaphragm form a Wheatstone bridge as shown here.



When pressure is applied to the diaphragm it causes a strain in the resistors. The resistance of the piezoresistors changes in proportion to this strain, and hence the change in pressure.



A typical specification of a piezoresistive pressure transducer can be found in the [reference section].

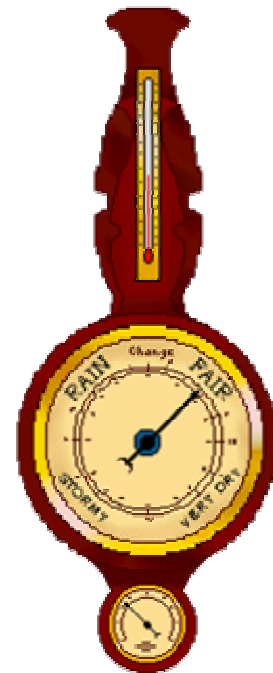
The range of piezoresistive pressure sensors is normally low, typically at a maximum of about 0 to 200 kPa. They are used where good repeatability, high accuracy, low hysteresis and long term stability are required. A typical application is in sensing the pressure at the bottom of a water tank. This pressure is directly related to the depth of water, and so the pressure sensor forms part of a level measurement system.

For measuring higher pressure ranges, instead of piezoresistors, bonded resistance strain gauges may be used. These are based on a similar principle to the piezoresistive strain gauge, in that the resistors are bonded to a diaphragm and formed into a Wheatstone bridge. They can measure pressures up to about 25000 kPa.

## BAROMETERS

A barometer is a pressure sensor specifically used to measure atmospheric pressure. Because of this they have to be sensitive, and measure absolute pressure. They are mainly used for meteorological purposes. High atmospheric pressure is usually associated with fine weather while low pressure usually predicts poor weather.

Barometers have existed for many years, and there are two basic types.



## Liquid in glass barometer

This barometer is a type of liquid manometer. It consists of a thin glass tube containing a liquid. The liquid is usually mercury to keep the length of the barometer as small as possible.

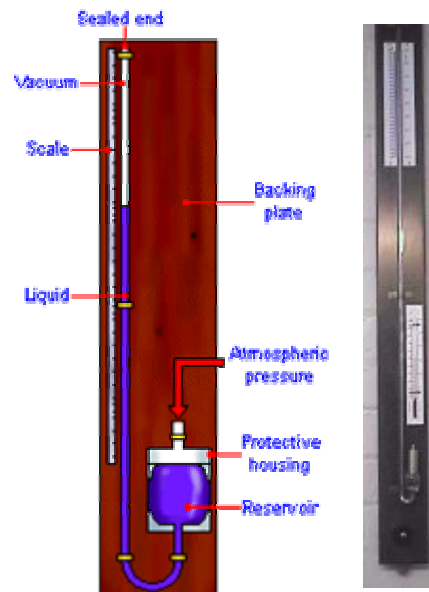
This diagram shows the basic design of a liquid in glass barometer. It consists of a U-shaped manometer fixed to a backing plate. One limb forms a reservoir, and is open to atmospheric pressure via a small hole. The other limb is a thin tube, containing a volume of liquid small in comparison to that contained in the reservoir. Like the inclined tube manometer, this allows the pressure to be read against a scale on one limb. The end of this limb contains a vacuum and is sealed.

**A pure vacuum is a space totally devoid of any matter, which therefore has no pressure. On Earth a pure vacuum is impossible to achieve. However, the term vacuum is applied to something having a pressure lower than atmospheric pressure.**

It is the vacuum which allows the barometer to measure absolute pressure. It is still measuring the difference in pressure between the two limbs. However, the pressure produced by the vacuum is lower than the local air pressure, and constant. Therefore, the pressure acting on the limb containing the vacuum can be considered negligible. The only significant pressure acting on the liquid in the barometer is the atmospheric pressure. Hence the height of the liquid in the tube is proportional to atmospheric pressure.

The level of the reservoir may be adjusted on some liquid in glass barometers. This allows it to be matched to the zero of the scale before readings are taken thus improving accuracy.

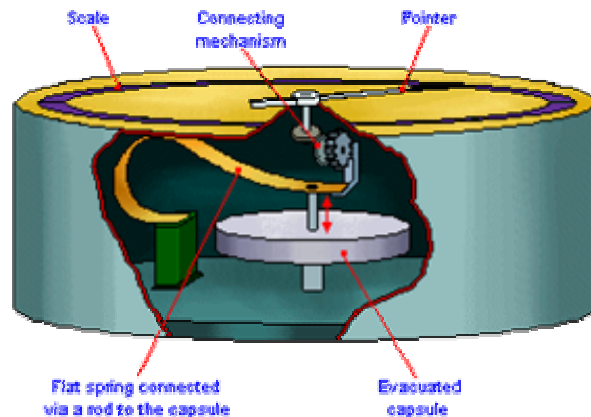
There are several designs of liquid in glass barometer. They are accurate but can be rather cumbersome. They also tend to be fragile, and their accuracy is significantly affected by temperature variations. They are usually in a fixed position and are often used for calibration of other pressure sensors or as a datum in laboratories



## Aneroid barometer

The word aneroid simply means something which does not contain liquid, and so distinguishes this type of barometer from the liquid in glass type.

The aneroid barometer, shown here, senses atmospheric pressure changes by means of a sealed metal capsule. One or two faces of the capsule are diaphragms. The capsule contains a partial vacuum. Because the pressure inside the capsule is lower than atmospheric pressure and constant, it is sensitive to changes in atmospheric pressure. If atmospheric pressure increases, the diaphragms move and the capsule flattens. If atmospheric pressure rises, the capsule expands. This displacement is detected





by a bar pressed on to the capsule by a strong spring. This is mechanically amplified by gears and levers and transmitted to a pointer on a calibrated scale.

The aneroid barometer is simpler to read and takes up less space than the liquid in glass barometer. It is not affected by temperature changes as significantly, but is less accurate mainly because of its mechanical parts. In fact, aneroid barometers are usually calibrated against liquid in glass barometers.

Aneroid barometers are commonly used for domestic purposes. They are likely to be calibrated in non-SI units, such as millimetres of mercury or bar. Some versions are calibrated with respect to likely weather conditions!

If electronic measurement is required, the movement of the diaphragm can be detected in terms of capacitance as discussed earlier in this section. This increases accuracy and sensitivity. Because atmospheric pressure changes with altitude, capacitive aneroid barometers sometimes form the basis of altimeters in aircraft.