INTRODUCTION TO CONTROL AND INSTRUMENTATION

INTRODUCTION TO CONTROL AND INSTRUMENTATION
A SunCam online continuing education course

INTRODUCTION

This course will present the following areas of control and instrumentation:

1) Control Loop definition, elements, and types
2) Study of elements of the control Loop:
    a) Set point, controllers, and amplifiers
    b) Sensors and transducers
    c) Instrument and measurements
    d) Motors, valves, and actuators
    e) Final Control Elements
        i) Electrical such as heaters, generators, etc.
        ii) Mechanical such as valves, levers, etc
3) Review of processes
    a) Physical aspect – response features
    b) Control Features – speed, inertia, etc.
4) Control Devices using:
    a) Analog
    b) Digital
5) Basic of motor controls
6) Control circuit diagrams
7) Common commercially available controllers

Instrumentation and control is the nervous system of industrial complexes, power generation, and basically all the processes that require some intelligence to accomplish the task of producing a product or process.

When a process is modified to improve its function, usually the best and most economic change of the system is to improve the control and sometimes instrumentation areas. Quality, quantity, and efficiency are directly related to the control and instrumentation systems. In a process, the efficiency of the controls reflects directly in the profitability and quality of the product or service obtained from a process or system.

Some examples of other benefits obtained by applying control systems are evident in environmental controls, which help to manage the waste and regulate the interface between the system and the environment. One application in this area is seen in control of emissions which use specialized instruments and controls to decrease the impact of pollutants in the atmosphere.

The growth of the computer industry and its techniques has provided an ever expanding technology in the controls area that consequently produces more efficient and sophisticated systems. These systems now can control more precisely the production of goods and the information given to the operators to refine the quality of products and services.

This course will walk you through the elements that make a control system and present to you the most common instrumentation used in industry.

Definitions

Instrumentation:

Is the use of technology and devices to detect and control physical and chemical characteristics of materials; this includes motion, light, color, acidity, etc.

Control System

Is the system that takes the information from instruments of a process or system and manipulates it using logic (algorithms) and then applies the results to a process or system to change its characteristics.

Process Control

It is the Control system that is used in the process and chemical industries. A process control has the characteristic of automatically regulating a process. Automatic in this context means that the process is controlled without the need of human intervention.

Variables

They are defined as the characteristic of the process. Some variables are temperature, speed, humidity, viscosity, density, etc. There are two basic types of variables: measured or controlled, and manipulated.

Control Loop

Control loop is a control system architecture that will manage a process using elements that sense, adjust, and act upon the process. We also can define it as the configuration by which the control system manipulates the control parameters.
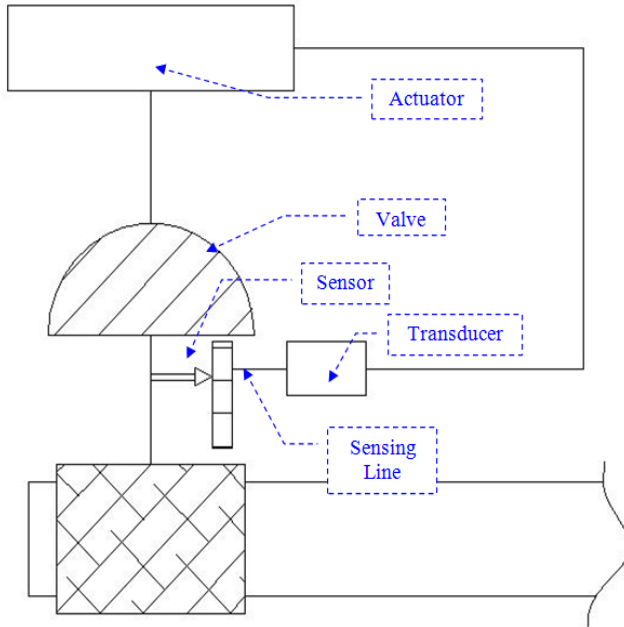
Figure 1 – Control Loop for a Valve Control

CONTROL LOOP DESCRIPTION, ELEMENTS AND TYPES

Open Loop

The control loop configuration could be **open**, like in the control of a valve to open. The controller receives the signal to open the valve and it does. That operation is completed without additional action. The loop is open because it starts at the open command and ends at the valve opening. It is known as an open ended control.

Closed Loop

A **closed loop** defines the action of sending a signal to a modulating valve to open it half way; the controller applies the open signal until the valve reaches the half way point. The position of the valve is determined by an instrument that detects the position and sends the signal back to the controller to close the loop. The loop is made from the controller to the valve actuator to the position device to the controller. See Figure 1 for a closed loop control.

Comparison between Closed and Open Loops

| Open Loop	Closed Loop
A measurement is detected	A measurement is detected
Monitoring is performed (usually manually)	Measurement is compared to a set value
No adjustment is made	Adjustment is made to the process
Return to measurement	Return to measurement, repeating the adjustment until the set value and measurement are equal.
EXAMPLES	
A conveyor belt carrying material	*Tank level control*
A measurement is made (scale)	A level sensor feeds measurement to a transducer
Monitoring is performed by an alarm bell	A comparison is made to set point at the controller
Reporting: Activation of alarm is made if weight is exceeded	Action: If level is low a signal is sent to an inlet valve to open. If level is high or equal to the set point a signal is set to inlet valve to close

Table 1 – Open and Close Loop Examples
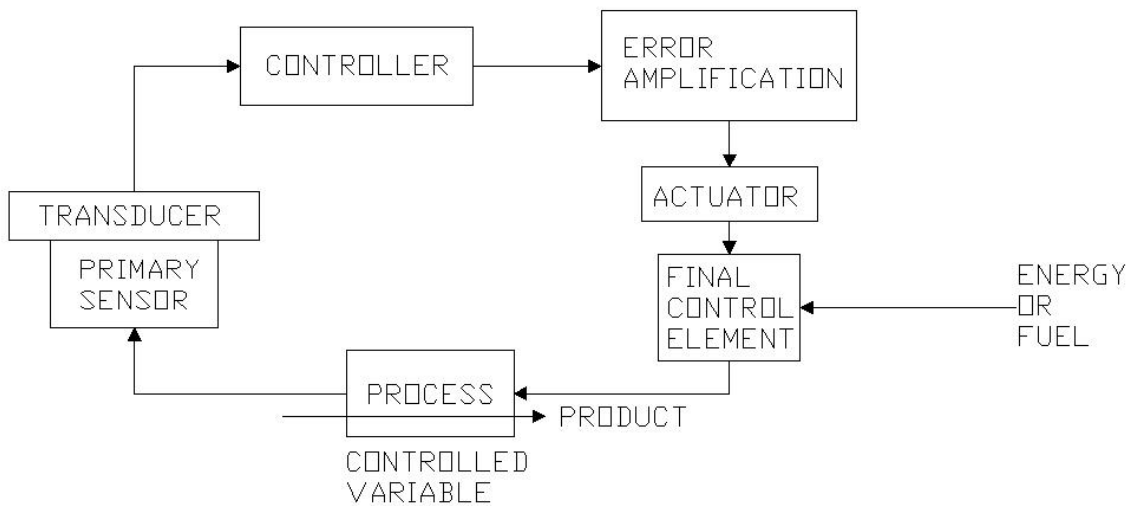
Figure 2 - Closed Loop diagram and components

Elements of a Control Loop

Process:
The controlled system is called the process. It could be defined as a conditioned situation that produces results that must be kept under an expected value or range of values. As you can see in Figure 2, the process is the area that has the product. Product in this case could be taken as a material, fluid, or whatever is produced, manufactured, or treated.

Primary Sensor

The primary sensor is normally an instrument that has properties to detect the physical property desired to be measured. An example is a thermocouple which produces a change in an electrical circuit proportional to the temperature; this signal is sent to a transducer to be detected and interpreted.

Transducer

This device translates the signal from the sensor normally into a processed electric signal that can be amplified and used by the controller.

Set Point

This is a fixed value that is contained in the controller. This value is set by the operator or by an intelligent algorithm or device. This value is compared to the measured value from the transducer. The difference of this comparison is called the **Error.**

Controller:

The controller is normally an electrical or electronic device that has the following functions:
- Compares the sensing signal from the transducer to the Set point (at the summation point)
- Produces an Error signal from the comparison
- Processes the error signal:
    - To convert it into a actuation signal
    - To manipulate it in order to condition it according to an algorithm, this algorithm will make it:
        - proportional to the error
        - as a function signal that anticipate changes
        - as a function signal that uses history of changes to apply the correction
        - as a function signal with a combination of the above features.

The manipulation of the error signal is processed by a mathematical operator called a control algorithm. An example of an algorithm is the PID or Proportional, Integral, Derivative algorithm. This Algorithm uses:

- the mathematical constant K or proportional multiplier actuates the final control element in a linear proportional way to the value of the error
- the integral operator to produce an actuator signal following a value based on the history of the previous errors
- the derivative operator to produce an actuator signal that which value anticipates the next change and is based on the slope of the error function

Other algorithms are available easily today in the controllers; an example could be the rate-lag operator which uses a combination of PID elements.

Amplifier

The amplifier increases the intensity of the signal until it is large enough to be able to be used by the actuator.

Actuator

The actuator is an electromechanical device that takes the actuation signal and converts it into motion following the actuation signal. This motion could be a position as in the case of a solenoid valve, on or off, or a motion, as in the positioning of a modulating or control valve.

Final Control Element

This component is the element upon which the actuator operates. This device is in contact with the process itself.
An example would be a valve which closes or opens as operated by the actuator and controls in such way the flow of a process, liquid, or gas.

PRIMARY SENSORS

Primary sensors detect the variable to be measured. The following sensing instruments will be presented on this part of the course:

- Pressure
- Temperature
- Level
- Flow

Instrument Characteristics

The following table presents the most important general characteristics of instruments and their generally accepted definitions

Characteristics	
Static	*Dynamic*
Applicable to variables that are not changing	Apply when variables are changing
Accuracy: Is the instrument characteristic or capability to present the real or actual measured variable If applied to a control system: it is the capability of the control system to maintain the actual measured value during the control process *Static error*: The difference between the actual or true value and the measured or indicated value Static error in a control system refers to the deviation from the desired control value contributed by the control system	*Fidelity* It is the capability of the instrument to correctly indicate or record a change in a measured variable For a control system it is the ability of the controller to follow the changes in the input variable with the correct output signal *Dynamic error* is the deviation of the controller output from its correct value
Reproductivity The ability of the instrument to produce identical values of the same measured variable when the measured value is the same under the same previous conditions A displacement from the same previous value is called *drift*	*Responsiveness* It is characteristic of the instrument to follow variable changes *Measuring lag* It is the measured inability of the instrument to follow a variable change The measured duration of this lag is called *dead time*

Characteristics	
Static	*Dynamic*
Sensitivity Is the magnitude of the smallest value that an instrument can measure or detect *Dead Zone* In instrumentation is the range where the instrument can not detect For control systems it is the area of control where the system can not respond	

PRESSURE

Definition

Pressure is a physical function of force and surface. The mathematical definition of pressure is F/A where F is force and A is area.
Mathematically:

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

Force is an action that causes distortion or movement.
Surface is a section of the two dimensional presentation of space.

Other expressions of pressure:

Hydraulic pressure in a press or tank: It can be expressed in water column height, mercury column height, psi, etc. This pressure is due to the weight of the mass of water plus the weight of the mass of air on the water surface. It has been found that the pressure of a liquid can be expressed as a function of the height of the column of liquid.

These expressions of pressure are based on experimental observations as well as calculations and deductions using physical laws. The equivalence of these measurements can be also done using dimensional analysis.

To demonstrate the above concepts we can use the case of the column of water pressure measurement.

See Figure 3 for reference to the following calculations.

One of the characteristics of matter is density. It is defined by the ratio between mass and volume that it occupies. Water density has been given the value of 1.
The relation that expresses density is:

$$\rho = \frac{Mass}{Volume} = 1 \text{ for water}$$

For specific density we can replace mass by weight and the equation becomes:

$$sd = \frac{Weight}{Volume} = 1 \text{ for water}$$

$$weight = sd\,(Volume)$$

$$P = \frac{F}{A} = \frac{Weight}{A} = \frac{sd\,(Volume)}{A}$$

But Volume = Area times height or

$$P = \frac{sd\,(Ah)}{A} = (sd)\,h, \text{ since for water sd} = 1$$

P = h   for water.

The pressure section AB of water in the tube in Figure 3 can be expressed by the distance between A and B. For another fluid the equivalence between density and specific has to be included in the relationship.
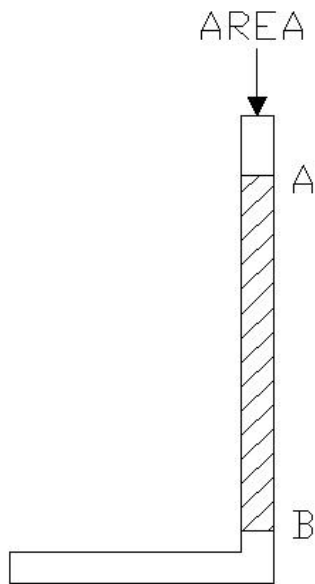

Figure 3 – Pressure vessel

Atmospheric Pressure

The column of atmospheric air has weight. Air applies pressure everywhere on earth that is exposed to the atmosphere. Because pressure depends on the height of column of fluid, atmospheric pressure is smaller at higher altitudes. This property is the basis of earlier altitude instruments. Also, water will boil using less heat at a higher altitude. Water will boil at a lower temperature in Mexico City than in New York City.
To measure atmospheric pressure:

- Fill a bottom sealed tube with mercury
- Seal the other end of the tube with your finger
- Turn the tube upside down
- Submerge the end sealed with the finger inside a tank containing mercury
- Let go of the finger as soon as the tube is vertical position

Gauge, Absolute and Differential Pressure

Pressure also can be expressed as gauge, differential and absolute pressure. **Gauge pressure** is the pressure that results of subtracting the atmospheric pressure from the pressure true value or Absolute Pressure. **Absolute pressure** is the true pressure measuring it in reference to zero pressure or vacuum. **Differential pressure** is the pressure of a system compared to the pressure of another system.

Other pressure units

Pascal:
The Pascal is the SI (The International System of Units, abbreviated SI from the French Le Système International d'Unitéspressure measurement).
The dimensional analysis is:

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

Force is given in newton and the area in square meter or a pascal is equal to 1 newton force per square meter area.
Pascal is used in metrology normally using its hundred times or hectopascal.
1 hectopascal or hpa is equal to 100 pascal or 100 pa. As a physics remainder: 1 newton is the force that accelerates the mass of one kilogram to one meter per second.

When the height of the column of mercury is measured, the value in inches is 29.9 in at sea level. This pressure is indicated as 29.9 in of mercury.

These units are equivalent to 14.7 psi or pounds per square inch = 1 atmosphere (atm) = 101.3 kPa (kilopascals) = 14.7 psi (pounds per square inch) = 760 torr.

Pressure Sensors

Instrument	Description	Application
Manometer	It is a U tube that contains a liquid. Levels at both sides are equal. One end of the tube is then closed; the other end is left open. The pressure to be measured is applied to the open end. The level will rise on the closed end and it will sink in the open end. The pressure is given by the difference in the levels.	• Measurement of pressure in liquid and gases • Blood pressure measurements. • See Figure 4
Bourdon-tube	• It is a mechanical instrument that senses pressure and converts it to displacement • The pressure indication is mechanically amplified using a pointer or indicator needle • The Bourdon-tube displacement is a function of the pressure applied • A set of two bourdon tubes mounted in one case is called a duplex gauge	• Many industrial applications for fluid and gas pressures • Hydraulic systems (hydraulic gauges) • Low-pressure Bourdon tubes (pressures up to 2000 psi) are often made of bronze. • High-pressure Bourdon tubes (pressures above 2000 psi) are made of stainless steel or other high-strength materials
Bellows Elastic Elements - Helical	• A bellows elastic element is a convoluted unit • It expands and contracts axially with changes in pressure. The pressure to be measured can be applied to either the outside or the inside of the bellows	• Used mostly for hydraulic fluid measurements. See Figure 5 - Bourdon Tube Manometer and Figure 6 - Helical Bourdon Pressure Instrument for its components

Instrument	Description	Application
Simple Bellows Element	• Bellows elastic elements are made of brass, bronze, stainless steel, beryllium-copper, or other metal • Motion of the element (bellows) is transmitted by suitable linkage and gears to a dial pointer. • Most bellows gauges are spring-loaded with a spring that opposes the bellows force and prevents full expansion of the bellows.	The principle used in this instrument can be used also to measure differential pressure. In this case there are two bellows chambers with mechanisms that subtract the two pressure produced movements.
Pressure Switches	In order to determine specific pressures, such as a high or low pressure, pressure switches are used to activate a signal that is sent to the monitoring and alarm systems.	Single pole single throw switches are frequently used for these applications. Electronic switches are also used in newer devices. See **Error! Reference source not found.**

Pressure Instrument Calibration

The calibration of a pressure instrument has been traditionally done using a method called the dead weight calibration.
A typical test set-up is shown in **Error! Reference source not found.**.
The setup works ion the following manner:

Step	Procedure
1	Load the measuring piston with calibrated weights
2	Add or retrieve load until the loaded measuring piston rises and appears to float on the fluid
3	Calculate the pressure using the formula $P = \dfrac{F}{A}$
4	Use the weights as the force and the area of the piston as the A

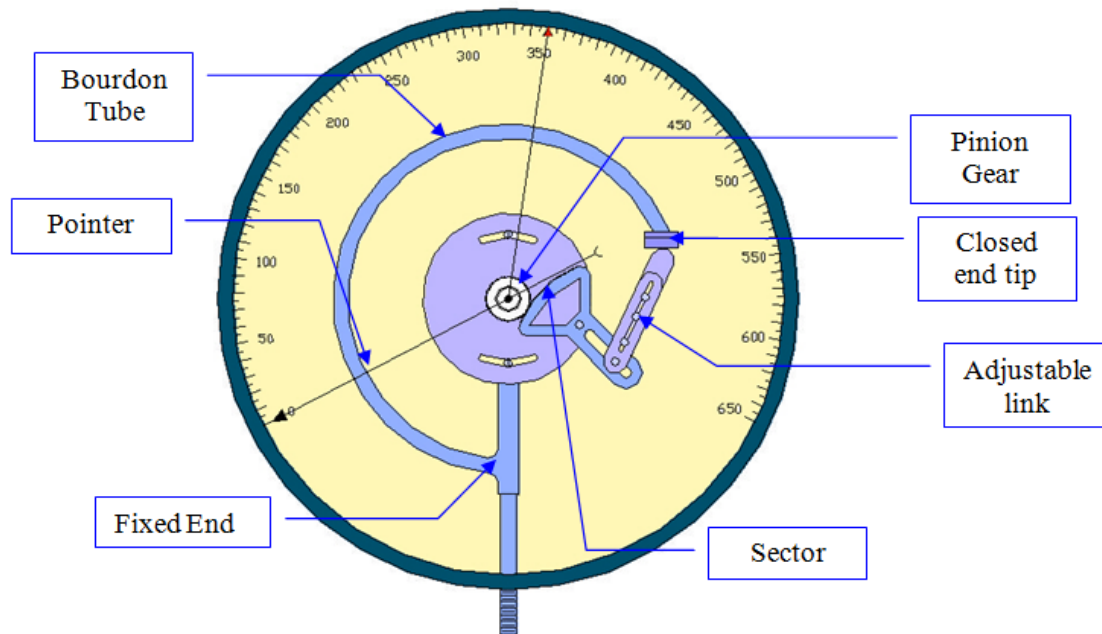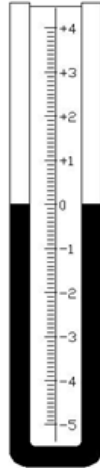## Pressure Instruments Figures

Figure 4 – U-Tube Manometer

Figure 5 - Bourdon Tube Manometer

Figure 6 - Helical Bourdon Pressure Instrument
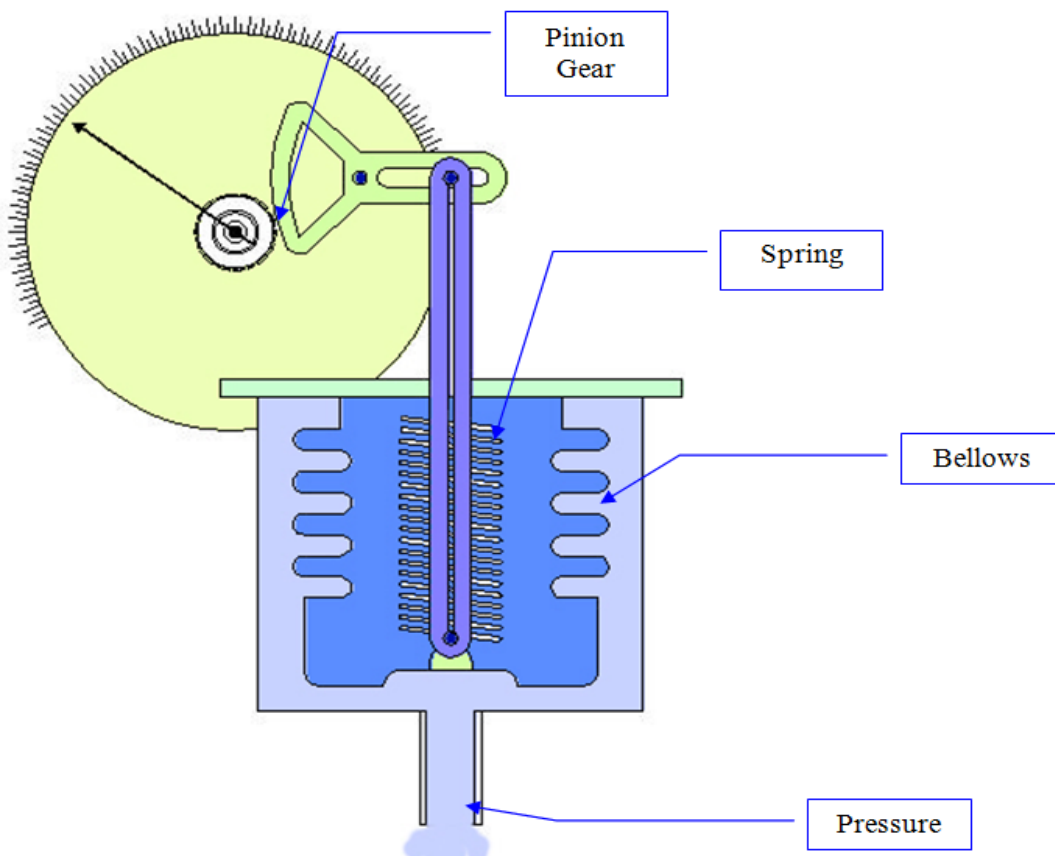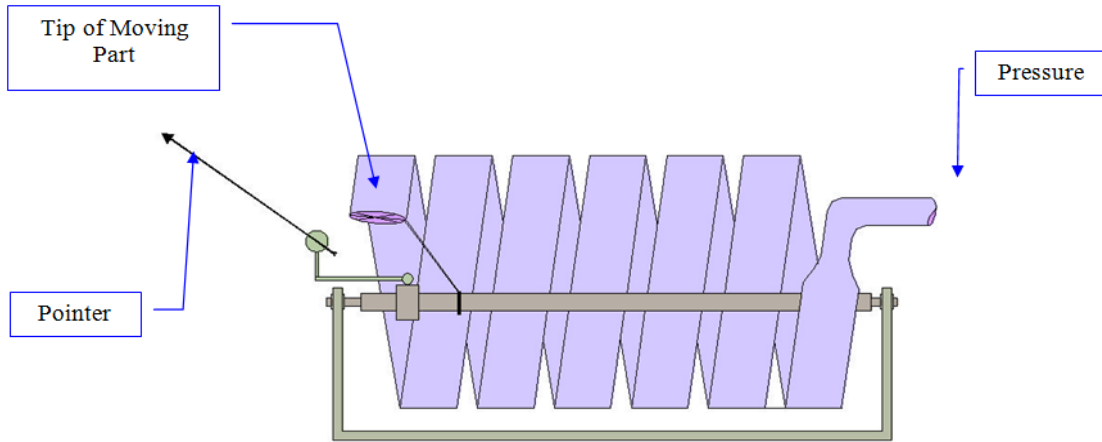
Figure 7 – Simple Bellows Gauge

Figure 8 - Pressure Switch Housing
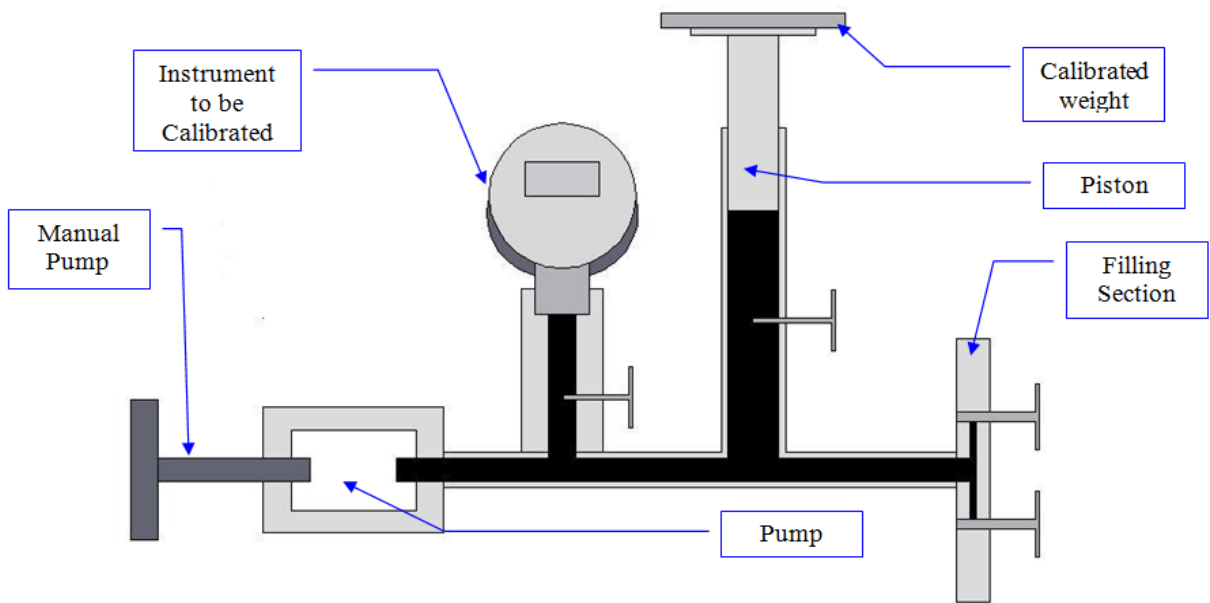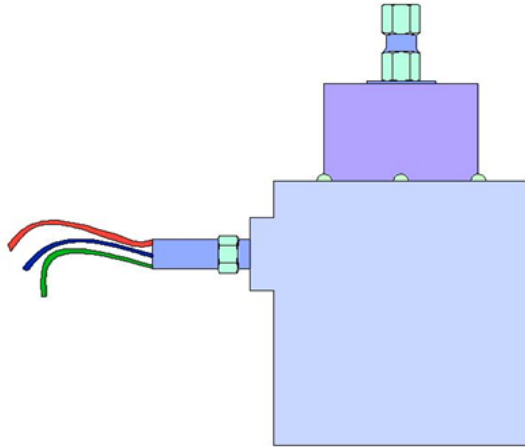
Figure 9 – Dead Weight test set up

TEMPERATURE

This section will present the basic concepts of temperature, its measurements, and techniques. Definitions and a small section of the physics of temperature will begin the section; later a presentation of the most commonly used temperature sensors and transducers will be outlined including reference material for practical engineering use.

Definitions

Temperature is defined as the degree of hotness or coldness that an element exhibits. This concept comes from practical evaluation of the thermal behavior of substances, most commonly water.

A most sophisticated definition would be: the measurement of temperature is the measurement of the average thermal energy per molecule contained in a material.

The unit used to describe the thermal energy per molecule of certain material is the degree of temperature. These units are normally arranged in a scale called the temperature scales.

An important place to calibrate a temperature scale is a point of equilibrium in the thermal point of a substance.

In water, there are several points of thermal equilibrium at a given pressure.

The most notable point for water is the point in which solid, liquid, and gas are at equilibrium (triple point). This point is given at normal atmospheric pressure of one atmosphere as the zero degree point for the Celsius thermal scale.

Another point of the scale calibration could be found at the point where liquid and gas water are at equilibrium at one atmosphere. This point was arbitrarily given the value of 100 on the Celsius scale. Then the scale was built dividing it into 100 equal divisions.

Other scales use other equilibrium points; the Fahrenheit scale uses a zero point as the point where a mixture of salt (NaCl) and water allows the existence of liquid and solid water to remain at equilibrium.

The relations shown below can help to convert Celsius to Fahrenheit and Fahrenheit to Celsius

$$C = \frac{5}{9} \text{ (F-32)}$$

$$F = \frac{9}{5} C + 32$$

Temperature Sensors

Temperature is measured using the fact that when exposed to temperature changes some materials suffer some kind of change. Some changes in a material are changes in physical properties and changed physical dimensions.
There many types of change that are caused by thermal changes; we will touch the following:

- Length
- Electrical
- Energy

Length
The change in length of some metals as well as the property of expansion and contraction when subjected to temperature changes are extensively used in temperature sensors.

Electrical

Generation
Due to electrochemical properties there will be a migration of electrons from one of the materials to the other. This effect is used in thermocouples.

Resistance
Because resistance is a thermal property of materials (discovered by Joule), it would be expected that a change in temperature would produce a change in resistance; this is used by RTDs.

Energy

Infrared
Infrared temperature measurement is used to measure temperature in radiating bodies and at a distance. Such measurement could be the temperature of an oven or the temperature of a remote hot object. The explanation of this method of temperature measurement uses quantum mechanics starting with Plank's radiation law.

Temperature Sensors – Length Based

The most commonly used sensor based on length changes is the bimetallic sensor. Its importance is due to its practical use and price. Bimetallic sensors are used in many electrical applications, including motor overload trip devices and temperature measuring indicators.

The device properties are based on the fact that a metal exposed to heat will expand or contract with heat. The length that a metal expands at given temperature is different for each metal.

Two strips of different metals joined together at both ends at a specific reference temperature will bend when the temperature that they experience is increased. The distortion will be the function of the temperature. One metal will expand more that the other, forcing the pair to bend. The distortion depends on the amount of temperature surrounding the metals.

This property can be used to create a thermometer as shown in **Error! Reference source not found.**.
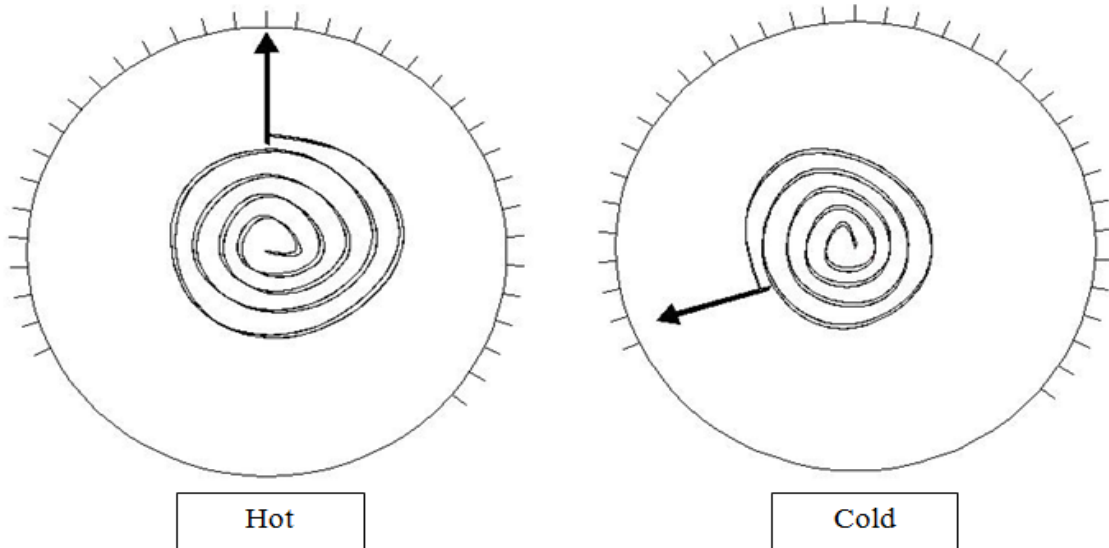

Figure 10 – Bimetallic Spiral Thermometer

The instrument shown in **Error! Reference source not found.**, is made with a spiral wound bimetallic wire. As the wire gets hot the wire size increases and bends due to the constraint of one metal by the other.

Electrical Based Temperature Sensors

Thermocouples

Generation of electricity is a phenomenon that occurs when two dissimilar metals are joined together. The reason for this effect is because each metal has a different level of energy due to its electronic level. This is referred sometimes as the energy well of the metal.

When two different metals are joined together with a small separation between them, there is a thermo ionic migration from the metal that has the smallest energy level.

This effect is called the tunnel effect and occurs for distances such that the electronic energy level of each metal superimposes over the other.

A distance of 10^{-7} centimeters would allow this effect to happen. A detailed explanation of this effect is beyond the intent of this course.

The previously described effect is called *thermocouple* effect. The increase in temperature will increase the amount of energy in the junction and more current will flow from one metal to the other.

Resistance Temperature Detectors or RTD

Resistance is always part of a conductor. Heat generated by a conductor by the flow of electrical current is intimately related to resistance. The temperature of a conductor will alter the value of the resistance of the conductor. An RTD is a device that detects temperature based on this property.

Normally a RTD is made with of fine coil of metal wrapped around a ceramic or glass core. To protect the element it is placed inside a sturdy probe.

The resistance of the metal used in the RTD is well documented at various temperatures. The selected materials have well established and documented change in resistance as the temperature changes.

In order to measure the temperature using an RTD, the RTD reference tables are based on the specific value of the resistance of the RTD and its variations with temperature.

RTD are used when important factors are essential:

- Accuracy
- Stability
- Repeatability
- Immunity to electrical noise

Additionally, the time response of RTDs is better than other thermal instruments used in the same applications, like thermocouples.

Both thermocouples and RTDs are placed in thermowells when the temperature is to be sensed inside a tank or a pipe. See Figure 8 –Thermowell.
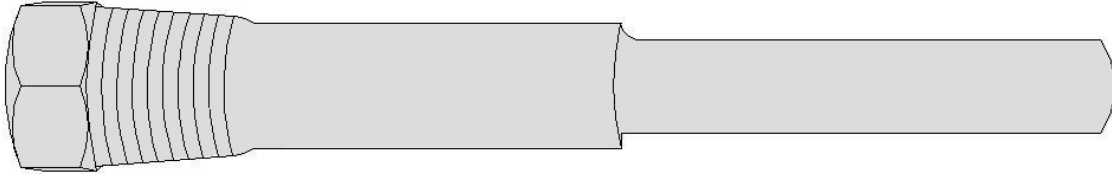

Figure 8 –Thermowell

Energy Based Sensors

Infrared detection is produced when light in the infrared frequency collides with materials. Some materials will react to the energy content of infrared waves and their reaction can be quantified and translated into temperatures. In quantum theory, using the Stefan-Boltzmann Law, we can say that the total radiation energy is proportional to the fourth power of the absolute temperature. The early twentieth century scientist Wien indicated in his "Displacement Law" that the product of the peak wavelength and the temperature is a constant. He was awarded the Nobel Prize for Physics for the year 1911. This relationship can be used to measure temperatures.

The sensor in an IR thermometer collects a small amount of energy (usually 0.0001 watt) radiated from the target, then it generates an electrical signal that is amplified by a sensitive amplifier and converted into voltage output.

An analog to digital chip (such as a 16 bit Analog-to-Digital Converter) digitizes the signal sending the signal to an Arithmetic Unit which solves a temperature equation based on Planck's Radiation Law; uses an algorithm to compensate for the ambient temperature and emissivity. The result of these manipulations produces a temperature reading.

LEVEL

Level Sensors

Level measurements are essential part of modern industry. Level of tanks containing fluids and solids are continuously monitored to determine amount of material, to prevent spills, and to determine needs for more material.

One way to classify level sensors is by how the measurement is made, either directly or indirectly, depending on the material that is being monitored.

Direct methods are used to measure liquid levels, granular material levels such as grains, and powder, such as flour or salts.

Indirect methods use other physical properties to indirectly determine the level of material. These other physical properties could be pressure of the vessel, which could vary with the increase or decrease of material in a container or weight of the material inside the container.

Another way to classify these instruments is by how the sensor senses the material. In this case, the classification is either continuous or a single point detection. The continuous sensors sense the level as it changes. The point detection method senses the level at a certain specific points. One example would be a low level point; another point would be a high level point. This type of sensor is normally a switch or switches that are located in such a way that they will be activated as the corresponding level is reached.

The following table will present the most common level sensors.

Level sensors

Sensor	Type/Description
Floats	This type of sensor is a direct measurement and point detection sensor. Traditionally used a floating ball connected to the controller by means of a rod or link, the movement of the ball is converted into a movement of a positioning lever that actuates the corresponding switch. More modern units use a floating cylinder containing a ferromagnetic material. See **Error! Reference source not found.**. This cylinder slides on a shaft that contains a magnetic link. The link moves as the level varies, the position of a cam on the other end of the link actuates switches mounted in the switching housing.
Pneumatic	This type of sensor is a direct measurement and point detection sensor. Pneumatic level sensors are used in hazardous areas, such as those classified as 1E by the NEC, or where there is no electric power, and in applications involving material such as sludge. The mechanism of these devices is as follows:

	When the level of the material changes it compresses a column of air which is in contact with a diaphragm. This diaphragm actuates a switch, which is in turn is used for determining the level.
Conductivity probes	This type of sensor is a direct measurement and point detection sensor. See **Error! Reference source not found.** Conductive probes use low voltages and currents. The current and voltage in this unit is very small; due to this feature these sensors could be classified according to the NEC as "Intrinsically Safe". Conductive sensors are made of solid-state materials. Some disadvantages are inherent of the units when used to measure materials that can coat the sensor, insulating it and thus decreasing its conductive sensing capability. Also, since the signals are very small, a good ground has to be present in the probe circuit to isolate noise and other parasitic signals. The sensor has two electrodes fed by a low voltage, low current signal that establishes a conductivity value. This value is matched to the liquid conductivity. This conductivity in turn is a function of the level
Vibrating Level	These sensors use a vibrating device vibrates at its resonant frequency. When the material contacts the probe it stops vibrating and the level switch is activated. There are two common types. The piezoelectric probes and the tuning fork type probe. This system is used for detection of very fine powders and granular solids. The position of the probes is important to prevent false level detections.
Capacitive	The system uses a capacitive sensing system between the probe and the material of which the level is sought. The circuit uses radio frequency signals. The sensors are designed to sense the dielectric property of the material, dielectric constants as low as 1.1 (ash) and as high as 88 (water) are within the detection range of these systems. Other use of this system is the detection of the interface between two non mixing liquids each having substantially different dielectric constant from the other. The detection of this interface uses a two probe system. The capacitance system is sensitive to electrostatic discharges, for this reason as in the conductivity system a good grounding system is required. See **Error! Reference source not found.**

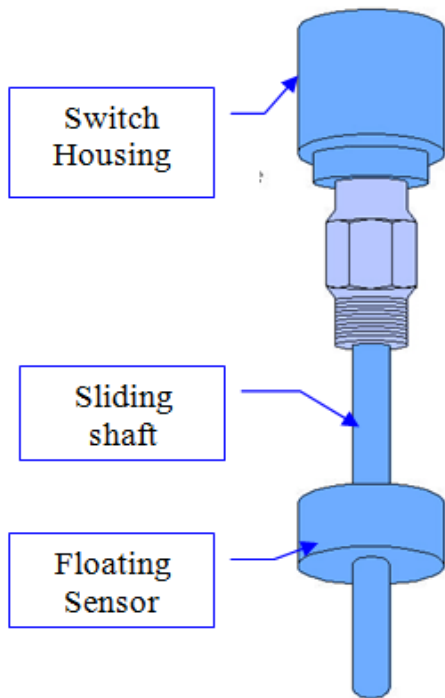| Ultrasonic	Ultrasonic probes are used to measure level at a distance. These instruments are of the non-contact type.
	The sensor does not need to be in contact with the substance being measured, but it needs a clear view of the surface. Some of the most common applications of these devices are measuring level for corrosive substances, for liquids such as slurries and grease, and waste applications. Also, you will find them measuring levels in grain silos and cement containers. The sensors work by emitting and receiving an ultrasonic frequency signal that is reflected from the surface off the material. The duration of the travel from the sensor and back is calibrated to reflect a distance. This distance is then computed using the dimensions of the system and then expressed as a level. The receiving sensor is usually part of the same housing with the emitter. Some problems are accuracy and repeatability of measurements when humidity changes in the area of the signal. This is because the speed of sound depends on the density of the medium where it is transmitted. The temperature variations also affect the measurement. For these reasons temperature and humidity compensation is sometimes an essential part of this level measuring system.
Radar Level Sensor	Radar transmitters are the logical extension of ultrasonic sensors in applications requiring non-contact measurement of liquid levels. They are the correct application for areas where vapor, dust, or a foaming surface makes ultrasonic measurement inaccurate. Radar sensor uses a microwave pulse to target liquids from the tip of the sensor to the bottom of a tank. This signal is a reliable pulse very little affected by environmental conditions.

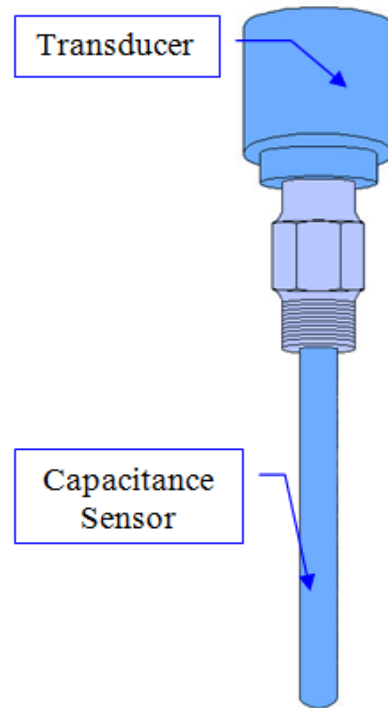## Level Sensor and Transducers Figures

Figure 12 – Float Level Transmitter
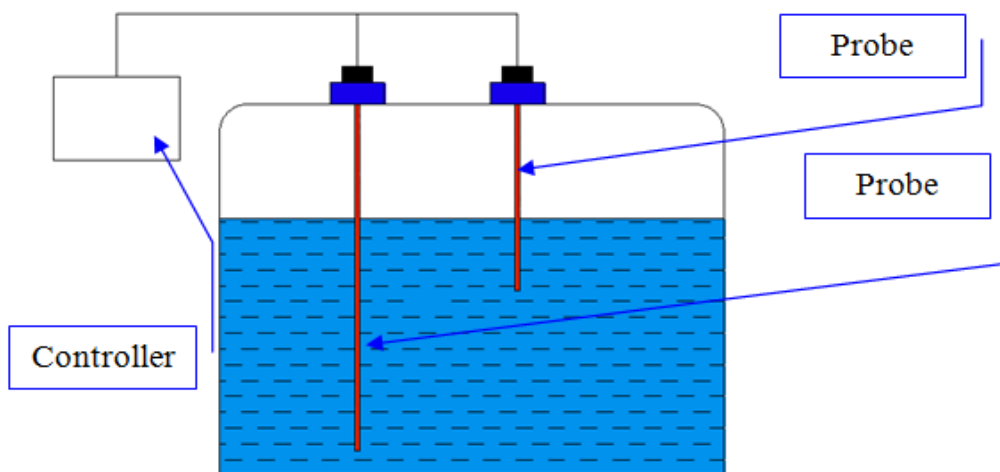

Figure 13 – Capacitance Level Transmitter

Figure 14 – Conductivity level system
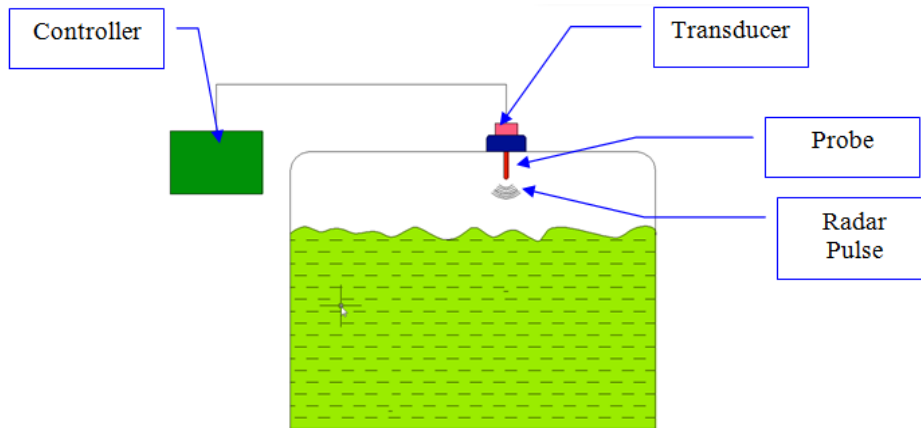
Figure 15 – Radar Instrumentation

FLOW

Flow is the movement of a fluid in a contained path. Flow measurements are normally classified in using two features of flow: Flow rate and Total flow.
Flow rate is the amount of flow that moves past a certain point per unit time.
Total Flow is the amount of flow that passes a given point during a period.

Flow instruments
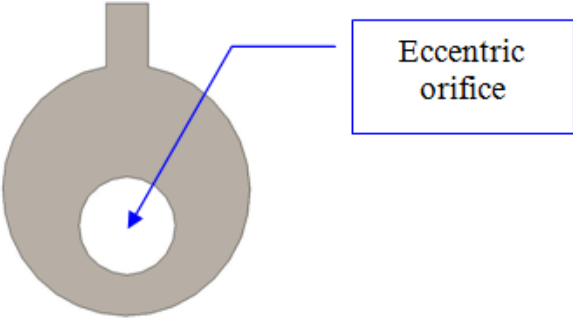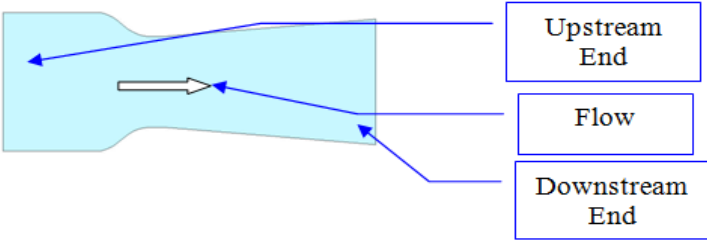
Flow instruments are designed to measure either flow rate or total flow. An instrument that can measure a combination is also available.

The following table presents the most common flow instruments:

Flow Rate Instruments

Instrument	Type and description
Flow Rate	
Differential Pressure	The principle of operation of differential pressure flow meters is based on the principle that the pressure drop across the meter is proportional to the square of the flow rate. The mathematical operation to obtain the flow rate is done by measuring the pressure differential and extracting the square root. A DP flow meter is made of two elements: • Primary element – creates the differential pressure (causing a change in the kinetic energy of the fluid) • Secondary element - Measures the DP, it contains the sensor and transducer to provide the signal or read-out that is converted to the actual flow value Design considerations: The unit must be properly matched to: • the pipe size • flow conditions • the liquid's properties

Differential pressure Primary elements: *Orifice Plates*	The orifice plate is a flat piece of metal that has an orifice or hole drilled or cut in it. The orifice is usually circular or concentric to the pipe but other shapes are also used. Installation is made locating the plate between two flanges. The orifice plate, by constraining the surface, reduces the flow and increases the velocity of the fluid, creating a different pressure at the exit of the fluid than at the inlet. Thus there is a differential pressure across the plate. A pressure measurement on both sides of the plate is made and the differential pressure used to calculate the flow rate as indicated above. One disadvantage of the orifice plate is that it adds losses to the flow because it restricts the flow which in turn, due to friction, adds resistance to the fluid flow. **Figure 16 – Orifice Plate**
Differential pressure Primary elements: *Ventury Tube*	Venturi tube uses the same principle of the orifice plate. The fluid id constricted passing through a reduced diameter flow way. The difference is that the device instead of being a plate with a hole is a section of pipe with a tapered entrance and a straight throat. See **Error! Reference source not found.**. These sensors do not have moving parts and they are more accurate, although considerably more expensive. **Figure 17 – Venturi Tube**

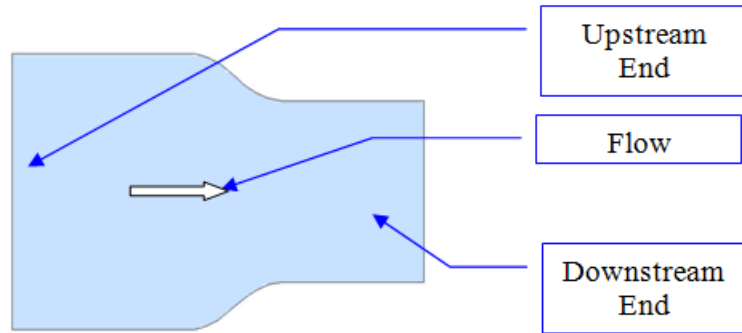|	
Differential pressure Primary elements:	The flow nozzle is an intermediate step between the orifice plate and the Venturi Tube. It looks very similar to the Venturi Tube; it resembles half of a Venturi Tube.
Flow Nozzle	The cost is less than a Venturi Tube but its accuracy is almost as much as the Venturi Tube

Figure 18 – Flow Nozzle

Location of the pressure taps	Pressure taps to measure differential pressure are located at distance from each other to be able to detect the pressure at the normal flow and the pressure after the constriction.
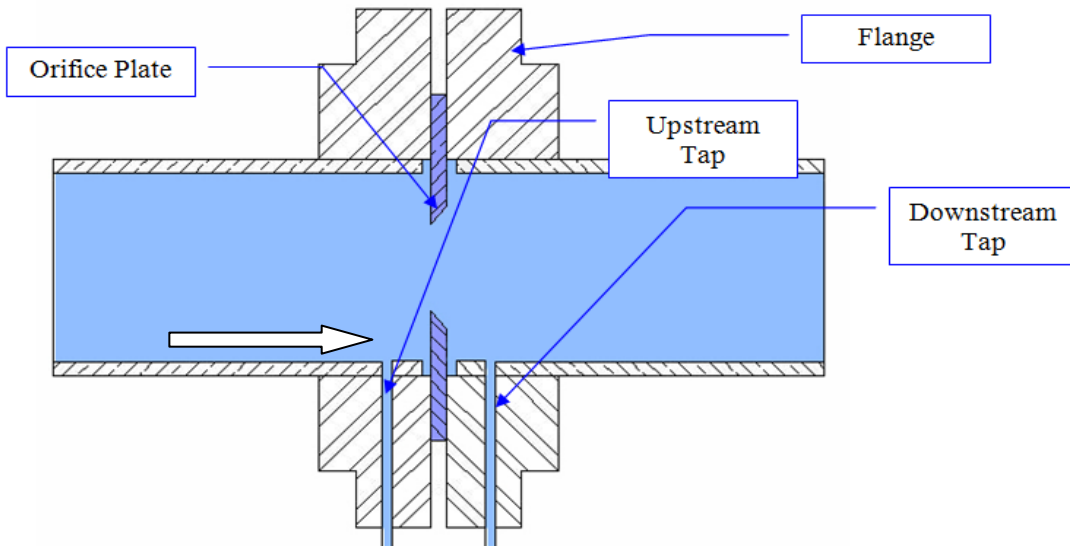
Figure 19 – Pressure tube location for DP measurements

Other Methods for Measuring Flow Rate

There are other methods to measure flow that are also used for conditions that do not require the same accuracy as that obtained by the differential pressure methods.
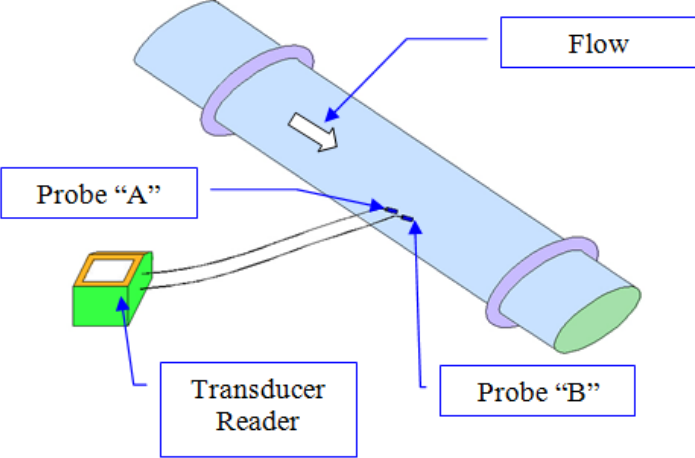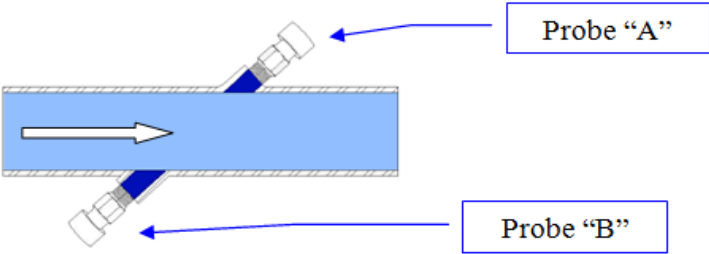
- Rotameter – The pipe area is varied using an inside float. The pipe at this point is vertical and the float moves along a scale calibrated in flow rate units. It is used for measuring the flow in gases and liquids
- Open channel methods: Weir, flumes, open nozzles

Total Flow Instruments

Instrument	Type and description
Total Flow	
Positive displacement	This method uses a counting technique to measure the flow. The system consists of a chamber in which the fluid enters. When the chamber is filled it discharges. The instrument counts this as one count. The calculations must take into account the volume of the chamber. Each time the chamber is filled determines a volume of fluid that has moved along the pipe. The number of times multiplied by the volume and divided by the unit time determines the total flow. **Figure 20 – Positive displacement flow meter**

Instrument	Type and description
	Total Flow
Ultrasonic Measurement	This method uses modern technology and its accuracy is high. The set up involves two probes located in the path of the flow. The figure below shows one type of installation. **Figure 21 – Ultrasonic Flow Generic Probe Locations** In the figure below, the flow is measured by sending an ultrasonic wave at point A and receiving it at point B. The duration of the wave from A to B determines the flow. The unit is calibrated at zero flow to establish speed and duration of wave at rest. **Figure 22 – Location of Ultrasonic Probes** This installation measures the flow comparing the travel time of the sound wave towards and against the flow and comparing the difference in speed.

MOTOR CONTROLS

Introduction

Motor Control is an area of control systems that pertains to the control of the most used motion actuator in industry: the electric motor. The electrical circuit connecting motors includes a power source and protection, and a manual starter with the overheat protection; the later is part of the motor control.

Today, due to the advances of motor control technology, the motor is controlled automatically. The motor control includes a sophisticated algorithm that is capable of making changes of speed and direction to the motor using ramping speeds and accelerations. Motors also have changed; the improvement in windings and copper alloys has made possible that a smaller motor can produce the same power output as the old larger one. These new motors are (if designed so) capable of sustaining harmonics and other non-sinusoidal feed signals.

Motor Controllers

A motor controller consists of a group of devices that govern, regulate, and energize or de-energize a motor.

The functions that a motor controller include:

- Starting
- Stopping
- Accelerating
- Reversing
- Protecting

There are two major types of motor controllers:

- Manual
- Automatic

Manual controller is as the name indicates: one in which the motor is being controlled by hand. Many systems still have manual controllers even if the motor is controlled automatically. The reason behind keeping a manual control is first for safety and second for maintenance of the motor or machine.

The majority of automatic controls performed today use two basically different methods:

- Relay logic
- Programmable equipment:

- o Programmable Logic Devices (PLC)
- o DCS equipment (computer system)

A typical manual controller diagram is shown in Figure 23 – Motor Manual Control below:
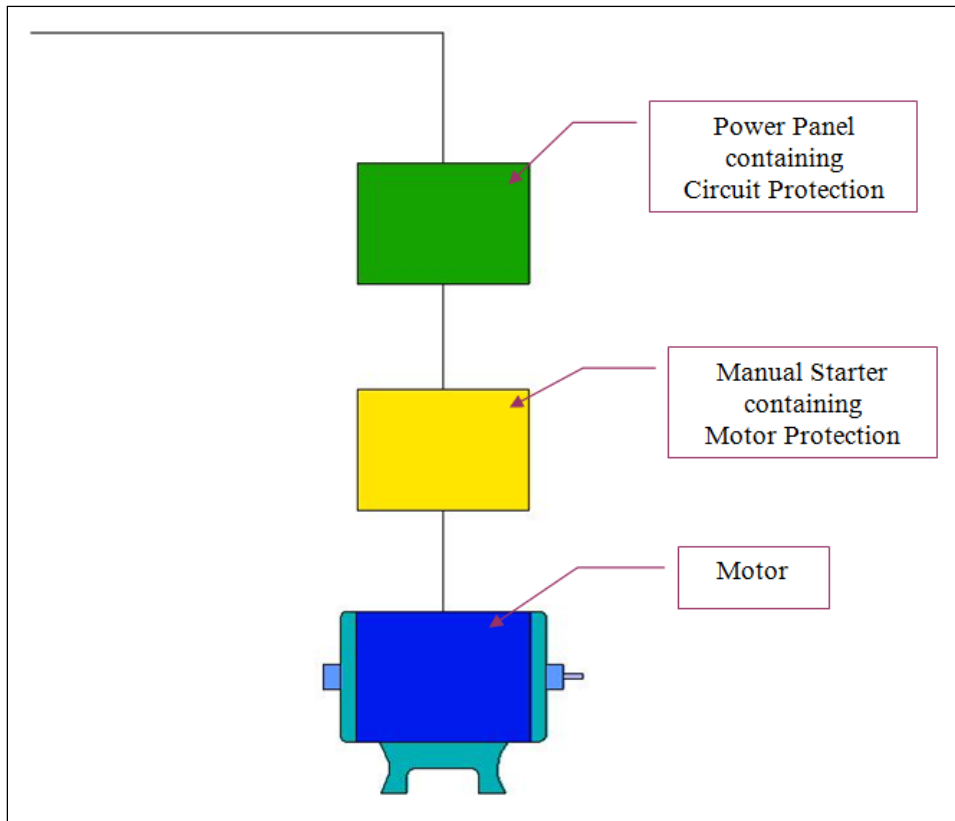

Figure 23 – Motor Manual Control

The circuit that controls a motor is regulated by the National Electrical Code. The rules in this code are designed to protect the public and equipment. It will protect primarily against fires but also against other electrical hazards. Additionally, to prevent a motor from extreme overheating, a means of protecting it from overcurrent (overload, short circuit, or ground fault) must be provided.

In Figure 24 – Motor Electrical Control Connection below, the power and control connections are shown in a schematic manner. The elements of this diagram show that power is connected to the motor via a controller. The controller will energize the motor and supply the power waveform if the controller has the capability to change the feeding power wave. Devices such as AC drives are designed to manipulate the incoming power wave and convert it in a power waveform of different frequency. This new power supplied to the motor will be able to rotate the motor at a different speed.
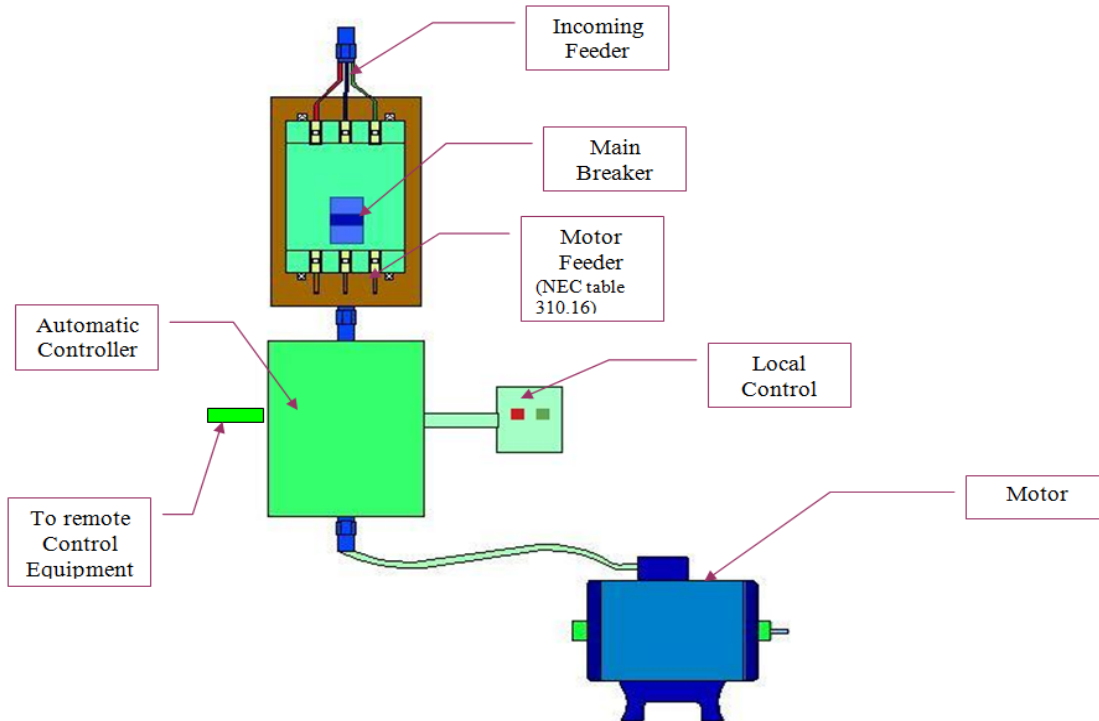
Figure 9 – Motor Electrical Control Connection

Motor Control Elements

The following table lists and describes the basic elements of motor control:

Motor Control	Function
Starter	Starter is the part of the control system that initiates the motor function. It contains the electromechanical components that permit electric current to reach the motor windings.
Overload Relays	Overload relays are protection elements against an over temperature in the motor that can cause motor failures due to overheating.

Control Stations	Control Stations are normally the remote operators of the motor starter. They also function as safety stopping stations (E Stops).
Relays and Contactors	Relays and contactors are elements that interlock permissive conditions to the motor running or stopping. The contactors are the large control components that allow motor current to be supplied to the motor. Contactor coils are normally activated by relay contacts.
Remote Actuators	These components are the permissive contacts that are included in the control logic that provide the desired conditions to the motor to run or to stop. Such components could be limit switches, level switches or other switch or contacts.

Starters

Since starters are the main motor controller, there also are two main types of starters:
- Manual
- Automatic

Manual Starters

These starters supply the simplest way to start a motor. They are usually toggle switches with an overload element connected in series with the contacts.
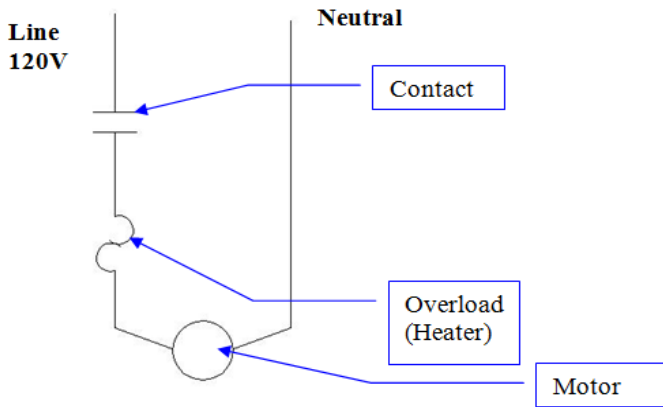The motor wires are connected directly to the starter. Schematic of this connection is shown below:

Figure 25 – Motor Manual Control Schematic

Application of manual motor starters is normally used in small motors. Motors called fractional motors are in this type of application. The term fractional refers to motor with horsepower ratings smaller than unity. However, fractional motors also include motors up to 10.5 horsepower.

Automatic starters

The most common mode of controlling motors in industrial environments is using an automatic system.
Earlier automatic systems relied on relay logic to control the starting and stopping of motors. More modern methods include Programmable Logic Controllers (PLC) and DCS systems that consist of computer systems and a software program to execute the logic. An intermediate system was available for a short time in which the logic was programmed using hardware programming and OP Amp (Operational Amplifiers) to program the logic in the system. This system is not very common.

Relay Logic

Relay logic is used to control the motor using relays and their contact arranged in a structure called ladder programming. A simple control using relay logic is described as below.
The system includes the starting motor coil (contactor or starter coil) a light to indicate that the motor is running, motor protection (thermal element) and the contacts from the contactor. This motor can be started either automatically by moving the selector switch to Automatic and starting by the action of the limit switch; or by moving the switch to selector switch to Manual. The C contacts are from the main contactor for the motor circuit. These contacts allow the voltage to be applied to the motor control circuits and to the motor.
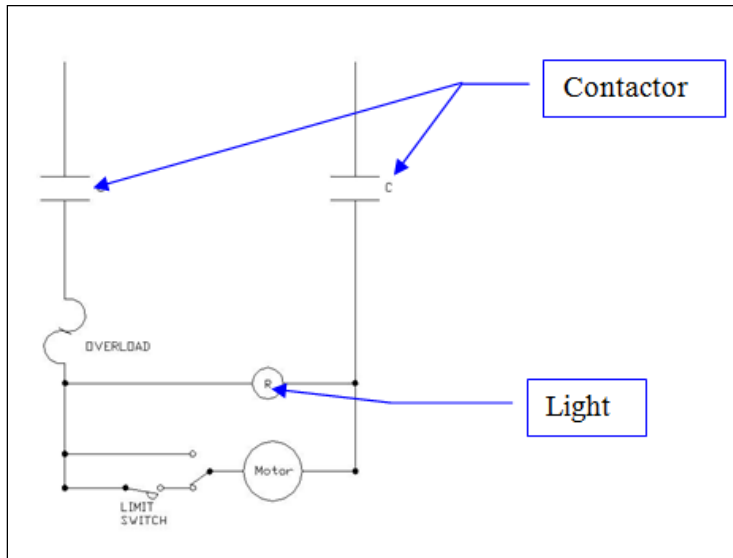
Figure 26 – Auto-Manual Motor Control

Relay logic, three-phase motor starting circuit is presented below in Table 3 – Motor control components. Also see Figure 27 – Basic Automatic Motor Starting and Control Circuit.

Component	Function
Stop push button	Opens the circuit branch that feeds the motor operating control coil (M), disconnecting the motor from the supply voltage
Start Push button	Closes the branch that energizes the motor operating control coil allowing the contacts to close and thus allows voltage to be applied across the motor
Starting coil	Is the motor operating control coil and acts as the primary auxiliary control device
Auxiliary starting coil contacts	Contacts from the starting coil. One of them is the *seal in contact*. This contact maintains the coil energized after starting.
Three Phase circuit feeder	Power conductors that energize the motor and the control circuit
Control Transformer	Transforms supply power voltage to control power voltage
Circuit protection	There are two protection sets: one that is connected immediately after the main switch and the other before the control transformer feed

Table 2 – Motor control components

The relay coils and contacts are arranged in rungs. The group of rungs is similar to the rungs of a ladder. This type of arrangement is called ladder programming. In the case shown in the schematics below, the ladder programming is made using relays; this is why the motor control using this technology is called relay logic.

When the programming uses an electronic device such as a computer based unit (PLC), the ladder is made in a virtual manner. This means that the relays and contacts are logic conditions that are established using computer logic. The final conditions that are to be produced or received as permissives in the logic are interfaced with the motor or real world device using input or output cards. The signals or conditions going or coming from the program to the real world are called inputs and outputs. The interface with the computer is made using hardware such as cards that contains micro relays and logic chips that can talk to both the computer hardware and to the relays or instrumentation in the field. All these software operations are performed using a PLC normally installed inside a cabinet of a unit in the MCC or Motor Control Center.

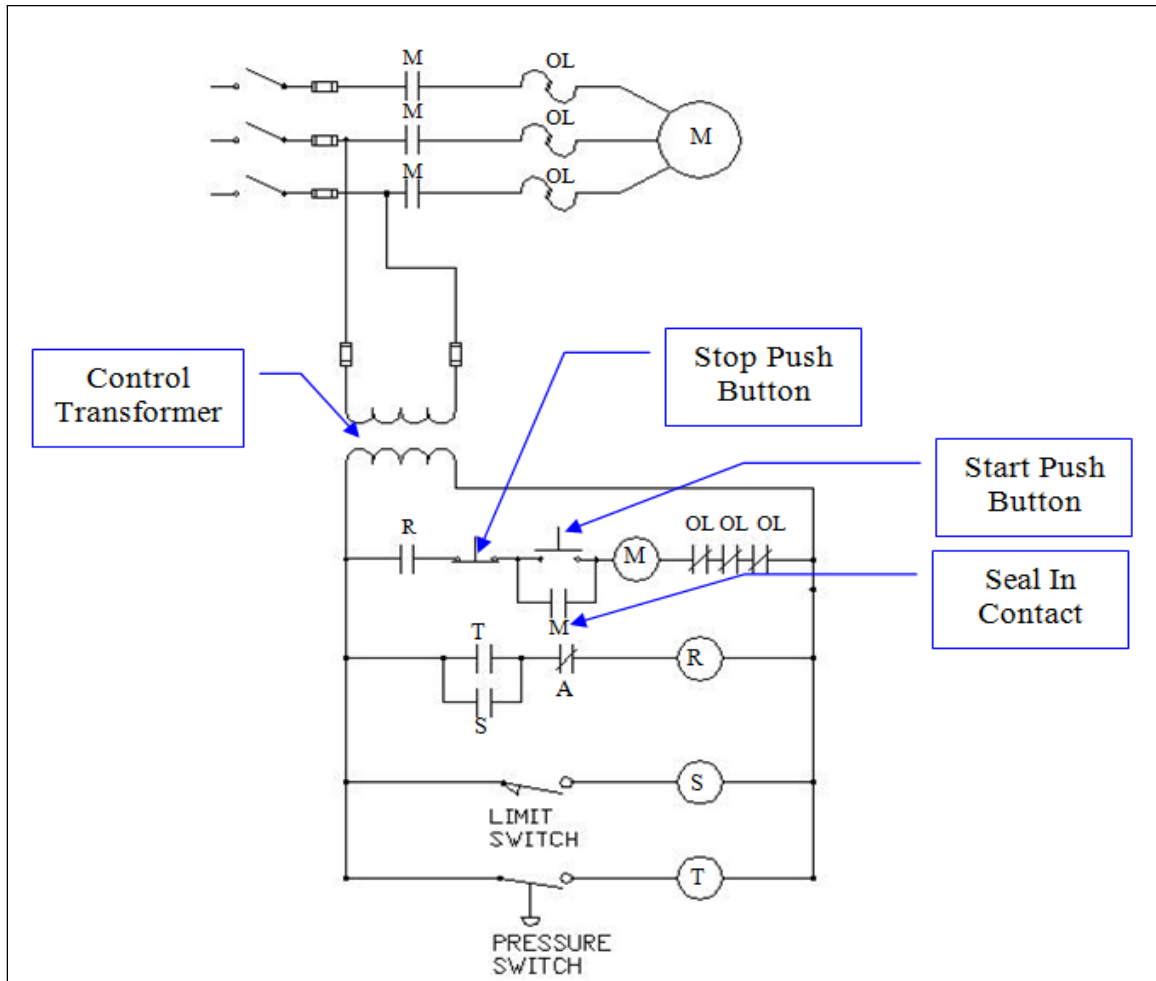The organization of these MCCs is further discussed below.

Figure 27 – Basic Automatic Motor Starting and Control Circuit

Modern Automatic Motor Controls

Modern Automatic Motor controls are normally placed inside a cabinet. This cabinet is a modular unit that contains a series of starters. The starters are mounted inside a sliding drawer called a bucket. Buckets are placed in sections. These sections are assembled in a group that makes the Motor Control Center. One of the sections contains the mains. Another section contains the controller or programming device. The most common programming device is the PLC. The programming is made using, among other software tools, a software based ladder. The bucket also houses lights, push buttons, and manual controls. Each individual starter is connected to a common bus (set of copper or copper clad aluminum bars that are connected to a main protection fused switch or breaker). The bus is located on the back of the cabinet. Wiring is normally placed and routed inside specific protected areas in each section. An MCC section is shown below.
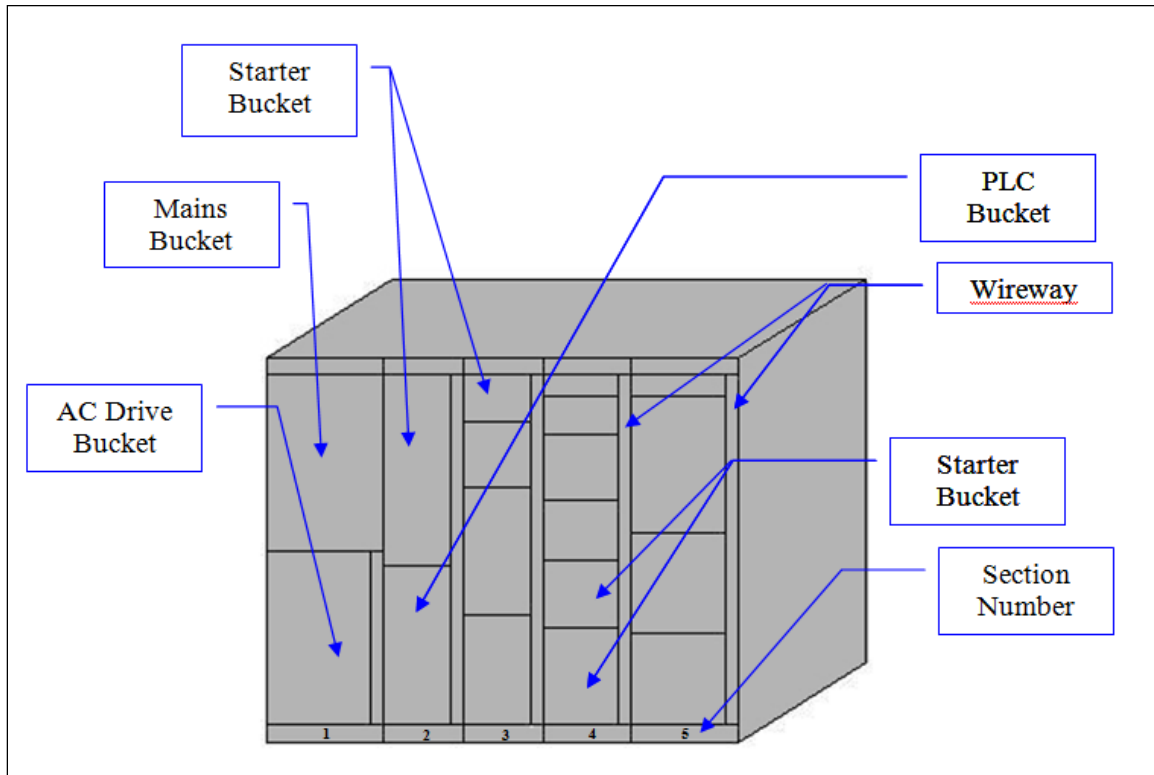
Figure 28 – Motor Control Center

Item	Description
Mains Bucket	Includes the main switch or breaker that feeds the whole MCC The protection is designed to protect the bus system
AC Drive Bucket	This space houses an AC drive. This device can control the start stop and sped ranges of an AC motor. Other items could be a control transformer and accessories to the AC drive
Starter Bucket	This bucket can contain the starter for a motor. The bucket contains also auxiliary relays, control transformer, push buttons, connection boards, and lights that are shown in the starter schematics
PLC Bucket	The PLC is housed in a space that has enough capacity to house the connection boards, and PLC with all the accessories, such as power supply, I/O cards, communication and control cards, etc.
Wireway	These channels are used to route the control wires from bucket to bucket such as from the PLC to the starters
Section Numbers	The numbers for each section are attached in this area using a plate. Each manufacturer chooses different layouts according with their deign philosophy. The MCC layout shown is a typical Allen Bradley™ design

Table 3 –Motor Control Center Components

Index of Tables and Figures