2024

Government of India

Department of Atomic Energy (DAE)

Waste Management Division (WMD)

Waste Immobilization Plant (WIP)

Trombay, Mumbai - 400085

PROJECT REPORT

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INTRODUCTION

BARC is a premier nuclear research facility with its headquarters based in Mumbai. BARC is a multi-disciplinary research center with extensive infrastructure for advanced research and development covering the entire spectrum of nuclear science, energy and related areas.

Govt. of India created the Atomic Energy Establishment, Trombay (AEET) on January 03, 1954. Dr. Homi J. Bhabha, the then prominent Indian scientist was instrumental behind the formation of this establishment. It was established to consolidate all the research and development activity for nuclear research and development activity for nuclear reactors and technology under the Atomic Energy Commission. After Homi J. Bhabha's death in 1966, the center was renamed as the Bhabha Atomic Research Center on January 22, 1967. The primary importance of BARC is a research center.

Dr. Homi J Bhabha

The research reactors developed and maintained at BARC are as followed :-

APSARA (1956; named by the then Prime Minister of India) , CIRUS(1960,the "Canada-India reactor" with assistance from Canada) , ZELINA (1961), Purnima I (1972) , Purnima 2 (1984) , DHRUVA (1985) , PURNIMA 3 (1990) , AHWR-CF (2008) and APSARA-U (2018).

The BARC also conducts research in biotechnology and has developed numerous disease resistant and high yielding crop varieties, particularly groundnuts.

MANDATE OF W.I.P

The Waste Immobilization Plant (WIP) operates within the Waste Management Division of the Bhabha Atomic Research Centre (BARC), adhering to a dual mandate focused on waste management and the separation of useful fission products for societal applications.

Firstly, the WIP is dedicated to effectively managing radioactive waste generated by various nuclear facilities. This involves employing advanced techniques to transform various forms of radioactive waste into stable and solid form. The goal is to ensure that these materials can be safely stored or disposed of without posing environmental or health risks.

Secondly, the WIP is tasked with the separation and recovery of useful fission products from the radioactive waste. These fission products, such as isotopes with medical, industrial, or research applications, are isolated and processed for potential reuse. This aspect of the WIP's mandate aligns with BARC's broader mission of promoting sustainable and beneficial applications of nuclear technology beyond electricity generation.

In essence, the WIP plays a crucial role in both safeguarding the environment and maximizing the utility of nuclear materials through efficient waste management and the extraction of valuable resources from nuclear waste streams.

HISTORY OF RADIO-ACTIVITY

Radioactivity refers to the spontaneous emission of particles or radiation from unstable atomic nuclei in a process known as radioactive decay. This phenomenon occurs when the balance between protons and neutrons in the nucleus is disrupted, leading to the release of energy forms such as alpha particles (helium nuclei), beta particles (electrons or positrons), gamma rays (high-energy photons), or neutron emission.

Radioactive decay is a natural process that occurs in radioactive materials, which can be found in nature or produced artificially. The rate of decay, characterized by a half-life, varies for different radioactive isotopes, ranging from fractions of a second to billions of years.

There are some very important terms that one must consider while going in contact with any Radioactive Zone –

- **Radioactivity :**- The rate of disintegration (transformation) or decay of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq).

- **Exposure :-** Radiation exposure is a measure of the ionization of air due to ionizing radiation from photons. The unit of exposure is Roentgen(R). One roentgen equals the amount of x or gamma radiation required to produce ions carrying a charge of 1 electrostatic unit (esu) per cubic centimeter (2.58×10^{-4} coulomb per kg) of dry air under standard conditions.

- **Absorbed Dose** :- The energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).
  1Gy=100rad

- **Equivalent dose (H_T)** :- In radiation protection, the absorbed dose averaged over a tissue or organ rather than a point, as is the case for dose equivalent) and weighted for the radiation quality that is of interest. For this quantity, the weighting factor is called the radiation weighting factor instead of the quality factor, as used in earlier dosimetric quantities.
- **Effective dose (E)** :- The sum of weighted equivalent doses to all tissues and organs of the body (ICRP 1991). $E = \Sigma w_T H_T$, where HT is the equivalent dose and w_T is the tissue weighting factor.

RADIATION UNITS

- **Becquerel (Bq) :-** SI unit for radioactivity, measuring disintegrations per second (1 Bq = 1 dis/s).

- **Curie:-** Traditional unit based on Radium-226's decay rate (1 Ci = 3.7 × 10^10 Bq).

- **Roentgen (R) :-** Measures radiation exposure by ionizing electrons in air (1 R = 2.58 × 10^-4 C/kg of air).

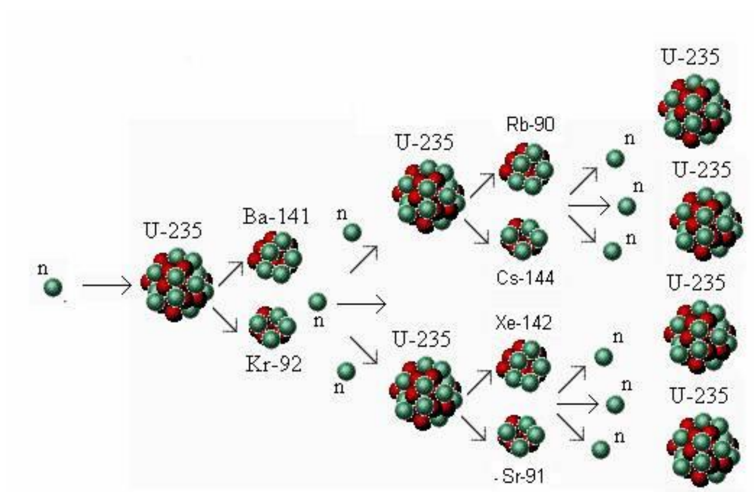
- **Rad or Gray (Gy) :-** Measures absorbed radiation dose (1 Gy = 100 rad = 1 J/kg).

- **Rem :-** Measures equivalent dose adjusted for biological effect using a weighting factor (WR) based on radiation type (1 rem = dose in rad × WR).

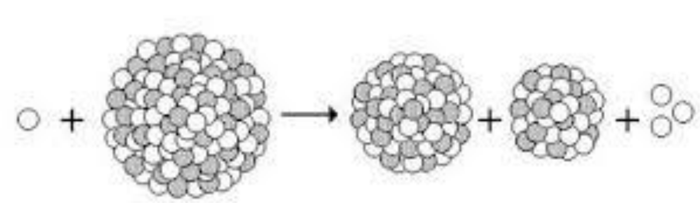
NUCLEAR FISSION

Nuclear fission is a reaction in which the nucleus of an atom splits into two or more smaller nuclei. The fission process often produces gamma photons, neutrons and releases a very large amount of energy even by the energetic standards of radioactive decay.

For heavy nuclides, it is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). For fission to produce energy, the total binding energy per nucleons of the resulting elements must be greater than that of the starting element.



Fission is a form of nuclear transmutation because the resulting fragments (or daughter atoms) are not the same element as the original parent atom. The two (or more) nuclei produced are most often of comparable



$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n + \text{Energy}$$

but slightly different sizes, typically with a mass ratio of products of about 3 to 2, for common fissile isotopes. Most fissions are binary fissions (producing two charged fragments.

Uranium-235 + Neutron → Fission product A + Fission product B + Neutrons + Energy

It is estimated that fission of a single uranium-235 nucleus is accompanied by the release of over 200 MeV (32 Pico Joules) energy. Hence it may be stated that 1 kg of uranium-235 is capable of producing the same amount of energy as about 2700 metric tons of coal!

TYPES OF RADIATION

Ionizing Radiation:- Ionizing radiation, with energy sufficient to ionize atoms by stripping electrons from them, poses risks such as cellular and DNA damage, leading to increased cancer risk. Radiation with energies above approximately 10 electron volts (eV) includes :

- **Alpha Particles :-** Consisting of helium-4 nuclei (two protons, two neutrons), alpha particles interact heavily with matter and are stopped by a few centimeters of air or millimeters of low-density material. They do not penetrate skin but pose hazards if ingested or inhaled, impacting health.

- **Beta Particles:-** These are energetic electrons ($\beta-$) or positrons ($\beta+$), more penetrating than alpha particles but less than gamma rays. They can be halted by a few centimeters of plastic or millimeters of metal. Beta radiation arises in radioactive decay and finds application in medical therapies like treating surface tumors.

- **Neutrons**:- Emitted during nuclear reactions, neutrons do not ionize atoms directly due to their neutral charge but induce radioactivity in materials they interact with. This neutron activation process is vital in medical and industrial uses, such as cancer treatment and material testing.

- **X-rays:-** Electromagnetic waves with wavelengths below 10 nanometers, X-rays differentially penetrate tissues—more so in soft tissue than bone—making them valuable for medical imaging without invasive procedures.

- **Gamma Rays:-** High-energy photons emitted post-alpha or beta decay, gamma rays penetrate deeply and are challenging to stop. They have applications in medical diagnostics and sterilization, owing to their ability to travel far through matter.

These radiation types serve critical roles in medicine, industry, and research but require careful handling due to their potential health risks when used improperly.

WASTE IMMOBILIZATION PLANT (WIP)

➢ General :

Radioactive waste is being produced by various processes in different field as in industrial, medical application, nuclear power generation and spent fuel reprocessing. Radioactive wastes are waste materials that contain radioactivity level greater then 'exempt level' and which require a proper treatment and conditioning before final disposal.
A nuclear power station uses only one pound of natural uranium to produce as much electricity as 1 tons of coal will produce in a conventional thermal power station. Hence the quantities of waste are also very small in case of nuclear power. Radioactive waste management strategies primarily aim at safe isolation of radioactivity in waste for a few half-lives (almost 10 half-lives).

- **Types of radioactive waste –**

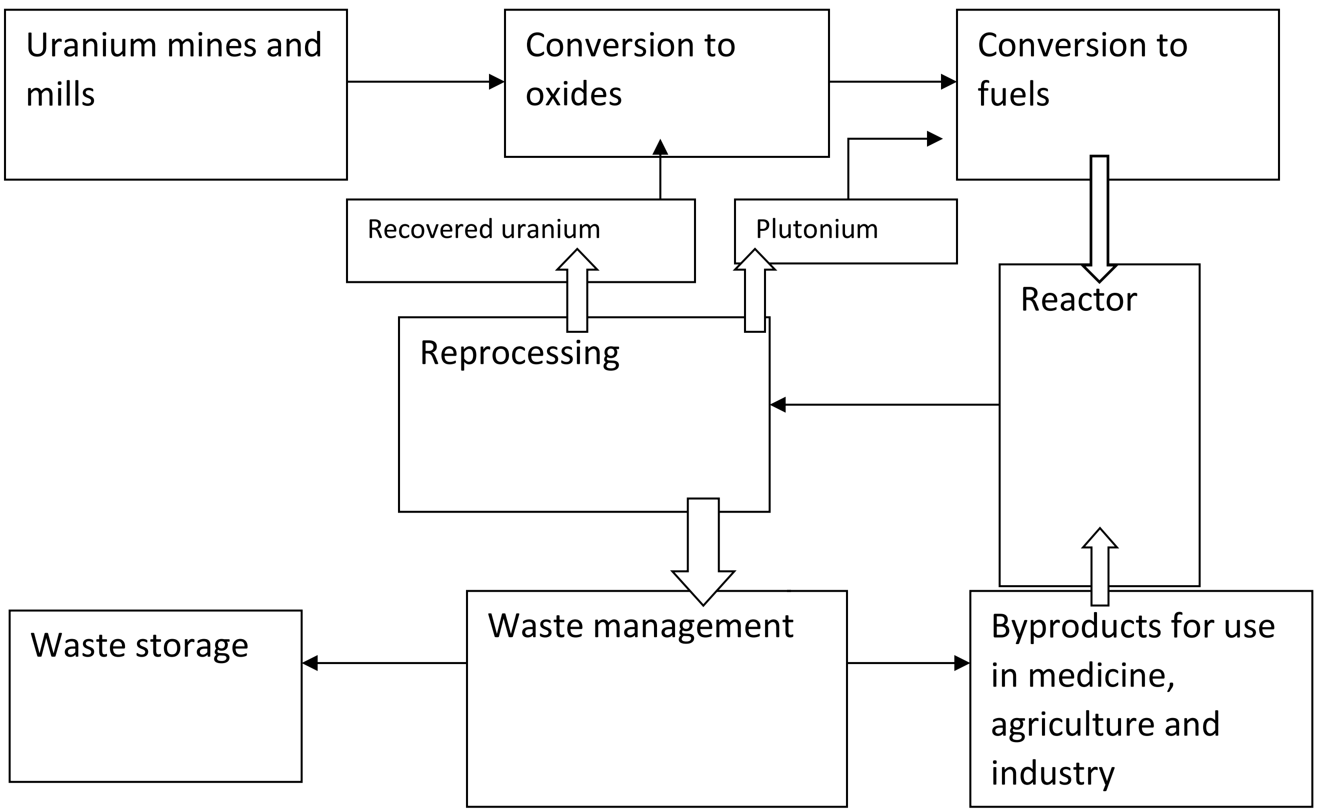
1. Liquid
2. Solid
3. Gaseous

Usually radioactive waste is generated in liquid form and very hazardous for environment due to its great flowing and mixing property and there is a chance of transmit radioactivity in living things. Management of these wastes includes collection, segregation, characterization, treatment, conditioning and handling.

- **Sources of Radioactive Wastes**:-

  - Mining and Milling of Uranium & Thorium
  - Nuclear fuel fabrication
  - Reactor operation and maintenance
  - Spent fuel reprocessing
  - Nuclear research laboratories
  - Isotope production facility
  - Isotope users – Industry, Healthcare, Agriculture etc

- **Nuclear fuel cycle:**



- **Waste management philosophy:**

  - Delay and Decay
  - Dilute and Disperse
  - Concentrate and contain

- **Basic principles of WMD (Waste Management Division) are as follows:-**

  - Waste minimization
  - Safe operation practices
  - Protection of working personnel & surrounding population
  - Preservation of quality of the environment.

➢ Process Section in WIP

Main work of process section is control all operation parameter during the vitrification of HLW. Here all operation of process are controlled during the round-off clock of shift. Main operation controlled by process section is following:

1. Vitrification operation

2. Evaporation

3. Solvent Extraction

4. Ion-exchange operation

5. Off-gas cleaning

6. PCW (Primary cooling water), SCW (secondary cooling water)

1. <u>Vitrification operation:</u> In the nuclear area, vitrification refers to the process of mixing radioactive waste with glass forming materials and forming them into glass matrix. The processing steps involved in vitrification are evaporation for concentrating the amount of radioactive particles, de-nitration, calcinations, glass melt formation, soaking and pouring. Heating in the vitrification operation is done by Induction heater.

Induction heating is a means of heating metal objects by causing electric currents (eddy currents) to flow in the surface of the metal. This is done by an alternating magnetic field applied to the metal object. Because the heat is developed directly within the metal itself, it heats up quickly and there is less heat loss than would be the case with other forms of indirect heating.

<u>2. Off-Gas Cleaning System</u>: Off-Gases generated from the vitrification process contain large amounts of radioactive constituents. These off-gases require suitable treatment for decontamination and reduction of toxicity before their release through the vitrification plant exhaust system.

In addition, air used for waste transfer operations, instrumentation services etc. of the vitrification plant is contaminated with radioactive droplets/aerosols. This air, too, requires suitable treatment for decontamination before release to atmosphere through plant exhaust system. Vitrification of Gas cleaning is done by HEPA filter.

➢ Utility Services

The utility services of mechanical department comprise of

- Compressed air
- Steam

The utility services provided are done using the workshops. Small scale fabrication works are also done in the mechanical workshops.

The compressor is a part of mechanical division which is responsible for providing the compressed air. The compressors are of 2 types:-

1. Horizontal compressor
2. Vertical compressor

The compressed air is used for air ejector operation, air lift, breathing and also used in instrumentation processes.

The boiler is used to produce dry saturated steam. The kind of boiler used is 3-pass horizontal smoke tube and oil-fired boiler. The 3-pass horizontal smoke tube is used to increase the surface area in contact with the liquid. The water provided to the boiler is soft water. The boiler produces dry saturated steam which is used for various purposes such as-

- Concentrating purpose during evaporation
- Steam jet transfer
- General heating
- Off gas heating

ROLE OF C&I SYSTEM

Control and Instrumentation (C&I) systems are essential in W.I.P for monitoring, controlling, and ensuring safety through the following roles.

- **Measurement of Critical Parameters :** C&I systems utilize sensors and instruments to measure critical parameters such as temperature, pressure, flow rates, and radiation levels in real-time.
- **Regulating Critical Parameters:** They maintain optimal process conditions by adjusting valves, pumps, heaters, or other actuators based on the measured parameters, ensuring stable and efficient operations.
- **Displaying Real-Time Parameters (RTP):** C&I systems provide operators with continuous updates on process and radiation parameters through clear, intuitive displays in control rooms.
- **Safety Interlocks:** These systems implement safety interlocks that automatically halt operations or trigger safety protocols if critical parameters exceed predefined limits, preventing accidents and ensuring personnel and environmental safety.
- **Alarm Systems (Audio & Video):** C&I systems generate audible and visual alarms to alert operators to abnormal conditions or emergencies, enabling quick response and intervention to mitigate risks.
- **Customized Report Generation:** They gather and analyze data over time to generate customized reports detailing process performance, trends, and compliance with regulatory requirements, aiding in decision-making and audits.
- **Trend Generation:** C&I systems analyze historical data to identify trends and patterns in process variables and radiation levels, facilitating predictive maintenance and process optimization.

In summary, Control and Instrumentation systems play a vital role in Plant processes by ensuring accurate measurement, precise regulation, safety enforcement, and real-time monitoring through advanced alarm systems and customized reporting capabilities. They are indispensable for maintaining operational efficiency, safety, and compliance across diverse plants in BARC

➢ Parts of C&I System

- Instrumentation nozzles & probes
- Field Instruments & Gadgets
- Signal & control cabling
- Data Acquisition & Control System (PLC)
- Supervisory Control System (SCADA)
- Radiation Monitoring System

MEASUREMENT METHODS

➢ AIR-PURGE METHOD FOR MEASURING LEVEL, DENSITY AND PRESSURE IN TANKS :-

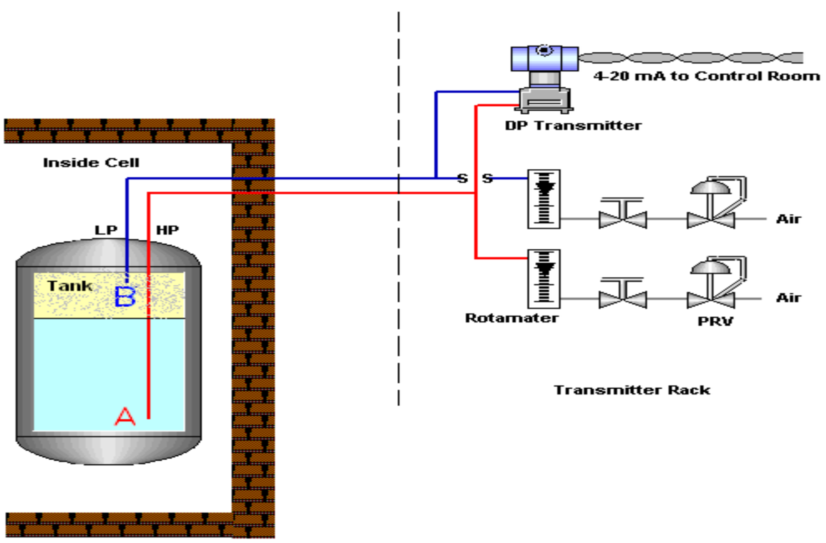
Air-purge method is a commonly employed measuring method in radioactive plants because of its numerous advantages. In this method, air at 20 – 30 nlph at 1Kg/cm^2 pressure is purged through probes inside the tank. It is a non-contact method as radioactive liquid inside the measured tanks does not come in contact with the sensing instruments. As the instruments can be located outside the cell at a sufficient distance, doing maintenance, troubleshooting etc. is quite safe and easy. Air purge method is quite simple technique as it does not have any moving components.

Design Features **:-** Purge probes are generally ½” SS 304 L pipes inserted into the equipment from top to designated heights and welded at the top of the equipment. Purge probes are also given 45^o cut at the bottom. Tip of the *level probe* is generally fixed 100 mm above the bottom of the equipment from inside. *Pressure probe* can be made flush to the top inside surface of the equipment. *Density probe* is fixed slightly above (say 300 mm) the level probe. Additionally, a probe similar to the level probe is also provided in all major equipment as a *spare probe*.

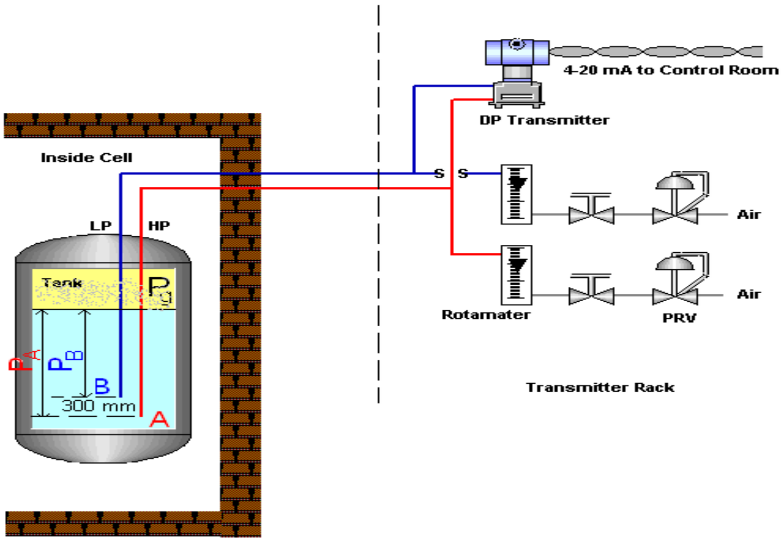
These probes are extended through the hot cell to the transmitter rack location using 1/4” SS 304 L pipes. Transmitter rack location is generally kept at least 5 m above the highest positioned equipment of the cell. In transmitter rack location, each probe is connected to respective transmitter using ¼” SS tubing.

To prevent the back flow of measured liquid through the purge probes (in case of pressurization inside the equipment) 2-way, normally-closed solenoid operated valves are installed in all purge probes except the pressure probe. The pressure inside the equipment is constantly monitored using a pressure switch fitted to the pressure probe. In case of loss of negative pressure in the equipment the pressure switch closes all the valves in the purge probes associated to that equipment. The pressure switch and the valves are hardwired to enhance the reliability of operation. To ensure the fail-safe nature the valves are kept open by constantly energizing their coils during normal operation.

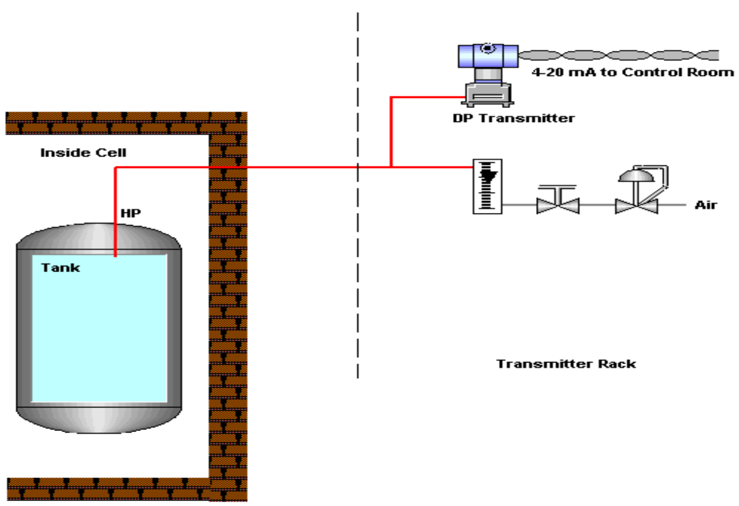
1. Level Measurement



2. Density Measurement



3. Pressure Measurement



➢ FLOW MEASUREMENT :-

Flow rates of different process and service fluids in this plant are measured by using meters as explained below.

1. Magnetic Flow Meter

It works on the principle of Faraday's law of electro-magnetic induction, which states that whenever a conductor moves in a magnetic field, an emf is induced across its ends and the magnitude of this emf is proportional to the speed with which the conductor moves and intensity of the field. Direction of current generated by this emf is given by Fleming's right hand rule. In an industrial type of magnetic flow meter the fluid passing through the meter serves as the conductor. Hence the conductivity of fluid puts a limit in the applicability of this kind of meter. Constructional details of a magnetic flow meter are as follows. A metallic pipe with flanges fitted at both ends, is coated in its inner surface with an insulating material and serves to be the metering tube. Two electrodes are attached to the tube flush with its inner surface. A coil surrounding the tube and energized with pulsating DC currents serves to generate magnetic field. Any conducting fluid passing through the tube cuts magnetic field and voltage induced in it appears across the electrodes. An electronic unit along with this tube processes this emf, generates 4-20 milli-ampere DC current output and transmits the same to analog input module of PLC. Magnetic flow meter possesses many advantages compared to conventional, obstruction flow elements. Some of them are listed below.

- Greater accuracy.
- Causes practically no pressure drop.
- Insensitive to variations in density and viscosity.
- Linear output etc.

2. Rotameter:-

They are probably most widely used flow element in any industry. They are simple, rugged and easy to install and maintain etc. Basic metering tube is a vertically held, tapered glass tube. A float made of stainless steel is put in the tube. The glass tube is held firmly in metallic casing with a glass cover on the front side to enable the view of float. A graduated scale fixed on the metal casing serves to indicate the flow rate. The position of the float inside the tube is a measure of flow rate and the same is inferred from the scale.

3. Vortex Flow Meter :

A vortex flow meter operates based on the principle that when a fluid flows past a bluff body (such as a shedder bar), alternating vortices (eddies) are shed downstream of the bluff body. The frequency of these vortices is proportional to the flow rate of the fluid. By detecting and counting these vortices, the flow rate can be accurately determined. Vortex flow meters are suitable for measuring both liquids and gases and offer good accuracy and reliability, especially in applications where the fluid contains solid particles or bubbles

4. Orifice Flow Meter :

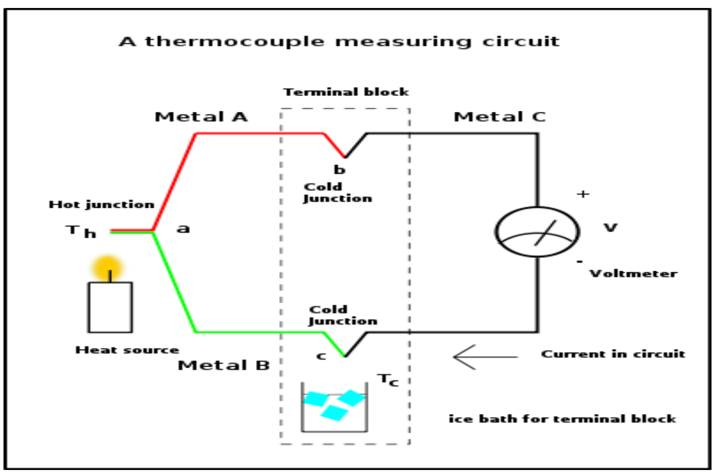
An orifice flow meter is a type of constant-area variable-head flow meter. It consists of a plate with a hole (orifice) through which fluid flows. The pressure difference across the orifice is measured to determine the flow rate. Orifice flow meters are simple, cost-effective, and widely used in industries for measuring the flow of liquids, gases, and steam. They provide reliable performance but may cause some permanent pressure drop in the system.

5. Thermal Mass Flowmeter:

A thermal mass flowmeter measures the mass flow rate of a fluid by utilizing the cooling effect of the fluid on a heated sensor. As fluid flows past the sensor, heat is transferred from the sensor to the fluid. The amount of heat transferred is proportional to the mass flow rate of the fluid. Thermal mass flowmeters are commonly used for gases and are known for their accuracy, especially in low-flow applications.

➢ TEMPERATURE MEASUREMENT:-

Temperature measurement in industrial settings relies significantly on thermocouples, which consist of two dissimilar conductors generating voltage with temperature variation. This voltage is pivotal for gauging temperature differences across the sensor. Thermocouples offer advantages like affordability, interchangeability, and broad temperature range measurement. They are self-powered and need no external excitation, though achieving high accuracy (<1°C error) can be challenging. Alloy selection varies with temperature needs and corrosion resistance. Extension wires economically bridge gaps between sensors and instruments. Electronic instruments compensate for terminal temperature variations, enhancing measurement precision. The ***See beck effect***, discovered by Thomas Seebeck in 1821, underlies thermocouple operation, where temperature gradients along dissimilar metals induce small currents. This principle extends beyond thermocouples, influencing various thermoelectric applications converting temperature gradients into electricity, crucial in energy harvesting and waste heat recovery technologies.



➢ THERMOCOUPLE TYPES

There are several different recognized thermocouple types available. Each type has different useful temperature ranges as well as different recommended applications. ASTM, which is recognized in the United States as the authority for temperature measurement, has established guidelines for the different thermocouple types. These guidelines cover composition, color codes, and manufacturing specifications.

❖ BASE METAL THERMOCOUPLES

Base metal thermocouple types are composed of common, inexpensive metals such as nickel, iron and copper. The thermocouple types E, J, K, N and T are among this group and are the most commonly used type of thermocouple. Each leg of these different thermocouples is composed of a special alloy, which is usually referred to by their common names.

- **Type E** – The type E thermocouple is composed of a positive leg of chromel (nickel/10% chromium) and a negative leg of constantan (nickel/45% copper). The temperature range for this thermocouple is –330 to 1600°F (-200 to 900°C). The Type E Thermocouple has the highest milli volt (EMF) output of all established thermocouple types. Type E sensors can be used in sub-zero, oxidizing or inert applications but should not be used in sulfurous, vacuum or low oxygen atmospheres. The color code for type E is purple for positive and red for negative.

- **Type J** – Type J thermocouples have an iron positive leg and a constantan negative leg. Type J thermocouples have a useful temperature range of 32 to 1400°F (0 to 750°C) and can be used in vacuum, oxidizing, reducing and inert atmospheres. Due to the oxidation(rusting) problems associated with the iron leg, care must be used when choosing this type for use in oxidizing environments above 1000°F.The color code for type J is white for positive and red for negative.
- **Type K** – The type K thermocouple has a Chromel positive leg and an Alumel (nickel/5% aluminum and silicon) negative leg. The temperature range for type K alloys is–328to 2282°F (-200 to 1250°C). Type K sensors are recommended for use in oxidizing or completely inert environments. Type K and type E should not be used in sulfurous environments. Because type K has better oxidation resistance then types E, J and T, its main area of usage is at temperatures above 1000°F but vacuum and low oxygen conditions should be avoided.
- **Type N** – Type N thermocouples are made with a Nicrosil (nickel – 14% chromium –1.5 % silicon) positive leg and a Nisil (nickel – 4.5% silicon -.1% magnesium) negative leg. The temperature range for Type N is –450 to 2372°F (-270 to 1300°C) and the color code is orange for positive and red for negative. Type N is very similar to Type K except that it is less susceptible to selective oxidation. Type N should not be used in vacuum and or reducing environments in an unsheathed design.
- **Type T** – Type T thermocouples are made with a copper positive leg and a constant negative leg. The temperature range for type T is –328 – 662°F (-

200 to 350°C) and the color code is blue for positive and red for negative. Type T sensors can be used in oxidizing (below 700°F), reducing or inert applications.

❖ NOBLE METAL THERMOCOUPLES

Noble metal thermocouples are manufactured with wire that is made with precious or "noble" metals like Platinum and Rhodium. Noble metal thermocouples are for use in oxidizing or inert applications and must be used with a ceramic protection tube surrounding the thermocouple element. These sensors are usually fragile and must not be used in applications that are reducing or in applications that contain metallic vapors.

- **Type R** – Type R thermocouples are made with a platinum/13% rhodium positive leg and a pure platinum negative leg. The temperature range for type R is 32 – 2642°F (0 to1450°C) and the color code is black for positive and red for negative.

- **Type S** – Type S thermocouples are made with a platinum/10% rhodium positive leg and a pure platinum negative leg. The temperature range for type S is 32 – 2642°F (0 to1450°C) and the color code is black for positive and red for negative.

- **Type B** – Type B thermocouples are made with a platinum/30% rhodium positive leg and a platinum/6% Rhodium negative leg. The temperature range for type r is 32 –3092°F (0 to 1700°C) and the color code is gray for positive and red for negative.

❖ REFRACTORY METAL THERMOCOUPLES

Refractory metal thermocouples are manufactured with wire that is made from the exotic metals tungsten and Rhenium. These metals are expensive, difficult to manufacture and wire made with these metals are very brittle. These thermocouples are intended to be used in vacuum furnaces at extremely high temperatures and must never be used in the presence of oxygen at temperatures above 500°F. There are several different combinations of alloys that have been used in the past but only one generally used at this time.

- **Type C** – the type C thermocouple is made with a tungsten 5% rhenium positive leg and tungsten 26% rhenium negative leg and has a temperature range of 32 – 4208°F (0 –2320°C). The color code for this type is white with red tracer for positive leg and red for the negative leg.

➢ Radiation Monitoring Instruments.

Major part of a radiation protection program is extensive monitoring to assure that radiation exposures are kept to a minimum for people working in a nuclear plant as well as those living in the vicinity. The activities include the monitoring of plant personnel, surveying areas with both fixed and portable instruments.

A wide variety of instruments are commercially available to meet these various requirements. They include ***area gamma monitors***, ***contamination monitors***, ***continuous air activity monitors*** etc. They are installed at various critical locations of the plant and generate alarms when the radiation levels exceed pre-defined limits. They generate 4-20 mA standard signals and alarm signals for PLC and subsequent monitoring in operator terminals.

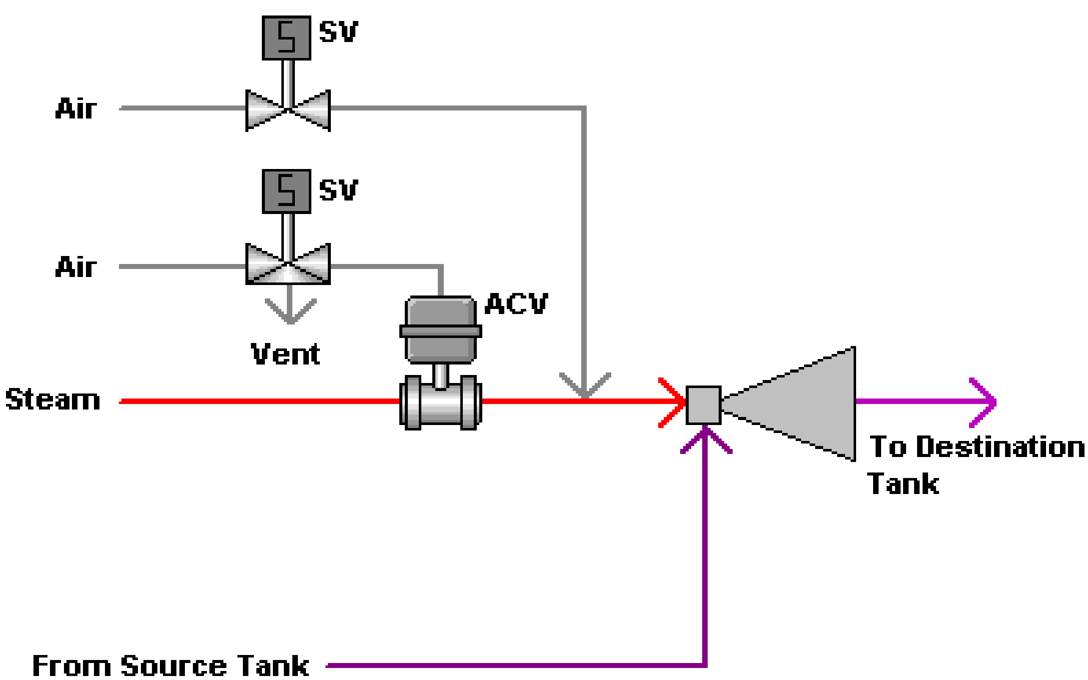
DETAILS OF TRIPS AND CLOSED-LOOP CONTROLS

1. Steam jet Control

Steam jet will not start/will stop if any of the following conditions is met

- Low level in the source tank
- High level in the destination tank
- High pressure in the destination tank

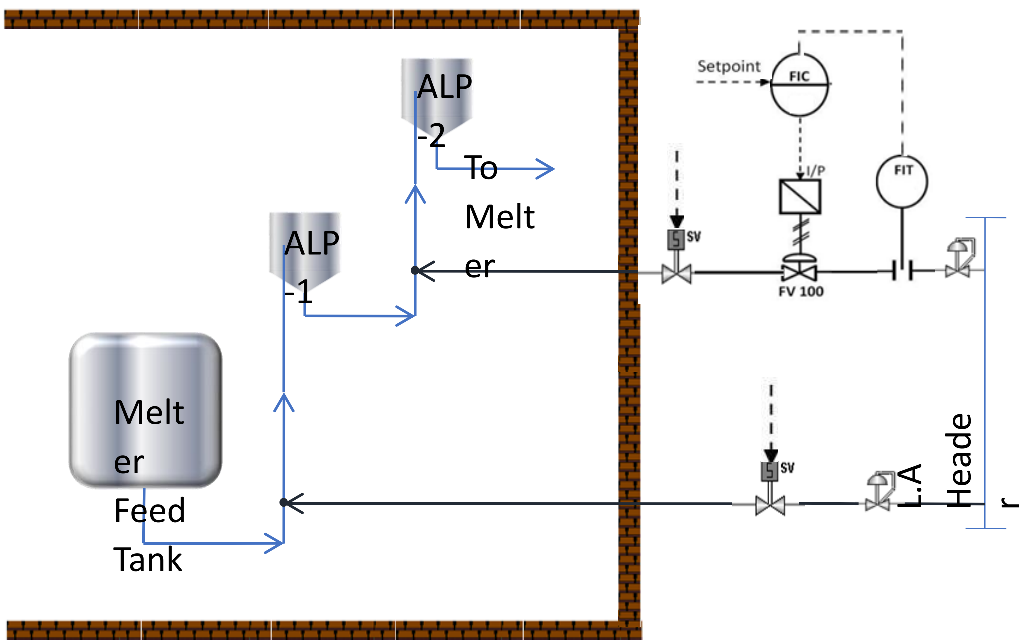
Steam jet will not start and will not stop (if already started) in case of low pressure in air header for siphon breaking
Whenever steam jet is stopped siphon breaking will start for



2. Air Lift Control

Air lift will stop/will not start if any of the following conditions is met.

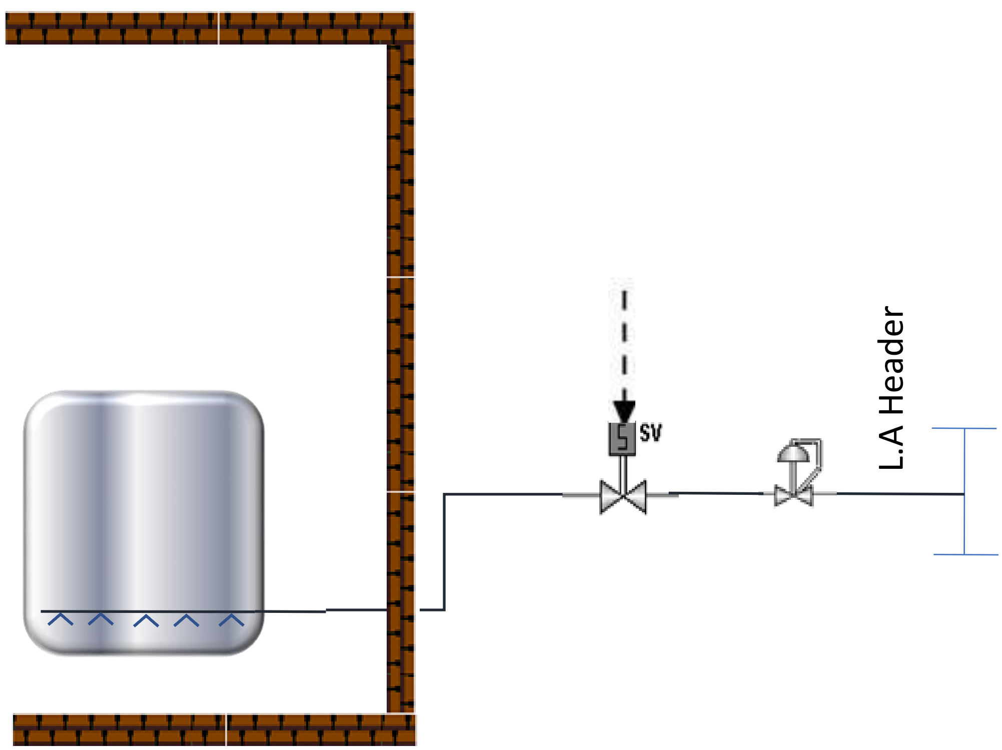
- Low level in the source tank
- High level in the destination tank
- High pressure in the destination tank



3. Air-purging Control

Air purging removes contaminants from enclosed spaces to maintain cleanliness and safety, crucial in industrial applications like pipelines, tanks, and reactors. The process controls airflow, timing, and duration, often automated to monitor pressure differentials and gas concentrations. This ensures compliance with environmental and safety regulations, managing emissions and maintaining air quality standards effectively.

- **Air-purging will not start/will stop in case of high pressure in the tank.**



PROGRAMMABLE LOGIC CONTROLLER (PLC)

• Introduction:

By definition, a PLC is a user-friendly, microprocessor based specialized computer that carries out control functions of many types and levels of complexity. Its purpose is to monitor crucial process parameters and adjust process operations accordingly. In other words PLCs are a type of process control computer: small, relatively inexpensive, industrial grade and easy to program, operate, maintain and repair.

• History & Evolution of PLC

Before the successful induction of PLC into industrial automation system, relay logic schemes comprising of large numbers of relays, timers, counters, process controllers etc. were in operational around the world for many decades. Automation systems based on such relay logic were large in size on account of lots of hardware used with lots of wirings and interconnections. In addition to being bulky, it also would bring the running plants into halt for many days if there were major modification works to be carried out. Loss of revenue faced by large industries during this non-productive shutdown period eventually paved the way for industrial grade PLCs.

The first PLC system evolved from conventional computers in the late 1960s and early 1970s. Among other industries, automotive plants were first to use PLCs. The PLC keyboard reprogramming replaced the rewiring of a panel full of wires, relays, timers and other components.

There was a major problem with these early 1970s computer/PLC reprogramming procedures. The programs were complicated and required a highly trained programmer to make the changes. Through the late 1970s, improvements were made in PLC programs to make them somewhat more user-friendly; in 1972, the introduction of the microprocessor chip increased computer power for all kinds of automation systems and lowered the computing cost. Robotics, automation devices and computers of all types, including the PLC, consequently underwent many improvements. PLCs became more affordable also.

In the 1980s, with computing power becoming cheaper, the PLC came into exponentially increasing use. An economical estimate states that the market for

PLCs grew from a volume of \$80 million in 1978 to \$1 billion per year by 1990 in America alone. With the price reductions and technical advances, applications of PLCs have mushroomed. Use of PLC has also expanded in safety systems and for redundancy for greater reliability.

• PLC: Major Advantages

Following are major advantages of using a programmable logic controller.

a) **Compact Size:** As hardware such as relays, contacts, timers, counters, process controllers etc. which formed the part of conventional relay logic system, are replaced by software and programmable control blocks in PLC, use of panels with smaller dimensions became possible in place of large sized relay logic panels.

b) **Flexibility:** In the past, each electronically controlled machine/device required its own dedicated controller; 10 machines might require 10 different controllers. Now it is possible to use a single model of PLC which can control all the 10 machines simultaneously. Each of the machines under PLC control would have its own distinct program.

c) **Implementing Changes and Correcting Errors:** With a wired relay-type panel, any program alteration requires time for rewiring of panels and devices. But any alteration in PLC program can easily be typed in quickly from a key board and it does not involve any rewiring. Latest PLC models even allow on-line editing with which PLC implements any modification without halting any of its activities.

d) **Large Quantities of Contacts:** The PLC has a large number of contacts for each coil available in its programming. But in a conventional relay logic system, relays generally come with a maximum of 04 contacts. If additional contacts are required for any modification purpose, extra relays need to be installed and wired. But with a PLC, use of additional contacts would mean just typing in extra contacts from a key board. Indeed a hundred contacts can be used from one relay- if sufficient computer memory is available.

e) **Pilot Running:** A PLC programmed circuit can be run and evaluated in the office or lab, before putting it into actual use. The program can be typed, tested, observed and modified if needed, saving valuable factory time. In contrast, conventional relay systems have been best tested on the factory floor, which can be very time consuming and any single mistake in wiring may cause equipment damage and/or personal injury.

f) **Visual Observation:** A PLC circuits operation can be seen during operation directly on a monitor. The operation or disoperation of a circuit can be observed as it happens. Logic paths light up on the screen as they are energized. Troubleshooting can be done more quickly during visual observation. PLC programs can be made, named and stored in sections and each variable in the program can be given pseudo names which indicate its duty in the process system instead of tagging them in terms of PLC addresses. This gives a physical feeling of making up a plant control virtually in the PLC programming environment. In addition to this, these kinds of programs are readily suited for future reference and presentation.

g) **Speed of Operation:** The operational speed of the PLC program is very fast in contrast to that of relays. The speed of PLC operation is determined by its scan time, which is a matter of milliseconds.

h) **Reliability & Maintainability:** Solid-state devices used in PLC are more reliable, in general, than mechanical systems of relays and timers. PLC is made of solid-state components with very high reliability rates. Consequently the control system maintenance costs are low and downtime is minimal.

i) Documentation: An immediate printout of the true PLC circuit is available in minutes, if required. There is no need to look for the blueprint of the circuit in remote files. The PLC prints out the actual circuit in operation.

j) **Security:** A PLC program change cannot be made unless the PLC is properly unlocked and programmed. Relay panels tend to undergo undocumented changes.

• PLC: Some Limitations/Precautions

Following are some of the limitations of, or some precautions involved in, using PLCs. For repair/maintenance of PLC hardware components, the end user is fully dependent on the manufacturer or authorizes service provider.PLC system hardware and software are found to obsolete very fast and this result in significant expenditure for system up gradation.

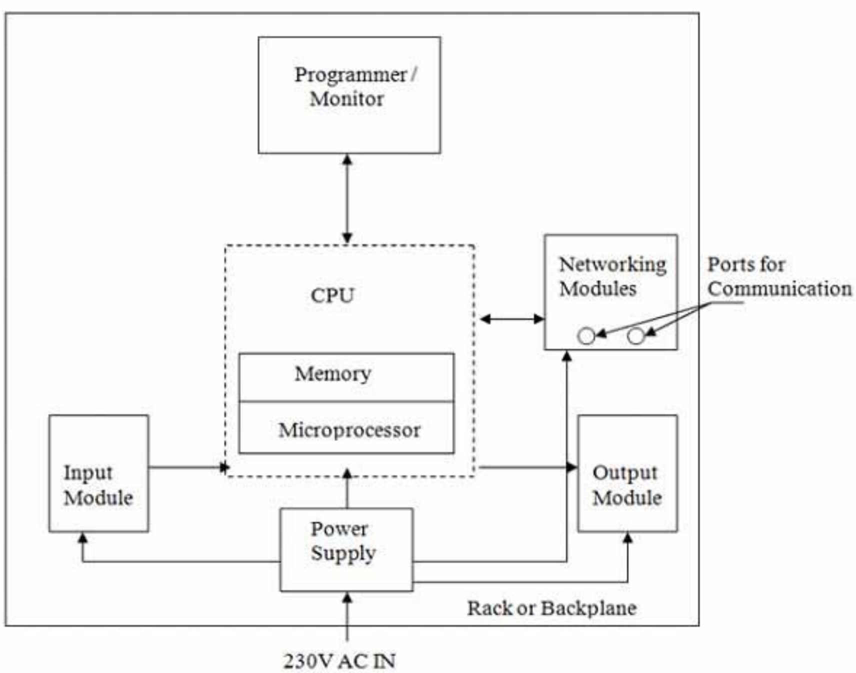
Certain process environments, such as high heat and vibration interfere with electronic devices in PLCs, which limit their use. For small sized process industry with lower level of complexities and program alteration is seldom done, use of simple relay logic panels is advantageous on cost basis. Another main disadvantage of using PLC is the requirement of trained personnel for its maintenance. In contrast, the conventional relay logic system, owing to its simplicity, can easily be maintained by any technician-level crew of the factory.

• Salient Features of Latest PLC Models

Latest PLC models have many attractive features. Some of them are listed below.

1. Hot redundant standby processors for more reliability.
2. More advanced control functions.
3. Capability for solving complicated mathematical functions.
4. More number of PID process-control loops.
5. More networking capabilities.
6. On-line edit facility.
7. System generated bits for fault detection.
8. More user-friendly programming methods.
9. Expandable program memory by the use of PCMCIA cards etc.

Figure – 3 Overall PLC System.



1. Central Processing Unit (CPU)

This can be considered as the brain of the system. It has got three subparts:

a. **Microprocessor**: - This is the computer center that carries out mathematic and logic operations.
b. **Memory**: - The area of the CPU in which data and information is stored and retrieved. It holds the system software and user program.
c. **Power Supply**: - This unit converts alternating current (AC) line voltage to various operational DC voltage levels required by various modules of PLC. It rectifies the line voltage, filters the rectified output and then regulates it against line and load variations.

2. Programmer/Monitor

The programmer/monitor (PM) is a device used to communicate with the CPU of PLC. It is the unit with which a PLC is configured and programmed. It can take various forms like hand-held terminals, industrial terminals and personal computers. In hand-held terminals inputting takes place through a membrane key pad and the display is usually a liquid crystal display (LCD). In industrial terminals and personal computers inputting occurs through a key board and display is a cathode ray tube (CRT) or LCD monitors. In either case PLC programming software supplied by the PLC-manufacturer is loaded in these devices.

3. Input/output Modules

Input and output modules are jointly called I/O modules in PLC terminology. The input modules have terminals into which outside process electrical signals, which are generally scaled into industrial standard of 4-20 milli amperes DC, generated by sensors and transducers are entered.
The output modules have terminals from which electrical signals are sent to activate relays, solenoids, various solid-state devices, motors and displays.

I/O modules contain various electronic circuits which do various signal processing techniques on the electrical signals they receive. These techniques include filtering, sample and hold, amplification, isolation, analog-to-digital & digital-to analog conversion, binary encoding, decoding, serial-to-parallel & parallel-to-serial conversion etc.

The actual physical location of operating process system can be thousands of feet away from the PLC panel.

4. Networking/Communication Modules

In some cases the CPU of a PLC may be required to exchange information with other PLCs, other intelligent devices, Human-Machine Interface terminals, I/O modules of the same PLC which are located at another rack/backplane other than the rack in which CPU located etc. Hence under such situations CPU of the

PLC is made to act as part of a network. It necessitates the use of networking/communication module as part of a PLC system. Its primary function is to make the data to be exchanged compatible to all the members of the network. In this process it implements some sort of industrial communication protocols. Today networking modules supporting various protocols such as Ethernet TCP/IP, Modbus etc. are available.

5. *Racks or Backplanes*

In a PLC panel, all its operational modules including the CPU are placed in racks or backplanes. Different buses such as address bus, control bus and data bus in the backplane serve for the interconnectivity of all the modules inserted in a rack. The racks are provided with slots for placing each module and some sort of locking arrangement is also provided at the top and bottom of the slot which firmly holds the inserted modules. Racks with 8, 10, 12 slots are common and their selection depends on the application. Generally one power supply module provides various operational DC voltage levels required for all other modules inserted in that rack.

• Input and Output (I/O) Modules.

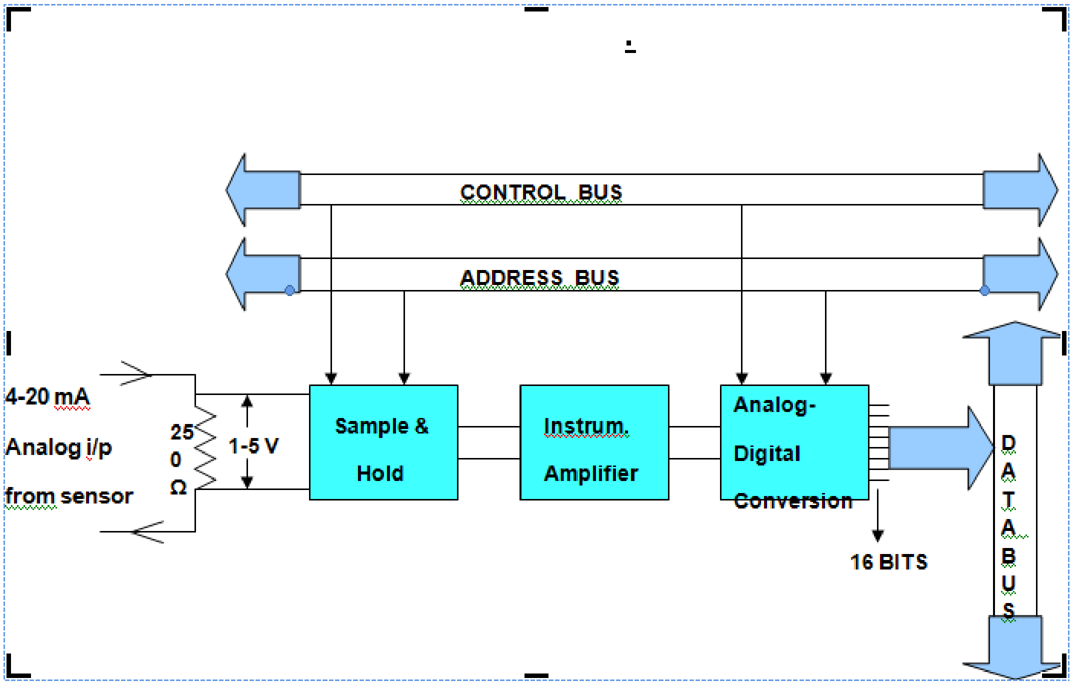
We get information in and out of a PLC through the I/O module. The input module terminals receive signals from field-mounted sensors and transducers, whereas output module terminals provide output voltages to actuate output devices connected in the process. Generally I/O modules are provided with LED/LCD status indicators on them.

One I/O module can handle signals from many devices. 4, 8, 12, 16, &32 channel I/O modules are commonly available in PLC market today.

I/O modules can be co-located in the same rack in which CPU module is placed, subjected to the availability of spare slots in that rack. Such I/O points are termed as ***local I/O.*** In some instances, where different units of a process plant are physically separated from each other, considerable amount of cabling can be saved if some I/O modules are placed at each of the plant locations and then they are networked to the CPU module located at some distant away from the plant using a pair of industry standard wires. These I/Os which are not placed in the main CPU rack are called ***remote I/O.***

I/O Modules are also classified based on the nature of the signals they process. Hence they are divided into four major groups are given below.

a) **Analog Input (AI) Modules:** They receive analog voltage or current signals generated by input sensors and transducers. Generally they are signals scaled in the industry standard range of 4-20 milli Amperes DC current and they correspond to process parameters such as pressure, level, density, flow rate, temperature, pH, moisture, conductivity etc. There are ***special modules*** which directly receives non-scaled raw signals from sensors. For example AI modules, specially designed for a particular type of thermocouple sensor for temperature measurement, houses additional electronic circuitry for amplification, cold junction compensation(CJC), voltage-to current conversion etc.



As eventually the processor of the PLC understands the language of 1s and 0s only, ***analog-to digital conversion (ADC)*** is an inevitable part of the AI module. The ***resolution of ADC*** used is a critical parameter as this puts a lower limit in the degree of resolving the variation of input parameters. A 12 bit ADC resolves the input variation to 1 part in 4096 of the scaled input range. Conversion time is also critical as large conversion time means slower sampling of process parameters. A typical AI module is shown in Figure.

b) Digital Input (DI) Modules: They receive electric signals of discrete nature and generally correspond to ON/OFF statuses of input devices. It is possible to wire an input device like a pressure switch (for example) to a DI module in such a way that whenever the input pressure to the switch exceeds a pre-defined level, a 24V DC voltage appears at the input terminal of the module and whenever the pressure is below the set level, 0V DC voltage appears at the module.

The input devices can be connected to a DI module in two ways. In one mode, the device is connected to the high potential side of the power supply and terminals of the module serve to drain current to the lower potential side of the supply. This kind of module is said to be operating in ***current sinking*** fashion. In contrast, if the device terminals serve to drain current to ground and module terminals are connected to higher potential side of the power supply, the module is said to be operating in ***current sourcing*** fashion. A typical DI module is shown in Figure.

Major specifications of DI module are number of channels per module, ON/OFF voltage levels, input impedance, input current, minimum ON/OFF currents, OFF-to-ON response time, ON-to-OFF response time etc.

c) Analog Output (AO) Modules: They serve to supply analog signals to actuate output devices like throttling valves which position their plugs anywhere between two limits (marked as 0% and 100%) depending on the strength of the signal supplied to them. ***Digital-to analog conversion (DAC)*** thus is an inevitable part of this module. Resolution and conversion time have great significance on plant performance because of similar reasons given for AI modules. Major specifications of AI modules are number of channels per module, resolution and conversion time of DAC, maximum loop impedance, linearity error, accuracy etc.

d) **Digital Output (DO) Modules:** They supply discrete electrical signals mainly to ON/OFF or OPEN/CLOSE output devices. These devices include motors, solenoid operated valves etc. Sometimes interposing relays are used to connect the load (devices) to this module. Interposing relays are mainly for two purposes. First they provide isolation between the electronic circuitry of the module and the load. Secondly the relay contacts can safely carry the load current whereas current rating of the solid state transistor switches in the module may be too low for larger loads. Major specifications of a do module include number of channels per module, maximum safe voltage, on voltage drop, current rating, and maximum leakage current, off-to-on & on –to-off response times etc.

• CPU Operation

The basic operating system of the PLC instructs the processor to operate through different activities in a sequential manner. Various major activities accomplished by the processor are summarized below.

a. Read inputs from the input image registers.
b. Solve the user program
c. Write outputs to output image registers.
d. Communicate with peripherals.
e. Self-diagnostics etc.

Upon completing the last activity, the processor is made to go back and start afresh all the tasks repeatedly. This cyclical operation of a processor is called ***CPU scanning.*** Time taken by the processor to finish one complete sequence is called scan time. The scan time in a PLC is a critical parameter because too large scanning time means updating the information regarding each input/output in PLC is less frequent. Generally the PLC scan time is in milli seconds. Scan time depends on bit size & clock speed of the processor and size of the user program. A watch dog timer in the processor keeps record of each scan time and sets its output whenever the scan time exceeds pre-defined limit. In most instances too long scan time is caused by bugs in the user program.

• CPU Programming.

Programming of CPU means creation of user program and entering various operational parameters of CPU such as speed of communication, baud rate, parity, number of bits in the frame, fail safe mode of operations, watch dog time setting etc.

Programming of CPU is done by using a device called programmer/monitor. It can take various forms like hand-held terminals, industrial terminals and personal computers. In all these forms programming software, supplied by the PLC manufacturer, is loaded into them. Generally these are Windows based software packages that support many of Windows-features such as cut/copy and paste between applications point and click editing, viewing and editing multiple applications at the same time.

- **Programming Methods.**

Standard ***IEC 1131-3*** defines five (5) types of programming methods. They are listed below.

a. Ladder Diagram.
b. Function Block Diagram.
c. Instruction List.
d. Structured Text.
e. Sequential Flowchart.

Among all the above methods, ladder diagram and function block diagram are most widely used because of their simplicity and ease of programming.

Human Machine Interface (HMI) Software Package

HMI software packages or sometimes called as ***Supervisory Control and Data Acquisition (SCADA)*** software synonymously are basically used to manage and monitor processes. They are installed in industrial or personal computer terminals which are then termed as ***operator console stations (OCSs).*** The so called OCSs can act as PLC programming terminal too. They communicate with PLC and thus aid plant operators to monitor and control processes more efficiently.

- **Functions of HMI**

Major functions common to any HMI package are listed below.

1. Depict the overall process flow diagram including all parameter measurements and controls in the monitor of OCS.
2. Display statuses or information of various equipment or devices in the plant in different standard formats such as numerical, bar graph, graduated dial, trend, report etc.
3. Provide control screens which accept commands of the operator and pass on these commands as inputs for PLC.
4. Animate symbols of equipment or devices in the graphics to indicate their operational statuses.
5. Storage of historical plant data and presentation of the same as trends and reports on request from operator.

6. Provide audio/visual alarm annunciation. Recorded sound files can be played at the occurrence of certain configured events.
7. Allow the administrator to configure the way data is displayed and the graphics are shown.
8. Develop a multi layered security system that controls user access according to functional groups or geographical areas.

• **Architecture of HMI**

Architecture of an HMI package can be divided into three (3) distinct areas of functionality:

1. Configuration
2. Runtime
3. Drivers

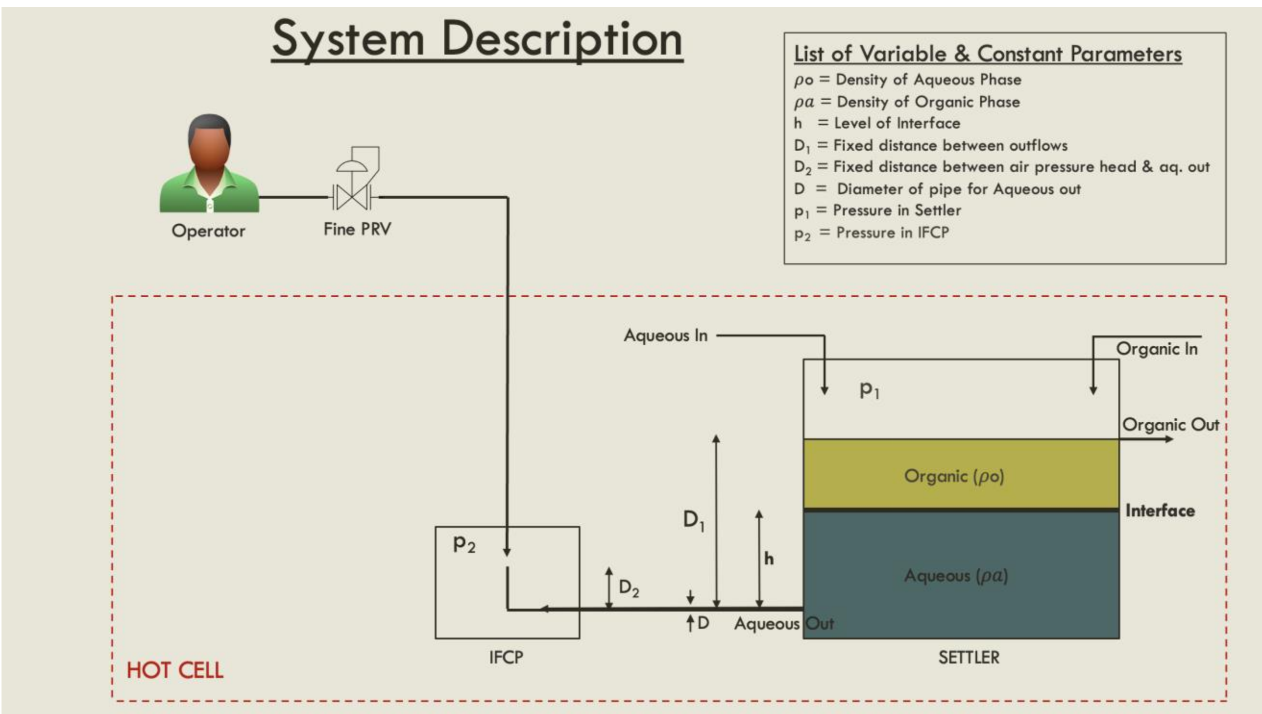
Configuration involves all tasks required to build a project such as creation of graphics, tagging of variables involved in it, configure the controls, configure the way data is to be displayed, configure the parameters essential communication with PLC etc.

Runtime is the implementation of a project in a live production environment. Drivers enable communication with devices like PLCs via a number of communication protocols. The driver defines the specific project settings required for HMI to communicate with a particular device. This includes information about boards, ports, devices, tag addressing etc.

Mini Project- Automatic Interface Control in Extractor/Stripper in a Solvent Extraction Plant

• System Description

There exists a system of 12 settler-mixer containers with an ***IFCP (Interface Controlled Pot)*** attached to the last stage. Taking this setup from the final stage, we have a container (settler-mixer) where organic and aqueous solvents are present and an IFCP attached to it. The setup looks like the following:



We have 2 inlets (for aq. and org. solvents to enter) and 2 outlets (for aq. and org. solvents to leave) in the Settler.

The org. outflow is at an overflow condition where the entire volume does not go beyond the constant height D1.

Similarly, the aq. outflow is at a constant height from the bottom of the tank and this height is taken as the base for all calculations. This pipe is attached to the

IFCP where the aq. solvent is finally drained out from the system, at a constant height D2.

• **Problem Description**

Due to the natural density difference among the aq. and org. solvents, an interface is formed in the settler and this level is what we seek to regulate, denoted by height 'h'. It, in the worst case, must not reach D1 or 0 as then the wrong solvent will start draining out. Hence, this process is currently controlled manually by an operator by operating a fine mechanical pressure regulating valve (PRV), which changes the pressure 'P2' in the IFCP. 'P1' is the constant pressure maintained in the settler. The difference in pressures P1-P2 changes the aq. volumetric flow (q_o) which in turn affects the interface level 'h'. The operator in control room, with access to parameters P_1 , P_2 , ρo , ρa , h communicates the changes to be made to the operator near fine PRV. However, this being a manual process, it is cumbersome, time-consuming and the setting of fine PRV for small pressure variations of the order of a few mmwc is quite difficult. An automatic interface control can circumvent these concerns!

Here is the outline and methodology as presented:

1. Exploring the possible Governing Laws and Principles
2. Checking the Applicability of these laws and principles using realistic process data
3. Developing Mathematical Model of the plant
4. Designing a Controller
5. Simulation Studies
6. Analysis of results

Governing Equation for the Rate of Accumulation of Aqueous Phase in the Settler:

Rate of Inward Volume – Rate of Outward Volume = Rate of Accumulation

$q_i - q_o = A\frac{dh}{dt}$

To find the relation between q_o and h, do we use Poiseuilles Law or Bernoulli's Equation ? Lets analyze:

1. ***Advantages of Poiseuille's:***
    a. It provides a linear relation.
    b. It is easy to design with system parameters.
2. ***Disadvantages of Poiseuille's:***
    a. It does not consider any sort of losses.
3. ***Advantages of Bernoulli's:***
    a. It considers acceleration losses.
    b. It is realistic in nature.
4. ***Disadvantages of Bernoulli's:***
    a. No frictional losses considered.
    b. Not linear in nature.

Additionally, at q_0 = 100 lph:

ΔP in Poiseuille's $\approx 1\, mmWc$

ΔP in Bernoulli's $\approx 10\, mmWc$

The ΔP in Bernoulli's obtained is realistic. Hence, we go ahead with it, by linearizing Bernoulli's Equation Around the Chosen Operating Point.

• Mathematical Modelling of the Plant

By applying Bernoulli's Equation in the plant, we get:

$$h(\rho a - \rho o)g + D_1\rho o g + p_1 = p_2 + \frac{1}{2}\rho a\{\frac{4q_o}{\pi D2}\}^2 + D_2\rho a g$$

.

.

$$q_o = \sqrt{[7.8378e^{-7}h + 5.5648e^{-7} + 1.9974e^{-10}p_1 - 1.9974e^{-10}p_2 - 6.8189e^{-7}]}$$

From the above equation, we can conclude that Bernoulli's Equation doesn't provide us a linear output.

Hence, we need to linearize the equation to proceed further.

Linearizing The Bernoulli's Equation Using Taylor Series Expansion

Taylor's Series Expansion :

If, $y = f(x)$

Then $y = y_0 + \frac{dy}{dx}\Big|_{x=x_0}\frac{(x-x_0)}{1!} + \frac{dx^2}{d^2y}\Big|_{x=x_0}\frac{(x-x_0)}{2!} + \frac{dx^3}{d^3y}\Big|_{x=x_0}\frac{(x-x_0)}{3!} + \ldots\ldots\ldots\ldots$

Here,

The operating point is (x_0, y_0)

Relation b/w q_o and other parameters in the operating region of interface

$q_o = f(p_1, p_2, h)$

Operating Point :-

$H = 180$ mm

$P_1 = -120$ mmWc

$P_2 = -110$ mmWc

So Using the above expansion, we can derive :

$$q_0 = Q_0 + \frac{\partial q_0}{\partial h}\Big|_{\substack{h=H\\p_1=P_1\\p_2=P_2}}\Delta H + \frac{\partial q_0}{\partial p_1}\Big|_{\substack{h=H\\p_1=P_1\\p_2=P_2}}\Delta P_1 + \frac{\partial q_0}{\partial p_2}\Big|_{\substack{h=H\\p_1=P_1\\p_2=P_2}}\Delta P_2$$

Here

$\Delta H = h - H$

$\Delta P_1 = p_1 - P_1$

$\Delta P_2 = p_1 - P_2$

N.B. : We have ruled out the other higher order terms which have very negligible effect.

After the final derivation, we find this relation :

$$q_0 = Q_0 + 0.00919 \times \Delta H + 0.000002342276 \times \Delta P_1 - 0.00002342276 \times \Delta P_2$$

It is the final linearized equation.

Putting this equation in the Governing Equation, we get :

$\Delta Q_i - \Delta Q_0 = A\frac{d\Delta H}{dt}$

.

.

.

$\Delta Q_i - 0.00919\Delta H - 0.000002342276\Delta P_1 + 0.000002342276\Delta P_2 = A\frac{d\Delta H}{dt}$

$$\boxed{\Delta Q_i - 0.00919\Delta H - 0.000002342276\Delta P_1 + 0.000002342276\Delta P_2 = 1.78 \times \frac{d\Delta H}{dt}}$$

The plant model (in red box) can be represented in

1. State-space Method or
2. Classical Transfer Function Method

• State-space Method

Using state-space method:

State variables are: ΔH

Inputs are: ΔP_1 , ΔP_2 , ΔQ_i

Outputs are: ΔH

Thus, expressions formed are:

$$\dot{\Delta H} = [\,0.0051629\,]\,\Delta H + [\,-0.00000131588539\,,\,0.00000131588539\,,\,0.5618\,]\begin{bmatrix}\Delta P_1\\ \Delta P_2\\ \Delta Q_i\end{bmatrix}$$

$$\Delta H = [\,1\,]\,\Delta H + [\,0\,]\begin{bmatrix}\Delta P_1\\ \Delta P_2\\ \Delta Q_i\end{bmatrix}$$

These can be further solved, however we choose the classical transfer function method owing to its ease of use for our, relatively, simple system.

• Classical transfer function method

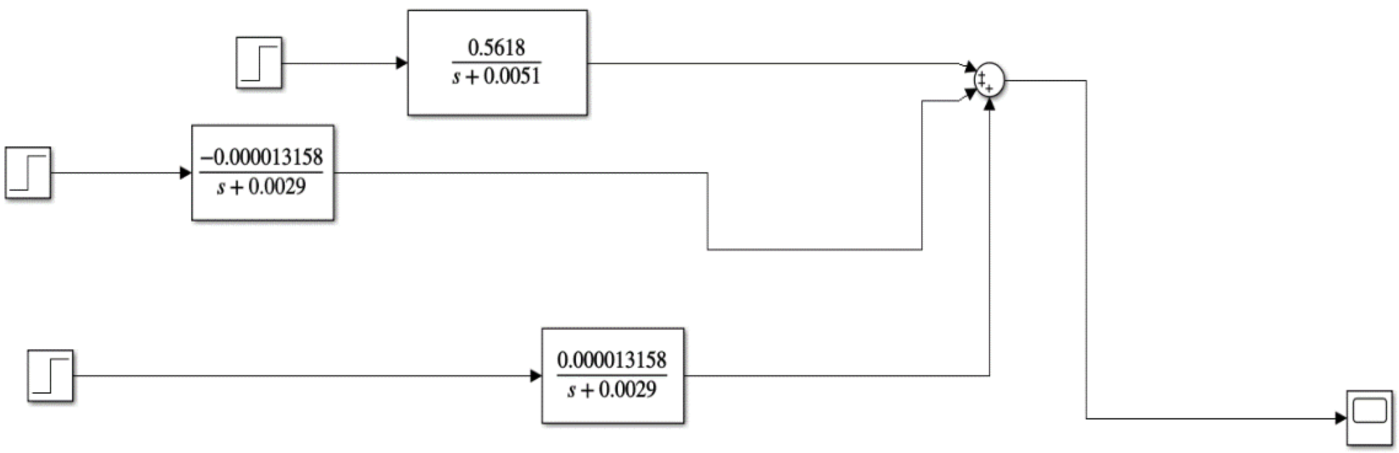
We have the following equation of the plant:

$$0.5618\,\Delta Q_i - 0.0051629\,\Delta H - 0.00000131588539\,\Delta P_1 + 0.00000131588539\,\Delta P_2 = \frac{d\Delta H}{dt}$$

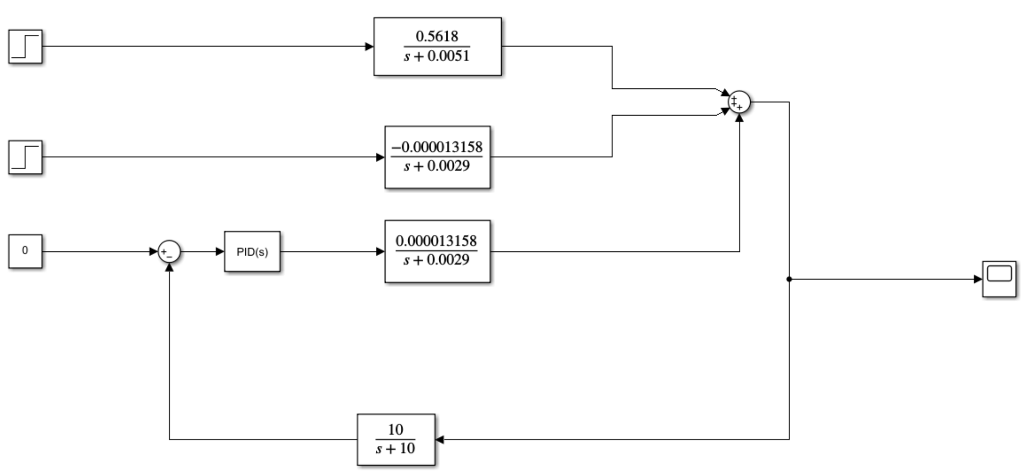
Now, We take Laplace Transform of the equation to get :

$$\boxed{0.5618\,\Delta Q_i(s) - 0.0051629\,\Delta H(s) - 0.00000131588539\,\Delta P_1(s) + 0.00000131588539\,\Delta P_2(s) = s\,\Delta H(s)}$$

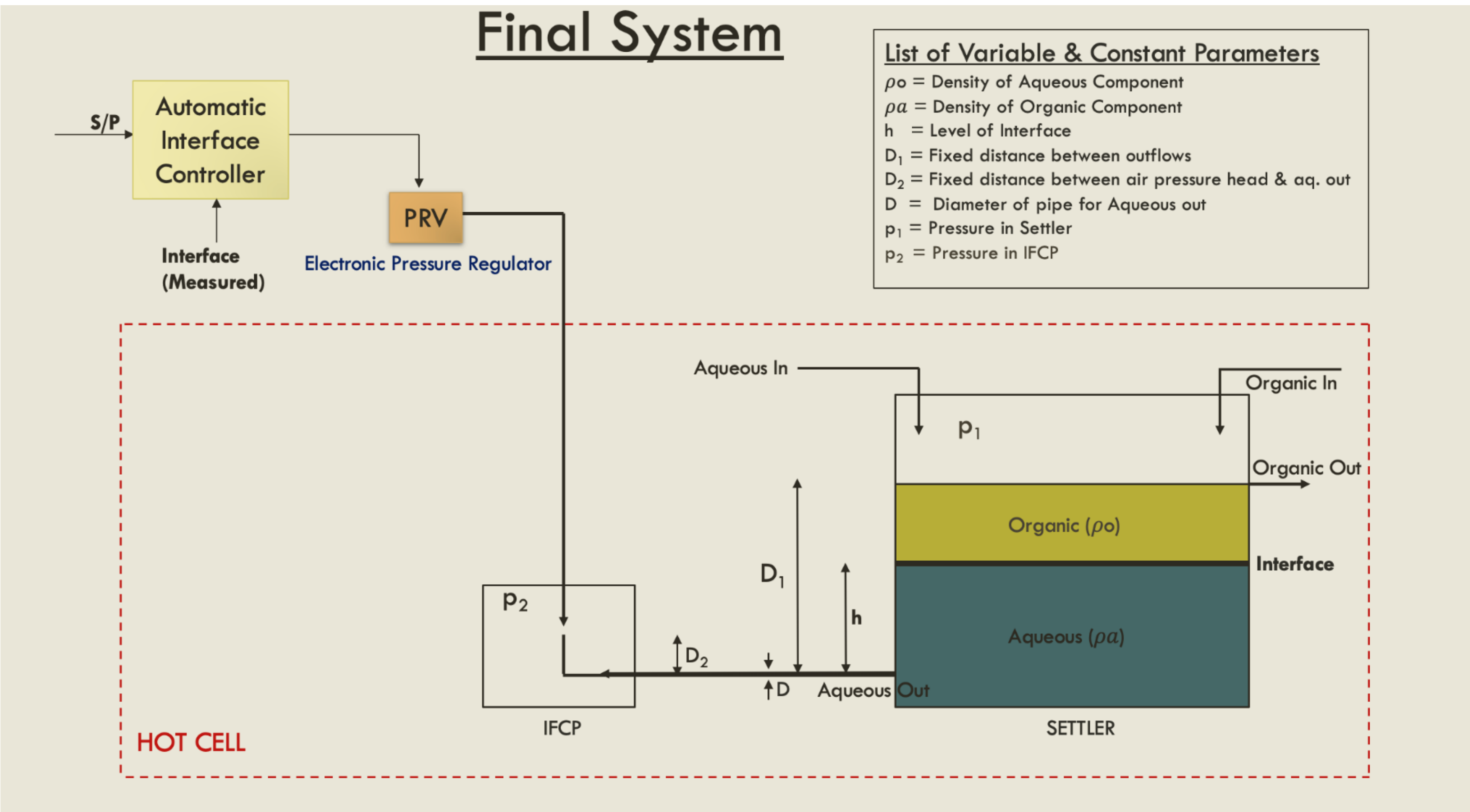
Rearranging, and taking ΔH(s) with respect to each of the other variables by keeping other two as zero, we get:



After closing the loop, and putting a PID controller, we get:



And, after putting this in our actual plant, we get the following:



• Results and Conclusion

Simulated Step Change in Aqueous-in Flow Rate (Q_i)

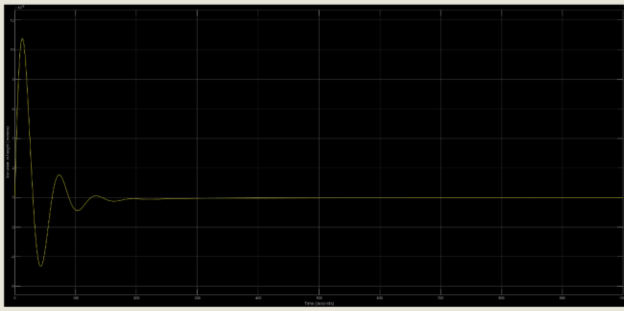


Fig 1.1 – When $\Delta Q_i = +10$ lph
Peak Overshoot ≈ 0.0099 mm
Settling Time < 100 sec

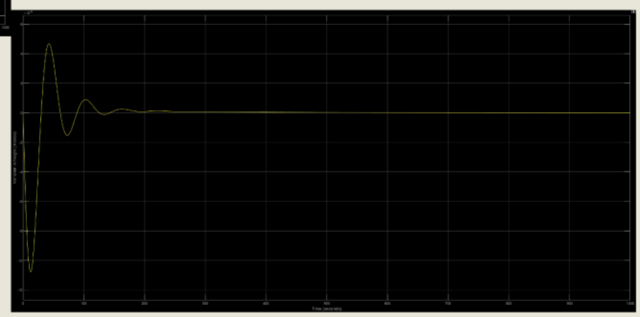


Fig 1.2 – When $\Delta Q_i = -10$ lph
Peak Undershoot ≈ 0.0099 mm
Settling Time < 100 sec

Simulated Step Change in Pressure in Settler(P_1)

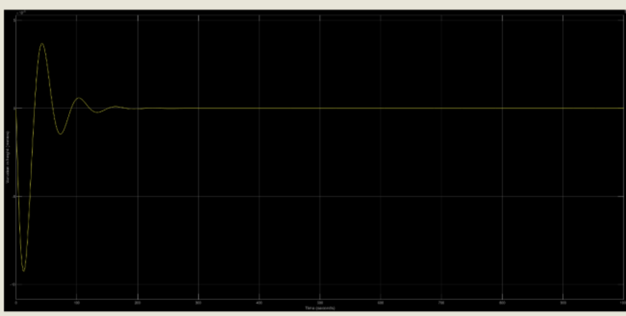


Fig 2.1 – When $\Delta P_1 = +10$ mmWc
Peak Undershoot ≈ 0.828 mm
Settling Time < 100 sec

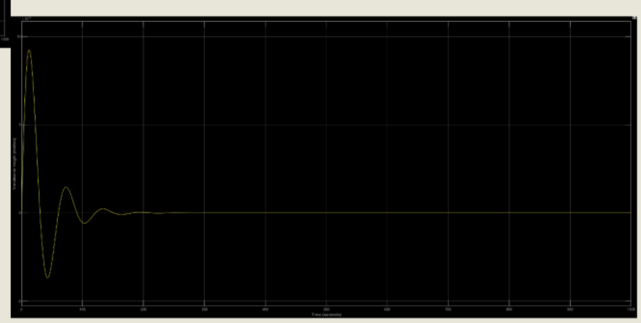


Fig 2.2 – When $\Delta P_1 = -10$ mmWc
Peak Overshoot ≈ 0.828 mm
Settling Time < 100 sec

Simulated Step Change in Set point of Interface(H)

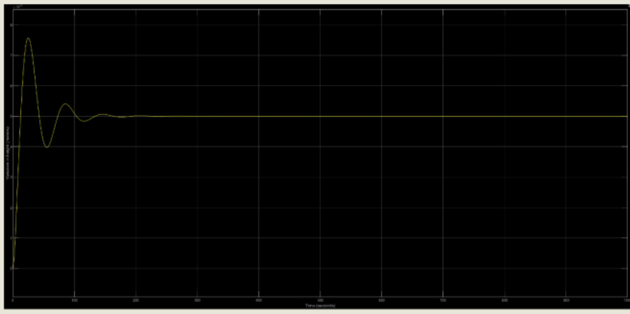
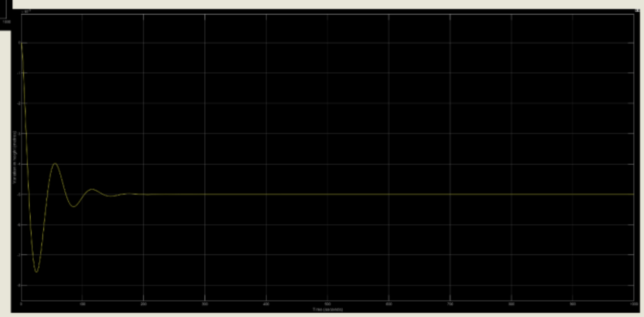


Fig 3.1 – When $\Delta H = +5$ mm
Peak Overshoot $\approx$ 6.75 mm
Settling Time < 100 sec

Fig 3.2 – When $\Delta H = -5$ mm
Peak Undershoot $\approx$ 6.75 mm
Settling Time < 100 sec



Simulated Step Change in Q_i & P_1 simultaneously

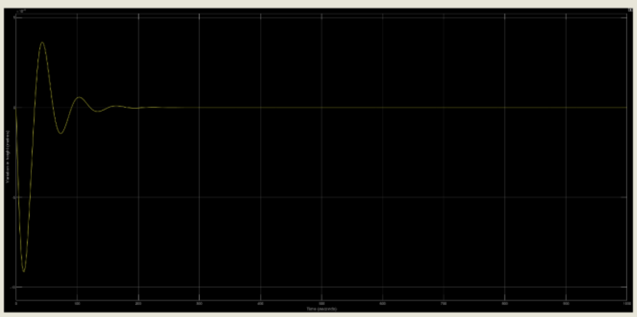


Fig 3.1 – When $\Delta P_1 = +10$ mmWc
$\Delta Q_i = +10$ lph
Peak Undershoot $\approx$ 0.036 mm
Settling Time > 100 sec

Considering ΔQ_i and ΔP_1 as disturbances, with ΔH as input change, and giving step input change for all of these, we can observe extremely satisfactory results, as the change in ΔH is low for all. The peak undershoot and settling time are also acceptable for all of the cases.

However, there is a difference between how ΔQ_i and ΔP_1 affect the system.

With a change of $\Delta Q_i = +10$ lph, we get Peak Overshoot $\approx$ 0.0099 mm.

With a change of $\Delta P_1 = +10$ mmWc, Peak Undershoot $\approx$ 0.828 mm.

- **Future Study**

It is observable that, although both are acceptable, a change of ΔP_1 affects the system much more than a change of ΔQ_i does.

1. Thus, as a future study, we can use a cascade loop controller with the inner loop regulating ΔP_1 to produce results which are even more consistent.
2. We can also use a neuro-fuzzy controller to introduce the human aspect into this system and gain more control over it with the classic steps-fuzzification, fuzzy set, and defuzzification.
3. We may use non-integer type controller where the order of derivative and integral in PID controller is a fractional value. This would introduce 2 more parameters apart from the classic 3, to gain more control over the system.
4. Adaptiveness and robustness are an integral aspect of any system which can never be overlooked. Adaptiveness of a system suggests how well the system is ready to change with the intentions of the operator while robustness suggests how well a system persists under unexpected changes in the system. We wish to measure and carefully regulate both in the future.
5. Hardware implementation and validation of this system simulated on MATLAB is a pending task. It would give more clarity over parts of the system that we have designed and real-life implementation can then be done once these results come out to be successful.

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