LESSON 1: INSTRUMENTATION EQUIPMENT

Introduction

This lesson describes the instrumentation techniques and equipment used to measure, indicate and manipulate the basic process parameters (***Level***, ***Flow***, ***Pressure***, ***Temperature*** and ***Neutron Flux***) in a typical industrial control environment. Most of the practical examples used are particularly applicable to CANDU electric generating stations.

TABLE OF CONTENTS

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 1: INTRODUCTION TO INSTRUMENTATION

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. Explain briefly, in your own words, the need for ***signal transmission***.
2. State the ***standard range*** of pneumatic signal in a typical instrumentation loop.
3. State the advantages and disadvantages of using a pneumatic signal transmission system.
4. State the standard range of ***electronic signals*** in a typical instrumentation loop.
5. State the advantages and disadvantages of using an electronic signal transmission system.
6. Explain the purpose of the "***live zero***" as applied in an instrumentation loop.
7. Calculate the value of an electronic signal, given the process condition and the signal range.
8. Calculate the process condition, given the pneumatic or electronic signal value and the signal range.
9. Calculate the values of dropping resistors needed using Ohm's Law, given the range of the current signal and the potential drop (i.e. voltage) required.
10. Explain briefly, in your own words, the function of ***trend recording***.

Introduction

- Instrumentation is used in almost every industrial process and generating system, where ***consistent*** and ***reliable*** operations are required.

- Instrumentation provides the means of monitoring, recording and controlling a process to maintain it at a desired state.

- A typical industrial plant such as an electric generating station (Figure 1) yields many process variables that have to be ***measured*** and ***manipulated***.

- Variables such as boiler level, temperature and pressure, turbine speed, generator output and many others have to be controlled prudently to ensure a ***safe*** and ***efficient*** station operation.

- Because of the continuous interactive nature of most industrial process systems, manual control is non-feasible and unreliable. With instrumentation, automatic control of such processes can be achieved.

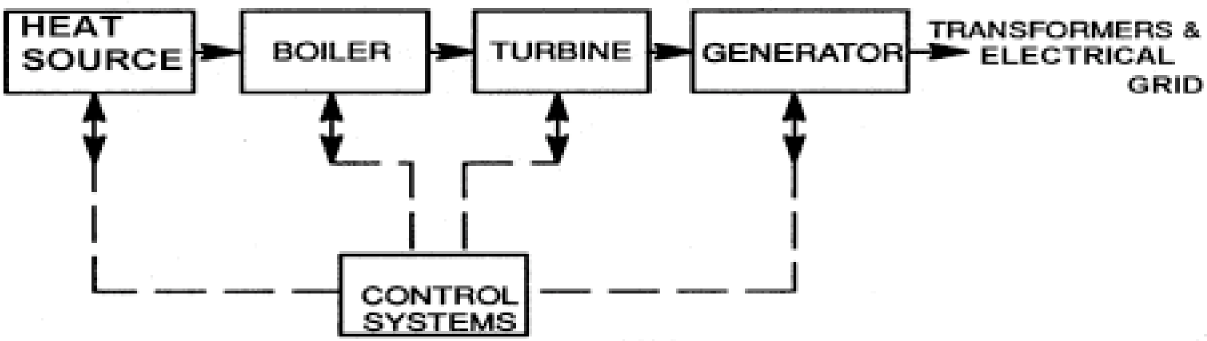


Figure 1. Simplified Electric Generating Station

us must be known.

- Specific instrumentation can be selected to measure, and to indicate process conditions so that a corrective action could be initiated if required.

- An instrument could be mounted at the process location to indicate the process state to the plant personnel. This form of data display is referred to as ***local or field indication***.

- Local indication is useful in many applications, but has the disadvantage that someone must travel throughout the plant in order to determine the system status.

- To bring all of these indicators into one single location (i.e. ***the central control room***), would mean transporting the actual process quantity to that location. This would result in ***hazardous conditions*** due to the presence of high pressure steam, high voltage, toxic gases, corrosive liquids, etc., in the control room.

- Instead of simply indicating the process status locally, or transporting the actual process to the control room, it would be desirable to be able to transmit a ***representative signal*** corresponding to the process status, to the central control room.

- By measuring and displaying this signal in the control room, the ***field process state*** can be determined. The read-out device mounted in the control room panel can be adjusted or calibrated to indicate the process value directly.

- Another advantage of being able to transmit a signal is that some signals may be analyzed by controllers or computers so that an ***automatic corrective action*** will be initiated if the process deviates from the desired operating point, called the setpoint.

- Also, if abnormal conditions arise, ***alarm units*** which are activated by these signals can be used to trigger ***annunciations*** in the control room or to cause a process to shut down safely.

The ***two standard methods*** of transmitting a signal are:

1. ***Pneumatic***
2. ***Electronic***

Pneumatic Signals

- A pneumatic process sensor coupled to a transmitter is used to monitor a process variable; such as ***level*** in a tank or ***pressure*** in a pipe.

- The output signal of the pneumatic transmitter is air pressure, the magnitude of which is ***directly proportional*** to the process variable being monitored.

- The standard industrial range for pneumatic signals is ***20 to 100 kPa(g)*** (kPa(g) = kPa above atmospheric), which corresponds to a ***0% to 100% process*** condition.

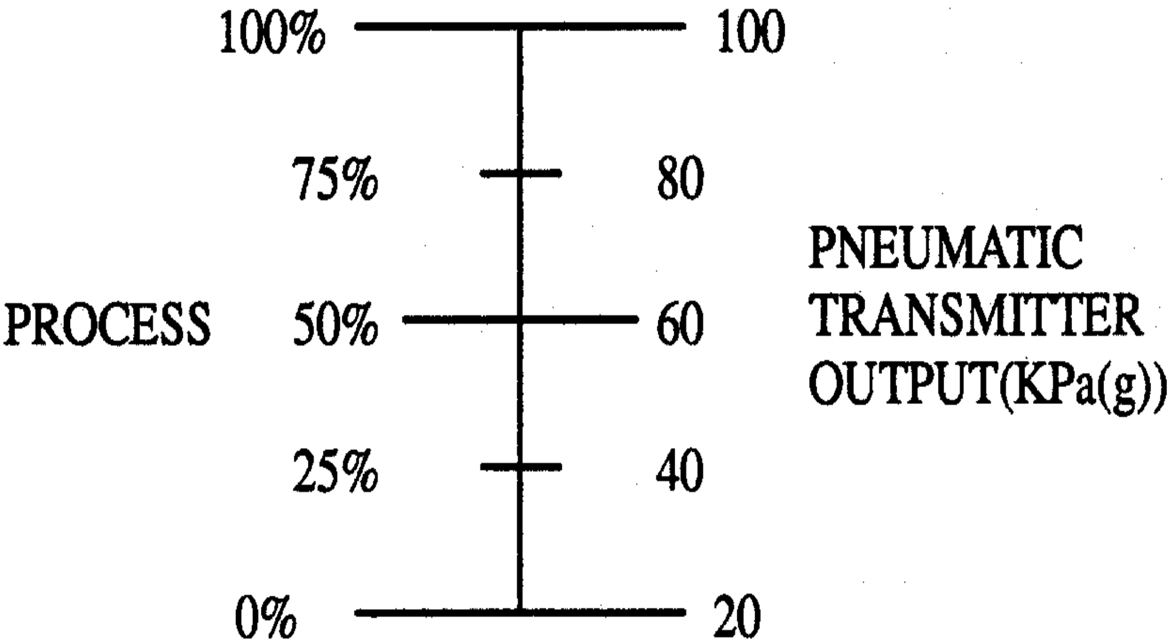


Figure 2. Pneumatic Signal vs Percent Process

- Note that the transmitter signal output starts at 20 kPa(g) – not 0 kPa(g).

- This 20 kPa(g) output is called a ***live zero***.

- A ***live zero*** allows control room staff to distinguish between a valid process condition of 0% (a 20 kpa(g) reading) and a disabled transmitter or interrupted pressure line (a 0 kpa(g) reading) – providing a coarse ***rationality check*** means.

Example

A 20 - 100 kPa(g) output pneumatic transmitter is used to the monitor water level inside a tank. The calibrated range is ***100 to 200 cm***. of water above the base of the tank. Calculate the output of the transmitter when the water level is at ***175 cm***. above the base of the tank.

Solution
Span (difference between the upper and lower limit) of the transmitter output

= 100 kPa - 20 kPa
= 80 kPa(g)

$$\text{Fraction of measurement} = \frac{175 - 100}{200 - 100} = 0.75$$

Output Signal = (Fraction of Measurement) x (Signal Span) + Live Zero
= 0.75 x 80 + 20
= 80 kPa(g)

Advantages and Disadvantages of Pneumatic Transmission.

- One advantage of a pneumatic system (over an electronic system) is that sparks will not be produced if a transmitter malfunction occurs, making it much safer when used in an ***explosive environment***.

- Furthermore, there is no ***electric shock*** hazard.

- On the other hand, a pressurized system can be dangerous if a line ruptures.

- Also, pneumatic signal lines are bulky and difficult to install.

- The biggest problem with pneumatic systems is that air is compressible. This means that a pressure transient representing a process change will only travel in the air line at ***sonic velocity*** (approximately 300 m/sec.). Long signal lines must therefore be avoided to prevent ***substantial time delays*** a serious drawback when you consider the size of our nuclear generating stations.

Electronic Signals

- For large industrial process applications such as generating stations where central control rooms are used, electronic signals are preferred and in many cases are used exclusively.
- The process condition is monitored and an electronic signal that is proportional to that process condition is produced by an electronic transmitter.
- The accepted industrial standard for electronic signals is now a **4 to 20 mA** current signal that represents the 0% to 100% process condition.
- Again, a ***live zero*** (4 mA) is used to distinguish between 0% process (4 mA) and an ***interrupted*** or ***faulted*** signal loop (0 mA).

The relationship between the process condition and electronic transmitter signal output is shown in Figure 3.

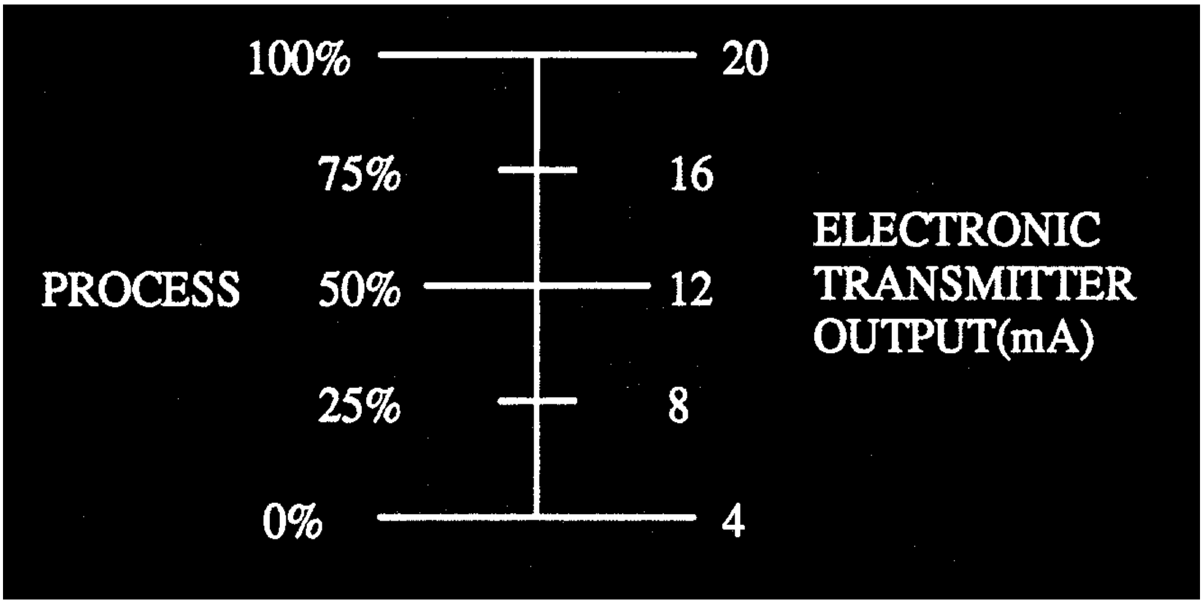


Figure 3. Electronic Signal Values vs Percent Process Measurement

Electronic Signal Example

- An electronic transmitter with an output of 4 - 20 mA is calibrated for a pressure range of 7 - 10 MPa(g). What pressure is represented by a 12 mA signal?

Solution

Span of transmitter 20 mA - 4 mA = 16 mA

$$\text{Fraction of Measurement Change} = \frac{\text{Output Signal - Live Zero}}{\text{Signal Span}}$$

$$= \frac{12 - 4}{16}$$

$$= 0.5$$

Actual Process Change = (Fractional Change) x (Process Span)
= 0.5 x (10 - 7 MPa)
= 1.5 MPa

Actual Process Value = Base Point + Process Change
= 7 + 1.5 MPa
= 8.5 MPa(g)

- When an electronic signal is used instead of a pneumatic signal the pressurized fluid ***transmission delay*** is eliminated.
- The electronic current signals travel at speeds which approach the speed of light.
- These current signals can be transmitted over long distances without the introduction of unnecessary time delays.
- In this course, it is intended that all transmitted signals will be electronic with the only use of other signals for the necessary final device operations.

The 4 - 20 mA Current Loop

- The simplified electronic transmitter can be considered as a ***variable resistor*** where the resistance is altered by the process condition. When used in series with a constant voltage power supply, a 4 - 20 mA current can be produced in the loop.
- Recall Ohm's Law, **I = V/R**
- By varying the resistance while the power supply voltage is kept at a constant value, the amount of current in a loop can be proportionally manipulated.
- The same two wires that power the transmitter also carry the signal. Using a current signal minimizes the number of wires needed and the effect of background noise, which is essentially induced voltage.
- Readout devices which can either be current or voltage sensitive can be used to provide a signal indication. To get a direct indication of the current signal, ***a milli-ammeter*** can be connected in series in the loop. Alternatively, a voltage sensitive device such as a ***voltmeter*** can be connected in parallel with a ***dropping resistor*** to sense the potential developed across the resistor by the current flow. (Figure 4).

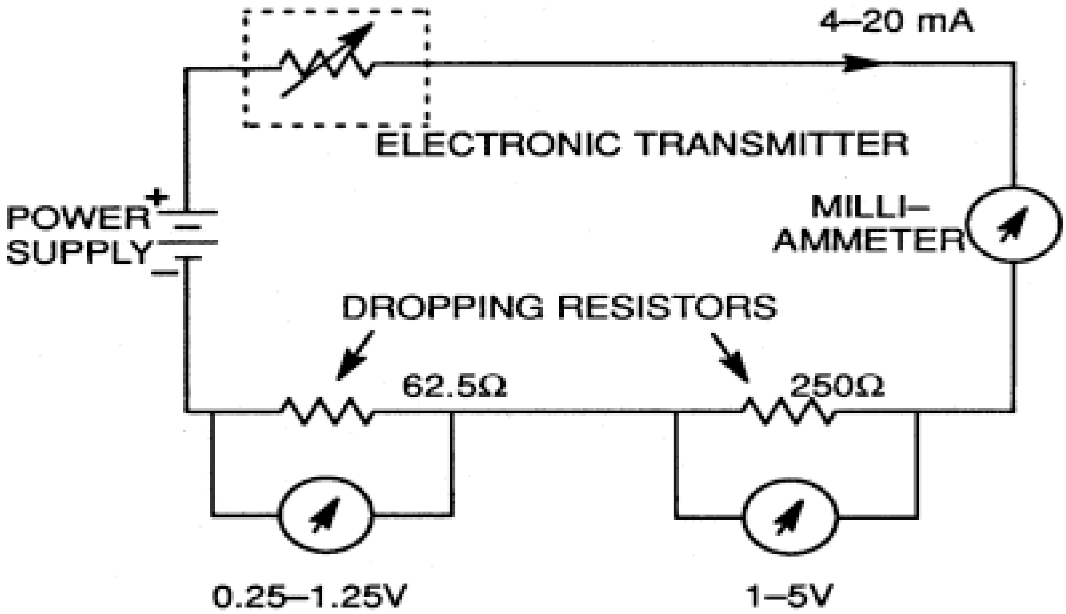


Figure 4. A Representative Current Signal Loop

Voltage Readout Devices

- Voltage sensitive instruments can respond to a voltage range of say 0.25 - 1.25V or 1 - 5V. To calculate the value of dropping resistor required, Ohm's Law can be used.

- Ohm's Law: **V = IR**

  or

  R = V/1

  where

  V = voltage across the resistor (Volt)
  I = current (Amp)
  R = resistance (Ω)

- If the values of V and I are known, R can be calculated.

Example

A dropping resistor is required to generate:
(a) a 0.25 - 1.25 V signal
(b) a 1 - 5 V signal

from a 4 - 20 mA current signal. Calculate the resistance value.

Solution
(a) When current = 20 mA, voltage = 1.25 V

By Ohm's Law, R = V / I = 1.25V / (20x10^{-3})A

= 62.5 Ω

(b) When current = 20 mA, voltage = 5 V

Again, by Ohm's Law, R = V / I = 5 V/ (20x10-3)A

= 250 Ω

Trend Recording

- Recorders are used in process loops so that permanent records of the process behaviour can be obtained. Historically, a recorder can detect the process signal and print it on a paper chart for easy read out and assessment

Inevitably, recorders can only carry a limited amount of chart paper and ink.

- Periodic changing of chart paper and inking problems had made the recorder one of the most troublesome instruments to service.

- Moreover, most controlled variables will be maintained quite steady if a plant is functioning in a stable (i.e. normal) mode of operation. Consequently, process recorders would be inking straight lines and no real advantage is realized by producing these records.

- Therefore, except for a few important processes parameters, or those which must be recorder for regulatory purposes, most of the process loops can be monitored by trend recorders as required.

- The trend recorder is just a recorder that is not permanently connected to a process loop. The trend recorder could be activated when a abnormal condition (process disturbance, tuning, etc.) arises to record the particular process parameter of interest.

- This management by exception documentation philosophy allows a trend recorder to be connected into one selected loop of several available via a wired jack panel.

- Assume that the trend recorder available requires a 1 - 5 V dc input as a function of the 4 - 20 mA current signal. The dropping resistor (250 Ω in this case) must be permanently installed in the current loop so that the transmitter circuit is not disrupted (open circuited) when the trend recorder is disconnected.

- The jack will be wired across this dropping resistor so that the recorder will respond to that loop signal when the lead connector is plugged in (Figure 5).

- Of course, the concept of Trend Recording has been adopted into computerized display systems and in these, selected variables can be chosen from a menu for display purposes. However, automatic archiving of data can also be implemented, even though that parameter has not been selected for display.

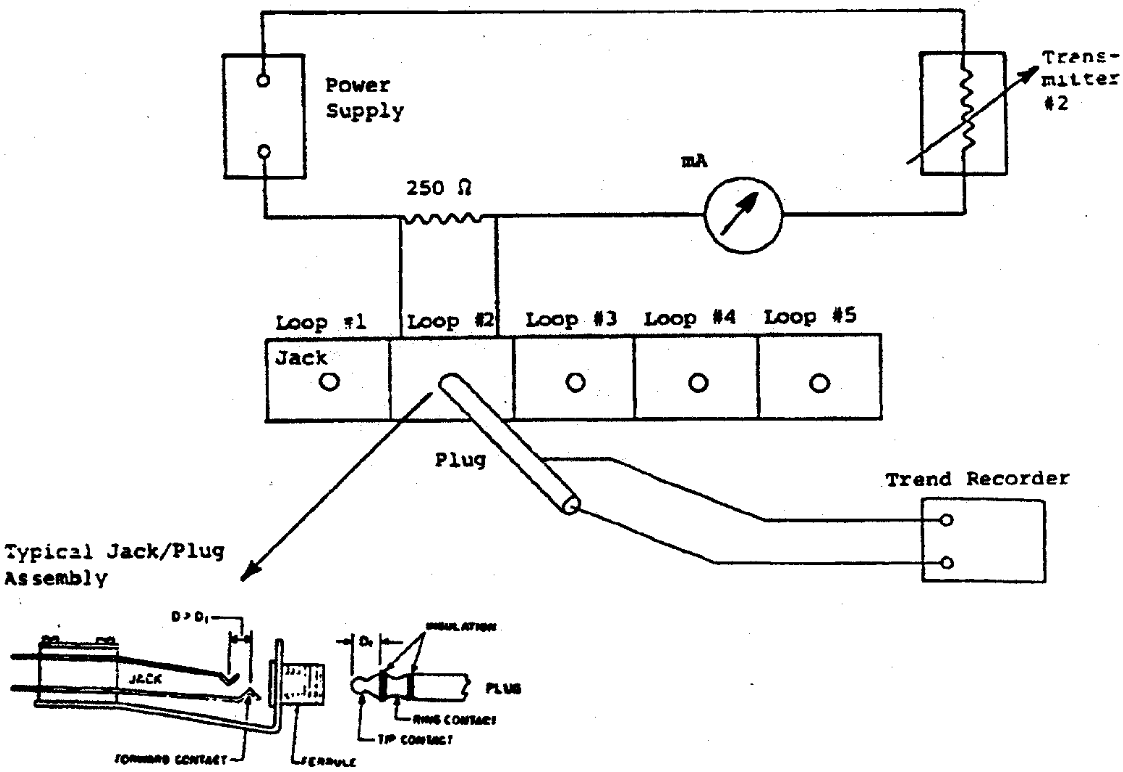


Figure 5. A Representative Trend Recorder Installation

ASSIGNMENT: Lesson 1

1) Why is signal transmission vital in the operation of large industrial process systems?

2) What is the accepted standard industrial range for pneumatic signals?

3) List two advantages and two disadvantages of a pneumatic system.

4) What is the standard instrument range for electronic signals?

5) Why are electronic signals used almost exclusively in industrial process systems, particularly electrical generating stations?

6) Both pneumatic and electronic signals employ a "***live zero***". Explain the purpose of this live zero.

7) A standard electronic transmitter is used to monitor the water temperature in a vessel. The transmitter is calibrated such that it responds to the temperature range of 50°C - 100°C. What is the transmitter output when the water temperature is 85°C? (Answer: 15.2 mA)

8) Explain briefly what a trend recorder is, and why one would be utilized.

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 2: ISA Symbols

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. Sketch the ***symbols*** representing three different kinds (pneumatic, electronic and hydraulic) of transmission line.

2. State the instrument which a given standard ISA symbol represents, with respect to its ***function*** and ***mounting*** location.

3. Sketch a simple flowsheet using standard ISA symbols, given the function and location of different instruments and the type of transmission line connecting them.

ISA Symbols

- To simplify drawings and flowsheets (instrumentation schematics) and therefore make process loops more easily understandable - instruments on drawings which show the ***location*** and ***function*** of different devices are represented by standard symbols.

- In North America, a convention based on ***Instrument Society of America*** (ISA) symbols has been adopted. (NB: There are local variations to some of the symbology).

Line Symbols

Transmission lines which link different instruments are shown in Figure 1.

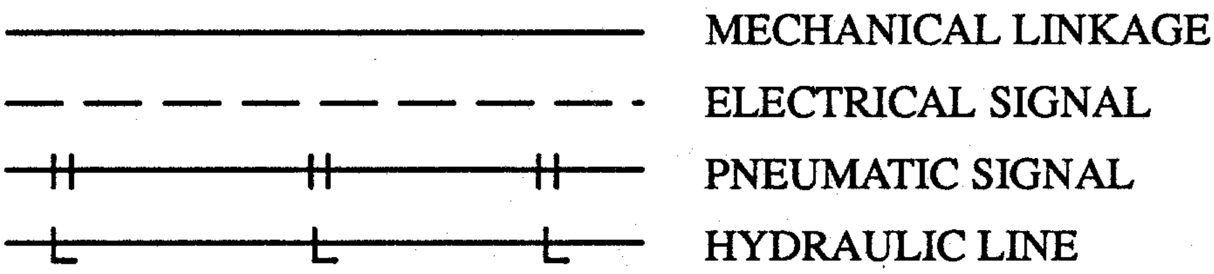


Figure 1. Symbols for Signal Transmission Lines

Instrument Symbols

- Instruments are identified by ***circles*** with ***lettered codes*** (two or three letters) inserted. This lettered code shows the instrument ***type*** and ***function***.

- In general, the ***process*** that is to be monitored by the instrument is indicated by the ***first letter*** of the coding, for example:
  - F = **F**low
  - L = **L**evel
  - P = **P**ressure
  - T = **T**emperature

- The second letter in the coding indicates the ***function*** of the instrument, for example:
  - FI = Flow **I**ndicator
  - FC = Flow **C**ontroller
  - LA = Level **A**larm
  - LR = Level **R**ecorder
  - PT = Pressure **T**ransmitter
  - TE = Temperature **E**lement

- In some cases, when the instrument is used for ***two purposes*** or when the function of the instrument has to be more clearly specified, a third letter is used, for example:

FIC = Flow **I**ndicating **C**ontroller
LAH = Level **A**larm **H**igh
LAL = Level **A**larm **L**ow

- A table of ***instrument identification codes*** is given in Table 1 at the end of this lesson.

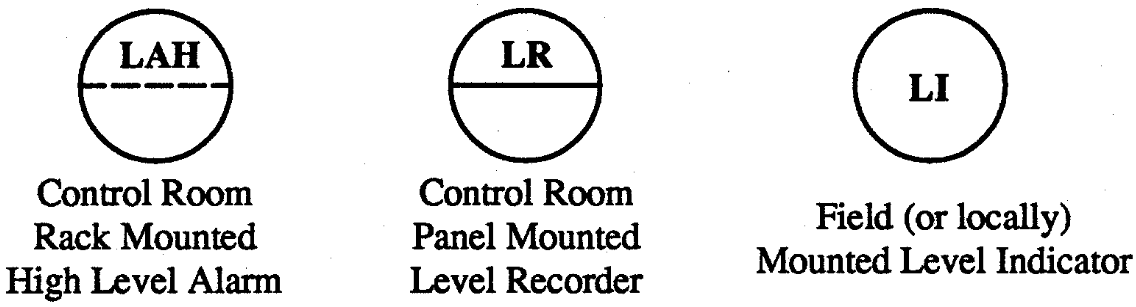
- To distinguish control room mounted instruments from local or field mounted instruments, a horizontal line drawn across the symbol diameter of the circle is used.

- A circle with ***lettered code only*** represents a ***field*** or ***locally mounted*** instrument.

- A circle with a ***solid*** line across its diameter and the lettered code above this line indicates a ***control room panel*** mounted instrument.

- A circle with a ***dotted*** line across its diameter indicates a ***control equipment room rack***, (i.e. usually behind the control panel), mounted instrument (See Figure 2).

Figure 2. ISA Symbols and The Instrument Location Representation



Symbol Example

A level loop consists of:

Level transmitter Level indicator	Field Mounted
Level controller Level recorder	Control Room Panel Mounted
High level alarm Low level alarm	Control Room Rack Mounted

The level transmitter is connected directly to the tank and the rest of the instruments are driven by the level transmitter and used to monitor and indicate the level in a tank.

Assuming that the signal transmitted is electronic, draw a representative flow sheet using ISA symbols.

Solution

The loop can be represented by ISA symbols as shown in Figure 3.

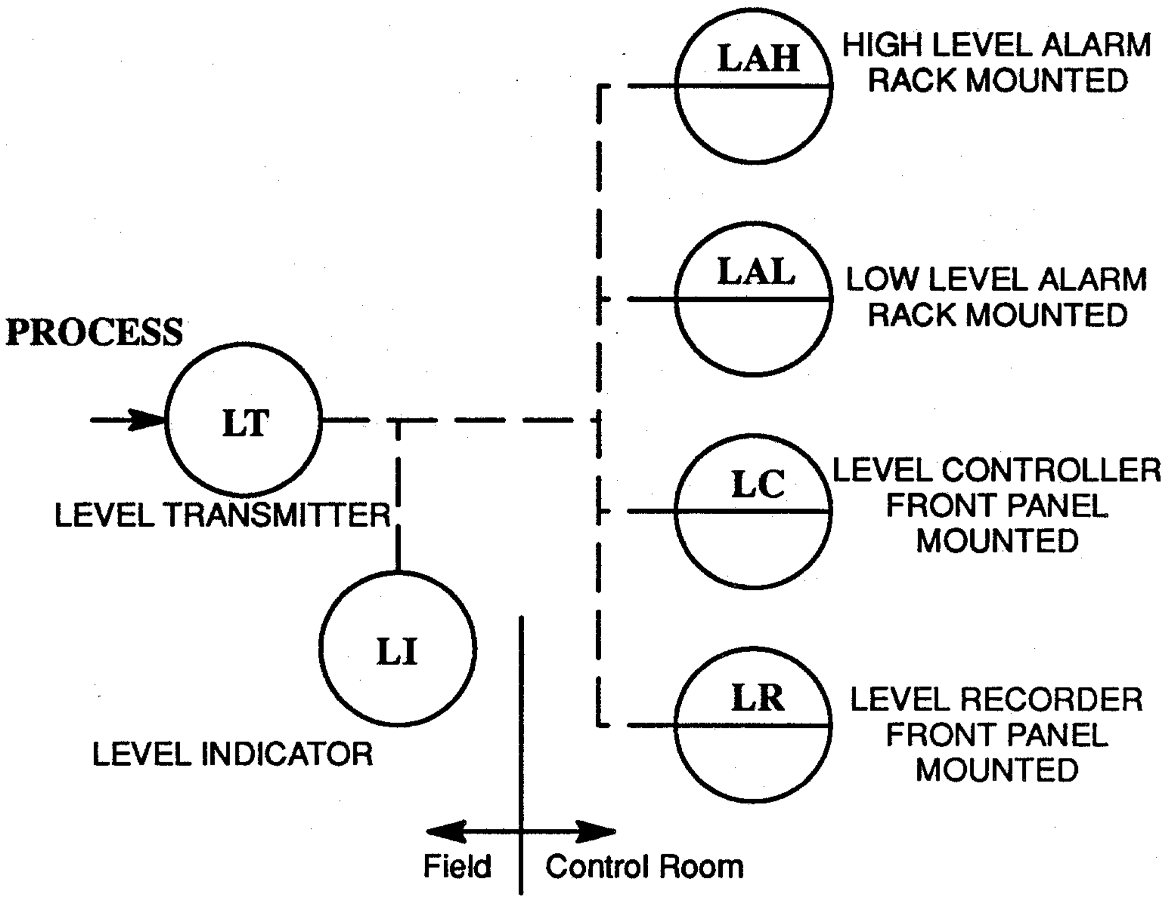


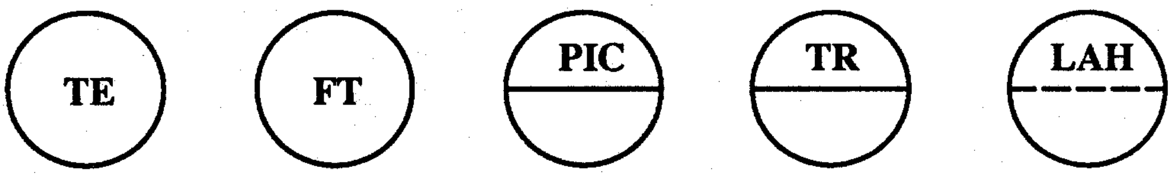
Figure 3. ISA Symbols Representation of a level Loop

Table 1. Instrument Identification Code

	FIRST LETTER	SUCCEEDING LETTERS		
	Measured Variable	**Read-out or Passive Function**	**Output Function**	**Modifier**
A	CURRENT	ALARM		AVERAGE
C			CONTROL	CONTACT
E		ELEMENT		
F	FLOW RATE			
G		GLASS		
H	HAND (MANUAL)			HIGH
I		INDICATE		
L	LEVEL			
M		MOTORIZED		MEDIAN
P	PRESSURE			
R	NEUTRON FLUX	RECORD	RELAY	
S		SOLENOID	SWITCH	
T	TEMPERATURE		TRANSMIT	
V				VALVE
W		WELL		
X			TRANSDUCER	
Y			COMPUTE	
Z	POSITION			

ASSIGNMENT: Lesson 1

1) State the functions and locations of the instruments represented by the following ISA symbols:



2) An electronic temperature loop which is used to monitor the temperature of the hot bleed from a heat exchanger consists of the following instruments:
   - Field mounted temperature transmitter and temperature indicator.

   -- Control room, panel mounted, temperature recorder and temperature indicating controller.

   Sketch a simple flowsheet for the above system using standard ISA symbols.

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 3: Pressure Instrumentation

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. Explain the basic operation of a ***differential pressure transmitter***, with respect to how differential pressure can be detected and how the pressure detected can be converted into an electronic signal.

Pressure Unit

Pressure is defined as force exerted on a unit surface area. Mathematically, we have:

P = F/A

where
P = Pressure (Pa)
F = Force (N)
A = Area (m^2)

- The basic unit of pressure in SI units is the ***Pascal*** (Pa).
- It is defined as force of 1 Newton (N) per square meter (m2). That is:

1 Pa = 1 N/m^2

- Since the Pascal (Pa) is a very small unit (1 Pa = 1.45 x 10^{-4} PSI), it is more common to use units of **kPa** (1 kPa = 1000 Pa) and **MPa** (1 MPa = 1000 kPa or 1 x 10^6 Pa) when we deal with the pressures we encounter in in typical industrial process applications.

Absolute and Gauge Pressures

- Pressure measurements can be stated as either ***gauge***, or ***absolute***.

- Gauge pressure is the unit we encounter in everyday work (e.g. tire ratings are in gauge pressure).

- A gauge pressure device will indicate zero pressure when bled down to ***atmospheric*** pressure (i.e. gauge pressure is in reference to atmospheric pressure – that pressure ***above atmospheric pressure***).

- ***Gauge*** pressure is denoted by a (***g***) at the end of the pressure unit (e.g. kPa(g)).

- ***Absolute*** pressure includes the effect of atmospheric pressure with the gauge pressure. It is denoted by an (***a***) at the end of the pressure unit (e.g. kPa(a).)

- An absolute pressure indicator would indicate ***atmospheric pressure*** when completely bled down - it would not indicate scale zero.

- The relationship between absolute pressure and gauge pressure is:

Absolute Pressure = Gauge Pressure + Atmospheric Pressure

- The standard value of atmospheric pressure is taken as the atmospheric pressure at sea level, which is 101.3 kPa.

- Note a reading of less than 101.3 kPa(a) indicates a vacuum condition. For example, a typical condenser pressure is 5 kPa(a) or a vacuum of 96.3 kPa.

Example

The pressure of the gas in a tank is 1000 kPa(a). What is the pressure in gauge units?

Solution

Gauge Pressure = Absolute Pressure - Atmospheric Pressure

Therefore, Gauge Pressure = 1000 kPa(a) - 101.3 kPa

= 898.7 kPa(g)

Figure 1 illustrates the relationship between absolute and gauge, note that the base point for gauge scale (0 kPa(g)) is taken as 101.3 kPa(a) – ***atmospheric pressure***

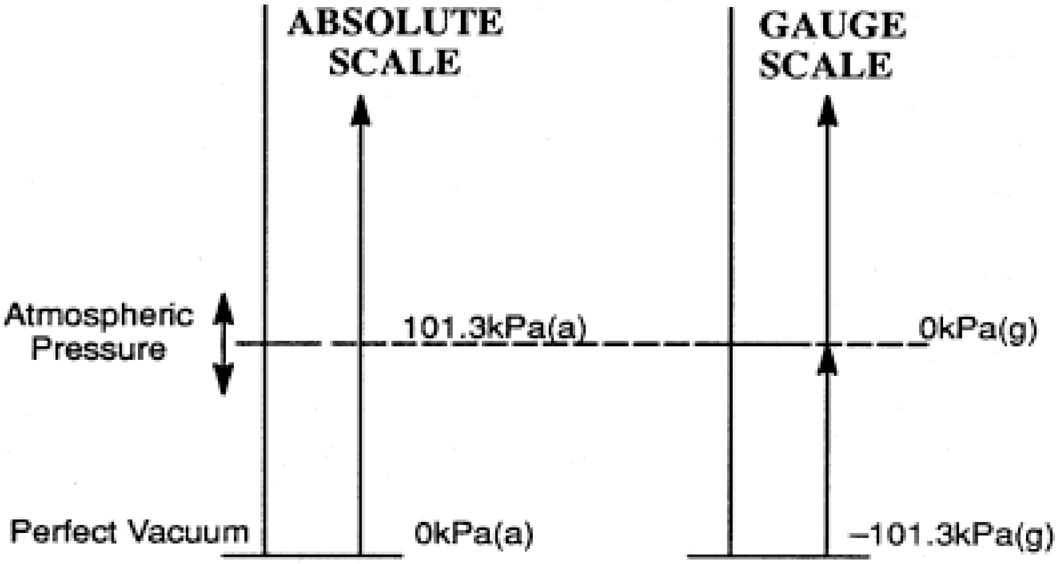


Figure 1: Relationship Between Absolute and Gauge Pressures.

Pressure Measurement

- In order to produce a standard (4 - 20 mA) electronic signal which represents the pressure in a process, the pressure must be sensed and a physically detectable motion or force in proportion to this applied pressure must be developed.

- To sense the process, we use a pressure sensor.

- Some typical pressure sensors or primary pressure elements are shown in Figure 2. They include ***diaphragms***, ***pressure bellows***, ***Bourdon tubes*** and ***pressure capsules***.

- With pressure sensors, physical motion is proportional to the applied pressure within the operating range.

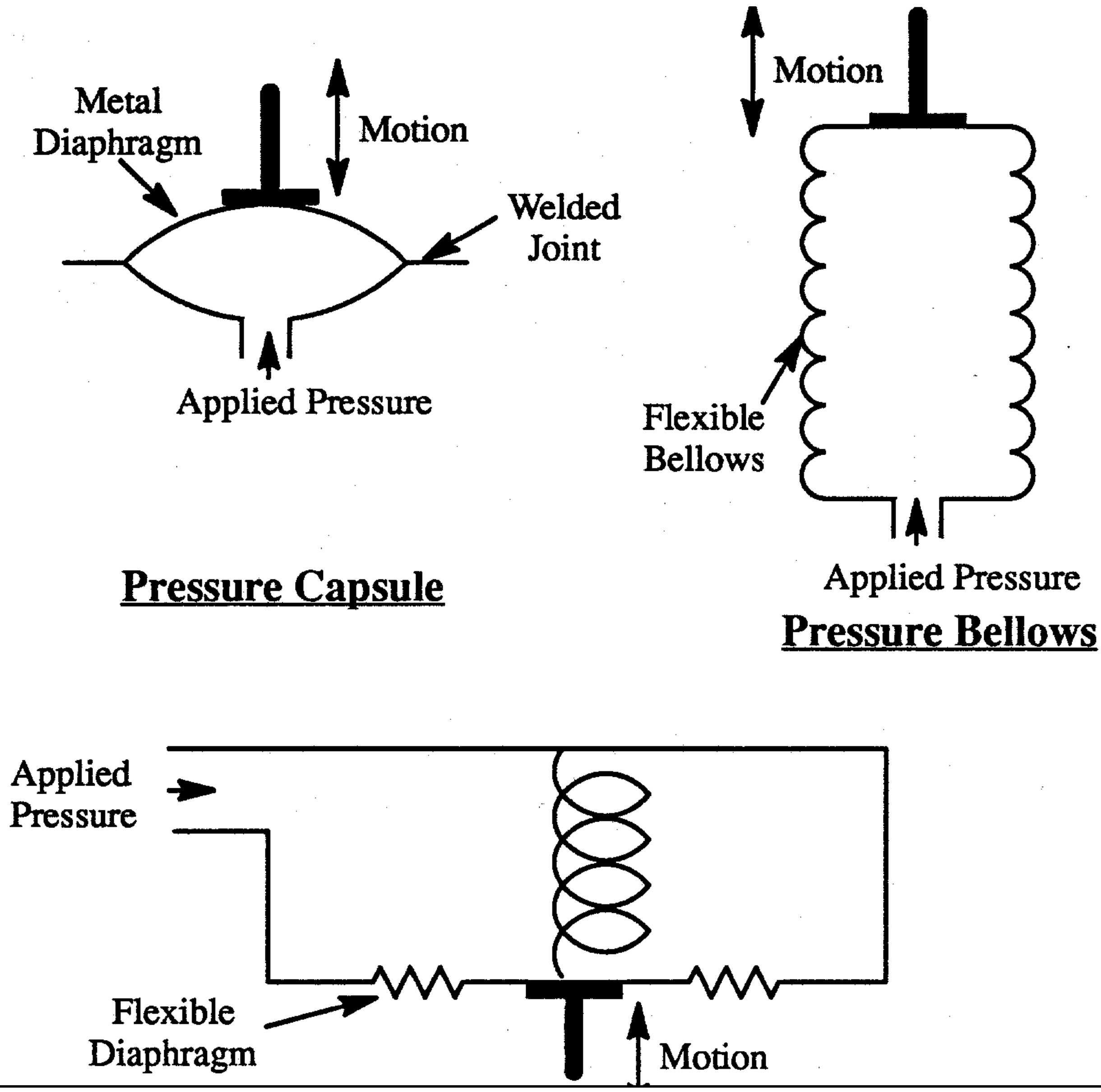
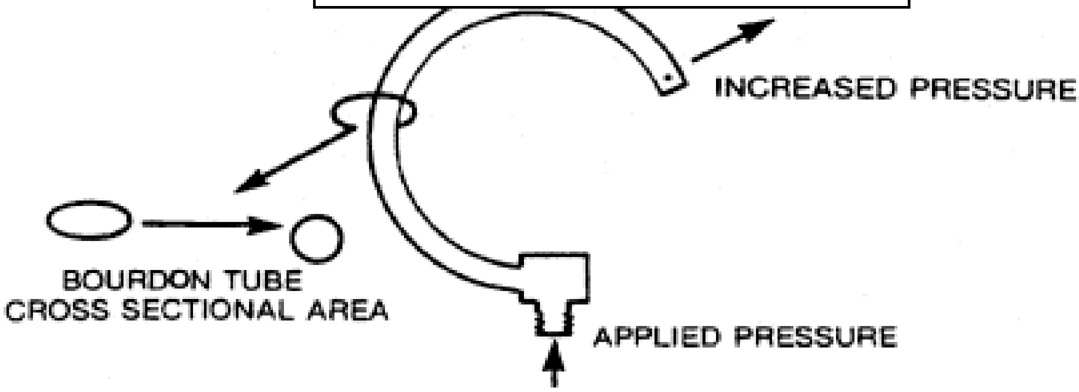


Figure 2. Primary Pressure Elements – Capsule, Bellows & Spring Opposed Diaphragm

Figure 2a: Bourdon Tube.



- Most pressure transmitters are built around the pressure capsule.

- They are usually capable of measuring <u>D</u>ifferential <u>P</u>ressure (that is, the difference between a high pressure input and a low pressure input) and hence they are usually called ***<u>DP transmitters or DP cells.</u>***

<u>Figure 3 shows the construction of a typical DP transmitter.</u>

- A differential pressure capsule is mounted inside a housing.
- One end of a ***force bar*** is connected to the capsule assembly so that the motion of the capsule can be transmitted out of the housing.
- A sealing mechanism is used where the force bar penetrates the housing. This seal also acts as the pivot point for the force bar.
- Provision is made in the housing for ***high pressure fluid*** to be applied on one side of the capsule and ***low pressure fluid*** on the other.
- Any difference in pressure will cause the capsule to deflect and create motion for the force bar.
- The top end of the force bar is connected to an ***electronic motion detector***, which via an electronic system, will produce a ***4 - 20 mA signal*** that is proportional to the force bar movement.

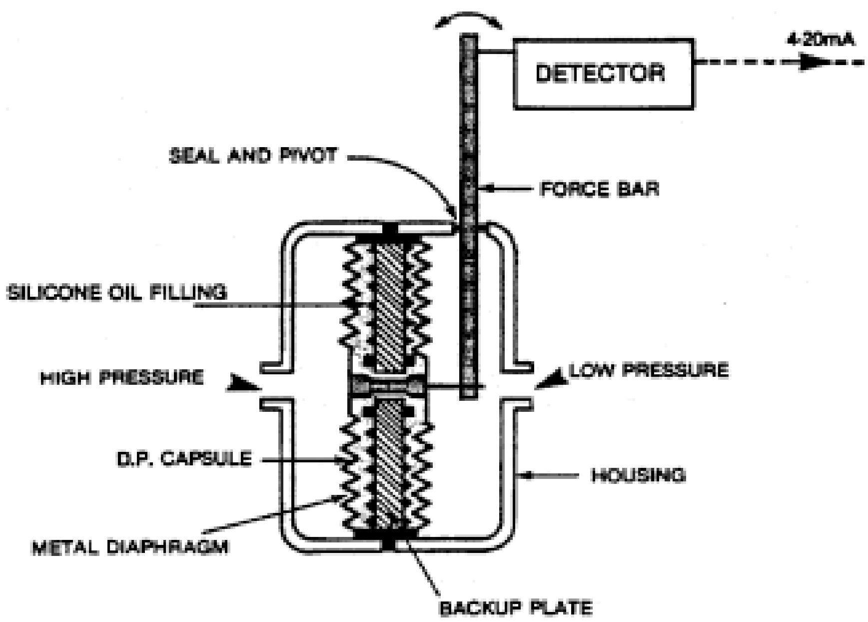


Figure 3: A Typical DP Transmitter Construction.

Four different kinds of ***electronic position detectors*** are currently used by pressure transmitter manufacturers. They are:

1. Inductive Detector (Fischer and Porter).
2. Variable Differential Transformer Detector (Foxboro).
3. Capacitive Detector (Rosemount).
4. Resistive (strain gauge) Detector (Gould).

Differential Pressure Capsules

- The DP capsule (refer to Figure 3) is formed by welding two metallic (usually stainless steel) diaphragms together.
- To provide over-pressurization protection, a solid plate with diaphragm matching convolutions is mounted in the center of the capsule.
- Silicone oil is used to fill the cavity between the diaphragm for even pressure transmission. Most DP capsules can withstand static pressure of up to 14 MPa (2000 psi) on both sides of the capsule without any damaging effect.
- However, the ***sensitive range*** for most DP capsules is quite low. Typically they are ***sensitive up to only a few hundred kPa of differential pressure.***
- Differential pressure that is significantly higher than the capsule range may damage the capsule permanently. When choosing a capsule for pressure measurement, it is important to match the capsule range with the anticipated differential pressure.

DP Transmitter Installation

- A typical DP transmitter installation for low pressure sensing is shown in Figure 4.

- A DP transmitter is used to measure the gas pressure (in gauge scale) inside a vessel.
- In this case, the low pressure side of the transmitter is ***vented*** to atmosphere, and the high pressure side is connected to the vessel through an ***isolating valve.***

- The isolating valve facilitates the removal of the transmitter

.
- The output of the DP transmitter is proportional to the gauge pressure of the gas in the tank, i.e., 4 mA when pressure is 20 kPa and 20 mA when pressure is 30 kPa.

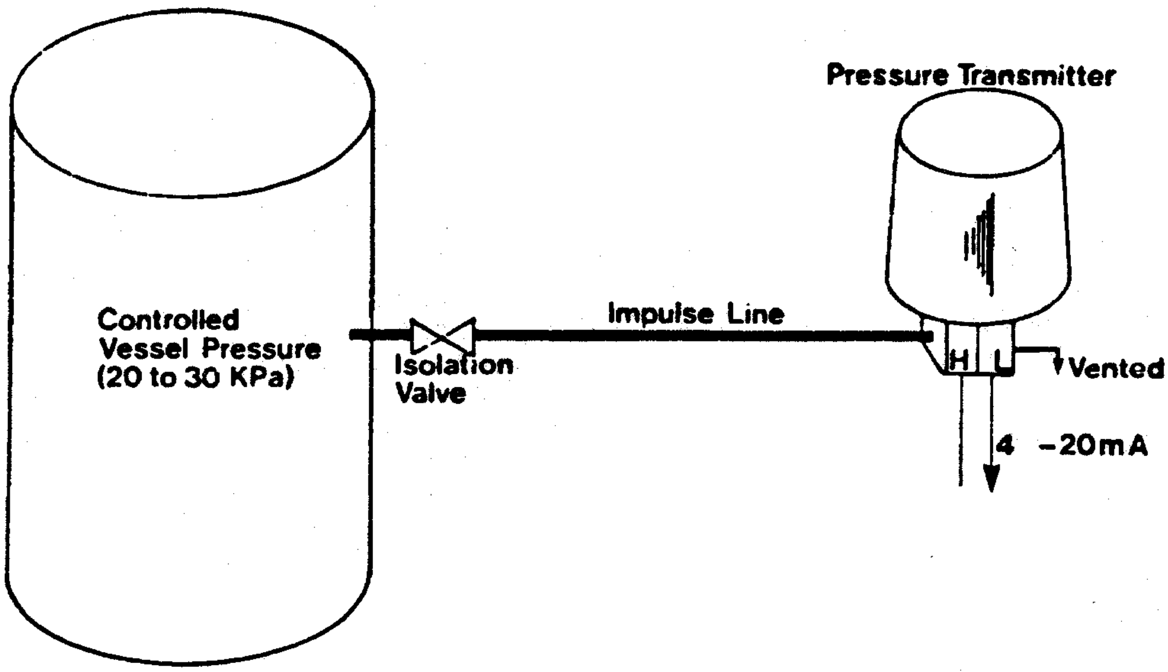


Figure 4: A DP Transmitter low pressure measurement application.

ASSIGNMENT: Lesson 1

1) Sketch a bar chart and state the relationship between ***absolute pressure*** and ***gauge pressure***. Clearly indicate a vacuum scale on this bar chart.

2) Sketch a typical ***DP transmitter device*** and explain the principle of operation.

3) Sketch and describe a DP transmitter ***low pressure installation*** used to measure the gauge pressure in a closed tank.
4) If a transmitter is calibrated to measure a pressure of 0-80 KpaG in order to develop a 4-20 mA current signal; what pressure will correspond to a signal of 13.5 mA? (answer: 47.5 kPaG)

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 4: Level Instrumentation

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. Sketch and explain the principle of an ***open tank level measurement*** installation using a level transmitter.
2. Sketch and explain the principle of a ***closed tank level measurement*** installation using a level transmitter and ***dry leg***.
3. Explain the purpose of a ***three-valve manifold*** in closed tank level measurement installations.
4. State the procedure required for valving a level transmitter:
   a) into service, and
   b) out of service
   when a three valve manifold is used.
5. Briefly explain the principle of operation of a closed tank, ***wet leg***, level measurement installation.
6. Briefly explain the need for
   a) ***zero suppression***, and
   b) ***zero elevation***
   in level measurement installations by reference to an example process application for each case.
7. Briefly explain the principle of operation of a ***bubbler*** level measurement system.
8. List two advantages of a bubbler system.

Inferential Level Measurement

- Inferential level measurement techniques obtain a level indication ***indirectly*** by monitoring the pressure exerted by the column of liquid.

- The pressure at the base of a vessel containing liquid is directly proportional to the liquid level in the vessel. As the level in the vessel rises, the pressure exerted by the liquid at the base of the vessel will increase linearly.

- Mathematically, we have the pressure and level dependency of:

$$\mathbf{P = S \cdot H}$$

where

P = Pressure (Pa)
S = Weight density of the liquid (N/m^3)
H = Height of liquid column (m)

- The ***level*** of liquid inside a tank can be determined from the ***pressure*** reading at the base of the tank, if the specific gravity of the liquid is constant.

- Differential pressure transmitters are the most commonly used instrumentation devices to measure the pressure at the base of a tank.

- When a DP transmitter is used for the purpose of measuring level, it will be called a ***level transmitter*** even though it is measuring pressure.

Open Tank Level Measurement Application

The simplest level transmitter application is the measurement of level in an open tank. Figure 1 shows a typical open tank level measurement installation.

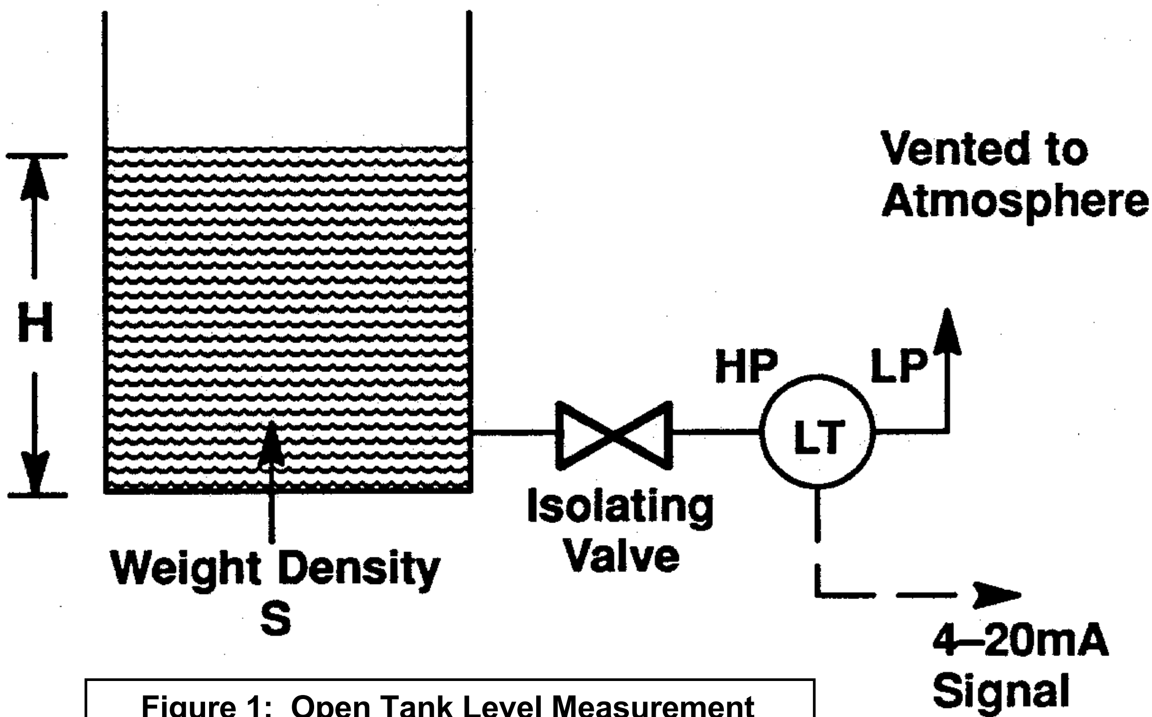


Figure 1: Open Tank Level Measurement

- If the tank is open to atmosphere, the ***high pressure side*** of the D/P level transmitter will be connected to the base of the tank.
- The ***low pressure side*** will be vented to atmosphere.
- In this manner, the level transmitter acts as a simple pressure transmitter. We have:

  $P_{high} = P_{atm} + S \cdot H$
  $P_{low} = P_{atm}$

- Differential pressure $\mathbf{DP = P_{high} - P_{low} = S \cdot H}$
- The level transmitter can be calibrated to output 4 mA when the tank is at 0% level and 20 mA when the tank is at 100% level.

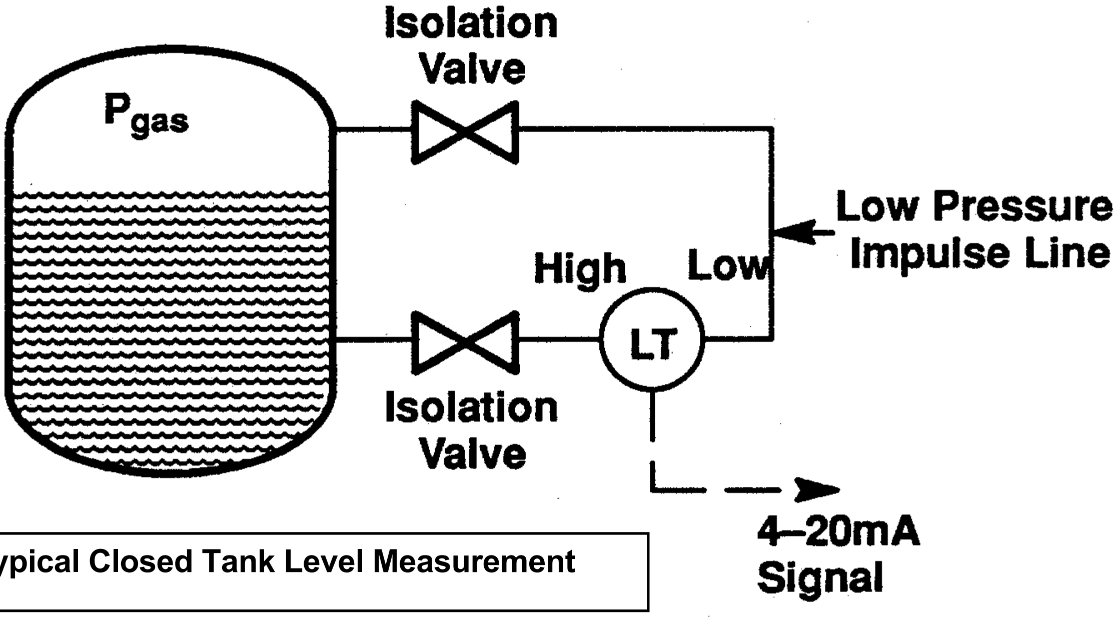


Figure 2: Typical Closed Tank Level Measurement

Closed Tank Application

- If the tank is closed, and a gas phase exists on top of the liquid, this ***gas phase pressure*** must be compensated for.
- A change in the gas pressure will cause a change in the measured pressure resulting in a corresponding transmitter output ***not related to level***.
- Moreover, the pressure exerted by the gas phase may be so high that the hydrostatic pressure of the liquid level column becomes insignificant. For example, the measured hydrostatic head in a steam generator may be only three meters (***30 kPa*** or so), whereas the steam pressure is typically ***5MPa***.
- ***Pressure Compensation*** can be achieved by applying the gas pressure to both the high and low pressure sides of the level transmitter.
- In the closed tank we have:

$$P_{high} = P_{gas} + S \cdot H$$
$$P_{low} = Pgas$$
$$\mathbf{DP = P_{high} - P_{low} = S \cdot H}$$

- The effect of the gas pressure is canceled and ***only the pressure due to the hydrostatic head of the liquid*** is sensed.
- When the ***low pressure impulse line*** is connected directly to the gas phase above the liquid level, it is called a ***dry leg.***

Three Valve Manifold

- To obtain maximum sensitivity, a pressure capsule that has a sensitive range which just exceeds the maximum hydrostatic pressure range of the liquid column should be used.

- However, as already mentioned, the gas pressure (P_{gas}.) is often much higher than the hydrostatic pressure (i.e. level head) that is to be measured.

- If the gas pressure is accidentally applied to only one side of the DP capsule (say during installation or removal of the DP transmitter), ***overranging*** of the capsule could occur and the capsule would be damaged.

- A ***three valve manifold*** is a device that is used to ensure that the capsule will not be over-ranged and allows ***isolation*** of the transmitter from the process loop.

- The three valve manifold consists of ***two block valves*** – a high pressure and a low pressure block valve - and an ***equalizing valve***.

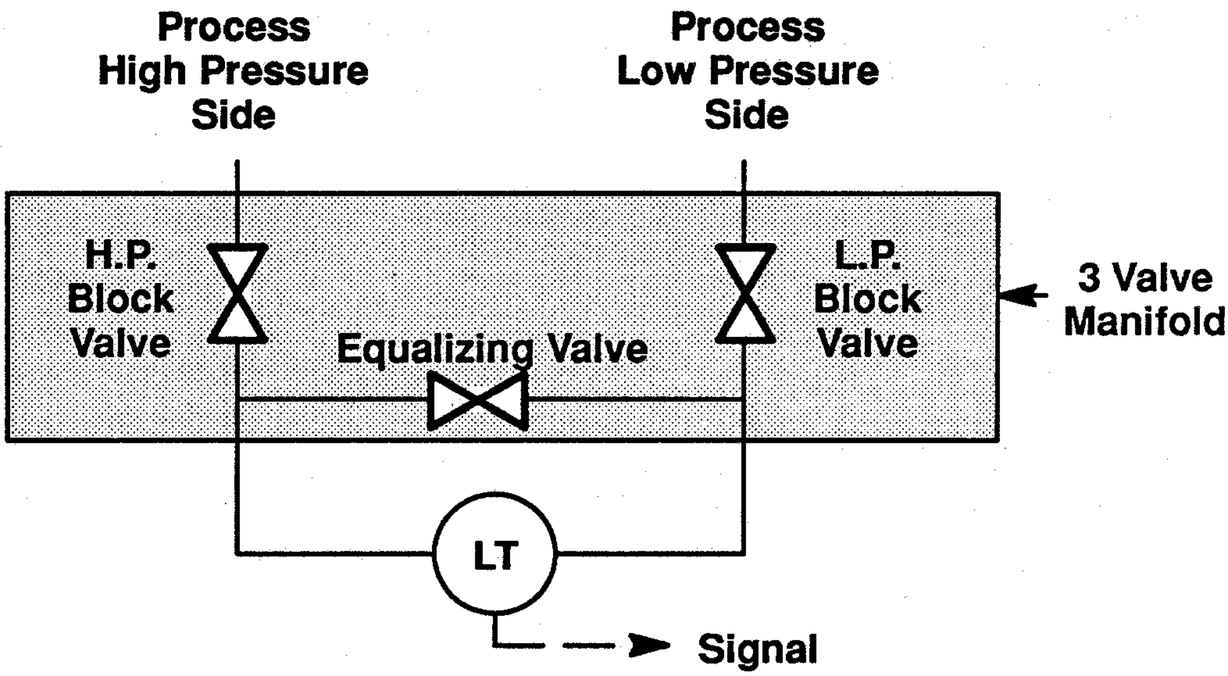


Figure 3: A Three Valve Manifold.

- During operation, the equalizing valve is closed and the two block valves are open to connect the process pressure across the D/P cell.

- When the transmitter is put into or removed from service, the valves must be operated in such a manner that the high pressure gas phase is ***not applied to only one side*** of the DP capsule.

Operational Sequences of Three-Valve Manifold - Valving a d/P Transmitter Into Service

- To valve the DP transmitter ***into service***, the following steps should be followed:

1. Check all valves closed.
2. Open the ***equalizing valve*** - this ensures that the same pressure will be applied to both sides of the transmitter, i.e. ***zero differential*** pressure.
3. Open the ***High Pressure block valve*** slowly, check for leakage from both the high pressure and low pressure side of the transmitter – ***still zero d/P***.
4. Close the equalizing valve - this locks the pressure on both sides of the transmitter – now look for leaks, should ***still be zero d/P***.
5. Open the ***low pressure block valve*** to apply the process pressure to the low pressure side of the transmitter and establish the working differential pressure.
6. The transmitter is now in service

- Note it may be necessary to ***purge any trapped air*** from the capsule housing as this can lead to level indication errors and create attendant control problems .

Operational Sequences of Three-Valve Manifold - Valving a Transmitter-out-of-Service

- Reversal of the previous steps allows the d/P transmitter to be removed from service – The starting operating state is with the ***equalizing valve closed*** and both ***block valves open***.

1. Close the ***low pressure block valve*** to trap pressure in the low side – check for leaks and ensure the indicated d/P does not change.
2. Open the ***equalizing valve*** to force ***d/P to zero***.
3. Close the ***high pressure block valve*** to isolate the transmitter.
4. Bleed down (i.e. vent) the pressure trapped in the d/P cell body – should

   continue to read zero d/P
5. The d/P transmitter is now out-of-service, isolated and depressurized.

Dry Leg System

A full ***dry leg*** installation with ***three valve manifold*** is shown in Figure 4.

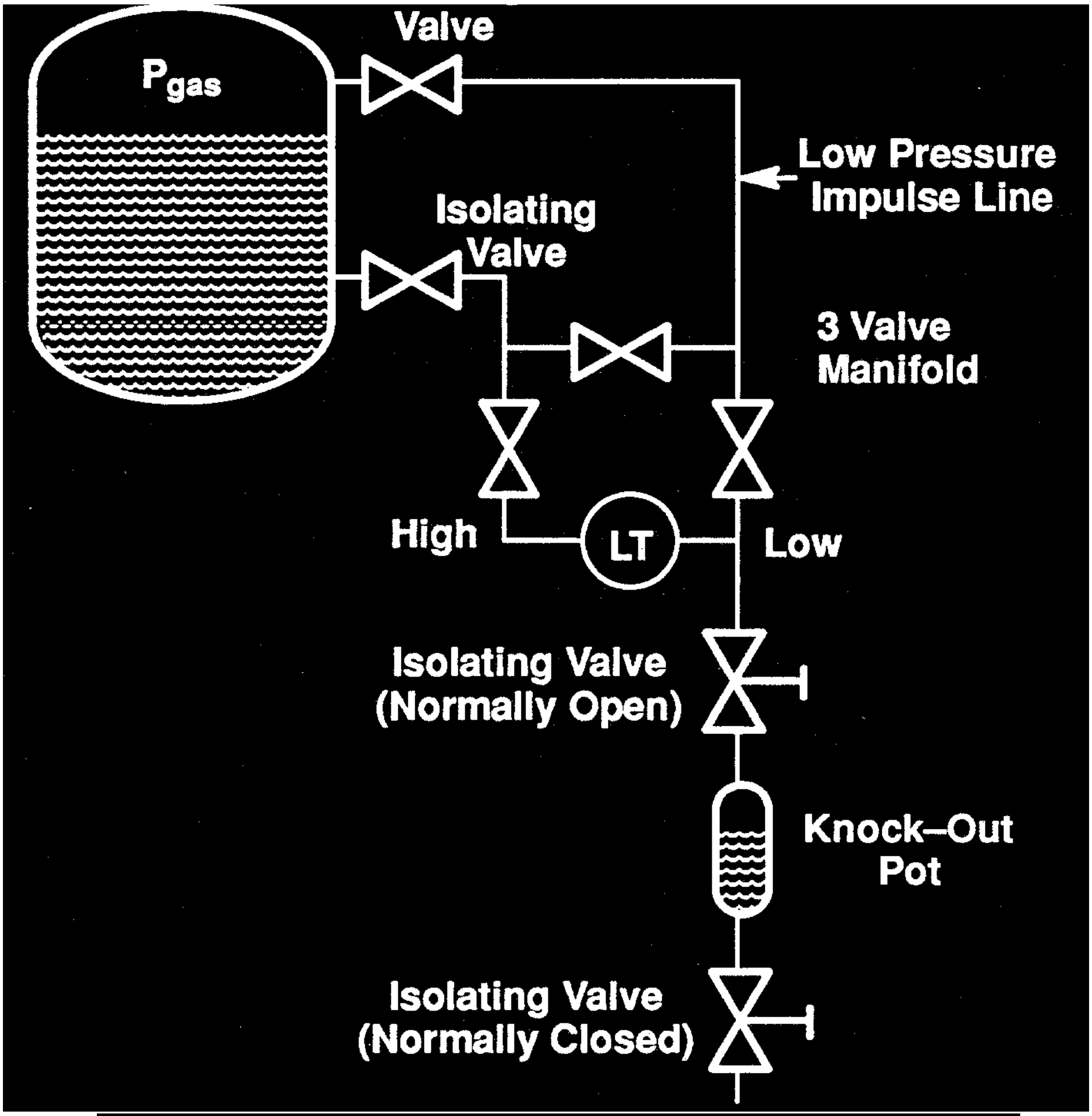


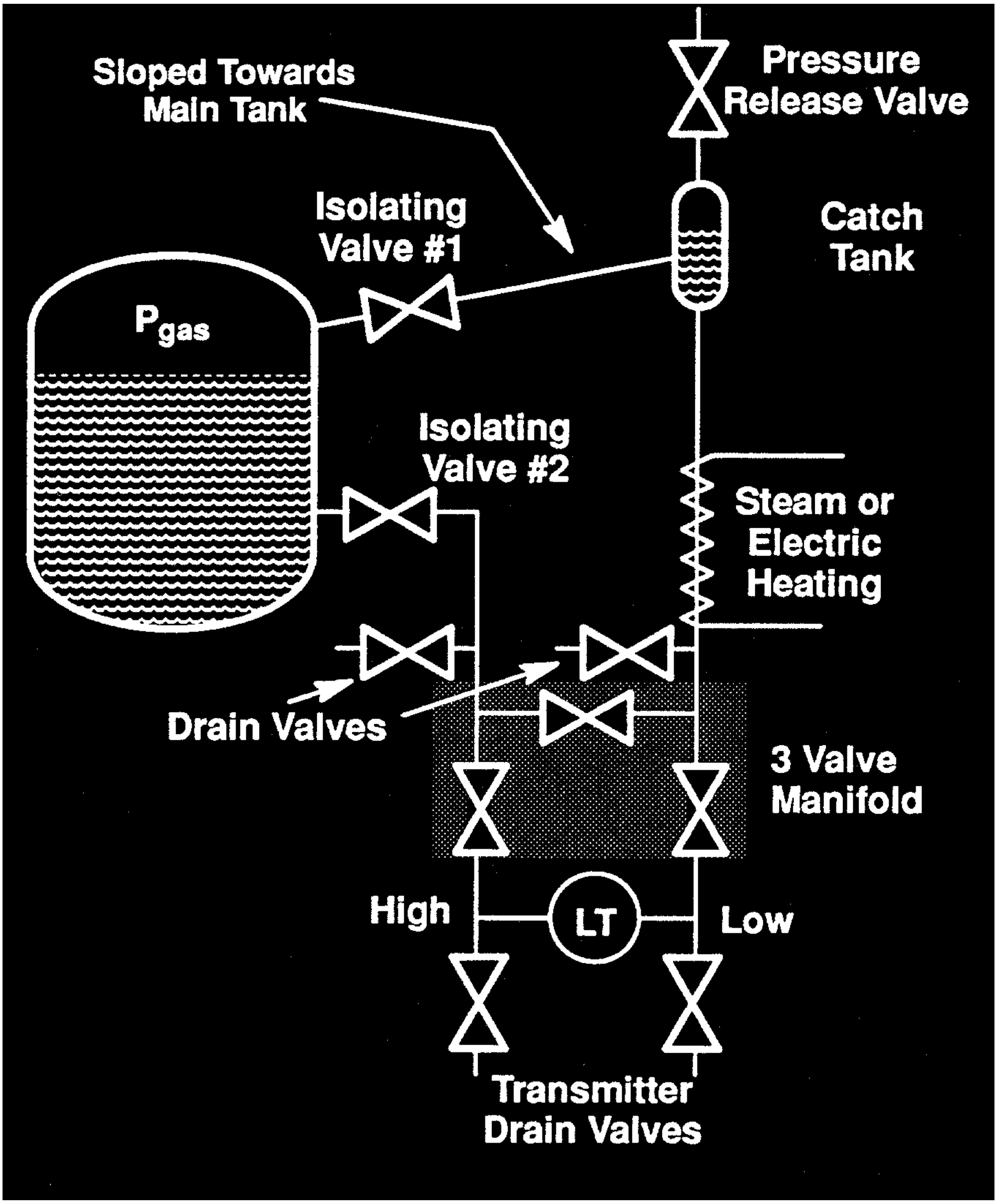
Figure 4: Dry Leg Installation with a Three Valve Manifold.

- If the gas phase is condensable, such as steam, ***condensate*** will form in the low pressure impulse line resulting in a column of liquid which exerts extra pressure on the low pressure side of the transmitter (i.e. transmitter will read in error low).
- A technique to solve this problem is to add a condensate or ***knock-out pot*** below the transmitter in the low pressure side as shown in Figure 4. Periodic draining of the condensate in the knock-out pot will ensure that the ***impulse line*** is free of liquid so that the dry leg is in fact dry.
- A disadvantage of the dry leg that restricts its use is the frequent maintenance that may be required. One example of a dry leg application is the measurement of liquid level in a closed tank with a purge cover gas pressure.

Wet Leg System

- In a wet leg system, the ***low pressure impulse*** line is completely filled with liquid (usually the same liquid as the process), and hence the name "***wet leg***".

A d/P level transmitter, with an associated three valve manifold, is used in an



identical manner to the dry leg system. Figure 5 shows a typical wet leg installation.

Figure 5: A Wet Leg Level Measurement Installation.

Wet Leg Installation Overview

- At the top of the low pressure impulse line is a small ***constant head*** catch tank.
- The vapour from the gas phase will condense in the wet leg and the catch tank.
- The catch tank, with the ***sloped interconnecting line*** back to the tank, maintains a ***constant*** hydrostatic pressure on the low pressure side of the level transmitter.
- This pressure error, being a constant low signal component, can easily be corrected for by calibration.
- If the tank is located outdoors, ***trace heating*** of the wet leg might be necessary to prevent it from freezing. Steam lines or an electric heating element can be wound around the wet leg to keep the temperature of the condensate above its freezing point.
- Note the two sets of ***drain valves***. The transmitter drain valves would be used to drain (bleed) the transmitter only. The two drain valves located immediately above the three valve manifold are used for impulse and wet leg draining or filling.

To isolate the wet leg transmitter installation for maintenance:

(a) Isolate the d/P transmitter using the standard three valve isolating procedure (described earlier in this module).

(b) Close the HP and LP isolating valves (isolate process). This gives two point isolation.

(c) Open pressure relief valve (bleed system pressure from wet leg). Reclose pressure relief valve and re-open after five minutes.

If there is a further release of pressure the upper isolation valve is passing. If no further leakage then leave valve open.

(d) Bleed system pressure from d/P cell using the transmitter drain valves.

Zero Suppression

In some cases, it is impossible to mount the level transmitter right at the base level of the tank. Say for ***maintenance access*** purposes, the level transmitter must be mounted X meters below the base of an open tank as shown in Figure 6.

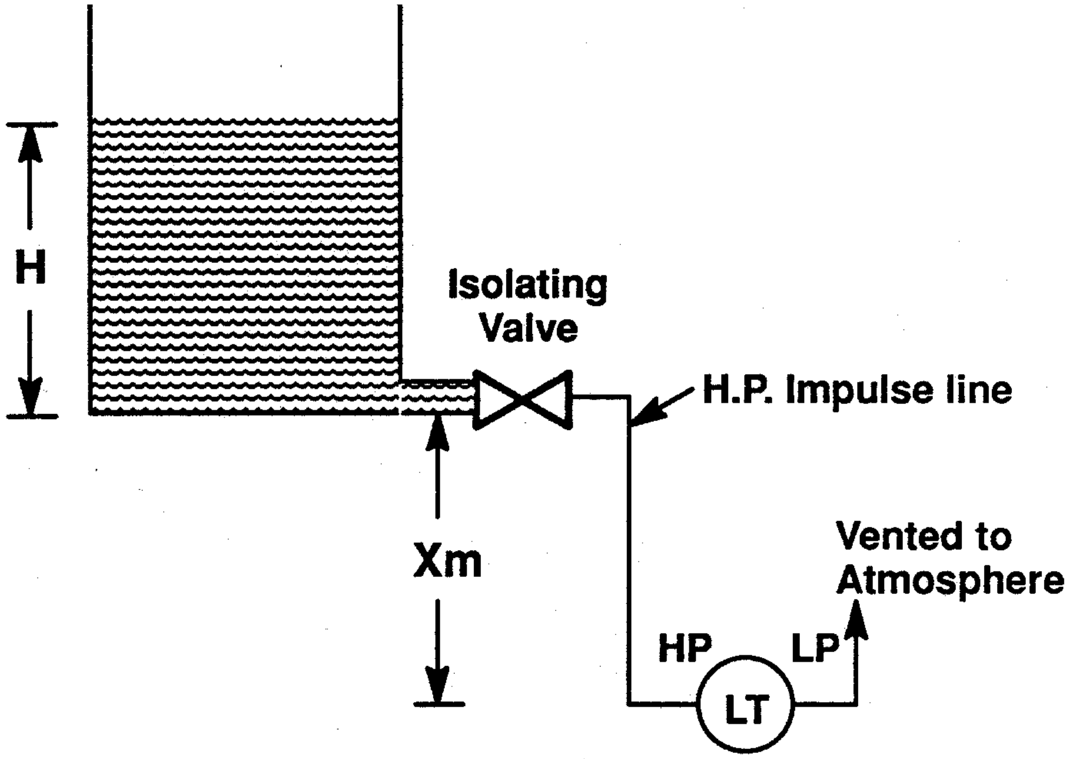


Figure 6: Level Transmitter with Zero Suppression.

- The liquid in the tank exerts a varying pressure, proportional to its level (H), on the high pressure side of the transmitter
- The liquid in the high pressure impulse line also exerts a pressure on the high pressure side. However, this pressure is a constant (**P = S · X**) and is present at all times.

- When the liquid level is at H meters, pressure on the high pressure side of the transmitter will be:

$P_{high} = S \cdot H + S \cdot X + P_{atm}$

$P_{low} = P_{atm}$

$DP = P_{high} - Plow = S \cdot H + S \cdot X$

Zero Suppression…continued

- That is, the pressure on the high pressure side of the d/P cell is always higher than the actual pressure exerted by the liquid column in the tank by ($S \cdot X$) – so the reading will be in ***error high***.
- This constant pressure would cause an output signal that is ***higher*** than 4 mA when the tank is empty and above 20 mA when it is full (if the transmitter is calibrated 4-20mA for the $S \cdot H$ range.)
- The transmitter has to be ***negatively biased*** by a value of $S \cdot X$ so that the output of the transmitter is proportional to the tank level ($S \cdot H$) only.
- This procedure is called ***Zero Suppression*** and is done during calibration of the transmitter.

Zero Elevation

- When a wet leg installation is used (see Figure 7), the low pressure side of the level transmitter will always experience a ***higher hydrostatic pressure*** than the high pressure side.
- This is due to the fact that the height of the wet leg (X) is always just greater than the maximum height of the liquid column (H) inside the tank.
- When the liquid level is at H meters, we have:

$$P_{high} = P_{gas} + S \cdot H$$

$$P_{low} = P_{gas} + S \cdot X$$

$$DP = P_{high} - P_{low} = S \cdot H - S \cdot X = -S(X - H)$$

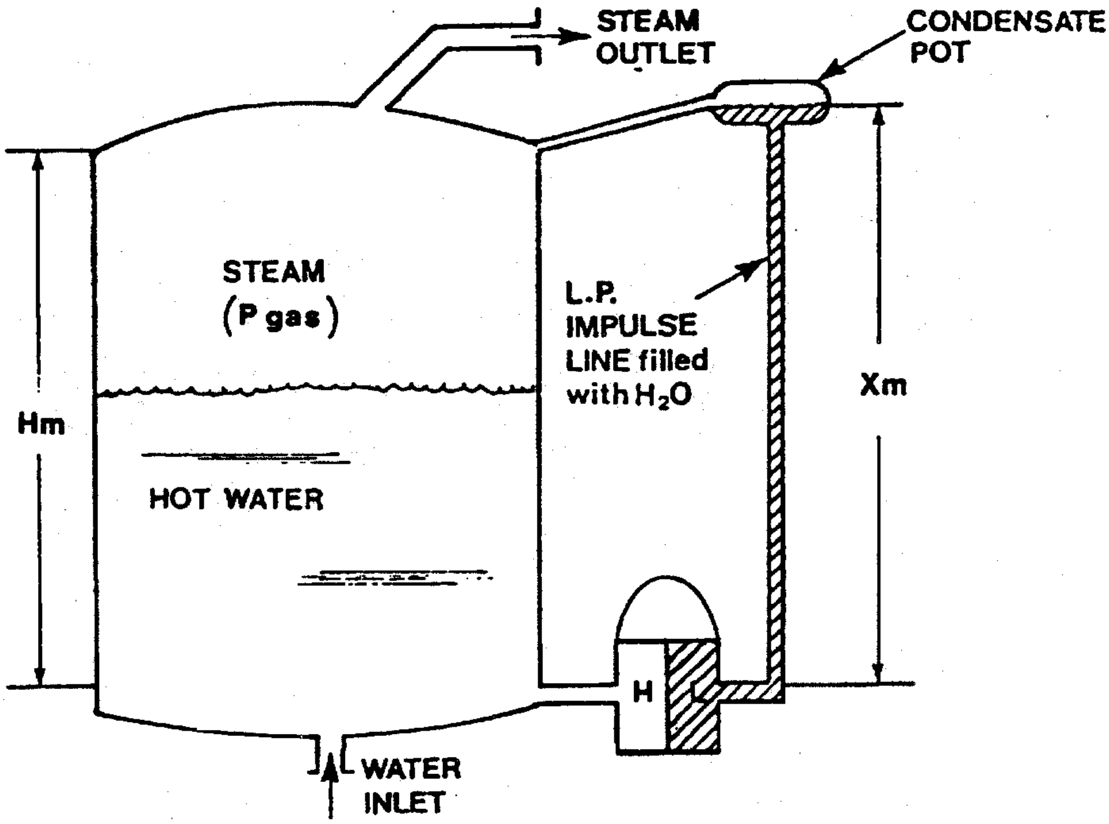


Figure 7: Simplified Wet Leg Installation.

- The differential pressure DP sensed by the transmitter shown in Figure 7. is always a ***negative value*** (i.e. the low pressure side has a higher pressure than high pressure side).
- The DP increases from P = -S · X to P = -S(X - H) as the tank level rises from 0% to 100%.
- If the transmitter is not calibrated for this constant negative error (-S · X), the transmitter output would ***read low*** at all times.
- To properly calibrate the transmitter, a ***positive bias*** (+S · X) is needed to elevate the transmitter output.
- This positive biasing technique is called ***<u>zero elevation</u>.***

Bubbler Level Measurement System

- If the process liquid contains suspended solids, or is chemically corrosive or radioactive, it is desirable to ***prevent*** that fluid from coming into ***direct contact*** with the level transmitter.
- In these cases, a ***bubbler level measurement system*** can be used.

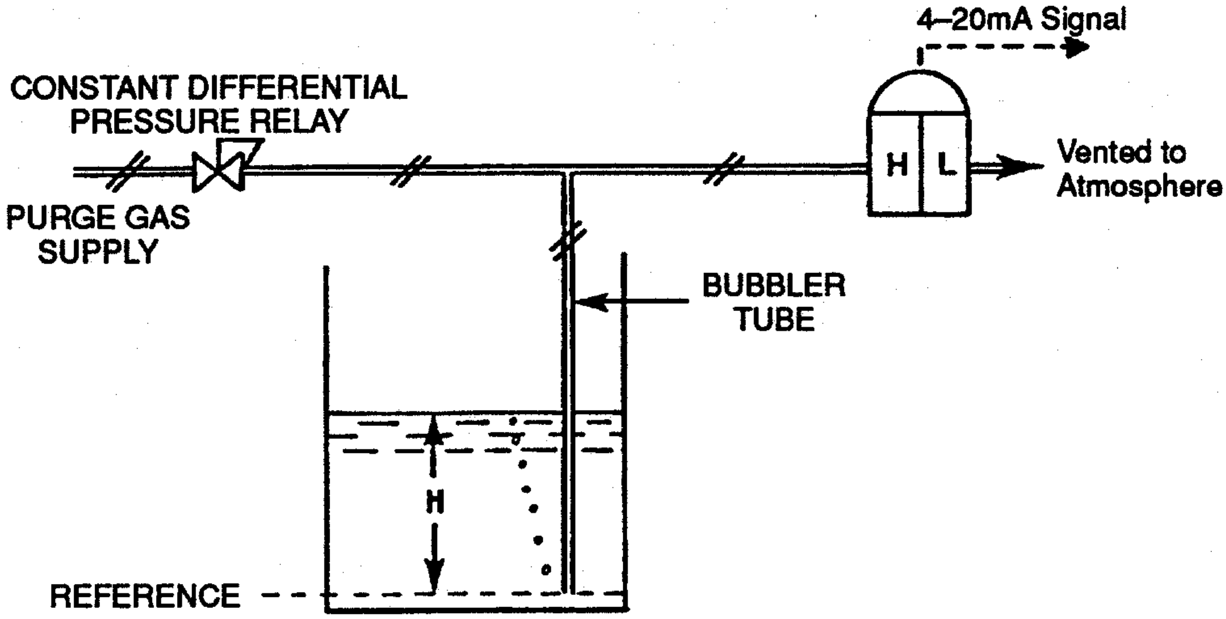


Figure 8: Bubbler Level Measurement System In Open Tank Application.

- As shown in Figure 8, a bubbler tube is immersed to the bottom of the vessel in which the liquid level is to be measured.
- A gas (called purge gas) is allowed to pass through the bubbler tube.
- Consider that the tank is empty. In this case, the gas will escape freely at the end of the tube and therefore the gas pressure inside the bubbler tube (called ***back pressure***) will be at atmospheric pressure.
- However, as the liquid level inside.the tank increases, pressure exerted by the liquid at base of the tank and at the opening of the bubbler tube increases.
- The hydrostatic pressure of the liquid acts as a pressure seal which restricts the escape of purge gas from the bubbler tube.
- As a result, the gas pressure in the bubbler tube will continue to increase until it just balances the hydrostatic pressure ($P = S \cdot H$) of the liquid.
- At this point the back pressure in the bubbler tube is exactly the same as the hydrostatic pressure of the liquid and it will remain constant until any change in the liquid level occurs.
- Any excess supply pressure will escape as bubbles through the liquid.

Open-Tank Bubbler Level Measurement System Description

- As the liquid level rises, the back-pressure in the bubbler tube increases proportionally, since the density of the liquid is constant.
- A level transmitter can be used to monitor this back-pressure.
- In an open tank installation, the bubbler tube pressure is connected to the high pressure side of the transmitter, while the low pressure side is vented to atmosphere. The output of the transmitter will be proportional to the tank level.
- A ***constant differential pressure relay*** is often used in the purge gas supply line to ensure that bubbling action occurs at all tank levels.
- The constant differential pressure relay maintains a ***constant flow rate*** of purge gas in the bubbler tube regardless of tank level variations or supply fluctuation.
- This ensures that bubbling will occur for the maximum tank level and the flow rate does not increase at low tank levels in such a way as to cause excessive disturbances at the surface of liquid.
- Note that bubbling action has to be continuous, or the measurement signal will not be accurate.
- An additional advantage of the bubbler system is that since it measures only the back-pressure of the purge gas, the exact location of the level transmitter is not important. The transmitter can be mounted some distance from the process.

Closed Tank Application For Bubbler System

- If the bubbler system is to be applied to measure level in a closed tank, some ***pressure regulating*** scheme must be provided for the gas space in the tank.

- Otherwise, the gas bubbling through the liquid will pressurize the gas space to a point where bubbler supply pressure cannot overcome the static pressure.

- The result would be no bubbler purge flow and, therefore, an inaccurate measurement signal.

- Also, as in the case of a closed tank inferential level measurement system, the low pressure side of the level transmitter has to be connected to the gas space in order to compensate for the effect of gas pressure.

- In this way, the bubbler medium (say helium) back-pressures are applied against both the high side and low sides of the d/P cell to provide a differential pressure signal proportional to the level in the closed tank.

LEVEL MEASUREMENT ASSIGNMENT

1. State the relationship between pressure at the base of the tank and liquid column height.
2. Sketch a level transmitter installation for a closed tank application. Show all necessary pipe connections.
3. Sketch and explain the function of a three valve manifold.
4. Describe an operating sequence for the three valve manifold when a d/P transmitter has to be placed into service. Assume that the static pressure could over-range the capsule if incorrectly applied.
5. What is the difference between a "dry" leg and a "wet" leg in closed tank application?
6. In a wet leg installation, the low pressure side of the DP transmitter always experiences a higher pressure than the high pressure side. What would be the effect of reversing the connections such that the wet leg is connected to the high pressure side of the transmitter.
7. When a wet leg installation is used, the "zero" has to be elevated. Explain the reason for this zero elevation.
8. Briefly explain the principle of operation of a bubbler system.
9. List the two main advantages of the bubbler system in a nuclear system.

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 5: Flow Instrumentation

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. State the relationship between ***flow*** and ***differential pressure*** developed across a flow restriction
2. Name the four most commonly used ***primary devices*** in flow measurement.
3. Sketch a flow measurement installation including an ***orifice plate***, three-valve manifold and flow d/P transmitter.
4. State the advantages and disadvantages of using the orifice plate as a primary device and compare with the ***venturi***.
5. State an application for each of a venturi tube, ***flow nozzle*** and ***elbow taps*** in an industrial process plant.

Energy and Flow Equation of Fluids

The total energy of fluid in a flow system is comprised of three components: potential energy, kinetic energy and pressure energy. When described in terms of ***meters head*** of the flowing fluid, we must consider:

Total Energy = Potential + Kinetic + Pressure

Which includes:

Z = Elevation of the center line of the pipe (m)

V = Velocity of the fluid (m/sec)

g = Acceleration due to gravity (9.8 m/sec^2)

P = Static Pressure (N/M^2)

ρ = Weight density of fluid (N/M^3)

Flow quantity inside a pipe is given as the product of the ***velocity*** of the fluid and the ***cross-sectional area*** of the pipe, that is:

$$\mathbf{Q = V \cdot A}$$

where

Q = ***Flow rate*** (m^3/sec)

V = ***Velocity*** (m/sec)

A = ***Cross-sectional area*** (m^2)

Now consider the flow in a pipe with a restriction as shown in Figure 1.

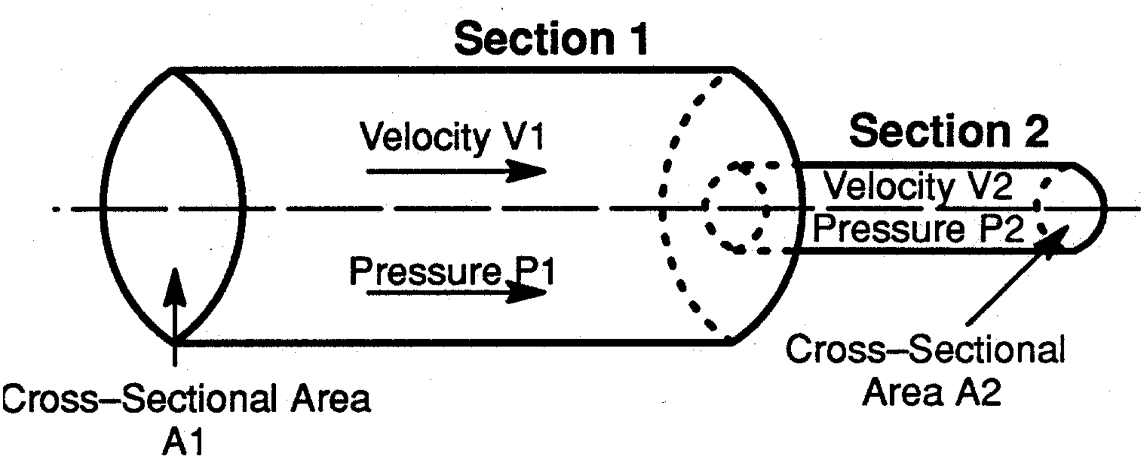


Figure 1. Flow in a Pipe with a Restriction

Flow in A Pipe With a Restriction

- If the flow is steady, then the ***same quantity*** of fluid must pass through the two different sections of the pipework in a given time. Section 2 has a smaller cross-sectional area than Section 1, therefore, the fluid must travel faster in Section 2 than in Section 1.

- Relating the flows for these two cross sectional areas:

  $\mathbf{Q = A_1V_1 = A_2V_2}$

  And when $A_1 > A_2$, then $V_1 < V_2$

- Because of the Principle of Conservation of Energy, an increase in velocity in Section 2, which causes an increase in kinetic energy, must be compensated for by a corresponding decrease in potential or pressure energy.

- We can write an equalization equation to approximate the change in the potential energy (mgh) and the change in kinetic energy (1/2 mv^2) resulting from this velocity change in the flowing fluid.

Change in Potential Energy = Change in Kinetic Energy

Mgh = _ Mv^2

Cancelling M from both sides and solving for V;

$v^2 = 2gh$

v = (2gh) –

v = (2g) –(h) –

v = K(h) –

- So the flowing ***velocity*** will be ***proportional to the square root*** of the ***differential pressure*** sensed across the flow restriction.

Q = AV = AK(h) –

Q = flow quantity

A= flow restriction area

K = flow constant

h= differential pressure measured across the restriction

- The ***flow rate*** is proportional to the ***square root of the differential pressure*** developed across a flow restriction.
- This is the principle behind flow metering – the flow can be calculated if we measure the differential pressure across a defined flow restriction
- In order to obtain a ***linear flow signal***, we must always take the square root of the measured differential pressure

Primary Devices

- To measure flow rate by means of differential pressure requires the use of a primary device, i.e. a device that creates a flow stream constriction.
- The most popular primary devices are ***orifice plates***, ***venturi tubes***, ***flow nozzles*** and ***elbow taps***.

Orifice Plate

- An orifice plate is basically a ***thin metal plate*** (1.5 to 6 mm in thickness) with a hole bored in the center.
- The orifice plate has a ***tab*** on one side where the specifications for the plate are stamped.
- The upstream side of the orifice plate usually has a ***sharp, square edge*** facing into the flow stream.

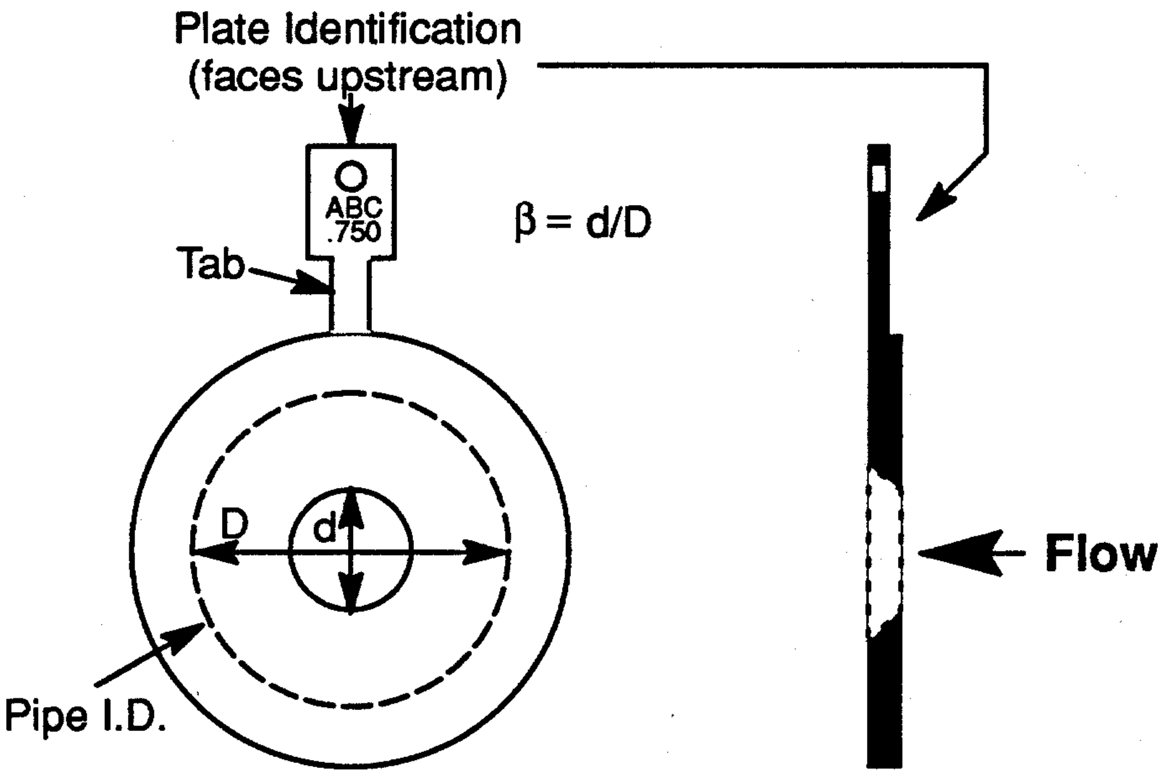


Figure 2: A Typical Orifice Plate.

Concentric Orifice Plate

- The orifice has a diameter that is between 30% to 75% of the inside diameter of the pipe work in which it is installed.

- The ratio of orifice bore diameter (d) to the pipe inside diameter (D) is called the ***Beta Ratio*** (b).

b = d/D

- For example, a b ratio of 0.5 indicates that the orifice bore diameter is 50% of the pipe inside diameter.

- When an orifice plate is installed in a flow line (usually clamped between a pair of flanges), the increase of fluid flow velocity through the reduced area at the orifice develops a differential pressure across the orifice.

- This differential pressure measured is a function of flow rate.

- The differential pressure generated is related to the b value of the orifice plate. The smaller the b ratio, the higher the ***differential pressure***.

- In practice, the choice of b ratio is a compromise between differential pressure desired and the flow rate required.

- With an orifice plate in the pipe work, static pressure increases slightly upstream of the orifice (due to ***back pressure*** effect) and then decreases sharply as the flow passes through the orifice.

- Flow downstream from an orifice reaches a minimum at a point called the ***vena contracta*** where the velocity of the flow is at a maximum.

- Beyond this point, ***static pressure*** starts to recover as the flow slows down.

- However, with an orifice plate, static pressure downstream is always considerably lower than the upstream pressure (i.e. permanent pressure loss).

- In addition some pressure energy is converted to sound and heat at the orifice plate.

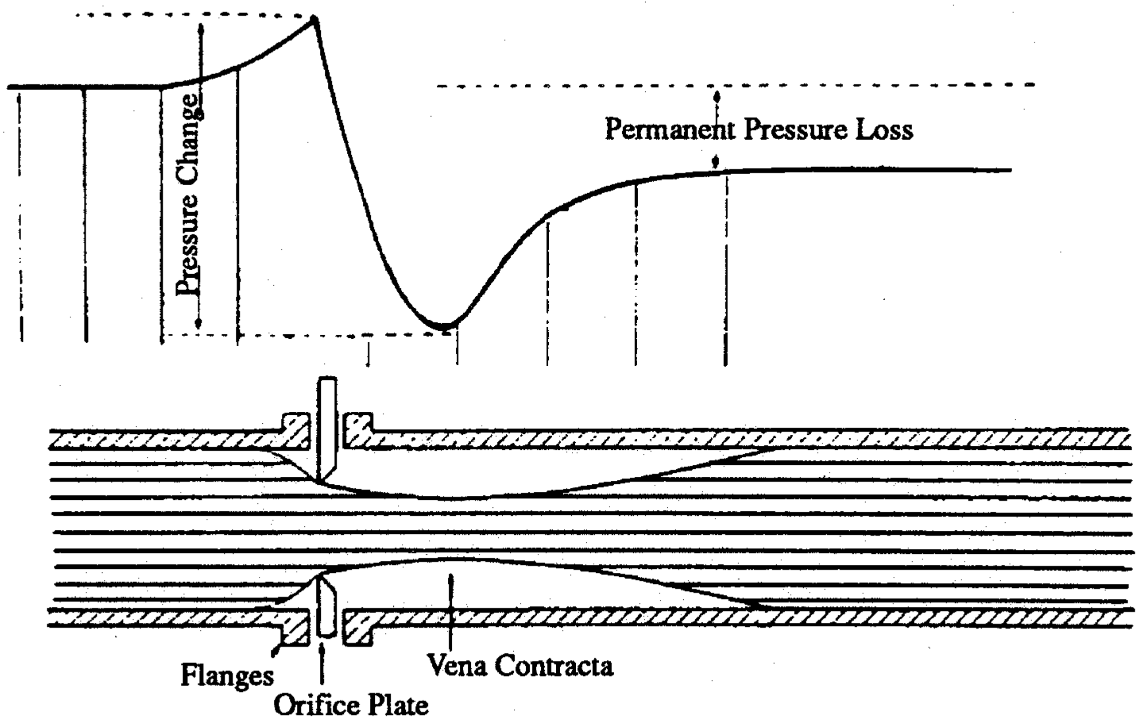


Figure 3: Orifice Plate Installation With Pressure Profile.

- From Figure 3, it can be seen that the ***measured differential pressure*** developed by flow through an orifice plate also depends on the location of the pressure sensing points or ***pressure taps***.

Pressure Tap Location

- ***Flange taps*** are the most widely used pressure tapping location.
- They are holes bored through the flanges, located ***one inch upstream*** and ***one inch downstream*** from the respective faces of the orifice plate.
- A typical flange tap installation is shown in Figure 4.
- The upstream (H) and downstream (L) sides of the orifice plate are connected to the high pressure and low pressure sides of a d/P transmitter.
- A pressure transmitter, when installed to measure flow, can be called a ***flow transmitter.***
- As in the case of level measurement, the flowing fluid static pressure in the pipework could be many times higher than the differential pressure created by the orifice plate.
- In order to use a capsule that is sensitive to ***low differential pressure***, a ***three-valve manifold*** has to be used to protect the d/P capsule from being over-ranged.

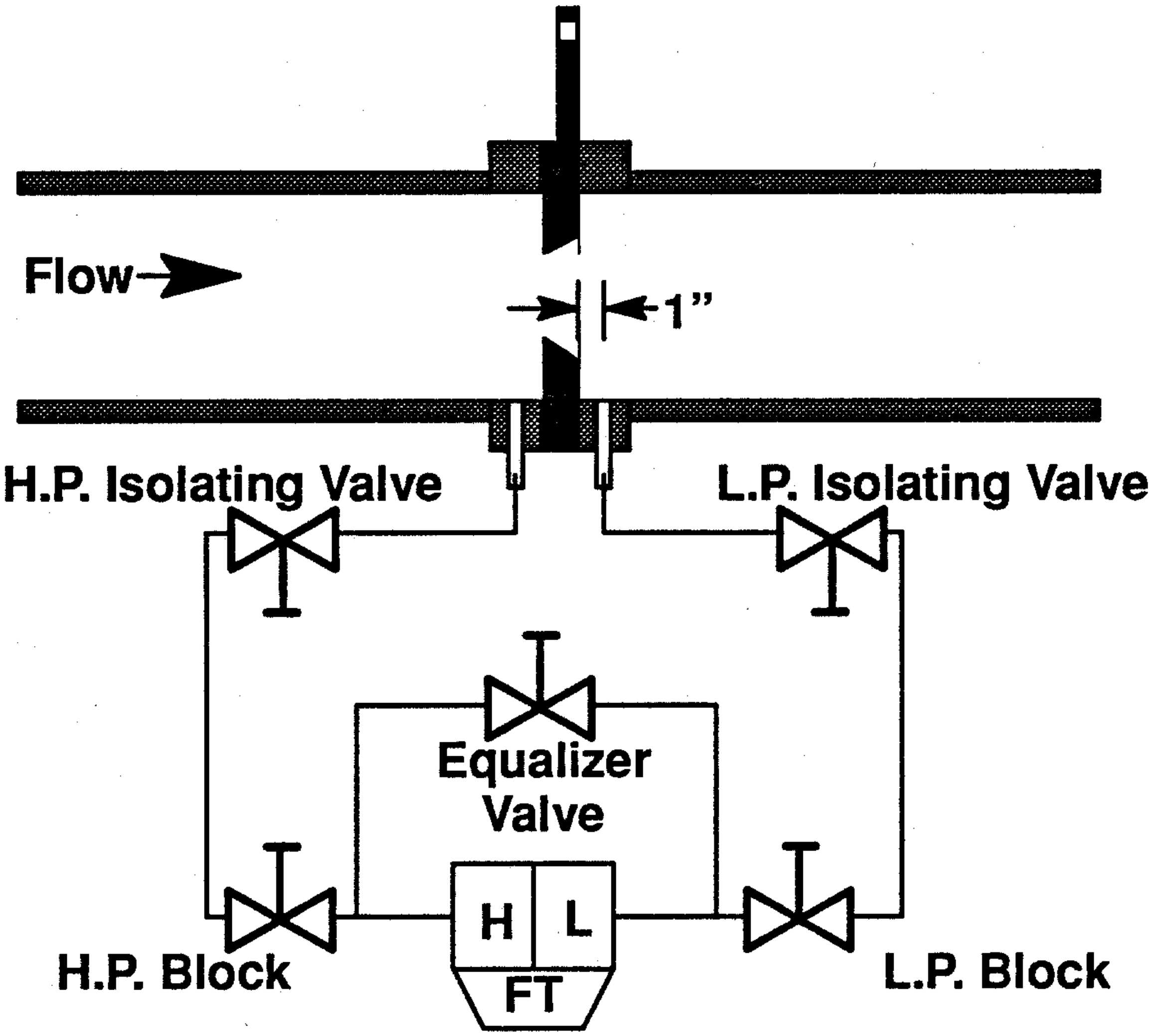


Figure 4: Orifice Plate with Flange Taps and 3 Valve Manifold.

- The ***same procedure*** for valving in and out the three valve manifold in a level installation is applied to flow installation.

Operation Sequences for Three-Valve Manifold

Valving Flow Transmitter Into Service

1. Check all valves closed – initial condition.
2. Open the equalizing valve – d/P cell should read zero differential.
3. Open the high pressure block valve to apply high pressure to both sides of the d/P cell – d/P cell should read zero differential.
4. Close the equalizing valve – trap high pressure in both sides, check for leaks – d/P cell should still read zero differential.
5. Open the low pressure block valve. Transmitter is now in service.

Removing Flow Transmitter From Service

1. Close the ***low pressure block valve*** – this traps the low pressure in the d/P cell and the differential reading should be unchanged.
2. Open the ***equalizing valve*** to equalize the high pressure across the d/P cell. Differential reading should now be zero. Note that no significant flow passes through the equalizing valve as all three valves are not open at the same time.
3. Close the ***high pressure block valve***. Transmitter is now out of service but pressure trapped in the d/P cell body must be bled away.

Other Types of Pressure Taps

Other common types of pressure take-offs include:

- ***Corner taps*** which are located right at the upstream and downstream faces of the orifice plates (Figure 5).

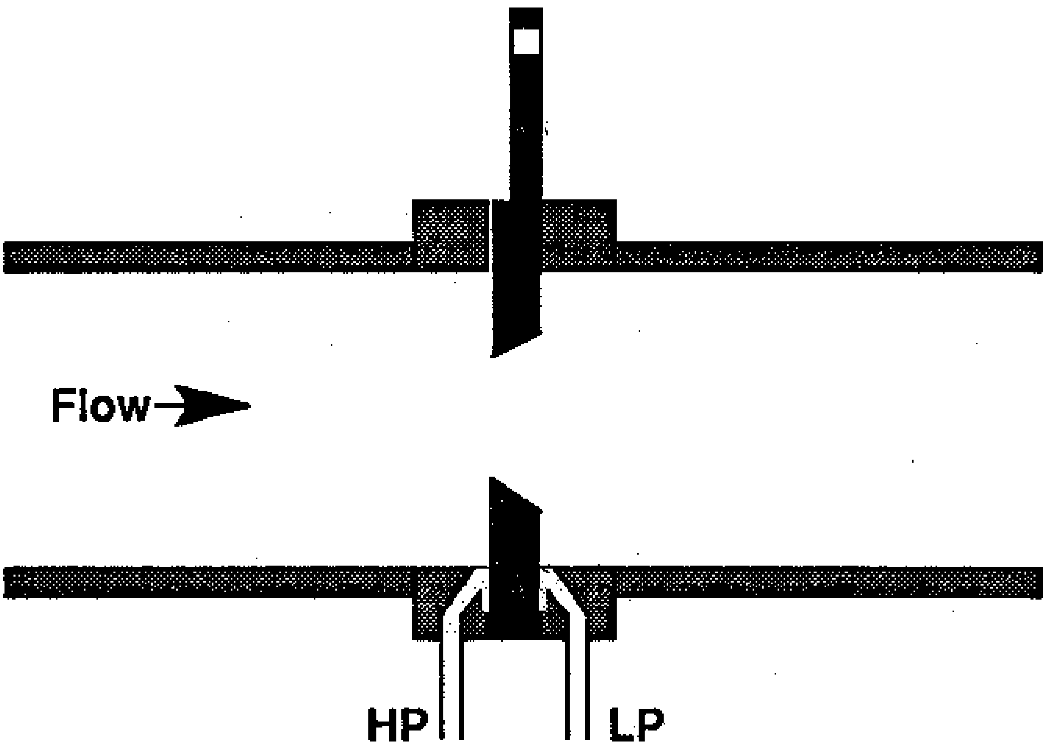


Figure 5: Orifice Plate with Corner Taps.

- ***Vena contracts taps,*** are located one pipe inner diameter upstream and at the point of minimum pressure, usually one half pipe inner diameter downstream

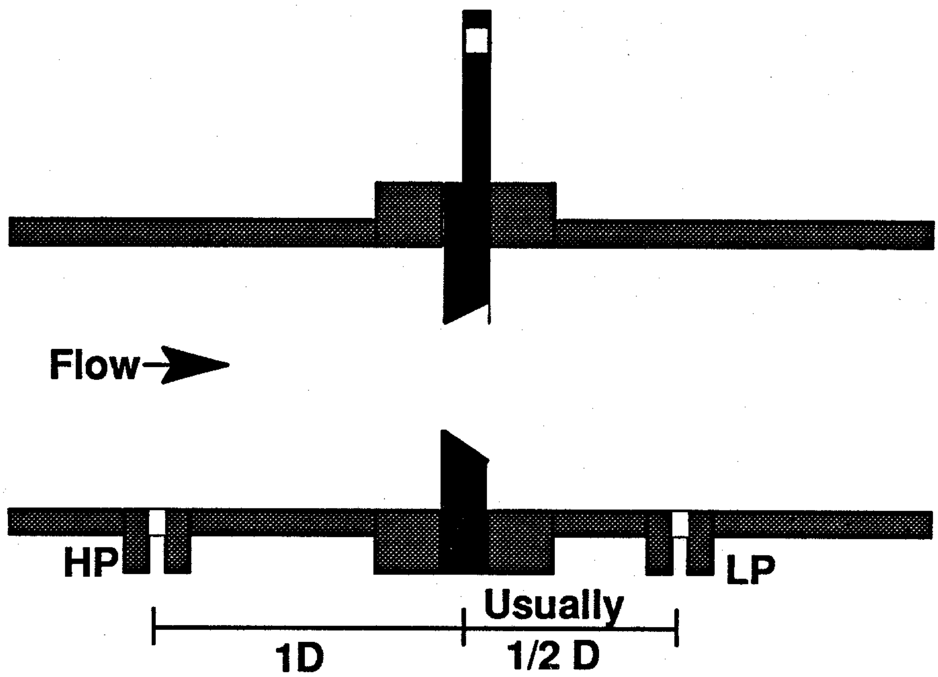


Figure 6: Orifice Plate with Vena Contracta

- ***Pipe taps,*** which are located two and a half pipe inner diameters upstream and eight pipe inner diameters downstream.
- When an orifice plate is used with one of the ***standardized pressure tap locations***, an on-location calibration of the flow transmitter is not necessary. Once the ratio and the kind of pressure tap to be used are decided, there are empirically derived charts and tables available to facilitate calibration.

Advantages And Disadvantages of Orifice Plate

Advantages of orifice plates include:

1. High differential pressure generated.
2. Exhaustive data available.
3. Low purchase price and installation cost.
4. Easy replacement.

On the other hand, disadvantages for use of orifice plates include:

1. High permanent pressure loss implies higher pumping cost.
2. Cannot be used on dirty fluids, slurries or wet steam as erosion will alter the differential pressure generated by the orifice plate.

Venturi Tubes

- For applications where high permanent pressure loss is not tolerable, a venturi tube (Figure 7) can be used.
- Because of its gradually curved inlet and outlet cones, almost no permanent pressure drop occurs.
- This design also minimizes wear and plugging by allowing the fluid flow to sweep suspended solids through without obstruction.

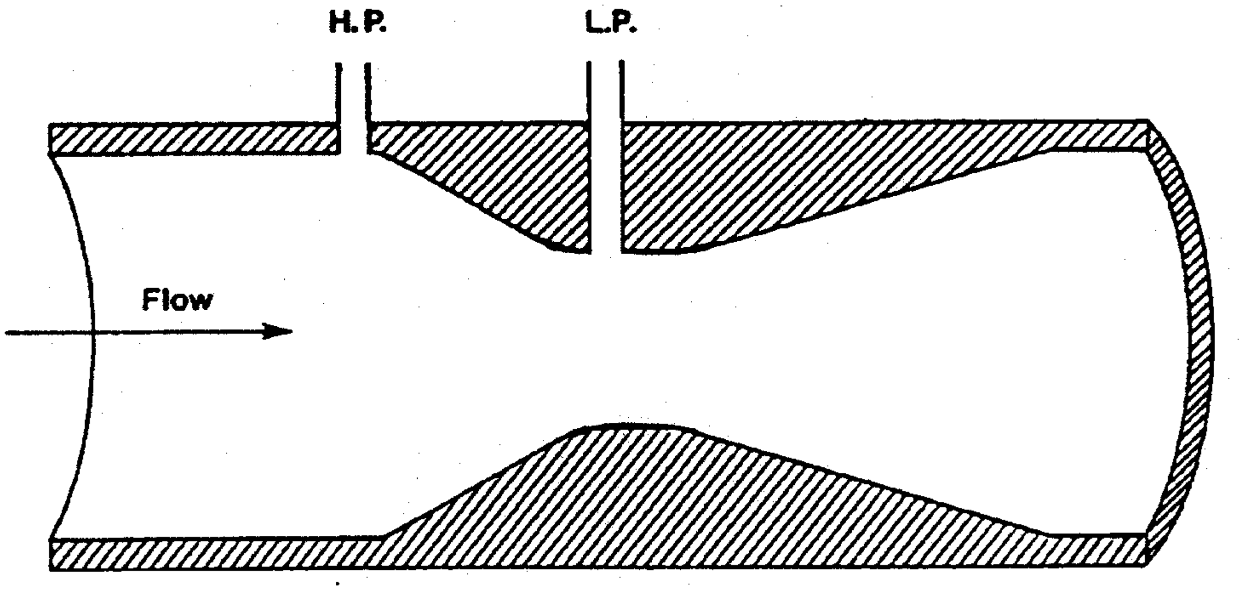


Figure 7: .A Venturi Tube.

- Venturi tubes have applications in many industrial processes to measure flow under a wide range of operating conditions.

Flow Nozzle

- A flow nozzle is also called a half venturi with flow characteristics between an orifice plate and a venturi tube. Figure 8 shows a typical flow nozzle installation.

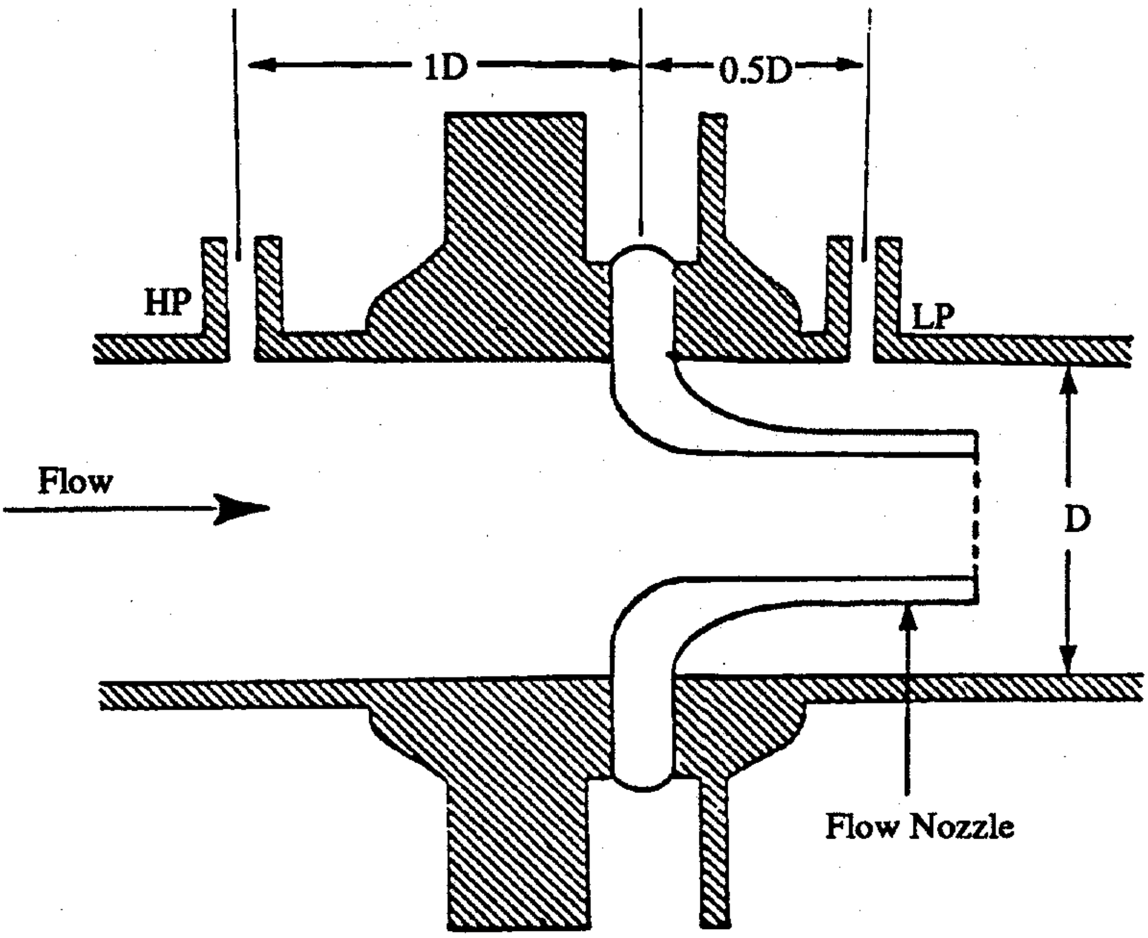


Figure 8: Representative Flow Nozzle Installation.

- Because of its streamlined contour, the flow nozzle has a ***lower permanent pressure loss than an orifice plate*** (but higher than a venturi).
- The ***differential*** the flow nozzle generates is also ***lower than an orifice plate*** (but again higher than the venturi tube).
- Flow nozzles are widely used for flow measurements at ***high velocities***.
- They are more rugged and ***more resistant to erosion*** than the sharp-edged orifice plate, and therefore are typically used in cases where the flow rate is high and the flow has a high gas content.

Elbow Taps

- Centrifugal force generated by a fluid flowing through an elbow can be used to measure fluid flow.
- As fluid goes around an elbow, a high pressure area is developed on the outer face of the elbow.
- If a flow transmitter is used to sense this high pressure and the lower pressure at the inner face of the elbow, flow rate can be measured.
- Elbow taps are typically used to measure steam flow from the boilers, where the large volume of saturated steam at high pressure and temperature could cause an erosion problem for other primary devices.
- Another advantage is that the elbows are often already in the regular piping configuration so no additional pressure loss is introduced.

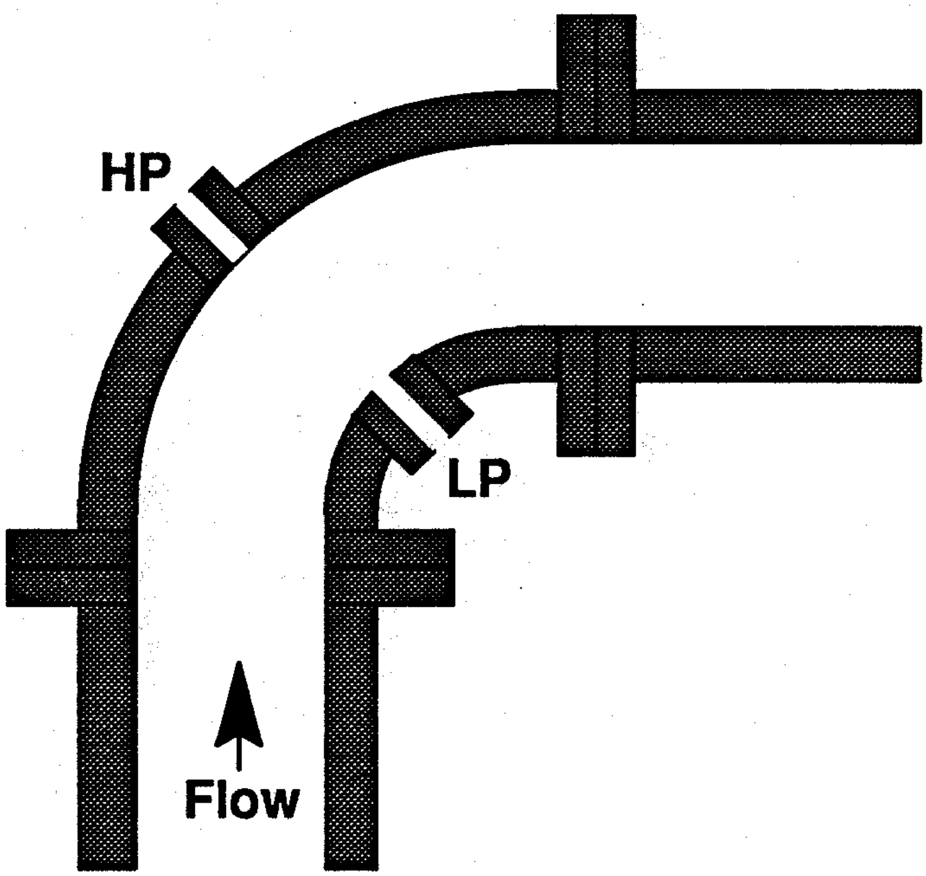


Figure 9: A Representative Elbow Tap

Flow Instrumentation ASSIGNMENT

1. State the relationship which exists between ***flow*** and ***differential pressure***.
2. What is a primary flow device? What are four commonly used ***primary devices*** in process plant flow measurement applications?
3. What is the purpose of a ***three valve manifold*** in a typical flow measurement? Describe the sequence of operation of the three valve manifold when the flow transmitter has to be removed from service.
4. Why is the selection of the type of ***pressure tap*** important to the final flow metering installation performance (i.e. differential pressure range, etc).
5. What is the major advantage and application of the following primary devices:
   a) ***venturi tubes***
   b) ***flow nozzles***, and
   c) ***elbow taps***?

LESSON 1: INSTRUMENTATION EQUIPMENT

MODULE 6: Temperature Instrumentation

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. Briefly describe how a typical "J" type ***thermocouple*** is constructed.
2. State the type, and magnitude of the signal which a thermocouple generates and describe briefly its relationship with temperature.
3. Define the terms ***measurement junction*** and ***reference junction*** in relation to a thermocouple and be able to calculate a sample circuit output.
4. Explain the need for ***extension grade wires*** in a thermocouple installation.
5. Explain the construction and principle of operation of a ***Resistance Temperature Detector*** (RTD).
6. Sketch a ***wheatstone bridge circuit*** to allow RTD temperature sensing.
7. Explain the need for ***three wire RTDs*** in temperature measurement.
8. State the functions of a ***thermal well***.

Temperature Instrumentation

- Temperature measurement is divided into two different types - ***local*** and control room (***remote***) measurement.
- Often local measurement is used when ***no control function*** is required and is usually for ***indication purposes only***.

Local Temperature Measurement

- In most industrial application the majority of ***local temperature measurements*** are provided by ***bimetallic thermometers***.
- A ***bimetallic strip*** is constructed by bonding two metals with different coefficients of thermal expansion (Figure 1 (a)).
- If heat is applied to the strip, the metal with the higher coefficient of expansion will expand more than the other.

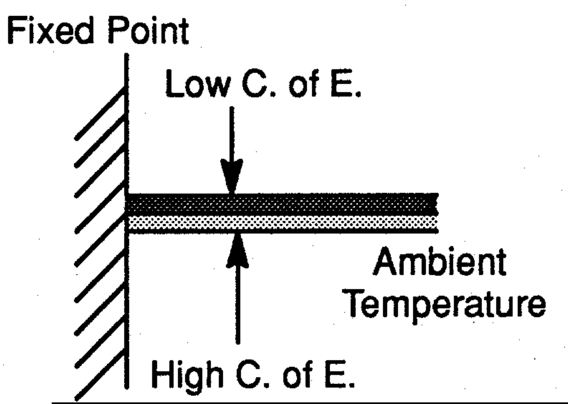


Figure 1 (a): A Bimetallic Strip

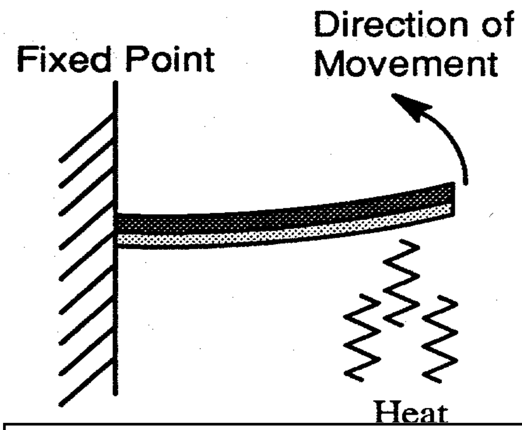


Figure 1 (b): Deflected Bimetallic Strip

- As a result of the application of heat, the whole metallic strip will bend in the direction of the metal with the lower coefficient. (Figure 1(b)).

Bimetallic Thermometer

- If a ***pointer*** is attached to the end of the bimetallic strip, ***indication of the temperature*** sensed by the strip can be obtained.
- In practice, since the magnitude of deflection of the strip is directly proportional to the square of its length, the bimetallic strip is usually ***coiled in a spiral*** or ***helix*** to increase its displacement.

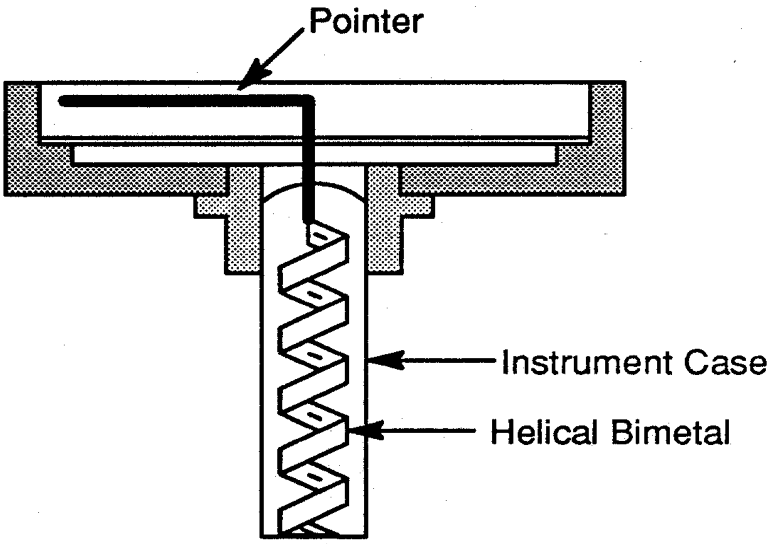


Figure 2: A Helical Bimetallic Thermometer

- Bimetallic thermometers in general are very ***rugged*** and require ***little maintenance***.
- For control room measurement, a 4 - 20 mA signal which is proportional to the temperature range we are interested in has to be generated. In many process industries ***Thermocouples*** (TC) and ***Resistance Temperature Detectors*** (RTD) are used for this purpose.

Thermocouple (TC) - Principle of Operation

- A thermocouple consists of two pieces of ***dissimilar metals*** with their ends joined together.
- When heat is applied to the junction, a voltage, in the range of millivolts (mV), is generated. A thermocouple is therefore said to be ***self-powered***.

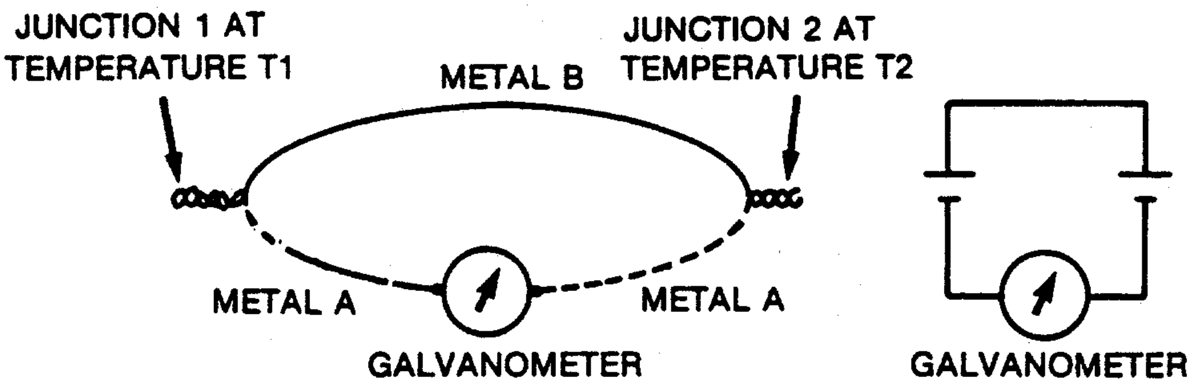


Figure 3: Thermocouple Circuit.

- The ***voltage*** (or emf) ***generated*** at each junction depends on junction temperature.
- If temperature T1 is higher than T2, then the voltage generated at Junction 1 will be higher than that at Junction 2.
- In the above circuit, the ***polarity*** of the voltage generated at the two junctions oppose each other.
- The ***net voltage*** (circuit emf) shown on the galvanometer depends on the relative magnitude of the voltages at the two junctions.
- In order to use a thermocouple to measure process temperature, one end of the thermocouple has to be kept in contact with the process while the other end has to be kept at a relatively constant temperature.
- The process contact junction is called the ***hot or measurement junction***.
- The other junction that is kept at constant temperature is called ***cold or reference junction.***
- The relationship between circuit emf and the junctions emf is:

  Circuit emf = Measurement emf - Reference emf

- If circuit emf and reference emf are known, measurement emf can be calculated.
- To convert the emf generated by a thermocouple to the standard 4-20 mA signal, a temperature transmitter is needed.

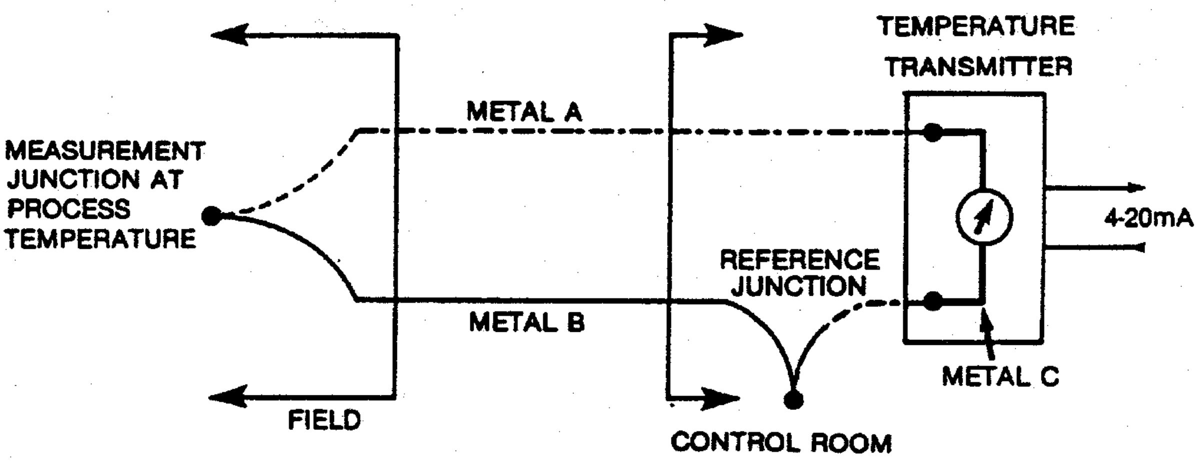


Figure 4: A Simplified Thermocouple Temperature Transmitter Circuit

- As shown in Figure 4, the temperature measurement circuit consists of a thermocouple which is connected directly to the temperature transmitter.
- There are two junctions in the circuit - a ***measurement junction*** and a ***reference junction*** which is kept at control room temperature.
- However, upon closer examination, there are ***actually more than two junctions*** in existence.
- There are two additional junctions formed by the metal C, which is the metal used inside the transmitter, and the metal A.
- An equivalent circuit diagram of for the transmitter circuit is shown in Figure 5.

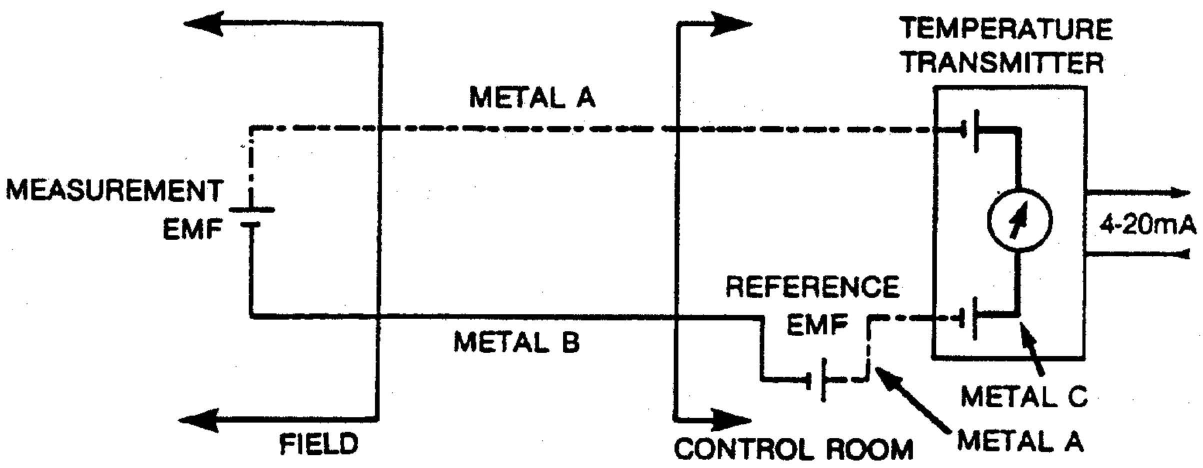


Figure 5: Equivalent Thermocouple Temperature Transmitter Circuit Diagram.

- From Figure 5 it can be seen that the emf generated by the metal A and C junctions are ***equal and opposite*** to each other in polarity.
- Therefore the ***net emf*** of the circuit is:

  Circuit emf = Measurement emf + A-C emf - A-C emf - reference emf

  = Measurement emf - reference emf

- That is, the metal C has no effect on the thermocouple circuit.
- It has been proved that for thermocouple circuits where a carefully selected third metal has been added, the reference junction itself can actually be eliminated.
- The emf generated by the junctions of the third metal is equivalent to the emf that would be generated by the reference junction at the same temperature.
- The transmitter becomes the reference junction as shown in Figure 6.

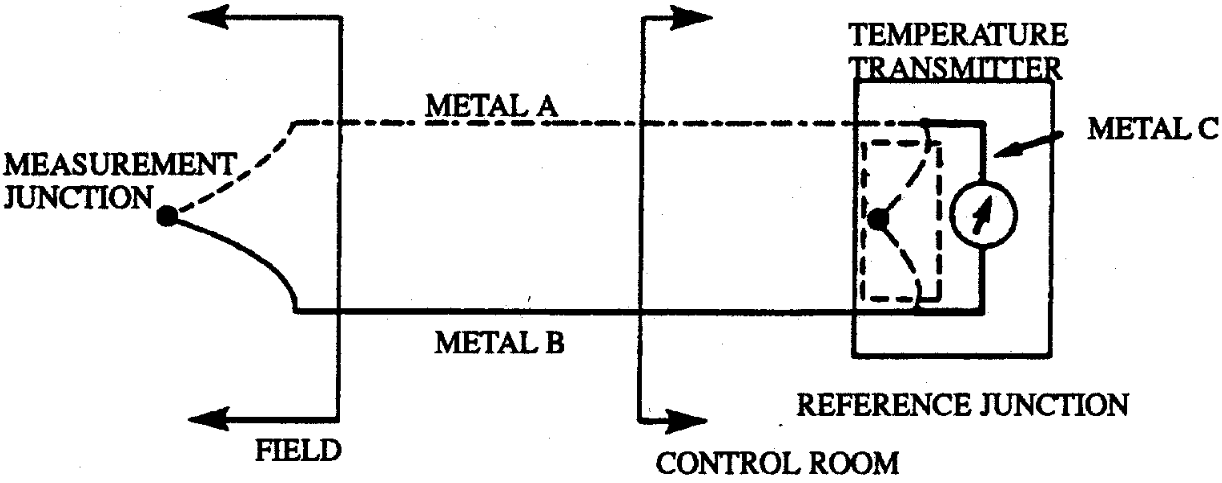


Figure 6: Thermocouple Circuit With Transmitter Acting As The Reference Junction.

- In practice, the transmitter is often installed in a relatively constant temperature environment to help maintain the reference emf constant.
- Since we know the total circuit emf and the reference junction emf, the measurement junction emf can easily be obtained by the relationship:

  Measurement emf = Total Circuit emf + Reference emf

- The transmitter, when properly calibrated, will produce a 4-20 mA signal that is directly proportional to the measurement emf and hence the process temperature.

Thermocouple Construction

- The materials used for thermocouple construction depend on the temperature range to which the thermocouple will be subjected.
- Several combinations of metals are used for the construction of thermocouples.
- A popular type of thermocouple is the "**J**" type which consists of ***iron*** and ***constantan*** (a nickel-copper alloy) wires with very high purity.
- The "J" type thermocouple has a fairly **linear relationship** between temperature and millivolt output in the range of **0 to 300∞C**, which suits many industrial applications.

Thermocouple Connecting Wires

- If the thermocouple is located some distance away from the transmitter, a connection between the thermocouple and the transmitter has to be made.
- However, if ordinary copper wires are used (which is expensive), additional junctions (say iron-copper and constantan - copper for a “J” type thermocouple) would be formed where the wires are joined.
- These additional junctions would become measurement junctions when they are subjected to a change in ambient temperature and could alter the signal sensed by the temperature transmitter.
- To eliminate this problem, **extension grade** thermocouple wires or compensating cables have to be used.
- Extension grade wires are made of the same, or with the same characteristic, materials as the thermocouple wires they are connected to.
- Extension grade wires can be of lower purity than the thermocouple wires or be of a cheaper material. (Important since some thermocouples use platinum as one of the metals).
- In general power plant applications, thermocouples are used around the turbine hall because of their ***rugged construction*** and ***low cost***.
- Thermocouples are not used in areas where high radiation fields are present (for example, in the reactor vault).
- Beta radiation (from neutron activation), essentially electrons, will induce a voltage in the thermocouple wires.
- Since the signal from thermocouple is also a voltage, the induced voltage will cause an error related to radiation fields sensed in the temperature transmitter output.

Resistance Temperature Detector (RTD) - Principle of Operation

- The Resistance Temperature Detector or RTD can be regarded as a high precision wire wound resistor whose ***resistance varies with temperature***.
- For metals, resistance is given by:

  $R = (r \times l) / A$

  where, R = resistance (W)

  P = resistivity (W-M)

  l = length (m)

  A = cross-sectional area (m^2)
- When the temperature of a metal changes, its physical dimensions also change (e.g. length increases, cross-sectional area decreases).
- Metals have a ***positive resistance temperature coefficient*** (i.e. as temperature increases, resistance increases).
- By measuring the resistance change of the metal, the temperature of the metal can be determined.
- Several different pure metals (such as platinum, nickel and copper) can be used in the manufacture of RTDs.
- A typical RTD probe contains a coil of very fine metal wire, allowing for a ***relatively large resistance change*** without a great space requirement.
- In applications that require high accuracy and linearity, platinum RTDs are used as process temperature monitors.
- To detect and measure the variations of resistance of the RTD, a temperature transmitter in the form of a Wheatstone bridge can be used. (Figure 7).

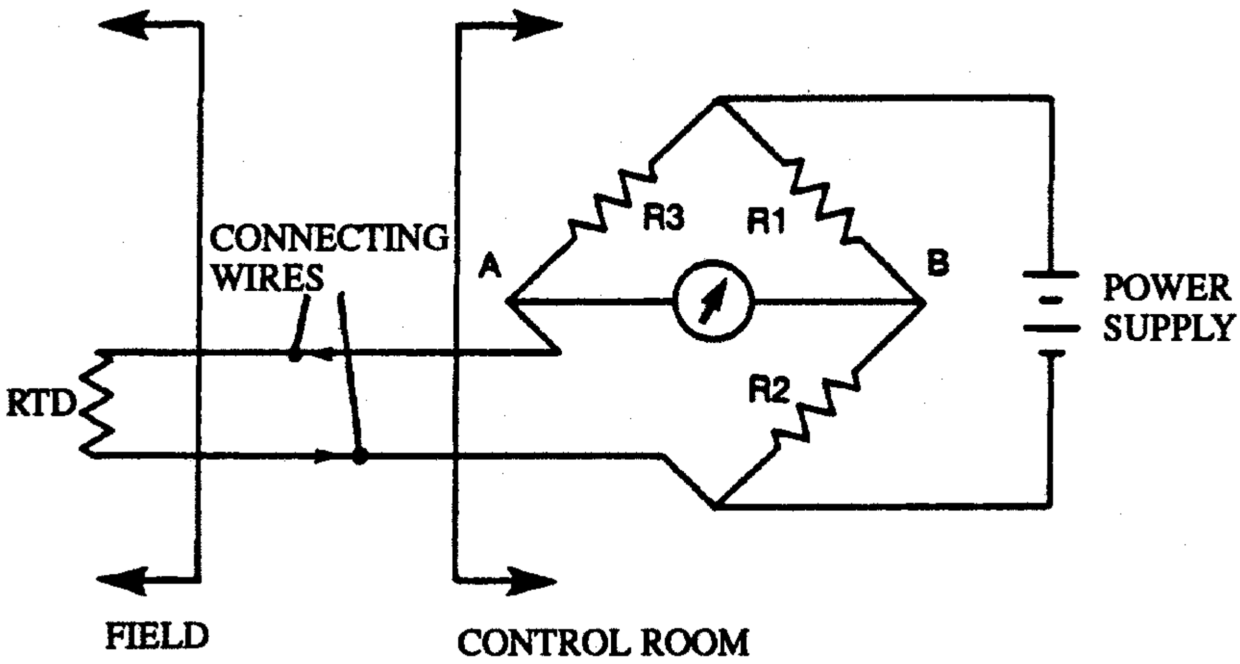


Figure 7: A Wheatstone Bridge Temperature Detector for an RTD.

- The Wheatstone bridge is an electric circuit consisting of four resistors, a galvanometer and a voltage source.

- In a Wheatstone bridge circuit, when the current flow in the galvanometer is zero (the voltage at point "A" equals the voltage at point "B") the bridge is said to be in null balance. A set ratio exists between the resistive elements.

- It can be shown that the galvanometer in the Wheatstone bridge detector reads null, when

$$\frac{R_1}{R_2} = \frac{R_3}{RTD}$$

- By keeping the resistance values for R_1, R_2 and R_3 constant, the resistance of the RTD can be determined by the reading the galvanometer.
- If the galvanometer is replaced by a detector circuit, a 4 - 20 mA signal which is proportional to the temperature range being monitored can be generated.
- A problem can exist when the RTD is installed some distance away from the transmitter.
- Since the connecting wires are long, the resistance of the wires changes as ambient temperature fluctuates. The variations in wire resistance could introduce an error in the transmitter.
- To eliminate this problem of connecting lead resistance changes, a three-wire RTD is used.

The Three-Wire RTD Installation

- Figure 8 illustrates a three-wire RTD installation in which the RTD connecting wires are made the same length, and therefore ***provide the same resistance in each branch of the bridge***.
- The power supply is connected across the Wheatstone bridge.

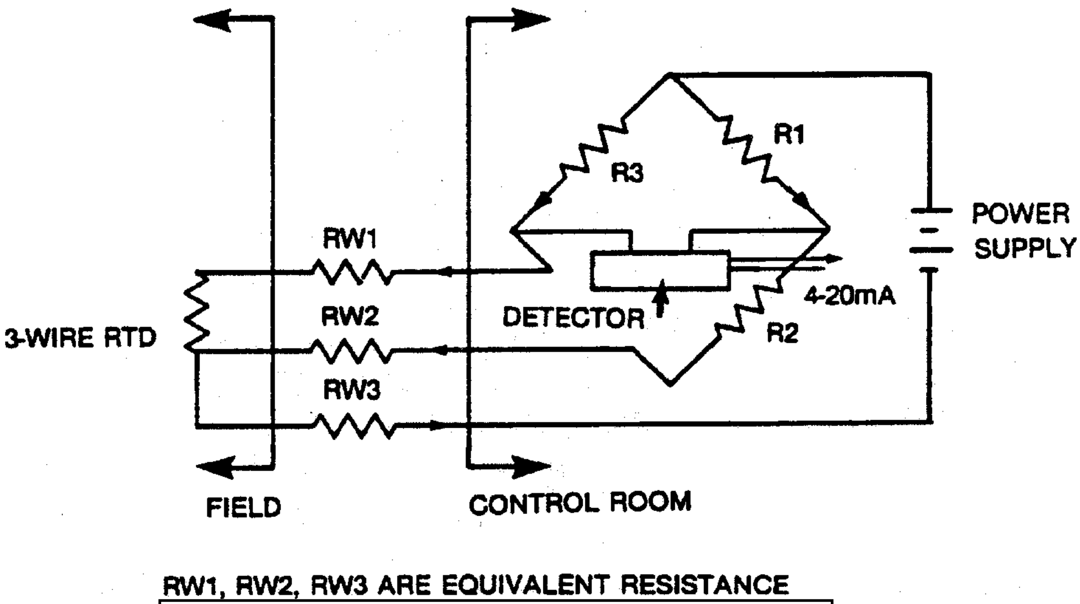


Figure 8. The three wire RTD wheatstone

- From Figure 8, it can be seen that the resistance of the right branch of the Wheatstone bridge is $\mathbf{R_1 + R_2 + RW_2}$.
- The resistance of the left branch of the bridge is $\mathbf{R_3 + RW_1 + RTD}$.
- Since $RW_1 = RW_2$, the result is that the resistances of the lead wires cancel and therefore the effect of the connecting wires is eliminated.
- In general, an RTD is not capable of measuring as wide a temperature range as a thermocouple but within its range it is ***more accurate*** and has ***higher sensitivity***.
- RTDs are used for temperature measurement in nuclear applications such as channel outlet temperatures, header temperatures, bleed temperatures, etc.
- Unlike thermocouples, beta radiation has minimal effect on RTDs

Thermal Wells

- The process environment where temperature monitoring is required, is often not only hot, but can also be pressurized and possibly chemically corrosive or radioactive.
- To facilitate removal of the temperature sensors for examination or replacement and to provide mechanical protection, the sensors are usually mounted inside thermal wells.

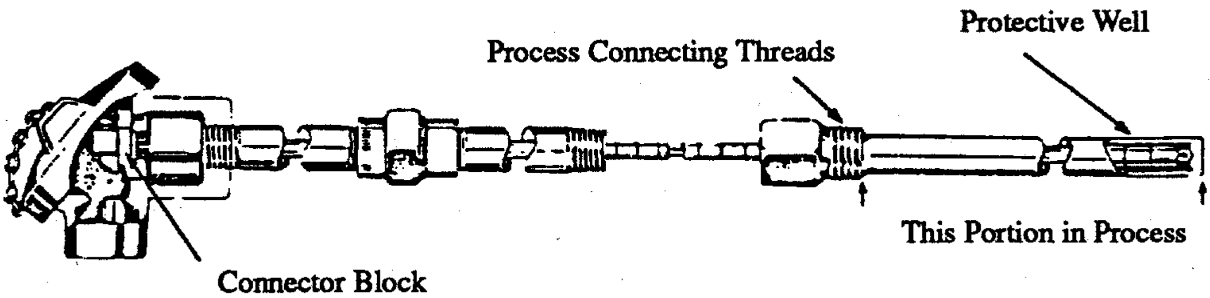


Figure 9: A Typical Thermal Well Installation.

Thermal well Response

- A thermal well is basically a hollow metal tube with one end sealed that is usually mounted permanently in the pipe work.
- The sensor is inserted into the well and makes contact with the sealed end.
- A drawback to thermal wells is the resulting longer response time
- An example of the temperature response for bare and thermal well installed sensors is shown in Figure 10.
- This thermal lag, however, can be decreased by minimizing the air space between the sensor and the well.

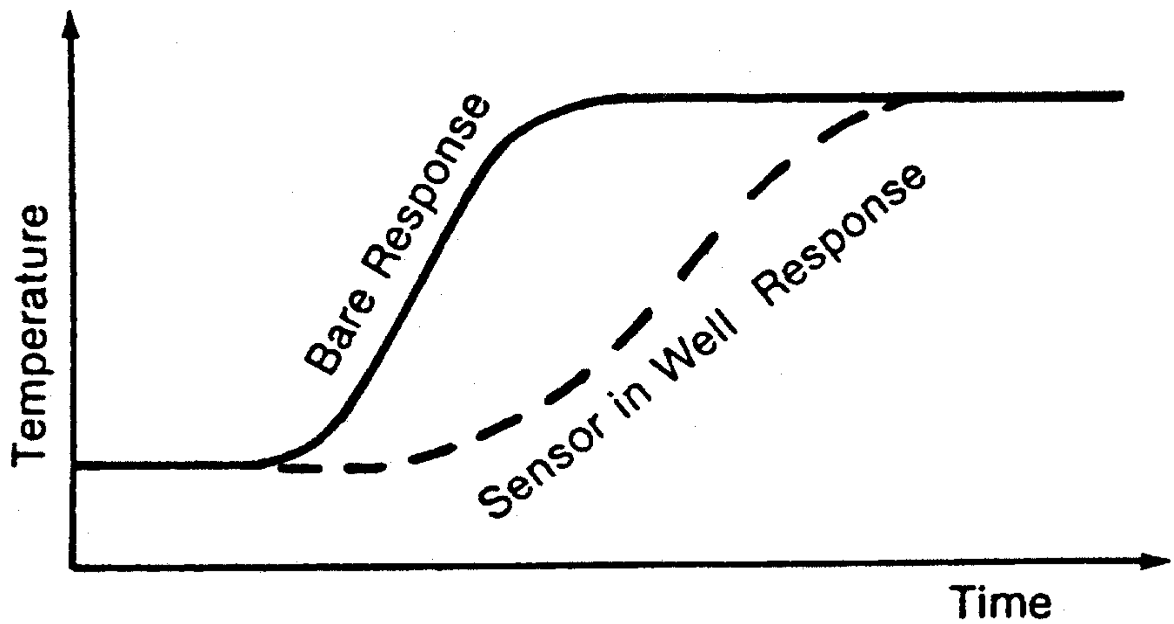


Figure 10: Response Curves of Bare Detector and Thermal Well Installation.

Table 1: Iron-Constantan (**Type J**) Conversion Table

CURVE S99J-0 For Iron-Constantan Thermocouples (Type J)

Reference Junction at 0∞C - 0.00 mV; at 25∞C, subtract 1.28 mV

∞C	mV	∞C	mV	∞C	mV	∞C	mV	∞C	mV
		0	0.00						
-200	-7.89	5	0.25	255	13.84	505	27.67	755	42.64
-195	-7.78	10	0.50	260	14.12	510	27.95	760	42.96
-190	-7.66	15	0.76	265	14.39	515	28.23	765	43.28
-185	-7.54	20	1.02	270	14.67	520	28.52	770	43.60
-180	-7.54	25	1.28	275	14.94	525	28.80	775	43.92
-175	-7.40	30	1.54	280	15.22	530	29.08	780	44.25
-170	-7.27	35	1.80	285	15.50	535	29.37	785	44.57
-165	-6.97	40	2.06	290	15.77	540	29.65	790	44.89
-160	-6.82	45	2.32	295	16.05	545	29.94	795	45.21
-155	-6.66	50	2.58	300	16.33	550	30.22	800	45.53
-150	-6.50	55	2.85	305	16.60	555	30.51	805	45.85
-145	-6.33	60	3.11	310	16.88	560	30.80	810	46.18
-140	-6.16	65	3.38	315	17.15	565	31.08	815	46.50
-135	-5.98	70	3.65	320	17.43	570	31.37	820	46.82
-130	-5.80	75	3.92	325	17.17	575	31.66	825	47.14
-125	-5.61	80	4.19	330	17.98	580	31.95	830	47.46
-120	-5.42	85	4.46	335	18.26	585	32.24	835	47.78
-115	-5.23	90	4.73	340	18.54	590	32.53	840	48.09
-110	-5.03	95	5.00	345	18.81	595	32.81	845	48.41
-105	-4.83	100	5.27	350	19.09	600	33.11	850	48.73
-100	-4.63	105	5.54	355	19.37	605	33.41	855	49.04
-95	-4.42	110	5.81	360	19.64	610	33.70	860	49.36
-90	-4.21	115	6.08	365	19.92	615	33.99	865	49.67
-85	-4.00	120	6.36	370	20.20	620	34.29	870	49.98
-80	-3.78	125	6.63	375	20.47	625	34.58	875	50.27
-75	-3.56	130	6.90	380	20.75	630	34.88	880	50.57
-70	-3.34	135	7.18	385	21.02	635	35.18	885	50.87
-65	-3.12	140	7.45	390	21.30	640	35.48	890	51.16
-60	-2.89	145	7.73	395	21.57	645	35.77	895	51.46
-55	-2.66	150	8.00	400	21.85	650	36.08	900	51.76
-50	-2.43	155	8.28	405	22.13	655	36.38	905	52.05
-45	-2.20	160	8.56	410	22.40	660	36.69	910	52.35
-40	-1.96	165	8.84	415	22.68	665	36.99	915	52.64
-35	-1.72	170	9.11	420	22.95	670	37.30	920	52.94
-30	-1.48	175	9.39	425	23.23	675	37.60	925	53.24
-25	-1.24	180	9.67	430	23.50	680	37.91	930	53.53
-20	-1.00	185	9.95	435	23.78	685	38.22	935	53.83
-15	-0.75	190	10.22	440	24.06	690	38.53	940	54.12
-10	-0.50	195	10.50	445	24.33	695	38.84	945	54.44
-5	-0.25	200	10.78	450	24.61	700	39.15	950	54.72
		205	11.06	455	24.88	705	39.47	955	55.02
		210	11.34	460	25.16	710	39.78	960	55.32
		215	11.62	465	25.44	715	40.10	965	55.61
		220	11.89	470	25.72	720	40.41	970	55.91
		225	12.17	475	25.99	725	40.73	975	56.20
		230	12.45	480	26.27	730	41.05	980	56.61
		235	12.73	485	26.55	735	41.36	985	56.80
		240	13.01	490	26.83	740	41.68	990	57.10
		245	13.28	495	27.11	745	42.00	995	57.39
		250	13.56	500	27.39	750	42.32	1000	57.69

MODULE 6: Temperature Instrumentation Assignment

1. What is a ***thermocouple*** and how is a thermocouple constructed?

2. Explain briefly how a thermocouple can be used to measure a process temperature.
3. Why are ***extension grade wires*** needed when connections have to be made between the thermocouple and the temperature transmitter?
4. What full scale mV range should be specified for a ***J-couple*** installation with a constant cold junction of 30 C and a hot junction which ranges from 30 to 250 C?
5. How is an RTD constructed?
6. Explain briefly how an RTD can be used to measure process temperature.
7. Sketch a simple wheatstone resistance bridge circuit to show how an RTD temperature value can be sensed.
8. Revise the diagram of question #7 to show how a ***three lead connection*** is used to minimize RTD errors due to lead wire resistance changes.
9. Why are temperature sensors such as thermocouples and RTDs mounted in thermal wells? How does the use of a thermal well effect the response of the temperature sensor?

Lesson 1: INSTRUMENTATION EQUIPMENT

MODULE 7: Control Valves and Accessories

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. State the combinations of pneumatic ***actuator*** and globe ***valve body*** required to provide:
   a) air to open action;
   b) air to close action.
2. State and sketch the three ***flow characteristics*** for the most common globe valves.
3. State a typical application for each of the three flow characteristics and explain why it is the most appropriate selection for that application.
4. State the effect of ***unbalanced force on valve position*** and explain with an example, how bench setting would correct this problem.
5. Briefly explain at least three advantages a ***positioner*** gives when it is used in conjunction with a control valve.
6. Describe the failure mode of a given control valve.
7. Sketch and describe a system ***pump head vs flow curve*** set to define installed valve differential conditions.
8. Explain, with a diagram, how a ***three-way solenoid valve*** can be used for ON/OFF control of a pneumatic valve.
9. State the formula which describes a control valve Cv factor. What is the Cv for a valve which will pass a water flow of 100 USGPM with a pressure drop of 25 psi? What flow would this valve pass when the pressure drop is 49 psi?
10. State why it is often advisable to use different sized valves in parallel when the process variable has a very large range.

MODULE 7: Control Valves and Accessories

Control Valves and Accessories

- The ***final control*** element in a system is used to vary the flow of a manipulated variable in an attempt to maintain a process parameter at a desired setpoint.
- Final control elements include control valves, metering pumps, dampers and louvers, variable pitch fan blades, and electrically driven control devices.
- The ***control valve*** is the most widely used type of final control element and it must perform satisfactorily with a minimum amount of maintenance attention, even in severe conditions of temperature, pressure, corrosion and contamination.
- A control valve functions as ***variable resistance*** in a pipeline. It provides a pressure drop, called ***throttling***, which limits the flow through a pipeline.

There are many different kinds of control valves in common use:
- globe valves,
- butterfly valves,
- ball valves,
- eccentric disc valves and
- diaphragm valves

Globe Valve

- Globe valves are the most frequently encountered control valves in process plants. Figure 1 shows the side view of a ***typical globe valve***, which is named after its globular shaped valve body.

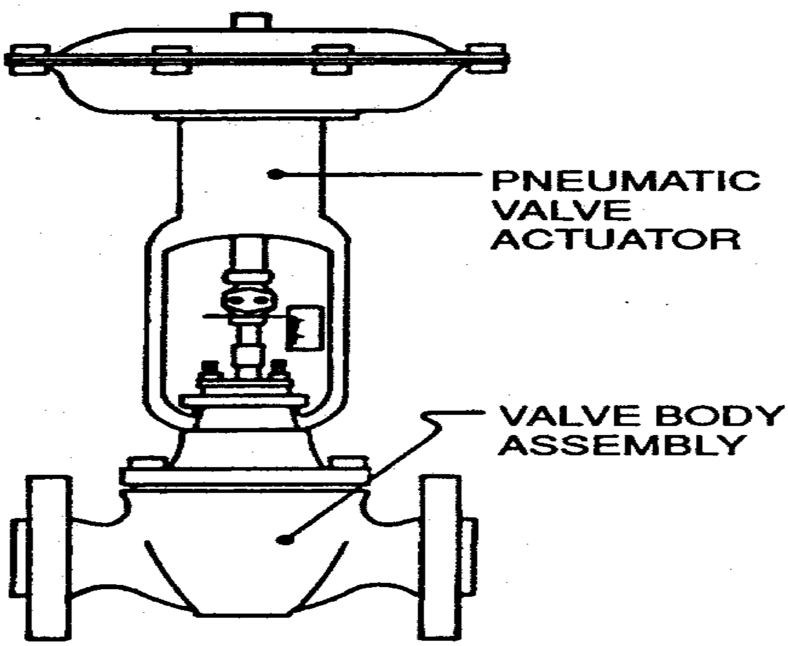


Figure 1: A Typical Globe Valve.

- The globe valve consists of two main components:

1. *The* ***valve actuator*** which converts electrical or pressure energy into valve stem movement which creates the regulating effect of the valve body.
2. *The* ***valve body*** which contains and regulates the fluid flow.

Globe Valve Body

- The globe valve body itself is made up of the components shown in Figure 2.
- The ***bonnet assembly*** is the part of the valve body through which the valve plug stem moves.

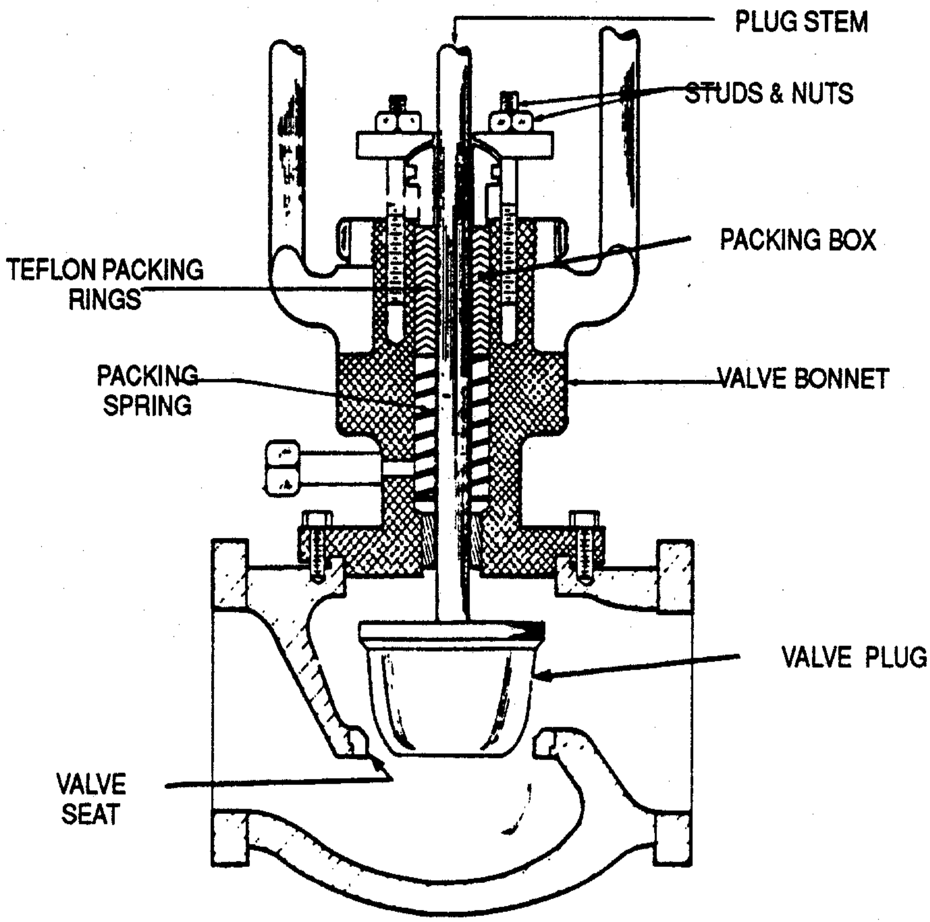
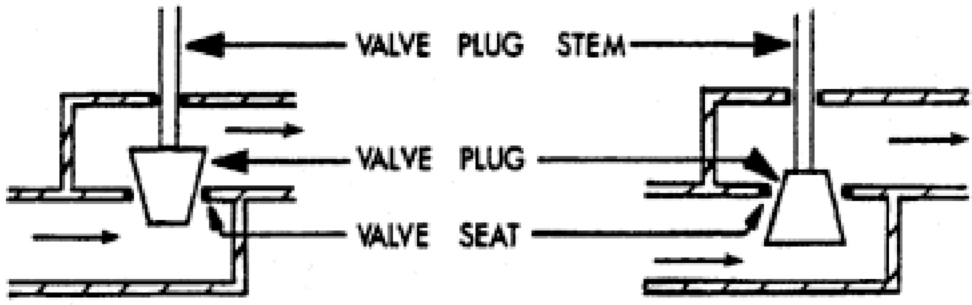


Figure 2: Cross-Sectional View of a Globe Valve

- The bonnet provides a means of ***sealing*** against leakage along the stem by using packing in the packing box. Force is exerted by the stud and nuts in the packing material to squeeze it against the walls of the packing box and the valve stem providing an effective seal.

- The ***valve stem*** extends through the bonnet to permit positioning of the ***valve plug***, and therefore provide a variable restriction to the fluid flow.

- Globe valve bodies can be classified as either ***direct*** or ***reverse acting***, as shown in Figure 3



a) Direct Acting (b) Reverse Acting

Figure 3: A Simplified Diagram Showing Control Valve Body Action.

- In a ***direct*** acting valve body, a downward movement of the valve plug stem results in the ***valve closing*** (Figure 3(a)).

- In a ***reverse*** acting valve body, a downward movement of the valve plug stem results in the ***valve opening*** (Figure 3(b)).

Valve Actuators

- A control valve actuator is a device which is used to drive the valve plug stem and therefore sets the position of the plug with respect to the valve seat.
- The most common valve actuator is the pneumatic diaphragm actuator. It is simple in construction and very reliable. It operates by the injection of a single, low pressure air signal into the diaphragm housing.
- A typical pneumatic diaphragm actuator is shown in Figure 4.

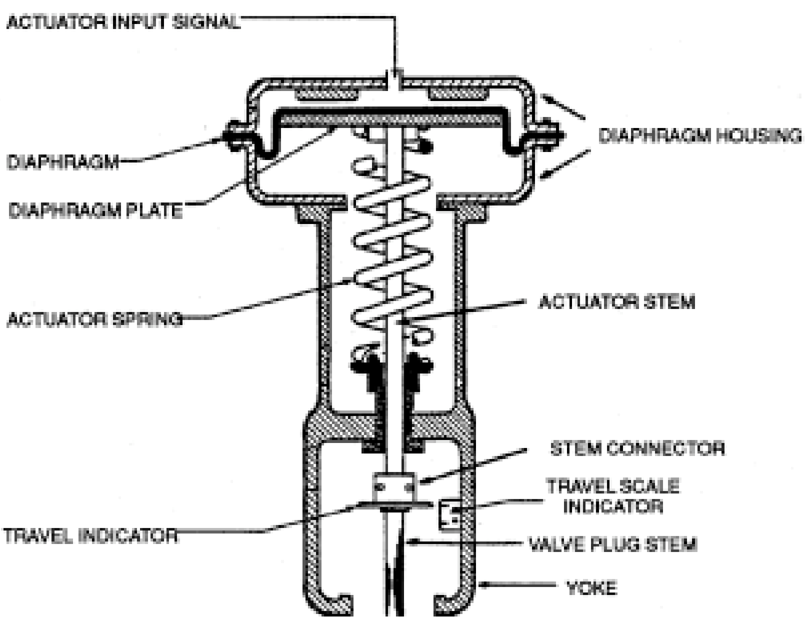


Figure 4: A Typical Pneumatic Diaphragm Actuator.

- The diaphragm housing is made up of two sections separated by a ***flexible diaphragm.***
- The air pressure applied on the diaphragm develops a ***working force***. This force is transmitted to the actuator stem via the diaphragm plate, which is a supportive metal disk attached to the diaphragm.
- The actuator spring provides a ***restoring force*** which positions and returns the actuator stem.
- The travel indicator (a pointer attached near the stem connector) indicates the valve travel on the indicator scale.
- The actuator is supported rigidly on the valve bonnet assembly by the ***yoke.***
- The actuator stem is connected by the ***stem connector*** to the valve plug stem.

ACTUATOR WORKING FORCE

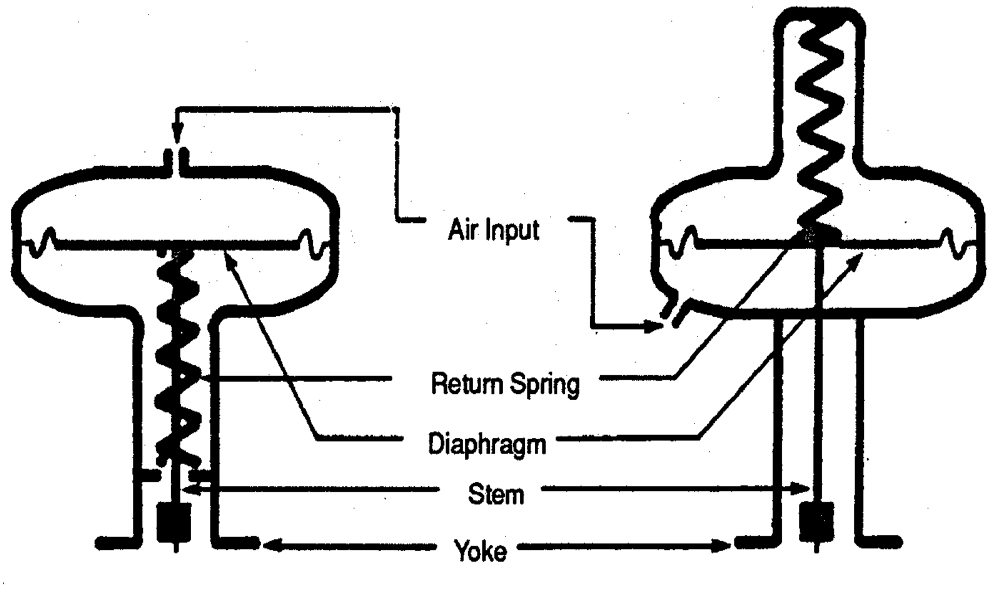
- The diameter of the diaphragm plate determines the force that will be applied to the actuator stem. For example, if the maximum input signal pressure is 100 kPa and the plate diameter is 30 cm, then:

Force applied to stem = **P**ressure x Plate **A**rea

= 100 kPa x 3.14 x $(0.15)^2$ m^2

= 7.07 KN (1590 lb)

- Although the signal pressure of 100 kPa seems to be fairly low, a substantial force can still be generated if the diaphragm diameter is large.
- Diaphragm actuators, as in the case of valve bodies, can be classified as either ***direct*** or ***reverse*** acting.
- A direct acting actuator will cause the actuator stem to be pushed downwards as a result of applying signal air to the top of the diaphragm (Figure 5(a)).
- The reverse acting actuator will push the actuator stem upwards as signal air is applied to the bottom of the diaphragm (Figure 5(b)).



(a) Direct Acting (b) Reverse Acting

Figure 5: Direct and Reverse Acting Actuators.

Valve Action

- Control valves can be assembled from various combinations of valve actuator and valve body.
- The combination of actuator and valve body is usually chosen to provide a particular *valve failure mode* should the compressed instrument air supply fail for any reason. The failure mode must be selected to suit the process requirements being controlled.

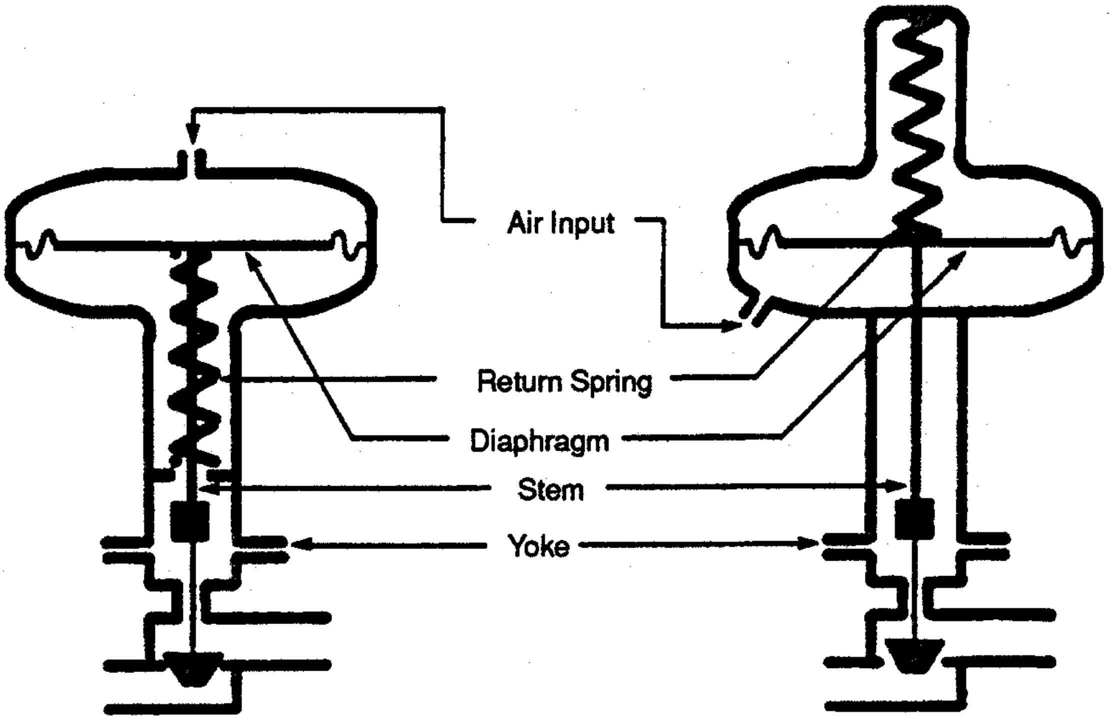


Figure 6(a)
Air to Close (A/C) Valve

Figure 6(b)
Air to Open (A/0) Valve

- Either failure mode can be obtained with a combination of direct or reverse acting ***actuator*** and direct or reverse acting ***valve body***.
- An ***air to close*** (A/C), and therefore ***fail open*** valve, can be obtained with the combination of a ***reverse*** acting actuator and a ***reverse acting*** valve body or a direct acting actuator and a direct acting valve body. (Figure 6(a)).
- Similarly, an ***air to open*** (A/O), and therefore ***fail close*** valve, can be obtained with a combination of ***direct*** actuator and ***reverse*** body or reverse actuator and direct body (Figure 6(b)).
- Note that often it is not possible to determine the over all action of a valve by observation alone. Reference to the valve nameplate or flowsheet identification is usually necessary for positive identification of the valve action.

Globe Valve Flow Characteristics

- The flow characteristic of a valve is the relationship between the flow capacity of the valve and the valve plug position.
- Flow capacity of a valve is the flowrate of the fluid through the valve under specified conditions.
- A standard method of defining a valve's flow capacity is to use the valve flow coefficient (CV).
- The valve flow coefficient is a function of flowrate of a specified fluid through the valve at a specified pressure drop across the valve (DP). (Usually expressed in U.S. gallons per minute at a DP of 1 psi, i.e., not S.I.)
- Mathematically, flowrate is related to valve coefficient (CV) and pressure drop across the valve (DP) by the equation:

$$Q = CV\sqrt{\Delta P / S}$$

where

Q = flowrate of the fluid
S = fluid specific gravity

Therefore $CV = Q\sqrt{S / \Delta P}$

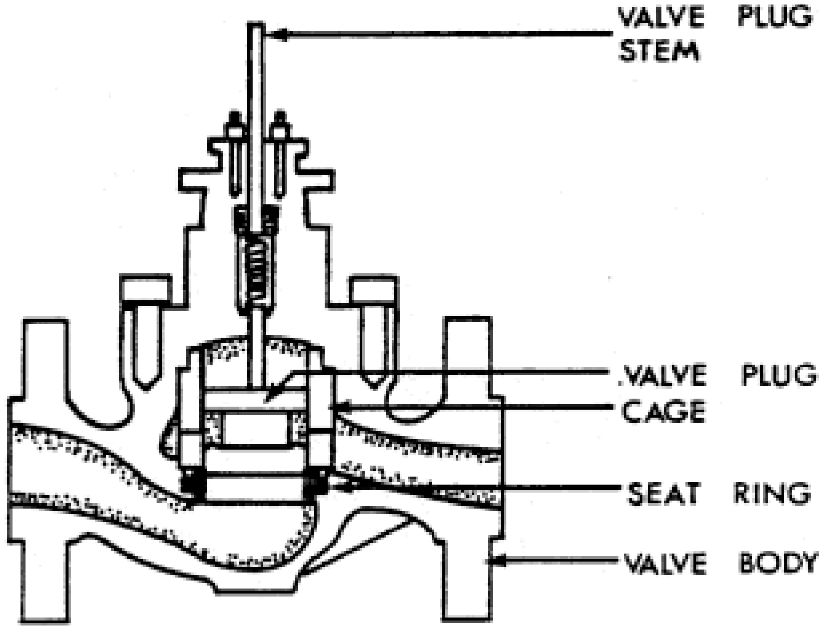


Figure 7: Valve Trim Components For a Globe Valve.

- The CV's of valves are determined experimentally by measuring the flowrate of the water (Q) when the pressure drop across the valve (DP) is 1 psi.
- CV's are often used to compare valves with each other. The valve with the higher CV will have a higher flow capacity.
- The most important ***valve trim component*** is the valve plug. The valve plug can be shaped to throttle the fluid flow with different flow characteristics.
- ***Valve flow characteristic*** curves are usually shown by plotting CV versus valve stem travel. The CV at each increment of stem travel is determined by measuring the fluid flowrate with a DP of 1 psi appearing across the valve.
- Flow characteristics fall into three major categories: ***quick opening, linear*** and ***equal percentage***.

Quick Opening Globe Valves

- A typical **quick opening** valve plug is shown in Figure 8(a).
- The plug is designed to provide full capacity with a very short stem travel.
- Figure 8(b) illustrates the relationship between valve travel and Cv of the quick opening valve.
- As shown in Figure 8(b), quick opening valve plugs achieve 80% of maximum Cv with only 50% valve travel.

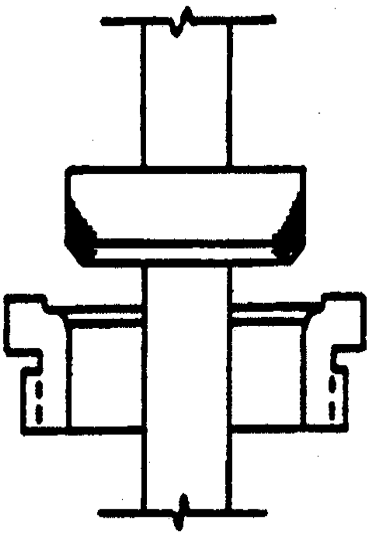


Figure 8a Quick **Opening Valve Plug**

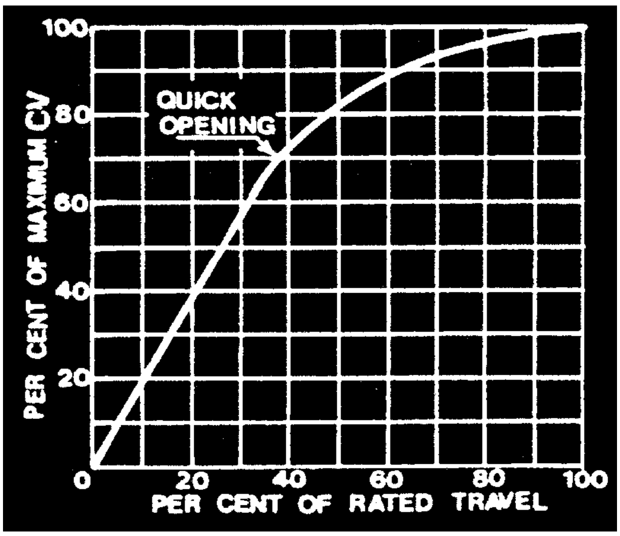


Figure 8(b **Flow Characteristic of Quick Opening Valves**

Quick opening valves - Application

- Quick opening valves are used primarily in an **ON/OFF** manner in situations where rapid responses are required.
- A typical application of quick opening valves in nuclear power plants is in shutdown systems where response time is critical. They are used in CANDU generating stations as poison injection valves.
- Shown in Figure 9 is the simplified **poison injection system** of a CANDU reactor shutdown system.
- The triplicated poison injection valve arrangement increases the reliability of the system.
- When a trip signal is received by the valves, they open to admit high pressure helium to the poison tank and therefore inject poison into the reactor.
- Total response time for the poison injection system is ***typically under 1.5 seconds***.

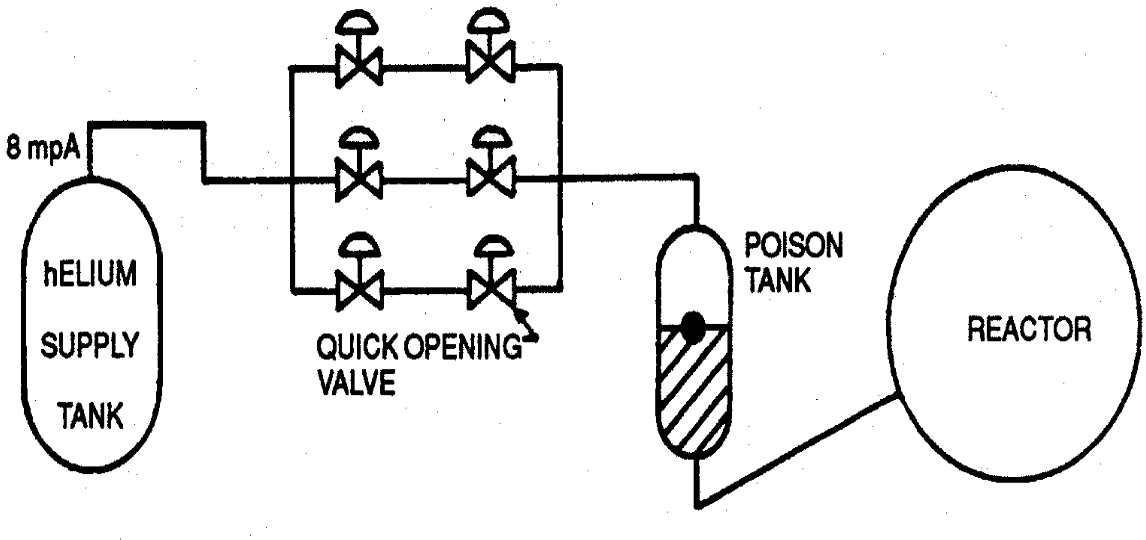


Figure 9: Simplified Poison Injection System for a CANDU reactor.

Linear Globe Valves

- A linear valve plug is designed to produce a linear relationship between valve travel and Cv.

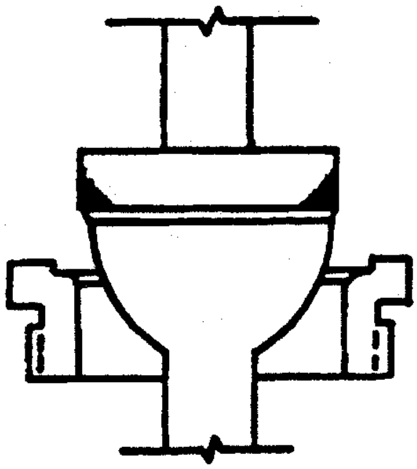


Figure 10(a)
A Typical Linear Valve Plug

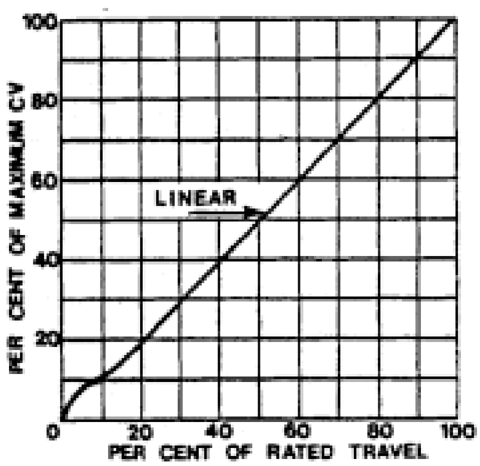


Figure 10(b)
Flow Characteristic of Linear Valve

- A typical linear valve plug is shown in Figure 10(a). Figure 10(b) shows the flow characteristic of a linear valve plug.

- To facilitate automatic control, a linear relationship between <u>flowrate</u> and <u>valve travel</u> is desirable. From Figure 10(b) it can be seen that for a linear valve plug, Cv and valve travel exhibit a linear relationship.
- Since flow rate (Q) is given as:

  $Q = Cv\sqrt{\Delta P / S}$

- If DP, which is the ***pressure drop across the valve***, *can be kept constant*, the flowrate will be linearly proportional to the valve travel.

LINEAR VALVE APPLICATION

- One application of a linear globe valve is in the primary heat transport (PHT) feed and bleed system for PHT pressure control.
- Linear globe valves are used as ***feed valves*** to throttle the discharge of the pressurizing pumps (Figure 11).
- The pressures at the discharge of the pressurizing pumps and the PHT system are fairly stable.
- Therefore the pressure drop across each valve is essentially constant. In this installation, the flow rate is linearly proportional to the valve travel.

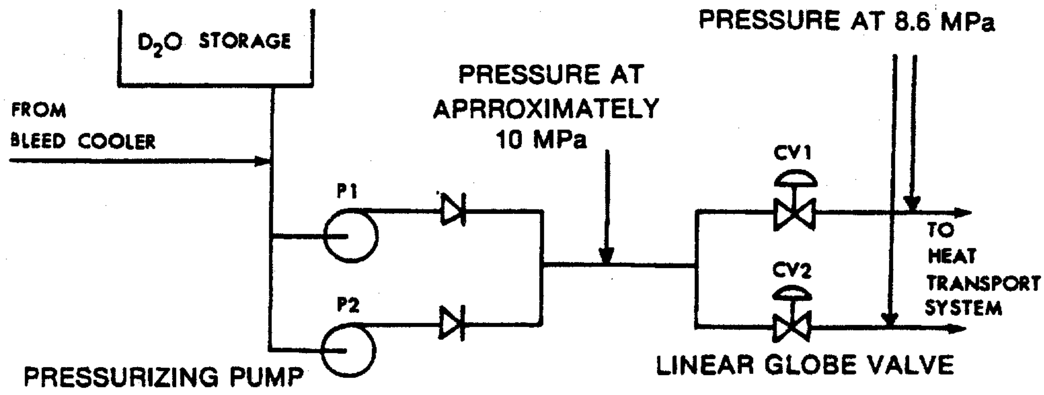


Figure 11 - PHT Linear valve installation

Equal Percentage Globe Valves

- An equal percentage valve gets its name because for equal increments in valve plug travel, the valve coefficient will change by the same predetermined percentage over its original value.

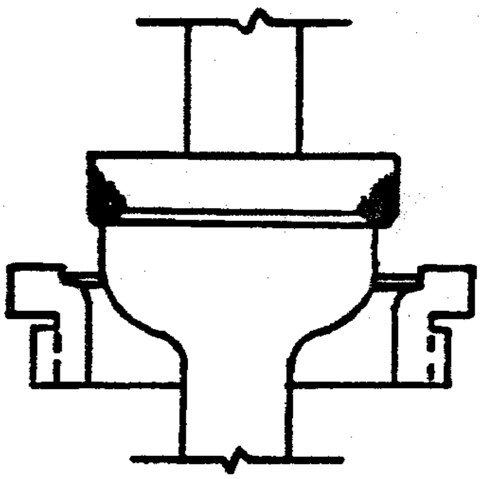


Figure 12(a): **A Typical Equal Percentage Valve Plug**

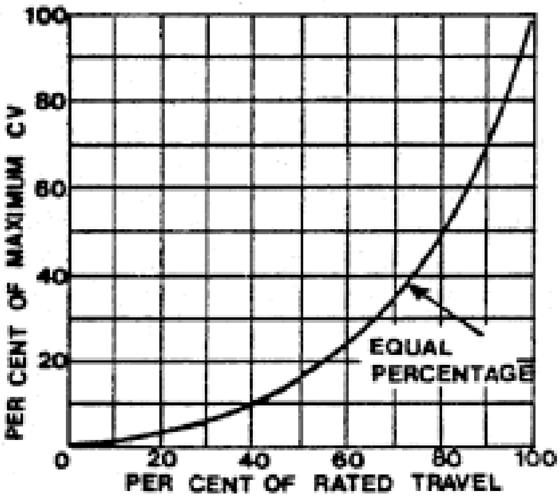


Figure 12(b): **Flow Characteristic of an Equal Percentage Valve**.

- For example, (refer to Figure 12(b)) if the valve plug position increases from 50% to 60% (an increase of 10%) the Cv increases from 17.5% to 25% (a 43% increase over 17.5%).
- For the same percentage (10%) increase in valve travel, say from 60% to 70%, the Cv increases from 25% to 36%, again a 43% increase when compared with the then initial Cv of 25%.
- Equal percentage valves are used in situations where there is a highly varying pressure drop (DP) across the valve.

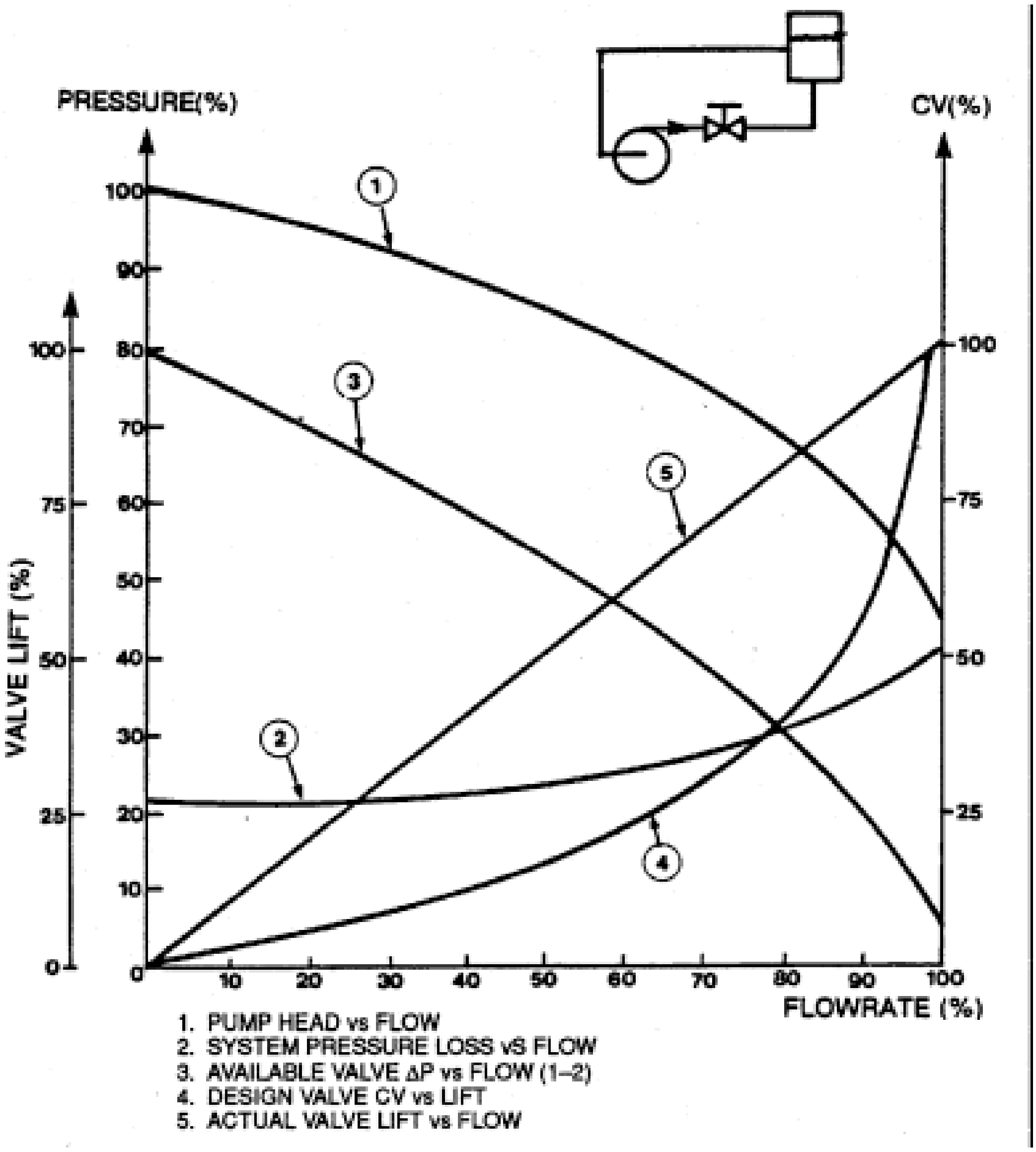


Figure 13 - Typical pump head curve with system losses

Pump Head vs System Loss Discussion

- Recall that for a typical centrifugal pump, pump head diminishes as flowrate increases. Also, as flowrate increases, system pressure, loss (static plus dynamic) increases.
- From Figure 13, it can be seen that the ***difference*** between the pump head curve (line 1) and system pressure loss (line 2) curve is the pressure (DP) that is allocated for the valve, (line 3).
- In this case, DP decreases rapidly as flowrate increases. Recall that flowrate across a valve is given by:

  $$Q = CV\sqrt{\Delta P / S}$$

- As DP decreases, the valve coefficient Cv has to increase drastically to compensate for the change in DP if a linear relationship between ***flowrate*** and ***valve travel*** is to be maintained.
- An equal percentage valve with flow characteristic as shown in line 4 is used for this purpose. The result is a Linear relationship between flowrate and valve lift as represented by line 5.
- An application of equal percentage valves in CANDU nuclear plants is for the control of light water flow into the ***Liquid Zone Control System*** (to obtain a relatively linear installed flow vs lift relationship). Figure 14 shows a simplified version of the system.

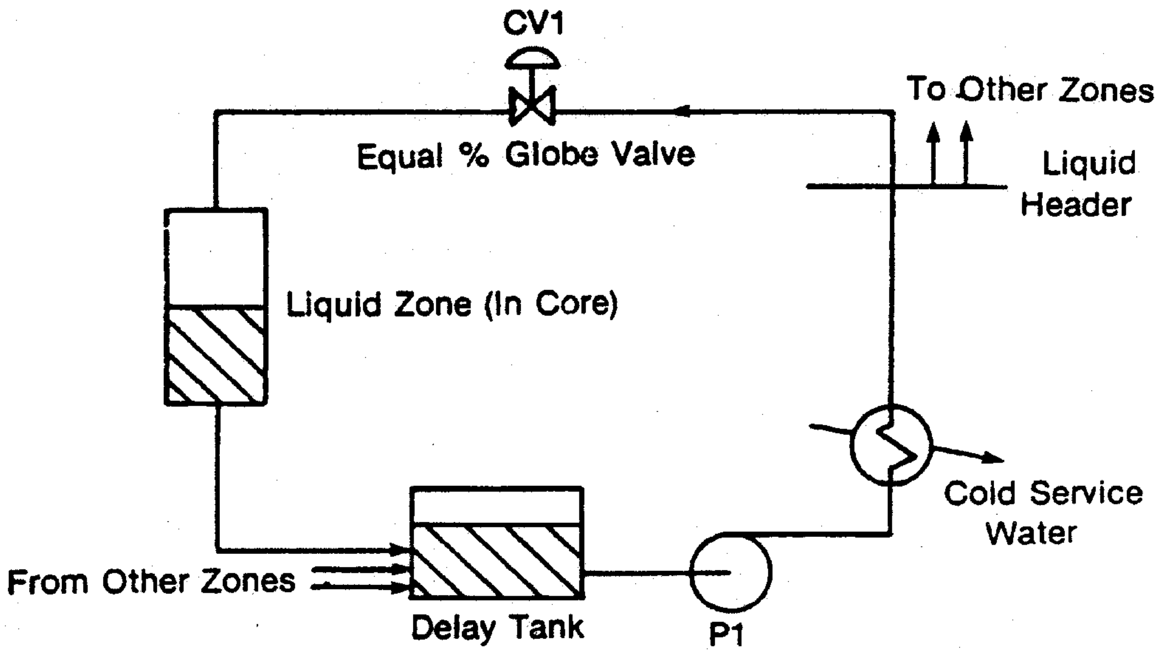


Figure 14: A Simplified Zone Level Control Circuit.

- In this system, the light water flow to the liquid zone is varied by valve CV1. The outflow from the liquid zone ***is kept constant***.
- In order to vary the water level in the zone, the inflow has to be increased or decreased.
- Valve CV1 has to control the inflow over the range 0.2 - 0.9 liters /sec. Because of this relatively large flow change, the system frictional (piping) losses will vary and be significant.
- In an attempt to linearize the installed flow characteristic, an equal percentage valve is used as CV1.

Bench Setting

- Assume that we have an **air-to-open** globe valve which consists of a direct acting actuator and a reverse acting valve body (Figure 15).

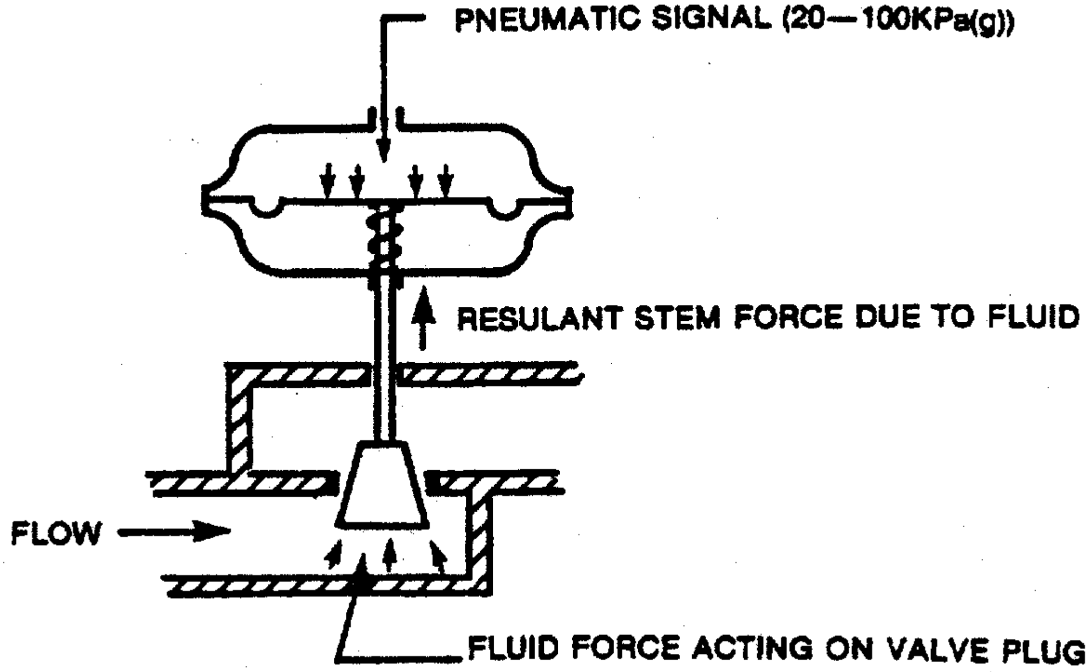


Figure 15: Air to Open Valve.

- The valve is usually calibrated (by adjusting the spring force) such that a 20 kPa signal applied to the actuator will cause the valve to be fully closed whereas a 100 kPa signal will cause it to be fully open.
- However, these settings do not take into account the pressure that is exerted by the process fluid on the valve plug when it is installed in a flow system.
- If the fluid pressure is high, the resultant force acting up on the valve plug will be able to offset part of the downward force exerted by the actuator.
- Assume the upward force exerted on the valve plug by the fluid is equivalent to the downward force generated by 10 kPa of the actuator pressure. When the signal pressure is 20 kPa, the net pressure effect on the diaphragm is only (20 - 10 kPa) 10 kPa. This will cause the valve to not start to open when the signal is 20 KPa - may have to go to 30 KPa to open
- Bench setting is the ***calibrating technique*** used to take into account the anticipated force exerted by the process fluid.
- For the air to open valve described above, bench setting would result in the valve spring being calibrated such that the valve is fully closed at 10 kPa and fully open at 90 kPa actuator pressure (with no line pressure present - on the bench, so it will be correct once installed).

Double-Ported Globe Valve

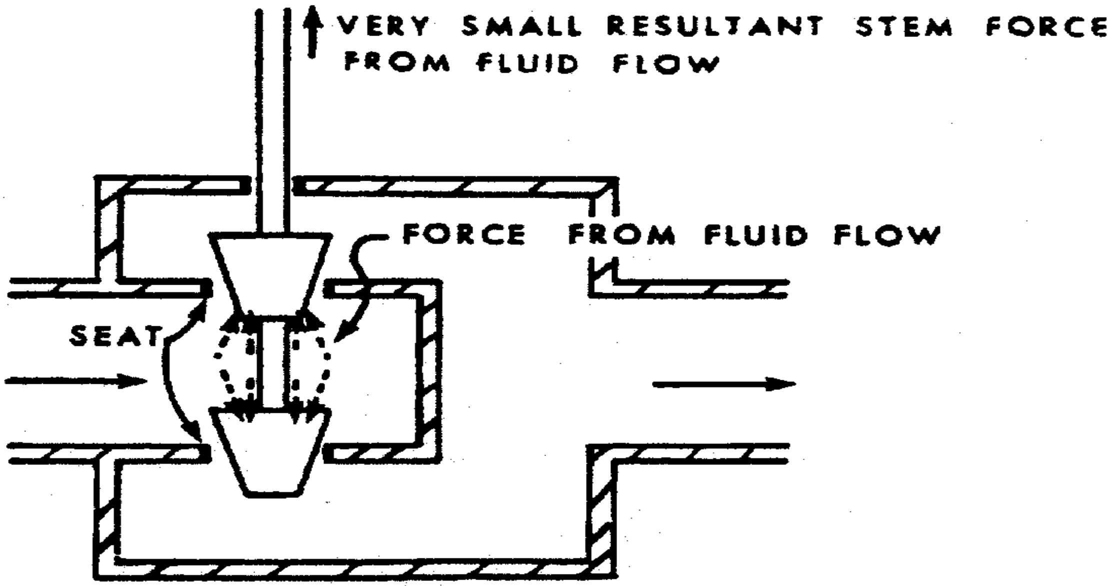


Figure 16: Double Seated Globe Valve.

- A globe valve can contain either one or two plugs. When there is only one plug, the valve is called ***single ported*** (refer to Figure 2 at the beginning of this module).
- When there are two plugs as shown in Figure 16, it is called a ***double-ported*** globe valve.
- The double-ported valve arrangement produces almost ***no unbalanced force*** on the valve stem.
- The fluid flows through the valve ports in opposite directions and therefore generates forces that offset each other.
- As a result, only a relatively ***small actuator force*** is needed for positioning the valve plugs.
- This makes the double-ported globe valve suitable for high pressure applications.
- In some CANDU plants, for example, double-ported globe valves are used to control feedwater flow to the boilers, where both pressure (7 MPa) and flowrate (250 kg/sec) are high.

Valve Positioners

- Pneumatic valve positioners are the most commonly used valve accessories. A valve positioner is a device which will accurately position a control valve in accordance with the pneumatic control signal.
- The control signal is routed to the positioner where comparison of the valve ***position*** (actual) to the ***control signal*** (desired) is used to develop an output pneumatic signal which operates the valve actuator.

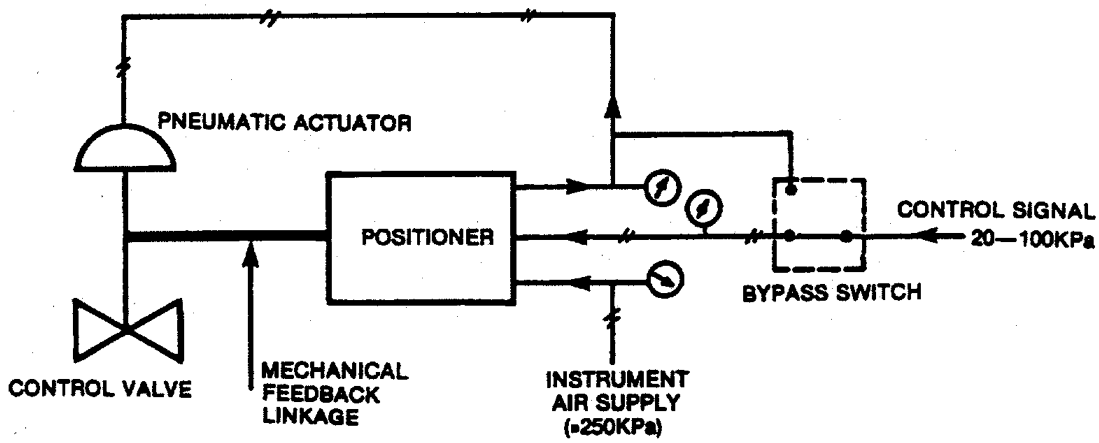


Figure 17: A Simplified Valve Positioner Installation.

- The positioner compares the control signal (the ***requested valve position***) with the actual valve position through the mechanical ***feedback*** linkage.
- If the valve position is incorrect, the positioner will either load or exhaust air from the valve actuator ***until the correct valve position is obtained.***
- A positioner requires both a ***control signal*** and an ***instrument supply air*** for normal operation. Most positioners come equipped with three gauges to indicate ***supply*** air pressure, ***control signal*** pressure and ***actuator diaphragm signal*** (output) air pressure,.

Advantages of the valve positioner include:

1. Minimizing the effect of ***friction, hysteresis*** and ***deadband*** on the valve stem. With a high pressure system, tighter valve stem packing is needed to prevent leakage and a high frictional force is generated. With a positioner valve stem movements of as little as 25 μm are possible.

2. Enables signal range change. A positioner can ***amplify*** the incoming control signal when a greater actuating force is needed. A 20-100 kPa control signal can be amplified to 40-200 kPa before being applied to the actuator.

3. Allows ***signal reversal***. A positioner can operate in either direct or reverse acting mode. For example, in reverse acting mode, an increase in control signal pressure causes a decrease in positioner output air pressure. For example, in reverse mode, a 100 - 20 kPa actuator signal would correspond to a 20 - 100 kPa control signal from the I/P transducer.

4. Increases the ***speed of response*** of the actuator. The speed of response of the valve actuator depends on:

   (a) the actuator volume, and

   (b) the flowrate of the control signal air.

   The positioner has a larger volumetric output capacity than other pneumatic devices, say an I/P transducer (typically 40 - 50 cfm vs 4 - 5 cfm). With a positioner, quicker fill of the actuator and therefore faster valve speed of response can be achieved.

5. Allows ***valve flow characteristic*** to be changed. Most valve positioners employ a rotating ***cam in the feedback*** system. This cam can be changed to simulate different valve flow characteristics.

   A linear globe valve can be used to respond in an equal percentage manner.

6. Allows ***split range*** operation. In a split range control loop, one controller is used to drive two control valves.

SPLIT-RANGE CONTROL

- An example of a split-range control loop is the wide range heat transport (PHT) pressure control loop as shown in Figure 18. In this system, both valves use the same 4 - 20 mA signal from the controller.
- The feed valve is A/C and the bleed valve is A/O. (Note the different range of signal the feed and bleed valve responds to.)
- Under normal conditions, i.e., PHT pressure constant, both valves are closed, i.e., signal at 63% for both valves).
- If the pressure in the PHT system starts to increase, the PT will send an increasing signal to the controller. This results in an increasing control signal applied to both the bleed and the feed valve. The bleed valve will open more (with the feed valve closed), removing more D_2O from the PHT system, while the feed valve stays closed. The net result is the pressure in PHT system remains constant.
- The opposite occurs if the pressure decreases, i.e., decreasing signal to both valves - feed increases while bleed decreases.

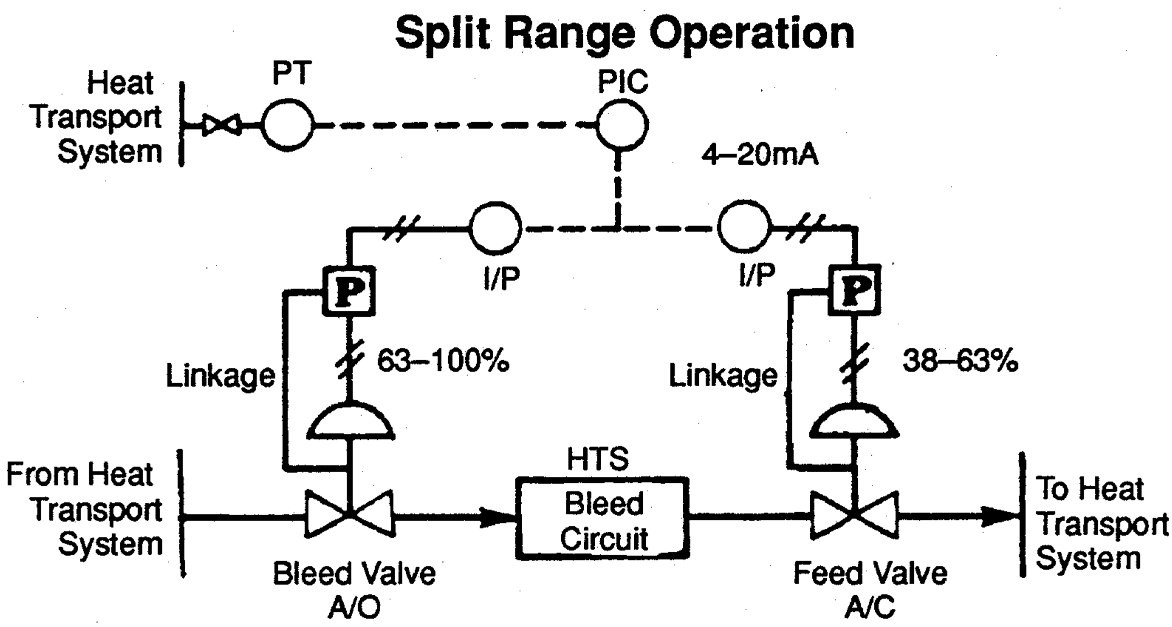


Figure 18: Split Range Control Loop for PHT Feed and Bleed Pressure Control.

Solenoid Valves

- A solenoid valve is an ***electrically operated valve*** where an electromagnet is used as an actuator to change the valve state.
- Solenoid valves are used only in an ***ON/OFF*** manner. In a two-way solenoid valve (shown in Figure 27), the valve is open when the solenoid coil is energized.
- The energized solenoid coil acts as an electromagnet which pulls the plunger and the valve disc upwards.
- The valve is closed when the coil is de-energized.
- The closing action of the valve is achieved by the weight of the plunger, valve stem and disc. Once the disc comes close to its seat, flow (from left hand side) will ***snap*** the valve tightly shut.

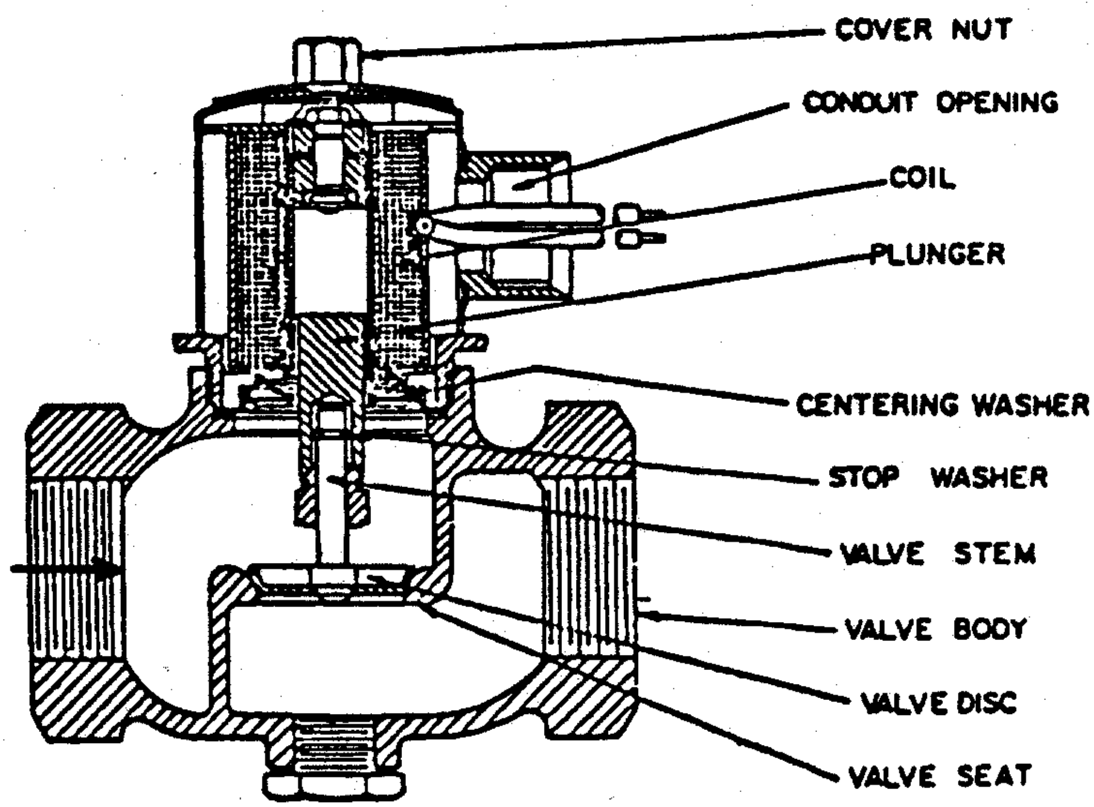


Figure 23: A Two-Way Solenoid Valve.

THREE WAY SOLENOID VALVE

- In a three-way solenoid valve, as illustrated in Figure 24, energizing the solenoid coil causes the valve to open from ***Port 1 to Port 2*** while de-energizing the coil causes the valve to open from ***Port 2 to 3***.

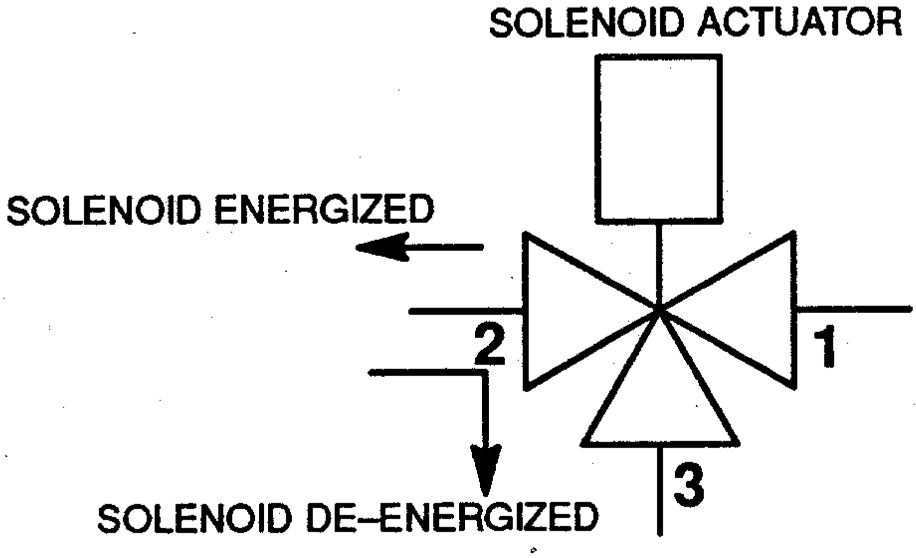


Figure 24: A Three-Way Solenoid Valve.

- A solenoid valve is often used in conjunction with a pneumatically actuated diaphragm control valve to obtain ON/OFF valve operation by an electrically applied signal.

- This arrangement, depending on the valve size, may be much more reliable, more powerful, less expensive and faster responding than using an all electric control valve.

Three Way Solenoid Valve Application

- Figure 25 shows an ON/OFF application of a three-way solenoid valve used to operate an air-to-open (A/0) pneumatically actuated control valve.

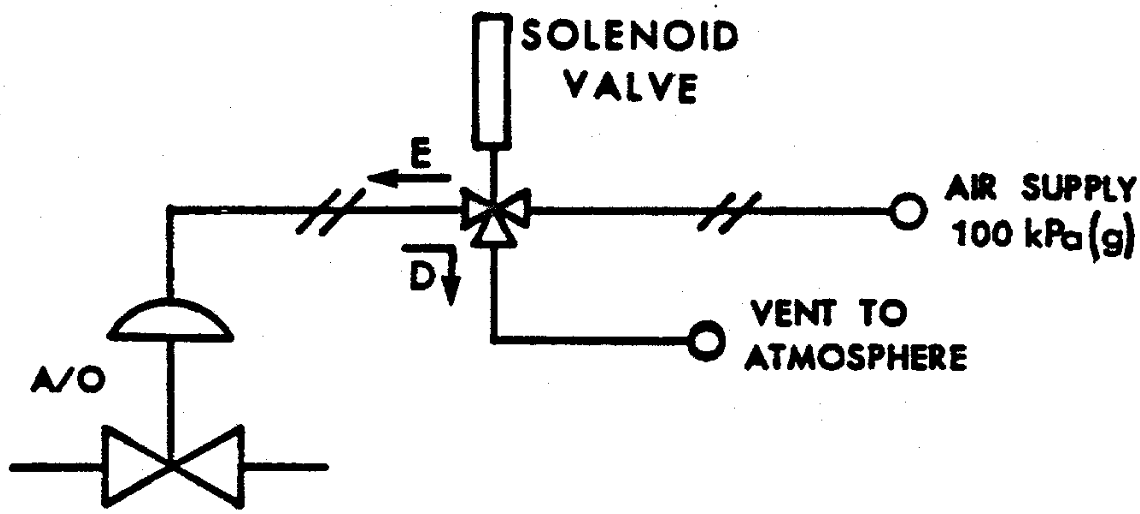


Figure 25: ON/OFF Application of a Solenoid Valve.

- When the solenoid valve is energized, 100 kPa(g) is applied to the A/O valve, keeping it fully open – note that this could be a pneumatic control signal rather than a fixed supply.

- When the solenoid valve is de-energized, the air supply (100 kPa(g)) is cut off, and simultaneously the pressure trapped in the control valve actuator is vented to atmosphere.

- So when the solenoid is de-energized, the A/O valve will drive fully closed under actuator spring action.

Use of Different Sized Valves in Parallel

- Many industrial processes have a large range of controlled flow requirements between 0-100% of the controllable range.
- Boiler level control is a typical example. The feed flow to the boiler must be adjusted from 0-325 Kg/sec to maintain boiler level at the setpoint over the entire range of possible steam flows i.e., feedwater and steam flows must always be in mass balance.
- The volume of feedwater required at full power conditions is large typically hundreds of kilograms per second of feedwater per boiler - and necessitates the use of a large Cv valve to meet the Cv flow requirements (10" or 25 cm is typical).
- If just one valve, capable of meeting the 100% requirement, was used, then control at low power (low flow) levels would be imprecise – the large valve would likely over correct or under correct when just opened a small amount.
- To overcome this disadvantage, two valves are provided, one with 100% capability and another with approximately 20% capability, in parallel to the larger valve.
- The operation of this type of system requires the smaller valve to open toward its maximum whilst the larger valve remains closed. As the small valve reaches approximately 75% opening, the large valve opens to begin to take up the flow.

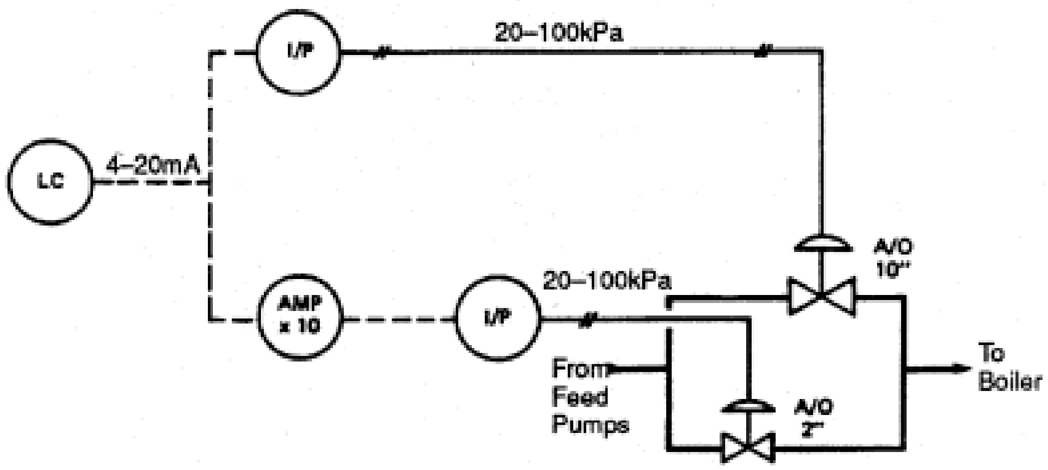


Figure 26. Typical Large/Small Control Valve Installation

MODULE 7: Control Valves and Accessories ASSIGNMENT

1. State the combinations of pneumatic actuator and globe valve body required to provide:
   a) ***air to open*** action;
   b) ***air to close*** action.
2. State and sketch the *three flow characteristics* for the most common globe valves.
3. State a typical application for each of the three flow characteristics and explain why it is the most appropriate selection for that application.
4. State the effect of ***unbalanced force*** on valve position and explain with an example, how bench setting would correct this problem.
5. Briefly explain at least three advantages a ***positioner*** gives when it is used in conjunction with a control valve.
6. Describe the ***fail state*** for a given valve.
7. Sketch and describe a ***system pump head vs flow curve*** set to define installed valve differential conditions.
8. Explain, with a diagram, how a ***three-way solenoid*** valve can be used for ON/OFF control of a pneumatic valve.
9. State the formula which describes a control valve Cv factor. What is the Cv for a valve which will pass a water flow of 100 USGPM with a pressure drop of 25 psi? What flow would this valve pass when the pressure drop is 49 psi?
10. State why it is often advisable to use different sized valves in parallel when the process variable has a very large flow range.