CH 42010: PROCESS PLANT OPERATION & SAFETY

LTP: 3-0-0, CRD: 3

Lecture 4

Operations at Steady State

STEADY STATE

- In systems theory, a system or a process is in a steady state if the variables (called state variables) which define the behavior of the system or the process are unchanging in time.

- In continuous time, this means that for those properties/variables 'p' of the system, the partial derivative with respect to time is zero and remains so:

$$\frac{\partial p}{\partial t} = 0 \quad \text{for all present and future } t.$$

- In discrete time, it means that the first difference of each property/variable is zero and remains so:

$$p_t - p_{t-1} = 0 \quad \text{for all present and future } t.$$

- A steady state flow process requires conditions at all points in an apparatus remain constant as time changes. There must be no accumulation of mass or energy over the time period of interest.

- The same mass flow rate will remain constant in the flow path through each element of the system. Thermodynamic properties may vary from point to point, but will remain unchanged at any given point.

STEADY STATE

- **Steady state is a more general situation than dynamic equilibrium.**
- While a dynamic equilibrium occurs when two or more reversible processes occur at the same rate, and such a system can be said to be in steady state.
- **A system that is in steady state may not necessarily be in a state of dynamic equilibrium**, because **some of the processes are not reversible**.

Source: Google Images

- The principle of steady state flow in thermodynamics and fluid mechanics states that the properties of a fluid, such as density, pressure, and velocity, remain constant at any given point in a system over time, as long as there is no change in the overall energy or mass of the system.

- This principle applies to both incompressible and compressible fluids but is more commonly used in the analysis of incompressible fluids.

STEADY STATE

- Steady state refers to a condition in a process system where all **operational parameters**, such as **temperature, pressure, flow rates, and concentrations**, **remain constant over time**.

- This happens when **the input and output rates of material, energy, and momentum are balanced**. Essentially, the system is in equilibrium, with no net accumulation or depletion within the process.

- For example: In a continuous chemical reactor, steady state is achieved when the rates of reactant addition and product removal are constant, and the internal conditions of the reactor remain unchanged.

STEADY STATE

Importance of Steady State in Plant Operations:

- **Efficiency:**
  - Achieving steady state ensures that the process operates at optimal conditions, maximizing productivity while minimizing waste.
  - Dynamic changes or unsteady conditions can lead to inefficiencies, such as energy loss or raw material wastage.
- **Product Quality:**
  - Many processes, such as chemical reactions or material synthesis, require stable conditions to produce consistent, high-quality products.
  - Variations in operating parameters during unsteady conditions can result in defects, impurities, or off-specification products.
- **Energy Conservation:**
  - At steady state, energy input matches the energy demands of the process, avoiding overuse or underutilization.
  - This reduces energy losses associated with frequent start-ups, shutdowns, or process fluctuations.

STEADY STATE

- **Challenges and Considerations in Achieving Steady State:**
  - Start-up and shutdown procedures often involve transient conditions where steady state is not yet established.
  - External factors, such as changes in feed composition or environmental conditions, can disrupt steady state.
  - Maintaining steady state requires proper instrumentation and control systems to monitor and adjust operational parameters continuously.

Practical Examples:

- **Distillation Column:**
  - At steady state, the column maintains constant temperature and composition profiles, ensuring the separation process is efficient and the desired purity levels are achieved.
- **Power Plant:**
  - Operating at steady state allows the plant to produce electricity at a consistent output, minimizing fuel consumption and wear on equipment.

PROCESS MODELS FOR STEADY STATE OPERATIONS

- Process models are mathematical representations of industrial systems that describe the relationships between inputs, outputs, and internal variables under specific conditions.
- In steady-state operations, these models assume that all system parameters remain constant over time, which simplifies the analysis and design of processes.

Key Components of Steady-State Models:

- **Mass Balance:** Ensures that the mass entering and leaving the system is balanced, with no accumulation.
  - Input − Output + Generation − Consumption = Accumulation
- **Energy Balance:** Describes how energy is transferred, used, or lost within the system.
  - Input − Output + Generation − Consumption = Accumulation
- **Equilibrium Relationships:** Governs reactions, phase separations, and transport phenomena under steady conditions.
  - Examples: Chemical reaction equilibrium or vapor-liquid equilibrium.

PROCESS MODELS FOR STEADY STATE OPERATIONS

➢ **How Steady-State Process Models Predict System Behavior?**

- **Prediction of Process Outputs:**
  - Process models allow engineers to calculate outputs, such as product composition, flow rates, and temperature, based on known inputs like feed conditions, pressure, and heat addition.
- **Simulation of Design Changes:**
  - By altering inputs (e.g., feed rate or reactor temperature), the model can predict how the process will perform under new conditions.
  - Example: In a distillation column, increasing reflux ratio can predict changes in separation efficiency.
- **Optimization of Operating Conditions:**
  - Models identify optimal operating points to maximize efficiency, yield, or energy conservation.
  - Example: A chemical reactor model can determine the ideal temperature and pressure for maximum conversion.
- **Sensitivity Analysis:**
  - Process models assess how sensitive the system is to variations in inputs, aiding in robust process design.
  - Example: A heat exchanger model can predict how small changes in inlet temperature affect outlet conditions.

PROCESS MODELS FOR STEADY STATE OPERATIONS

- **Benefits of Steady-State Models in Industrial Operations**
- **Improved Process Control:** Helps maintain steady operations by identifying key control variables and set points.
- **Design Validation:** Verifies the feasibility of proposed process designs before implementation.
- **Economic Analysis:** Evaluates the cost-effectiveness of different operating scenarios.
- **Process Safety:** Identifies conditions that might lead to unsafe operations, such as overheating or excessive pressure.
- **Applications of Steady-State Process Models**
- **Chemical Reactors:**
  - Steady-state models predict conversion rates, yields, and heat requirements.
  - For example, models of plug-flow or continuously stirred tank reactors (CSTR) are used to evaluate reaction performance.
- **Heat Exchangers:**
  - Models calculate heat transfer rates and temperature profiles, optimizing energy usage in heating or cooling processes.
- **Distillation Columns:**
  - Predicts the number of stages, reflux ratio, and feed conditions needed for desired separation.
- **Water Treatment Plants:**
  - Models predict the removal efficiency of contaminants and chemical usage under steady conditions.

STEADY STATE OPERATIONS

Mass Balances

- Input − Output + Generation − Consumption = Accumulation
- For fluids, it is difficult to analyze a system (or volume) from fluid by considering or tracking the same particle.

- A system [also called a closed system] is a quantity of matter of fixed identity. No mass can cross a system boundary.

- For fluids we assumed a definite volume in space that forms the required environment and we can apply mechanics principles on the volume. Such volumes are called **control volumes**.

- A **control volume** [also called an open system] is a region in space chosen for study. Mass can cross a control surface (the surface of the control volume).

- The fundamental conservation laws (conservation of mass, energy, etc.) apply directly to systems.

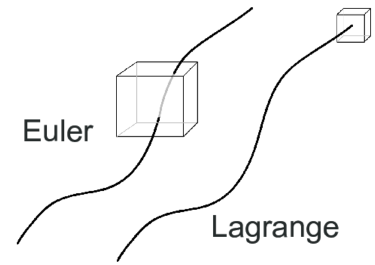
- The **conversion from system analysis to control volume analysis** is represented by **Reynolds Transport Theorem (RTT)**.

$$\frac{d}{dt}\int_{\Omega(t)} f\,dV = \int_{\Omega(t)} \frac{\partial f}{\partial t}dV + \int_{\partial\Omega(t)} (\vec{v}_b \cdot \vec{n})\, f\,dA$$

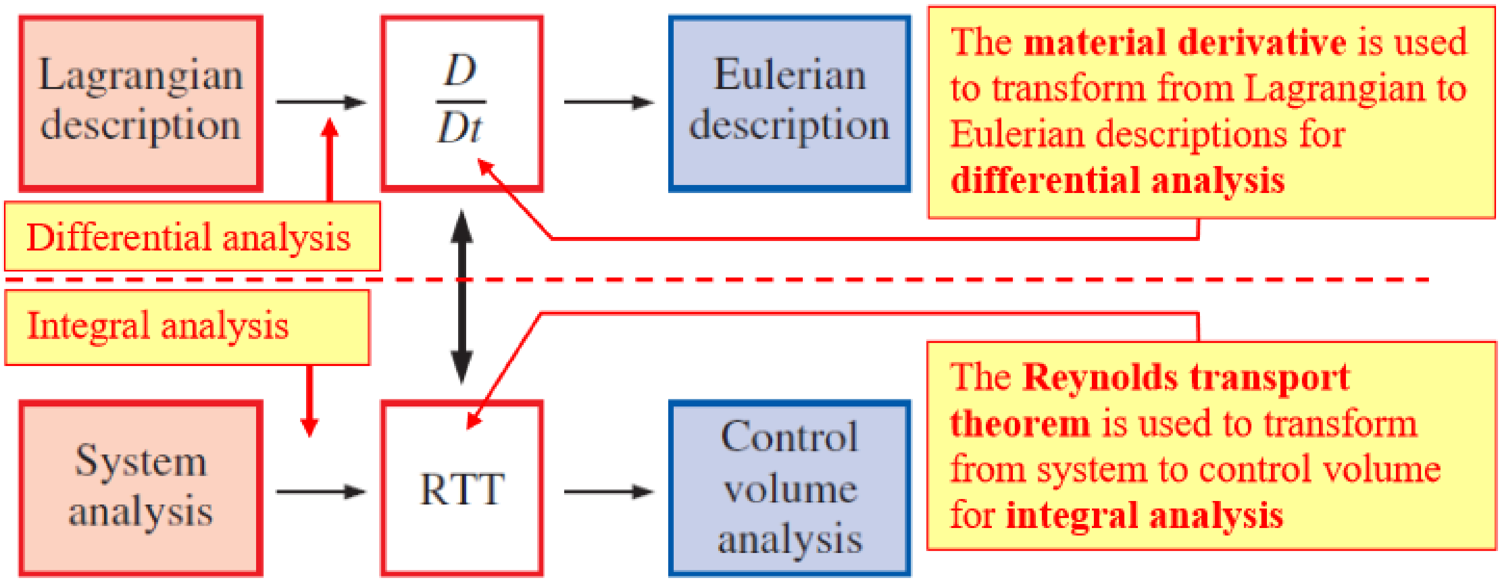
STEADY STATE OPERATIONS

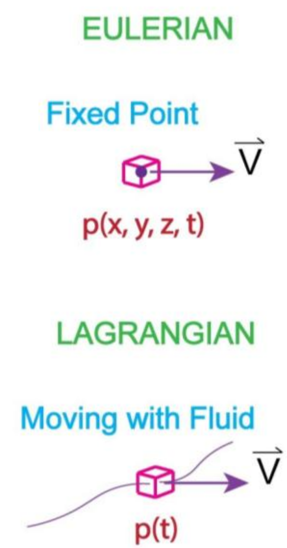
Mass Balances

Analogy b/w Material derivative and the RTT



There is a direct **analogy** between the transformation from **Lagrangian** to **Eulerian** descriptions (**for differential analysis** using infinitesimally small fluid elements) and the transformation from **systems** to **control volumes** (**for integral analysis** using large, finite flow fields):





In both cases, the fundamental laws of physics (conservation laws) are ***known*** and apply directly to the analysis on the left (Lagrangian or system).
These laws of physics must be ***transformed*** so as to be useful in the analysis on the right (Eulerian or control volume).

Source: Google Images

STEADY STATE OPERATIONS

Mass Balance in a Reactor

$$\frac{d}{dt}\left(\int_{CV} c dV\right) = \sum_{inflows} Q_i c_i - \sum_{outflows} Q_i c_i + \int_{CV} r dV$$

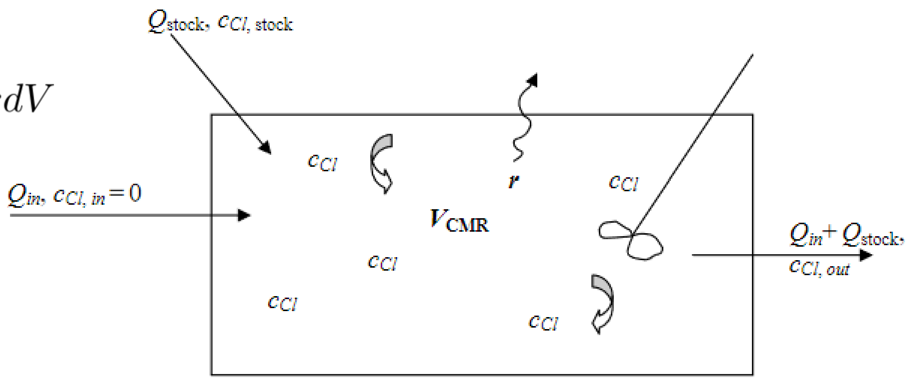
where *r* is the reaction rate expression and corresponds to the rate of generation of *i* in the *CV*, with units of mass/volume-time.

Example 1. We wish to disinfect a solution flowing at 0.8 m^3/s as it passes through an intensely mixed 3600-m^3 tank. The influent contains 10^4 bacterial cells per liter and no chlorine, and we plan to dose it with a stock solution containing 1000 mg/L at a rate that will cause the chlorine concentration in the tank to be 2 mg/L. The chlorine reacts with the water in such a way that it is depleted at a rate (in mg/L-h) given by $r_{Cl} = (-0.20/\text{h})c_{Cl}$. When exposed to chlorine, the bacterial die off at a rate (in cells/L-s) given by: $r_{bact} = -\frac{(0.05/\text{s})c_{Cl}}{1\ \text{mg/L} + c_{Cl}} c_{bact}$. When the system is operating at steady state, what flow rate of stock solution is required, and what bacterial concentration should be expected in the effluent from the tank?

STEADY STATE OPERATIONS

Mass Balance in a Reactor

$$\frac{d}{dt}\left(\int_{CV} cdV\right) = \sum_{inflows} Q_i c_i - \sum_{outflows} Q_i c_i + \int_{CV} rdV$$



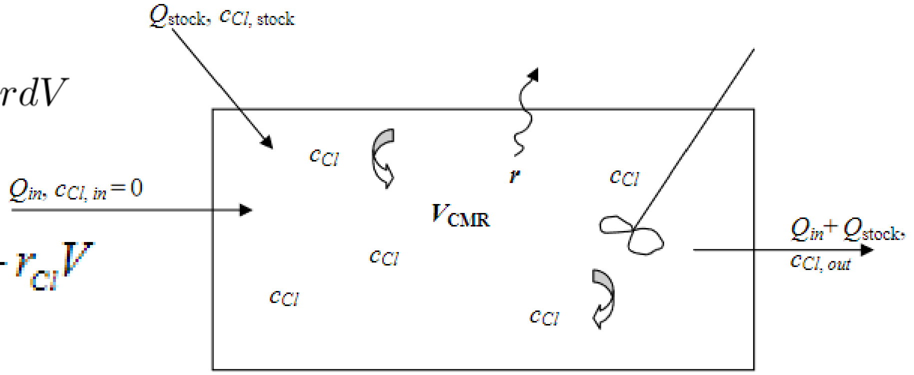
Applying the mass balance equation to Cl:

- The system is operating at steady state, so the term on the left of the equation is zero.
- The reactor is intensely mixed with steady flows. As a result, the Cl concentration is the same everywhere inside the tank (c_{Cl}), and that concentration is also the concentration in the effluent (since the effluent must come from somewhere inside)
- The reaction rate will be the same throughout the tank, which allows us to take r_{Cl} be taken outside the integral on the far right.
- Therefore, noting that there are two inflows (the main inflow stream and the stock solution containing Cl) and one outflow, and that the main inflow stream contains no chlorine.

STEADY STATE OPERATIONS

Mass Balance in a Reactor

$$\frac{d}{dt}\left(\int_{CV} c\,dV\right) = \sum_{inflows} Q_i c_i - \sum_{outflows} Q_i c_i + \int_{CV} r\,dV$$



$$0 = Q_{in}\cancel{c_{Cl,in}} + Q_{stock}c_{Cl,stock} - \left(Q_{in} + Q_{stock}\right)c_{Cl} + r_{Cl}V$$

$$0 = Q_{stock}\left(c_{Cl,stock} - c_{Cl}\right) - Q_{in}c_{Cl} + r_{Cl}V$$

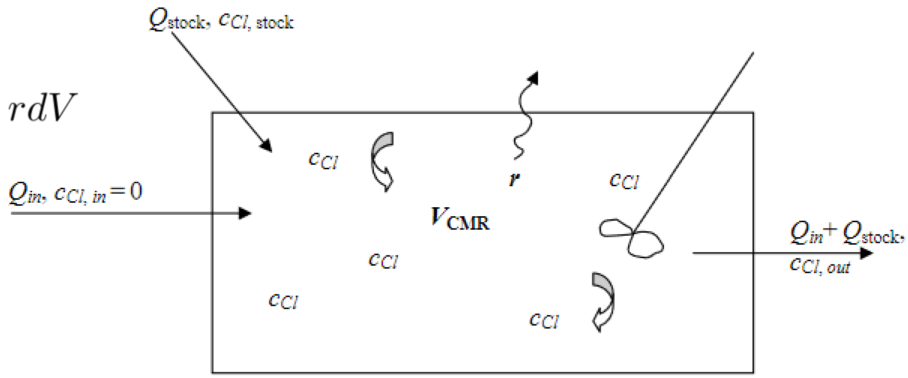
$$Q_{stock} = \frac{Q_{in}c_{Cl} - r_{Cl}V}{c_{Cl,stock} - c_{Cl}} = \frac{Q_{in}c_{Cl} - \left[\left(-0.2/\mathrm{h}\right)c_{Cl}\right]V}{c_{Cl,stock} - c_{Cl}} = \frac{\left(Q_{in} + \left(0.2/\mathrm{h}\right)V\right)c_{Cl}}{c_{Cl,stock} - c_{Cl}}$$

$$= \frac{\left[\left(0.8\ \mathrm{m^3/s}\right)\left(3600\ \mathrm{s/h}\right) + \left(0.2/\mathrm{h}\right)\left(3600\ \mathrm{m^3}\right)\right]\left(2\ \mathrm{mg/L}\right)}{1000\ \mathrm{mg/L} - 2\ \mathrm{mg/L}} = 7.21\frac{\mathrm{m^3}}{\mathrm{h}} = 2.00\frac{\mathrm{L}}{\mathrm{s}}$$

STEADY STATE OPERATIONS

Mass Balance in a Reactor

$$\frac{d}{dt}\left(\int_{CV} c\,dV\right) = \sum_{inflows} Q_i c_i - \sum_{outflows} Q_i c_i + \int_{CV} r\,dV$$



$$\frac{d}{dt}\left(\int_{CV} c_{bact}\,dV\right) = \sum_{\text{inflows}} Q_i c_{bact,i} - \sum_{\text{outflows}} Q_i c_{bact,i} + \int_{CV} r_{bact}\,dV$$

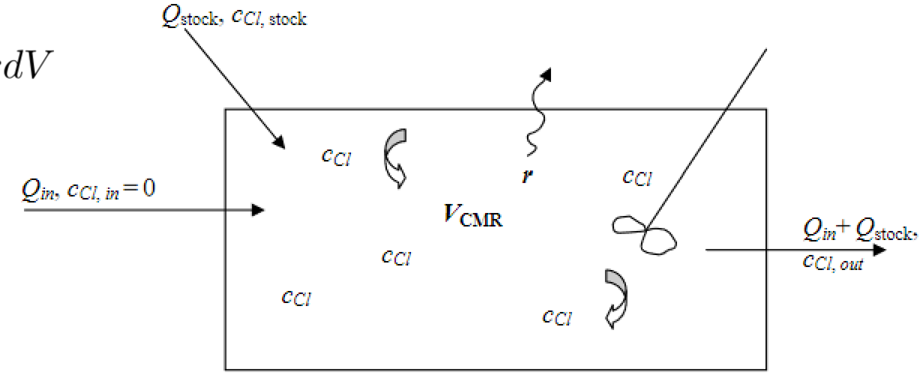
$$0 = Q_{in} c_{bact,in} + Q_{stock}\,\cancel{c_{bact,stock}} - \left(Q_{in} + Q_{stock}\right) c_{bact} + r_{bact} V$$

$$= Q_{in} c_{bact,in} - \left(Q_{in} + Q_{stock}\right) c_{bact} - \left\{\frac{\left(3.0\ \text{min}^{-1}\right) c_{Cl}}{1\ \text{mg/L} + c_{Cl}}\, c_{bact}\right\} V$$

STEADY STATE OPERATIONS

Mass Balance in a Reactor

$$\frac{d}{dt}\left(\int_{CV} c\,dV\right) = \sum_{inflows} Q_i c_i - \sum_{outflows} Q_i c_i + \int_{CV} r\,dV$$



$$c_{bact} = \frac{Q_{in} c_{bact,in}}{\left(Q_{in} + Q_{stock}\right) + \frac{\left(3.0\ \text{min}^{-1}\right) c_{Cl}}{1\ \text{mg/L} + c_{Cl}} V}$$

$$= \frac{\left(0.8\,\frac{\text{m}^3}{\text{s}}\right)\left(10^4\,\frac{\text{cells}}{\text{L}}\right)}{\left(0.8\,\frac{\text{m}^3}{\text{s}} + 4.3\,\frac{\text{m}^3}{\text{h}}\left(\frac{1\ \text{h}}{3600\ \text{s}}\right)\right) + \frac{\left(3.0\ \text{min}^{-1}\right)\left(2\ \text{mg/L}\right)}{1\ \text{mg/L} + 2\ \text{mg/L}}\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(3600\ \text{m}^3\right)} = 66\,\frac{\text{cells}}{\text{L}}$$

- Thus, the bacterial concentration is reduced from 10,000 to 66 cells/L as the water passes through the tank.

STEADY STATE OPERATIONS

Energy Balance in a Reactor

- Most of reactions are not carried out isothermally.
- For non-isothermal reactors (adiabatic and nonadiabatic) we need the energy balance together with the mass balances in order to arrive at reactor design equations.
- However, even for isothermal reactors we need the energy balance to determine what heat duty is necessary in order to keep the reactor isothermal.
- The energy balance is the principle of **conservation of energy** or the **first law of thermodynamics** as applied to our reaction system

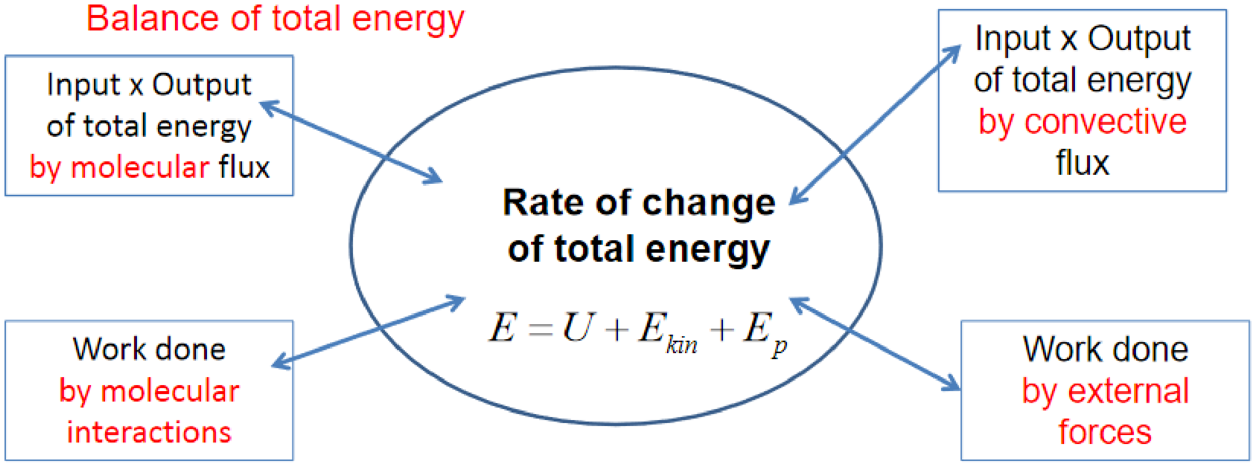
The balance of total energy involves:

Internal energy
mechanical energy (kinetic energy)
potential energy
....

R.B.Bird, W.E.Stewart, E.N.Lightfoot : Transport Phenomena, 2nd Edition, J.Wiley&Sons, N.Y. 2007

Transformation of various kinds of energy

Balance of total energy



Main reason to study energy balances : assesment of temperature of reacting system (reactor)

STEADY STATE OPERATIONS

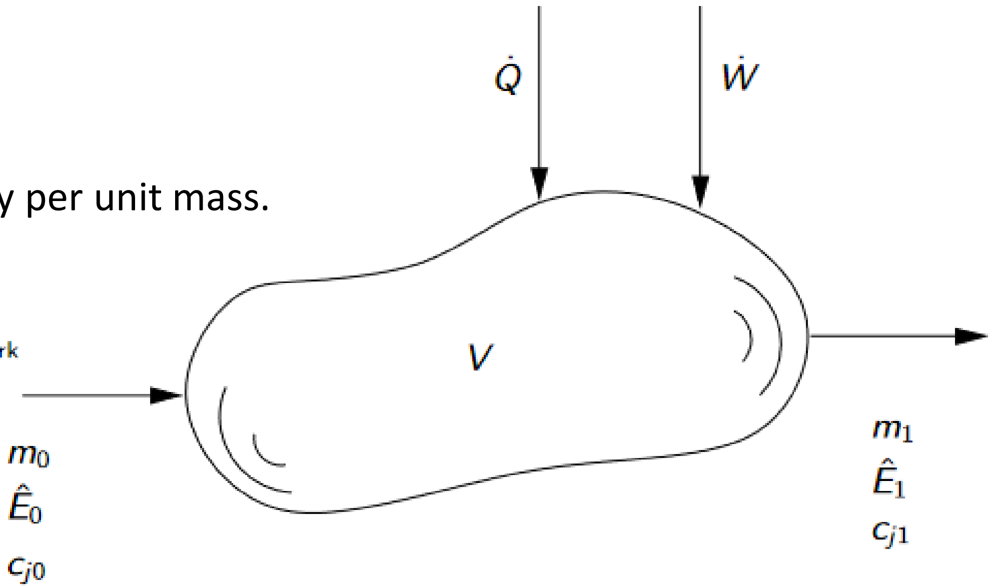
Energy Balance in a Reactor

We derive the energy balance by considering an arbitrary reactor volume element:

$$\frac{dE}{dt} = m_0\hat{E}_0 - m_1\hat{E}_1 + \dot{Q} + \dot{W}$$

in which the hat indicates an energy per unit mass.

$$\underbrace{\dot{W}}_{\text{total work}} = \underbrace{\dot{W}_f}_{\text{flow streams}} + \underbrace{\dot{W}_s}_{\text{shaft work}} + \underbrace{\dot{W}_b}_{\text{boundary work}}$$



The statement of conservation of energy for this system takes the form,

$$\left\{ \begin{matrix} \text{rate of energy} \\ \text{accumulation} \end{matrix} \right\} = \left\{ \begin{matrix} \text{rate of energy} \\ \text{entering system} \\ \text{by inflow} \end{matrix} \right\} - \left\{ \begin{matrix} \text{rate of energy} \\ \text{leaving system} \\ \text{by outflow} \end{matrix} \right\}$$
$$+ \left\{ \begin{matrix} \text{rate of heat} \\ \text{added to system} \end{matrix} \right\} + \left\{ \begin{matrix} \text{rate of work} \\ \text{done on system} \end{matrix} \right\} \quad (1)$$

STEADY STATE OPERATIONS

Energy Balance in a Reactor

Work done by the flow streams: $\dot{W}_f = v_0 A_0 P_0 - v_1 A_1 P_1 = Q_0 P_0 - Q_1 P_1$

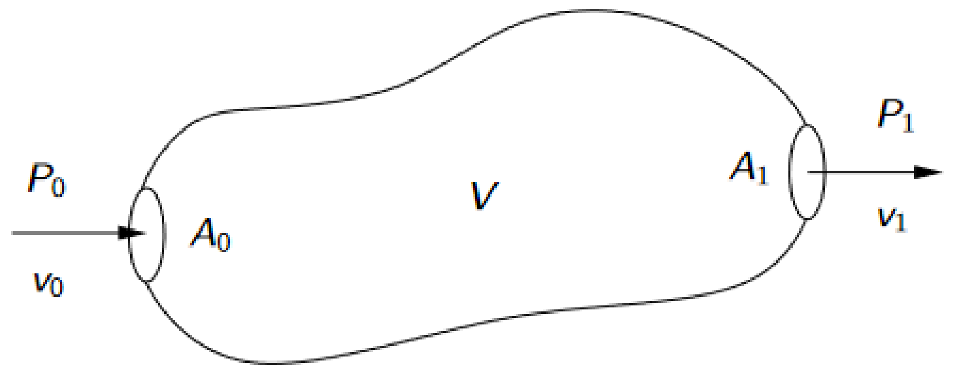


Figure 6.2: Flow streams entering and leaving the volume element.

We also can express the volumetric flowrate as a mass flowrate divided by the density, $Q = m/\rho$

$$\dot{W}_f = m_0 \frac{P_0}{\rho_0} - m_1 \frac{P_1}{\rho_1}$$

The overall rate of work can then be expressed as

$$\dot{W} = \dot{W}_f + \dot{W}_s + \dot{W}_b = m_0 \frac{P_0}{\rho_0} - m_1 \frac{P_1}{\rho_1} + \dot{W}_s + \dot{W}_b \qquad (6.4)$$

STEADY STATE OPERATIONS

Energy Balance in a Reactor

The total energy may be regarded as composed of many forms. Obvious contributions to the total energy arise from the internal, kinetic and potential energies.[1]

$$\hat{E} = \hat{U} + \hat{K} + \hat{\Phi} + \cdots$$

For our purposes in this chapter, we consider only these forms of energy. Recalling the definition of enthalpy, $H = U + PV$, or expressed on a per-unit mass basis, $\hat{H} = \hat{U} + P/\rho$, allows us to rewrite Equation 6.2 as

$$\frac{d}{dt}(U + K + \Phi) = m_0 \left(\hat{H} + \hat{K} + \hat{\Phi}\right)_0 - m_1 \left(\hat{H} + \hat{K} + \hat{\Phi}\right)_1 + \dot{Q} + \dot{W}_s + \dot{W}_b \qquad (6.5)$$

[1] In some cases one might need to consider also electrical and magnetic energies. For example, we might consider the motion of charged ionic species between the plates in a battery cell.

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

Since the batch reactor has no flow streams Equation 6.5 reduces to

$$\frac{d}{dt}(U + K + \Phi) = \dot{Q} + \dot{W}_s + \dot{W}_b \tag{6.6}$$

In chemical reactors, we normally assume the internal energyis the dominant contribution and neglect the kinetic and potential energies. Normally we neglect the work done by the stirrer, unless the mixture is highly viscous and the stirring operation draws significant power [3]. Neglecting kinetic and potential energies and shaft work yields

$$\frac{dU}{dt} + P\frac{dV_R}{dt} = \dot{Q} \tag{6.7}$$

in which $\dot{W}_b = -PdV_R/dt$.

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

It is convenient to use enthalpy rather than internal energy in the subsequent development. Taking the differential of the definition of enthalpy gives for $V = V_R$

$$dH = dU + PdV_R + V_R dP$$

Forming the time derivatives and substitution into Equation 6.7 gives

$$\frac{dH}{dt} - V_R \frac{dP}{dt} = \dot{Q} \tag{6.8}$$

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

For *single-phase systems*, we consider the enthalpy as a function of temperature, pressure and number of moles, and express its differential as

$$dH = \left(\frac{\partial H}{\partial T}\right)_{P,n_j} dT + \left(\frac{\partial H}{\partial P}\right)_{T,n_j} dP + \sum_j \left(\frac{\partial H}{\partial n_j}\right)_{T,P,n_k} dn_j \qquad (6.9)$$

The first partial derivative is the definition of the heat capacity, C_P.

$$C_P = V_R \rho \hat{C}_P$$

The second partial derivative can be expressed as

$$\left(\frac{\partial H}{\partial P}\right)_{T,n_j} = V - T\left(\frac{\partial V}{\partial T}\right)_{P,n_j} = V(1 - \alpha T)$$

in which $\alpha = (1/V)(\partial V/\partial T)_{P,n_j}$ is the coefficient of expansion of the mixture.
The final partial derivatives are the partial molar enthalpies, $\overline{H}_j$

$$\left(\frac{\partial H}{\partial n_j}\right)_{T,P,n_k} = \overline{H}_j$$

so Equation 6.9 can be written compactly as

$$dH = V_R \rho \hat{C}_P dT + (1 - \alpha T) V_R dP + \sum_j \overline{H}_j dn_j \qquad (6.10)$$

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

Forming the time derivatives from this expression and substituting into Equation 6.8 gives

$$V_R \rho \hat{C}_P \frac{dT}{dt} - \alpha T V_R \frac{dP}{dt} + \sum_j \overline{H}_j \frac{dn_j}{dt} = \dot{Q} \tag{6.11}$$

We note that the material balance for the batch reactor is

$$\frac{dn_j}{dt} = R_j V_R = \sum_{i=1}^{n_r} \nu_{ij} r_i V_R, \quad j = 1, \ldots, n_s \tag{6.12}$$

which upon substitution into Equation 6.11 yields

$$V_R \rho \hat{C}_P \frac{dT}{dt} - \alpha T V_R \frac{dP}{dt} = -\sum_i \Delta H_{Ri} r_i V_R + \dot{Q} \tag{6.13}$$

in which ΔH_{Ri} is the heat of reaction

$$\Delta H_{Ri} = \sum_j \nu_{ij} \overline{H}_j \tag{6.14}$$

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

A plethora of special cases — incompressible

We now consider several special cases. If the reactor operates at constant pressure ($dP/dt = 0$) *or* the fluid is incompressible ($\alpha = 0$), then Equation 6.13 reduces to

Incompressible-fluid or constant-pressure reactor.

$$\boxed{V_R \rho \hat{C}_P \frac{dT}{dt} = -\sum_i \Delta H_{Ri} r_i V_R + \dot{Q}} \qquad (6.15)$$

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

A plethora of special cases — constant volume

Change from T, P, n_j to T, V, n_j by considering P to be a function of $T, V (V = V_R), n_j$

$$dP = \left(\frac{\partial P}{\partial T}\right)_{V,n_j} dT + \left(\frac{\partial P}{\partial V}\right)_{T,n_j} dV + \sum_j \left(\frac{\partial P}{\partial n_j}\right)_{T,V,n_k} dn_j$$

For reactor operation at constant volume, $dV = 0$, and forming time derivatives and substituting into Equation 6.11 gives

$$\left[V_R \rho \hat{C}_P - \alpha T V_R \left(\frac{\partial P}{\partial T}\right)_{V,n_j}\right] \frac{dT}{dt} + \sum_j \left[\overline{H}_j - \alpha T V_R \left(\frac{\partial P}{\partial n_j}\right)_{T,V,n_k}\right] \frac{dn_j}{dt} = \dot{Q}$$

We note that the first term in brackets is $C_V = V_R \rho \hat{C}_V$ (see Exercise 6.23)

$$V_R \rho \hat{C}_V = V_R \rho \hat{C}_P - \alpha T V_R \left(\frac{\partial P}{\partial T}\right)_{V,n_j}$$

The pressure derivative with respect to the moles can be shown to be (see Exercise 6.23)

$$\left(\frac{\partial P}{\partial n_j}\right)_{T,V,n_{k \neq j}} = \frac{\overline{V}_j}{V \kappa_T}$$

in which $\kappa_T = -(1/V)(\partial V/\partial P)_{T,n_j}$ is the isothermal compressibility of the mixture, and $\overline{V}_j$ is the partial molar volume.

STEADY STATE OPERATIONS

Energy Balance in a BATCH Reactor

A plethora of special cases — constant volume

Substitution of these two thermodynamic relations and the material balance yields the energy balance for the constant-volume batch reactor

Constant-volume reactor.

$$\boxed{V_R \rho \hat{C}_V \frac{dT}{dt} = -\sum_i \left(\Delta H_{Ri} - \frac{\alpha}{\kappa_T} T \Delta V_{Ri}\right) r_i V_R + \dot{Q}} \qquad (6.16)$$

If we consider an ideal gas, it is straightforward to calculate $\alpha T = 1$, $\kappa_T P = 1$, and $\Delta V_{Ri} = \bar{\nu}_i (RT/P)$, where $\bar{\nu}_i = \sum_j \nu_{ij}$. Substitution into the constant-volume energy balance gives

Constant-volume reactor, ideal gas.

$$\boxed{V_R \rho \hat{C}_V \frac{dT}{dt} = -\sum_i \left(\Delta H_{Ri} - RT\bar{\nu}_i\right) r_i V_R + \dot{Q}} \qquad (6.17)$$

where $\bar{\nu}_i = \sum_j \nu_{ij}$.

STEADY STATE OPERATIONS

Energy Management – Why?

- **Energy Efficiency:**

  - Steady-state operations provide a consistent framework for evaluating and optimizing energy inputs relative to outputs.
  - Efficient energy use reduces operating costs and enhances overall profitability.

- **Environmental Impact:**

  - Reducing energy waste minimizes greenhouse gas emissions and supports environmental sustainability.
  - Efficient operations ensure compliance with environmental regulations.

- **Process Stability:**

  - Maintaining steady energy flow ensures the reliability of critical process parameters, such as temperature, pressure, and reaction rates.
  - Stability minimizes wear and tear on equipment, reducing maintenance costs.

- **Product Quality:**

  - Consistent energy management ensures that the required conditions for production are met, maintaining high-quality output.

STEADY STATE OPERATIONS

Energy Management - Strategies for Energy Management at Steady State

- **Energy Audits and Monitoring:**

  - Conduct regular audits to identify inefficiencies in energy usage.
  - Use advanced sensors and meters to monitor energy consumption in real time.

  - Example: Monitoring heat losses in heat exchangers or steam systems can highlight areas for insulation improvement.

- **Optimization of Process Conditions:**

  - Operate equipment at optimal load conditions to maximize efficiency.
  - Fine-tune parameters such as temperature, flow rate, and pressure to minimize energy input for the desired output.

  - Example: Adjusting boiler pressure to meet steam demand without excess production reduces fuel consumption.

- **Waste Heat Recovery:**

  - Implement heat recovery systems to capture and reuse energy from hot exhaust gases, cooling water, or process streams.
  - Use recovered heat for preheating feedstocks, generating steam, or space heating.

  - Example: A regenerator in a distillation process recycles heat from outgoing streams to preheat incoming feeds.

STEADY STATE OPERATIONS

Energy Management - Strategies for Energy Management at Steady State

- **Upgrade Equipment and Technology:**
  - Replace outdated machinery with energy-efficient models, such as variable-speed pumps or high-efficiency motors.
  - Use advanced control systems, like distributed control systems (DCS) or artificial intelligence, to optimize operations.

- **Use Renewable Energy Sources:**
  - Incorporate solar, wind, or biomass energy where feasible to reduce dependence on fossil fuels.
  - Example: Solar-powered water heating for pre-process operations.

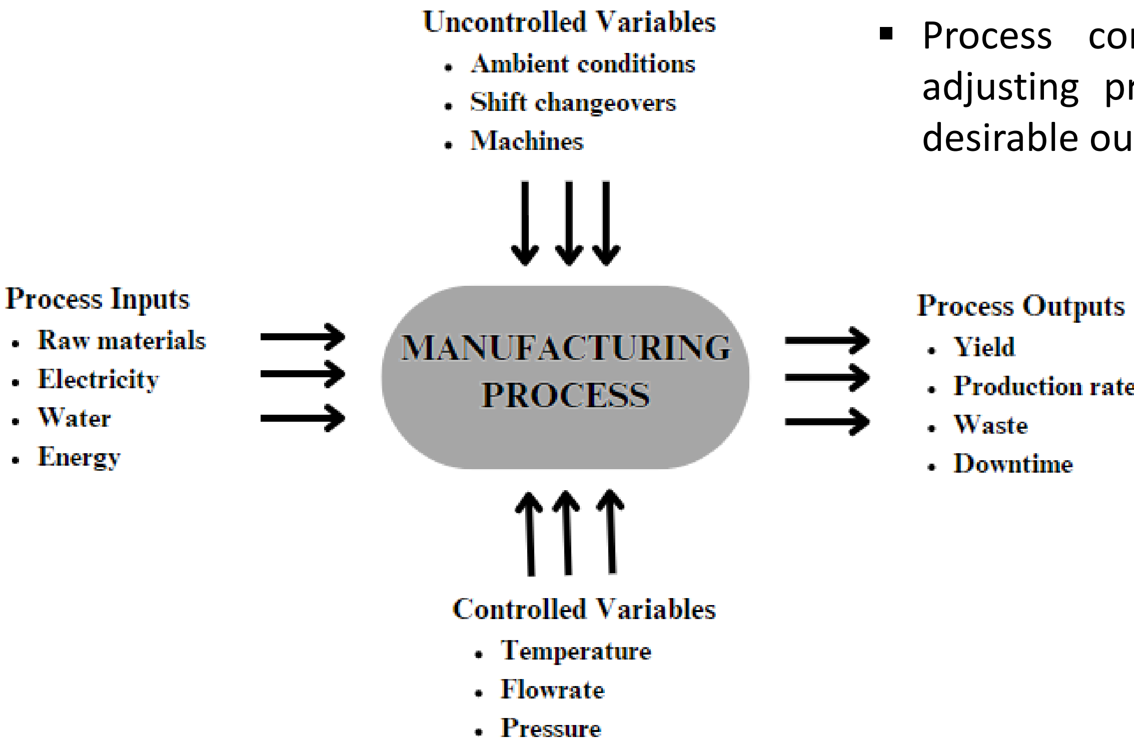
- **Minimize Idle Time:**
  - Avoid operating equipment at low loads or when not in use.
  - Schedule processes to align with peak efficiency hours to reduce energy losses.

- **Insulation and Maintenance:**
  - Properly insulate equipment like pipes, tanks, and boilers to prevent energy loss.
  - Regular maintenance ensures equipment operates at peak efficiency, minimizing energy wastage.

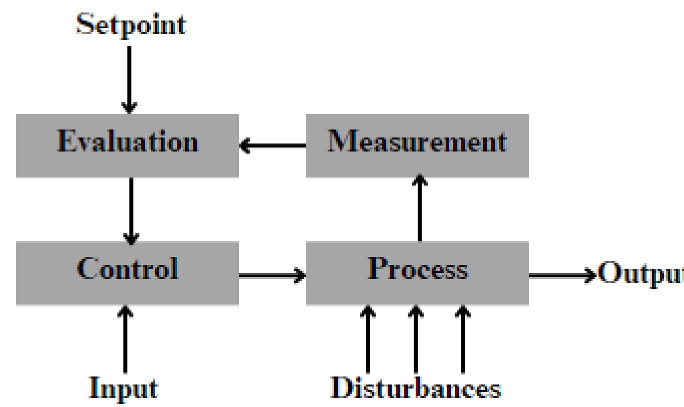
- **Energy Storage Systems:**
  - Use batteries or other storage technologies to manage excess energy generated during low-demand periods.

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State



- Process control refers to the monitoring and adjusting process parameters to get a preset or desirable output.

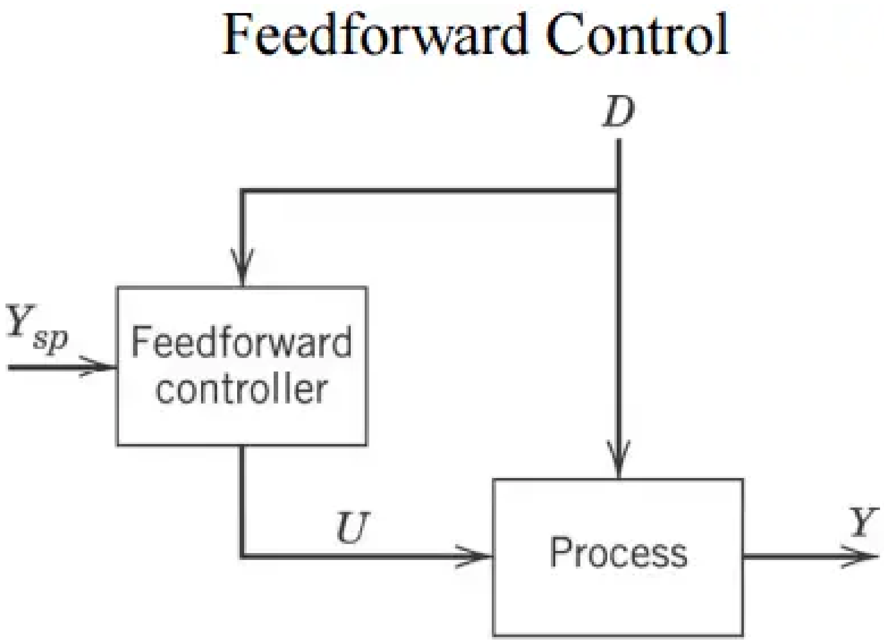


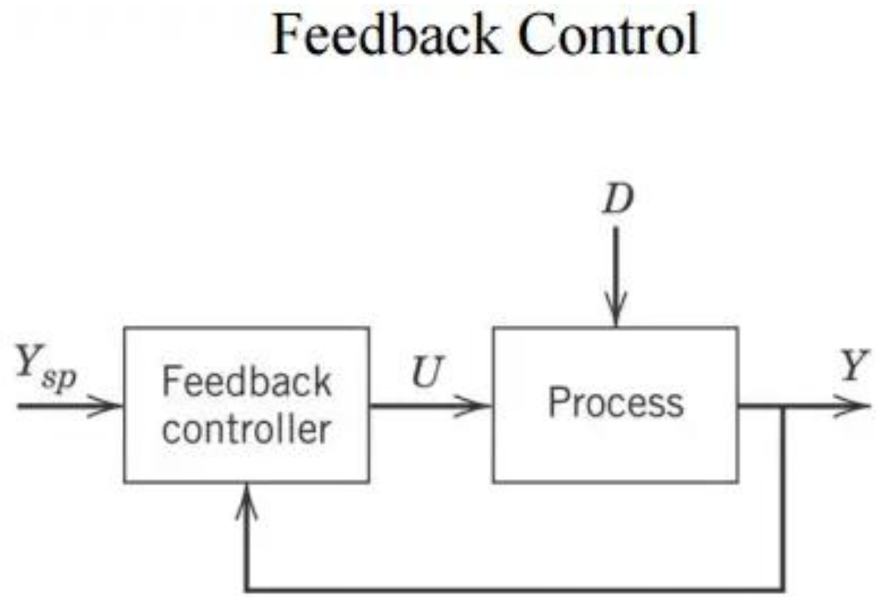
- Deployment of automated process control systems delivers the following benefits:
  - Energy Efficiency
  - Increase Automation & Throughput
  - Quality Assurance
  - Improved Safety

Source: Google Images

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State





Source: Google Images

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State

ADVANTAGES

- Corrective action occurs as soon as the controlled variable deviates from the set point, regardless of the source and type of disturbance.
- Feedback control requires minimal knowledge about the process to be controlled; it particular, a mathematical model of the process is not required, although it can be very useful for control system design.
- The ubiquitous PID controller is both versatile and robust. If process conditions change, retuning the controller usually produces satisfactory control.

DISADVANTAGES

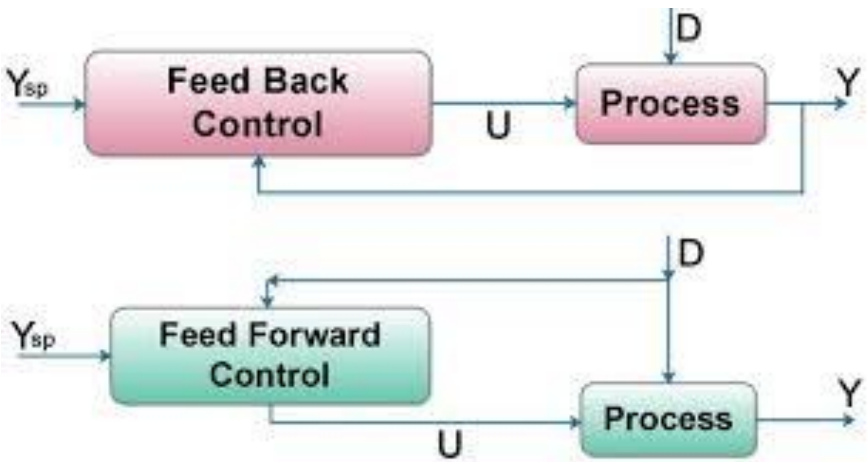
- No corrective action is taken until after a deviation in the controlled variable occurs. Thus, perfect control, where the controlled variable does not deviate from the set point during disturbance or set-point changes, is theoretically impossible.
- Feedback control does not provide predictive control action to compensate for the effects of known or measurable disturbances.
- It may not be satisfactory for processes with large time constants and/or long time delays. If large and frequent disturbances occur, the process may operate continuously in a transient state and never attain the desired steady state.
- In some situations, the controlled variable cannot be measured on-line, and, consequently, feedback control is not feasible.

FEEDBACK CONTROL

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State

- The basic concept of **feedforward control** is to measure important disturbance variables and take corrective action before they upset the process.



Source: Google Images

FEEDFORWARD CONTROL

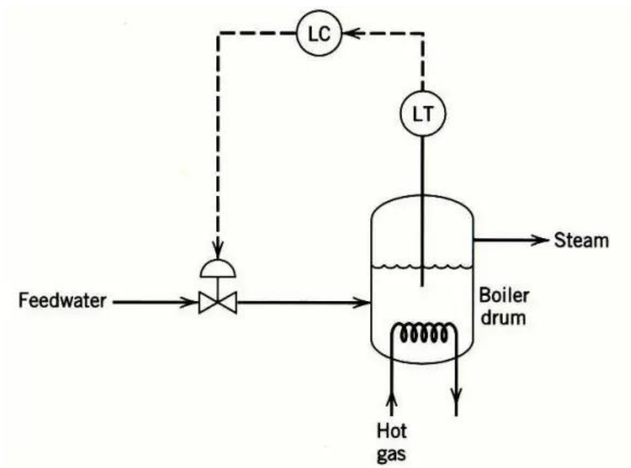
DISADVANTAGES

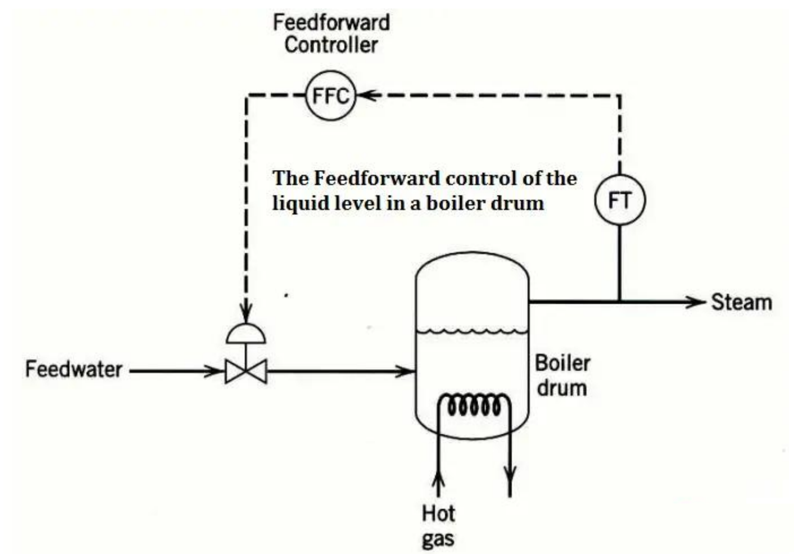
- The disturbance variables must be measured on-line. In many applications, this is not feasible.
- To make effective use of feedforward control, at least an approximate process model should be available. In particular, we need to know how the controlled variable responds to changes in both the disturbance and manipulated variables. The quality of feedforward control depends on the accuracy of the process model.
- Ideal feedforward controllers that are theoretically capable of achieving perfect control may not be physically realizable. Fortunately, practical approximations of these ideal controllers often provide very effective control.

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State

A boiler drum with a conventional feedback control system is shown in Fig.1 The level of the boiling liquid is measured and used to adjust the feedwater flow rate.





This control system tends to be quite sensitive to rapid changes in the disturbance variable, steam flow rate, as a result of the small liquid capacity of the boiler drum. Rapid disturbance changes can occur as a result of steam demands made by downstream processing units.

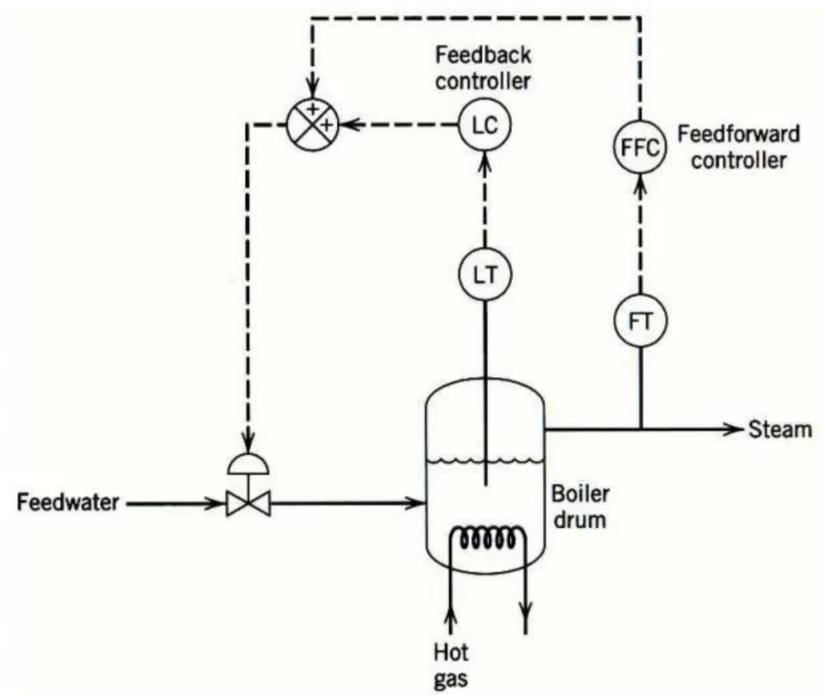
The feedforward control scheme in below Fig can provide better control of the liquid level. Here the steam flow rate is measured, and the feedforward controller adjusts the feedwater flow rate.

Source: Google Images

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State

In practical applications, feedforward control is normally used in combination with feedback control.



Feedforward control is used to reduce the effects of measurable disturbances, while feedback trim compensates for inaccuracies in the process model, measurement error, and unmeasured disturbances.

Source: Google Images

STEADY STATE OPERATIONS

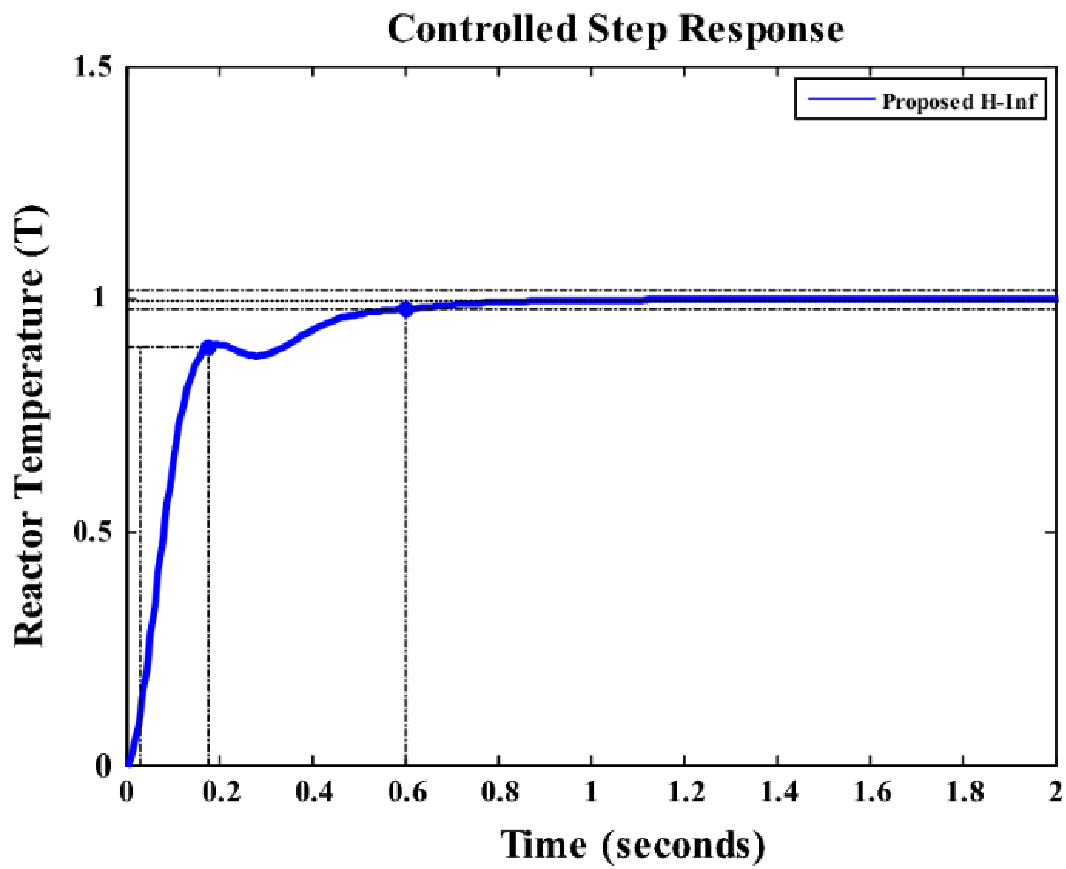
Process Control for Maintaining Steady State

Controller	Estimates	When to use	Examples
P	Present	Systems with slow response, systems tolerant to offset	Float valves, thermostats, Humidistat
I	Back	Not often used alone, as is too slow	Used for very noisy systems
D	Forward	Not used alone because it is too sensitive to noise and does not have set point	None
PI	Present & Back	Often used	Thermostats, Flow control, Pressure control
PID	All Time	Often used, most robust, but can be noise sensitive	Cases where system has inertia that could get out of hand; i.e. temperature and concentration measurements on a reactor to avoid runaway

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State

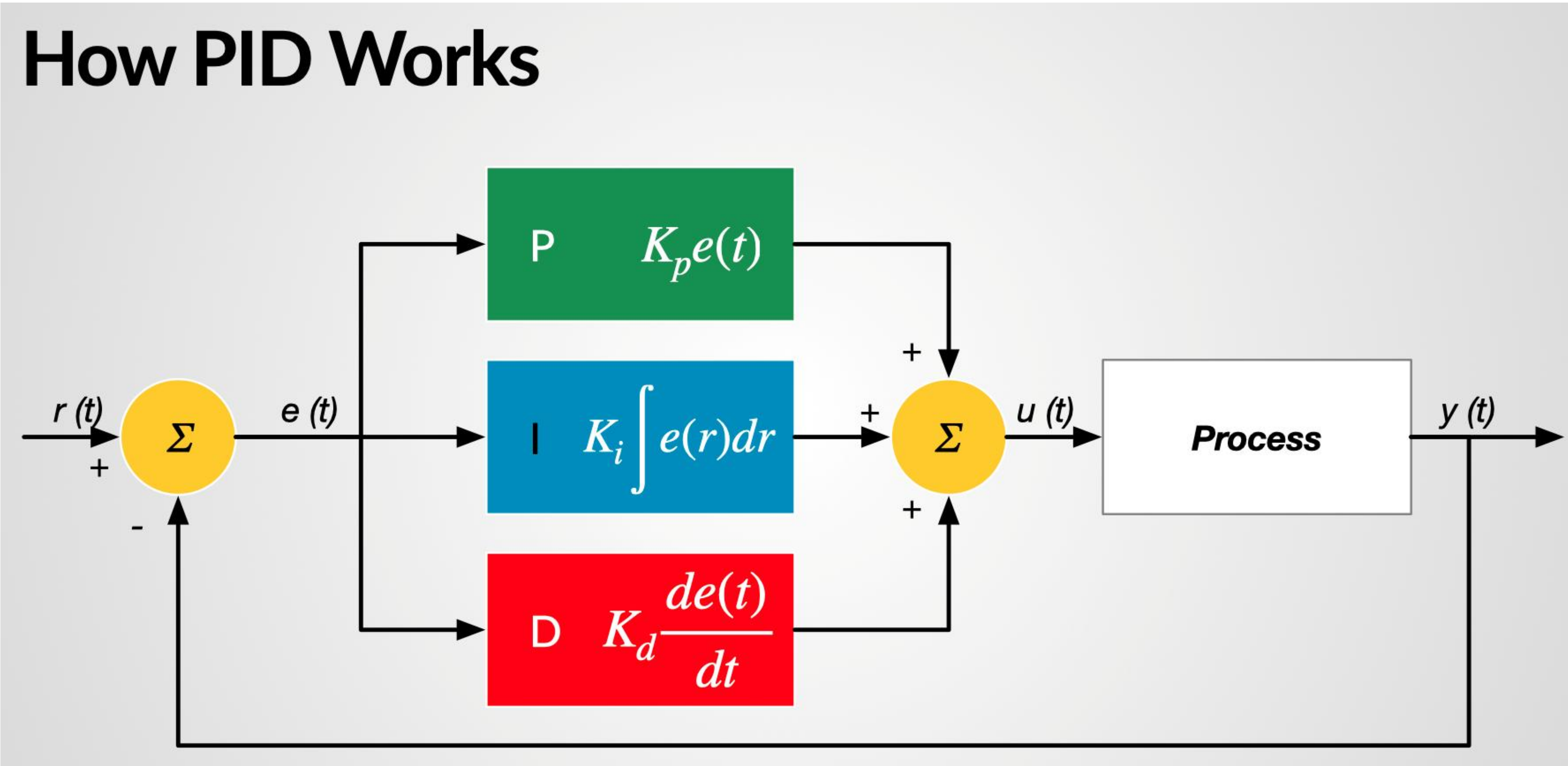
Control Technique	*Advantages*	*Disadvantages*
PID Control	Simple and easy to implement	Susceptible to noise and disturbances
	Affordable and widely used	Limited in handling complex systems
	Tuning is easy	Non-linear systems may be difficult to control
	Good for low and medium-bandwidth systems	May not be suitable for high-bandwidth systems
H∞ Control	Robust and effective for complex systems	Difficult to implement and requires advanced knowledge
	Can handle nonlinear systems	Expensive and time-consuming
	Resistant to disturbances and noise	Difficult to tune and requires expertise
	Provides a guaranteed level of performance	This may lead to over-conservative designs



Source: Google Images

STEADY STATE OPERATIONS

Process Control for Maintaining Steady State



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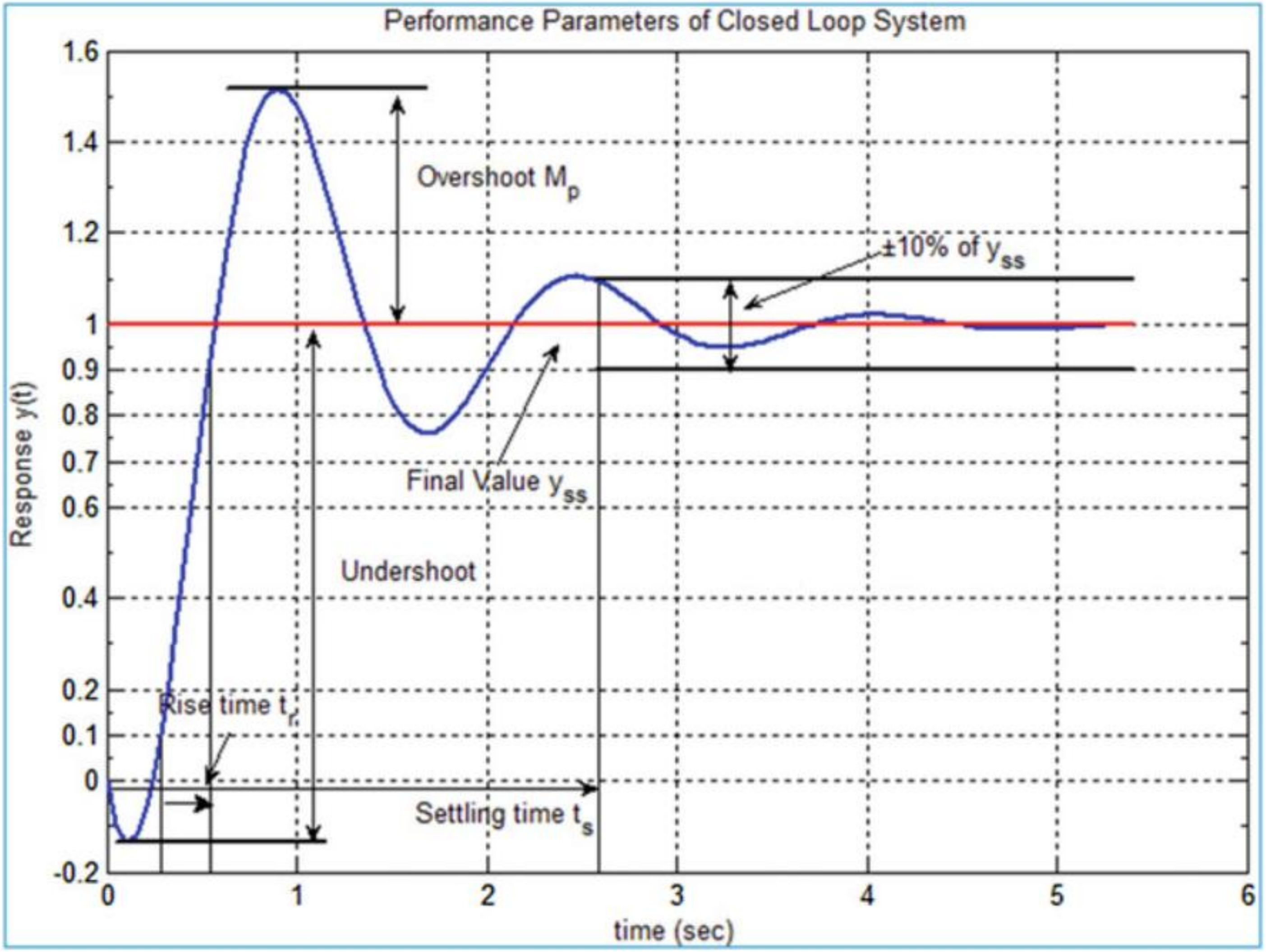
STEADY STATE OPERATIONS

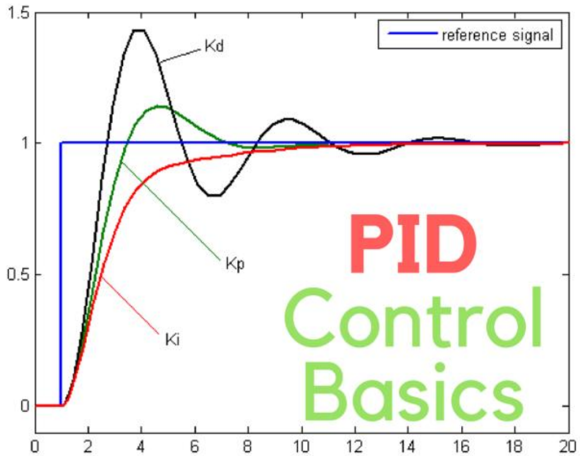
Process Control for Maintaining Steady State

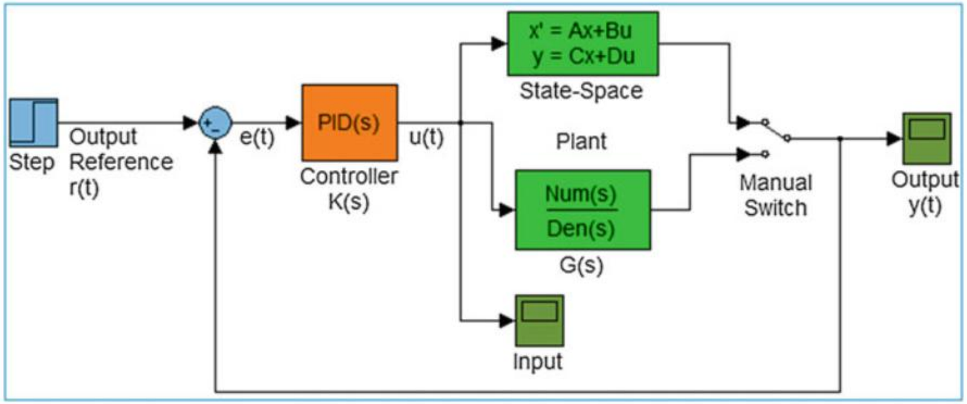


Source: Google Images

STEADY STATE OPERATIONS

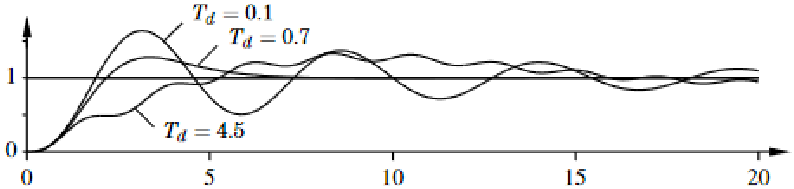
Process Control for Maintaining Steady State

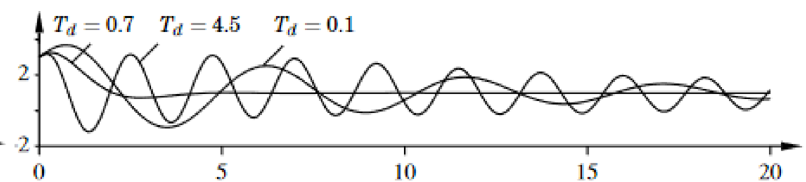




$$K(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_I}{s} + K_D \cdot s$$

This is the second-order transfer function required to solve for the numerator or denominator from this equation. This will be achieved by taking inverse Laplace transform term-by-term and then finding an actual transfer function. There is often a requirement to use the controller as either PI or PD due to simplification and lesser design specifications. The integral parameter K_I controls the steady-state error which may occur due to the proportional term K_p. Damping overcomes the overshoot, and the speed of the response regulates by the derivative parameter K_D.





Source: Google Images

CH 42010: PROCESS PLANT OPERATION & SAFETY

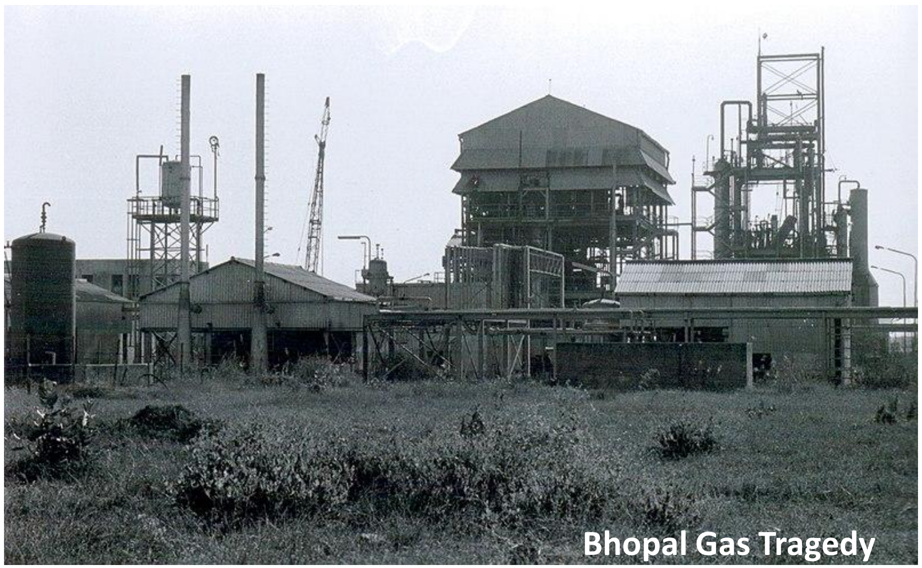
LTP: 3-0-0, CRD: 3

Lecture 5

Emergency Response Strategy for Plants

INTRODUCTION TO EMERGENCY SITUATIONS

- Types of emergencies that can arise in industrial settings: **Fires, Explosions, Chemical spills, Gas leaks,** and **Power failures**



Bhopal Gas Tragedy

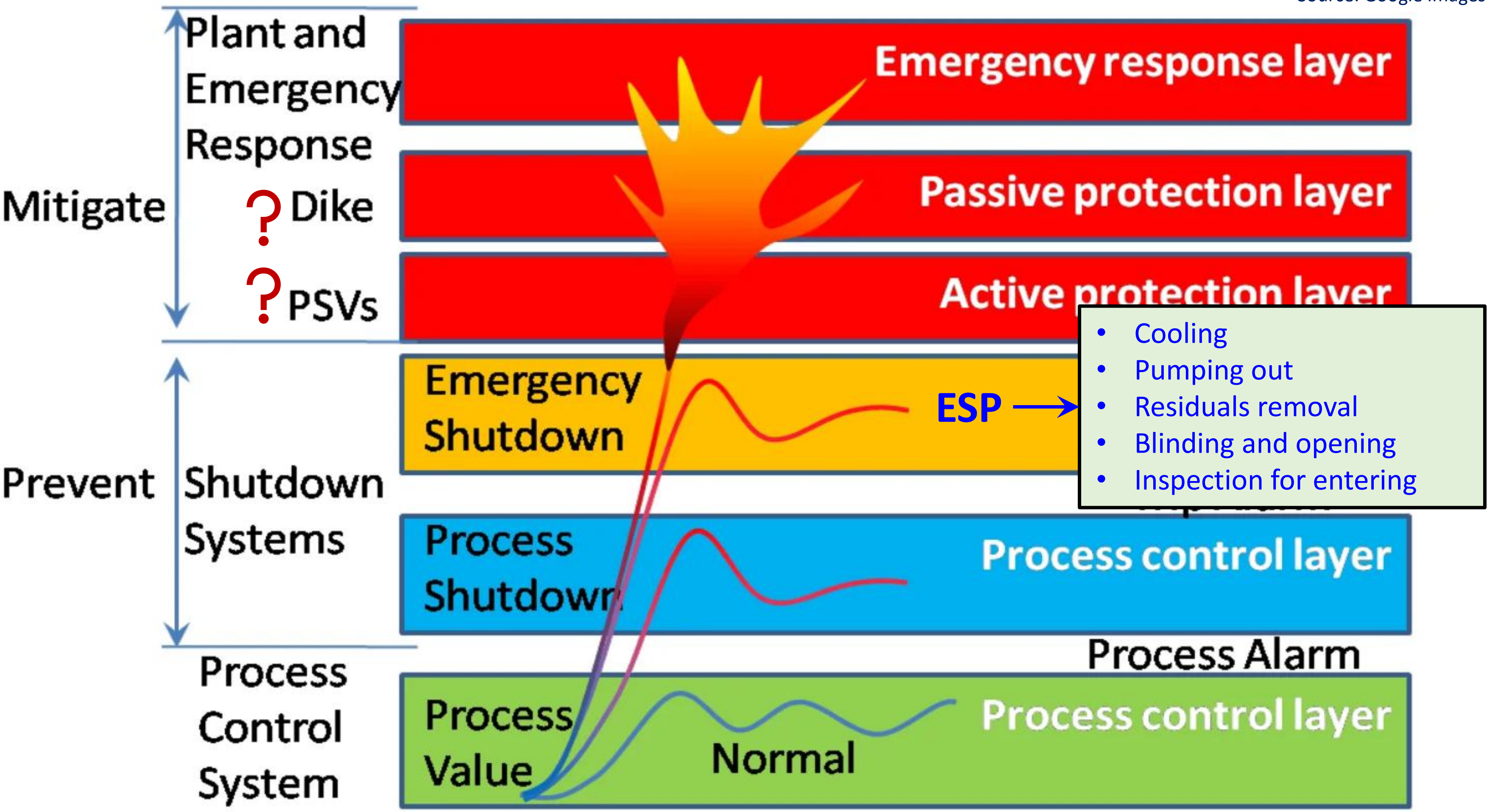
Deepwater Horizon Oil Spill

EMERGENCY RESPONSE PLANNING (ERP)

Source: Google Images

EMERGENCY SHUTDOWN PROCEDURES (ESP)

Source: Google Images

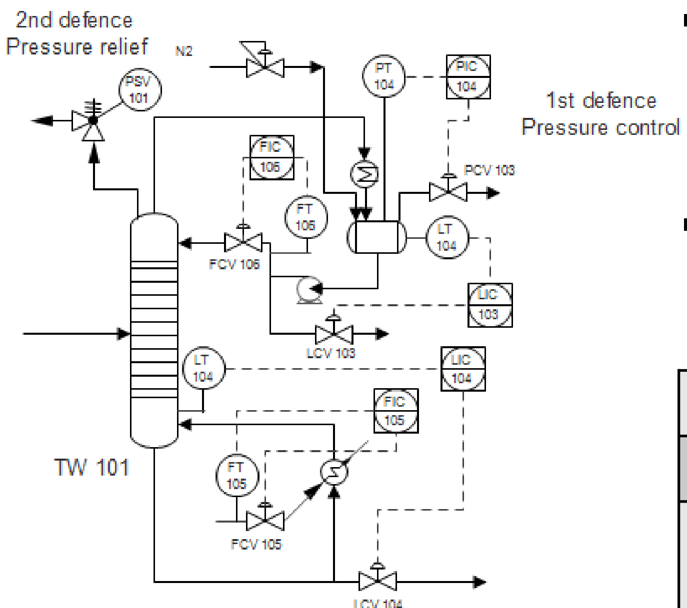


Dikes or Containment systems: Type of protection layer used to prevent the release of hazardous materials in the event of a spill or leak

PSV – Pressure Safety Valve
The Last Line of Defence

EMERGENCY SHUTDOWN PROCEDURES (ESP)

PSV – Pressure Safety Valve & RV – Relief Valve



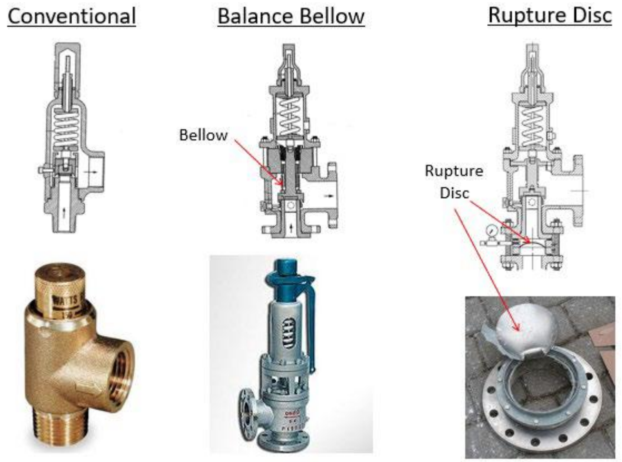
- Overpressure of a chemical process plant may lead to major hazards (fire, explosion, and toxic release)
- The 1st line of defense against overpressure hazard is good pressure control: **PCV** – Controlling the process pressure within a safe operating pressure region
- The 2nd line of defense against overpressure hazard is to install **PSV/RV** to relief liquid or gases before excessive pressures are developed

RV	**PSV**
Primarily for liquid service	Steam, gas & vapor service
RV should open at the set pressure (normally less than 10% of operating P) and reaches full capacity at 25% overpressure. RV closes as the system pressure returns to the set pressure.	PSV should open at the set pressure and reseat after reaching approximately 4% below set P.

Source: Google Images

EMERGENCY SHUTDOWN PROCEDURES (ESP)

PSV – Pressure Safety Valve & RV – Relief Valve



All reliefs devices should be inspected for their functionality and set pressure during shut-down.

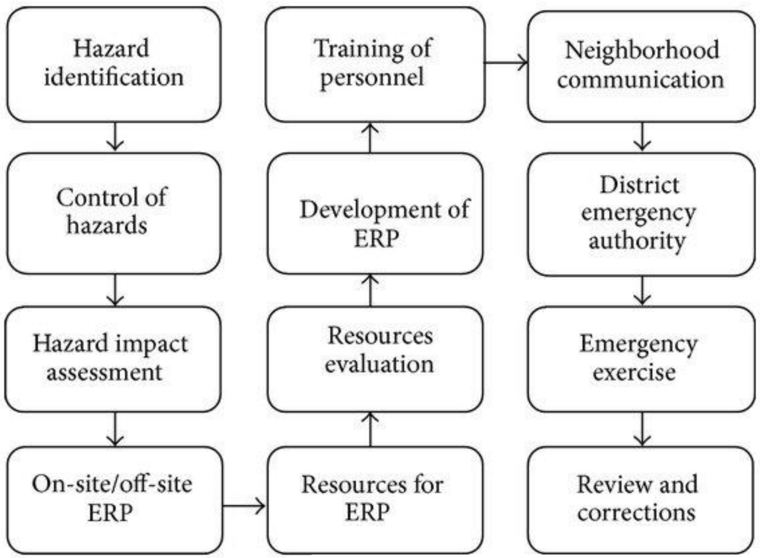
Source: Google Images

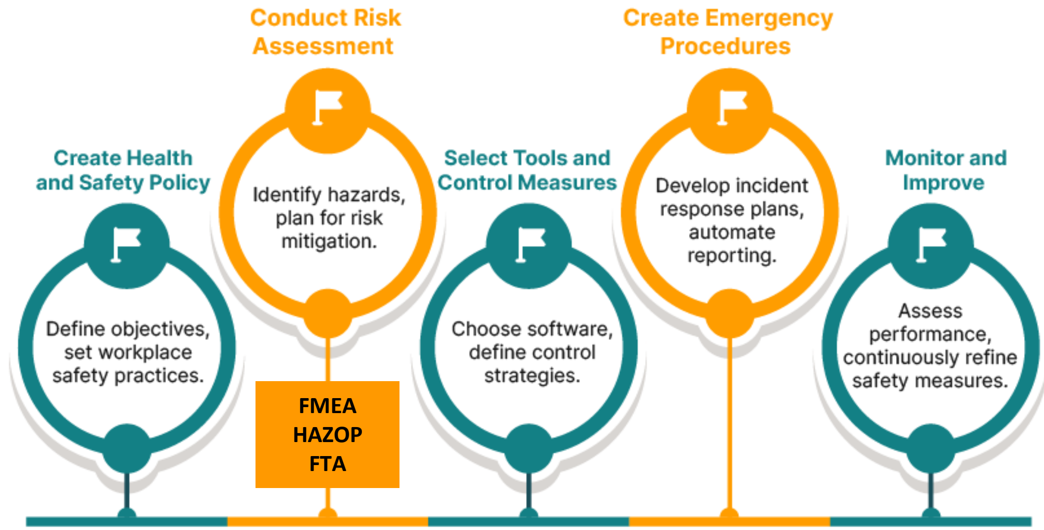
- **Guidelines** where RVs should be installed:
  - **All vessels** need reliefs, including reactors, storage tanks, towers and drums.
  - **Blocked-in sections** of cool liquid-filled lines which are exposed to heat (e.g., cooling water side of a heat exchanger) or refrigeration need reliefs.
  - **Positive displacement pumps, compressors and turbines** need reliefs on the discharge side.
  - **Vessel steam jackets** are often rated for low pressure steam. Reliefs are installed in jackets to prevent excessive steam pressures due to operator error or pressure regulator failure.
  - **Storage vessels** need pressure and vacuum reliefs to protect against pumping in or out of a blocked-in vessel or against the generation of a vacuum by condensation.

- **Spring operated PSV/RV** which can be used repeatedly:
  - **Conventional**.
  - **Balanced Bellow**: eliminating the back pressure effect when the device activates and avoid direct contact of corrosive media with spring etc.

- **Rupture Disc**: A calibrated sheet of metal designed to rupture at a specified pressure. Can be used one time only.

EMERGENCY RESPONSE PLANNING (ERP)





- Plant-specific emergency procedures and emergency shutdown processes for critical equipment
- Importance of proper signage, alarms, and emergency lighting
- Evacuation procedures and Communication protocols

Source: Google Images

EMERGENCY RESPONSE PLANNING (ERP)

Governmental Rules & Regulations (Govt. of India)

- Factory Acts & Rules
- Boiler Act 1923
- State Boiler Rules
- Indian Boiler Regulations 1950
- The Petroleum Act & Rules
- The Explosive Act & Rules
- The Insecticide Act & Rules
- The Poisonous Acts & Rules
- The Electricity Act & Rules
- Gas Cylinder Rules 1981
- Static & Mobile Pressure Vessels 1981
- Water & Air Pollution Control Acts & Rules
- Environment Protection Act 1986 & Rules
- Hazardous Waste Management Rules 1989
- MSIHC Rules 1989
- Chemical Accident Rules 1996
- Bio Medical Waste Rules 1998
- Building & Construction Act 1996.
- Radiation protection Rules
- Atomic Agency Act

Source: Google Images

EMERGENCY RESPONSE PLANNING (ERP)

Governmental Rules & Regulations (Govt. of India)

BIS Standards

Code For Safety	BIS Standards
Laboratory Safety	4209
Classifications of Dangerous Goods	1446
Classifications of Hazardous Chemicals	4607
LPG Installations	6044
Acetylene Cylinders	8433
Static Electricity	7689
Fire Safety of Buildings	3594
Plant lay out, Safe practice	8089 / 8091
Code For Occupational Safety & Health Audit	14489
OISD has published the Safety Standards for all refineries, LPG bottling Plants, Gas terminals, ONGC & GAIL installations.	OISD 105 TO 231

Oil Industry Safety Directorate (OISD) – Ministry of Petroleum and Natural Gas

PERSONAL SAFETY

Protective Equipments (PPE) - fire-resistant clothing, breathing apparatus, and chemical-resistant gloves.

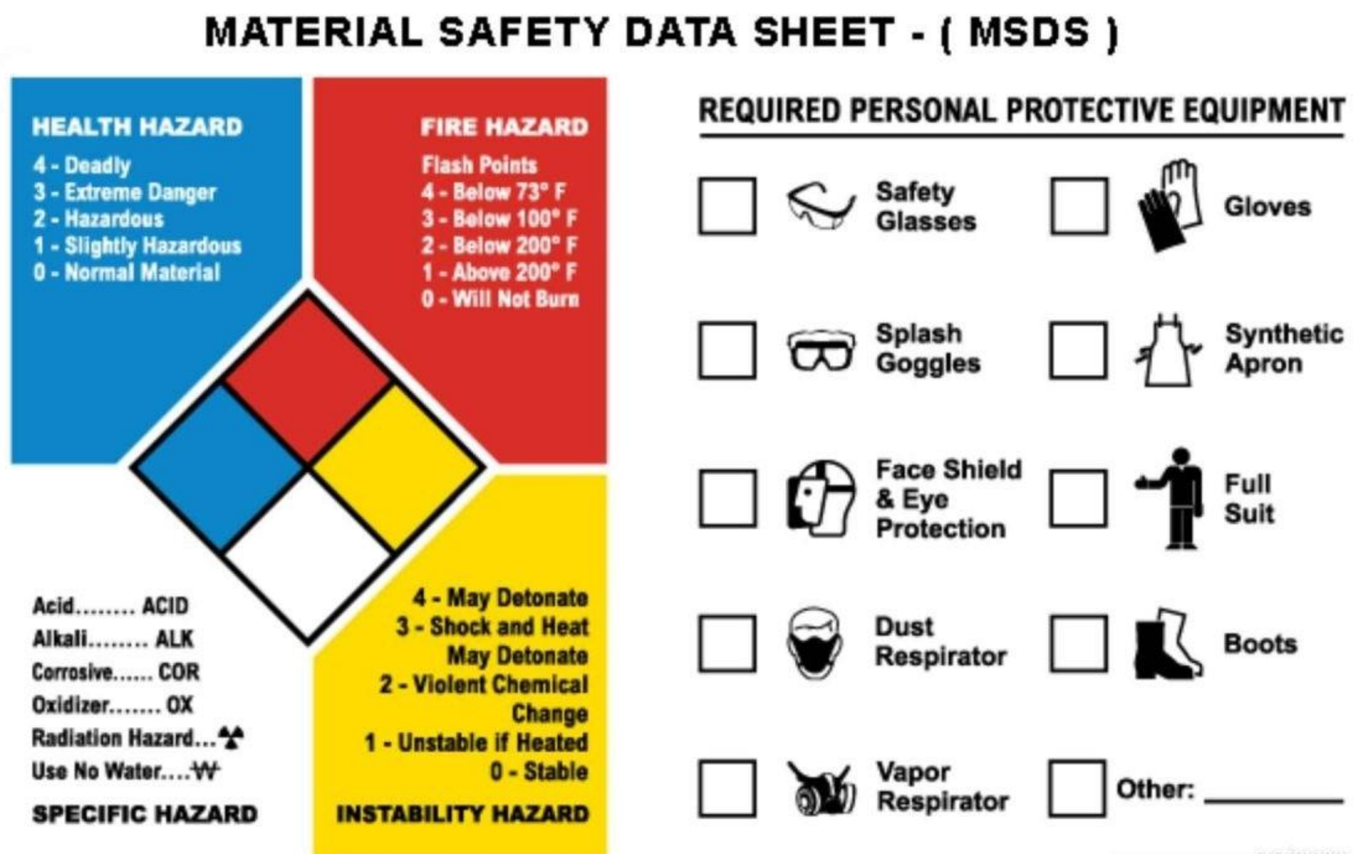
https://www.osha.gov/sites/default/files/publications/osha3151.pdf

American National Standards Institute (ANSI)

Occupational Safety and Hazard Administration (OSHA) requires PPE to meet the following ANSI standards

- **Eye and Face Protection:** ANSI Z87.1-2010, ANSI Z87.1-2003, or ANSI Z87.1-1989(R1998).
- **Head Protection:** ANSI Z89.1-2009, ANSI Z89.1-2003, or ANSI Z89.1-1997.
- **Foot Protection:** ASTMF-2412-2005 and ASTMF-2413-2005, ANSI Z41-1999, or ANSI Z41-1991.
- **Electrical Rubber Insulating Equipment:** ASTM D120-09, ASTM D-178-01 (2010), ASTM D-1048-12, ASTM D-1049-98 (2010), ASTM D-1050-05 (2011), or ASTM D1051-08.

PERSONAL SAFETY

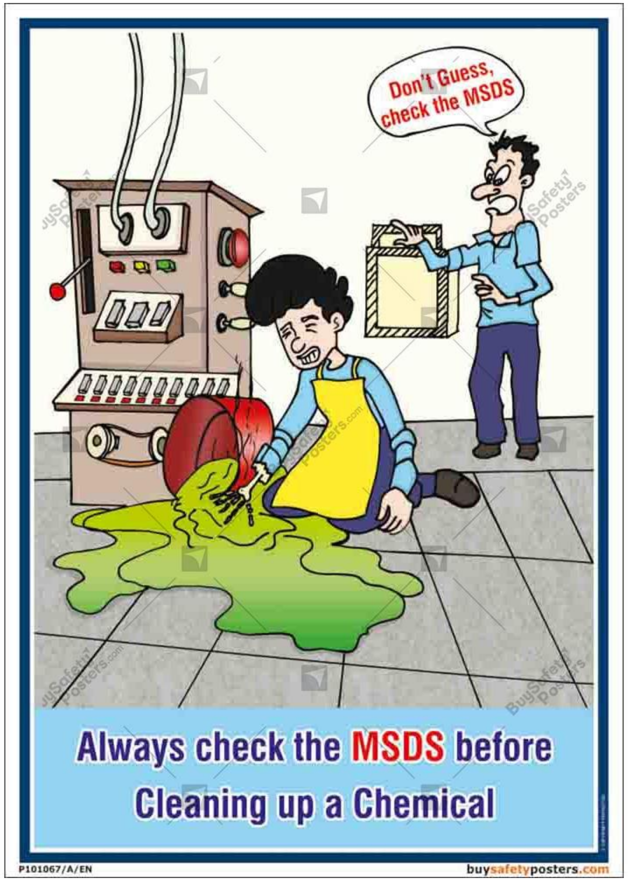


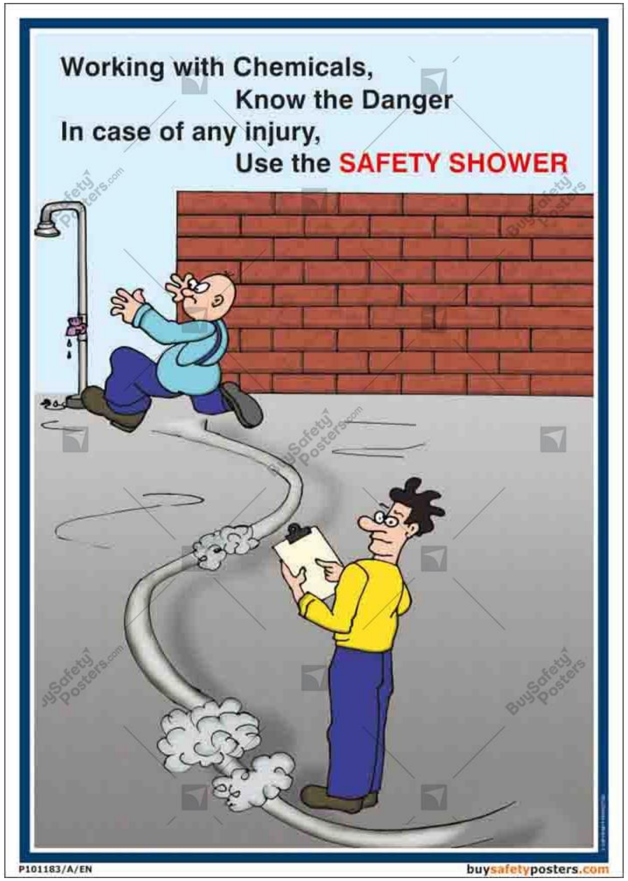
Sulfuric Acid (Conc.)

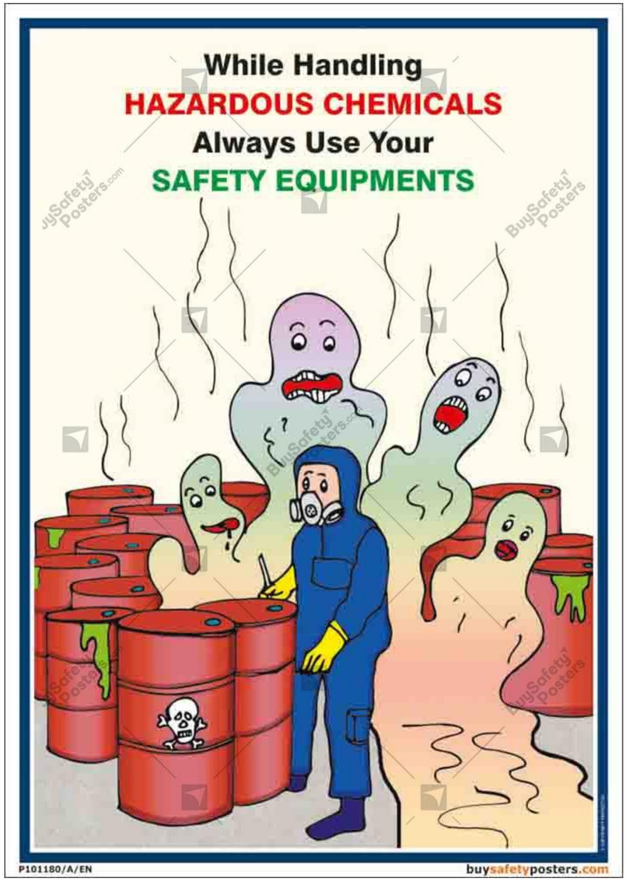
Methanol

Source: Google Images

PERSONAL SAFETY

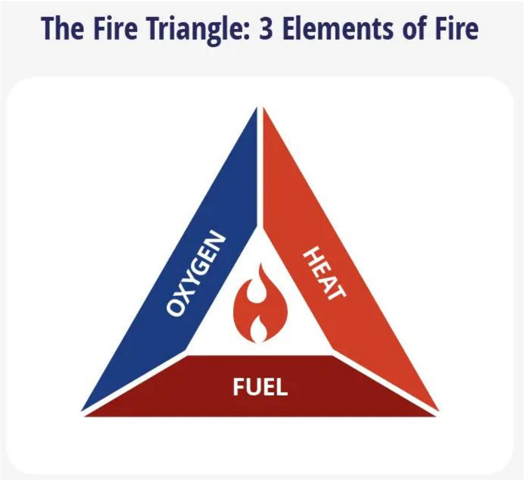


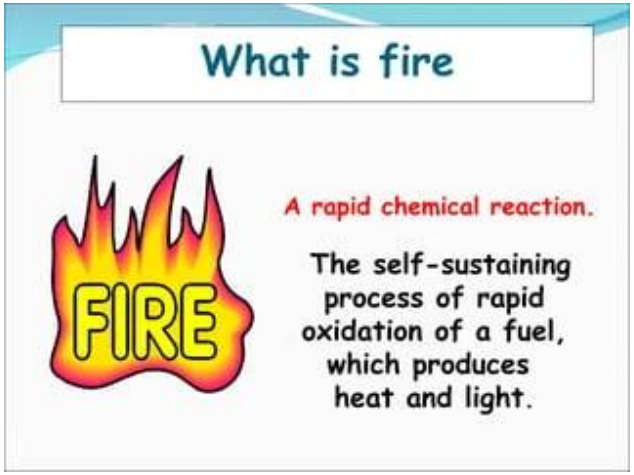


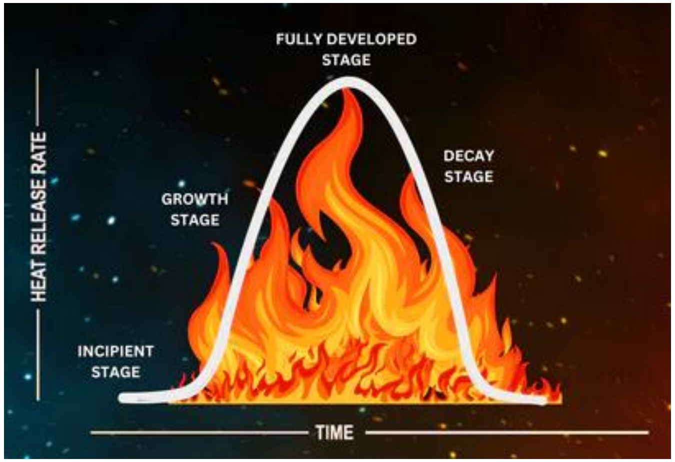


Source: Google Images

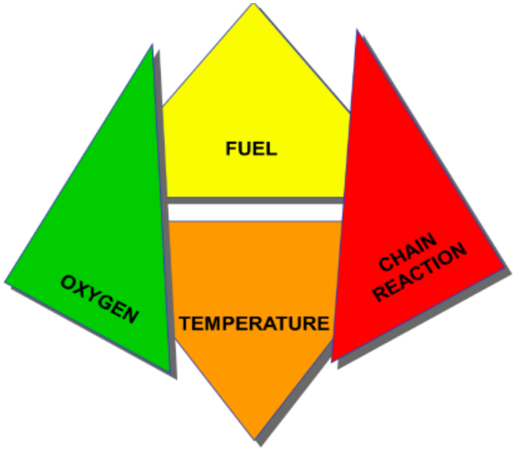
FIRE SAFETY

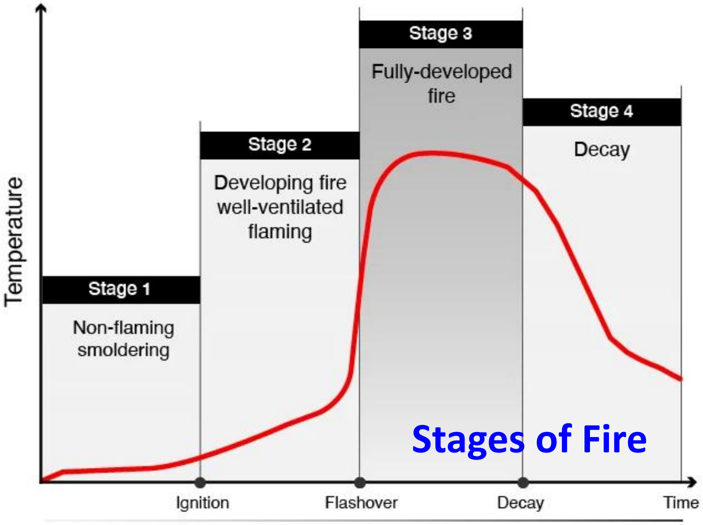






Fire Tetrahedron





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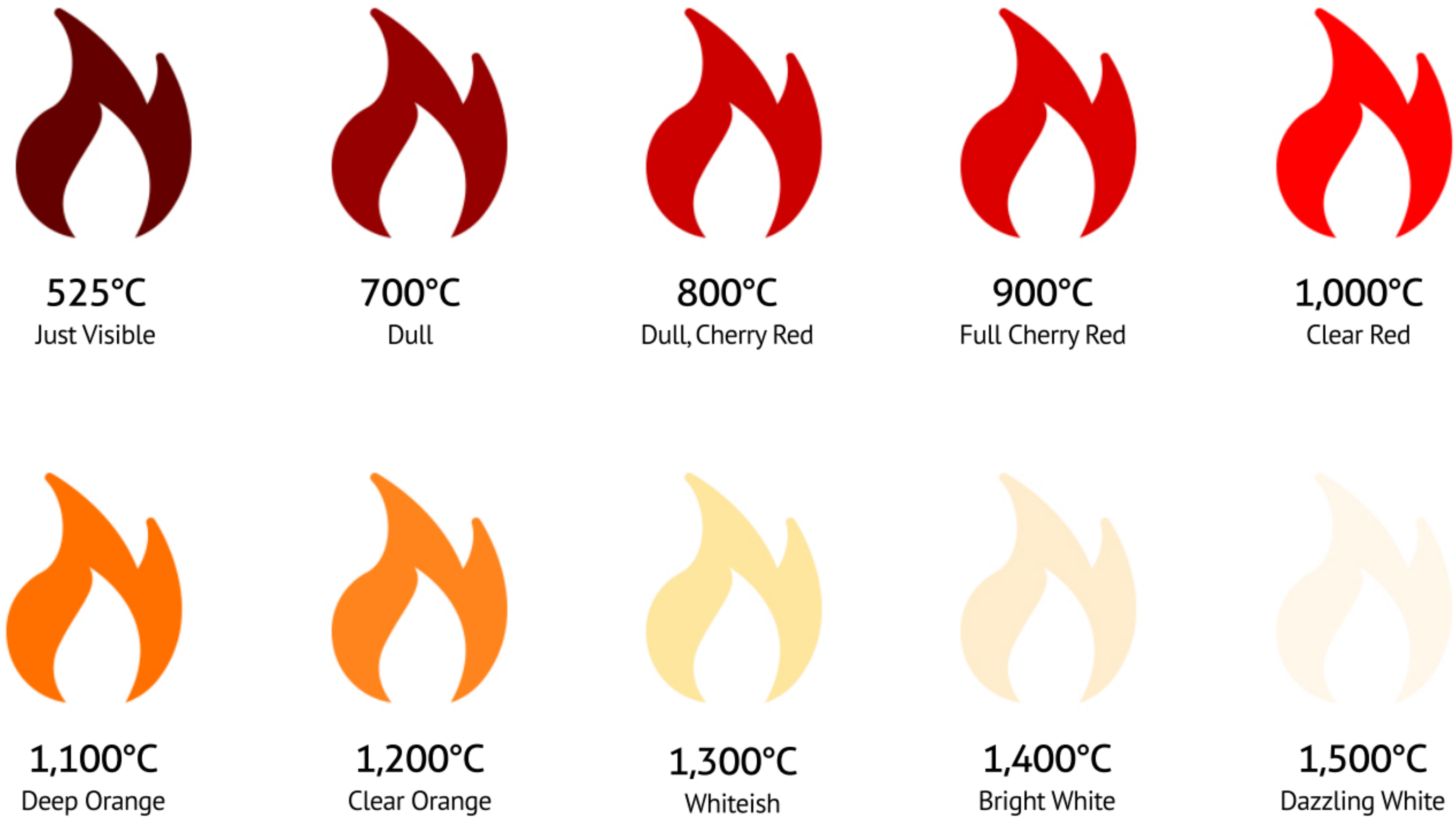
FIRE SAFETY

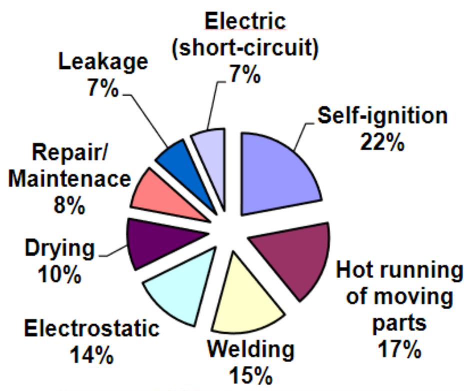


The Temperature of Fire

Source: Google Images

FIRE SAFETY AND PREVENTION

CAUSES OF FIRE IN A CHEMICAL PLANT

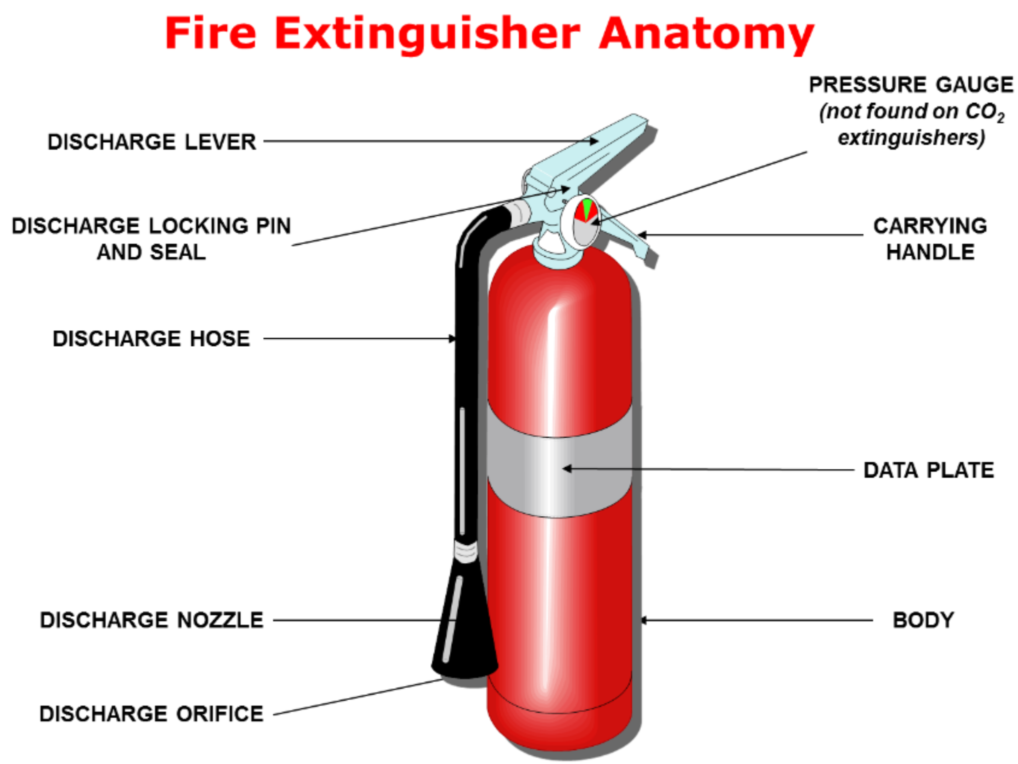


Fire Extinguisher Type

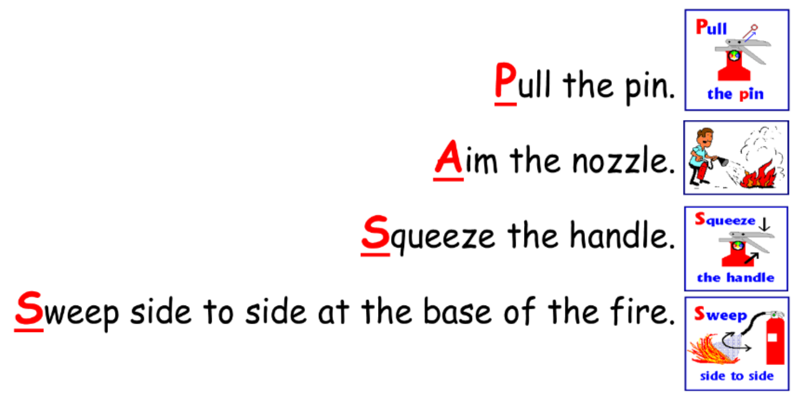
		Powder	Foam	CO^2	Water	Wet Chemical
CLASS A	**Solids** (e.g. wood, plastic, paper)	✓	✓	✗	✓	✗
CLASS B	**Flammable Liquids** (e.g. solvents, paint, fuels)	✓	✓	✓	✗	✗
CLASS C	**Gases** (e.g. butane, propane, LPG)	✓	✗	✗	✗	✗
CLASS D	**Metals** (e.g. lithium, magnesium)	✓	✗	✗	✗	✗
ELECTRICAL	**Equipment** (e.g. computers, servers, TVs)	✓	✗	✓	✗	✗
CLASS F	**Cooking Oils** (e.g. cooking fat, olive oil)	✗	✗	✗	✗	✓

Source: Google Images

FIRE SAFETY AND PREVENTION

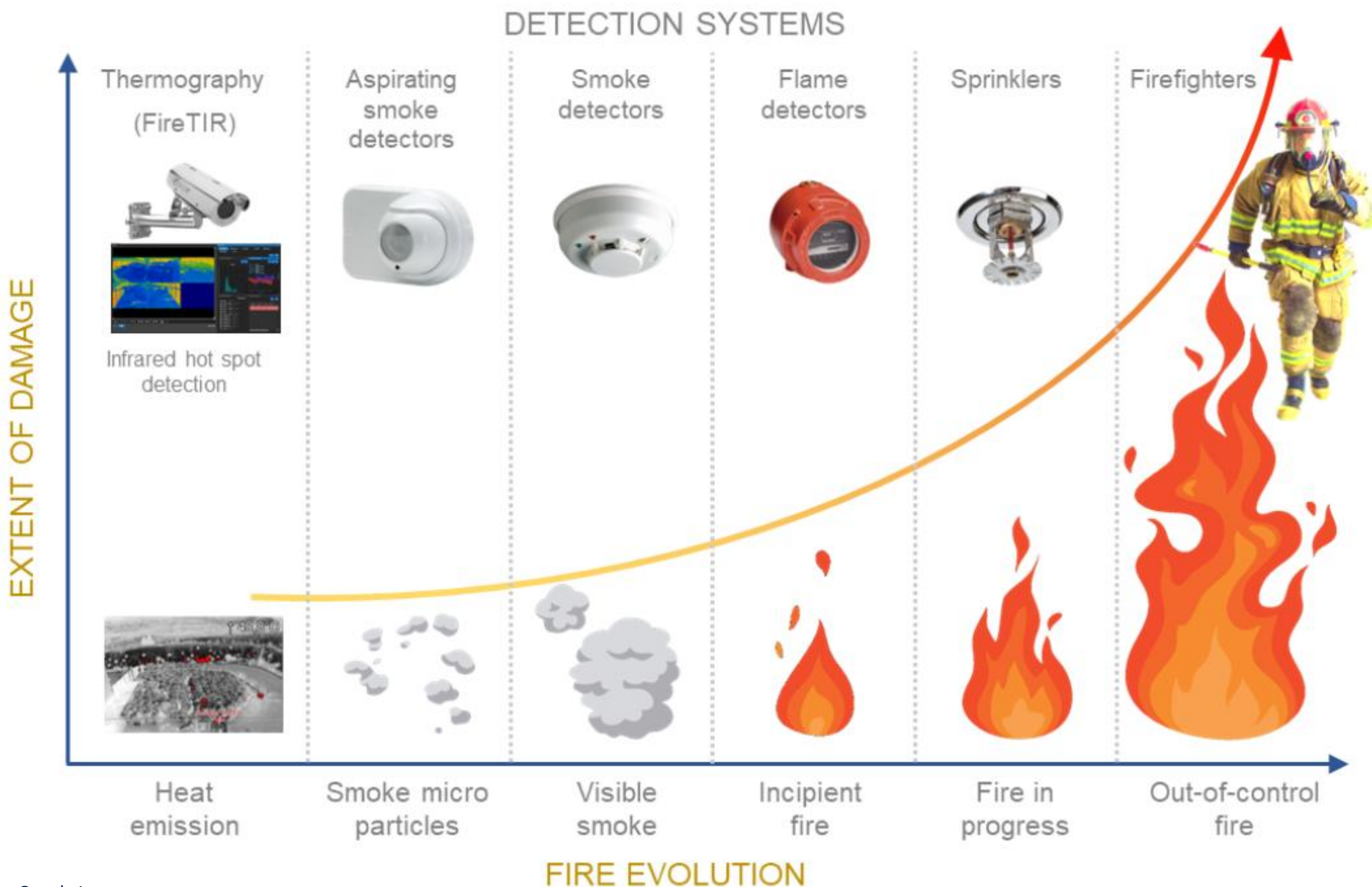


Remember this acronym when using an extinguisher – P. A. S. S.



Source: Google Images

FIRE SAFETY AND PREVENTION



Source: Google Images

FIRE SAFETY AND PREVENTION

Pool Fire

Liquid spills onto the ground, forming a pool. The volatile liquid (petrol) evaporates into the atmosphere, forming a flammable mixture, igniting, and forming a pool fire. The heat vaporizes more fuel, and air is drawn in around the side to support combustion. Danger to people is by direct thermal radiation.

Flash Fire

Relatively volatile spilled material (example: propane, butane, LPG) forms a pool with rapid evaporation forming sizeable vapor cloud, drifted away by wind, ignited by ignition source to form flash fire. People is at risk from thermal radiation effect.

Torch Fire

High pressure release of gas from a pressure vessel or pipeline ignites almost immediately, forming torch fire with flame length tens of meters. Danger arises from thermal radiation and also impingement on adjacent pressurized vessel containing liquefied petroleum gas (LPG) may cause vessel failure from **boiling liquid expansion vapor explosion** (**BLEVE**).

Pool fire, water is sprayed to cool down the hot tank wall to

Torch fire

Fireball

Jet fire

Pool fire

Flash fire / VCE

Source: Google Images

FIRE SAFETY AND PREVENTION

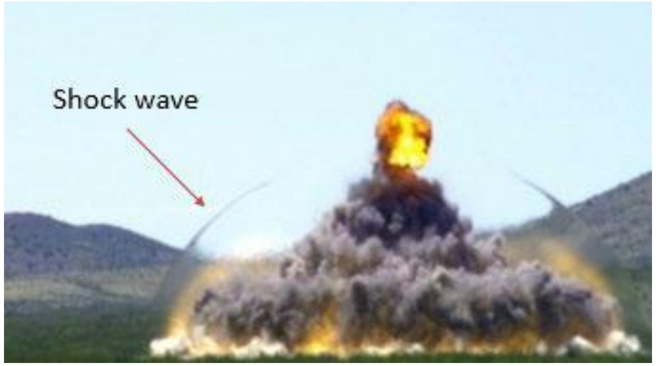
- **Explosion** is sudden and violent release of energy physically or chemically. Examples of chemical explosion are explosion from explosive material and exothermic chemical reaction.

- Examples of physical explosion are explosion due to fracture of a vessel containing high pressure gas or steam due to over pressure.

- In general, explosion can be divided into two types:

  - **Deflagration:** resulting shock wave moving at the speed less than speed of sound (Mach Number < 1).

  - **Detonation:** resulting shock wave moving at the speed greater than speed of sound (Mach Number > 1), i.e., shock wave followed closely by a combustion wave.



1) UVCE

2) Dust Explosion

3) BLEVE

Source: Google Images

FIRE SAFETY AND PREVENTION

Unconfined Vapor Cloud Explosion (UVCE)

It is an explosion due to the ignition of large pre-mixed cloud of flammable vapor and air of concentration within the flammable range.

Popular example:
Flixborough, 1974 in which a major leak of hydrocarbon occurred at a reactor non-standard modified piping, forming vapor cloud, ignited and led to UVCE.

Confined Vapor Cloud Explosion (CVCE)

Vapor explosion occurs within a vessel or building.

Popular example: Abbeystead disaster, 1984, in which methane gas in water pumping station ignited killing several visitors.

Dust Explosion (DE)

Results from the rapid combustion of fine combustible solid particles (dust in grain silo, iron & aluminum dust).

Popular example: New Orleans in 1977 in which 45 silos containing corn, wheat and soy beans were involved.

Boiling Liquid Expanding Vapor Explosion (BLEVE)

Vessel containing flammable liquid (e.g., LPG) is heated by fire from neighbouring vessel. The flammable liquid vaporized and build pressure, vessel weakened and finally ruptures creating vapor cloud and explodes. Casualties are from blast effect, thermal radiation or missiles.

Popular example: Feyzin 1966 involving propane tank and San Juanico, Mexico City 1984 involving LPG tank.

EVACUATION PROCEDURES

- **EMERGENCY EVACUATION**
- Emergency evacuation is the urgent immediate egress or escape of people away from an area that contains an imminent threat, an ongoing threat or a hazard to lives or property.

- In situations involving hazardous materials or possible contamination, evacuees may be decontaminated prior to being transported out of the contaminated area.

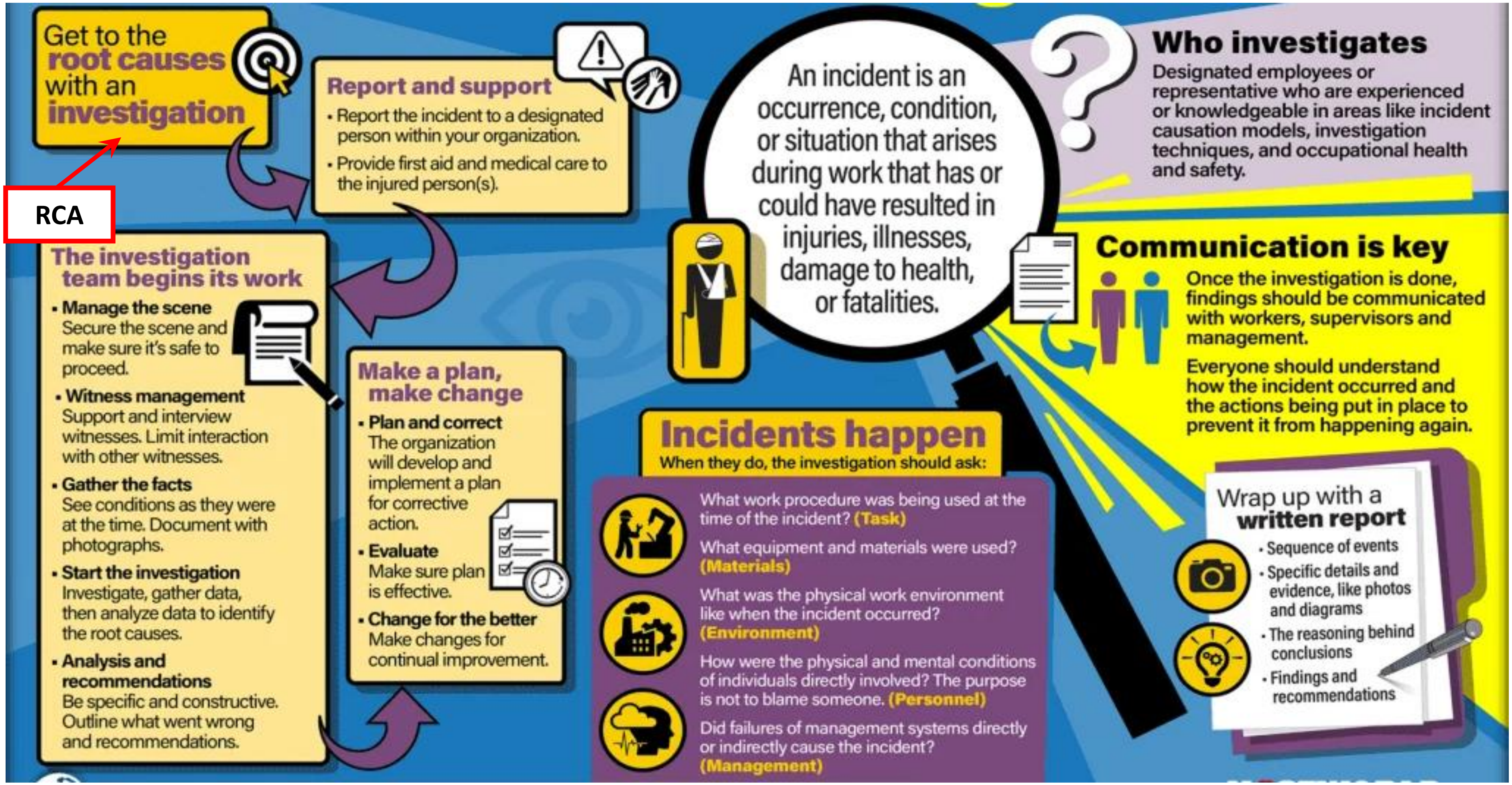
- **Evacuation Sequence:**
  - Detection
  - Decision
  - Alarm
  - Reaction
  - Movement to an area of refuge or an assembly station
  - Transportation

- The time for the first four phases is usually called pre-movement time.

- The most common equipment to **facilitate emergency evacuations** are **fire alarms**, **exit signs**, and **emergency lights**. Some structures need special emergency exits or fire escapes to ensure the availability of alternative escape paths.

Source: Google Images

POST-EMERGENCY PROCEDURES & INCIDENT INVESTIGATION



Source: Google Images

CH 42010: PROCESS PLANT OPERATION & SAFETY

LTP: 3-0-0, CRD: 3

Lecture 6

Plant Test Runs and Rating Calculations

PLANT TEST RUN (PTR)

- **PTR:** a controlled trial or assessment conducted in an industrial plant to evaluate the performance, efficiency, and safety of the equipment, systems, and processes under actual operating conditions.

- During a PTR, the plant operates at specific conditions—**often at full capacity** or **under varying loads**—to collect data on key parameters such as temperature, pressure, flow rates, and product quality.

- The **primary purposes** of a PTR include:

  - **Validating Performance:** Ensuring the equipment and systems meet the design specifications and performance criteria.
  - **Troubleshooting & Optimization:** Identifying any operational bottlenecks, inefficiencies, or potential areas for improvement.
  - **Quality Control:** Confirming that the production process can consistently produce outputs that meet quality standards.
  - **Safety Verification:** Testing operational safety protocols and ensuring compliance with safety regulations.
  - PTRs are essential during the **commissioning phase** (when a new plant or equipment is being started for the first time) and for ongoing **performance evaluations** to maintain or improve efficiency and safety.

PLANT TEST RUN

- **Data Collection and Instrumentation**
  - Importance of accurate data collection and selecting suitable sensors and instruments.
  - Calibration and validation of equipment before the test run.
  - Online and offline data collection methods.

- **Analyzing and Interpreting Test Run Data**
  - Statistical analysis of collected data to identify trends and operational patterns.
  - Calculations for equipment rating based on operational data and thermodynamic principles.
  - Use of simulation software or tools to predict performance under different conditions.

- **Safety and Compliance During Test Runs**
  - Ensuring that test runs are conducted safely, with all personnel trained on emergency shutdown procedures (ESP).
  - Compliance with regulatory standards, industry best practices, and environmental considerations.
  - Risk assessment to anticipate potential hazards associated with specific equipment.

- **Reporting and Documentation**
  - Preparing comprehensive test reports that include methodology, data, analysis, conclusions, and recommendations.
  - Importance of documenting deviations from expected performance and troubleshooting approaches.

OPTIMUM DESIGN

Cost of sides: c_s
Cost of bottom: c_b
Cost of top: c_t

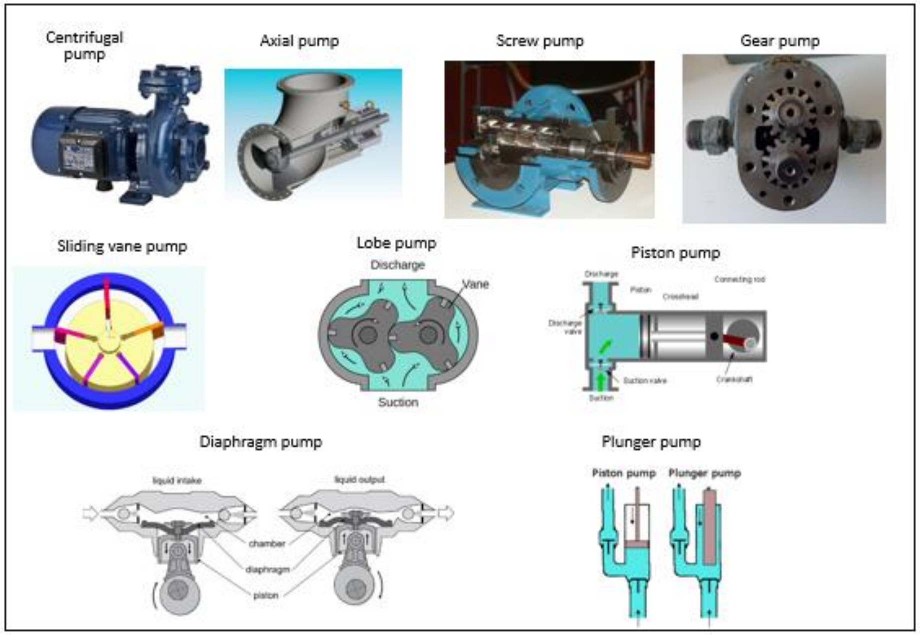
Q. You need to design a cylindrical storage vessel with diameter (D) of your choice. Evaluate the design criteria.

Source: Google Images

ROTATING EQUIPMENTS – PUMPS, COMPRESSORS, TURBINES

PUMPS

- Pump is a machine to move or transport incompressible fluids.
- Classification of Pumps:
  - **Dynamic Pump:**
    - ➢ May have 100% slips if the discharge valve is closed.
    - ➢ Therefore, no excessive pressure build up will occur if the discharge valve is closed.
    - ➢ The dynamic pump efficiency is lower than positive displacement pumps.
    - ➢ They have relatively high flow rates at relatively high operating speed with low maintenance costs.
    - ➢ Two types of dynamic pump are: **a) Centrifugal pump**, & **b) Axial pump**.



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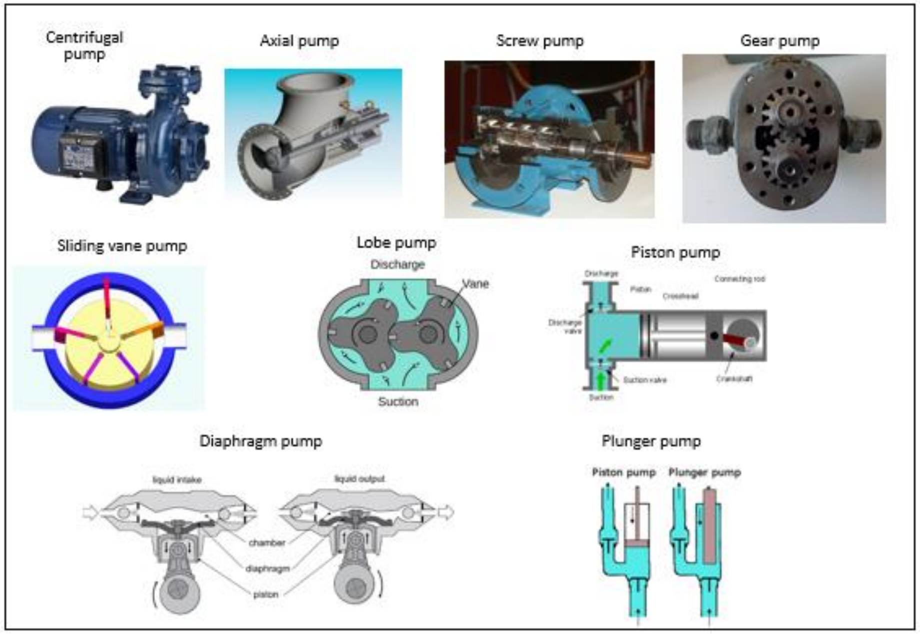
ROTATING EQUIPMENTS – PUMPS, COMPRESSORS, TURBINES

PUMPS

- Pump is a machine to move or transport incompressible fluids.
- Classification of Pumps:
  - **Positive Displacement Pump:**



➢ Operate by forcing a fixed volume of fluid from the inlet pressure section to the discharge section of the pump.

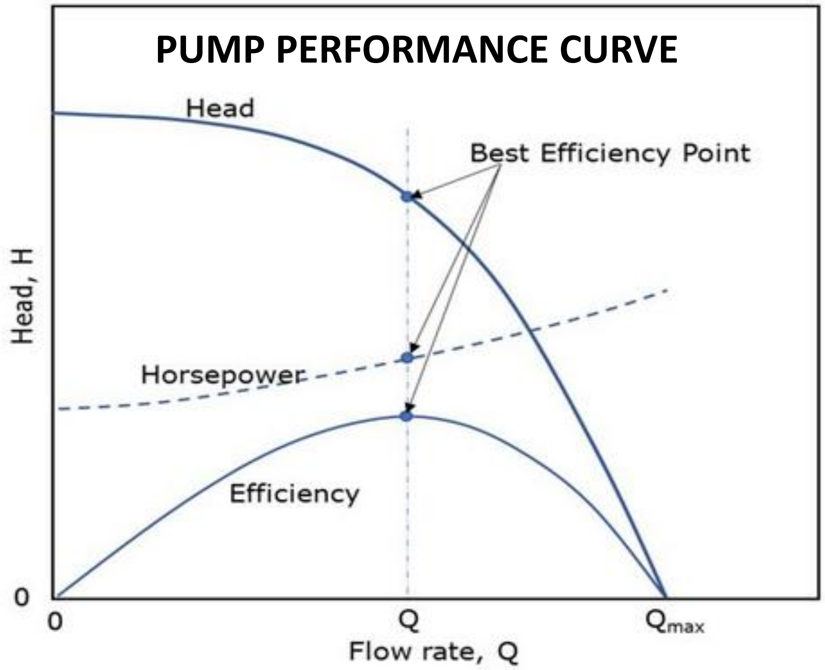
➢ They have relatively low capacity, operating at lower speed but able to produce higher pressure than dynamic pumps.

➢ Therefore, if the discharge valve is closed, the pressure will increase and may damage the discharge pipe if pressure relief is not provided.

➢ The positive displacement pump may be classified into: **a) Rotary pump** such as **screw pump, gear pump, sliding vane pump** and **lobe pump**, & **b) Reciprocating pump** such as **piston pump, diaphragm pump** and **plunger pump**.

Source: Google Images

RATING CALCULATIONS – PUMPS

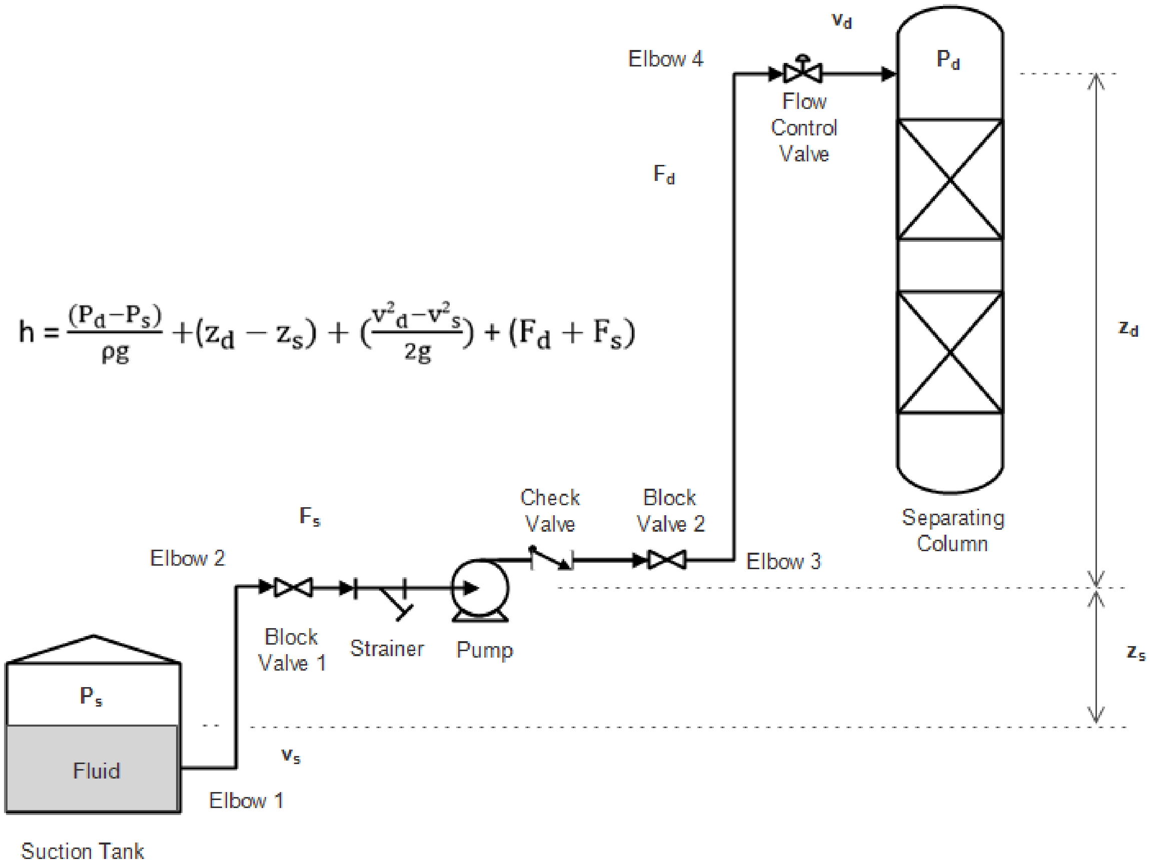


Source: Google Images

- Two main criteria for pump selection are the **capacity** and **pump head**.
- Manufacturers use pump head (in the unit of water height) instead of pressure for pump specifications.
- The process designer has to calculate the required pump head when pumping a fluid from a location to another.
- Then, one has to refer to the pump performance curve to select suitable pump for the operating condition.
- The pump in the left figure is suitable at the operating condition (pump head, flowrate and horsepower) at the best efficiency point (maximum efficiency).

Pump Head = Pressure Head + Elevation Head + Velocity Head + Pipe & Fittings Head

RATING CALCULATIONS – PUMPS



$$h = \frac{(P_d - P_s)}{\rho g} + (z_d - z_s) + \left(\frac{v^2{}_d - v^2{}_s}{2g}\right) + (F_d + F_s)$$

- **Pumps in series:** Total discharge pressure is equal to the addition of the particular discharge pressures of each pump and the total flow is equal to the flow of one pump, which is the flow of the smaller pump (if the pumps are not of the same capacity).

$$H_T = H_1 + H_2 + H_3 + \dots$$

$$Q_T = Q_1 = Q_2 = \dots = Q_{min}$$

- **Pump in parallel:** Total discharge pressure is equal to discharge pressure of one pump & the total flow rate is the addition of the flow of each pump.

$$H_T = H_1 = H_2 = H_3 = \dots$$

$$Q_T = Q_1 + Q_2 + Q_3 + \dots$$

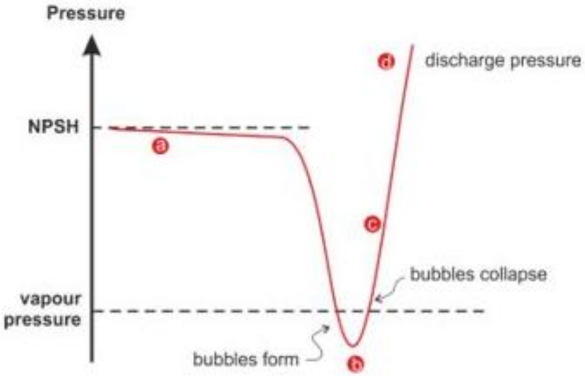
Source: Google Images

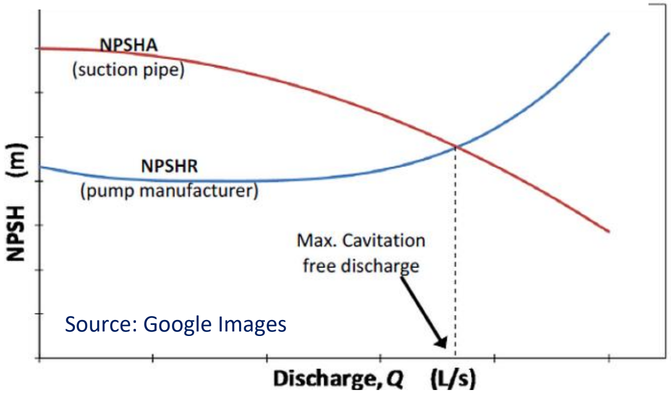
RATING CALCULATIONS – PUMPS

Cavitation on a Pump Impeller

- If the pressure of the pump < vapor pressure of the fluid, vapor will form.
- As the fluid moves to the higher-pressure region, the bubbles will collapse and cavitation occurs.
- The implosion of the bubbles may cause pitting to the impeller.
- Cavitation is a common problem for centrifugal pump.

- The following techniques can be used to **avoid cavitation** in a pump:
  - Avoid low pressure if possible.
  - Pressurize the supply tank or increase the level of the supply tank.
  - Reduce the fluid temperature.
  - Use a larger pipe diameter to reduce minor losses in the suction pipe.
  - Use special cavitation-resistant materials or coatings.
  - Available net positive suction head (NPSHA) > Required NPSH (NPSHR).
- The NPSHR is provided by the pump supplier or can be estimated using the graphical techniques from various literatures.





Source: Google Images

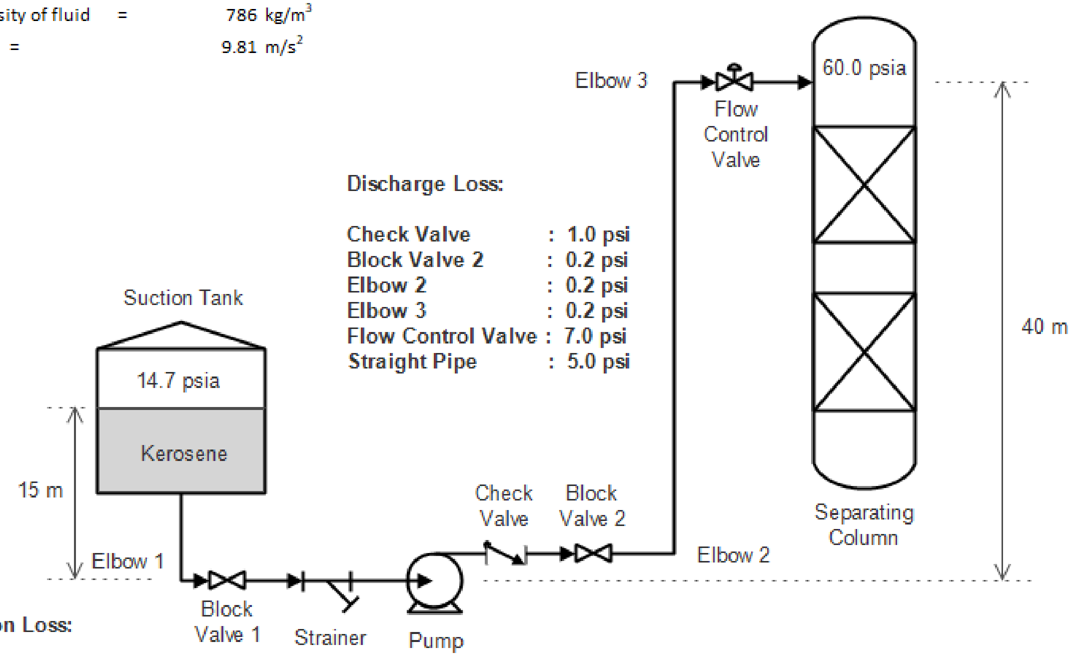
RATING CALCULATIONS – PUMPS

ASSIGNMENT

Q1. Calculate the required pump head (in meters) for the following system. The suction pressure is 14.7 psia (atmospheric pressure) and the suction fluid level is elevated 15 m from center of the pump. The calculated friction and fitting loss for suction and discharge pipes are given as in figure below. The discharge pressure is 40 psia and the level of the discharge fluid is elevated 40 m from the center of the pump. The pumping fluid is liquid kerosene. Since the suction level is above the pump center, it must be distracted with the Z_d, when using the equation. Head due to velocity is negligible. Use safety factor of 1.1 for the calculation.

Density of fluid = 786 kg/m^3

g = 9.81 m/s^2



Suction Loss:

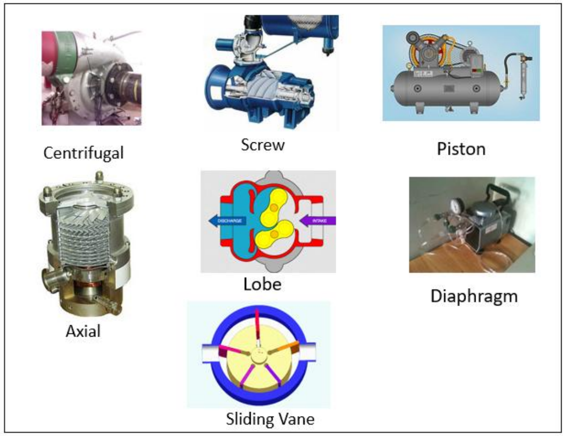
Elbow 1	:	0.2 psi
Block Valve 1	:	0.2 psi
Strainer	:	5.0 psi
Straight Pipe	:	0.5 psi

100000 $kg/m.s^2$ = 14.504 lb/in^2

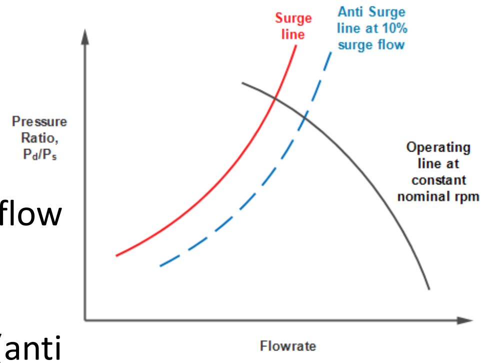
Text Book: Introduction to Fluid Mechanics, Fox, McDonald, Pritchard

COMPRESSORS

- Compressor is a machine to move or transport gas or vapor (Compressible Fluids).
- Classification of Compressors:
    - **Dynamic compressor**
        - **Centrifugal compressor**
        - **Axial compressor**
    - **Positive displacement compressor**
        - **Rotary compressor** such as **screw, sliding vane** and **lobe compressor**.
        - **Reciprocating compressor** such as **piston** and **diaphragm compressor**.



- **Centrifugal compressor:** surge is noisy unstable operation caused by periodic backflow due low inlet flow (flow < surge limit flow).
- This unstable operation may cause mechanical damage and lead to major hazards.
- **To avoid surging**, the compressor must always be operated above control limit (anti surge line). Control limit is the control line for the minimum flow at 10% of the surge limit.
- If **compressor surging occurs**, operator should do the following immediately: **i) Fully open the compressor by-pass valve (or recirculation valve)** and ii) **Close the compressor inlet valve to the minimum opening**. Usually, the compressor inlet valve is mechanically locked at minimum opening.



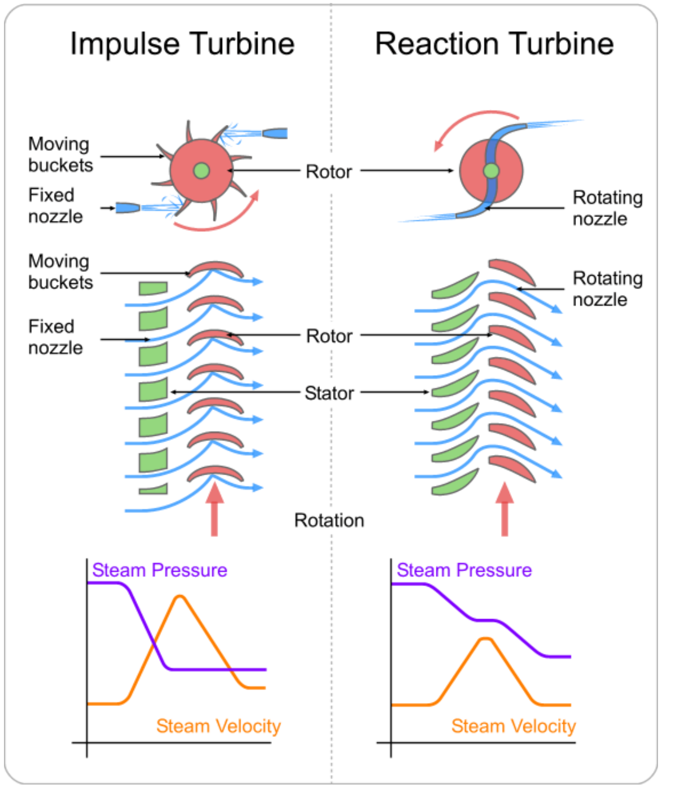
Typical Surge Compressor Curve

Source: Google Images

ROTATING EQUIPMENTS – PUMPS, COMPRESSORS, TURBINES

TURBINES

- Steam turbines are widely used as prime movers, i.e., they are used to drive pump, compressor or electric generator.
- Steam turbine is selected as the prime mover when a lot of steam is expected to be produced in a plant. Work is obtained through the expansion of steam.
- Normally, a turbine will be backed up by electric motor prime mover.
- Steam turbine converts steam/thermal energy into mechanical energy.
- Both types of turbines can be:
  - **Condensing:** exhaust steam is condensed. Thus, the pressure is less than atm. pressure.
  - **Non-condensing:** exhaust steam is at pressure higher than atm. and used for other process.



Source: Google Images

RATING CALCULATIONS – PIPES

Minimum Wall Thickness for a Pipe (ASME 31.3)

- Minimum wall thickness of a process pipe for a specific internal pressure according to ASME 31.3 Code is given by:

$$t = \frac{P \times D}{2\left(S \times E + P \times Y\right)}$$

  - P = Design pressure (psig)
  - D = Pipe outside diameter (in)
  - S = Allowable stress in tension (psi)
  - E = Longitudinal joint quality factor
  - Y = Wall thickness correction factor

$$t_{min} = t + CA$$

  - t_{min} = Pipe thickness + Corrosion allowance
  - CA = Corrosion allowances

$$t_{nom} = \frac{t_{min}}{0.875}$$

  - t_{nom} = Nominal thickness

RATING CALCULATIONS – PIPES

Minimum Wall Thickness for a Pipe (ASME 31.3)

- Determine the pipe wall thickness according to ASME 31.3 Code for the following conditions:
  - Design *T* = 800 °F.
  - Design *P* = 800 psig.
  - Pipe outside diameter = 10 in.
  - Material: Carbon Steel A106, Grade B, Seamless.
  - Corrosion allowance = 0.0625 in.

Material	Spec.	Grade	Allowable stress (psi) functions of temperature														
			100°F	200°F	300°F	400°F	500°F	600°F	700°F	800°F	900°F	1000 °F	1100°F	1200°F	1300°F	1400°F	1500°F
Carbon Steel	A 106	B	20000	20000	20000	20000	18900	17300	16500	10800	6500	2500	1000				
C-1/2 Mo	A 335	P1	18300	18300	17500	16900	16300	15700	15100	13500	12700	4000	2400				
1 1/4-1/2 Mo	A 335	P11	20000	18700	18000	17500	17200	16700	15600	15000	12800	6300	2800	1200			
18 Cr - 8 Ni pipe	A 312	TP304	20000	20000	20000	18700	17500	16400	16000	15200	14600	13800	9700	6000	3700	2300	1400
16 Cr-12 Ni- 2 Mo pipe	A 312	TP316	20000	20000	20000	19300	17000	17000	16300	15900	15500	15300	12400	7400	4100	2300	1300

Allowable Stress at designated temperature (source: Carruci V.A., 2000)

Correction Factor (source: Carruci V.A., 2000)

MATERIAL	TEMPERATURE					
	≤ 900°F	950°F	1000°F	1050°F	1100°F	≥1150°F
Ferritic Steels	0.4	0.5	0.7	0.7	0.7	0.7
Austenitic Steels	0.4	0.4	0.4	0.4	0.5	0.7
Other Ductile Metals	0.4	0.4	0.4	0.4	0.4	0.4
Cast Iron	0	-	-	-	-	-

RATING CALCULATIONS – PIPES

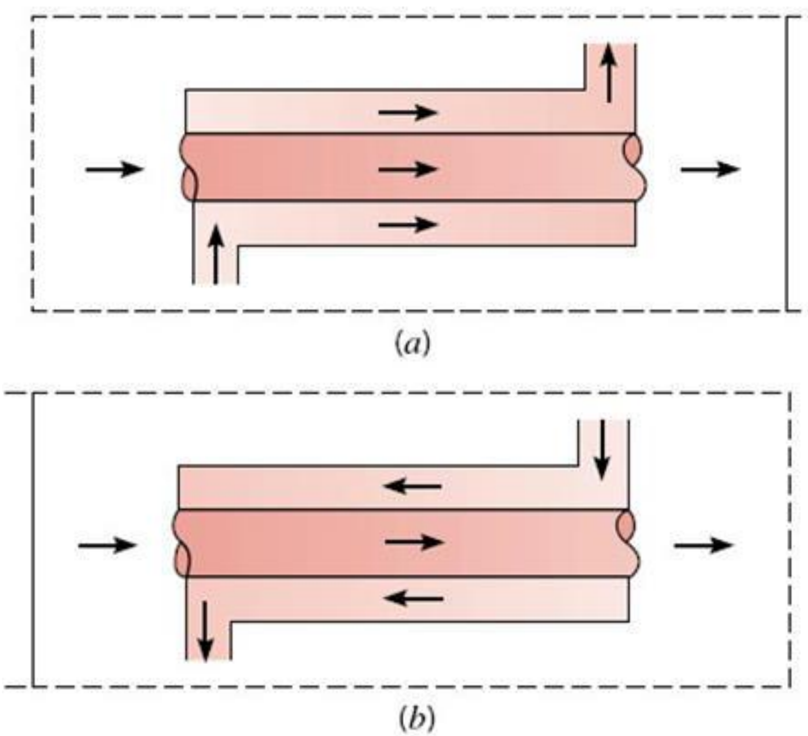
Minimum Wall Thickness for a Pipe (ASME 31.3)

Spec. No	Class(or Type)	Description	Joint quality factor, E
		Carbon Steel	
API	-	Seamless pipe	1.00
5L	-	Electric resistance welded pipe,	0.85
	-	Electric fusion welded pipe, double butt, straight or spiral seam	0.95
A 53	Type S	Seamless pipe	1.00
	Type E	Electric resistance welded pipe	0.85
	Type F	Furnace butt welded pipe	0.60
A 106	-	Seamless pipe	1.00
		Low and Intermediate Alloy Steel	
A 333	-	Seamless pipe	1.00
	-	Electric resistance welded pipe	0.85
A 335	-	Seamless pipe	1.00
		Stainless Steel	
A 312	-	Seamless pipe	1.00
	-	Electric fusion welded pipe, double butt seam	0.85
	-	Electric fusion welded pipe, single butt seam	0.80
A 358	1, 3, 4	Electric fusion welded pipe, 100% radiographed	1.00
	5	Electric fusion welded pipe, spot radiographed	0.90
	2	Electric fusion welded pipe, double butt seam	0.85
		Nickel and Nickel Alloy	
B 161	-	Seamless pipe and tube	1.00
B 514	-	Welded pipe	0.80
B 675	All	Welded pipe	0.80

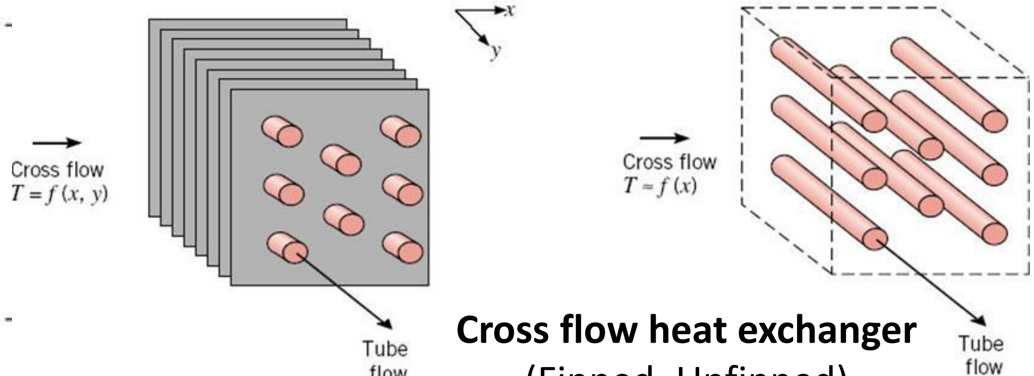
Joint Quality Factor
(source: Carruci V.A., 2000)

HEAT EXCHANGERS (HXs)

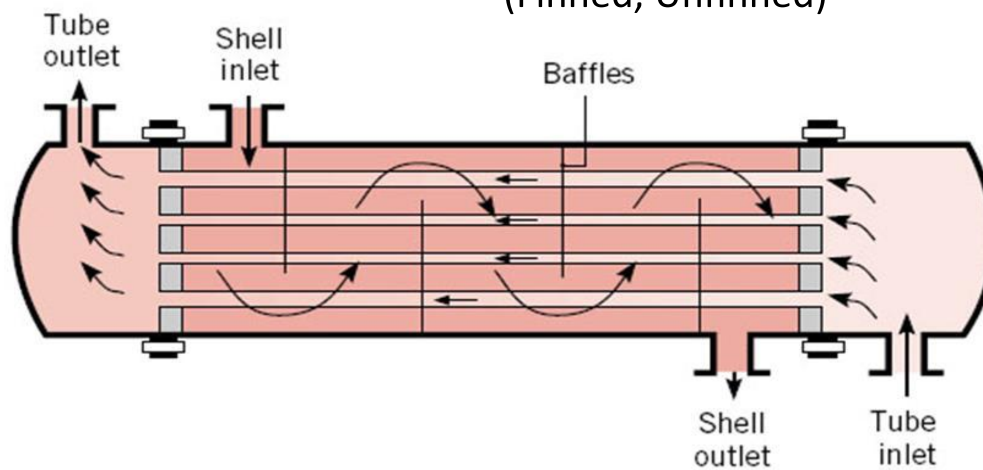
- Devices used to exchange thermal energy between at least two fluids.



Concentric tube heat exchanger
Parallel flow, Counter flow



Cross flow heat exchanger
(Finned, Unfinned)



Shell-and-tube heat exchanger
(One/more-tube and One-shell pass, Cross-Counter Flow Mode)

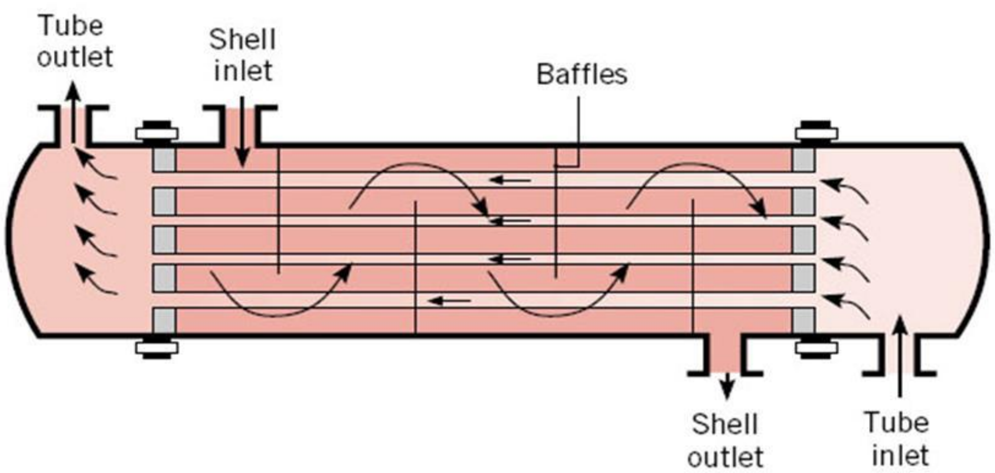
Source: Google Images

HEAT EXCHANGERS (HXs)

- Devices used to exchange thermal energy between at least two fluids.
- An engineer often finds himself or herself in a position:

➢ to select a heat exchanger (Sizing) that will achieve a specified temperature change in a fluid stream of known mass flow rate: log mean temperature difference (or LMTD) method.

➢ to predict the outlet temperatures of the hot and cold fluid streams in a specified heat exchanger (Rating): effectiveness (ε)–NTU method.



Shell-and-tube heat exchanger

(One/more-tube and One-shell pass, Cross-Counter Flow Mode)

Source: Google Images

HEAT EXCHANGERS (HXs)

- The main basic Heat Exchanger equation is:

$$Q = U \times A \times \Delta T_m$$

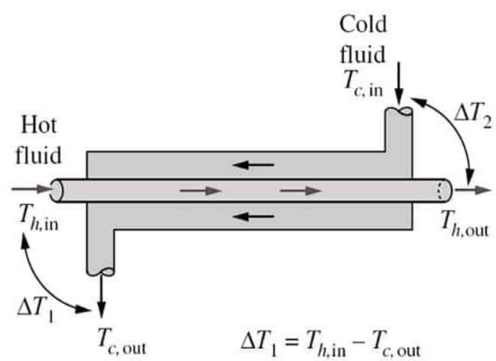
$$Q = m \times C_p \times \Delta T_m$$

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

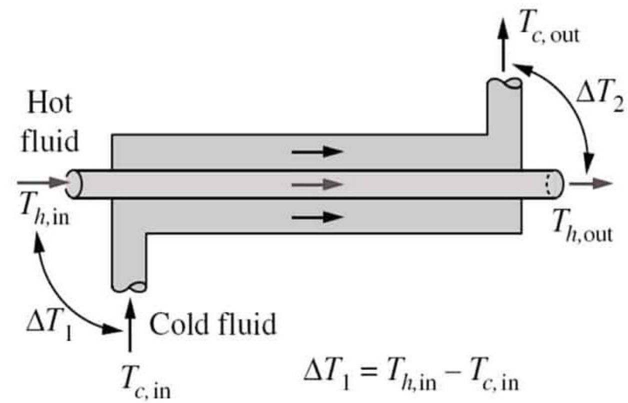
LMTD FORMULA

Assumptions: a) Fully developed conditions, b) Constant cross-sectional areas, c) Constant properties

The **effective** representation of temperature difference



$\Delta T_1 = T_{h,\text{in}} - T_{c,\text{out}}$
$\Delta T_2 = T_{h,\text{out}} - T_{c,\text{in}}$



$\Delta T_1 = T_{h,\text{in}} - T_{c,\text{in}}$
$\Delta T_2 = T_{h,\text{out}} - T_{c,\text{out}}$

Source: Google Images

Where:

A = Heat transfer area (m²) (ft²)

Q = Heat transfer rate (kJ/h) (Btu\h)

U = Overall heat transfer coefficient (kJ/h.m².°C) (Btu/h°F)

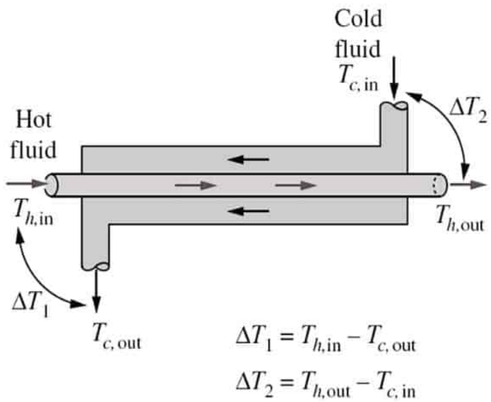
ΔT_m = Log mean temperature difference

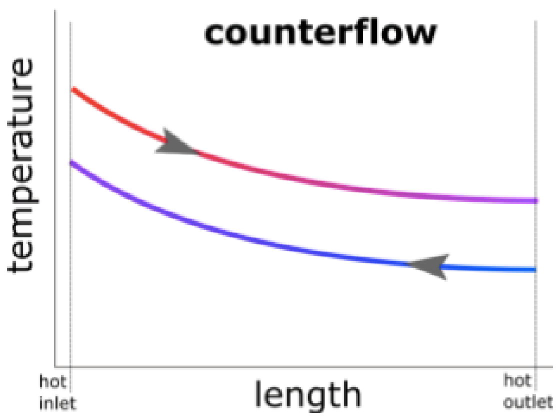
HEAT EXCHANGERS (HXs)

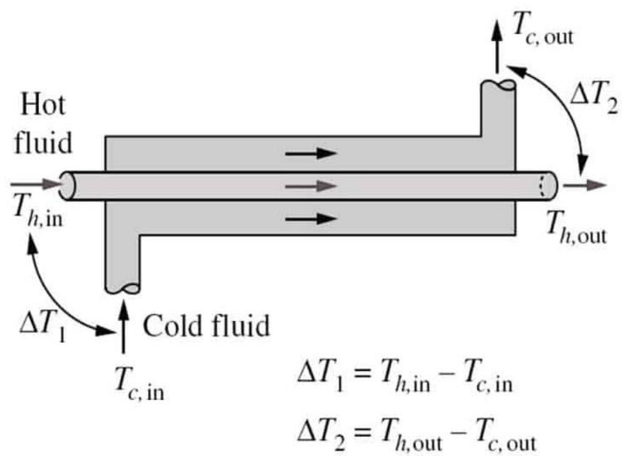
$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

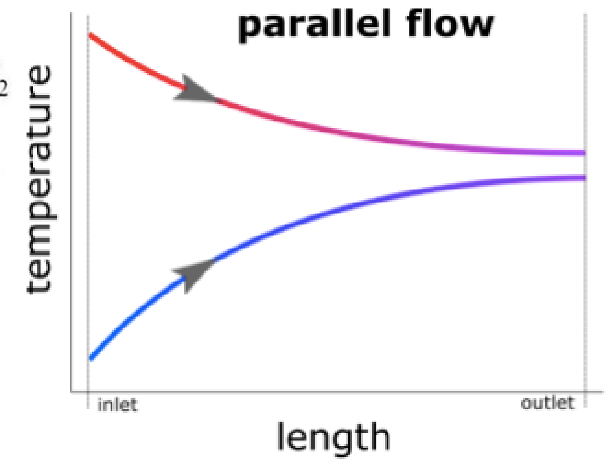
LMTD FORMULA

The **effective** representation of temperature difference









- **Counter Flow HX:** This distributes the heat more evenly across the heat exchanger and allows for maximum efficiency. In theory, the cold fluid can exit the heat exchanger at a higher temperature than the temperature of the hot fluid outlet, although in reality this is very difficult to achieve.

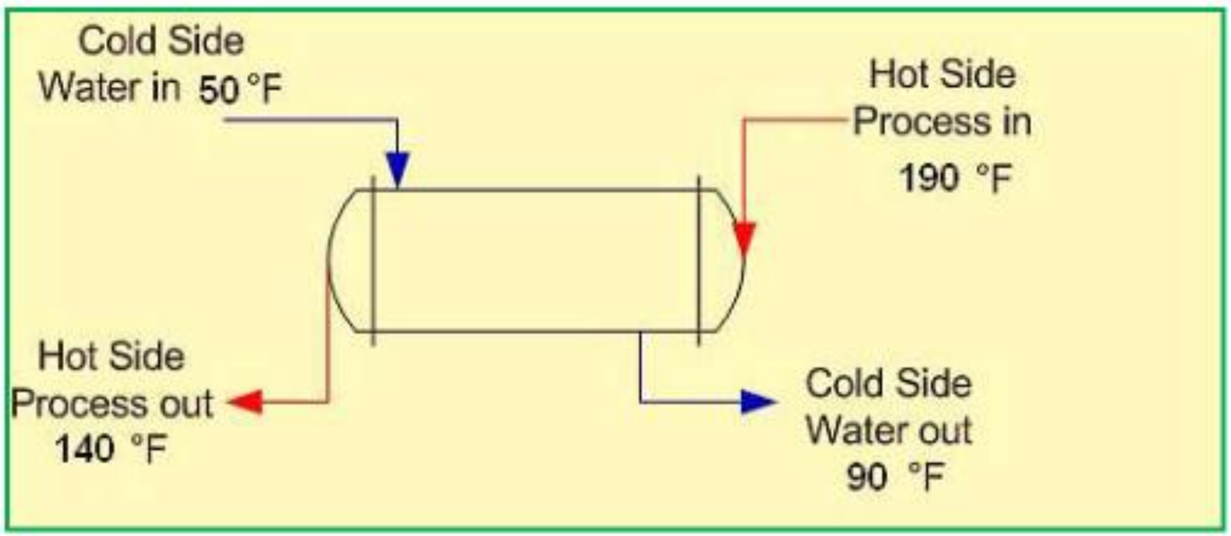
Source: Google Images

RATING CALCULATIONS – HXs

ASSIGNMENT

Q1. Estimate the heat exchanger area needed to cool 55,000 lb/h of a light oil (specific heat = 0.74 Btu/lb.°F) from 190°F to 140°F using cooling water that is available at 50°F. The cooling water can be allowed to heat to 90°F. An initial estimate of the Overall Heat Transfer Coefficient is 120 Btu/hr.ft^2.°F. Also estimate the required mass flow rate of cooling water.

Q2. Taking the shell and tube heat exchanger described in **Q1**, how many tubes of 3.0-inch diameter and 10 ft length should be used?



RATING CALCULATIONS – HXs

ε – NTU METHOD

A second kind of problem encountered in heat exchanger analysis is **(a) the determination of the heat transfer rate** and (b) the outlet temperatures of the hot and cold fluids for **prescribed fluid mass flow rates** and **inlet temperatures** when the type and size of the heat exchanger are specified.

- In such situations we use the **Effectiveness (ε)-NTU method**
- **NTU: Number of Transfer Units** = Non-dimensional parameter

- **ε – NTU method** is used to **calculate the rate of heat transfer** in HXs (especially parallel flow, counter current, and cross-flow exchangers) **when there is insufficient information to calculate LMTD.**

- The effectiveness of a heat exchanger depends on the geometry of the heat exchanger as well as the flow arrangement.

- Therefore, different types of heat exchangers have **different effectiveness relations**.

RATING CALCULATIONS – HXs

ε – NTU METHOD

- ε – NTU method is used to calculate the rate of heat transfer in heat exchangers (especially parallel flow, counter current, and cross-flow exchangers) when **there is insufficient information to calculate LMTD**.

$$\varepsilon = \frac{Actual\ heat\ transferred}{Maximum\ heat\ that\ could\ possibly\ be\ transferred\ from\ one\ stream\ to\ the\ other}$$

Mathematically this is equal to:

$$\varepsilon = \frac{C_h\,(T_{h,in} - T_{h,out})}{C_{min}\,(T_{h,in} - T_{c,in})} = \frac{C_c\,(T_{c,out} - T_{c,in})}{C_{min}\,(T_{h,in} - T_{c,in})}$$

- **Reason:** The fluid with lower heat capacity will be the one that undergoes the maximum temperature change, i. e.,

$$Q = C_{min}\Delta T_{max}$$

$$Q = \varepsilon C_{min}\,(T_{h,in} - T_{c,in})$$

$$NTU = \frac{UA}{C_{min}} = \frac{Heat\ Rate\ Capacity\ of\ HX}{Heat\ Rate\ Capacity\ of\ Flow}$$

Definitions and relationships

$$NTU \equiv \frac{U_o A_o}{C_{min}}; \quad C_r \equiv \frac{C_{min}}{C_{max}}; \quad \varepsilon \equiv \frac{Q}{Q_{max}}$$

NTU : Number of Transfer Units

$$C_{min} = Minimum\ of\ (C_c, C_h)$$

$$C_{max} = Maximum\ of\ (C_c, C_h)$$

$$C_c = \dot{m}_c c_{pc}; \quad C_h = \dot{m}_h c_{ph}$$

C_c, C_h : thermal capacity of (cold, hot) fluid flow

ε : heat exchanger effectiveness

$$Q_{max} = C_{min}(T_{h1} - T_{c1})$$

$$Q = C_c(T_{c2} - T_{c1}) = C_h(T_{h1} - T_{h2})$$

$$\varepsilon = \frac{Q}{C_{min}(T_{h1} - T_{c1})} = \frac{C_c(T_{c2} - T_{c1})}{C_{min}(T_{h1} - T_{c1})} = \frac{C_h(T_{h1} - T_{h2})}{C_{min}(T_{h1} - T_{c1})}$$

$$\varepsilon = f(NTU, C_r, flow\ arragement)$$

$$NTU = g(\varepsilon, C_r, flow\ arragement)$$

RATING CALCULATIONS – HXs

ε – NTU METHOD

$$\varepsilon = f\left(\frac{UA}{C_{min}}, \frac{C_{min}}{C_{max}}\right) = f\left(NTU, C_r\right)$$

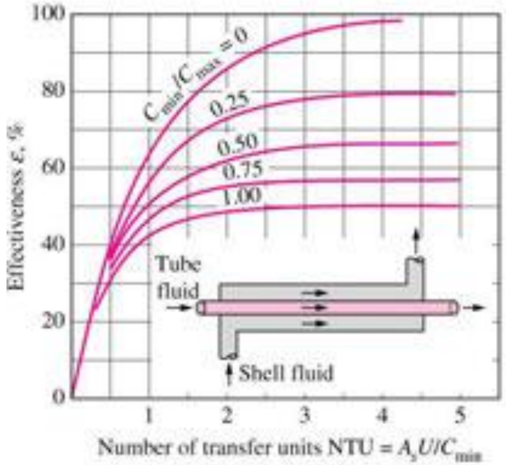
Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 + c)]}{1 + c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 - c)]}{1 - c\exp[-\mathrm{NTU}(1 - c)]}$
2 *Shell-and-tube:* One-shell pass 2, 4,…tube passes	$\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\dfrac{1 + \exp[-\mathrm{NTU}\sqrt{1 + c^2}]}{1 - \exp[-\mathrm{NTU}\sqrt{1 + c^2}]}\right\}^{-1}$
3 *Cross-flow (single-pass)* Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\mathrm{NTU}^{0.22}}{c}[\exp(-c\,\mathrm{NTU}^{0.78}) - 1]\right\}$
C_{max} mixed, C_{min} unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{-c[1 - \exp(-\mathrm{NTU})]\})$
C_{min} mixed, C_{max} unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\,\mathrm{NTU})]\right\}$
4 *All heat exchangers with c = 0*	$\varepsilon = 1 - \exp(-\mathrm{NTU})$

$$c = C_r$$

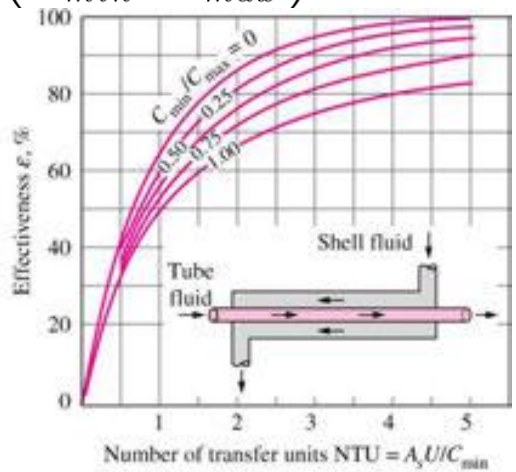
RATING CALCULATIONS – HXs

ε – NTU METHOD

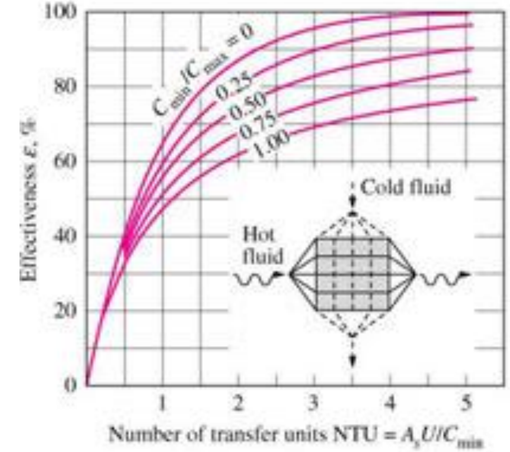
$$\varepsilon = f\left(\frac{UA}{C_{min}}, \frac{C_{min}}{C_{max}}\right) = f\left(NTU, C_r\right)$$



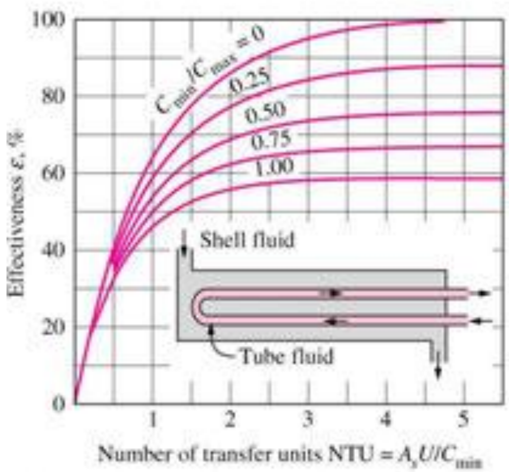
(a) Parallel-flow



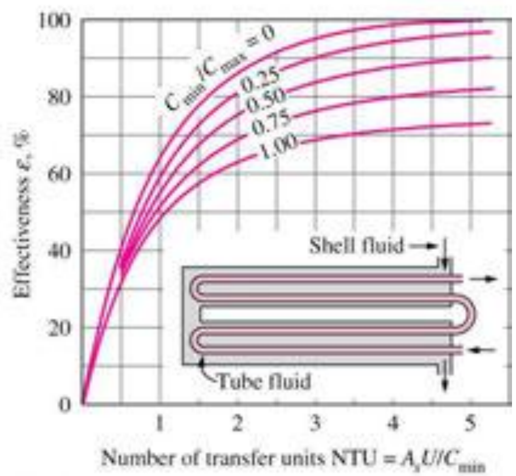
(b) Counter-flow



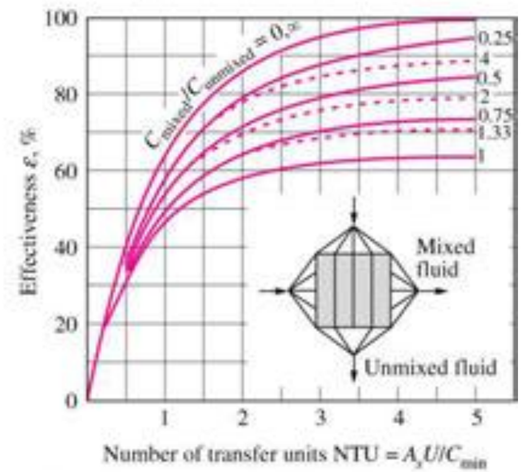
(e) Cross-flow with both fluids unmixed



(c) One-shell pass and 2, 4, 6, … tube passes



(d) Two-shell passes and 4, 8, 12, … tube passes



(f) Cross-flow with one fluid mixed and the other unmixed

RATING CALCULATIONS – HXs

ε – NTU METHOD

$$NTU = \frac{UA}{C_{min}} = \frac{Heat\ Rate\ Capacity\ of\ HX}{Heat\ Rate\ Capacity\ of\ Flow}$$

For specified values of U and C_{min}, the value of NTU is a measure of the surface area A. Thus, the larger the NTU, the larger the heat exchanger.

The effectiveness of a heat exchanger is a function of the number of transfer units NTU and the capacity ratio C_r.

$$\varepsilon = f\left(\frac{UA}{C_{min}}, \frac{C_{min}}{C_{max}}\right) = f\left(NTU, C_r\right)$$

- When all the inlet and outlet temperatures are specified, the size of the heat exchanger can easily be determined using the LMTD method.

- Alternatively, it can be determined from **ε – NTU** method by first evaluating the effectiveness from its definition and then the NTU from the appropriate NTU relation.

RATING CALCULATIONS – HXs

ε – NTU METHOD

- The value of the effectiveness ranges from 0 to 1.

- It increases rapidly with NTU for small values (up to about NTU = 1.5) but rather slowly for larger values. Therefore, the use of a HX with a large NTU (>3) and thus a large size cannot be justified economically, since a large increase in NTU in this case corresponds to a small increase in effectiveness.

- For a given NTU and capacity ratio $c = C_{min} / C_{max}$, the counterflow HX has the highest effectiveness, followed closely by the cross-flow HX with both fluids unmixed. The lowest effectiveness values are encountered in parallel-flow HX.

$$c = C_r$$

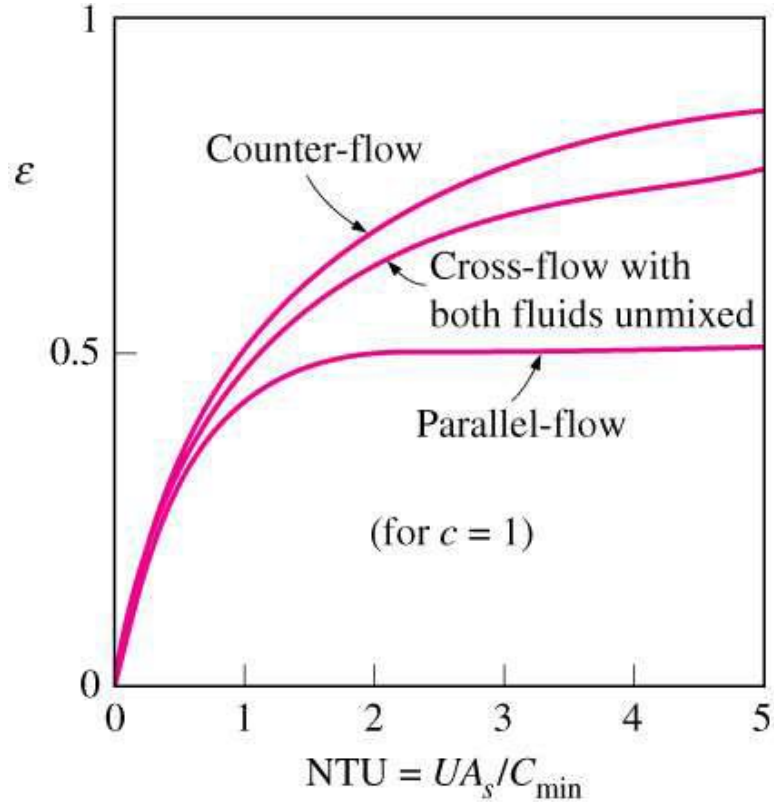


FIGURE 11–27
For a specified NTU and capacity ratio c, the counter-flow heat exchanger has the highest effectiveness and the parallel-flow the lowest.

RATING CALCULATIONS – HXs

ε – NTU METHOD

- The effectiveness of a heat exchanger is independent of the capacity ratio *c* for NTU values of less than about 0.3.

- The value of the capacity ratio *c* ranges between 0 and 1.

- For a given NTU, the effectiveness becomes a maximum for $c = 0$ (e.g., boiler, condenser) and a minimum for $c = 1$ (when the heat capacity rates of the two fluids are equal).

$$c = C_r$$

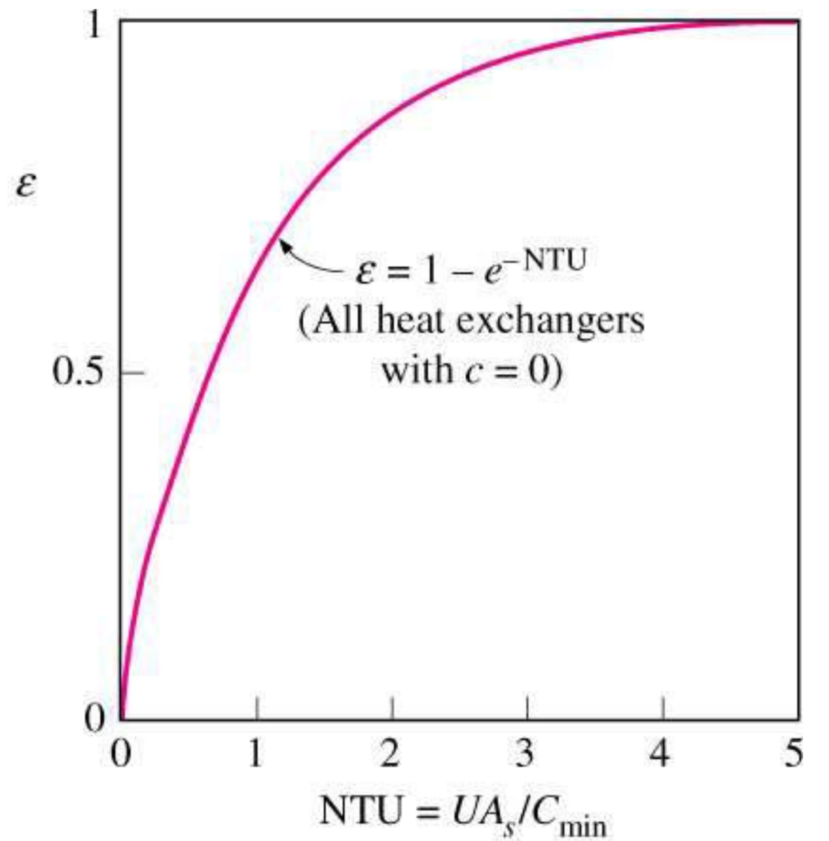


FIGURE 11–28

The effectiveness relation reduces to $\varepsilon = \varepsilon_{max} = 1 - \exp(-NTU)$ for all heat exchangers when the capacity ratio $c = 0$.

RATING CALCULATIONS – HXs

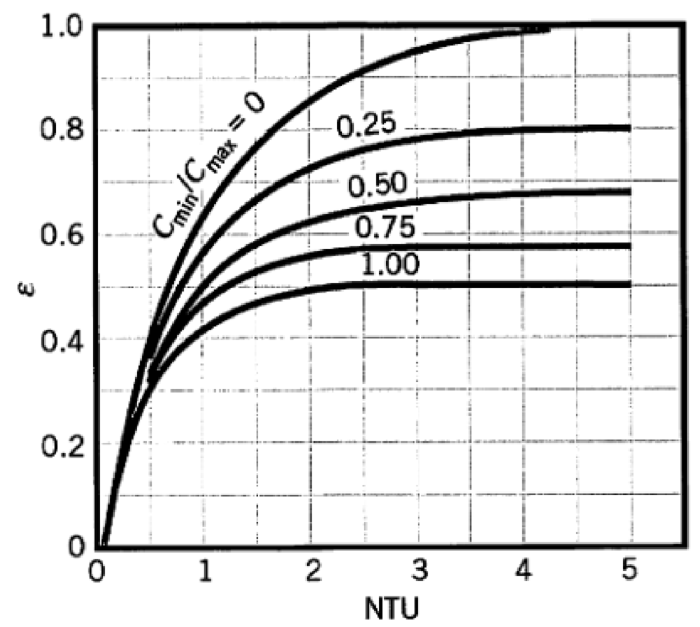
ASSIGNMENT

Q1. Consider the following parallel flow HX specification:

Cold flow enters at 40 °C, Cold heat capacity is C_c = 20000 W/K
Hot flow enters at 150 °C, Hot heat capacity is C_h = 10000 W/K
Area is 30 m^2, and Overall heat transfer coefficient is 500 W/m^{2}K.

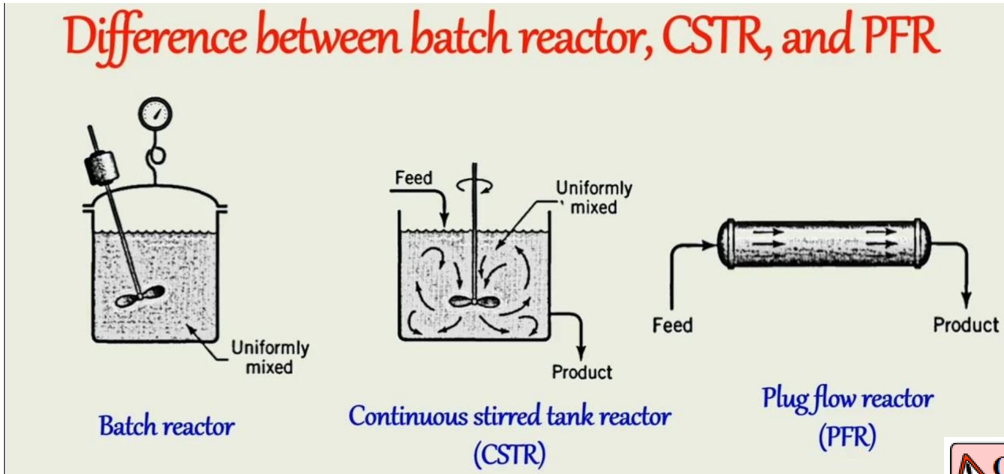
Determine the heat transfer rate and the exit temperatures.

Q2. Suppose we have the same problem as **Q1**, but A is unknown and we want exit temperature of the hot fluid to be 90°C. Then calculate A, from LMTD and ε-NTU method. How many tubes of 0.3 m diameter and 10 m length should be used?



CHEMICAL REACTORS

- A chemical reactor is an enclosed volume in which a chemical reaction takes place.



Conversion, Yield, Extent of Reaction

- **Conversion**

$$\text{Conversion} = \frac{\text{amount of reagent consumed}}{\text{amount of supplied}}$$

$$\text{Conversion} = \frac{\text{(amount in feed stream) - (amount in product stream)}}{\text{amount of supplied}}$$

Conversion

$$X_i = \frac{-\mathrm{d}\,N_i}{N_{i,0}} = \frac{N_{i,0} - N_i}{N_{i,0}} = -\frac{\xi \nu_i}{N_{i,0}} \qquad (1.4.1)$$

- **Yield**

$$\text{Yield} = \frac{\text{mols of product produced} \times \text{stoichiometric factor}}{\text{mols of reagent converted}}$$

$$\text{Stoichiometric factor} = \text{Stoichiometric mols of reagent required per mol of product produced}$$

$$\text{Plant yield} = \frac{\text{mols of product produced} \times \text{stoichiometric factor}}{\text{mols of reagent fed to the process}}$$

- **Extent of reaction** is a quantity that measures the extent to which the reaction has proceeded.

Extent of Reaction

$$\xi = \frac{\mathrm{d}\,N_i}{\nu_i} = \frac{N_i - N_{i,0}}{\nu_i} \qquad (1.3.1)$$

Source: Google Images

CHEMICAL REACTORS

- A chemical reactor is an enclosed volume in which a chemical reaction takes place.

- **Extent of reaction**

For a general reaction:

$$\mathrm{aA} + \mathrm{bB} \rightarrow \mathrm{cC} + \mathrm{dD}$$

The extent of reaction is given by:

$$\xi = \frac{\Delta n_i}{\nu_i}$$

where:

- Δn_i = change in the number of moles of species i
- ν_i = stoichiometric coefficient of species i (negative for reactants, positive for products).

Units:

- The extent of reaction is typically expressed in **moles** (mol).

Physical Meaning:

- If $\xi = 0$ → No reaction has occurred.
- If $\xi = 1$ (or some other finite value) → The reaction has progressed by that amount.
- If ξ **is at equilibrium**, it indicates the final extent of reaction under given conditions.

Source: Google Images

CHEMICAL REACTOR DESIGN

GENERAL MOLE BALANCE OF A REACTOR

$$
\begin{array}{ccccccc}
\text{In} & - & \text{Out} & + & \text{Generation} & = & \text{Accumulation} \\
\begin{bmatrix} \text{Rate of} \\ \text{flow of } i \text{ in} \\ \text{(moles/time)} \end{bmatrix} & - & \begin{bmatrix} \text{Rate of} \\ \text{flow of } i \text{ out} \\ \text{(moles/time)} \end{bmatrix} & + & \begin{bmatrix} \text{Rate of} \\ \text{generation of} \\ i \text{ by chemical} \\ \text{reaction} \\ \text{(moles/time)} \end{bmatrix} & = & \begin{bmatrix} \text{Rate of} \\ \text{accumulation} \\ \text{of } i \\ \text{(moles/time)} \end{bmatrix} \\
n_i|_V & - & n_i|_{V+\delta V} & + & G_i & = & \dfrac{\mathrm{d}\,N_i}{\mathrm{d}\,t}
\end{array}
$$

where n_i is the molar flowrate of species i (with units of moles sec^{-1}) and N_i is number of moles of component i in the reactor. The above mole balance is performed about

Batch Reactor Design Equations

Basis	Differential	Integral
Moles	$\dfrac{\mathrm{d}\,N_i}{\mathrm{d}\,t} = r_i V$	$t = \displaystyle\int_{N_{i,0}}^{N_{i,f}} \dfrac{\mathrm{d}\,N_i}{r_i V}$
Concentration	$\dfrac{\mathrm{d}\,C_i}{\mathrm{d}\,t} = r_i$	$t = \displaystyle\int_{C_{i,0}}^{C_{i,f}} \dfrac{\mathrm{d}\,C_i}{r_i}$
Extent of Reaction	$\dfrac{\mathrm{d}\,\xi}{\mathrm{d}\,t} = \dfrac{r_i V}{\nu_i}$	$t = \nu_i \displaystyle\int_0^{\xi} \dfrac{\mathrm{d}\,\xi}{r_i V}$
Conversion	$\dfrac{\mathrm{d}\,X}{\mathrm{d}\,t} = -\dfrac{r_i V}{N_{i,0}}$	$t = -N_{i,0} \displaystyle\int_0^{X} \dfrac{\mathrm{d}\,X}{r_i V}$

Source: Google Images

CHEMICAL REACTOR DESIGN

GENERAL MOLE BALANCE OF A REACTOR

Continuously Stirred Tank Reactor Design Equations

Basis	Algebraic
Moles	$V = \frac{n_{i,0} - n_{i,f}}{-r_{i,f}}$
Concentration	$V = \frac{v\left(C_{i,0} - C_{i,f}\right)}{-r_{i,f}}$
Extent of Reaction	$V = \frac{\xi \nu_i}{r_{i,f}}$
Conversion	$V = \frac{n_{i,0} X}{-r_{i,f}}$

Source: Google Images

CHEMICAL REACTOR DESIGN

GENERAL MOLE BALANCE OF A REACTOR

Plug Flow Reactor Design Equations

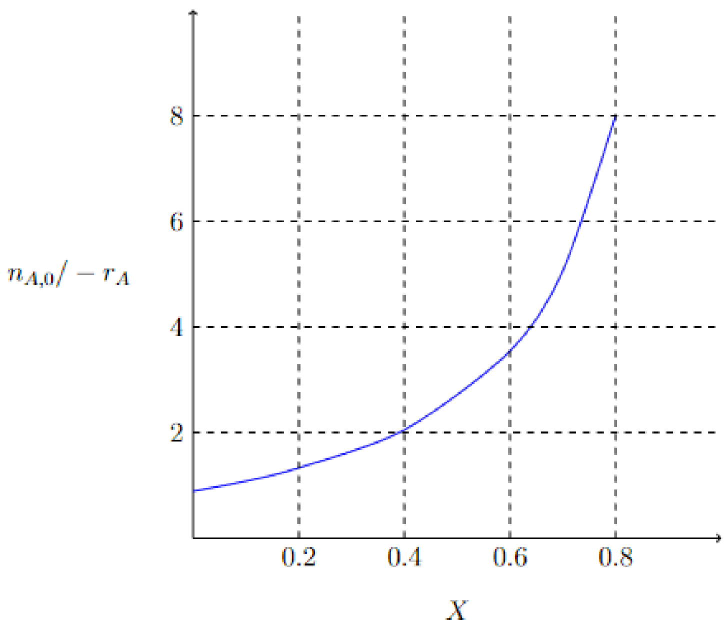
Basis	Differential	Integral
Moles	$\frac{\mathrm{d}\, N_i}{\mathrm{d}\, V} = r_i$	$V = \int_{n_{i,0}}^{n_{i,f}} \frac{\mathrm{d}\, n_i}{r_i}$
Concentration	$\frac{\mathrm{d}\, C_i}{\mathrm{d}\, V} = \frac{r_i}{v}$	$V = v \int_{C_{i,0}}^{C_{i,f}} \frac{\mathrm{d}\, C_i}{r_i}$
Extent of Reaction	$\frac{\mathrm{d}\, \xi}{\mathrm{d}\, V} = \frac{r_i}{\nu_i}$	$V = \nu_i \int_{0}^{\xi} \frac{\mathrm{d}\, \xi}{r_i}$
Conversion	$\frac{\mathrm{d}\, X}{\mathrm{d}\, V} = -\frac{r_i}{n_{i,0}}$	$V = -n_{i,0} \int_{0}^{X} \frac{\mathrm{d}\, X}{r_i}$

Source: Google Images

LEVENSPIEL PLOTS

$$\text{CSTR:} \qquad V = \frac{n_{A,0}X}{-r_{A,f}} \qquad \text{PFR:} \qquad V = n_{A,0}\int_0^X \frac{\mathrm{d}\,X}{-r_A}$$

Figure shows some real data for an isothermal reaction with conditions of T = 500 K, P = 8.2 atm, and n_{A0} = 0.4 mol s^{-1}. In order to size a reactor from experimental rate data, we first need to plot $n_{A,0}/-r_A$ (m^3) as a function of X (this plot is called a **Levenspiel plot**).



From our CSTR equation we develop,

$$V = \left(\frac{n_{A,0}}{-r_{A,f}}\right) \times X \tag{4.5.1}$$

The volume is therefore equal to the area of a rectangle of height $n_{A,0}/-r_{A,f}$ and base X on the Levenspiel plot as shown in Figure 4.3(a) below for the example of $X = 0.8$,

$$V = \left(\frac{n_{A,0}}{-r_A}\right) \times X = 8\,(\mathrm{m}^3) \times 0.8 = 6.4\,\mathrm{m}^3$$

From our PFR equation we develop,

$$V = \int_0^X \left(\frac{n_{A,0}}{-r_A}\right) \mathrm{d}\,X \tag{4.5.2}$$

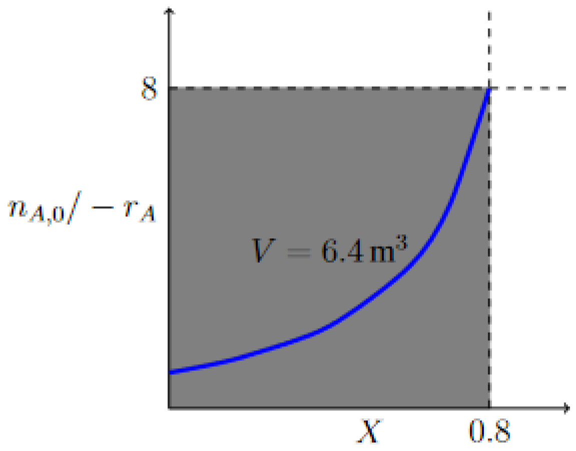
The volume is therefore equal to the area under the curve of $n_{A,0}/-r_{A,f}$ against X on the Levenspiel plot as shown in Figure 4.3(b) below for the example of $X = 0.8$.

The integration can be performed using the trapezium rule (or Simpson's rule) with known data points (taken from the curve). Alternatively one could count/estimate the area on graph paper. For this example the volume is,

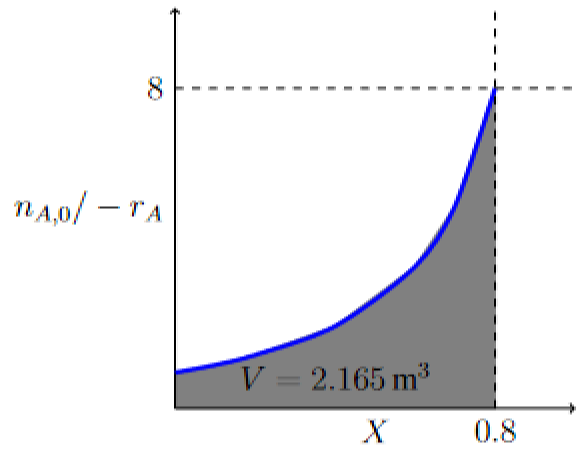
$$V = 2.165\,\mathrm{m}^3$$

Source: Google Images

OPTIMIZATION OF REACTOR VOLUME



(a) CSTR



(b) PFR

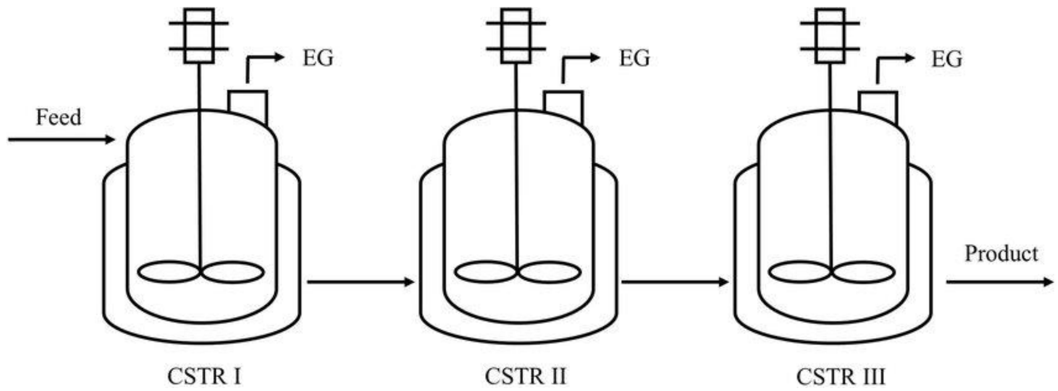
Source: Google Images

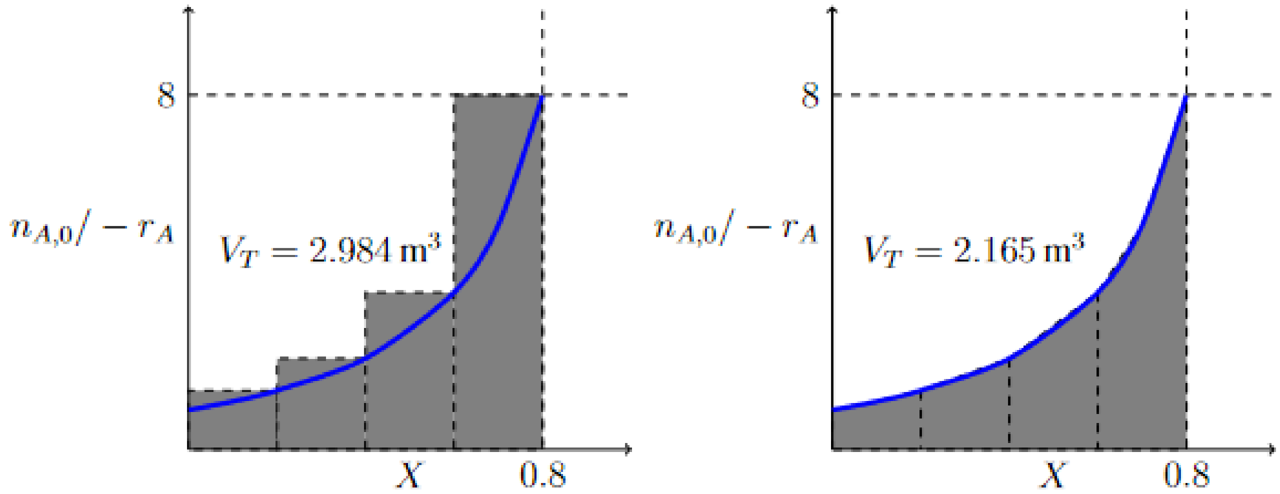
PFR vs CSTR

The CSTR volume required is greater than the PFR volume for the same conversion and reaction conditions.

The concentration in the CSTR everywhere is equal to the exit concentration, so that the reaction rate is proportional to the exit concentration over the entire volume of the CSTR. In a PFR, the concentration of the reactant A gradually decreases along the reactor until it reaches a minimum value given by the exit concentration. As a consequence, the concentration of A in the PFR is always greater than that in the CSTR when the same exit conversion is achieved. Because the rate is proportional to the concentration of A, the rate is also greater everywhere in the PFR versus in the CSTR.

OPTIMIZATION OF REACTOR VOLUME



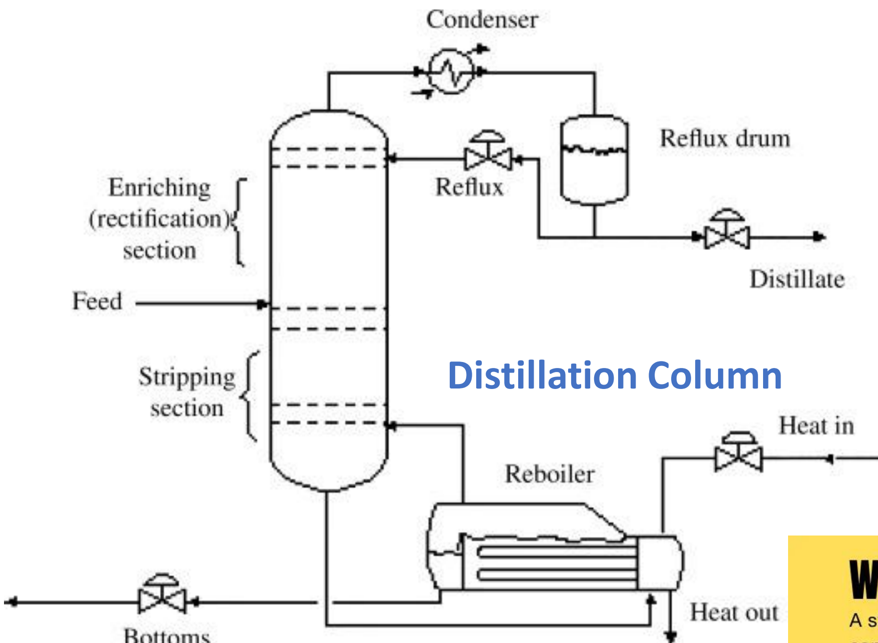


(a) CSTR (b) PFR

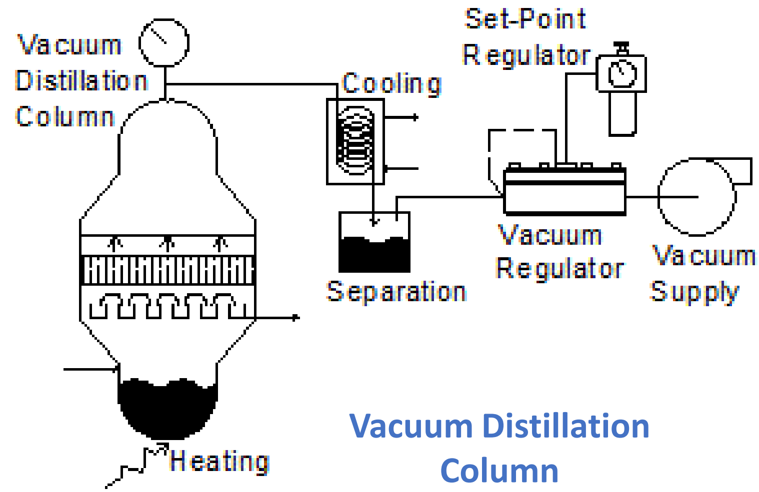
- Putting **CSTRs in series reduces the volume required**.
- **An infinite number of CSTRs in series is equivalent to a PFR**.
- Putting **PFRs in series is equivalent of a longer PFR**.

Source: Google Images

MANY MORE PROCESS PLANT EQUIPMENTS …

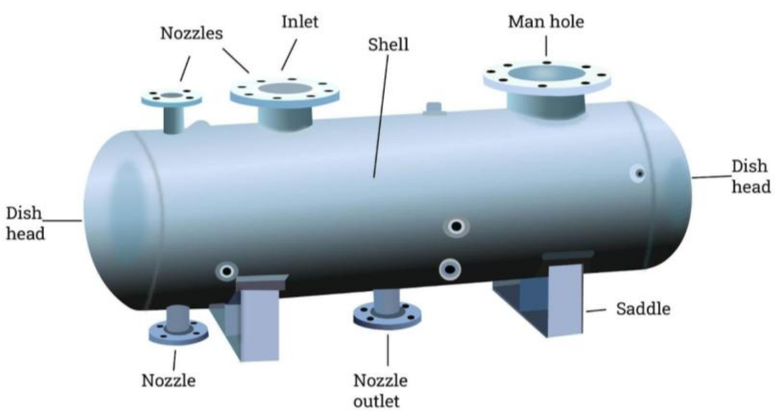


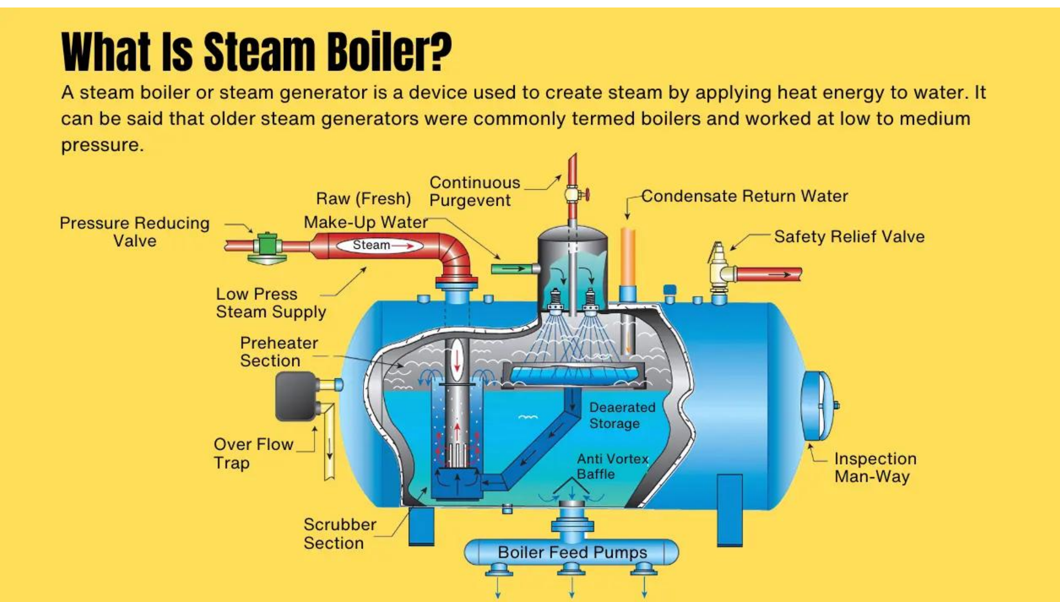
Distillation Column



Vacuum Distillation Column

Pressure Vessel





Source: Google Images

CH 42010: PROCESS PLANT OPERATION & SAFETY

LTP: 3-0-0, CRD: 3

Lecture 7

Plant Systems for Utilities & Auxiliary Services

CHEMICAL PROCESS UTILITIES

- Apart from raw materials, chemical process industries and specially the manufacturing unit requires essential services to smoothly carry out a process which converts the raw materials into products.

- These services are called utilities, which aid to the maintaining the desired operating conditions for the manufacturing of finished products.

- Broadly utilities can be classified as the system required to provide air, water, and electricity, to the unit.

- Major utilities required for typical chemical/production industry are:

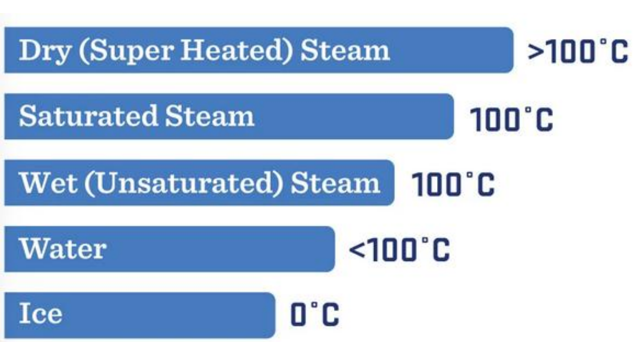
  - Boilers
  - Compressors
  - Condensers, Refrigeration, Air Conditioning
  - Water Treatment Plants
  - Cooling Towers
  - Turbines
  - Air, Water, Fuel, Furnace, Insulation etc.

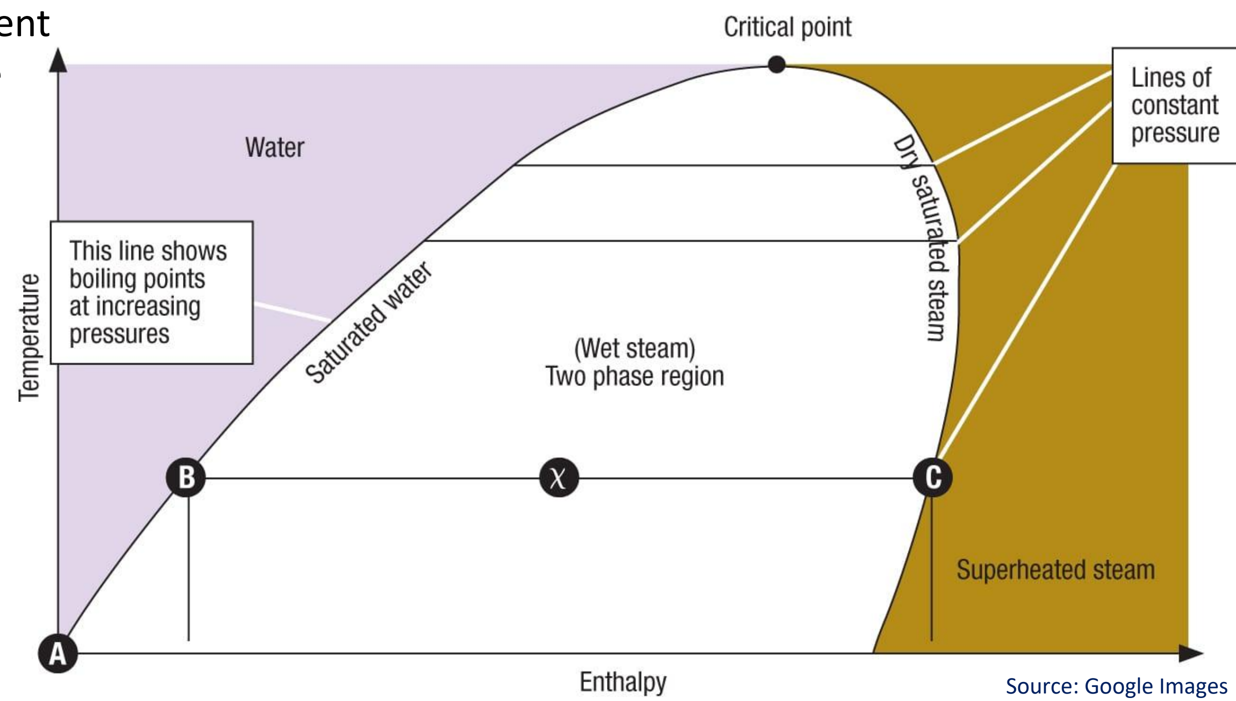
CHEMICAL PROCESS UTILITIES

- Utilities can also pose serious economical and technical ill effects if not engineered well.
- Increasing demand of water and fuels, increases the cost of the utilities required.
- Proper understanding related to the consumption and management of utilities is essential.
- Examples:
  - If a very high pressure steam is supplied to the HXs, which is not designed to handle them, will eventually damage it.
  - When a transformer works under load or overload, the energy losses are high. Efficiency will be maximum when the iron loss (eddy currents and hysteresis loss) equals to the copper loss (current dependent loss).
- Generally, **Cost to Utility = Generation Cost + Transmission Cost**
- Sometimes, **depreciation and capital recovery cost** is also added to it. If the utility is outsourced, then this is cost is simply added as material (water, air, gas, fuel, electricity etc.) cost to the project.
- Optimization and utility calculation (heating and cooling) is measured by **PINCH ANALYSIS.**

STEAM GENERATION AND DISTRIBUTION

- Steam has been a popular mode of conveying energy since the industrial revolution.
- Steam is used for generating power and also used in process industries such as sugar, paper, fertilizer, refineries, petrochemicals, chemical, food, synthetic fibre and textiles.
- The following characteristics of steam make it so popular and useful to the industry:
  - Highest specific heat and latent heat
  - Highest heat transfer coefficient
  - Easy to control and distribute
  - Cheap and inert





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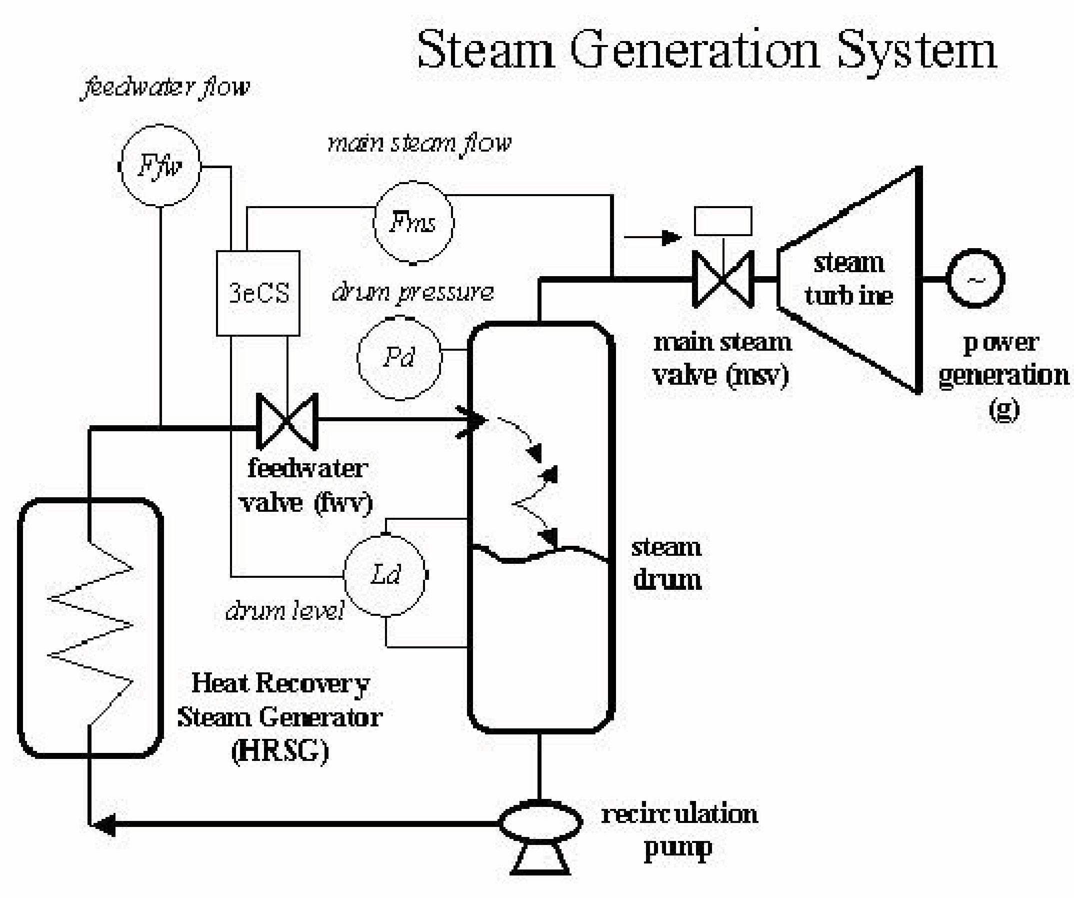
STEAM GENERATION

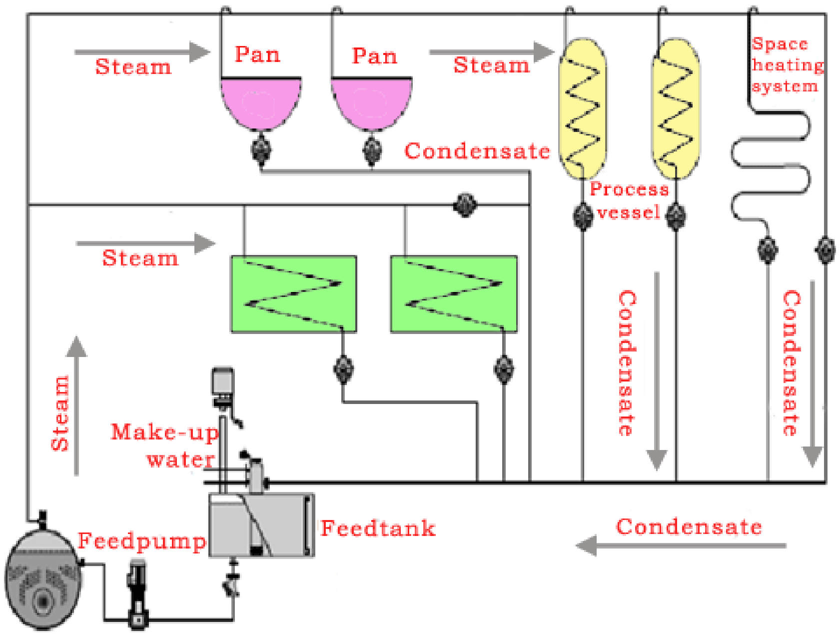


Source: Google Images

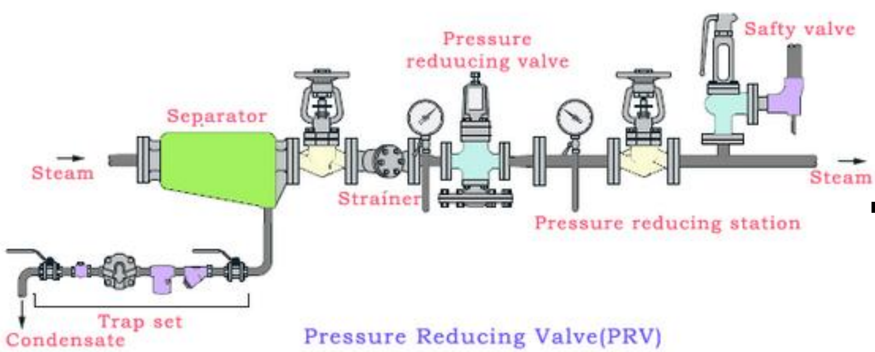
- **Plant Steam (Utility Steam)**

  - Plant steam, or utility steam, is "typical" for industrial steam generation systems.
  - It can be at a variety of pressures, but is typically saturated.
  - Plant steam usually has boiler chemicals or additives to prevent corrosion, so in many cases, it cannot be directly added to products.
  - Utility steam is sometimes referred to by the pressure it's distributed at: either low, medium, or high pressure steam.
  - The exact pressure of each of these will vary at different locations and industries.

STEAM DISTRIBUTION SYSTEM (SDS)



Basic Steam Distribution



Pressure Reducing Valve(PRV)

Source: Google Images

Design of SDS

- **Steam-generating working pressure:** Maximum pressure at which the boiler or the co-generation plant can produce steam. It depends on the type and capacity of the boiler, the fuel used, and the process requirements.

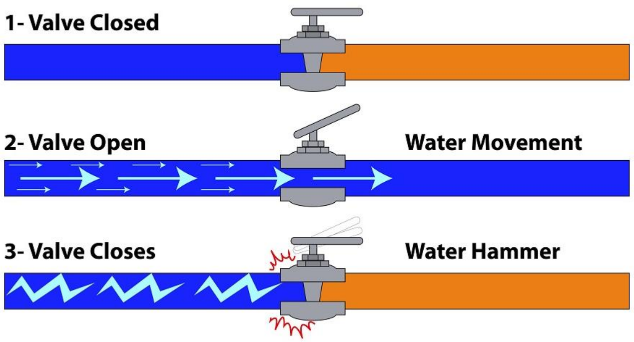
- **Minimum pressure requirement at process end:** Minimum pressure at which the steam-consuming equipment can operate efficiently and safely. It depends on the type and capacity of the equipment, the process conditions, and the safety margins.

- **Pressure loss in SDS:** This is the difference between the steam-generating pressure and the process pressure. It is caused by frictional resistance in the pipes and fittings, condensation in the pipes due to heat transfer to the surroundings, and pressure-reducing valves (PRVs) if used.

- **Steam quality:** Measures how dry and saturated the steam is. It depends on the boiler's design, operation, and maintenance, plus the condensate removal system. **Poor steam quality can cause wet steam, leading to erosion, corrosion, water hammer, reduced heat transfer efficiency, and equipment damage.**

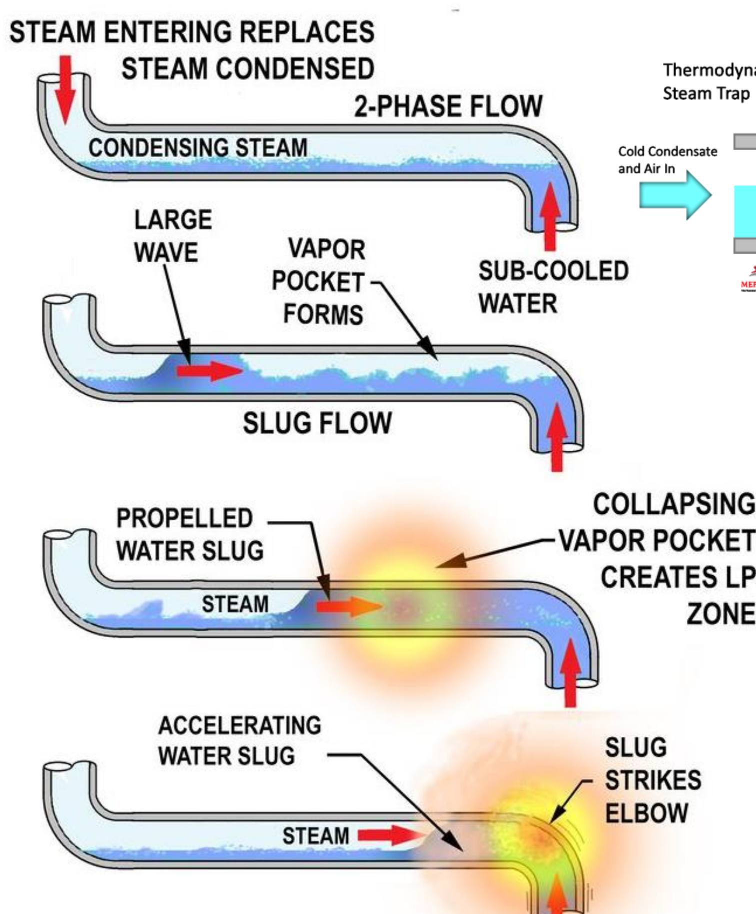
WATER & STEAM HAMMERING

WATER HAMMERING

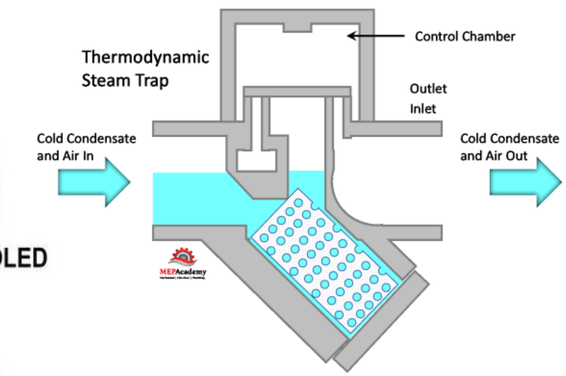



Pipe Broken from Water Hammer

- The problem of water hammer can be eliminated by positioning the pipes so that there is a continuous slope in the direction of flow. A slope of at least 12 mm in every 3 m is necessary, as also an adequate number of drain points every 30 to 50 m.



STEAM HAMMERING



STEAM TRAPS

For example, a 100 mm well lagged pipe of 30 m length carrying steam at 7 kg/cm^2 pressure can condense nearly 10 kg of water in the pipe in 1 hour.

Source: Google Images

COMPRESSED AIR SYSTEM (CAS)

- **Capacity of a Compressor**
  - It is the full rated volume of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition prevailing at the compressor inlet.
  - It sometimes means actual flow rate, rather than rated volume of flow.
  - This also termed as **Free Air Delivery (FAD)** i.e. air at atmospheric conditions at any specific location. Because the altitude, barometer, and temperature may vary at different localities and at different times, it follows that this term does not mean air under identical or standard conditions.

TABLE 3.1 GENERAL SELECTION CRITERIA FOR COMPRESSORS

Type of Compressor	Capacity (m^3/h)		Pressure (bar)	
	From	To	From	To
Roots blower compressor single stage	100	30000	0.1	1
Reciprocating				
– Single / Two stage	100	12000	0.8	12
– Multi stage	100	12000	12.0	700
Screw				
– Single stage	100	2400	0.8	13
– Two stage	100	2200	0.8	24
Centrifugal	600	300000	0.1	450

- **Compressor Efficiency Definitions**
  - Several different measures of compressor efficiency are commonly used:
    - Volumetric efficiency
    - Adiabatic efficiency
    - Isothermal efficiency
    - Mechanical efficiency
  - Most Common are: **Isothermal efficiency** & **Volumetric efficiency**

Source: Google Images

COMPRESSED AIR SYSTEM (CAS)

Isothermal Efficiency

$$\text{Isothermal Efficiency} = \frac{\textit{Isothermal Power}}{\textit{Actual Measured Input Power}}$$

Isothermal Power (in kW) = $P_1 \times Q_1 \times \ln\left(\frac{r}{36.7}\right)$

Absolute intake pressure (kg/cm^2) = P_1

Absolute delivery pressure (kg/cm^2) = P_2

Free air delivered (m^3/hr) = Q_1

Pressure ratio = $r = \frac{P_2}{P_1}$

- **Important:** The calculation of isothermal power does not include power needed to overcome friction and generally gives an efficiency that is lower than adiabatic efficiency. The reported value of efficiency is normally the isothermal efficiency. This is an important consideration when selecting compressors based on reported values of efficiency.

Volumetric Efficiency

$$\text{Volumetric Efficiency} = \frac{\textit{Free Air Delivered } (m^3/min)}{\textit{Compresser Displacement}(m^3/min)}$$

Compressor displacement =

$$\frac{\pi}{4} \times D^2 \times L \times S \times \chi \times n$$

Cylinder bore (m) = D

Cylinder stroke (m) = L

Compressor speed (rpm) = S

Number of cylinders = n

Type of cylinders =

$\chi = 1$ for single acting cylinders

$\chi = 2$ for double acting cylinders

EFFICIENT OPERATION OF CAS

TABLE 3.2 EFFECT OF INTAKE AIR TEMPERATURE ON POWER CONSUMPTION		
Inlet Temperature (°C)	Relative Air Delivery (%)	Power Saved (%)
10.0	102.0	+ 1.4
15.5	100.0	Nil
21.1	98.1	– 1.3
26.6	96.3	– 2.5
32.2	94.1	– 4.0
37.7	92.8	– 5.0
43.3	91.2	– 5.8

TABLE 3.7 TYPICAL COOLING WATER REQUIREMENTS	
Compressor Type	Minimum quantity of Cooling Water required (in litres per minute) for 2.85 m^3/min. FAD at 7 bar
Single-stage	3.8
Two-stage	7.6
Single-stage with after-cooler	15.1
Two-stage with after-cooler	18.9

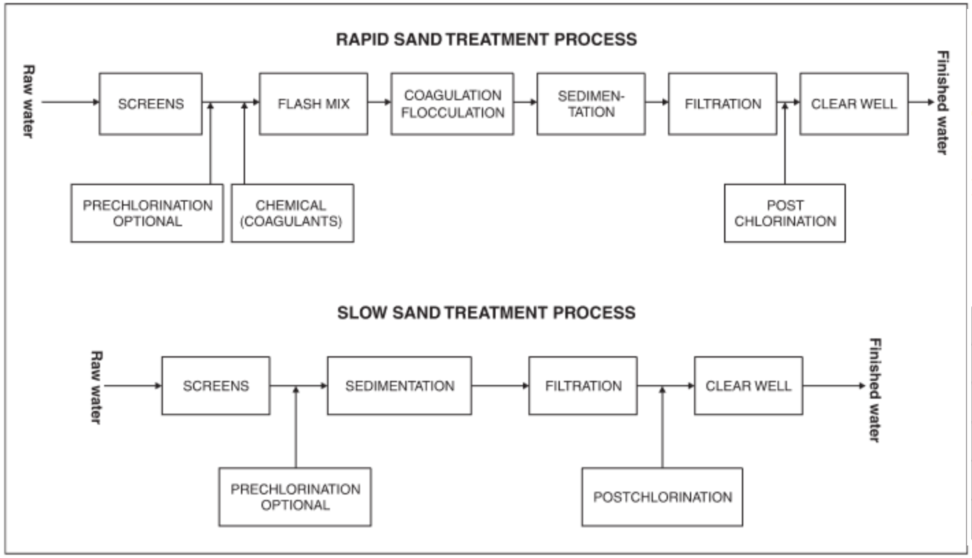
TABLE 3.4 MOISTURE IN AMBIENT AIR AT VARIOUS HUMIDITY LEVELS	
% Relative Humidity	Kg of water vapour per hour for every 1000 m^3/min. of air at 30°C
50	27.60
80	45.00
100	68.22

TABLE 3.3 EFFECT OF PRESSURE DROP ACROSS AIR INLET FILTER ON POWER CONSUMPTION	
Pressure Drop Across air filter (mmWC)	Increase in Power Consumption (%)
0	0
200	1.6
400	3.2
600	4.7
800	7.0

TABLE 3.5	EFFECT OF ALTITUDE ON VOLUMETRIC EFFICIENCY		
Altitude Meters	Barometric Pressure milli bar*	Percentage Relative Volumetric Efficiency Compared with Sea Level	
		At 4 bar	At 7 bar
Sea level	1013	100.0	100.0
500	945	98.7	97.7
1000	894	97.0	95.2
1500	840	95.5	92.7
2000	789	93.9	90.0
2500	737	92.1	87.0

* 1 milli bar = 1.01972×10^{-3} kg/cm^2

WATER SUPPLY & TREATMENT



5.4.1 COAGULATION AND FLOCCULATION

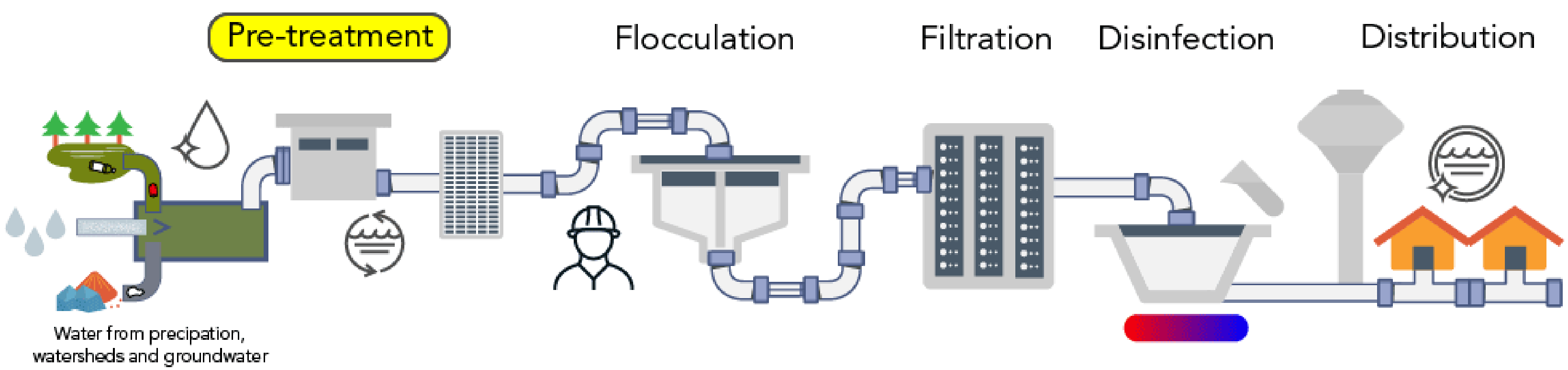
5.4.1.1 Purpose

The purpose of coagulation and flocculation is to remove particulate impurities, especially non-settleable solids (particularly colloids) and colour from the water being treated. Non-settleable particles in water are removed by the use of coagulating chemicals.

5.4.1.2 Chemical Coagulants Commonly used in Treatment Process

TABLE 5.1: CHEMICAL COAGULANTS

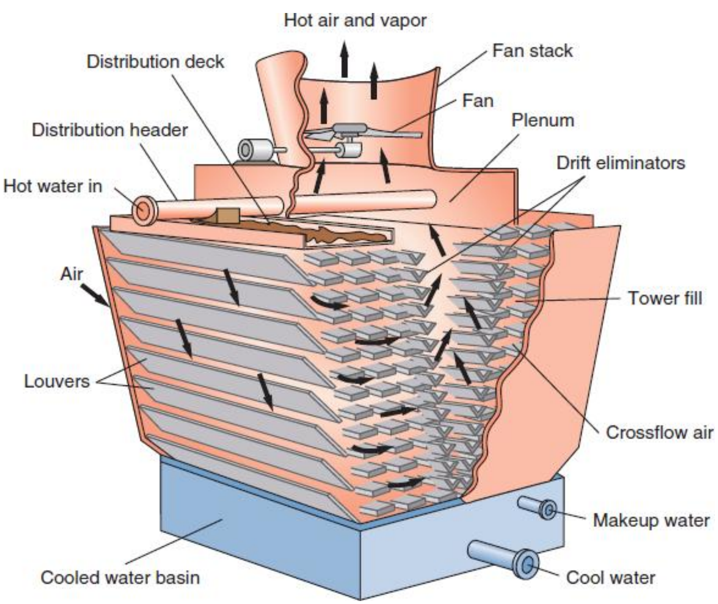
Name	Formula	Coagulant Primary/Aid
Ferric Alum	$Fe_2.(SO_4)_3.Al_2(SO_4)_3.24H_2O$	Primary
Poly Aluminium Chloride	$\{Al_2(OH)_{2.7}\,Cl_{3.3}\}_{15}$	Primary
Ferric Chloride	$FeCl_3.6H_2O$	Primary
Calcium Hydroxide	$Ca(OH)_2$	Primary/Aid
Calcium Oxide	CaO	Primary/Aid



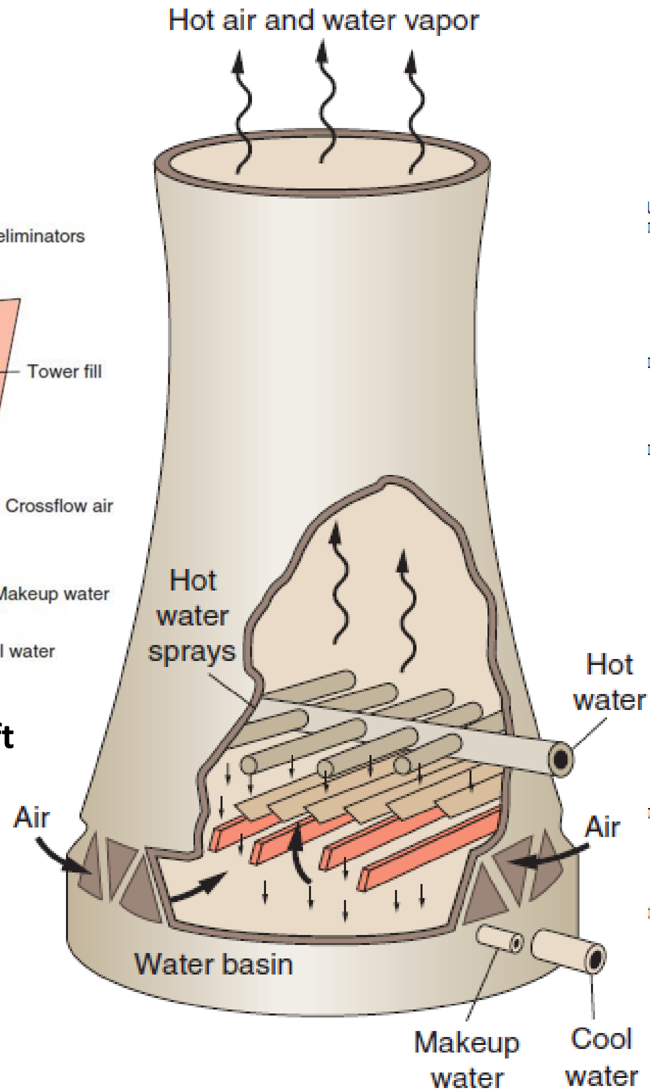
- **Discuss more about it in the upcoming lectures !!!**

Source: Google Images

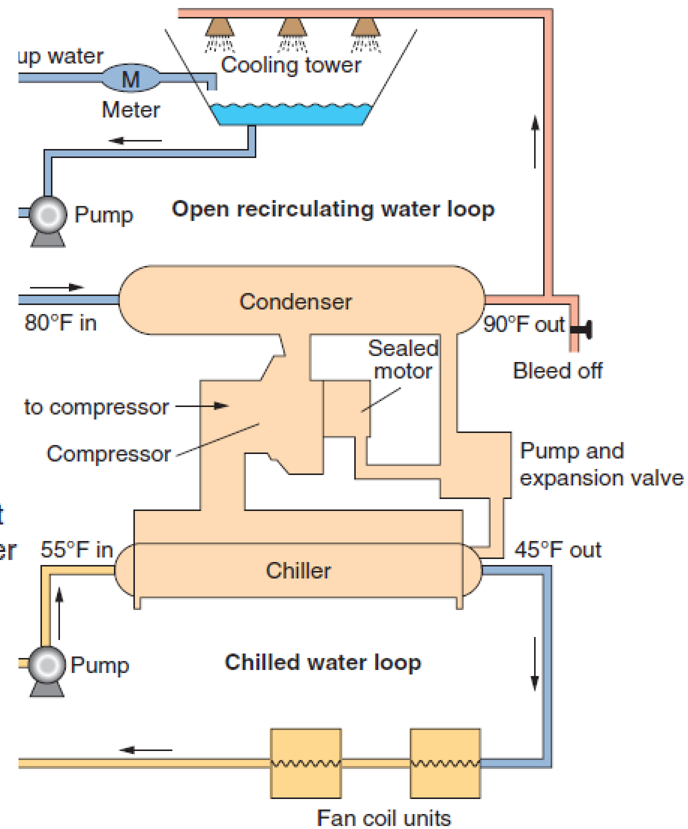
COOLING SYSTEMS



Cooling tower with induced draft



Hyperbolic cooling tower with natural draft

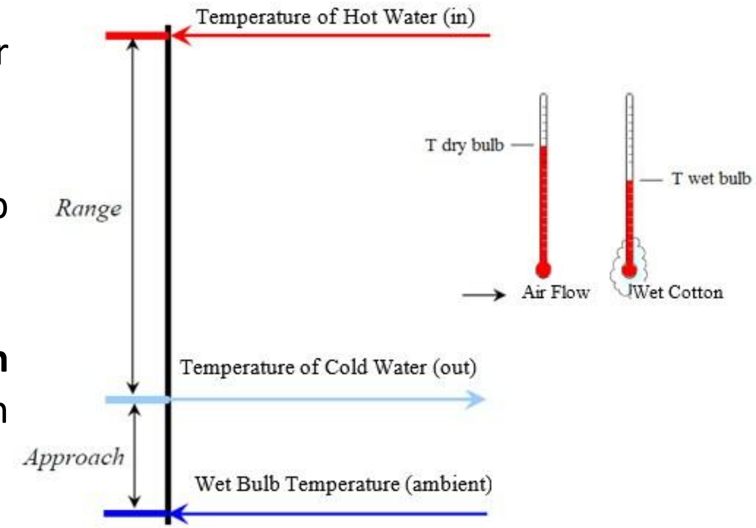


Components of a complete air conditioning system

Source: Google Images

COOLING TOWER (CT)

- **CT Range =** CT inlet water temperature – CT outlet water temperature
- **CT Approach =** Cold Water Temperature – Ambient Wet Bulb Temperature
- **Make up water Requirement** in m^3/hr **(M)** = **Evaporation Loss** in m^3/hr **(E)** + **Drift Loss** in m^3/hr **(D)** + **Blow Down** in m^3/hr **(B)**
- **Cycles of concentration (C.O.C) =** Dissolved solids in circulating water / Dissolved solids in make up water
- **Evaporation Loss** (m^3/hr) = 0.001 × circulation rate (m^3/hr) × (T_1-T_2); T_1-T_2 = Temp. difference b/w inlet & outlet water.
- **Blow Down =** Evaporation Loss / (C.O.C. – 1)
- **Cooling Tower Efficiency =** (Hot Water Temp. – Cold Water Temp.) × 100/(Hot Water Temp. – Wet Bulb Temp.)
- **Cooling Tower Efficiency =** Range/ (Range + Approach) × 100



- **L/G Ratio** $\Rightarrow L(T_1 - T_2) = G(h_2 - h_1)$

$$\Rightarrow \frac{L}{G} = \frac{h_2 - h_1}{T_1 - T_2}$$

T_1 = hot water temperature (°C) (°F);
T_2 = cold water temperature (°C) (°F);
h_2 = enthalpy of air-water vapor mixture at exhaust wet-bulb temperature (Btu/lb);
h_1 = enthalpy of air-water vapor mixture at inlet wet-bulb temperature (Btu/lb)
L/G = liquid to gas mass flow ratio

Source: Google Images

COOLING TOWER (CT)

Q1. A CT cools 1000 lpm from 95°C to 85°C at 72°C wet bulb temperature and operates at 3 cycles of concentration. Calculate Range, Approach, Heat Rejection, Drift Loss, Evaporation Loss, Bleed Rate and Make-up water requirements. Assume drift loss to be 0.2%.

1. **Range:** (HWT – CWT) =
2. **Approach:** (CWT – WBT) =
3. **Heat Rejection (in kW):** $Q = \dot{m} \times c_p \times \Delta T$
4. **Drift Loss:** (0.002 × Flow Rate) =
5. **Evaporation Loss:** 0.001 × Range × Circulation rate =
6. **Bleed Rate/Blow Down:** (Evaporation Loss / (Cycles-1) =
7. **Make-up Requirements:** Drift Loss + Evaporation Loss + Bleed Rate =

COOLING TOWER (CT)

Q1. A CT cools 1000 lpm from 95°C to 85°C at 72°C wet bulb temperature and operates at 3 cycles of concentration. Calculate Range, Approach, Heat Rejection, Drift Loss, Evaporation Loss, Bleed Rate and Make-up water requirements. Assume drift loss to be 0.2%.

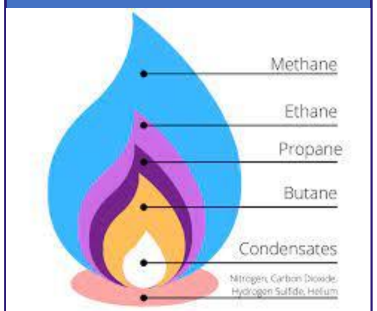
1. **Range:** (HWT – CWT) = 95 - 85 = 10°C
2. **Approach:** (CWT – WBT) = 85 - 72 = 13°C
3. **Heat Rejection:** $Q = \dot{m} \times c_p \times \Delta T = (1000/60) \times 4.186 \times 10 = 698 \text{ kW}$
4. **Drift Loss:** (0.002 × Flow Rate) = 0.002 × 1000 = 2 lpm
5. **Evaporation Loss:** 0.001 × Range × Circulation rate = 0.001 × 10 × 1000 = 10 lpm
6. **Bleed Rate/Blow Down:** (Evaporation Loss / (Cycles-1) = 10 / (3-1) = 5 lpm
7. **Make-up Requirements:** Drift Loss + Evaporation Loss + Bleed Rate = 2 + 10 + 5 = 17 lpm

FUEL & LUBRICATION SYSTEMS

FUEL SYSTEMS

Types of Fuels

Natural Gas



- **Composition:** Methane (primary)
- **Applications:** Industrial burners, turbines, heaters

Oil

- **Types:** Heavy fuel oil (HFO), light fuel oil (LFO), and diesel
- **Applications:** Engines, boilers, and backup generators

Solid Fuels

- **Examples:** Coal, biomass.
- **Applications:** Specific applications & environmental considerations.

Alternative Fuels

- **Examples:** Hydrogen, biodiesel, and synthetic fuels.
- **Applications:** Emerging trends and sustainability.

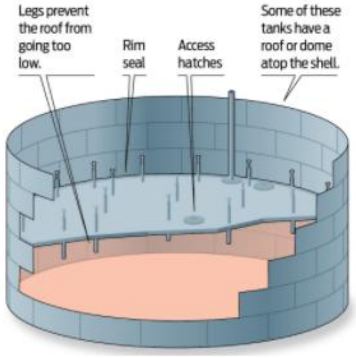
Source: Google Images

FUEL & LUBRICATION SYSTEMS

- **Fixed roof tanks** are used for liquids with very high flash points (e.g., fuel oil, bitumen).
  - Cone roofs, dome roofs and umbrella roofs are usual.
  - These tanks may be insulated and heated with steam coils to prevent the product to become too viscous, thus plugging pipework and becoming potentially unpumpable.
  - Dome roof tanks are meant for tanks having slightly higher-than-atmospheric storage pressure (e.g., slop oil).

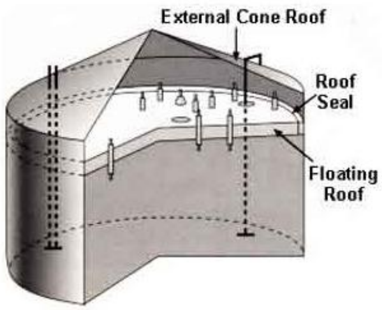
Liquefied gases (such as LPG, butane, propylene, etc.) may be stored in spherical tanks (or Horton spheres).

- **Floating roof tanks** are broadly divided into external floating roof tanks (usually referred to simply as floating roof tanks, or FR tanks) and internal floating roof types (IFR Tanks).
  - IFR tanks are used for liquids with lower flash points (e.g., jet fuel, petrol, ethanol).
  - They are essentially cone-roof tanks with an internal floating roof travelling vertically up and down along with the liquid level. This floating roof traps the vapour from low flash-point fuels.
  - Floating roofs are supported with legs or cables on which they rest. FR tanks do not have a fixed roof, being open at the top, and have a floating roof only.
  - Medium flash point liquids such as naphtha, kerosene, diesel, and crude oil are stored in these tanks.



External Floating Roof Tank

VS



Internal Floating Roof Tank

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FUEL & LUBRICATION SYSTEMS

LUBRICATION SYSTEMS

Principles of Lubrication:

- **Purpose:** Minimize friction, reduce wear, and prevent overheating.
- **Lubricant types:**
  - Liquid (oil), semi-solid (grease), and solid (graphite).
  - Selection criteria based on temperature, load, and speed.

Types of Lubrication Systems:

- **Manual Lubrication**: Grease guns, oil cans.
- **Automatic Lubrication**: Centralized systems for bearings, gears, and chains.
- **Circulating Systems**: Used in turbines, compressors, and large machinery.

Maintenance of Lubrication Systems:

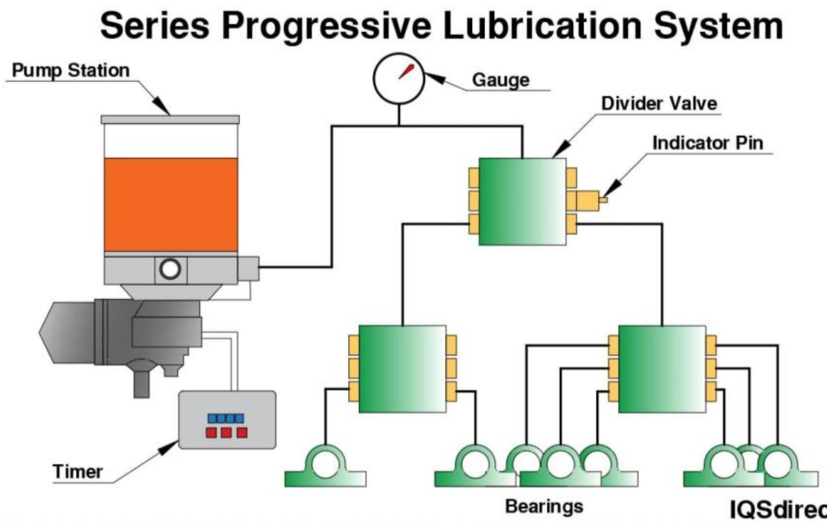
- Checking lubricant levels and quality.
- Detecting contamination and degradation (e.g., particle analysis, viscosity measurement).
- Replacing filters and cleaning systems.

Reliability Considerations:

- Impact of improper lubrication: Increased downtime, excessive wear, and energy loss.
- Predictive maintenance using tools like vibration analysis and thermography.

Components of Lubrication Systems:

- Pumps and reservoirs.
- Filters and strainers.
- Valves and distribution systems (e.g., single-line, dual-line, and circulating systems).



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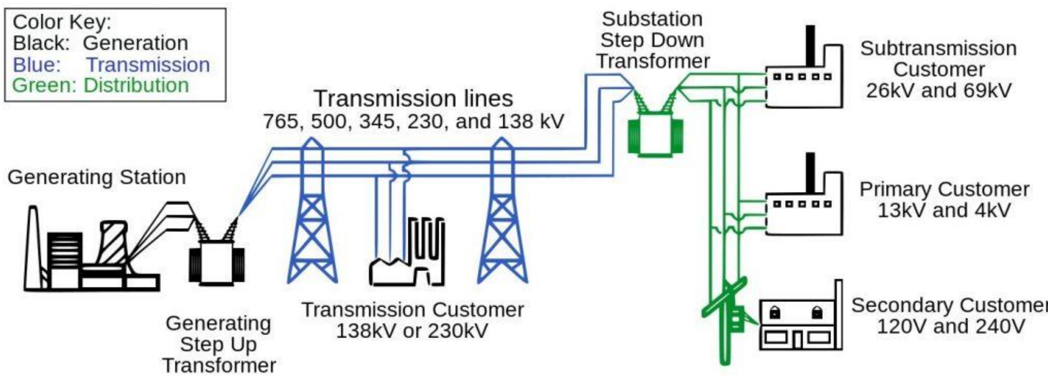
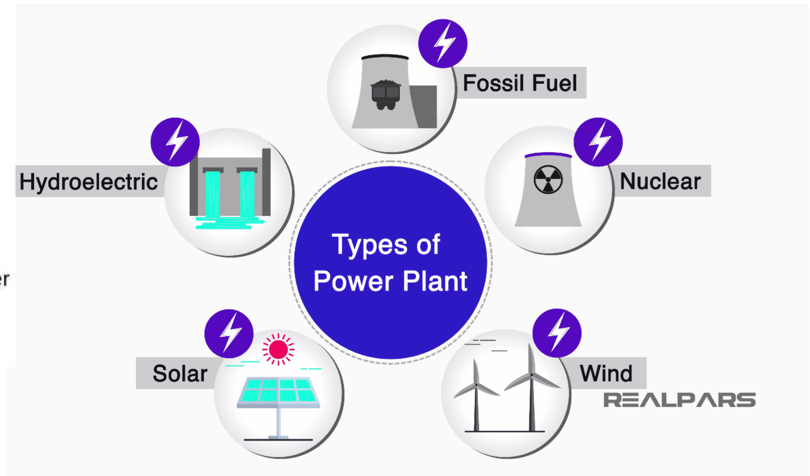
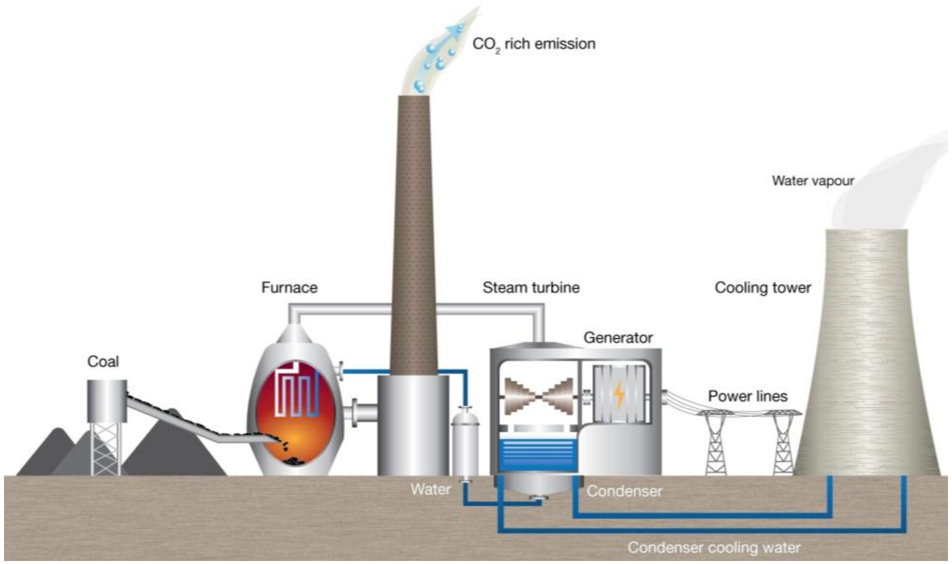
ELECTRICAL POWER SYSTEMS





- **Coal-fired power station**



- About 70 % of power generating capacity in India is from coal based thermal power plants.
- Coal is pulverized to the consistency of talcum powder.
- Then powdered coal is blown into the water wall boiler where it is burned at temperature higher than 1300°C.
- The heat in the combustion gas is transferred into steam.
- This high-pressure steam is used to run the steam turbine to spin.
- Finally turbine rotates the generator to produce electricity.

Source: Google Images

ELECTRICAL POWER SYSTEMS

POWER TRANSMISSION SYSTEMS

Generation Efficiency η_1	Efficiency ranges 28 – 35 % with respect to size of thermal plant, age of plant and capacity utilisation
Step-up Station η_2	Step-up to 400 / 800 kV to enable EHV transmission Envisaged max. losses 0.5 % or efficiency of 99.5 %
EHV Transmission & Station η_3	EHV transmission and substations at 400 kV / 800 kV. Envisaged maximum losses 1.0 % or efficiency of 99 %
HV Transmission & Station η_4	HV transmission & Substations for 220 / 400 kV. Envisaged maximum losses 2.5 % or efficiency of 97.5 %
Sub-transmission η_5	Sub-transmission at 66 / 132 kV Envisaged maximum losses 4 % or efficiency of 96 %
Distribution Station η_6	Step-down to a level of 11 / 33 kV. Envisaged losses 0.5 % or efficiency of 99.5 %
Primary Distribution η_7	Distribution is final link to end user at 11 / 33 kV. Envisaged losses maximum 5 % of efficiency of 95 %
End user Premises	**Cascade efficiency from Generation to end user** $= \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 \times \eta_5 \times \eta_6 \times \eta_7$

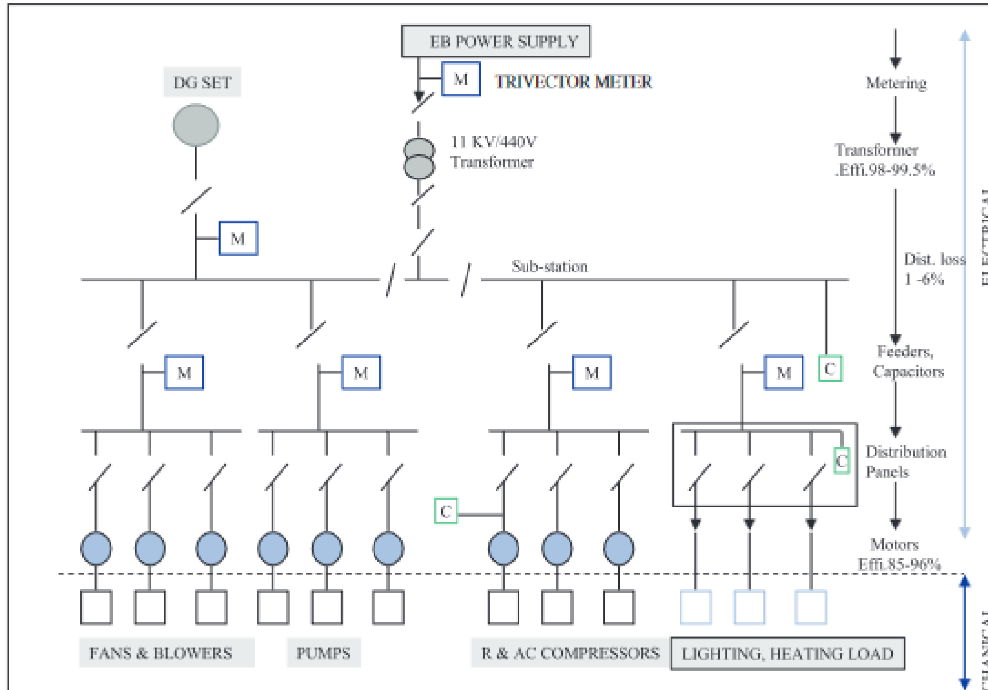


Figure 1.3 Electrical Distribution System –Single Line Diagram

- The standard technical losses are around 17 % in India (Efficiency = 83%). But the figures for many of the states show T & D losses ranging from 17 – 50 %.

Source: Google Images

ELECTRICAL POWER SYSTEMS

TABLE 1.3 LOSSES IN ELECTRICAL DISTRIBUTION EQUIPMENT

S.No	Equipment	% Energy Loss at Full Load Variations	
		Min	Max
1.	Outdoor circuit breaker (15 to 230 KV)	0.002	0.015
2.	Generators	0.019	3.5
3.	Medium voltage switchgears (5 to 15 KV)	0.005	0.02
4.	Current limiting reactors	0.09	0.30
5.	Transformers	0.40	1.90
6.	Load break switches	0.003	0.0 25
7.	Medium voltage starters	0.02	0.15
8.	Bus ways less than 430 V	0.05	0.50
9.	Low voltage switchgear	0.13	0.34
10.	Motor control centers	0.01	0.40
11.	Cables	1.00	4.00
12.	Large rectifiers	3.0	9.0
13.	Static variable speed drives	6.0	15.0
14.	Capacitors (Watts / kVAr)	0.50	6.0

TABLE 1.4 TROUBLE SHOOTING OF ELECTRICAL POWER SYSTEMS

System Problem	Common Causes	Possible Effects	Solutions
Voltage imbalances among the three phases	Improper transformer tap settings, single-phase loads not balanced among phases, poor connections, bad conductors, transformer grounds or faults.	Motor vibration, premature motor failure A 5% imbalance causes a 40% increase in motor losses.	Balance loads among phases.
Voltage deviations from rated voltages (too low or high)	Improper transformer settings, Incorrect selection of motors.	Over-voltages in motors reduce efficiency, power factor and equipment life Increased temperature	Correct transformer settings, motor ratings and motor input voltages
Poor connections in distribution or at connected loads.	Loose bus bar connections, loose cable connections, corroded connections, poor crimps, loose or worn contactors	Produces heat, causes failure at connection site, leads to voltage drops and voltage imbalances	Use Infra Red camera to locate hot-spots and correct.
Undersized conductors.	Facilities expanding beyond original designs, poor power factors	Voltage drop and energy waste.	Reduce the load by conservation load scheduling.
Insulation leakage	Degradation over time due to extreme temperatures, abrasion, moisture, chemicals	May leak to ground or to another phase. Variable energy waste.	Replace conductors, insulators
Low Power Factor	Inductive loads such as motors, transformers, and lighting ballasts Non-linear loads, such as most electronic loads.	Reduces current-carrying capacity of wiring, voltage regulation effectiveness, and equipment life.	Add capacitors to counteract reactive loads.
Harmonics (non-sinusoidal voltage and/or current wave forms)	Office-electronics, UPSs, variable frequency drives, high intensity discharge lighting, and electronic and core-coil ballasts.	Over-heating of neutral conductors, motors, transformers, switch gear. Voltage drop, low power factors, reduced capacity.	Take care with equipment selection and isolate sensitive electronics from noisy circuits.

Source: Google Images

CH 42010: PROCESS PLANT OPERATION & SAFETY

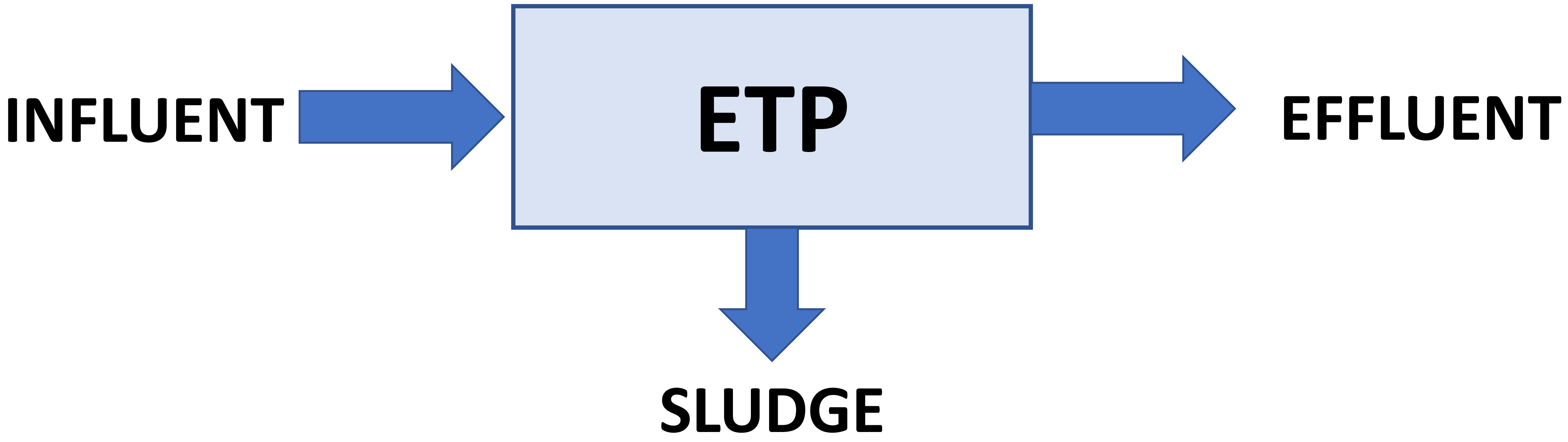
LTP: 3-0-0, CRD: 3

Lecture 8

Handling of Plant Effluent

EFFLUENT TREATMENT PLANT (ETP)

- **ETP (Effluent Treatment Plant)** is a process design for treating the industrial waste water for its reuse or safe disposal to the environment.
- **Influent:** Untreated industrial waste water.
- **Effluent:** Treated industrial waste water.
- **Sludge:** Solid part separated from waste water by ETP.



EFFLUENT TREATMENT PLANT (ETP)

Need of ETP:

- To clean industry effluent and recycle it for further use.
- To reduce the usage of fresh/potable water in Industries.
- To cut expenditure on water procurement.
- To meet the Standards for emission or discharge of environmental pollutants from various Industries set by the Government and avoid hefty penalties.
- To safeguard environment against pollution and contribute in sustainable development.

Design of ETP:

- The design and size of the ETP depends upon:
  - Quantity and quality of the industries discharge effluent.
  - Land availability.
  - Monetary considerations for construction, operation & maintenance.
  - Area dimension depends on:
    - Quality of wastewater to be treated,
    - Flow rate
    - Type of biological treatment to be used .
  - In case of less available land, CETP (Common Effluent Treatment Plant) is preferred over ETP

EFFLUENT TREATMENT PLANT (ETP)

Treatment Levels & Mechanisms of ETP:

- **Treatment levels:**
  - Preliminary
  - Primary
  - Secondary
  - Tertiary (or advanced)

- **Treatment mechanisms:**
  - Physical
  - Chemical
  - Biological

Preliminary Treatment Level

- **Purpose:** Physical separation of big sized impurities like cloth, plastics, wood logs, paper, etc.

- Common physical unit operations at Preliminary level are:
  - **Screening:** A screen with openings of uniform size is used to remove large solids such as plastics, cloth etc. Generally maximum 10mm is used.
  - **Sedimentation:** Physical water treatment process using gravity to remove suspended solids from water.
  - **Clarification:** Used for separation of solids from fluids.

EFFLUENT TREATMENT PLANT (ETP)

Primary Treatment Level

- **Purpose:** Removal of floating and settleable materials such as suspended solids and organic matter.
- **Methods:** Both physical and chemical methods are used in this treatment level.

- **Chemical unit processes:**
  - Chemical unit processes are always used with physical operations and may also be used with biological treatment processes.
  - Chemical processes use the addition of chemicals to the wastewater to bring about changes in its quality.
  - Example: pH control, coagulation, chemical precipitation and oxidation.
- **pH Control:**
  - To adjust the pH in the treatment process to make wastewater pH neutral.
  - **For acidic wastes** (low pH): $NaOH$, Na_2CO_3, $CaCO_3$ or $Ca(OH)_2$.
  - **For alkali wastes** (high pH): H_2SO_4, HCl.

Primary Treatment Level

- **Chemical Coagulation and Flocculation:**
    - Coagulation refers to collecting the minute solid particles dispersed in a liquid into a larger mass.
    - Chemical coagulants like **$Al_2(SO_4)_3$ {also called alum} or $Fe_2(SO_4)_3$** are added to wastewater to improve the attraction among fine particles so that they come together and form larger particles called **flocs**.
    - A **chemical flocculent (usually a polyelectrolyte)** enhances the flocculation process by bringing together particles to form **larger flocs** , which settle out more quickly.
    - Flocculation is aided by **gentle mixing** which causes the **particles to collide**.

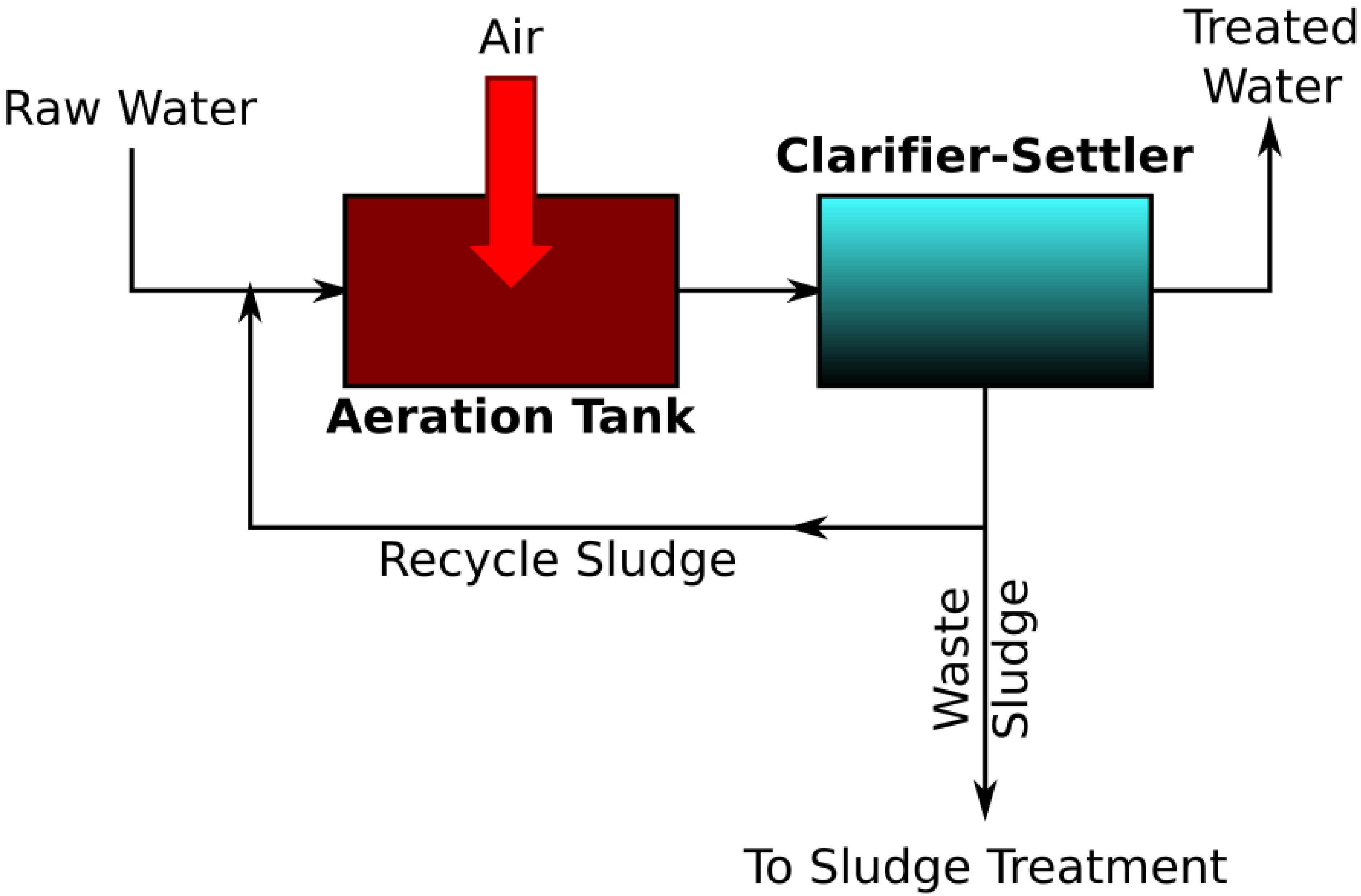
EFFLUENT TREATMENT PLANT (ETP)

Secondary Treatment Level

- **Methods:** Biological and chemical processes are involved in this level.
- **Biological unit process**
  - To remove, or reduce the concentration of organic and inorganic compounds.
  - Biological treatment process can take many forms but all are based around microorganisms, mainly bacteria.
- **Aerobic Processes**
  - Aerobic treatment processes take place in the **presence of air (oxygen)**.
  - Utilizes those microorganisms (aerobes), which use molecular/free oxygen to assimilate organic impurities i.e. convert them in to carbon dioxide, water and biomass.
- **Anaerobic Processes**
  - The anaerobic treatment processes take place in the **absence of air (oxygen)**.
  - Utilizes microorganisms (anaerobes) which do not require air (molecular/free oxygen) to assimilate organic impurities.
  - The final products are methane and biomass.

EFFLUENT TREATMENT PLANT (ETP)

Biological Wastewater Treatment Alternatives in Secondary Treatment



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EFFLUENT TREATMENT PLANT (ETP)

Tertiary/Advanced Treatment Level

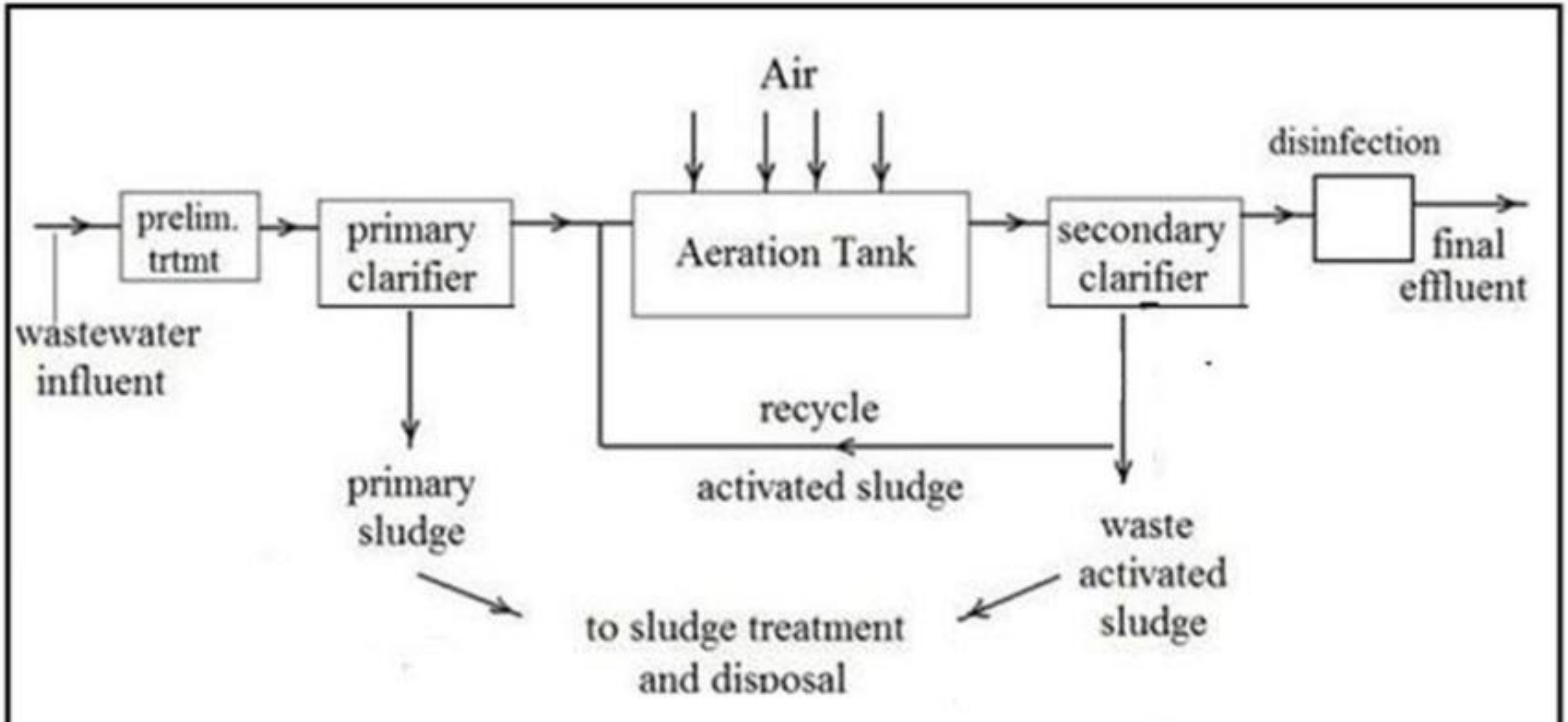
- **Purpose:** Final cleaning process that improves wastewater quality before it is reused, recycled or discharged to the environment.

- **Mechanism:** Removes remaining inorganic compounds, and substances, such as the nitrogen and phosphorus. Bacteria, viruses and parasites, which are harmful to public health, are also removed at this stage.

- **Methods:**
  - **Alum:** Used to help remove additional phosphorus particles and group the remaining solids together for easy removal in the filters.
  - **Chlorine contact tank** disinfects the tertiary treated wastewater by removing microorganisms in treated wastewater including bacteria, viruses and parasites.
  - **Remaining chlorine** is removed by adding sodium bi-sulphate just before it's discharged.

EFFLUENT TREATMENT PLANT (ETP)

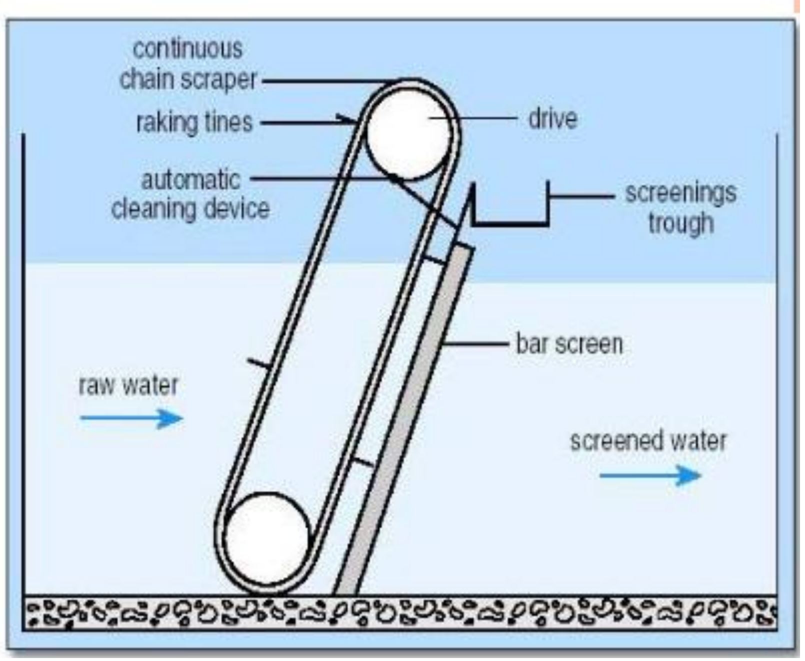
Flowchart of ETP

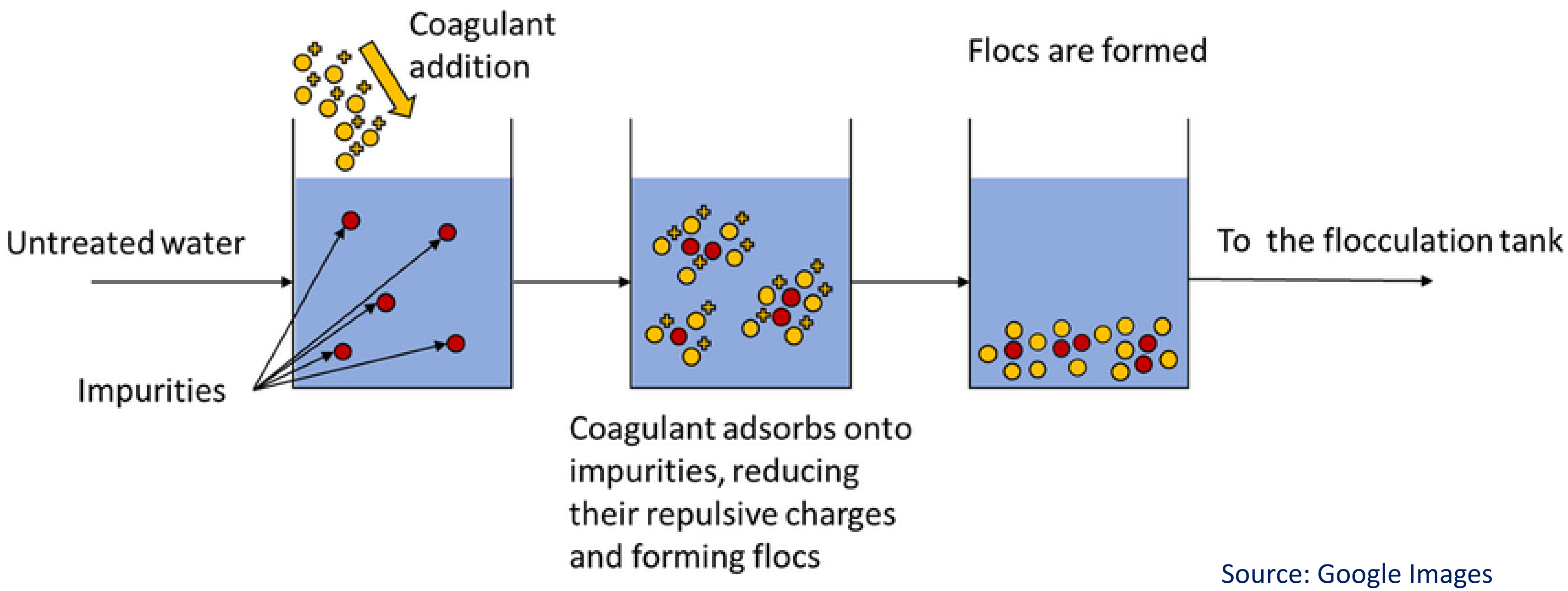


Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

- **Treatment Methods**
  - **Physical**: Screening, sedimentation, filtration.
  - **Chemical**: Coagulation, neutralization, advanced oxidation processes.
  - **Biological**: Activated sludge process, bio-filtration, anaerobic digestion.
  - **Advanced treatment options:** Membrane filtration, ion exchange, and adsorption methods.

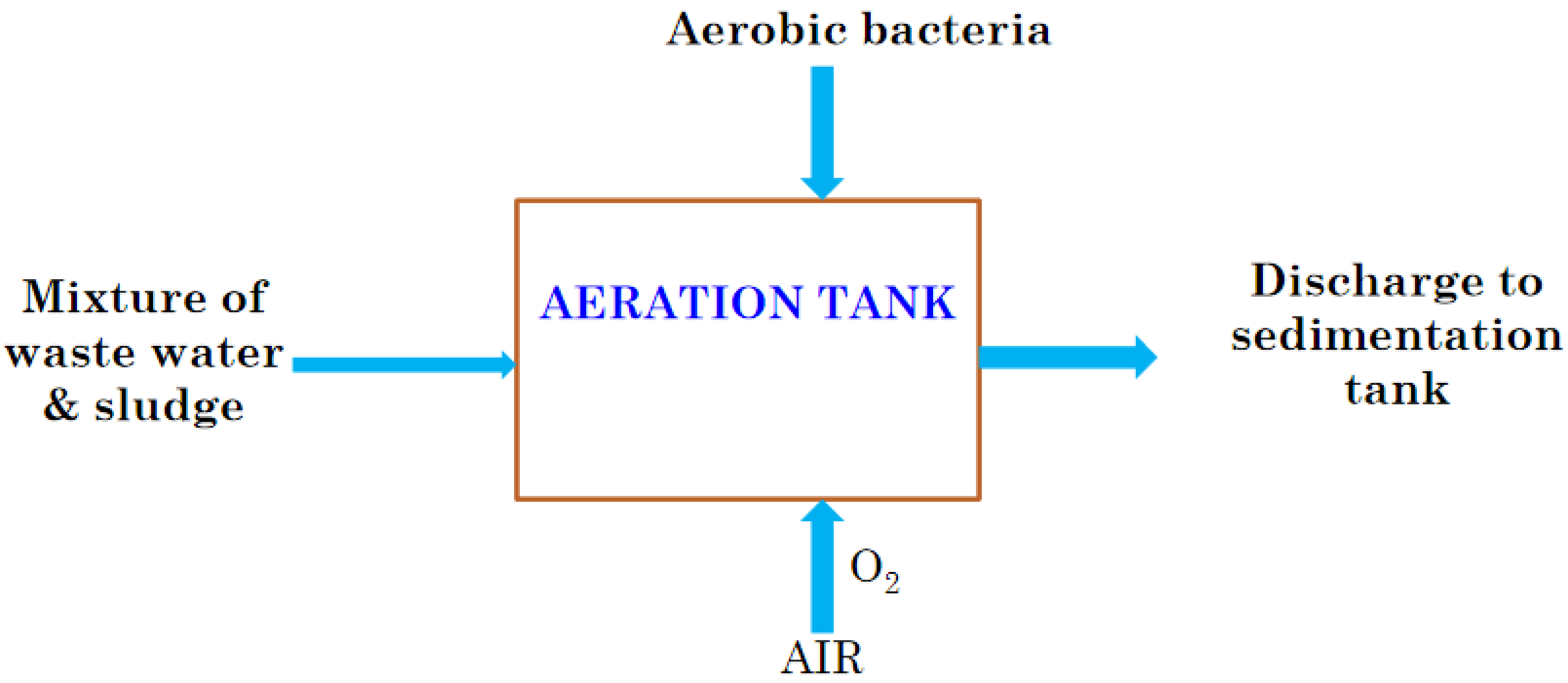




Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

SCHEMATIC DIAGRAM OF AERATION



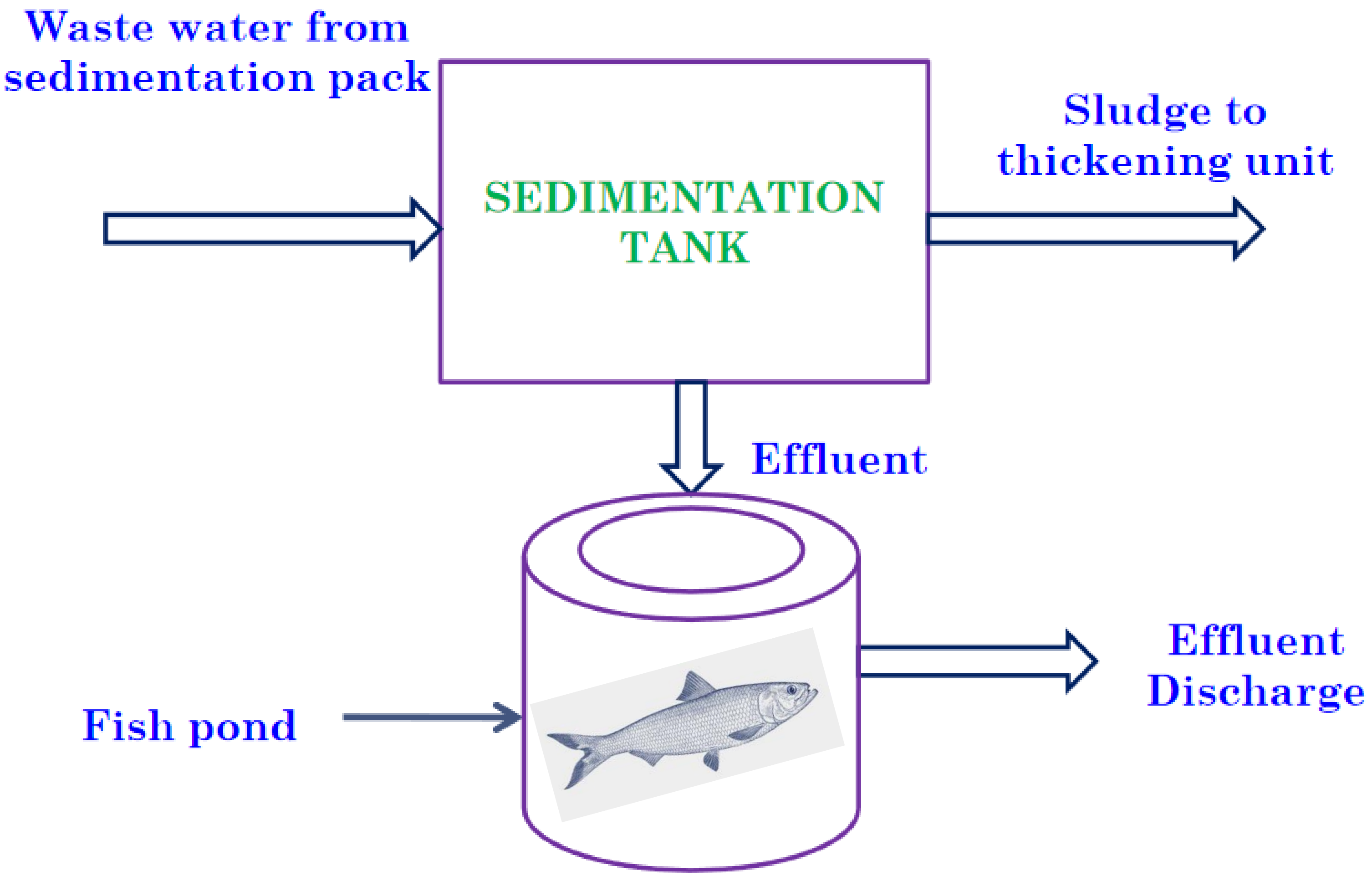
Reaction in Aeration Tank:

$$\text{ORGANIC MATTER} + O_2 \xrightarrow[\text{NUTRIENT}]{\text{BACTERIA}} CO_2 + HO_2 + \text{HEAT}$$

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

SCHEMATIC DIAGRAM OF SEDIMENTATION TANK



Fish Pond is used to see survival of fishes to ascertain fitness of water for disposal

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Effluent Characterization

Physicochemical Parameters

pH

Solid Content

Temperature

Odour

Organic Content

Biological Oxygen Demand (BOD)

Chemical Oxygen Demand (COD)

Total Organic Carbon (TOC)

Others

Oil and Grease

Nitrogen and Phosphorous

EFFLUENT TREATMENT PLANT (ETP)

Effluent Characterization

Physicochemical Parameters

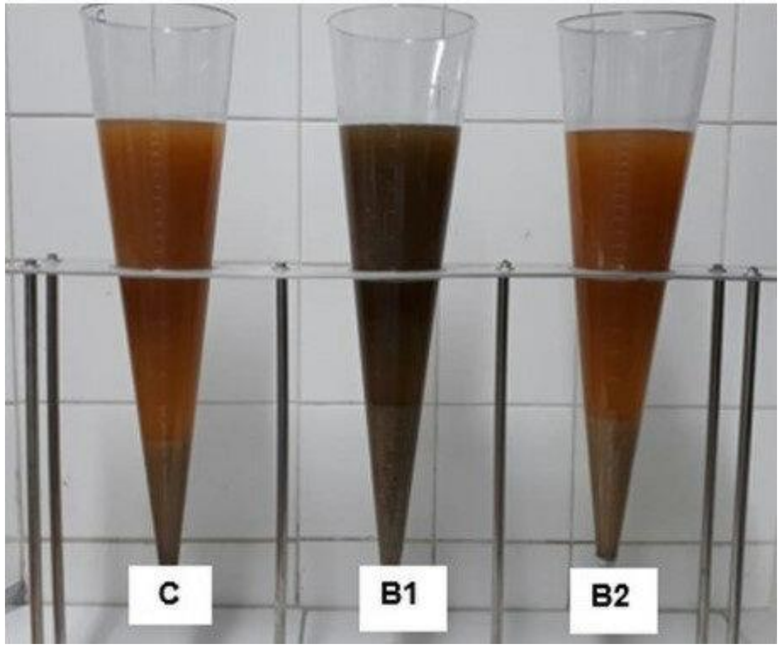
pH

Solid Content

Temperature

Odour

- The solids which settle are usually measured with an **Imhoff cone** (see Figure), in which a known amount of water (e.g., 1 litre) is placed.
- The solids which settle are estimated at fixed times, usually after 10 minutes and after 2 hours.
- The admissible amounts that can be discharged depend on each regulation, but discharge of wastewaters is usually not permitted if they contain solids winch settle after 10 minutes.



Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Effluent Characterization

Organic Content

Biological Oxygen Demand (BOD)

Chemical Oxygen Demand (COD)

Total Organic Carbon (TOC)

Biological Oxygen Demand	Chemical Oxygen Demand
Definition	
It is the amount of oxygen the microbes require to decompose the organic matter under aerobic conditions.	It is the total amount of oxygen required to break down the organic matter by chemical oxidation.
Test	
It can be determined by putting a sealed water sample under specific temperature conditions for five days.	It can be determined by placing a water sample with a strong oxidising agent under specific temperature conditions for a short period.
Value	
Lower than COD.	Higher than BOD.
Use	
• It is used to waste loadings in treatment plants. • Evaluation of BOD removal efficiency of the waste plants.	• To quantify the amount of oxidisable pollutants found in water bodies. • It provides a measurement on how an effluent will affect the water body.

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

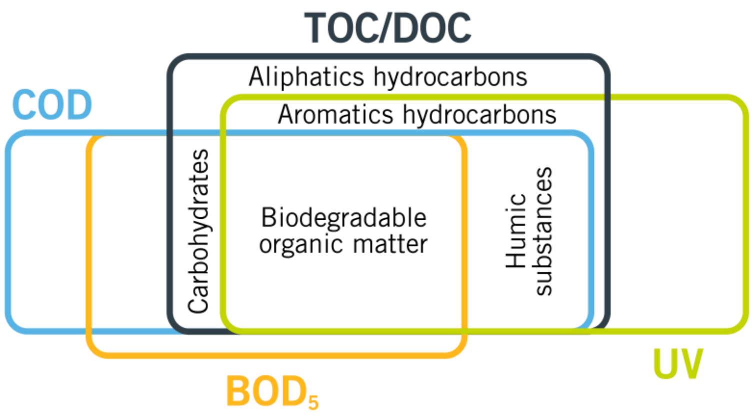
Effluent Characterization

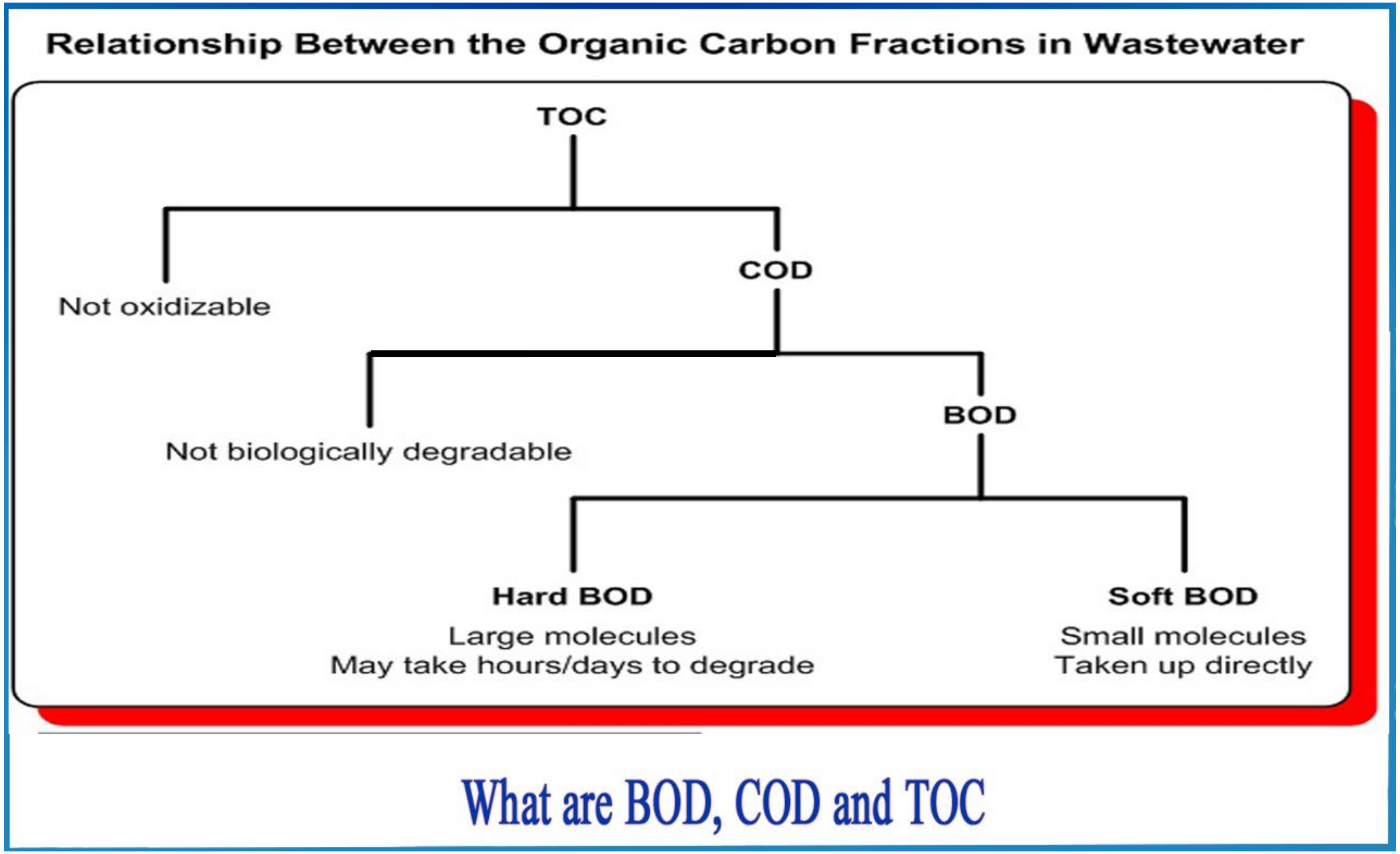
Organic Content

Biological Oxygen Demand (BOD)

Chemical Oxygen Demand (COD)

Total Organic Carbon (TOC)





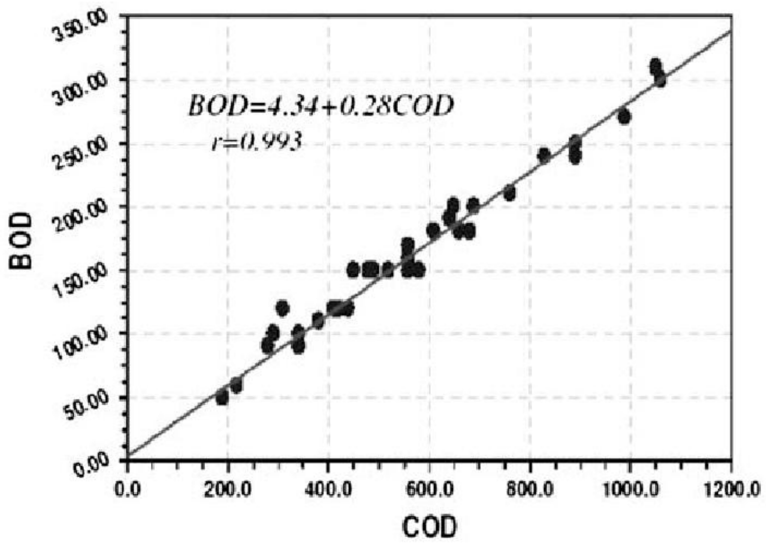
Source: Google Images

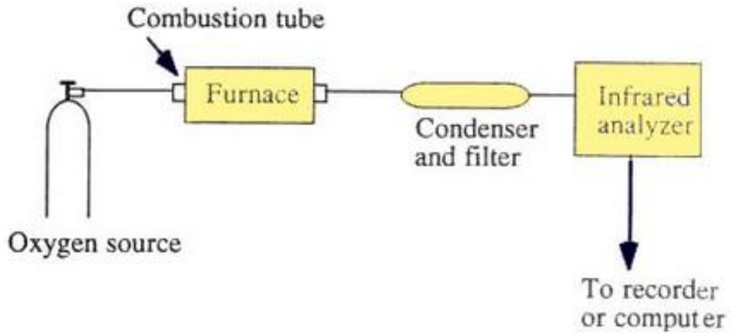
EFFLUENT TREATMENT PLANT (ETP)

Effluent Characterization

Parameter	COD	BOD_5	TOC
Oxidant Used	$K_2Cr_2O_7$ $Mn_2(SO_4)_3$	Oxidation by microorganisms	O_2 $K_2S_2O_8$ Heat Combination of the above with various catalysts
Most Suitable Use	Rapid and frequent monitoring of treatment plant efficiency and water quality	Modeling treatment plant process and the effects organic compounds on the dissolved oxygen content of receiving waters	Measures amount of total of organic carbon in samples
Test Completion Time	1-1/2 to 3 hours	5 days (for standard BOD test)	Several minutes to hours
Advantages	• Correlates with BOD on waste with constant composition • Toxic materials do not affect oxidant • Changes in the COD value between influent and effluent may parallel BOD content and supplement BOD results • Short analysis time	• Most closely models the natural environment when used with the proper "seed"	• Correlates with BOD on waste with constant composition, but not as closely as COD • Short analysis time
Disadvantages	• Interference from chloride ions • Some organic compounds are not oxidized completely	• Toxic materials kill microorganisms • Microorganisms do not oxidize all materials present in waste • Inaccuracies when used with improper "seed" • Lengthy test period	• Requires expensive equipment • Some organic compounds are not oxidized completely • Measures Total Organic Carbon and not oxygen demand

Source: Hach, "The Science of Chemical Oxygen Demand" Technical Information Series, Booklet No. 9, by Wayne Boyles.





TOC ANALYZER

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Removal Efficiency (RE) / Reduction Efficiency (RE)

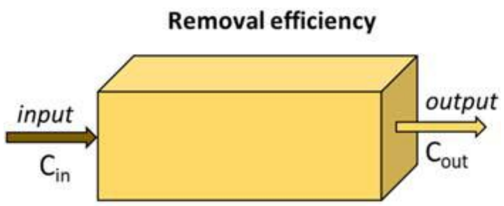
$$E = \frac{\text{Input concentration} - \text{Output concentration}}{\text{Input concentration}}$$
$$= \frac{\text{Removed concentration}}{\text{Input concentration}} = 1 - \frac{\text{Output concentration}}{\text{Input concentration}}$$
$$= 1 - \text{Remaining fraction}$$

$$E_{\text{biological}} = \frac{\text{Influent total COD} - \text{Effluent soluble COD}}{\text{Influent total COD}} \tag{7.12}$$

where:

Influent total COD = usual (total) COD measured in the influent (mg/L)
Effluent soluble COD = soluble or filtered COD, reflecting the remaining fraction of influent COD, and excluding the COD associated with suspended solids (particulate COD) (mg/L)

Equation 7.12 can be used for COD or BOD; the concept is the same.



$$E = \frac{C_{in} - C_{out}}{C_{in}} = 1 - \frac{C_{out}}{C_{in}}$$

- For some constituents, we express concentrations in terms of their order of magnitude, which is a way of comparing their relative size. In engineering, water quality and treatment systems, base 10 logarithmic comparisons are usually always implied.

Removal efficiency in terms of log reduction values (LRV)

$$\text{LRV} = log_{10}\, C_{in} - log_{10}\, C_{out} = log_{10}\left(\frac{C_{in}}{C_{out}}\right) = -\, log_{10}\left(\frac{C_{out}}{C_{in}}\right)$$

Relationship between RE as percentages and LRV

$$\text{LRV} = -\log_{10}(1 - E) = -\log_{10}\left(1 - \frac{E(\%)}{100}\right) = \log_{10}\left(\frac{100}{100 - E(\%)}\right)$$

$$E(\%) = 100 \times \left(1 - 10^{-LRV}\right)$$

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

RE & LRV Calculation

- The **most probable number (MPN)** is **a statistical method used to estimate the viable numbers of bacteria in a sample by inoculating broth in 10-fold dilutions** and is based on the principle of extinction dilution.

Q1. In the ETP, you obtained the following E. coli values: influent = 1.00×10^8 MPN/100 mL; effluent concentration = 1.00×10^5 MPN/100 mL. Calculate the reduction efficiencies as percentage and $\log_{10}$ reduction values (LRV).

From Equation 7.2, you obtain the reduction efficiency in relative and in percentage values:

$$E = \frac{C_{in} - C_{out}}{C_{in}} = \frac{1.00 \times 10^8 - 1.00 \times 10^5}{1.00 \times 10^8} = \mathbf{0.999 = 99.9\%}$$

In order to express the reduction efficiency in terms of LRV, using Equation 7.5, you have three different options:

$$LRV = \log_{10}(1.00 \times 10^8) - \log_{10}(1.00 \times 10^5) = 8.0 - 5.0 = \mathbf{3.0}$$

$$LRV = \log_{10}[(1.00 \times 10^8)/(1.00 \times 10^5)] = \log_{10}(1.00 \times 10^3) = \mathbf{3.0}$$

$$LRV = -\log_{10}[(1.00 \times 10^5)/(1.00 \times 10^8)] = -\log_{10}(1.00 \times 10^{-3}) = -(-3.0) = \mathbf{3.0.}$$

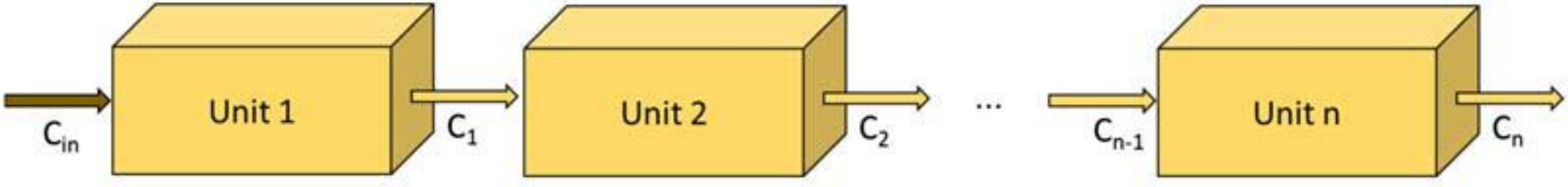
Equations 7.6 and 7.7 can be used to convert $E(\%)$ into LRV and vice versa:

$$\mathbf{LRV} = -\log_{10}\left(1 - \frac{E(\%)}{100}\right) = -\log_{10}\left(1 - \frac{99.9}{100}\right) = -(-3.0) = \mathbf{3.0}$$

$$E(\%) = 100 \times (1 - 10^{-LRV}) = 100 \times (1 - 10^{-3}) = 100 \times 0.999 = \mathbf{99.9\%}$$

EFFLUENT TREATMENT PLANT (ETP)

RE & LRV Calculation for Units in Series



$$E_1 = \frac{C_{in} - C_1}{C_{in}}$$

$$LRV_1 = log_{10} C_{in} - log_{10} C_1$$

$$E_2 = \frac{C_1 - C_2}{C_1}$$

$$LRV_2 = log_{10} C_1 - log_{10} C_2$$

$$E_n = \frac{C_{n-1} - C_n}{C_{n-1}}$$

$$LRV_n = log_{10} C_{n-1} - log_{10} C_n$$

$$\boldsymbol{E_{\text{overall}} = 1 - [(1 - E_1) \times (1 - E_2) \times \cdots \times (1 - E_n)]}$$

$$\boldsymbol{LRV_{\text{overall}} = \text{LRV}_1 + \text{LRV}_2 + \ \ldots + \text{LRV}_\text{n}}$$

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

RE & LRV Calculation for Units in Series

For treatment units placed in series, the overall percentage removal efficiency of the combined treatment units is based on the multiplication of the remaining fractions of the constituent in each unit.

$$\boxed{E_{\text{overall}} = 1 - [(1 - E_1) \times (1 - E_2) \times \cdots \times (1 - E_n)]}$$

For instance, in a complete treatment system there may be three process units placed in series, with the following reduction efficiencies: Unit 1 = 90%, Unit 2 = 99.9%, and Unit 3 = 99%.

$$E_{\text{overall}} = 1 - [(1 - 0.90) \times (1 - 0.999) \times (1 - 0.99)] = 0.999999$$

$$E_{\text{overall}}(\%) = 100 \times \left(1 - \left[\left(1 - \frac{90}{100}\right) \times \left(1 - \frac{99.9}{100}\right) \times \left(1 - \frac{99}{100}\right)\right]\right) = 99.9999\%$$

$$\boxed{\text{LRV}_{\text{overall}} = \text{LRV}_1 + \text{LRV}_2 + \cdots + \text{LRV}_n}$$

In the example above, the LRV values in each unit are Unit 1 =1 log, Unit 2 = 3 log, and Unit 3 = 2 log.

$$\text{LRV}_{\text{overall}} = 1 + 3 + 2 = 6 \log_{10} \text{unit reduction}$$

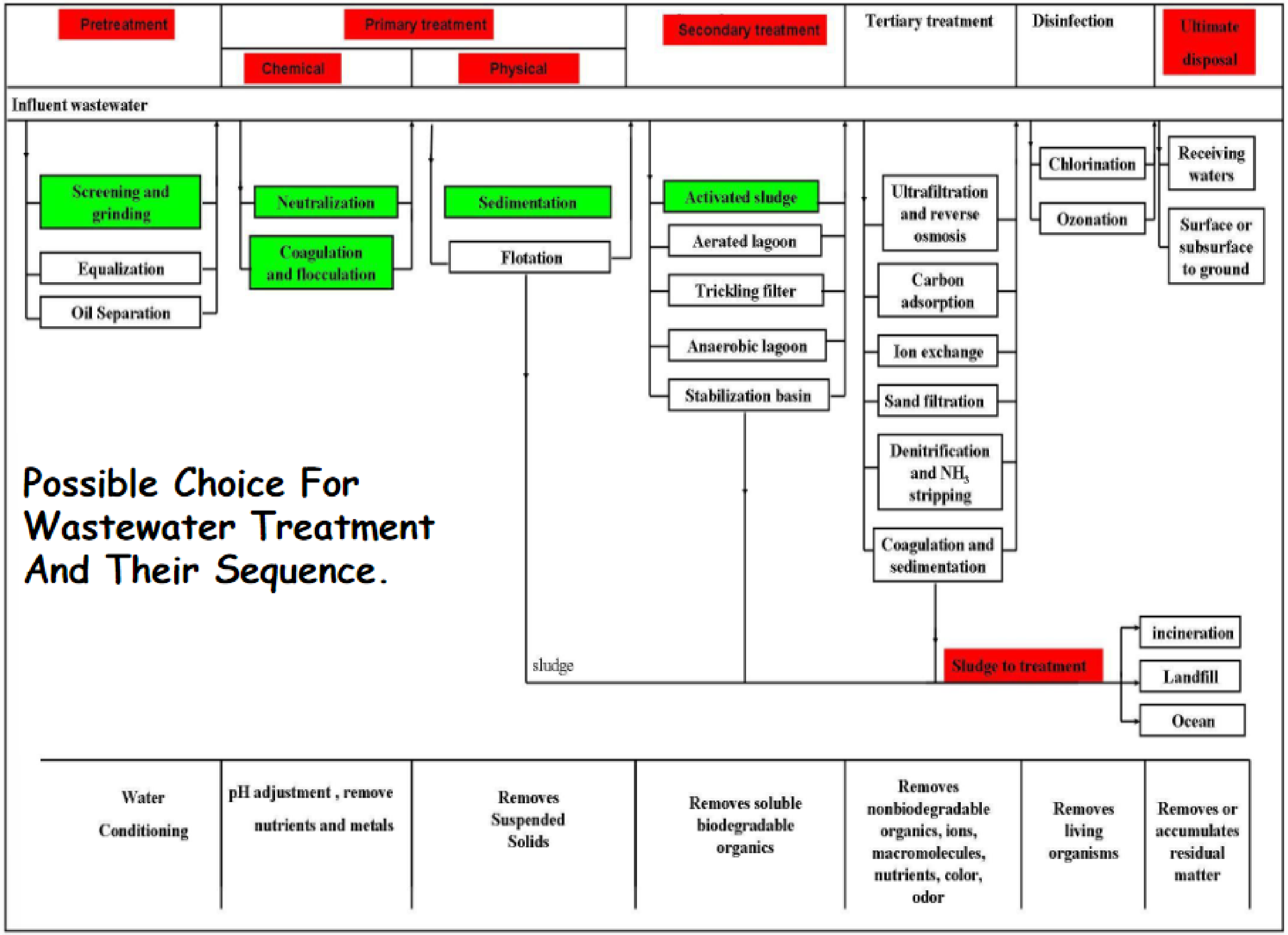
Check if 6 log-units reduction is equivalent to 99.9999%?

EFFLUENT TREATMENT PLANT (ETP)

Assignment

Q1. You obtained the following mean values of influent and effluent concentrations of the constituent you are analysing in your treatment plant: (a) summer: C_{in} = 25 mg/L, C_{out} = 10 mg/L and (b) winter: C_{in} = 45 mg/L, C_{out} = 15 mg/L. Assume the following mean flow rates: mean influent flow during the summer (rainy period) = 1000 m^3/d and mean influent flow during the winter (dry period) = 400 m^3/d. Calculate the influent, effluent and removal load. Interpret the results.

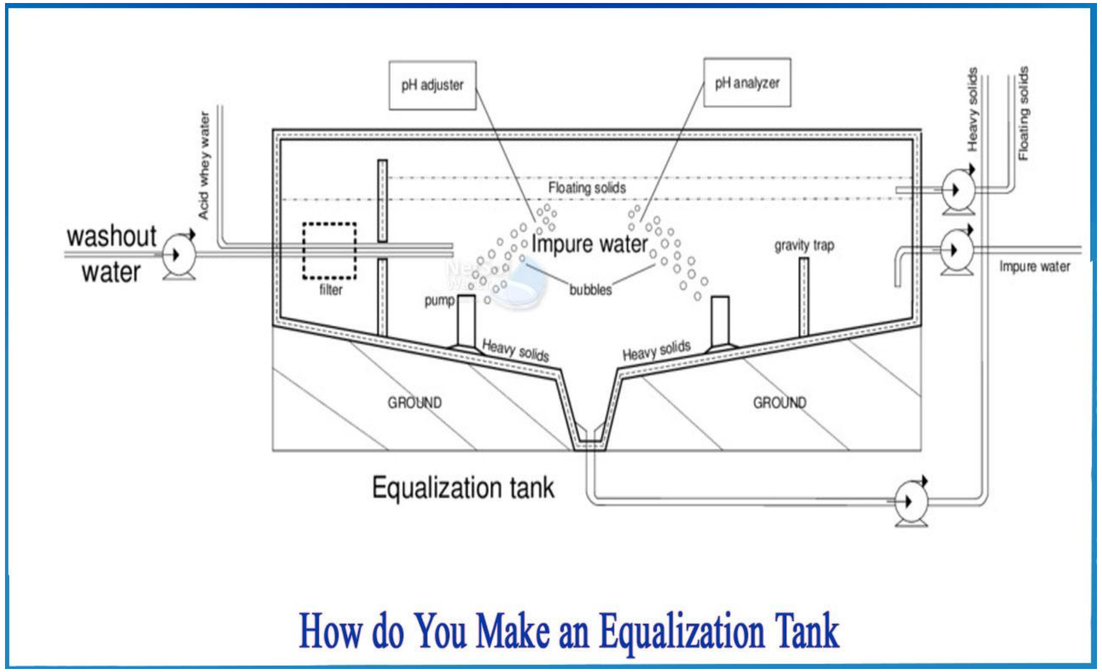
EFFLUENT TREATMENT PLANT (ETP)



Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

ETP PLANT OPERATION

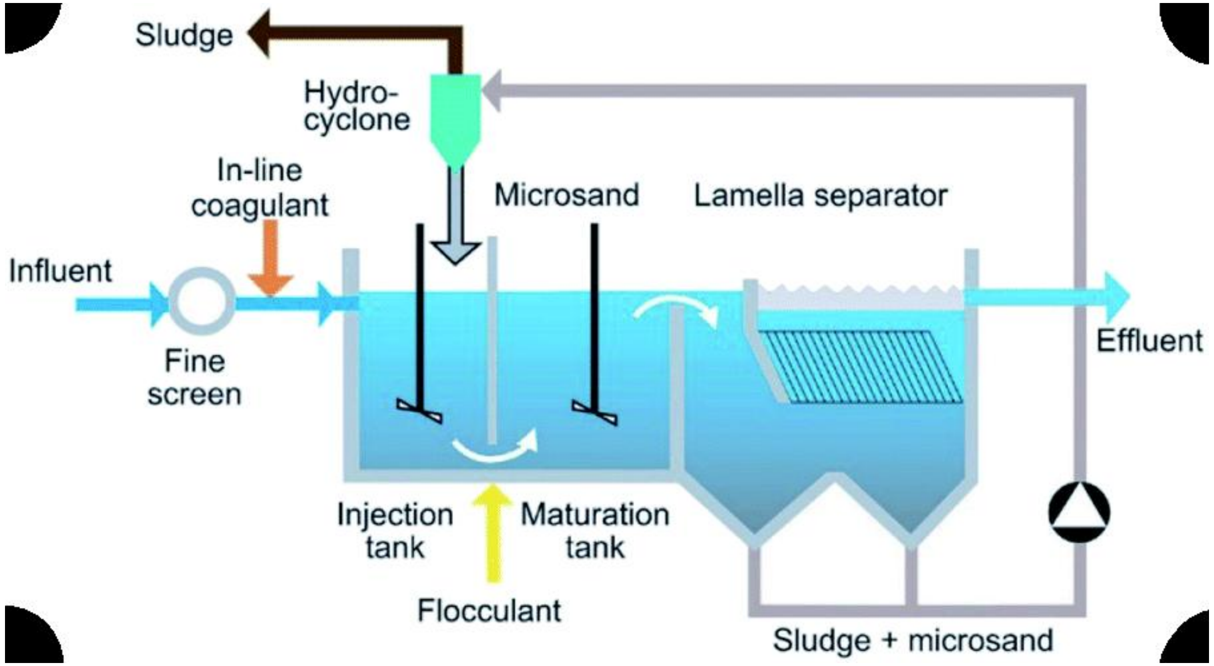


- **Screen chamber:**
  - **Remove relatively large solids** to avoid abrasion of mechanical equipments and clogging of hydraulic system.
- **Collection tank:**
  - The collection tank **collects the effluent water** from the screening chamber, stores and then pumps it to the equalization tank.
- **Equalization tank:**
  - The effluents do not have similar concentrations at all the time; the pH will vary time to time.
  - Effluents are stored from **8 to 12 hours** in the equalization tank resulting in a homogenous mixing of effluents and helping in neutralization.
  - It **eliminates shock loading** on the subsequent treatment system.
  - Continuous mixing also **eliminates settling of solids** within the **equalization tank**.
  - **Reduces SS, TSS**.

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

ETP PLANT OPERATION



- **Flash mixer:** Coagulants were added to the effluents:
  - **Lime: (800-1000 ppm)** To correct the **pH upto 8-9**
  - **Alum: (200-300 ppm)** To **remove colour**
  - **Poly electrolyte: (0.2 ppm)** To **settle the suspended matters & reduce SS, TSS**.
- The addition of the above chemicals by efficient rapid mixing facilitates homogeneous combination of flocculates to produce microflocs.

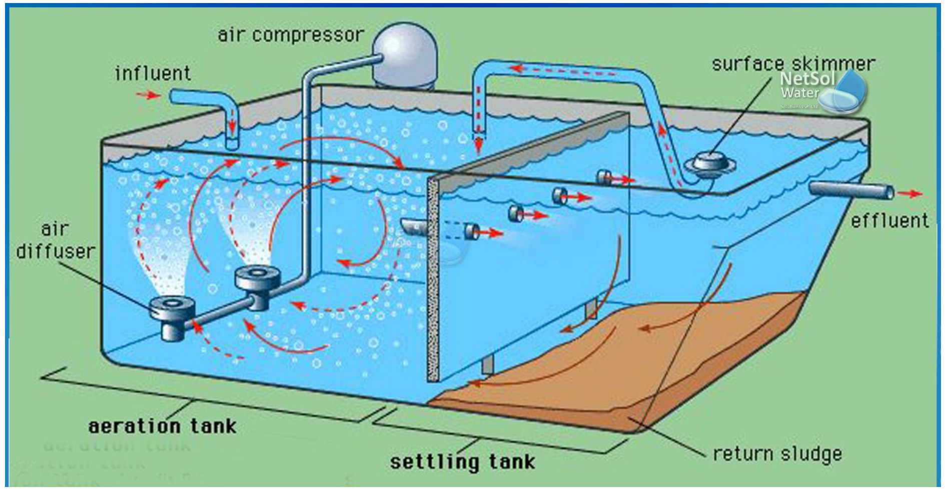
- **Clarriflocculator:** In the clarriflocculator the water is circulated continuously by the stirrer.
  - Overflowed water is taken out to the aeration tank.
  - The **solid particles are settled down**, and collected separately and dried; this **reduces SS, TSS**.
  - Flocculation provides **slow mixing** that leads to the **formation of macro flocs**, which then **settles out** in the clarifier zone.
  - The settled solids i.e. primary sludge are pumped into sludge drying beds.

Source: Google Images

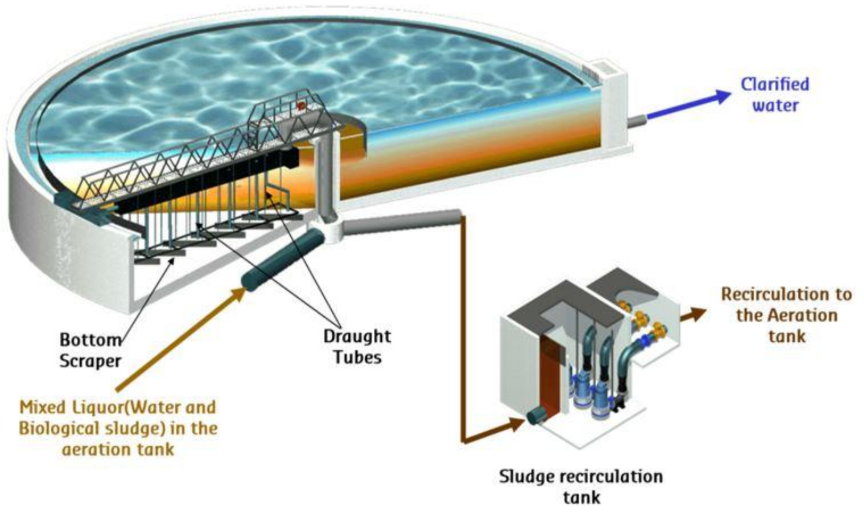
EFFLUENT TREATMENT PLANT (ETP)

ETP PLANT OPERATION

- **Aeration tank:**
  - The water is passed like a thin film over the different arrangements like staircase shape.
  - **Dosing of Urea and DAP is done**.
  - Water gets direct contact with the air to dissolve the oxygen into water.
  - **BOD & COD values of water is reduced up to 90%.**



- **Clarifier:**
  - The clarifier **collects the biological sludge**.
  - The overflowed water is called as treated effluent and disposed out.
  - The outlet water quality is checked to be within the accepted limit as delineated in the **norms of the Bureau of Indian standards**.
  - Through pipelines, the treated water is disposed into the environment river water, barren land, etc.



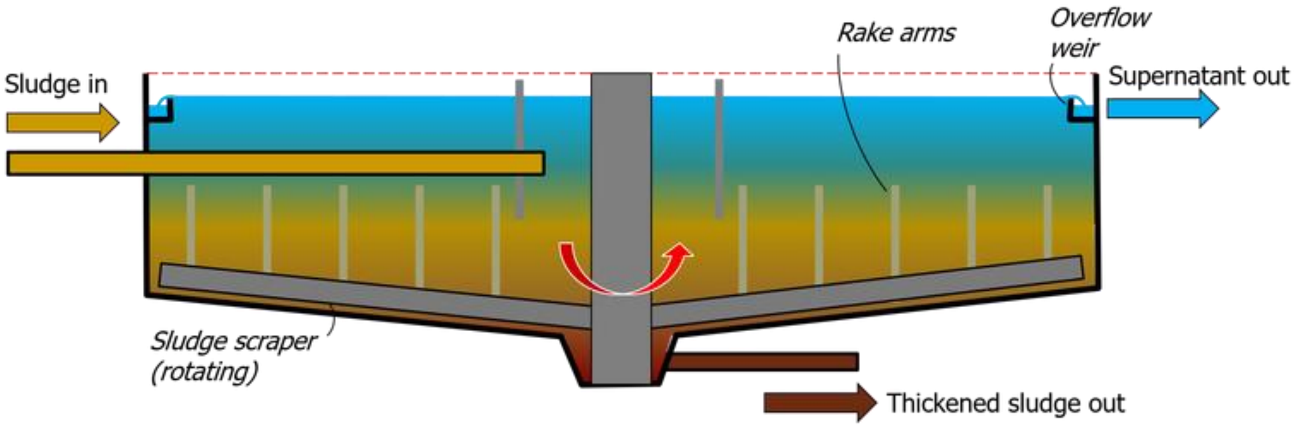
Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

ETP PLANT OPERATION

- **Sludge thickener:**
  - The inlet water consists of **60% water + 40% solids**.
  - The effluent is passed through the centrifuge.
  - Due to **centrifugal action**, the solids and liquids are separated.
  - The sludge thickener reduces the water content in the effluent to **40% water + 60% solids**.
  - The effluent is then reprocessed and the sludge collected at the bottom.

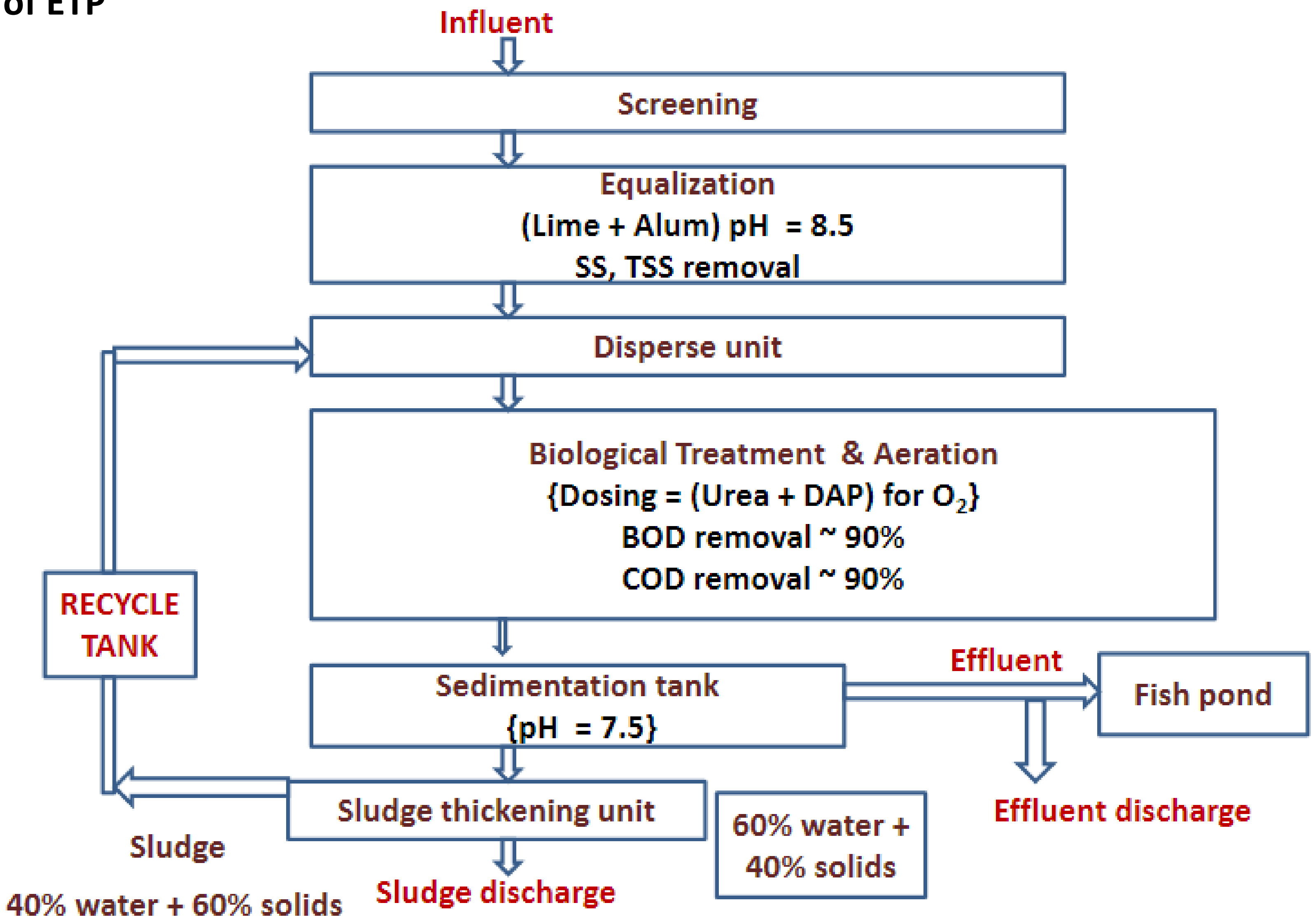
- **Drying beds:**
  - Primary and secondary sludge is dried on the drying beds.



Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Detailed Flowchart of ETP



Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Selection for ETP

Wastewater characteristics	Wastewater quality	Treatment options
Low TDS and low BOD	Low organic	Chemical treatment
Low TDS and high BOD	Organic effluent	Anaerobic + aerobic treatment
Low TDS and high COD	Highly organic	Chemical oxidation by hydrogen peroxide or ozone or sodium hypochlorite Chemical + biological treatment
	Refractory	Chemical oxidation + biological treatment
High TDS	Inorganic salts	Solar evaporation Forced evaporation (after separation of volatile organic matter) Membrane separation
High TDS and high COD	Highly organic effluent	Incineration (based on calorific value) +Secure landfill of incineration ash
	Waste is not easily biodegradable but toxic	Thermal Decomposition Chemical oxidation (hydrogen peroxide, ozone, *etc.*) Evaporation + Secured landfill
	Waste is not toxic but mostly inorganic salts	Chemical treatment (recovery, precipitation *etc.*) Evaporation + secured landfill of evaporated residue

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Selection for ETP

Performance	Treatment option	Efficiency (%)
High	Chemical precipitation→bio-oxidation→chemical precipitation→sand filtration →activated carbon adsorption	BOD : 84-93 COD : 80-90 SS : 77-98
	Chemical precipitation→bio-oxidation→sand filtration→dual media filtration	
	Chemical precipitation (3 stage)→media filtration→activated carbon adsorption	
	Ozonation→bio-oxidation→sand filtration→activated carbon adsorption.	
Moderate	Electro-coagulation→bio-oxidation→chemical precipitation→sand filtration→activated carbon adsorption.	BOD : 68-79 COD : 60-73 SS : 64-78
Low	Bio-oxidation→sand filtration→dual media filtration→activated carbon adsorption	BOD : 56-70 COD : 48-65 SS : 52-74
	Chemical precipitation→sand filtration→activated carbon adsorption	
	Catalytic oxidation	BOD : 24-25 COD : 21-23 SS : 56-60

Source: Google Images

EFFLUENT TREATMENT PLANT (ETP)

Safety Standards for ETP

Parameters	Discharge Effluent Standards into ISW
pH	5.5-9.0
SS	100
TDS	2100
COD	250
BOD $_{(3d,\ 27°C)}$	30
Oil & Grease	10
Chlorides	600
Sulphates	1000
Phosphates	5
Ammoniacal-N	50
Fluoride	2.0
Arsenic	0.2
Cyanide	0.2
Mercury	0.01
Iron	3
Manganese	2
Chromium	2
Copper	3
Zinc	5
Nickel	3
Lead	0.1
Selenium	0.05

All values are expressed in mg/l, except pH
ISW-Inland Surface Waters.

Source: Google Images

Chemical	Potential Health Effect
Benzene	Known human carcinogen
Arsenic	Known human carcinogen[i]
Styrene	Reasonably anticipated to be a human carcinogen
Polycyclic aromatic hydrocarbons (PAHs)	Reasonably anticipated to be a human carcinogen[ii]
Lead	Neurotoxicant
Zinc	Neurotoxicant
Cadmium	Known human carcinogen[i]
Chromium	Known human carcinogen[i] Respiratory irritant
VOCs and SVOCs (e.g. benzathiazole, hexane, toluene, formaldehyde)	Respiratory irritants or asthma triggers Neurotoxicants Some are known human carcinogens[i]
Phthalates	Reproductive toxicant
Crystalline Silica	Known human carcinogen[i] Respiratory irritant
Latex	Allergen
Particulate matter	Respiratory irritant or asthma trigger

*For a more extensive list of chemicals of concern identified in turf see https://www1.nyc.gov/assets/doh/downloads/pdf/eode/turf_report_05-08.pdf

EFFLUENT TREATMENT PLANT (ETP)

Safety Standards for ETP

- Indian standards for quality tolerances for a few industrial uses are noted below:

    - IS: 201 Water quality tolerances for the textile industry
    - IS: 2724 Water quality tolerances for the pulp and paper industry
    - IS: 3957 Water quality tolerances for ice manufacture
    - IS: 4251 Water quality tolerances for the processed food industry
    - IS: 4700 Water quality tolerances for the fermentation industry

- The following Indian Standards lay down tolerance limits for industrial effluents:

    - IS: 2296-1974 Extent of pollution of inland surface waters permitted by discharge of effluents
    - IS: 2490-1974 Tolerance limits for industrial effluents discharged into inland surface waters : Part I General
    - IS: 3306-1974 Tolerance limits for industrial effluents discharged into public sewers
    - IS: 3307-1977 Tolerance limits for industrial effluents discharged on land for irrigation purposes
    - IS: 7968-1976 Tolerance limits for industrial effluents discharged into marine coastal areas.

https://cpcb.nic.in/generalstandards.pdf

CH 42010: PROCESS PLANT OPERATION & SAFETY

LTP: 3-0-0, CRD: 3

Lecture 9

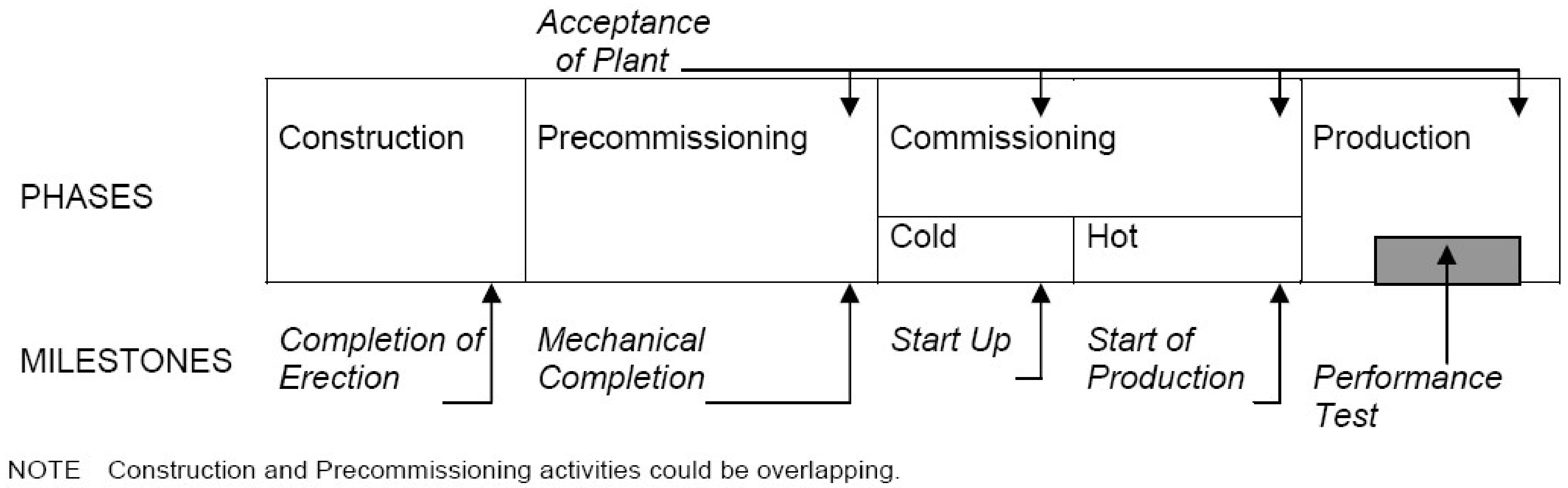
Safe Commissioning of Plants

PLANT COMMISSIONING

- **Plant commissioning** is a critical phase in the lifecycle of any industrial facility.
- It marks the transition from construction to operation, where systems and components are tested, inspected, and fine-tuned to ensure they function as intended.
- This crucial step sets the stage for a plant's long-term success and efficiency.

The Purpose of Plant Commissioning

- At its core, plant commissioning is all about making sure that a newly constructed or modified facility is ready for safe and reliable operation.
- It involves a series of systematic processes, meticulously designed to identify and rectify any issues that may arise during initial startup.



Definition of phases and milestones

Source: Google Images

PLANT COMMISSIONING

- **Key Phases of Plant Commissioning:**

  - **Pre-commissioning:** This phase involves a comprehensive review of engineering designs and documentation to verify that everything has been constructed according to specifications. It also includes a check on all equipment and systems to ensure they are installed correctly.

  - **Mechanical Completion:** At this stage, all systems, instruments, and components are installed, and the plant is deemed mechanically complete. It's the first tangible milestone, indicating that construction work is finished.

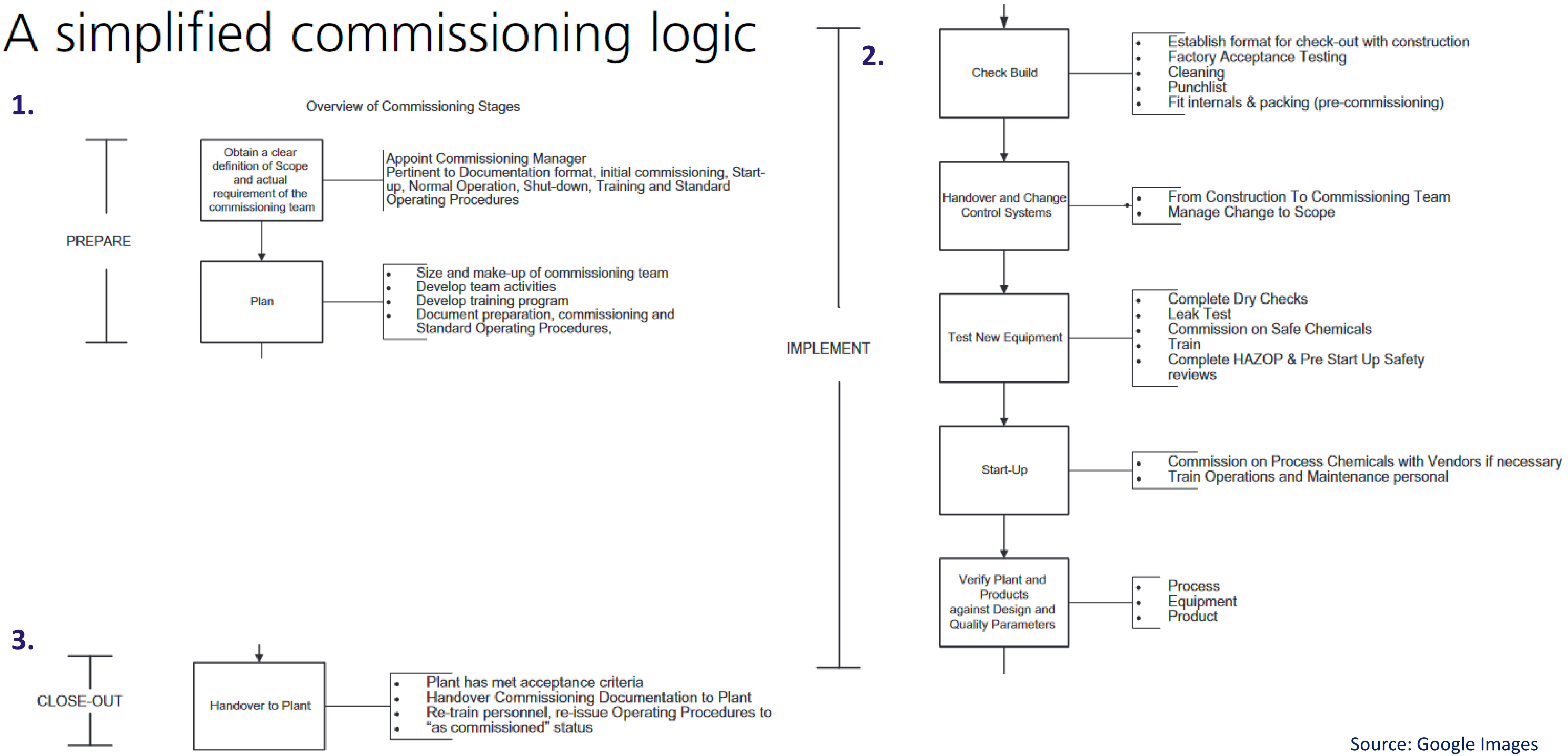
  - **Cold Commissioning:** In this phase, the plant is operated without any process fluids to ensure that all equipment operates as intended. This helps identify any mechanical issues before actual production begins.

  - **Hot Commissioning:** Here, the plant is operated with process fluids. This phase tests the functionality of all systems under actual operating conditions. It's a crucial step to ensure that the plant can handle real-world scenarios.

  - **Performance Testing:** Performance tests are conducted to verify that the plant meets its design specifications. This includes testing the capacity, efficiency, and reliability of various systems.

PLANT COMMISSIONING

A simplified commissioning logic



Source: Google Images

PLANT COMMISSIONING

Commissioning phase one—Prepare

Commissioning Terminology Capturing Lessons Learnt

The tasks on the following bulleted list are, at a minimum, those that must be considered during the preparation phase of process plant commissioning; they are in chronological order and consistent with the required flow of activities during this initial phase.

- Appointing the Commissioning manager
- Commissioning Scope
- Contracts
- Commissioning in highly regulated industries
- Budget Estimation
- Prioritized asset Systemization
- Support design
- Develop Initial Commissioning Plan, Philosophy and Strategy
- Commissioning Risk Management
- Appointment and composition of the Commissioning Team, Roles, responsibilities, organisation chart and interview considerations
- Suitable, Qualified and Experienced Personnel (SQEP), for commissioning
- Documentation and sign off requirements, required for commissioning preparation
- Devise assignment details, site and office requirements, consumables and procure commissioning chemicals
- Create commissioning documents and the System File
- Control, Instrument, Electrical commissioning document preparation
- Mechanical commissioning document preparation
- Develop Training Materials
- Develop Standard Operating Procedures
- Developing Commissioning Schedules and Contingency plans
- Determination of Commissioning Readiness and Commissioning Team Audits
- Devise Handover Procedure
- Devise commissioning tagging system
- Commissioning Terminology
- Capturing Lessons Learnt

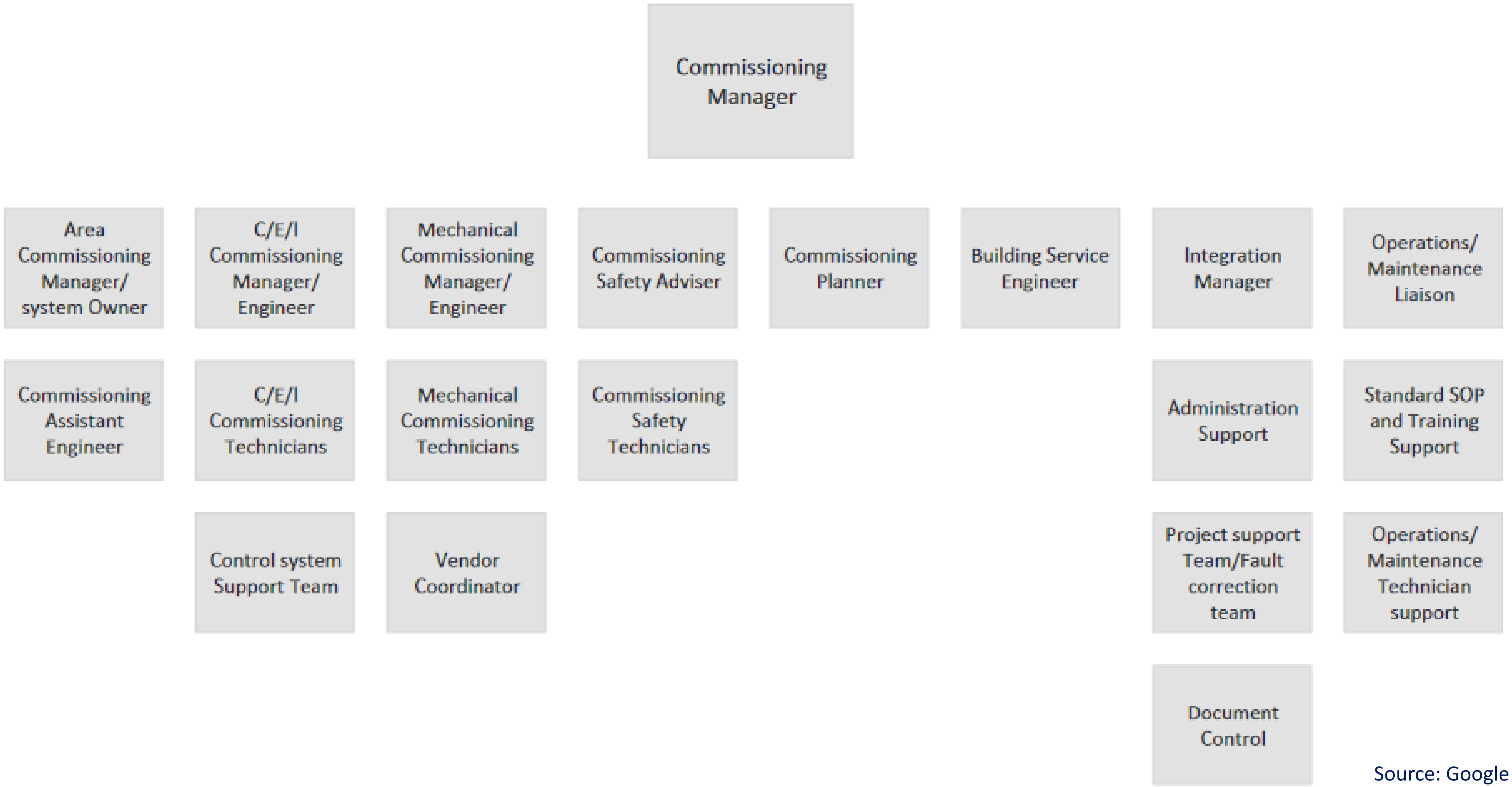
A sample table of contents for a commissioning system file

Table of Contents

1. System P&IDs
2. Decontamination procedure and isolation register
3. System cleaning procedures
4. Hazard Study and actions
5. Bill of Materials
6. Equipment Check Sheets, off and on site checks
7. System Punch lists
8. Action upon Alarm Sheet
9. Handover Certificate Construction/Maintenance to Commissioning
10. Project documentation check sheet prior to introduction of safe chemicals
11. Safe Chemical Commissioning authorization and Precommissioning Procedures
12. Leak Test Checklist and Procedures
13. Instrument Check Sheet
14. Motor Check Sheets
15. Interlock Check procedures
16. Emergency Shutdown System check procedures
17. DCS sequence test procedures
18. Relief Stream Check Sheets
19. Critical Insulation Checks
20. Critical Gasket Installation Checks
21. Lubrication Check Sheet
22. Preservation Check Sheet
23. PSSR, Plant Checkout prior to introduction of Hazardous Chemicals
24. Documentation Requirements for Ongoing Maintenance Group
25. Authority to Introduce Process Chemicals, check sheet, and Certificate
26. Commissioning Procedures
27. Standard Operating Procedures
28. Control System Lockdown
29. Commissioning to Plant Handover Certificate

Source: Google Images

PLANT COMMISSIONING

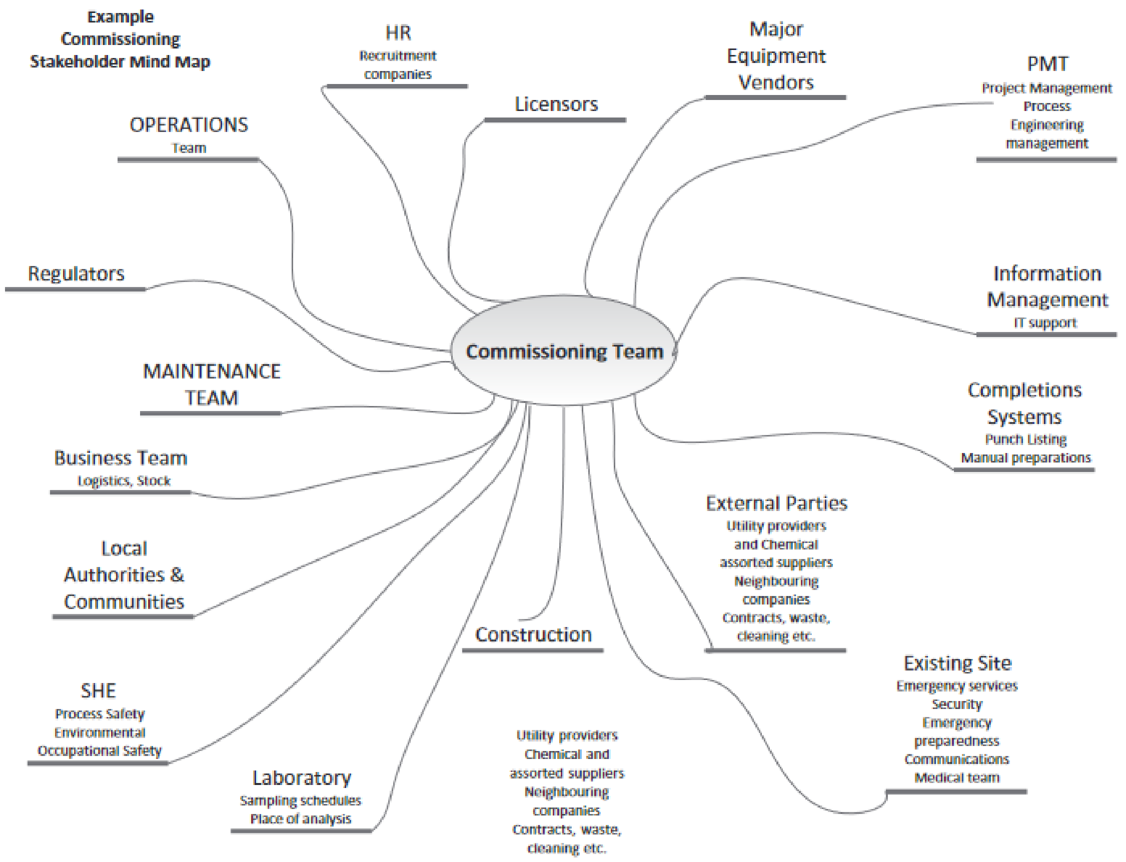


Source: Google Images

PLANT COMMISSIONING

Suitably Qualified and Experienced Personnel (SQEP) for Commissioning

		Phase			
		Preparation/Front End engineering	Construction	Pre-commissioning	Commissioning/Start-up
Role	Commissioning Manager	Formation and selection of the commissioning team	Manages schedule execution	Audits pre-commissioning checks for compliance	Oversees safe and compliant commissioning execution
		Develops commissioning element of contracts	Ensures commissioning paperwork is compliant	Manages team working hours	Manages progress tracking system
	Area Commissioning Manager/System Owner	Assists in systemization process	Monitors build and advises of inconsistencies, (Quality Reports)	Witnesses all testing, (loop test, cleanliness etc.)	Delivers commissioning of systems
		Development of procedures	Procures all system related spares and consumables	Manages Commissioning Hazard studies	Prepares for handover
	Mechanical Commissioning Engineer	Develops Procedures	Develops mechanical testing protocols with construction	Ensure mechanical testing is compliant, (pressure tests, alignments etc.)	Ensures robust breakdown rectification
		Assists team recruitment	Ensures a preservation system is operating	Manages mechanical team to ensure support	Manage mechanical fault rectification, design intent not met



Source: Google Images

PLANT COMMISSIONING

Key Documents

- Piping and Instrument Diagrams (P&ID)
- Process Flow Diagrams (PFD)
- Relevant Engineering Standards
- Vendor Installation, Operating, and Maintenance Manuals (IOM)
- Basis of Design Documents
- Functional Design Documents by discipline
- Safety Case Documents
- Insulation and Painting Standards
- Instrument Function-Testing Procedures
- Instrument Loop Drawings
- The Equipment List (Process, Electrical, Instrumentation, Civils, and Control)
- Pipeline Tables (or line lists)
- All Engineering Data Sheets, including Instrument Data Sheets
- Electrical Distribution Drawings
- Electrical One-Line Diagrams
- Functional Logic Diagrams
- User Requirement Specification (URS) for Control Systems
- Shutdown, Interlock, and Alarm Summaries and Matrices
- Detailed Equipment Manufacturers Drawings
- Detailed Vessel Internals Drawings
- Lubrication List and Schedule
- Material Safety Data Sheets (MSDS)
- Specific Procedures for Simulation Testing
- Control Narrative
- Cause and Effect Diagrams/Schedules
- Functional Design Document (FDS) for Control Systems
- Copy of all completed Hazard Studies
- Relevant Management of Change documents (MOC)
- Project-related procedures

Electrical, control, and instrumentation documents

- Main electrical installation, switchgear, transformers, Motor Control Centers (MCC), and power cables
- Lighting and small power
- Control systems (Distributed Control Systems—DCS, and or Programmable Logic Controllers—PLC), including off-line testing of control sequences
- Various instrument and electrical cabling including identification labels and tags
- Instrument calibration and instrument range consistency
- Existing equipment sanity check
- Loop test paperwork development, checking, and testing including Alarm tests
- Motor checking and testing
- Software Interlock and Emergency Shut-down testing, both “dry” and “wet”
- DCS/PLC sequence checking and testing, both “dry” and “wet”
- Emergency, hard-wired checking and testing, both “dry” and “wet”
- Protocol for change management through the commissioning effort
- Specialist vendor installation including Vendor package checks including “as installed” paperwork and drawings
- Air conditioning (HVAC) for various rooms and cabinets
- Training to the requirements of all project groups including fellow commissioning team members, operations personnel, and maintenance teams
- Final check-out and lockdown protocols for all control and electrical systems prior to start-up
- Attendance of and paperwork check of all C/E/I related Site Acceptance Tests (SAT)
- Earth leakage testing or protective conductor current testing
- Earthing or grounding packages

PLANT COMMISSIONING

DCS/PLC Fault Log: Please Describe in Detail all Issues with the Control System Here

Date	Time	What was the Request and or Last Action	What has the DCS Done/Problem	Comments/Resolution from Control Engineer	Signed Off
13/09/2005	10:00	Control sequence A1 called for ammonia pump to start	Ammonia pump did not start when required and no failure alarm was activated	Two problems now resolved Pump did not start due to bad wiring termination on the control block (new terminations for another system have been conducted in the panel today) Failure alarm had been silenced in software, now activated and authority to override the alarm raised to commissioning manager level	SW 13/09/2005
13/09/2005	10:30	Washer outlet valve asked to open by sequence	Outlet valve V21 did open but showing incorrect color (cyan when OPEN not green)	Action completed on system by software engineer	SW 13/09/2005

Date	Time	What was the Request and or Last Action	What has the DCS Done/Problem	Comments/Resolution from Control Engineer	Signed Off
13/09/2005	14:30	Feed sequence called for feed rate ramp down	Feed rate ramp down did not activate when sequence requested it. Controller put to local auto control and feed rate reduced	Issue still under investigation	
14/09/2005	07:50	Sequence requested ammonia addition	Ammonia totalizer did not quantify the ammonia addition	Software issue, resolved	SW 14/09/2005
14/09/2005	11:15	Operator attempted to start both grading trains simultaneously on different feed recipes	Unable to start both grading sides on different recipes	This is acceptable as the software recipe for the grading train does not allow for different recipes Operator given re-training on recipe selection	SW 14/09/2005
14/09/2005	14:20	Sequence called for vent fan to start	Vent fan started, but the fan did not change status from red (stopped) to green (run)	Software issue, resolved	SW 14/09/2005

PLANT COMMISSIONING

LOOP TEST SHEET

System: **Ammonia**	P&ID: **2005**	Project: **Washer Upgrade**
Loop Number: **LIC 101**	Description	**Ammonia Day Tank Level Control**

Alarm Settings	L = **20%**	LL = **10%**	H = **70%**	HH = **80%**
Actual alarm values	L = 21%	LL = 10%	H = 70%	HH = 80%
Alarms needing reset	Not required			

Post test statement			Signed FRI.
The loop is installed as shown on the P&ID and loop diagram	YES	NO	
The loop will perform as designed	YES	NO	

Field Labelling	OK – N/A	Instrument	
Motor push buttons	N/A	Air Isolation correct	OK
Motors	N/A	Accessible	OK
Control/On-Off Valves	OK	Location correct per Loop diagram and P&ID	YES
Instruments and cabel	OK	Input continuity check — See loop sheet	OK
Orifice Plates	N/A	Calibration	OK
Junction Box	OK	Range check with Control system	OK
Marshalling Cabinet	OK	Loop direct/reverse action	OK
DCS/PLC Panel	~~OK~~ N/A	Serial number correct	OK
Local Panels	OK	State change OK on control system	YES
General electrical wiring	N/A	**Control- On/Off valves**	
Other	N/A	Position 0% = mA = 0	–
MCC Room		Position 25% = mA = 8	–
Starters and push buttons	N/A	Position 50% = mA = 12	–
Lighting suitable	OK	Position 75% = mA = 16	–
Accessibility of terminations	OK	Position 100% = mA = 20	–
Fuse/breaker lock box available	N/A	Valve positioner operates correctly	N/A
Heating adequate	N/A	State change OK on control system	YES
Cooling adequate	N/A	Fail position checked — AIR ISOLATED & BLED	OK
Cabinet air fan acceptable?	N/A		
Labels on cabinet door correct	N/A	**Interlock tested**	N/A
Wires labeled	OK		
Cables labelled	OK	**Documentation**	
Other	N/A	Interlock data on loop and P&ID correct	N/A
DCS and or I/O Room		All loop diagram data correct	YES
DCS/PLC panels labelled	N/A	Master copy red lines for final mark up	OK
Termination panel access suitable	OK	Control room has copy until as built issued	TO BE ISSUED LATER
Termination drawing suitable	OK		
Fuse in place	NO	— LEFT OUT WILL BE INSERTED DURING COMMISSIONING	
Motor			
Megged/rating	N/A		
Rotation			
State change OK on control system			
Signed for Instrument/Control / Electrical	FW	Date	6/7/2004
Signed for process	C SMITH	Date	6/7/2004

Instrument Check Sheets

Project: Evaporator Upgrade 99 — System: 12 - EVAP

Loop No.	Description	In position in Field	Tested on DCS & Ready for Commissioning? Signed / Date
FE-1224	Flow Element on line 6" EVP 119064	Yes	Yes PK 6/7/99
FIT-1224	Flow indicating Transmitter on line 6" EVP 119064	Yes	Yes PK 6/7/99
FV-1224	Flow control valve on line 6" EVP 119064	Yes	Yes PK 6/7/99
FY-1224	Flow control valve Actuator	Yes	Yes WH 6/7/99
FE-1234	Flow Element on line 12" STM 119057	Yes	Yes WH 10/7/99
FIT-1234	Flow indicating Transmitter on line 12" STM 119057	Yes	Yes WH 7/7/99
FE-1235	Flow Element on line 3" STM 119035	Yes	Yes PK 7/7/99
FIT-1235	Flow indicating Transmitter on line 3" STM 119035		
PI-1297	Pressure Indicator on seal water line	Yes	Yes PK 7/7/99
PI-1298A	Pressure Indicator on LP Steam line	Yes	Yes PK 7/7/99
PT-1298	Pressure Transmitter on LP Steam line	Yes	Yes PK 8/7/99
PI-1212A	Pressure Indicator on Evaporator	Yes	Yes WH 8/7/99
PIT-1212	Pressure indicating Transmitter on Evaporator	Yes	Yes WH 6/7/99
LIT-1293	Level indicating Transmitter Condensate Tank	Yes	Yes PK 11/7/99
LIT-1393	Level indicating Transmitter on Evaporator	Yes	Yes PK 11/7/99
TE-1291	Temperature Element on Evaporator outlet duct	Yes	Yes WH 7/7/99
TIT-1291	Temperature indicating Transmitter on Evaporator outlet duct	Yes	Yes WH 8/7/99
TE-1295	Temperature Element on inlet Heat Exchanger duct	Yes	Yes PK 11/7/99
TIT-1295	Temperature indicating Transmitter on inlet Heat Exchanger duct	Yes	Yes PK 6/7/99
TV-1295	Temperature Control Valve on LP Steam line 12" STM 119057	Yes	Yes WH 6/7/99

PLANT COMMISSIONING

Mechanical documents prepared during commissioning

- Isometric drawing to P&ID sanity check
- Pipeline cleanliness checks and procedures
- Construction and installation checks
- Vessel and equipment checks (off- and on site)
- Mechanical documentation check
- Vendor and proprietary equipment checkout
- Lubrication
- Alignment checks
- Preservation checks
- Training
- Stores

Lubrication Schedules

Project: P12 Plant Expansion | P&ID's: 27, 28, 29 & 30

System : Process Scrubbing

Equipment Number	Description	Lubrication installed to correct specification	Date and sign
112-125	Scrubber Circulation Pump	Supplied by client	6-2-03
113-125	Cooling Tower Pump	Installed by Vendor	6-2-03
113-130	Cooling Tower Pump	Installed by Vendor	6-2-03
113-135	Cooling Tower Pump	Installed by Vendor	6-2-03
113-165	Sulphuric Acid addition Pump	Installed by Vendor	6-2-03
113-150	Sodium Hypochlorite Metering Pump	Installed by Vendor	6-2-03
113-155	Dispersant Metering Pump	Installed by Vendor	6-2-03
113-160	Surfactant Metering Pump	Installed by Vendor	6-2-03
113-165	Cooling Tower Fan	Installed by Vendor	6-2-03
113-170	Cooling Tower Fan	Installed by Vendor	6-2-03
112-135	Cooler Recirculation Pump	Supplied by client	6-2-03
112-140	Cooler Recirculation Pump	Supplied by client	6-2-03
114-155	Low Stage Compressor 1	Supplied by client	10-2-03
114-145	High Stage Compressor 1	Supplied by client	10-2-03
114-150	High Stage Compressor 2	Supplied by client	10-2-03
114-250	Low Stage Compressor 2	Supplied by client	10-2-03

System list of pipe work to be cleaned

Project: Utilities Upgrade Project | System: UTL - Utilities | Page 1 of 10

Author: M Killcross | P&IDs: 110107, 110108, 110109

PLEASE NOTE PRIOR TO THE CLEANING :

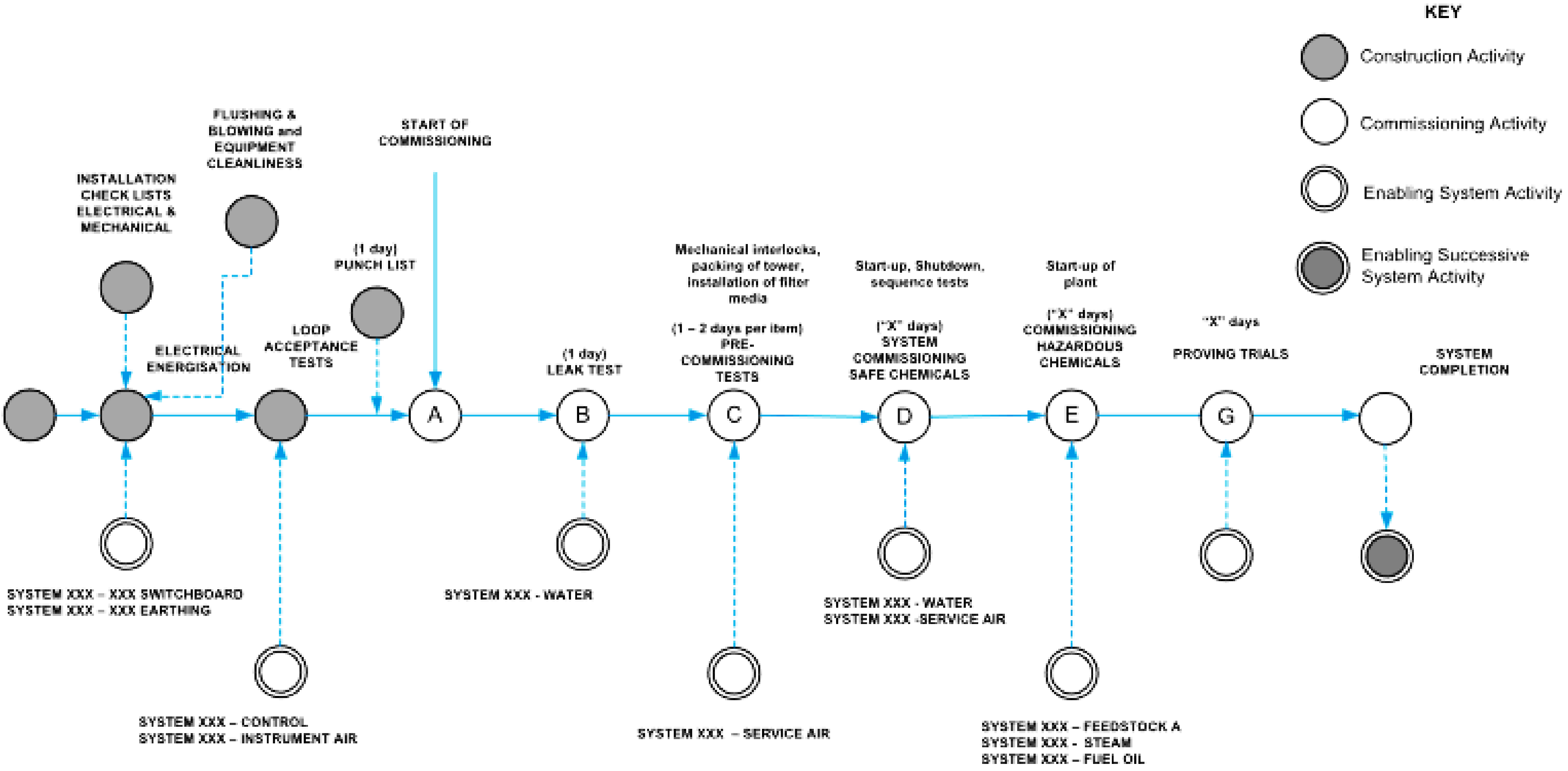
- All open pipe ends MUST be secured to avoid excessive movement.
- Always blow away from any vessels.
- Position target plates if required, to deflect debris to a safe location and or use as proof of cleanliness.
- All personnel not associated with the blow are to be removed from the area.
- All personnel involved with any high-pressure blow MUST wear ear protection.
- After the cleaning process, all open pipe ends MUST be closed to avoid recontamination. If pipework is left for a period, after the clean, then a visual inspection of the pipe needs to be done, prior to its commissioning.

NOTE:
No instrument should be connected to the Air supply until the pipe and associated instrument air tubing has been blown clear and proved clean.

PIPE	DESCRIPTION	TYPE OF CLEAN	SIGNED / DATE
Plant Air Supply System			
None given	Air inlet to Compressor A	Blow/visual	Final inspection GS 14-1-2007
None given	Air inlet to Compressor B	Blow/visual	Visual inspection GS 14-1-2007
PA-06091-2"	Compressor A to filter bank	Blow	air blow GS 14-1-2007
PA-06092-2"	Compressor B to filter bank	Blow	air blow GS 14-1-2007
PA-06095-3/4"	Filter bank by-pass to Receiver	Blow	air blow GS 14-1-2007
PA-0693-2"	Filter Banks to Receiver	Blow	air blow GS 15-1-2007
PA-06001-2"	Air Receiver Outlet	Blow	air blow GS 15-1-2007
Utility Water System			
UW-06016-3"	Utility Water Tank overflow	~~Flush~~ VISUAL	Visual inspection prior to filling GS 14-1
UW-06089-2"	Utility Water Tank vent	~~Flush~~ VISUAL	Visual inspection GS 14-1-2007
UW-06017-4"	Utility Water Pump inlet	water Flush	PB 16-1-2007
UW-06018-4"	Utility Water Pump inlet P-0608	" Flush	PB
UW-06019-4"	Utility Water Pump inlet P-0607	" Flush	PB
UW-06020-3"	Utility Water Pump outlet P-0608	" Flush	PB
UW-06021-3"	Utility Water Pump outlet P-0607	" Flush	PB
UW-06022-3"	Utility Water Pump common outlet	" Flush	PB
UW-06023-11/2"	Utility Water Pump spill back line to tank	" Flush	PB

PLANT COMMISSIONING

Commissioning test logic diagram



PLANT COMMISSIONING

Considerations for inclusion in a commissioning execution plan

General

- Confirm the commissioning team's scope
- Define design review attendance
- Definition of Fault Management system
- Definition of Temporary Commissioning Defeat System
- Completion of Documentation Matrix (what the commissioning group needs from the project)
- Completion of the Inspection and Test Plan
- Definition of the Factory Acceptance Test Plan
- Define process and protocol for Vessel Closure
- Accommodation arrangements and assignment strategy
- Definition of the schedule requirements (including table of norms)
- Draft Philosophy document
- Develop the tracking system
- Agree on the communication strategy
- Define radio requirements
- Define the team training matrix and requirements
- Confirm who will procure the first fill of chemicals
- Devise the commissioning Hazard study templates
- Determine any safety case testing protocols
- Define budget
- Define and share the commissioning systems in priority order
- Define any site integration protocols and policies
- Establish a safety store including PPE
- Define and establish commissioning tracking and Dashboard systems
- Develop a commissioning risk review process
- Create the lessons learned register
- Develop and issue the commissioning terminology document
- Develop a commissioning readiness protocol
- Define the policy for chemical introduction and communication
- Develop a commissioning audit program
- Consider and plan for laboratory requirements
- Develop the commissioning log system
- Plant Deep Clean strategy

Organization

- Develop team structure
- Draft a roles and responsibilities document including a stakeholder mind map
- Select and hire the commissioning team (may be via the Unit or facility)

Handover

- Define punch list protocol
- Define handover (various stages) protocol
- Draft Handover paperwork
- Define building and structure acceptance criteria

Suitably qualified and experienced personnel (SQEP)

- Define SQEP policy
- Define SQEP process
- Define who will be SQEP—commissioning team and which other disciplines

PLANT COMMISSIONING

Documentation

- Agree on the paperwork system and draft template System File
- Confirm the storage system and protocol for paperwork
- Define handover documentation, all phases of turnover
- Appoint owner and document commissioning library
- Assign matrix and managers for updating latest revision of project documents required by the commissioning team
- Define commissioning labels, signs, tags, and barrier policy (include procurement plan)

Mechanical

- Devise mechanical commissioning document requirements
- Draft mechanical documentation
- Confirm spares strategy
- Procure Spares
- Devise Store systems
- Define lubrication strategy
- Define preservation strategy
- Define statutory equipment provision
- Define relief stream installation policy
- Devise commissioning paperwork
- Devise Vendor contact and callout information
- Devise and then confirm Site Acceptance Test protocol

Instrumentation

- Define and confirm loop (functional) testing protocol
- Devise safety testing policy
- Confirm calibration strategy
- Devise commissioning paperwork
- Define panel and I/O room management protocols
- Define power-up protocols
- Devise Vendor contact and callout information
- Devise and then confirm Site Acceptance Test protocol

Control

- Define control and/or temporary control room arrangements (potentially with ongoing operations)
- Devise commissioning paperwork
- Define control panel and I/O room management protocols (in conjunction with instrumentation team)
- Define power-up protocols
- Devise Vendor contact and callout information
- Devise and then confirm Site Acceptance Test protocol
- Devise software correction policy and plan including software change management
- Devise plan for control hardware delivery and power-up

PLANT COMMISSIONING

Electrical

- Devise commissioning paperwork
- Define Motor Control center panel and room management protocols (in conjunction with instrumentation/electrical team)
- Define power-up protocols
- Devise Vendor contact and callout information
- Devise and then confirm Site Acceptance Test protocol

Facility level CEP

- Define consumables and spares requirements
- Develop strategy documents per facility
- Develop an isolation matrix
- Develop pre-commissioning/construction completion check sheets, then manage to completion
- Develop a commissioning system file and all procedures
- Manage a commissioning hazard study process
- Develop waste management plans per facility including water management, conservation, and testing.
- Develop facility process flow diagrams
- Develop an analytical schedule for the facility

Document/procedure type	% Status	Docs completed	Docs to go	Docs in progress	Docs not started
Check sheet	97.7	786	58	50	8
Pre-commissioning	86.7	163	66	59	7
Commissioning procedures	95.0	109	20	20	0

Test Document Reference	Title	Description	% Complete	Date Complete	Witnessed by
25-C01	Check sheet - Flushing or blowing	*Line here should reflect number of flushes to conduct*	25 (average of total tests)		
25-C02	Check sheet - Loop Tests	*Line here should reflect number of loops to test*	50 (average of total tests)		
25-C03	Check sheet - Motor Rotations	*Line here should reflect number of motors to turn*	100 (average of total tests)	26.10.18	MK
25-C04	Check sheet - Lubrication	*Line here should reflect number of individual equipment to lubricate*	25 (average of total tests)		
25-C05	Check sheet - Primary Punch list				
25-C06	Check sheet - Punch list				
25-Pre001	Pre-commissioning - Tanker Loading Interlock	Tank 1 mechanical interlock test	100	1.11.18	MK
25-Pre002	Pre-commissioning – Feed Pump system non-return valves	Internal check of Feed Pump non-return valve internals			
25-Com001	Commissioning – Cooling System	Procedure to charge cooling system with glycol			
25-Com002	Commissioning – Feed Pump	Procedure to commission the Feed Pump recycle to the Tanker Loading Tank			

PLANT COMMISSIONING

STEP	TITLE	DESCRIPTION	Duration
1	Inspections	Attendance at factory acceptance tests and inspections	1-2 days (in-country) 3-4 days continental 7-14 days intercontinental
2	Training	Training periods for plant and maintenance operatives (classroom training)	1-4 days
3	Check construction	Periods to check construction progress and quality (per system)	3-6 weeks
4	Cleanliness	Test and clean pipe and equipment	4 hours per test
5	Punch list	Per system	0.5 to 2 days
6	Loop testing	Final test from field device to control system	3 hours per loop
7	Motor checks	Correct rotation and start/stop function	2 hours per motor
8	Leak testing	Full system tests	1 – 3 days
9	Dry sequence checks	Per sequence within a system	< 5 steps = 5 hrs <15 steps = 10 hrs >15 sequences = 30 hrs Vendor package = 50 - 150 hrs
10	Water commissioning	Per system (includes initial loop tuning)	1-3 days
11	Water sequence checks	Per sequence within a system	See step 9
12	Commissioning Hazard Study	Hazard Studies 4 and 5	1 day per study
13	Initial Chemical commissioning	Per system	1-3 days
14	Initial Plant Operation	For the plant	3-6 weeks Project dependant
15	Ramp to design rate	For the Plant	3 weeks
16	On the job Training	For all shift and day teams	6 months
17	Consolidation period	Updating of documentation with best operational knowledge	3 months

Number	Area	Topic	Readiness Required	Proof of Readiness	Actions	Readiness indicator
12	Plant	Equipment & Spares	All temporary commissioning equipment and consumables procured, stored and ready to use.	Visual check of items in store Specific lists identified per discrete procedures	**Complete commissioning equipment and procurement exercise.** **Please include a review of potential spares commissioning may need.** **(MH/JR)**	
13		Hazard Studies	HSE 5 complete and all outstanding actions understood and documented?	HSE 5 review minutes	**HSE 5 to be organised, dates provisionally in the diary** **(Engineering)**	
14	Procedures	Waste	Waste management plan established and operational?	Commissioning specific waste management plan For in place		

Example table of commissioning readiness

It incorporates a **Red, Amber, and Green (RAG) rating system** of identifying status per action.

- Red — Cannot move to actual commissioning execution
- Amber — Can move into commissioning but actions still outstanding must be closed ASAP
- Green — Actions all closed, line item ready to move to the next stage gate

PLANT COMMISSIONING

Summary

- **Step 1 – Planning**

  - There are several activities that take place off-site prior to the commissioning team mobilizing to site during the design and construction phases of a project.
  - The commissioning team is defined during the design/construction phase, to determine the core members of the commissioning team as well as the support resources required from elsewhere on the project.
  - **Members** of the commissioning team are the electrical/mechanical/automation key discipline leads, consultant subject matter experts (SME), contractors, vendor reps, and owner's reps.
  - Commissioning documentation is defined and prepared in advance of the commissioning phase. This includes the test plans and test procedures to be executed during commissioning, and checklists required, as well as drawings.
  - It is critical that the construction team deliver an accurate set of red-line drawings to the commissioning team in order that the correct installed configuration of equipment in the field is accurately documented.
  - The construction and commissioning teams will perform a walkthrough to identify any contract deviations or deficiencies, and list all items on a **deficiency tracking list**.

PLANT COMMISSIONING

Summary

- **Step 1 – Planning**

  - Deficiencies are then classified as **Type-A, Type-B, or Type-C**, identifying when each must be complete.
    - **Type-A** is a showstopper, and must be complete before proceeding to the next activity.
    - **Type-B** does not need to be addressed immediately and does not impact subsequent activities, but must be rectified prior to handover to the owner.
    - **Type-C** deficiencies are minor defects and are agreed by the owner to be rectified after handover to the owner.

  - Safety management systems need to be established prior to commencing any commissioning activities. The energy isolation procedures, also known as **Lock Out Tag Out (LOTO)** process, needs to be established and points of contact identified as responsible for the process.

  - **Hazard identification and risk assessment (HIRA)** specific to the commissioning phase. Ensuring all staff are trained and aware of emergency shutdown procedures. Use of **personal protective equipment (PPE)**, and **isolation protocols** to protect personnel during testing. **Pre-startup safety reviews (PSSR)** to verify that **safety systems (alarms, shutdowns, etc.)** are functional.

PLANT COMMISSIONING

Summary

Lock Out Tag Out (LOTO)

- Lockout tagout is a protection system against unintentional exposure to hazardous energy from equipment and machinery.
- A lockout device, such as a padlock, secures the energy isolating device while a tagout device (i.e. a tag) warns employees not to use the equipment.
- By locking and tagging the machinery or equipment and isolating it from energy sources, LOTO reduces the risks of accidents and injuries.
- It also reduces the need for costly repairs or replacements and extends the lifespan of equipment.

PLANT COMMISSIONING

Summary

- **Step 2 – Factory Acceptance Testing (FAT)**

  - During the design and procurement phase of the project, a critical step prior to equipment delivery to site is FAT.
  - FAT verifies that the equipment is designed per specification before leaving the factory, where any issues discovered are much easier and cheaper to fix, rather than delaying testing until equipment is installed on-site.
  - FAT can consist of hardware verification such as dielectric testing of major equipment, or panel wiring of any control cabinets.
  - FAT can also consist of integrated testing, where automation or protection/control logic is loaded into the hardware and verified for correct design and functionality.
  - Integrated FAT is the most thorough verification, and reduces schedule risk, in order that any errors are discovered prior to site testing.
  - Thorough FAT will always make on-site commissioning go much better if it is known in advance that the hardware delivered to site already works with the logic design.

PLANT COMMISSIONING
Summary

- **Step 3 – Mechanical Completion**

  - Mechanical completion occurs at the end of construction once equipment is installed.
  - There is often a formal handover process with forms required to be signed confirming that equipment is installed per the design.
  - The construction team and commissioning team will perform a walkthrough to inspect the installation and confirm there are no deficiencies. Any deficiencies are noted and added to the deficiency list, with associated classification.
  - Confirmation of basic installation is confirmed, such as valves installed in the correct direction, and all wiring point-to-point checks and megger tests (insulation resistance (IR) testing) have been completed.
  - P&ID drawings are traced in the field to ensure all air/oil/water auxiliaries are available. The construction team will verify that drawings are marked up (red-green drawings) to indicate the as-installed condition, and mechanical completion is the point in time when the red-line drawings are delivered to the commissioning team.
  - At each mechanical completion, a deficiency list is generated and any Type-A deficiencies rectified before moving into the pre-commissioning phase.

PLANT COMMISSIONING

Summary

COMMISSIONING PROCESS

- **Step 4 – On-Site Commissioning**

  - Upon mechanical completion of each portion of the work, and deficiencies agreed to, pre-commissioning activities can then commence.
  - For mechanical systems, pre-commissioning activities consist of cleaning and flushing of pipes, pressure testing, and leak testing.
  - Any rotating equipment such as a pump are bump tested, which means rotating for the first time on site to verify current draw, pressure, and flow rates. There may be an initial run-in period of motors and pumps to verify vibration and heating/cooling as well as confirm no infant mortality issues.
  - For electrical systems, pre-commissioning activities consist of panel energization, communication checks, loop checks (internal and external), and verification of any wiring to the central control room if required.
  - Pre-commissioning checklists are completed for each piece of equipment, and may be witnessed by consultant SME to verify tasks are being completed.
  - As each equipment pre-commissioning is complete, new deficiencies are added to the deficiency list (existing from FAT or mechanical completion walkthrough), categorized, and all Type-A deficiencies rectified.

PLANT COMMISSIONING

Summary

COMMISSIONING PROCESS

- **Step 4 – On-Site Commissioning**

  - Once all mechanical and electrical components are complete, system commissioning can begin, where all the electrical and mechanical equipment works together as a system for the first time.
  - Auxiliary systems are brought online followed by major apparatus, and interfaces are verified for all equipment. It is now that all the systems are available and ready for startup of the plant processes.
  - Commissioning checklists are completed and witnessed by consultant SMEs.
  - Similar to previous stages, the deficiency list is updated with any newly discovered deficiencies, and all Type-A deficiencies are rectified prior to moving to the next steps.

PLANT COMMISSIONING

Summary

COMMISSIONING PROCESS

- **Step 5 – Process/System Startup**

  - At this stage, the plant process can now be started. This could consist of a power transmission system, biological nutrient removal system, or any other industrial plant manufacturing or specialized system.
  - Mechanical process are slowly started, and piping is configured for the initial operating scenarios. Flows are started and monitored to ensure correct operation.
  - Electrical interfaces are verified and power is slowly ramped up to operating levels.
  - Automation is executed and fault scenarios are tested and verified.
  - The equipment undergoes analysis at each stage to ensure the plant process is operating as specified.
  - The Consultant SME and Owner reps are present to verify correct operation of the plant process. The plant is not up and running and functioning as a system – ready for fine-tuning to optimize the process.

PLANT COMMISSIONING

Summary

COMMISSIONING PROCESS

- **Step 6 & 7 – Performance Verification & Operational Readiness**

  - Any fine tuning of the plant process operation is conducted by the commissioning team with consultation with the consultant SME and with the owner.
  - Once tuned, the contract may require a trial period where the plant process is expected to operate uninterrupted for a period of time. This could be 24 hours or 30 days for example, dependent on the contract requirements. Should the system operation be interrupted, the trial period starts over.
  - Once the trial period is completed successfully, the **Provisional Acceptance Certificate (PAC)** is issued to the contractor. The contract may also specify a performance guarantee period, where the plant processes are expected to meet certain contractual criteria over a period of time.
  - The performance guarantee period may have commercial impacts dependent on the performance achieved.
  - Once the performance guarantee period is complete and commercial impacts have been determined, the **Final Acceptance Certificate (FAC)** is issued to the contractor.