Chemical Plant Design

Introduction

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

Objectives of Chemical Plant Design

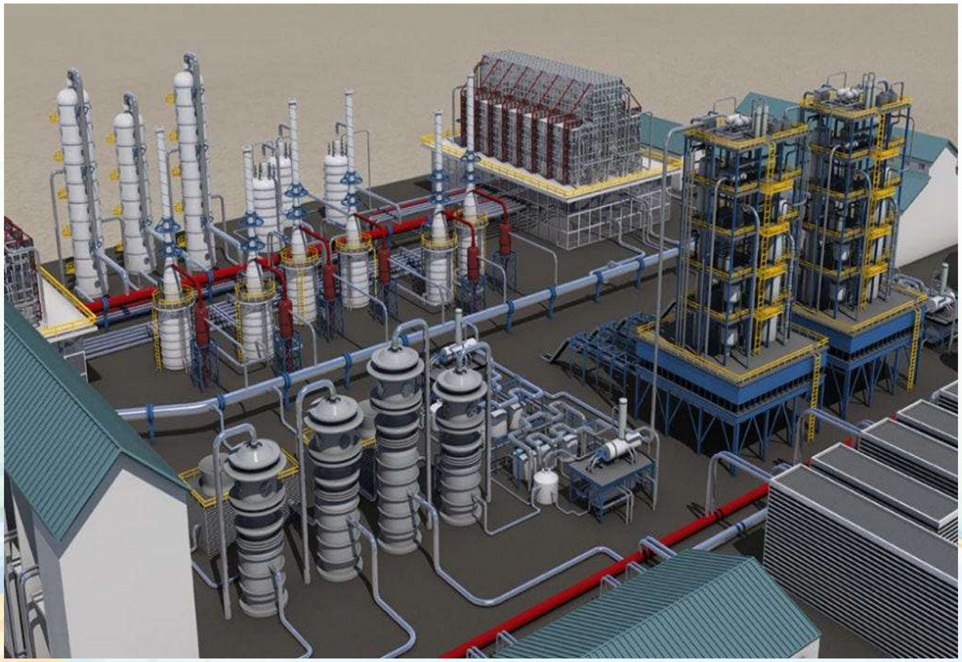
- This course will cover two major aspects of chemical engineering:
  1. Design of a chemical engineering plant and
  2. Economic analysis of a chemical engineering process.
- The course objectives and learning outcomes are as follows:
  - To introduce the basic concepts in plant design, engineering economics, and safety features as applied to chemical engineering processes and operations.
  - By the end of the course, the students will know the essentials of how to conceptualize and develop a chemical engineering process and how to perform a complete economic analysis of the chemical engineering plant.
  - Appreciate the importance of safety in design and operation.

Plant Design and Chemical Engineering

- One important purpose of chemical engineering is to create new material wealth that are useful for mankind and society, by chemical transformation or biological transformation or physical separation of materials.
- As a chemical engineer, you must:
  - Develop, Design, Construct
  - Operate industrial plants in which materials will undergo a change to form such useful products that are useful for society and mankind in an economic and safe manner
  - Also, it must be profitable.
- For that, you must choose the best pieces of equipment, the best interconnections among these equipment.
- You must arrive at best operating conditions and overall the operation must be safe, reliable and profitable
- Now, how do you do this will be the subject for this course

What is Plant Design

- Plant design is defined as the creative activity where we generate ideas, and then translate them into interconnected equipment and processes for producing the new materials or for significantly upgrading the value of existing materials in a safe, reliable, and economic way.



Classes of Chemical Products

- The chemical engineering plants produce a broad range of products.
- An approximate classification of these products can be:

1) Commodity of bulk chemicals:

- Commodity or bulk chemicals are produced in large volumes.
- The important considerations here is chemical composition, purity, and price.
- If we define the value addition as difference of selling price and cost price of products and raw materials, respectively .
- Selling price of products minus cost price of raw materials is the value addition.
- So, the value addition for commodity or bulk chemicals is generally low.
- Examples: PE, Acetone, H_2SO_4, N_2, O_2

2) Fine Chemicals:

- Fine chemicals are produced in smaller volumes compared to commodity or bulk chemicals.
- Important considerations here also are chemical composition, purity and price.
- Examples: Chloropropylene oxide, dimethyl formamide (solvent for resins, polymers)
- Value addition that is selling price of products minus cost price of raw materials are relatively higher compared to bulk chemicals.

3) Specialty or Functional chemicals:

- These we produce in low volumes, but they are very high value products.
- Here important consideration is primarily their effect, not chemical composition.
- We buy these products for their effect.
- For example, pharmaceuticals, pesticides, perfumes, flavorings.
- The value addition is very high compared to other two category products.

Commodity or bulk chemicals	Fine chemicals or Specialty chemicals
• High capital cost is required because we produce them at large scale. • We keep the operating cost as low as possible. • There will be designated equipment for specific process steps. • Generally, these are produced as continuous operations.	• They are low volume products • They require low capital cost, low operating cost. • They are manufactured in multipurpose equipment or plant. So the same plant or equipment can be used to produce various types of fine or specialty chemicals. • They are generally produced in batch plants.

Process Design

- A process is any operation or group of operations which allows something to be accomplished.
- Chemical process design is the selection and sequencing of units for desired physical , chemical or biochemical transformation of materials.
- This involves specification of equipment and materials of construction, specification of operating conditions, utilities and auxiliaries as well as principal instrumentation.
- Process design can be the design of new facilities, or it can be the modification of expansion of existing facilities.
- The design starts at a conceptual level and ultimately ends in the form of fabrication and construction plans

Process Synthesis

- It is the step in design where the chemical engineer selects the unit operations, the component parts, their interconnections and operational conditions to create an optimized process flowsheet or flow diagram that meets given objectives and constraints.
- These objectives and constraints are mostly related to economics of the process. But we must also consider the environmental impact and safety issues
- By flowsheet or flow diagram, we mean a diagrammatic representation of the chemical engineering process.

Mathematical Programming

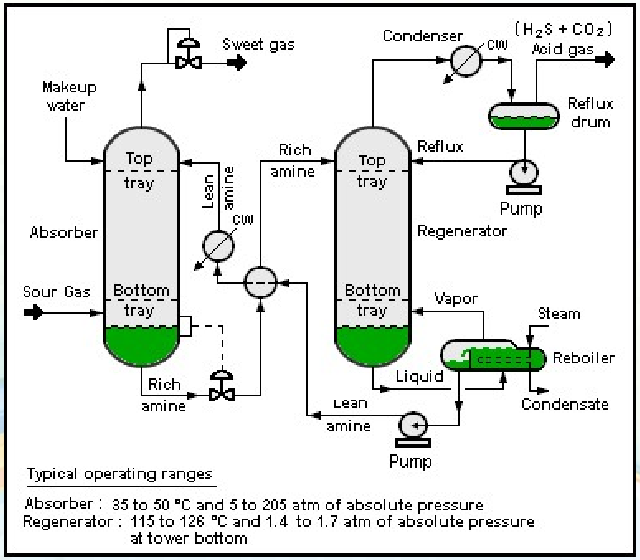
- Recently the use of mathematical programming techniques such as nonlinear programming (NLP), mixed integer nonlinear programming (MINLP) for generating optimal flowsheets has received considerable attention.
- So the optimal flowsheets are not only arrived at by using your experience, you can also take help of mathematical techniques to arrive at most optimum process flowsheet.
- This has been possible with advent of computer software that are very powerful in problems.
- These methods move beyond simple simulation to answer the question:

"What is the best possible process structure and operating conditions?"

Process Simulation

- Simulation is the mathematical model of the process to predict process behavior.
- To perform a simulation, you need the process flowsheet for the process.
- Simulations are of two types:
  - Steady state simulation: mass balance information, energy balance information are the target for performing steady state simulation.
  - Dynamic simulation: we are interested in knowing how the process variables vary with time.
- Dynamic simulation will give you more detailed information. The time varying information of the process variables can be obtained by performing a dynamic simulations

- Once a flowsheet and the process inputs and operating conditions have been specified, then this can be posed as a mathematical formulation, as a mathematical problem and can be simulated to obtain the steady state information as well as the dynamic information.
- So by simulations we will
  - Get information about process variables
  - Equipment sizing
  - Evaluation of design performance
  - Control and monitoring
- For control and monitoring, dynamic simulation will be very useful.



As a Chemical Engineer

- Use plant design to include all engineering aspects involved in the development of either a new, modified or expanded industrial plant.
- Will make economic evaluation of new processes,
- Design or specify individual pieces of equipment and their interconnections.
- Select plant location,
- Develop a plant layout for coordination of overall operations
- Perform safety analysis

Why Chemical Plant Design

- Why should chemical engineers design a plant?
- Why should he/she produce a new product or expand or modernize the existing manufacturing facilities for a product?
  - Generally, the reply will all come from economic considerations. The return on investment must be favorable.
  - But of course, sometimes strict regulations on safety and environmental issues can compel a manufacturing plant to update their design.
  - The design engineer must do the following preliminary plant design analysis:
    - ✓ Process design,
    - ✓ Selection of process equipment and materials
    - ✓ Preliminary plant layout and location considerations to estimate labor, building and land cost.
    - ✓ Manufacturing cost analysis.

- *Based on these above analysis, if a decision is taken to design a plant, then only a detailed commercial plant design is taken up.*
- *So before we undertake a detailed commercial plant design a preliminary design must be done to understand that commercial plant design may be a success*

Use of Dsign in Industries

- New Design:

  The design is used for new design of producing materials such as petrochemicals, industrial gases, pharmaceuticals, polymeric materials, biochemical, foods, agrochemicals etc.

- Known plant but different locations or different capacity.:
  - Suppose, there is a manufacturing plant in one city.
  - Now, the management wants to set up another plant in a different city.
  - It may be required to redesign the process, particularly if that plant is of different capacity.
  - We are going to set up the same plant, but it is a different capacity.

Use of Dsign in Industries

- Plant Improvement/Retrofitting:
  - Debottlenecking of plant,
  - Increase plant capacity,
  - Increase plant efficiency,
  - Decrease cost,
  - Pollution minimization, increase standards of safety.

Chemical Plant Design Requirements

- It requires basic engineering principles:

  Thermodynamics, Reaction engineering, Transport processes, Knowledge of process equipment design, Computer technology etc.

- Practical understanding of the limits imposed by industrial conditions.

  It's the difference between what should work on paper and what can work in the messy, constrained reality of a factory, a mine, a construction site, or a power plant.

- We also need wisdom, creativity and lot of imagination.

  "Imagination is more important than knowledge" Albert Einstein

Major Goals of Engineering design

1. Eliminate non-optimal solution with as little effort as possible.

   Since design activity is often iterative, because the design problems are mostly under defined and there is no true solution or there is no true optimal solution. There are always more than one solutions. But there may be better solution when you have many alternatives.

2. Produce a financial estimate.

3. Understand the risk that the process poses to society and the environment

4. Produce the documentation required to build the process.

- *This usually leads to an iterative design methodology that begins with a low level of detail in the solutions and progressively creates more and more detail of fewer possible solutions until an optimal one is found.*
- *The key decision-making tools at each stage will be*
  - *Economic viability*
  - *Safety*
  - *Environmental concerns*

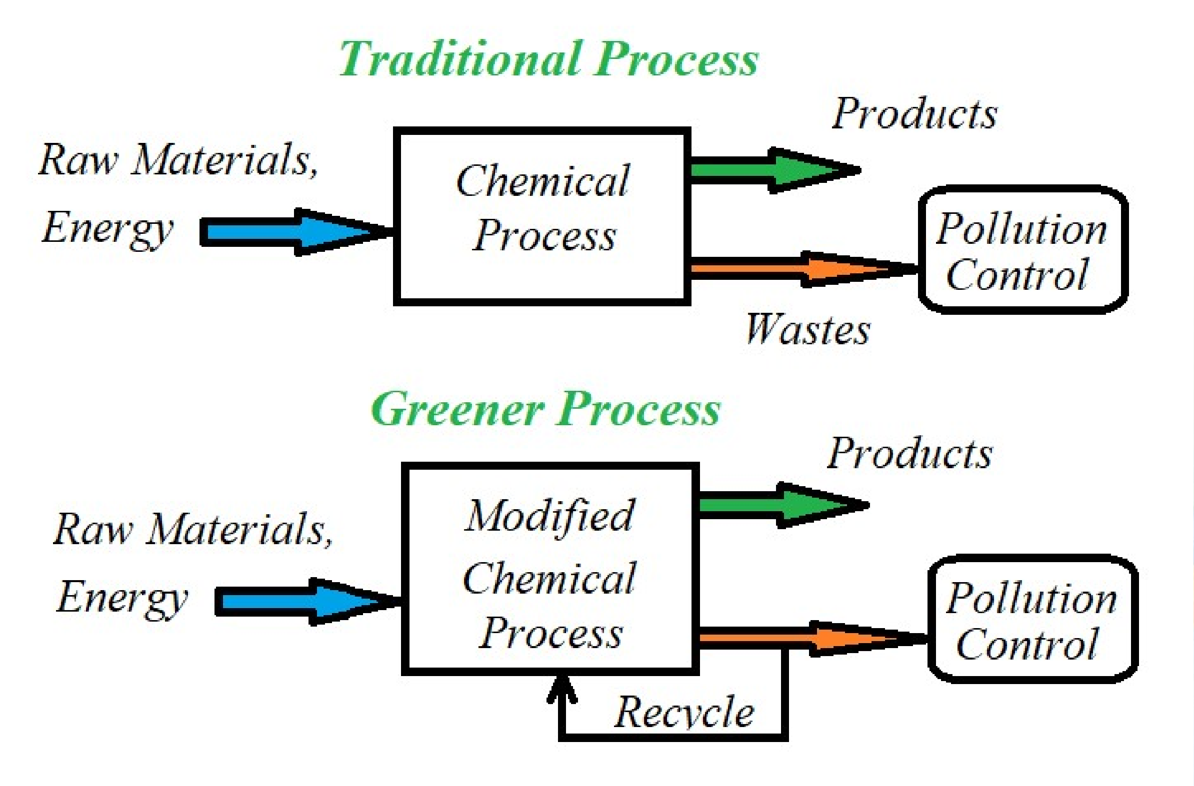
Design Constrains

- Considering various ways of achieving the design objectives. While doing so, the designer will be constrained by many factors.
- These constraints will narrow down the number of possible designs.
- Some constraints are very rigid constraints, they are fixed in variable and the designers have no control over these constraints.
- Physical laws, government regulations, codes and standards are external constrains that you cannot relax these constraints.
- There are some constraints which less rigid. They are flexible to some extent. The designer has some control over these constraints.
- Choice of process, choice of operating conditions, selection of materials and equipment are internal constrains

Aim for Sustainable Design

- Design new chemical processes as part of sustainable industrial activity that retains the capacity of ecosystems to support both life and industrial activity into the future.
- The needs of the present must be made without compromising the needs of future generations.
- It is important that we meet the needs for present, but at the same time, it is also equally important that we must not compromise the needs for future generations.
- Raw materials: so that waste is minimize waste, Preserve for future.
- Energy: preserve fossil fuels, Prevent the buildup of carbon dioxide and also you must preserve water for future

Aim for Sustainable Design



- Economic
- Safe
- Low environmental impact
- Low waste
- Efficient operation
- Correct raw materials
- Efficient use of energy
- Efficient use of water

Codes and Standards for Design

- Plant design should take account of the relevant codes and standards.
- Conformity between projects can be achieved if standard designs are used whenever practicable.
- Modern engineering codes and standards cover a wide range of areas including:
  - Materials, properties and compositions.
  - Testing procedures for example for performance, compositions and quality.
  - Preferred sizes, for example, for tubes, plates, and standard sections.
  - Design methods, inspection and fabrication.
  - Codes for practice for plant operation and safety.

Design Factors (Design Margins)

- Uncertainties in design arise from uncertainties in the design data that you use and also from the approximations that you make during design calculations.
- Include a degree of over design which you call design factor or design margin or safety factor. This is required so that the design meets product specifications and operate safely as initially conceived.

- A factor of around 4 on the tensile strength is normally used in general structural design to allow uncertainty in material properties, fabrications etc
- The process stream average flows calculated from material balances are typically increased by a design factor of 10% and it gives some flexibility in process operations

Chemical Plant Design

Typical Deign Steps

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tlines

- Typical design steps for a chemical plant
- Factors affecting selection of a process
- Levels of design accuracy

A Design Problem

- Design problems are generally under-defined and thus many solutions are possible.
- There is no absolutely correct solution to a design problem.
- There may be a better solution because many alternatives are possible.
- Since many alternatives are possible, you will be able to find better solutions.
- But it is hard to get the best solution.

A Design Problem

Design Problem:

Store a cryogenic liquid so that you can minimize seasonal variation in temperature

Design Solution 1:

Design an underground tank and let us bury the storage tank say one meter below the ground

Design Solution 2:

Design above-ground tank for easy maintenance and you use extra heavy insulation

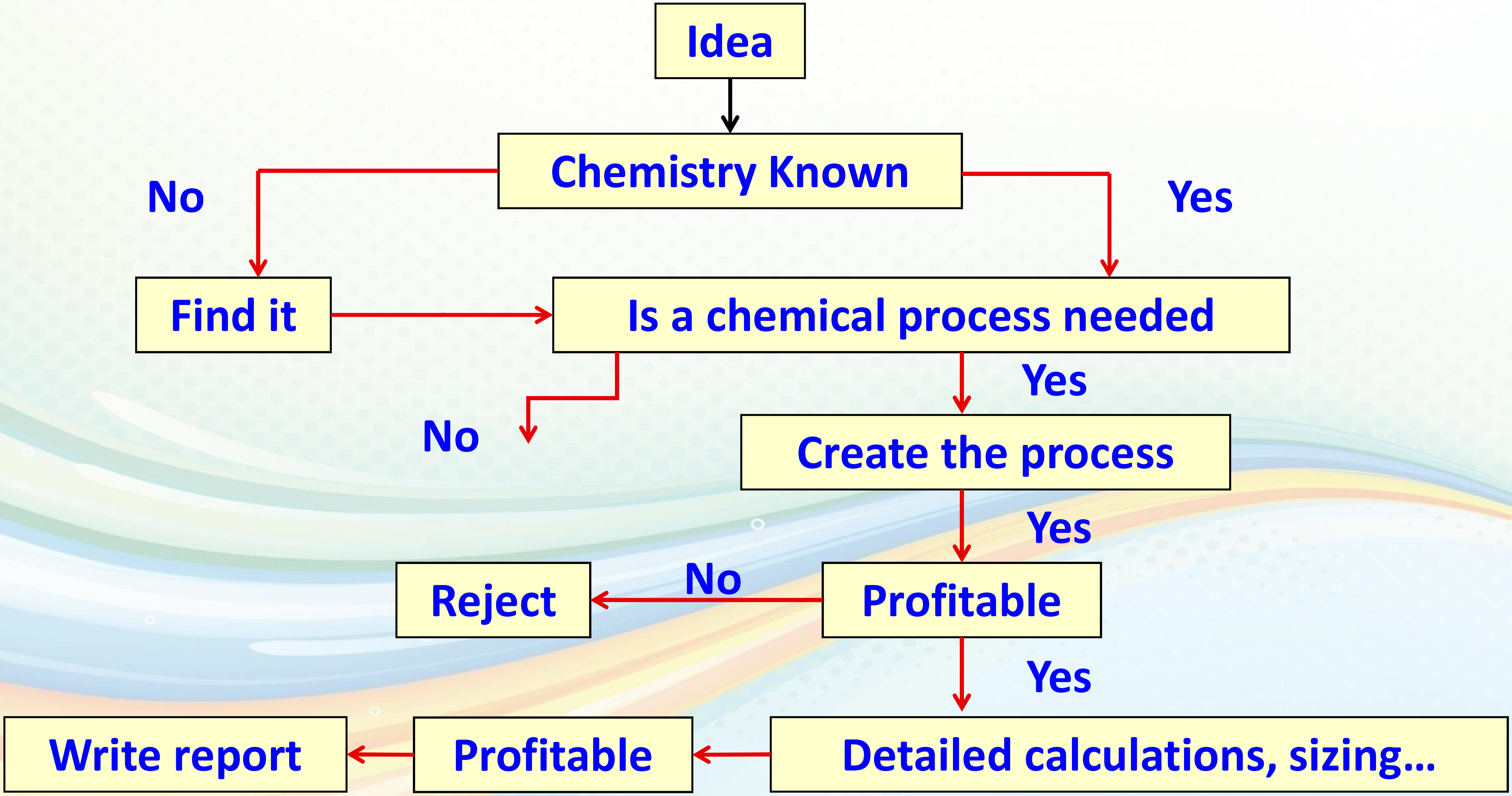
How to Choose from Alternatives?

- If appropriate material of construction is chosen and executed properly either design can function satisfactorily
- How will you choose one from possible several alternatives?
- Several factors will contribute
  - ✓ Economics
  - ✓ Environmental and safety concerns
  - ✓ Location
  - ✓ Political climate
  - ✓ Aesthetics
  - ✓ etc.

Process Design Development

1. Conception and definition
2. Flow sheet development
3. Design of equipment
4. Economic analysis
5. Optimization
6. Reporting or documentation

Design Steps



General Design Steps

1. Process Research
   - Preliminary market survey
   - Lab scale experiments
   - Production of research samples
   - Form design team
2. If positive results
   - Phase development
   - Pilot plant
   - Commercial development plant
   - Inspection of the product, customer satisfaction

This leads to data, information needed for full scale plant

General Design Steps

3. If negative: discard the idea or look for alternative(s)
4. Complete market analysis
5. Capital cost
6. Profit analysis
7. Fund
8. Final Process Design

Working out design details: control, services, plant layout, pricing….

Typical Design Steps of a Chemical Process

1. First recognize a societal or engineering need.
   - ✓ Make a market analysis for a new product.
2. Create one or more potential solutions to meet this need.
   - ✓ Make a literature survey and patent search.
   - ✓ Identify the preliminary data required.
3. Undertake preliminary process synthesis of these solutions.
   - ✓ Determine reaction, separations, their operating conditions.
   - ✓ Recognize environmental safety and health concerns.

4. Assess profitability of preliminary process or processes.
    - ✓ If negative, reject process and create new alternatives.

5. Refine required design data.
    - ✓ Establish property data with appropriate software.
    - ✓ If necessary, verify experimentally the key unknowns in the process.

6. Prepare detailed engineering design.
    - ✓ Develop base case if economic comparison is required.
    - ✓ Prepare process flow sheet
    - ✓ Integrate and optimize process
    - ✓ Check process controllability
    - ✓ Size equipment
    - ✓ Estimate capital cost

7. Reassess the economic viability of process.
   - ✓ If negative, either you modify the process or investigate other process alternatives.

8. Review the process again for environmental safety and health effects.
   - ✓ Remember your design must satisfy these conditions.

9. Provide a written process design report.

10. Complete the final engineering design, which involves:
    - ✓ Determination of equipment layout and specification,
    - ✓ Development of piping and instrumentation diagram,
    - ✓ Preparing bits for the equipment or the process plant.

1. Procure equipment if work is done in-house.
2. Provide assistance if requested in the construction phase.
3. Assist with startup and trial runs. Trial runs are also known a

   shakedown runs.
4. Finally, initiate production.
   - ✓ All the design steps may not be necessary for a simple design projects
   - ✓ Commercially unproven technology may require additional desig steps.
   - ✓ The order of design steps may be altered.

Sequence of steps in developing a project

Process identification	Design Fixed
Laboratory scale process research	Detailed economic evaluation
Bench scale investigations	Engineering flow scheme
Preliminary economic evaluation	Basic design
Process development	Detailed construction plan
Mass and energy balance	Detail design
Detailed process design	Procurement
Site selection	Construction
Refined economic evaluation	Startup

Design Steps: Source of New Ideas

Research:

Most large chemical companies invest a portion of their total gross sal
on some type of research.

A product will be sold if it is better in quality or low cost than
competitive product.

Basic research and applied research

Basic research consists of exploratory studies driven by scientific curiosit

No obvious commercial value to the discoveries .

End use of such research is not specified.

Example: How did the universe begin?

What are the electrons composed of?

Design Steps: Source of New Ideas

Applied research has a definite goal and it seeks to solve a practic problem.

Example: Improve energy efficiency in the plant,

Develop a new approach to manufacture a product.

Other sources: The idea may also come from:

- ✓ Sales department as the result of customer request or to meet competing product.
- ✓ Anyone in plant operation.
- ✓ Engineering department may originate new process.
- ✓ Accidental discoveries:

Teflon by Roy J. Plunkett at the DuPont in 1938.

Penicillin by Sir Alexander Fleming in 1928.

Process Design Development: Literature Review

- Thorough literature search is required for profitable design: latest data flowsheet, equipment, good simulation models etc
- Useful sources for design engineer:

Scientific indexes	Handbook	Magazine
Chemical abstracts Engineering index Applied Science and Technology Index	• Perry's Chemical Engineers' Handbook • Handbook of Chemistry and Physics • Unit Operations Handbook, • Chemical Processing Handbook	• Chemical Marke Reporter • Chemical Engineering Wo

Software:

Process simulators such as Aspen Plus, HYSIS, CHEMCAD

Databank: DECHEMA

Process Design Development: Patent Search

- A patent is the right granted to an inventor by the government th permits the inventor to exclude other form making, selling or using t invention for a specified period of time.
- After a patent expires, the invention becomes public property and can used freely by anyone
- Design engineers must be aware of patents to avoid duplication of desig protected by these patents
- Expired patents can provide helpful information in the design of seco generation processes.
- Patents are available in major libraries.
- Patents are also available on the internet now

Process Creation

- In this step, to create a new process or to significantly improve an existi process, we find one or more practical solutions to the design problem
- This step is most creative: Involves the synthesis of various configuratio of processing operations that will convert raw materials to products in reliable, safe and economical manner with a high yield and minimu undesirable byproducts or waste.

Traditional method:

Use past experience, use of heuristics or rule of thumb.

Modern methods:

Treat synthesis problem as a quantitative problem and u mathematical programming, computer simulations

Batch Vs. Continuous

ontinuous operations: Preferred for large scale production, production o ommodity chemicals, petroleum products, plastics, paper, solvents etc.

ontinuous plants typically run for 90 to 95% of 365 days, which is 876 ours

dvantages: Improved process control, More uniform product quality educed labor cost, More economical for large volumes, Less fouling etc

atch and semi batch Operations: Preferred, when production rates ar mall. Manufacture of specialty chemicals, pharmaceuticals, bio-chemicals o hen the product demand is intermittent.

dvantages: Flexibility, Multi-product batch plant, Improved control i emi-batch operations, Easy scale-up from laboratory and maintenance

Major drawback for batch operations is batch-to-batch variability

Process Selection

How to select a process from several alternatives?

What will be the basis for comparison?

1- Technical factors

a) Process flexibility

b) Mode of operation

- ✓ Batch continuous
- ✓ Semi-batch or semi-continuous

c) Special controls involved

d) Commercially yields

e) Technical difficulties involved

f) Energy requirements

g) Special auxiliaries required

h) Possibility of future developments

i) Health and safety hazards involved

Process Selection

2- Raw materials	3- Waste products and byproducts
✓ Present and future availability ✓ Processing required ✓ Storage requirements	✓ Amount produced ✓ Value ✓ Potential markets and uses ✓ Manner of discard ✓ Environmental aspects

Process Selection

4- Equipment	5- Plant location
✓ Availability ✓ Materials of construction ✓ Initial cost ✓ Maintenance and installation cost ✓ Replacement requirements ✓ Special designs	✓ Amount of land required ✓ Transportation facilities ✓ Proximity to markets and raw material sources ✓ Availability of service and power facilities ✓ Availability of labor ✓ Climate ✓ Legal restriction and taxes

Process Selection

6- Cost	7- Time factor
✓ Raw materials	✓ Project completion deadline
✓ Energy	✓ Process development required
✓ Depreciation	✓ Market timelines
✓ Other fixed charges	✓ Value of money
✓ Processing and overhead	
✓ Special labor requirements	
✓ Real estate	
✓ Patent rights	
✓ Environmental controls	

Process Selection

8- Process considerations
✓ Technology availability
✓ Raw materials common with other processes
✓ Consistency of product within company
✓ General company objectives

Types of Process Design: Levels of Design Accuracy

- One out of 15 proposed new processes is ever actually constructed.
- Avoid loss of money on one hand and we must not lose business opportunit on the other hand.
- Engineering evaluation is an essential activity at all stages of any promisin project from the conception of the new process to final stage of construction.
- Depending on the accuracy and detail required, design engineers generall classify process designs in the following five levels:
  1. Order of magnitude designs
  2. Study or factor designs
  3. Preliminary designs
  4. Detailed estimate designs
  5. Final process designs

Order of magnitude designs and study or factored designs

- No actual process design is involved.
- Used only to determine very quickly the level of investment that may be required for a proposed design project.
- Identify raw materials, identify products and utilities to try to come up very quickly with the level of investment that is required

Preliminary designs

- Used as a basis for determining whether further work should be done on a proposed process. Approximate process methods and approximate cost estimates are prepared.
- Design details and the time spent on calculations are kept to a minimum

Detailed estimate designs

- This is done if preliminary design shows good prospect
- Here the cost and profit potential of the process is determined
- Exact specifications are not given for the equipment
- Piping and layout work is minimized

Final process design

- Undertaken if detailed estimate design indicates commercial succes
- Complete specifications are presented for all components of the plant
- Accurate cost analysis based on quoted prices is done
- Profit analysis and plant-wide controllability studies are done
- Includes detail documentation for immediate construction of project

Chemical Plant Design

Flow Diagrams

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Chemical Engineering Department
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Outlines

Flow Diagram: Classification

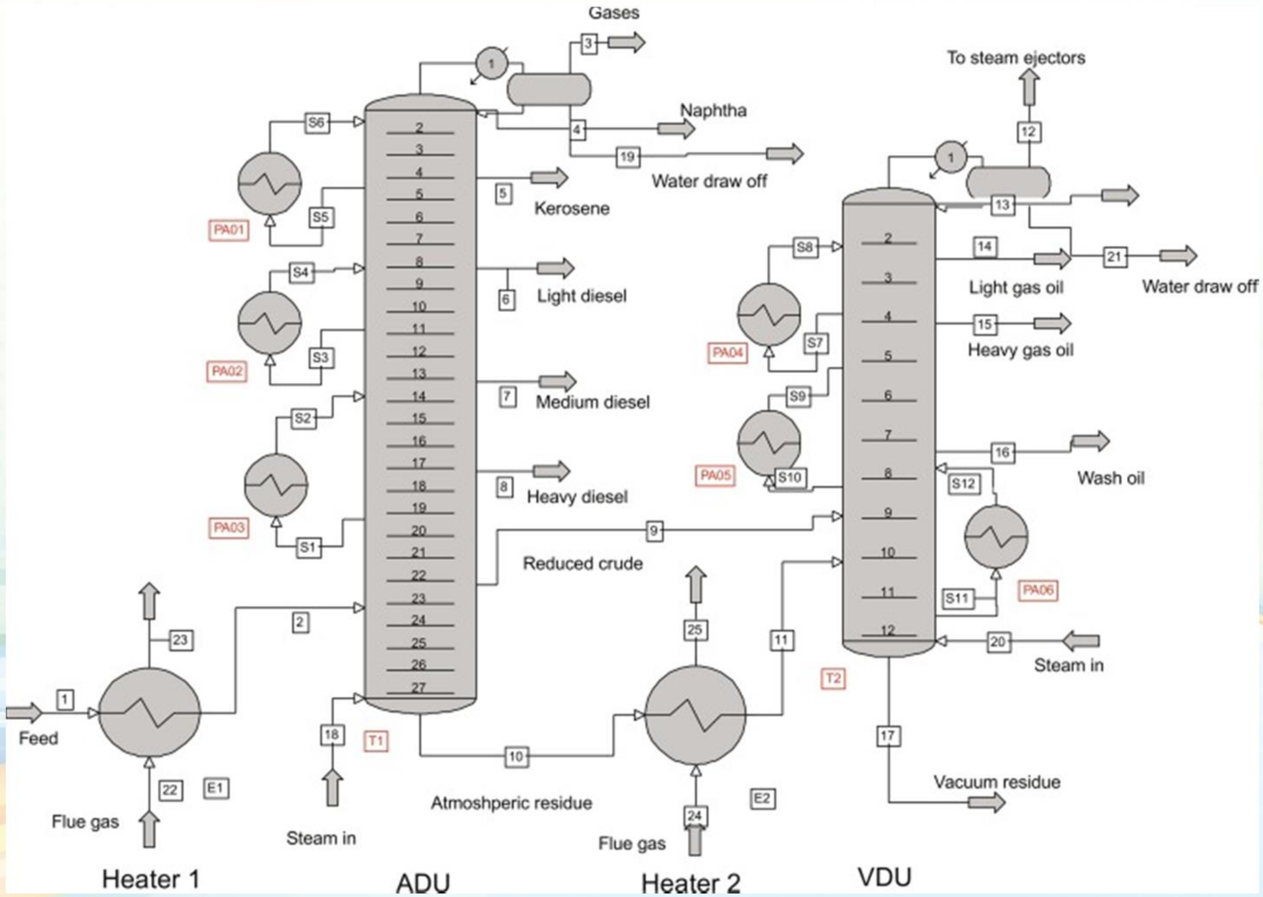
Block Flow Diagram

Process Flow Diagram

General Characteristics of Process Flow Diagram

Chemical Engineering Flow Diagram

- A picture is worth a thousand words
- Flow diagrams offer a very effective way of communicating information about a process.



Chemical Engineering Flow Diagrams

- A flow diagram is a diagrammatic model of the process that simplifies the visualization or manufacturing procedure.
- Flow diagrams show:
  - ✓ The sequence of the equipment and unit operations involved in the process
  - ✓ The energy flow
  - ✓ The stream connections, stream flow rates and compositions
  - ✓ The operating conditions
  - ✓ All necessary auxiliary equipment such as pumps, compressors, turbines, etc.

Chemical Engineering Flow Diagrams

- Flow diagrams can be classified into three general categories:

1- Qualitative flow diagrams:

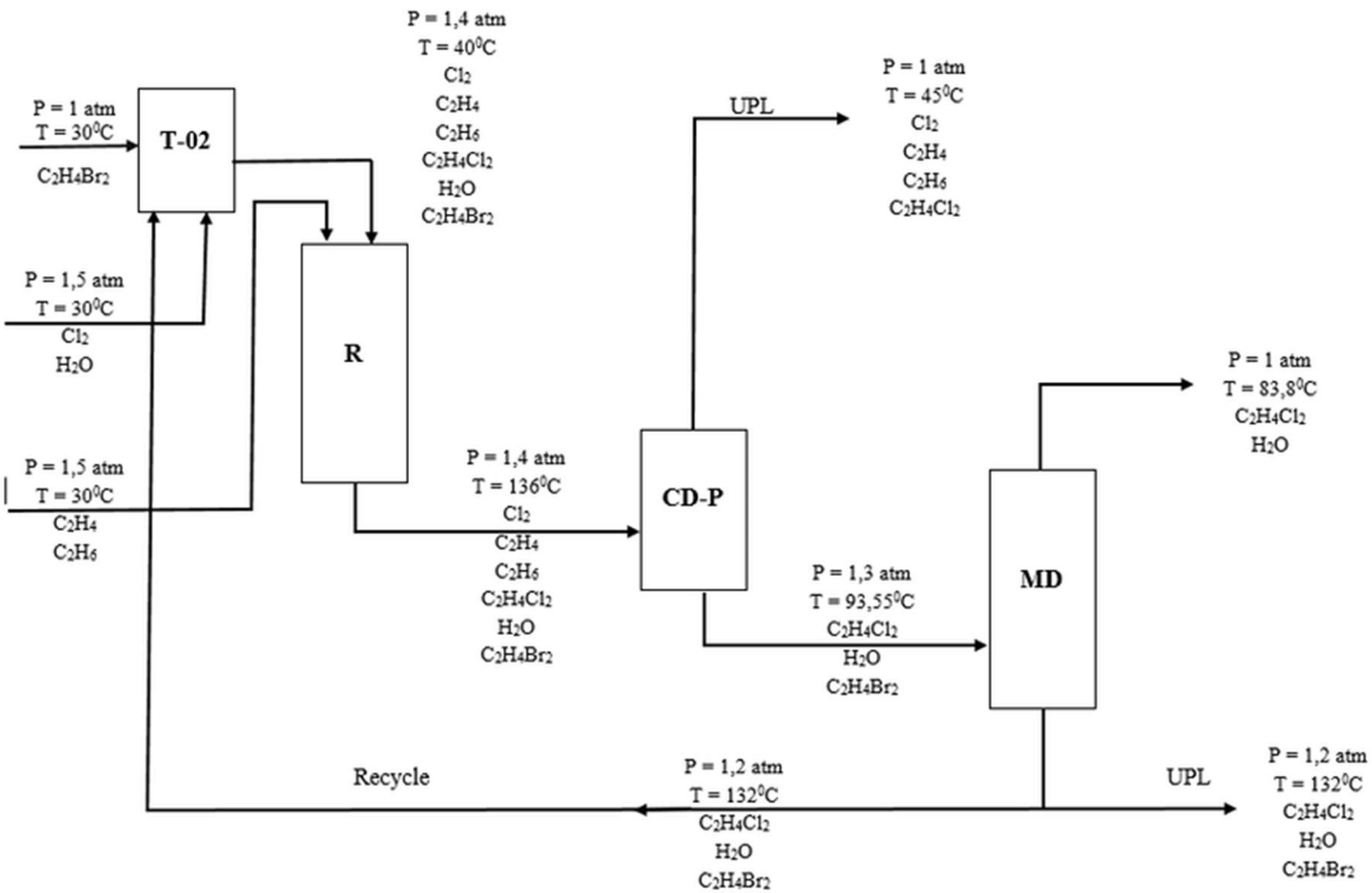
A qualitative flow diagram indicates the flow of materials, unit operations involved, equipment necessary and special information on operating temperatures and pressures.

2- Quantitative flow diagrams:

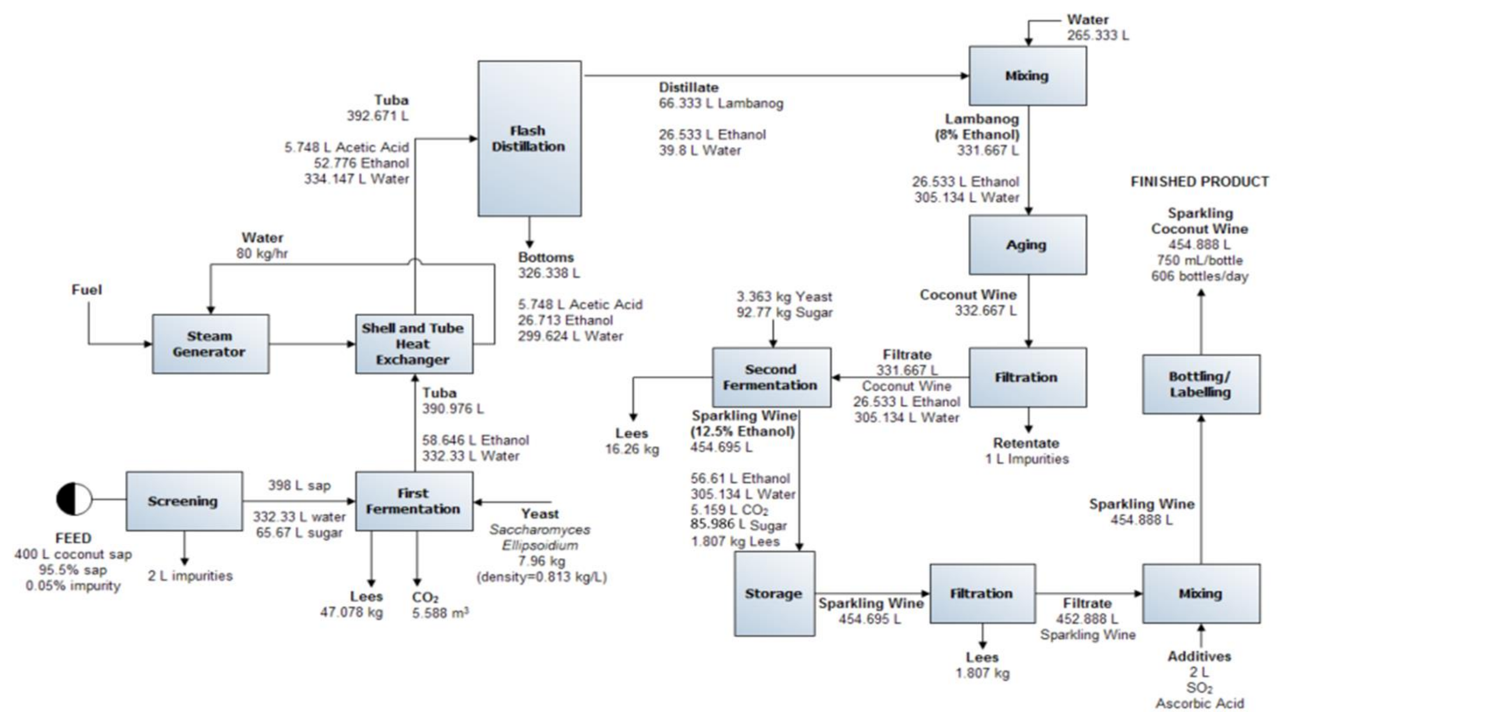
A quantitative flow diagram shows the quantities or materials required for the process operations.

3- Combined detail:

The combined-detail type of diagram shows the qualitative flow pattern and also equipment specification, quantitative data and sample calculations


P = 1 atm
T = 30⁰C
C2H4Br2
T-02
P = 1,4 atm
T = 40⁰C
Cl2
C2H4
C2H6
C2H4Cl2
H2O
C2H4Br2
P = 1,5 atm
T = 30⁰C
Cl2
H2O
R
P = 1,5 atm
T = 30⁰C
C2H4
C2H6
P = 1,4 atm
T = 136⁰C
Cl2
C2H4
C2H6
C2H4Cl2
H2O
C2H4Br2
CD-P
UPL
P = 1 atm
T = 45⁰C
Cl2
C2H4
C2H6
C2H4Cl2
P = 1,3 atm
T = 93,55⁰C
C2H4Cl2
H2O
C2H4Br2
MD
P = 1 atm
T = 83,8⁰C
C2H4Cl2
H2O
Recycle
P = 1,2 atm
T = 132⁰C
C2H4Cl2
H2O
C2H4Br2
UPL
P = 1,2 atm
T = 132⁰C
C2H4Cl2
H2O
C2H4Br2

QUANTITATIVE PROCESS FLOW DIAGRAM



SRD CORPORATION – LUCBAN SPARKLING WINE PLANT

		DESIGN LAYOUT BY	DRAWING DESCRIPTION	PROJECT DURATION
San Roque Distillery UST 5CHE-C GROUP SAN ROQUE DISTILLERY, CORP. LUCBAN SPARKLING WINE PLANT	Production of *Cocus Nucifera* Sparkling Wine through Charmat Process	LIEZYL DELA CRUZ PROCESS DESIGN ENGINEER SAN ROQUE DISTILLERY, CORP.	PROPOSED QUANTITATIVE PROCESS FLOW DIAGRAM FOR LUCBAN SPARKLING WINE PLANT	JANUARY - APRIL 2016

Flow Diagrams: Classification

- Depending on the level of details required several types of flow diagrams are used
- Simplified representation: Block flow diagram (BFD)
- Pictorial representation: Equipment are drawn in a stylized pictorial form.

➢ Process flow diagram (contain much detail information than BFD)

➢ Piping and instrumentation diagram (P&ID) (important for control system design and safety (HAZOP) analysis.

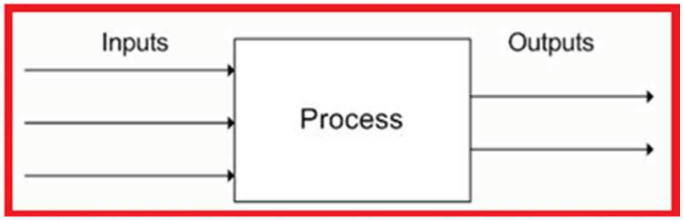
➢ P&ID diagram also known as engineering flow sheet or mechanical flow sheet.

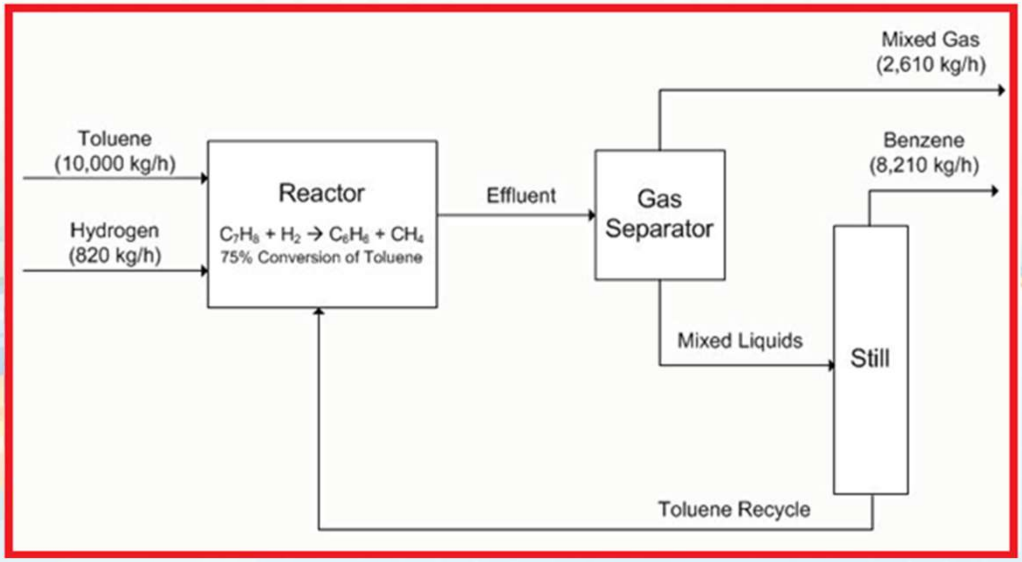
Block Flow Diagram (BFD)

- *A block flow diagram represents the main processing sections in terms of functional blocks.*
- *It is the simplest form of block diagrams.*
- *In block flow diagram each block can represent a single piece of equipment or a complete stage in the process.*
- *The stream flow rates, compositions and the conditions at each stage can be shown*
- *Useful for representing simple processes.*
- *Limited use for complex processes.*

Block Flow Diagrams: Classification

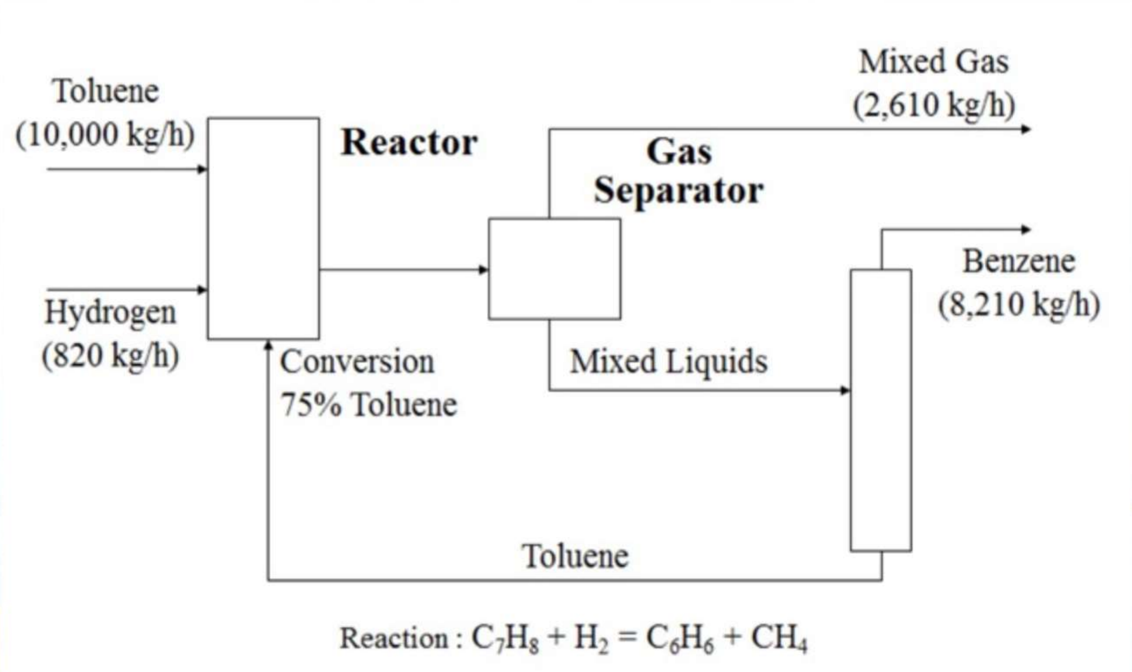
- *The Block Flow Diagram can take one of the following two forms:*
- *Block Flow Process Diagram: BFD drawn for a single process*
- *Block Flow Process Diagram: BFD drawn for a complete plant involving many processes*





Block Flow Process Diagram: Example

- *Toluene and hydrogen react to produce benzene and methane.*
- *The noncondensable gases are separated and discharged.*
- *The Benzene product and the unreacted Toluene are separated by distillation.*
- *Toluene is recycled back to the reactor and the Benzene removed in the product stream.*



Block Flow Plant Diagram

- *A block flow plant diagram is used for a complete chemical complex. A plant may involve several processes and each block in this diagram represents a complete chemical process.*
- *We may also draw a block flow process diagram for each block in the block flow plant diagram.*
- *Block flow plant diagram gives a complete picture of what this plant does and how all the different processes interact.*
- *To keep the diagram simple and easily readable only limited information is provided for each process unit*

Process Flow Diagram (PFD)/Process Flow-Sheet

- The PFD contains large amount of information and engineering data necessary for the design of a chemical process
- One company's PFD may contain slightly different information than the process flow diagram for the same process from another company.
- The symbols used may also vary to some extent from organization to organization.
- The process flow diagram is the authorized process blueprint. This document is used to define, construct, and operate the chemical process.

Process Flow Diagram (PFD): Characteristics

- All the major pieces of equipment in the process will be represented on the process flow diagram along with a description of the equipment.
- Each piece of equipment will be assigned a unique equipment number and a descriptive name.
- All process flow streams are shown and identified by a number. A complete mass and energy balance of the process showing the composition, flow rate and temperature of every stream is usually included in a process flow diagram
- All utility streams supplied to major equipment are shown.

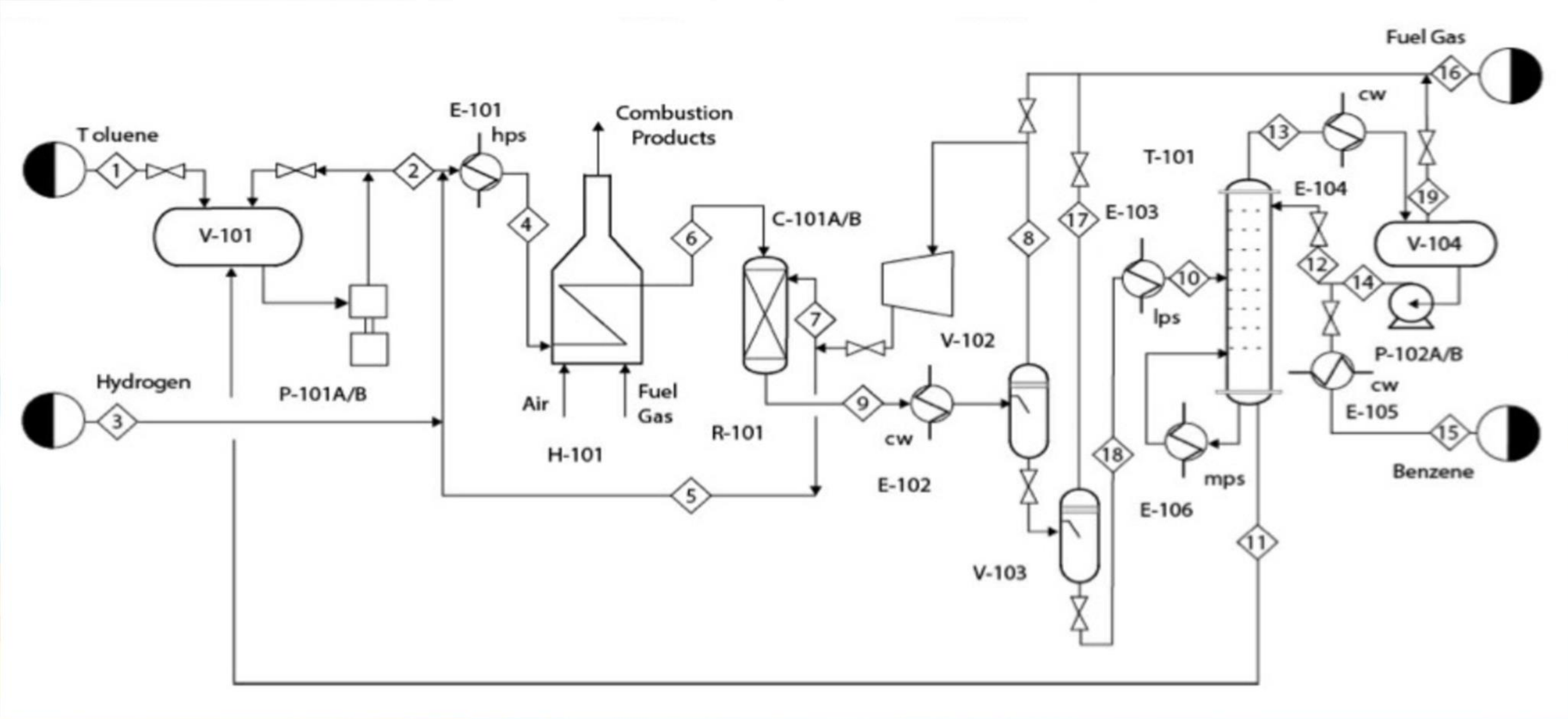
- A process flow diagram also indicates the location of every control valve. Basic control loops illustrating the control strategy used to operate the process during normal operations will be shown. It may be noted here that specification of control valve helps in sizing of pumps and compressors.
- A process flow diagram usually does not include minor piping details such as size, specification, rating etc.
- It also does not include instrument details and minor bypass lines.
- Process flow diagrams are usually drawn on large sheets of papers. The sizes may be typically 2 feet by 3 feet and several connected sheets may be required for a complex process.
- By convention, flow is from left to right, with raw materials entering from the left and finished products or waste streams leaving at the right.

Process Flow Diagram (PFD): Characteristics

- *The flow sheet is oriented horizontally with the equipment elevations in the diagram resembling those in the real process.*
- *Process streams are designated with heavy lines.*
- *If streams cross without mixing, that means two streams cross without mixing then one line is broken to allow space at the crossing point.*
- *Arrowheads are drawn at each line angle to indicate flow direction*

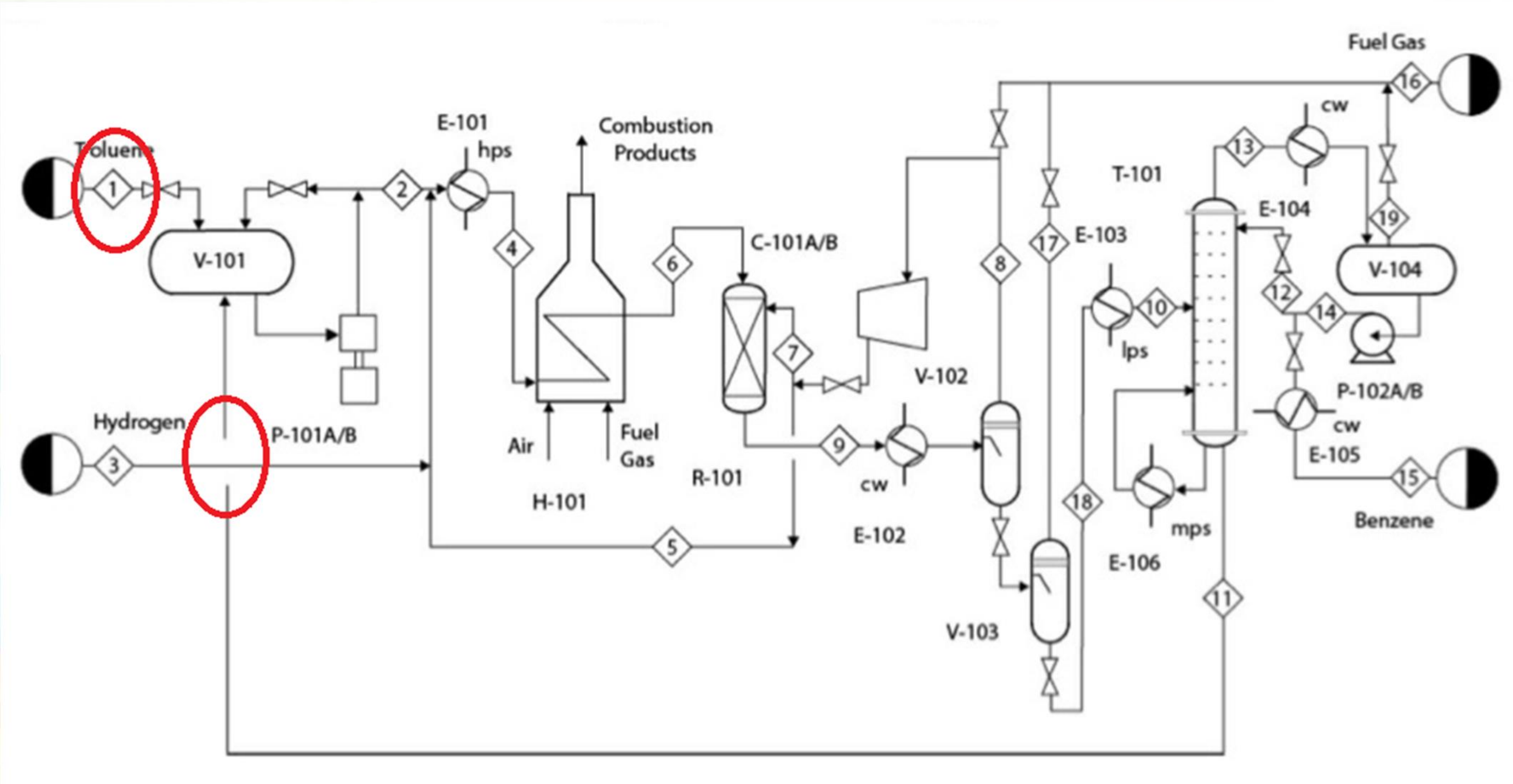
Block Flow Process Diagram: Example

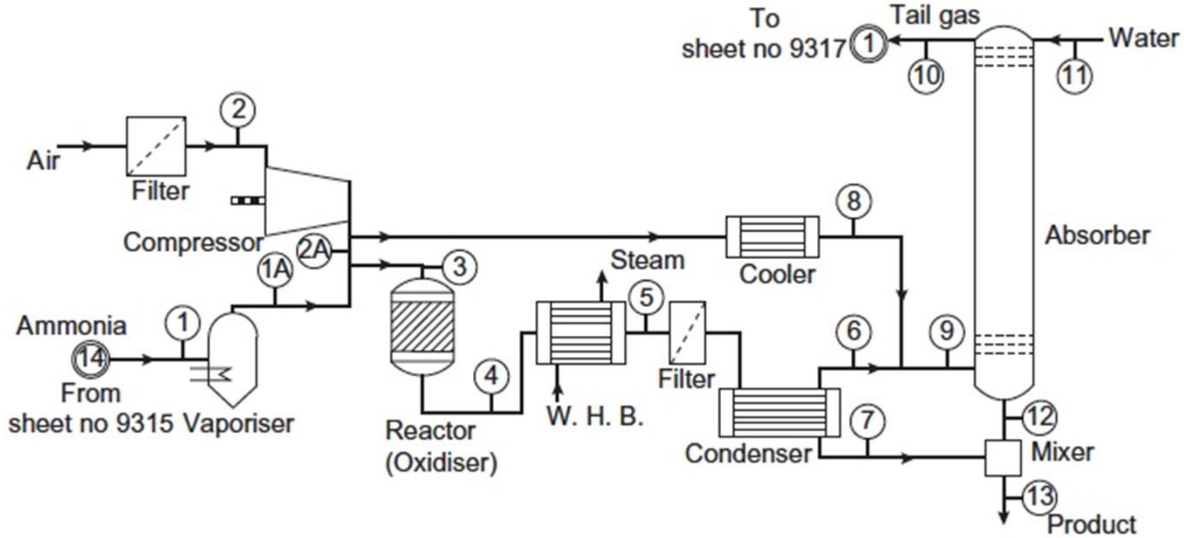
- $C_7H_8 + H_2 \longrightarrow C_6H_6 + CH_4$



Block Flow Process Diagram: Process Stream

- Diamonds symbols are located in the flow lines.
- Numerical identification is there for each process stream.
- Flow direction shown by arrows on flow lines.
- Flow line shown with arrows giving direction of flow.
- Flow goes from left to right whenever possible.
- Light stream gases toward top with heavy streams, liquids and solids, towards bottom.
- If lines cross then the horizontal line is continuous and the vertical line is broken.


Fuel Gas
16
cw
13
E-101
hps
Combustion
Products
Toluene
1
2
T-101
E-104
19
17
E-103
V-101
4
6
C-101A/B
8
V-104
12
14
10
7
lps
V-102
P-102A/B
Hydrogen
P-101A/B
Air
Fuel
Gas
9
cw
3
R-101
E-105
H-101
cw
15
18
Benzene
mps
E-102
5
E-106
11
V-103



Flows kg/h pressures nominal

Line no. Stream component	1 Ammonia feed	1A Ammonia vapor	2 Filtered air	2A Oxidiser air	3 Oxidiser feed	4 Oxidiser outlet	5 W.H.B. outlet	6 Condenser gas	7 Condenser acid	8 Secondary air	9 Absorber feed	10 Tail(2) gas	11 Water feed	12 Absorber acid	13 Product acid	C & R Construction Inc
NH_3	731.0	731.0	—	—	731.0	Nil	—	—	—	—	—	—	—	—	—	Nitric acid 60 percent
O_2	—	—	3036.9	2628.2	2628.2	935.7	(935.7)(1)	275.2	Trace	408.7	683.9	371.5	—	Trace	Trace	100,000 t/y
N_2	—	—	9990.8	8644.7	8644.7	8668.8	8668.8	8668.8	Trace	1346.1	10,014.7	10,014.7	—	Trace	Trace	Client BOP chemicals
NO	—	—	—	—	—	1238.4	(1238.4)(1)	202.5	—	—	202.5	21.9	—	Trace	Trace	SLIGO
NO_2	—	—	—	—	—	Trace	(?)(1)	967.2	—	—	967.2	(Trace)(1)	—	Trace	Trace	Sheet no. 9316
HNO_3	—	—	—	—	—	Nil	Nil	—	850.6	—	—	—	—	1704.0	2554.6	
H_2O	—	—	Trace	—	—	1161.0	1161.0	29.4	1010.1	—	29.4	26.3	1376.9	1136.0	2146.0	
Total	731.0	731.0	13,027.7	11,272.9	12,003.9	12,003.9	12,003.9	10,143.1	1860.7	1754.8	11,897.7	10,434.4	1376.9	2840.0	4700.6	
Press bar	8	8	1	8	8	8	8	8	1	8	8	1	8	1	1	Dwg by Date
Temp. °C	15	20	15	230	204	907	234	40	40	40	40	25	25	40	43	Checked 25/7/1980

Block Flow Process Diagram: Uses

- The process flow sheet is drawn up from material and energy balances made over the complete process and each individual unit to determine the mass flows, the energy flows and the service requirements.
- Computer Aided flow-sheeting is normally done these days.
- Most calculations of process flow diagram are now carried out using commercial process simulation software.
- Process flow diagram is a very important document in process design and it is used for preparing:
  - ✓ Control scheme, piping and instrumentation diagram
  - ✓ Plant layout, piping network design, equipment design
  - ✓ Operating manuals and operator training
  - ✓ Comparison of operating performance with the design

Block Flow Process Diagram: Equipment Numbering

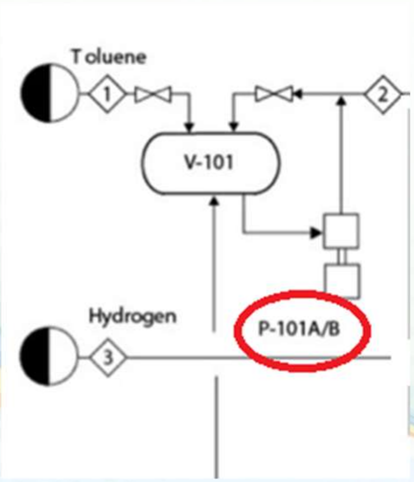
- Process Equipment: general format is XX-YZZ A/B
- XX: One or two letter designation for the equipment classification
- For example:

R - Reactor	TK – Storage Tank	C – Compressor or Turbine	H – Fired Heater
T - Tower	V - Vessel	E – Heat Exchanger	P - Pump

- Y designates a process area within the plant (100, 200, 300 etc.)
- ZZ is the number designation for each item in an equipment class.
- A/B identifies parallel units or backup (spare) units not shown on a process flow diagram.

Block Flow Process Diagram: Equipment Numbering Example

- *P-101 A/B: the letter P means the equipment is a pump*
- *P-101 A/B: 1 of 101 means pump is located in area 100 of the plant*
- *P-101 A/B: 01 means that this particular pump is numbered 01 in the unit 100*
- *P-101 A/B: a backup pump is installed*
- *There are two identical pumps. P-101 A and P-101 B.*
- *One pump will be operating while the other is idle*
- *The horizontal line is not broken but the vertical line is broken, which means cross without mixing*



Stream Flow Rates and Compositions

These data will be displayed either directly on the process flow diagram or included in an accompanying flow summary table

For a simple process:

If the process has few pieces of equipment, then the data can be shown in blocks alongside the process stream lines. Only a limited information can be shown this way.

For a complex process:

Each stream line is numbered and the data tabulated at the bottom of a sheet.

Alterations and additions can be done very easily

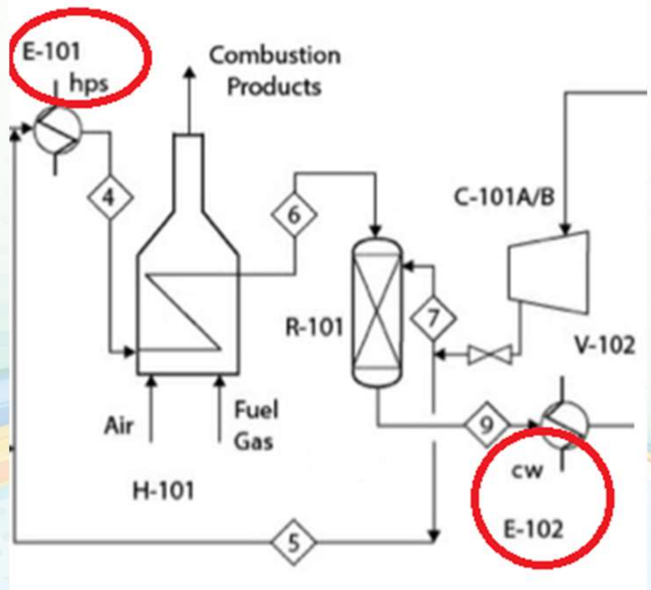
Process Flow Diagram: Utility Streams

- Chemical plants require several utilities such as electricity, compressed air, cooling water, refrigerated water, steam, condensate return, inert gas for blanketing, chemical sewer, wastewater treatment and flares. Each utility is identified by initials as follows:

lps: low pressure steam	wr: river water from river 25 °C returned at less than 35 °C
mps: medium pressure steam	rw: refrigerated water
hps: high pressure steam	ng: natural gas
htm: heat transfer media organic	fg: fuel gas
cw: cooling water from cooling tower 30 °C return at less than 45 °C	

Process Flow Diagram: Utility Streams

- E-101: the equipment is a heat exchanger
- E-101 A/B: 1 for 101 represents heat exchanger is located in area 100 of the plant
- E-101: And 01 is that this is numbered 01 in unit 100
- hps : high pressure steam



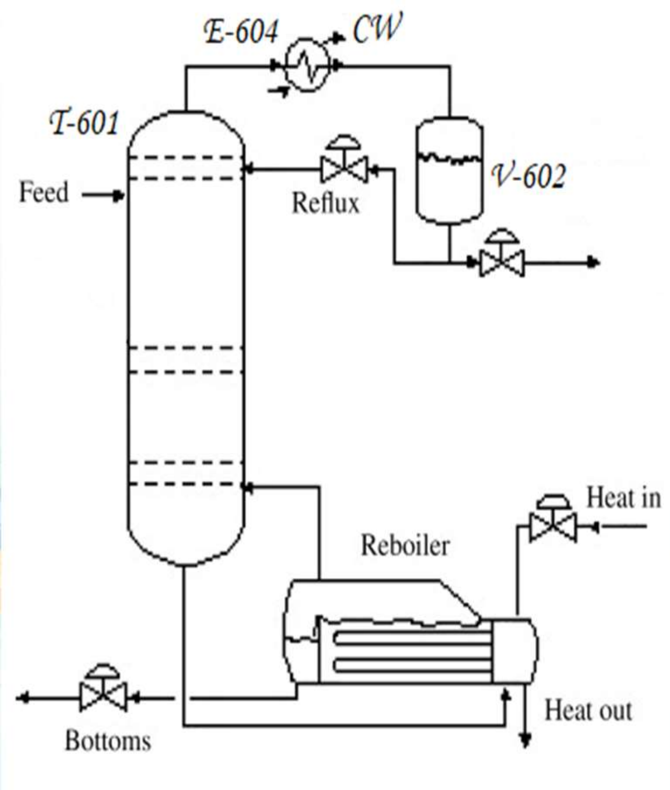
Process Flow Diagram: Stream Information

Essential information	Optional information
• Stream number • Temperature (°C) • Pressure (bar) • Vapor fraction • Total mass flow rate normally in (kg/h) • Total mole flow rate normally (kmol/h) • Individual component flow rate (kg/h)	• Component mole fractions • Component mass fractions • Individual component flow rates (kmol/h) volumetric flow rates (m^3/h) • Significant physical properties (density, viscosity). • Other thermodynamic (heat capacity, enthalpy) • Stream name

- For batch processes we express mass/energy per unit batch.
- For example, kg /batch kWh/batch

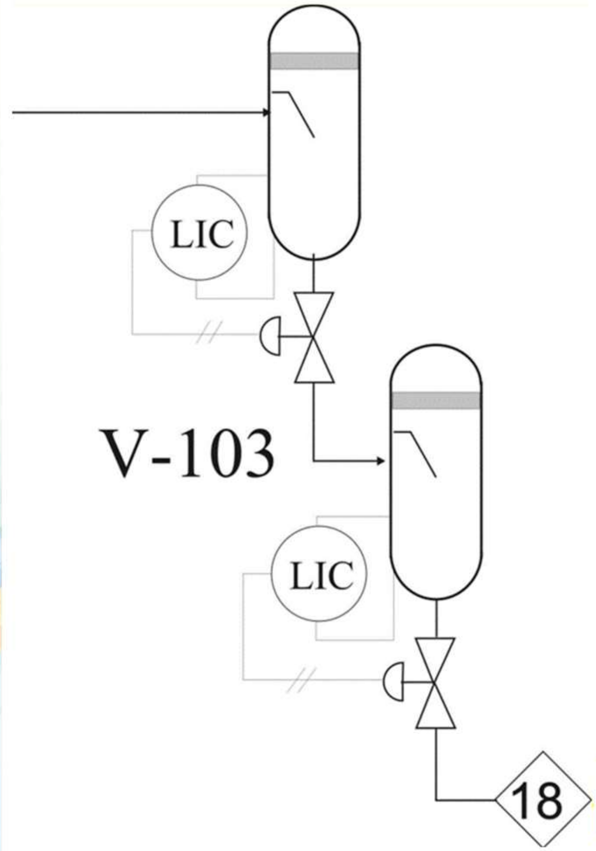
Process Flow Diagram: Use Unambiguous Letters

- Use unambiguous letters for new equipment
- If a turbine is to be included, you should not use symbol T for turbine.
- T is already used for towers, normally use C for compressor as well as turbine.
- If we replace old vessel V-602 with a new one of different design, use a different number V-619.

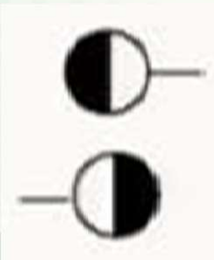


Process Flow Diagram Shows Basic Control Loops

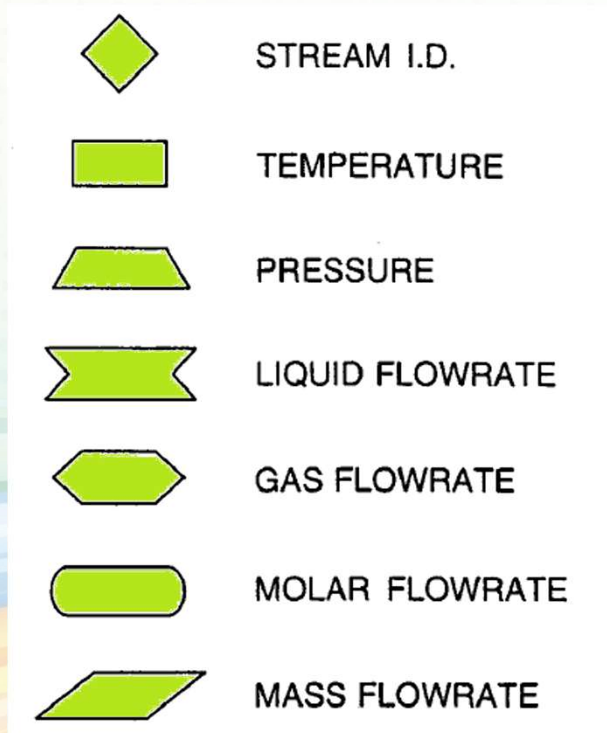
- *Often the basic control loops those involving maintaining material balance and reactor controls are included on the process flow diagram.*
- *Instrumentation and other control loops are not shown*

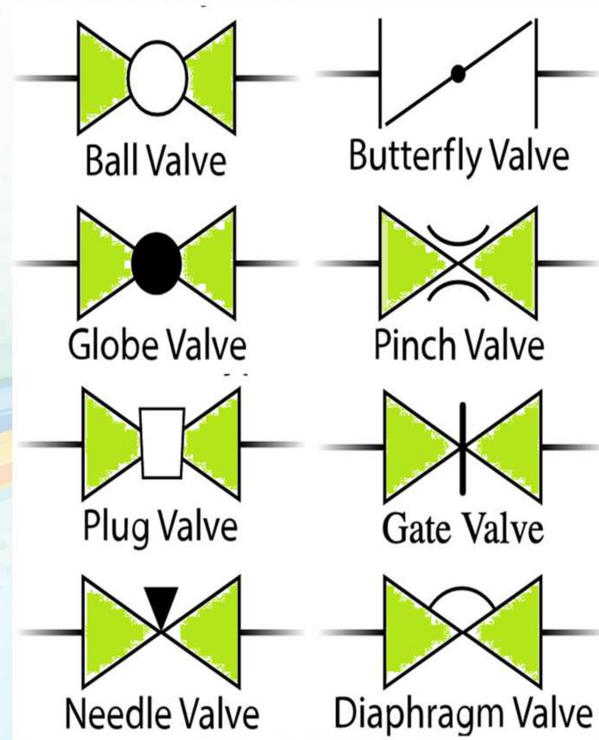


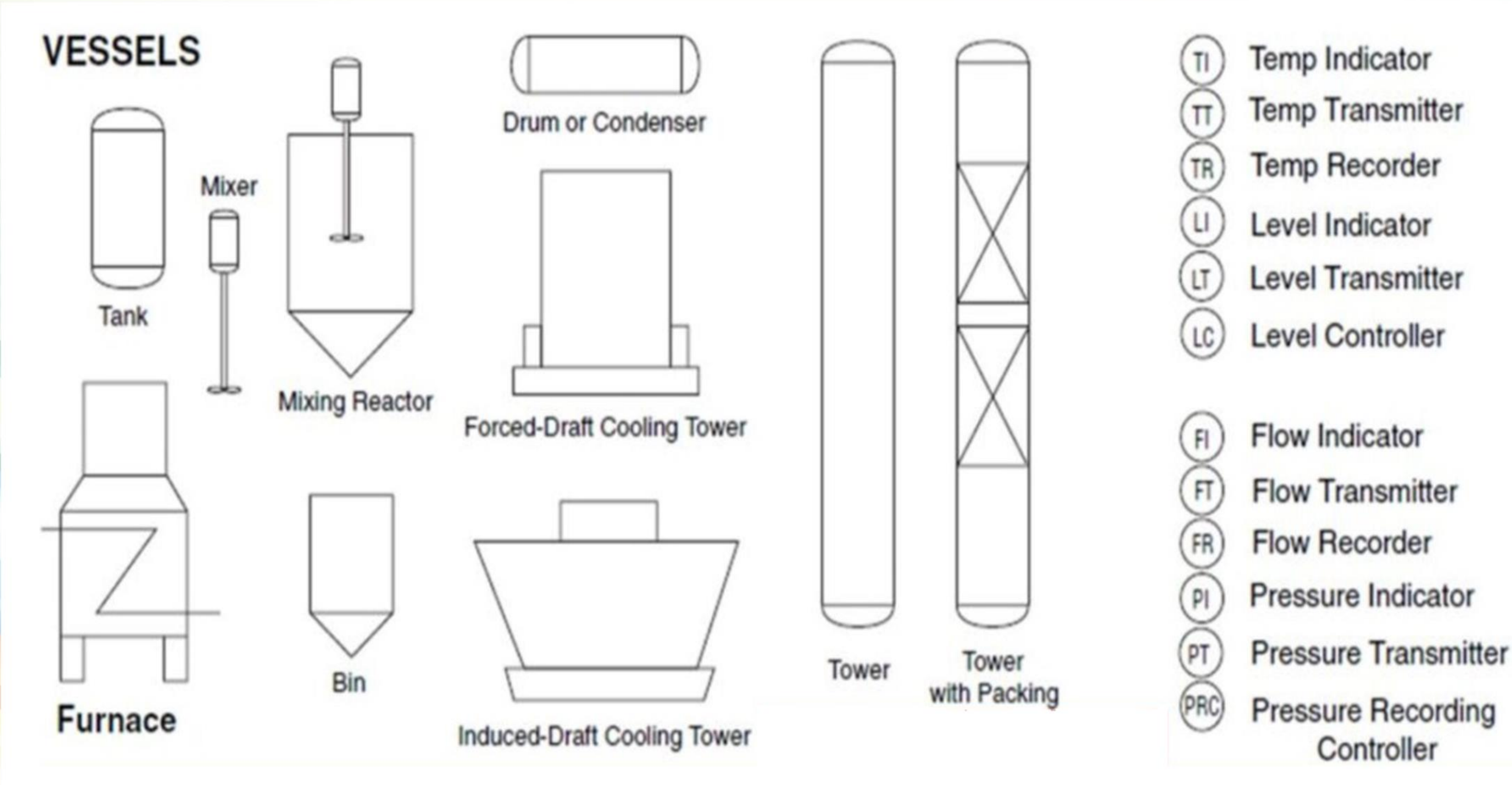
Process Flow Diagram Flowsheet Symbols

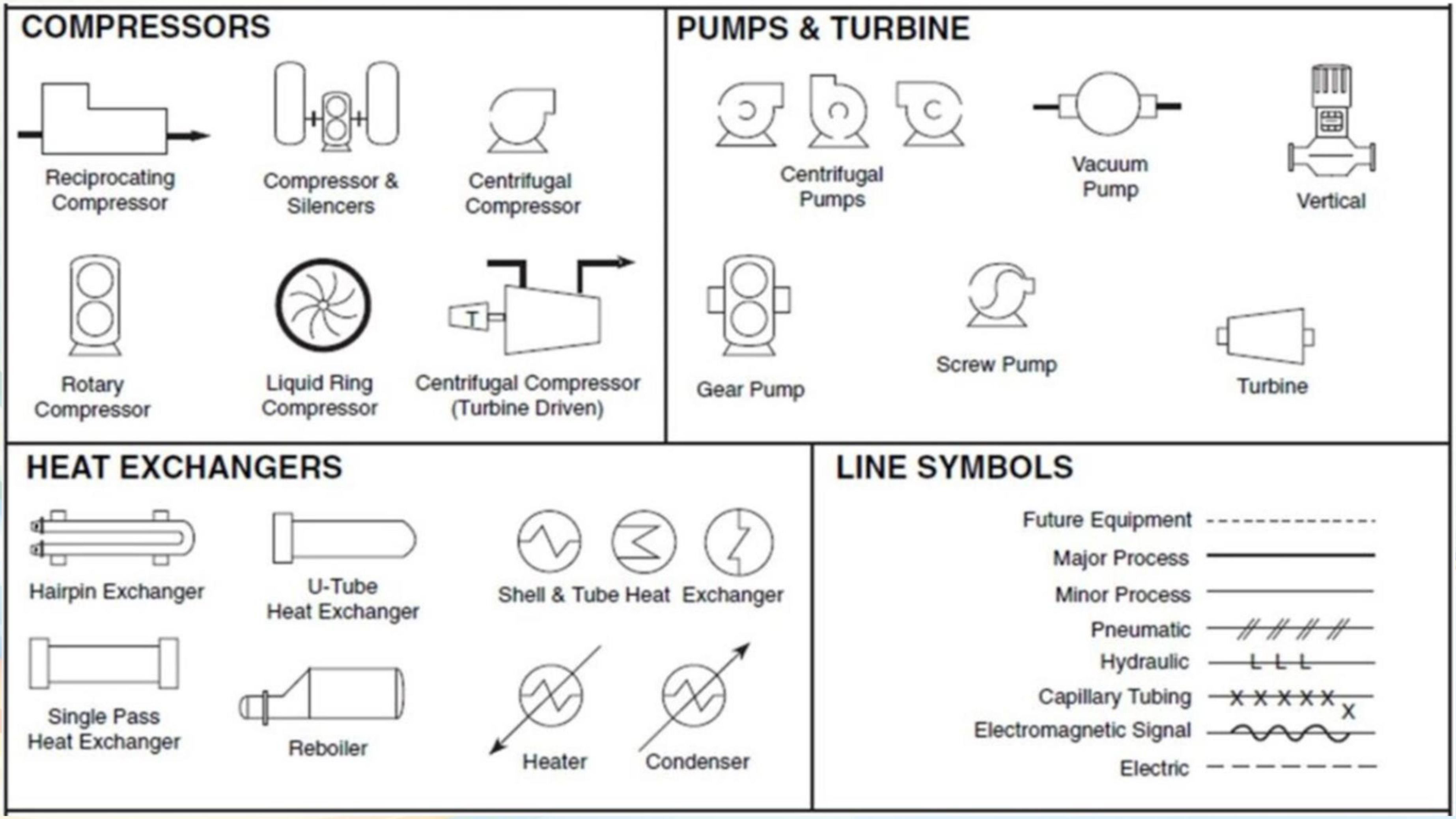


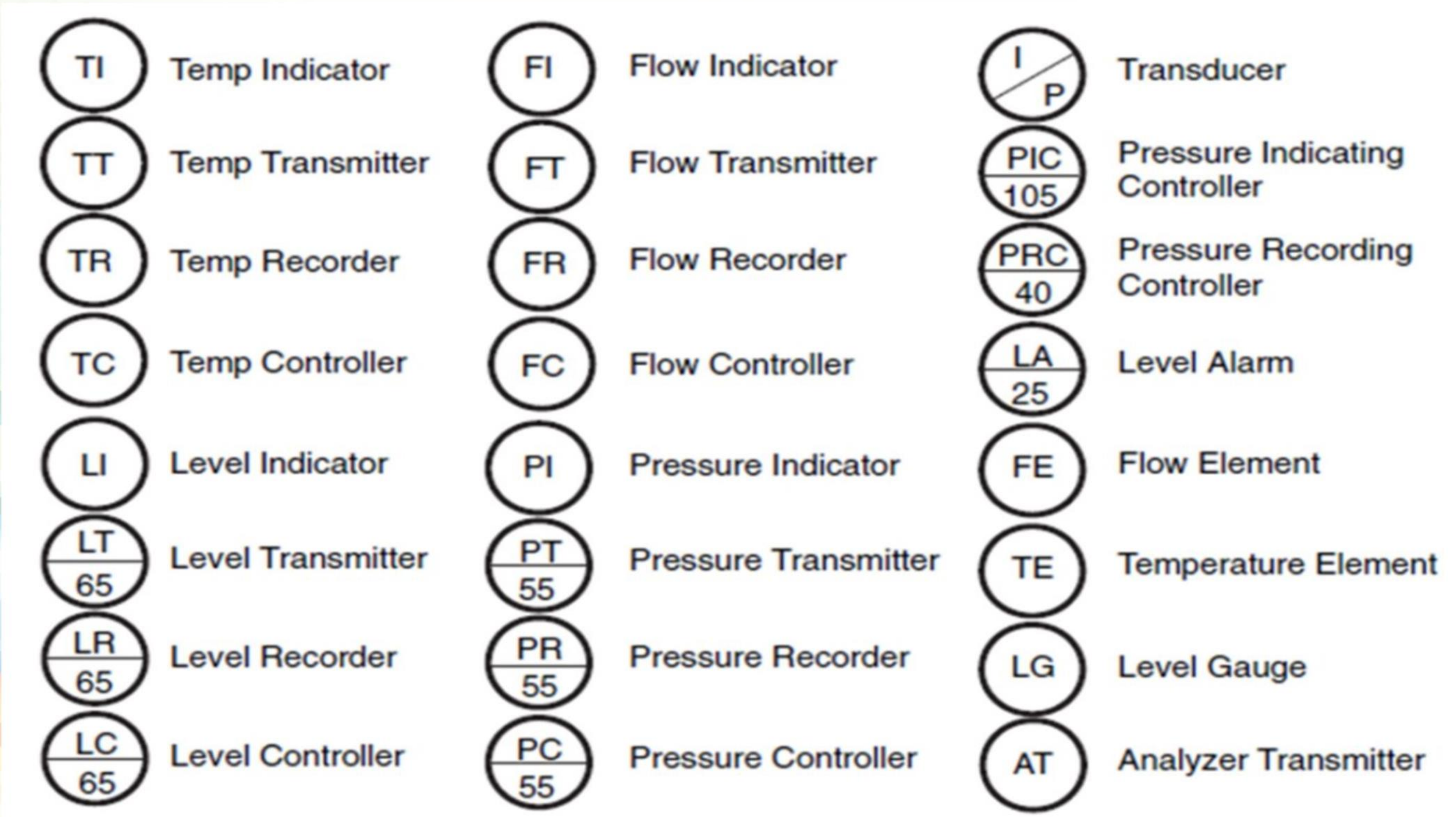
- *Product input*
- *Product output*

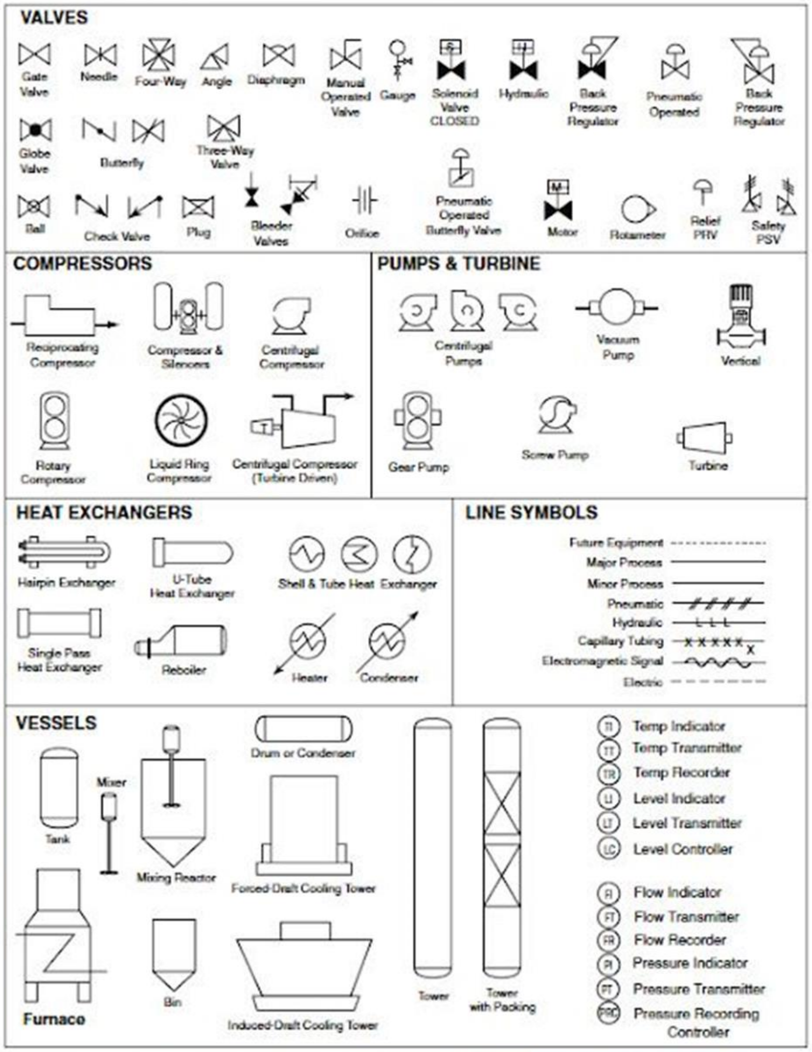




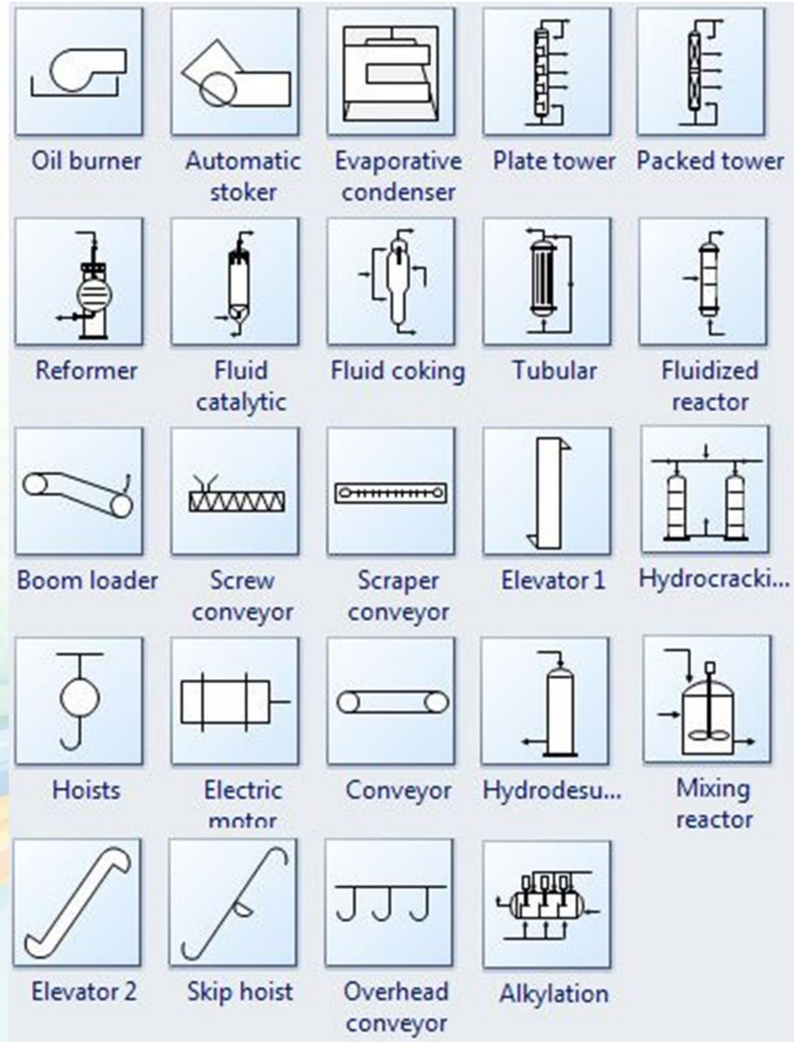

VESSELS
Tank
Mixer
Mixing Reactor
Drum or Condenser
Forced-Draft Cooling Tower
Furnace
Bin
Induced-Draft Cooling Tower
Tower
Tower with Packing
TI
Temp Indicator
TT
Temp Transmitter
TR
Temp Recorder
LI
Level Indicator
LT
Level Transmitter
LC
Level Controller
FI
Flow Indicator
FT
Flow Transmitter
FR
Flow Recorder
PI
Pressure Indicator
PT
Pressure Transmitter
PRC
Pressure Recording Controller


COMPRESSORS
Reciprocating Compressor
Compressor & Silencers
Centrifugal Compressor
Rotary Compressor
Liquid Ring Compressor
Centrifugal Compressor (Turbine Driven)
T
PUMPS & TURBINE
Centrifugal Pumps
Vacuum Pump
Vertical
Gear Pump
Screw Pump
Turbine
HEAT EXCHANGERS
Hairpin Exchanger
U-Tube Heat Exchanger
Shell & Tube Heat Exchanger
Single Pass Heat Exchanger
Reboiler
Heater
Condenser
LINE SYMBOLS
Future Equipment
Major Process
Minor Process
Pneumatic
Hydraulic
Capillary Tubing
Electromagnetic Signal
Electric

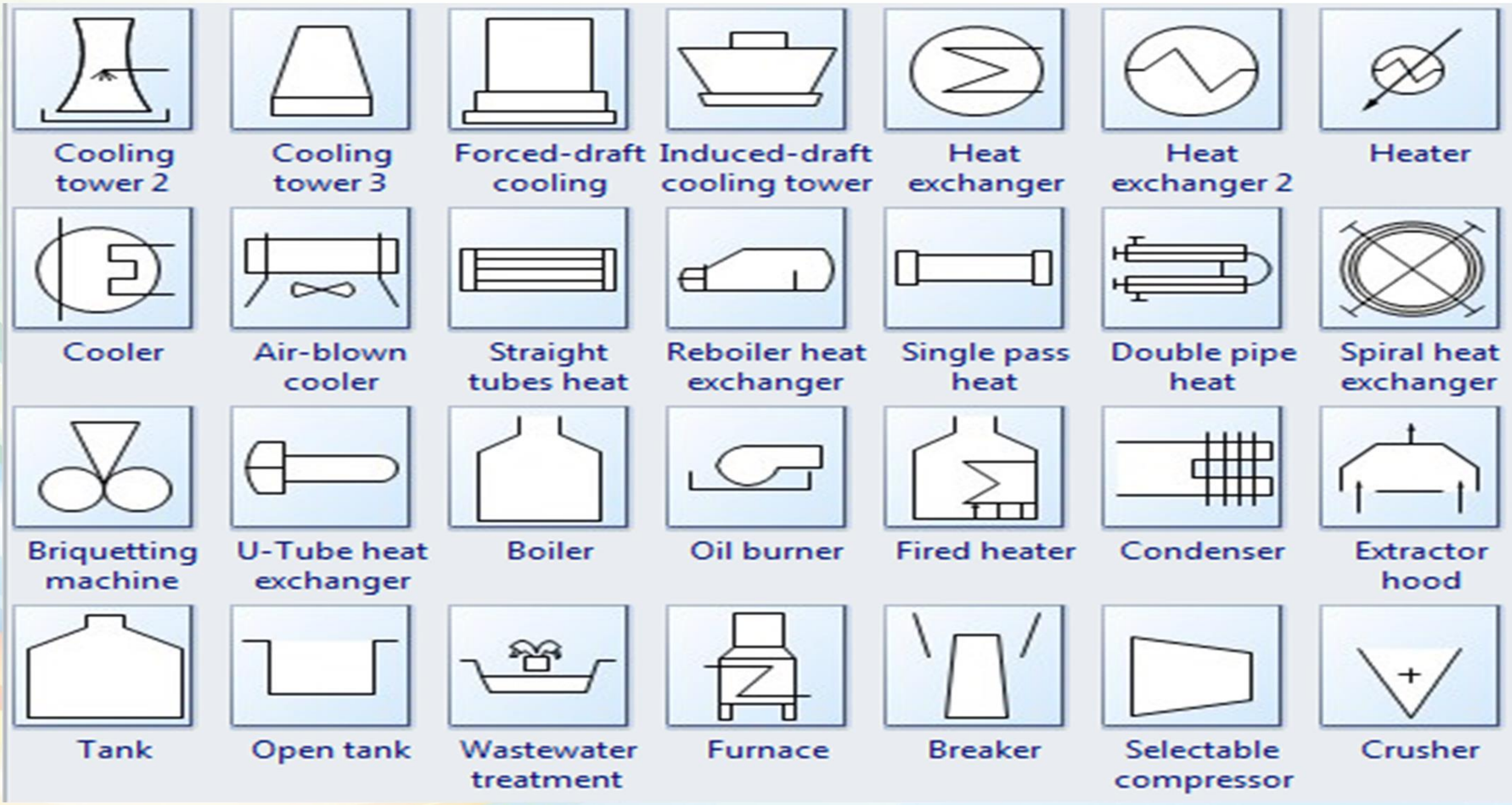

TI Temp Indicator
TT Temp Transmitter
TR Temp Recorder
TC Temp Controller
LI Level Indicator
LT 65 Level Transmitter
LR 65 Level Recorder
LC 65 Level Controller
FI Flow Indicator
FT Flow Transmitter
FR Flow Recorder
FC Flow Controller
PI Pressure Indicator
PT 55 Pressure Transmitter
PR 55 Pressure Recorder
PC 55 Pressure Controller
I P Transducer
PIC 105 Pressure Indicating Controller
PRC 40 Pressure Recording Controller
LA 25 Level Alarm
FE Flow Element
TE Temperature Element
LG Level Gauge
AT Analyzer Transmitter



VALVES
Gate Valve
Needle
Four-Way
Angle
Diaphragm
Manual Operated Valve
Gauge
Solenoid Valve CLOSED
Hydraulic
Back Pressure Regulator
Pneumatic Operated
Back Pressure Regulator
Globe Valve
Butterfly
Three-Way Valve
Ball
Check Valve
Plug
Bleeder Valves
Orifice
Pneumatic Operated Butterfly Valve
Motor
Rotameter
Relief PRV
Safety PSV
COMPRESSORS
Reciprocating Compressor
Compressor & Silencers
Centrifugal Compressor
Rotary Compressor
Liquid Ring Compressor
Centrifugal Compressor (Turbine Driven)
PUMPS & TURBINE
Centrifugal Pumps
Vacuum Pump
Vertical
Gear Pump
Screw Pump
Turbine
HEAT EXCHANGERS
Hairpin Exchanger
U-Tube Heat Exchanger
Shell & Tube Heat Exchanger
Single Pass Heat Exchanger
Reboiler
Heater
Condenser
LINE SYMBOLS
Future Equipment
Major Process
Minor Process
Pneumatic
Hydraulic
Capillary Tubing
Electromagnetic Signal
Electric
VESSELS
Tank
Mixer
Mixing Reactor
Drum or Condenser
Forced-Draft Cooling Tower
Tower
Tower with Packing
Furnace
Bin
Induced-Draft Cooling Tower
Temp Indicator
Temp Transmitter
Temp Recorder
Level Indicator
Level Transmitter
Level Controller
Flow Indicator
Flow Transmitter
Flow Recorder
Pressure Indicator
Pressure Transmitter
Pressure Recording Controller



Oil burner
Automatic stoker
Evaporative condenser
Plate tower
Packed tower
Reformer
Fluid catalytic
Fluid coking
Tubular
Fluidized reactor
Boom loader
Screw conveyor
Scraper conveyor
Elevator 1
Hydrocracki...
Hoists
Electric motor
Conveyor
Hydrodesu...
Mixing reactor
Elevator 2
Skip hoist
Overhead conveyor
Alkylation


Cooling tower 2
Cooling tower 3
Forced-draft cooling
Induced-draft cooling tower
Heat exchanger
Heat exchanger 2
Heater
Cooler
Air-blown cooler
Straight tubes heat
Reboiler heat exchanger
Single pass heat
Double pipe heat
Spiral heat exchanger
Briquetting machine
U-Tube heat exchanger
Boiler
Oil burner
Fired heater
Condenser
Extractor hood
Tank
Open tank
Wastewater treatment
Furnace
Breaker
Selectable compressor
Crusher

Process Flow Diagram: Conclusions

- Process flow diagram not only provides all of the information needed to understand the chemical process, it also provides sufficient information on the equipment energy and material balances to establish process control protocol and to prepare cost estimates to determine the economic viability of the process.
- After construction of the plant, it is used:
  - ✓ For training of operators and new engineers
  - ✓ Regularly to diagnose operating problems that will arise
  - ✓ To predict the effects of changes on the process

Chemical Plant Design

Plant Layout

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

Outlines

- *Site layout*
- *Plant layout*
- *Ethics in Engineering Design*

Site and Plant Layout: General Consideration

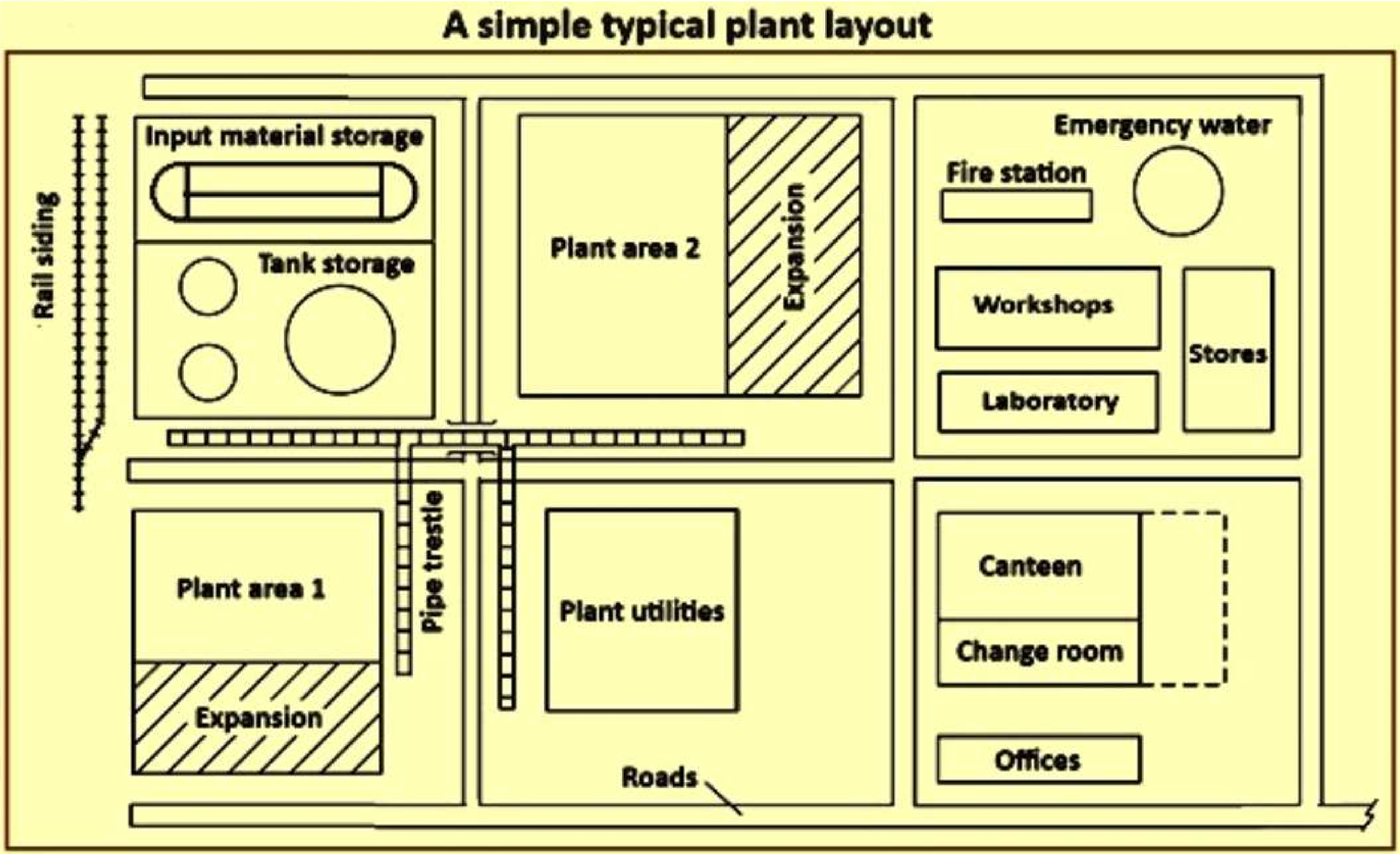
- What will be the layout or arrangement of process units in the plant?
- What will be the layout of the equipment within these processing units?
- These should be taken up after process flow diagrams are completed and before detail piping, structural, and electrical design begin.
- The proper layout of processing areas, storage areas, handling areas etcetera plays an important role in determining ease of operation and construction cost as well as manufacturing cost. Therefore, the layout must be planned very carefully.
- Attention must be given to possible future expansion and also problems that may arise.

Site and Plant Layout: General Consideration

- The laying out of a plant is mostly an art, a good plant layout will place equipment such that operation is easy and the following are minimized:
  - ✓ The number of people required to operate the plan and the other operating cost.
  - ✓ Construction cost and maintenance cost
  - ✓ The cost of the planned future revision or expansion
  - ✓ Damage to persons and property in case of a fire or explosion.
- All of these goals cannot be made simultaneously. For example to reduce potential losses in case of fire your plant must be spread out, but if you spread out your plants the pumping cost will increase and possibly also you will require more manpower for operation.

Site Layout: Units in a Typical Layout

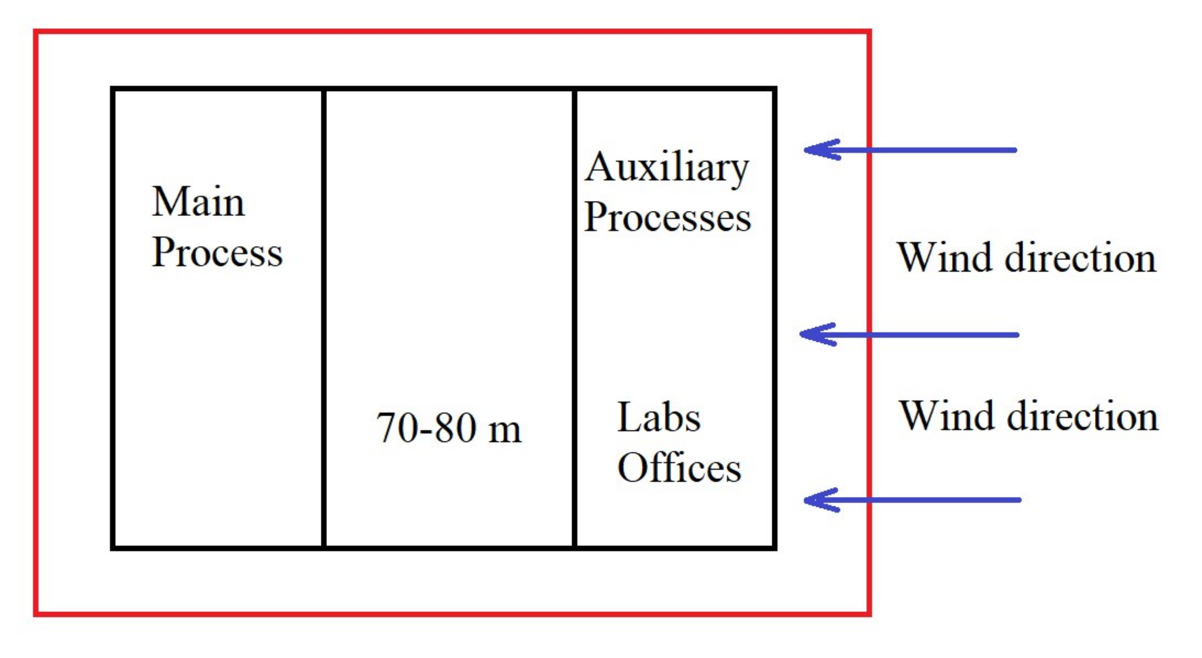
1. Main processing units 2. Storage for raw materials and products; this will be tank farms and warehouses 3. Maintenance workshop 4. Stores, for maintenance and operating supplies 5. Laboratories for process quality control 6. Fire stations and other emergencies services	7. Utilities: such as steam boilers, compressed air, power generation, refrigeration 8. Effluent disposal plant: waste water treatment, solid liquid waste collection 9. Offices for general administration 10. Canteens and other amenities buildings such as medical centres 11. Parking lots


A simple typical plant layout
Rail siding
Input material storage
Tank storage
Plant area 2
Expansion
Emergency water
Fire station
Workshops
Stores
Laboratory
Pipe trestle
Plant area 1
Expansion
Plant utilities
Canteen
Change room
Offices
Roads

Site Layout

- No two plants are exactly the same. There is no single ideal plant layout.
- However, proper layout in each case will include arrangement of processing areas, storage areas and handling areas for efficient coordination in production as well as management.
- First, determine the direction of the prevailing wind. All equipment that may spill flammable materials should be located such that if a spill occurs the prevailing winds cannot carry any vapors over the plant where they could be ignited by an open flame or a hot surface.
- Consider all neighboring facilities. It has happened in the past when one plant has been badly damaged because of spills at another neighboring plant.

Site Layout



Auxiliary Processes:

Power generation, cooling water pumps, cooling towers, compressors, boilers, control equipment, air

- Personnel space should be located upwind.
- Wind conditions will aid removal and dispersion of pollutants.

Site Layout

- The process units and ancillary buildings should be laid out to give the most economical flow of materials and personnel around the site.
- The distance between occupied buildings and plant buildings will be governed by the need to reduce the dangers of explosion fire and toxicity.
- Occupied buildings should not be cited downwind of hazardous plant areas.
- Hazardous processes must be located at a safe distance from other buildings. Evacuation routes should not be blocked by poor plant layout. Personnel with general site responsibilities should be housed in buildings cited in a non-hazard area near the main entrance.
- Consideration must also be given to the future expansion of the site.

Site Layout

- Process units are typically sited and arranged to ensure a smooth flow of materials through each processing step, from raw material intake to final product storage.
- Process units are normally spaced at least 30 meter effort from other utilities or buildings, greater spacing must be needed for hazardous processes.
- Next decide the location and arrangement of the principle ancillary buildings, so as to minimize the time span by personnel in travelling between the buildings.
- Many people will work at administration offices and laboratories; they should be located well away from potentially hazardous processes.

Site Layout

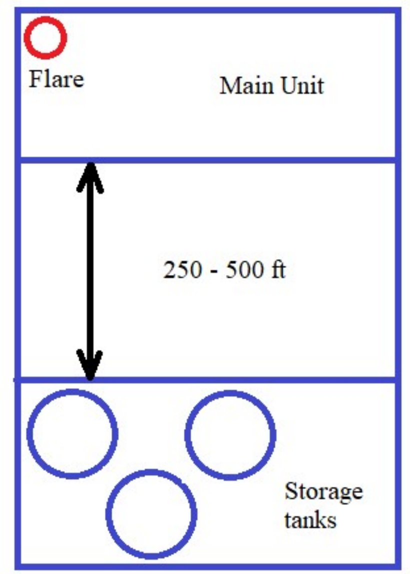
- Control rooms are normally located near the processing units, but those with potentially hazardous processes may have to be cited at a safer distance.
- The location of the main process units determines the layout of the plant roads, pipe alleys and drains.
- Good access roads to each building are needed for construction operation and maintenance.
- Utility buildings should be cited to give the most economical run of pipes to and from the process units

Site Layout

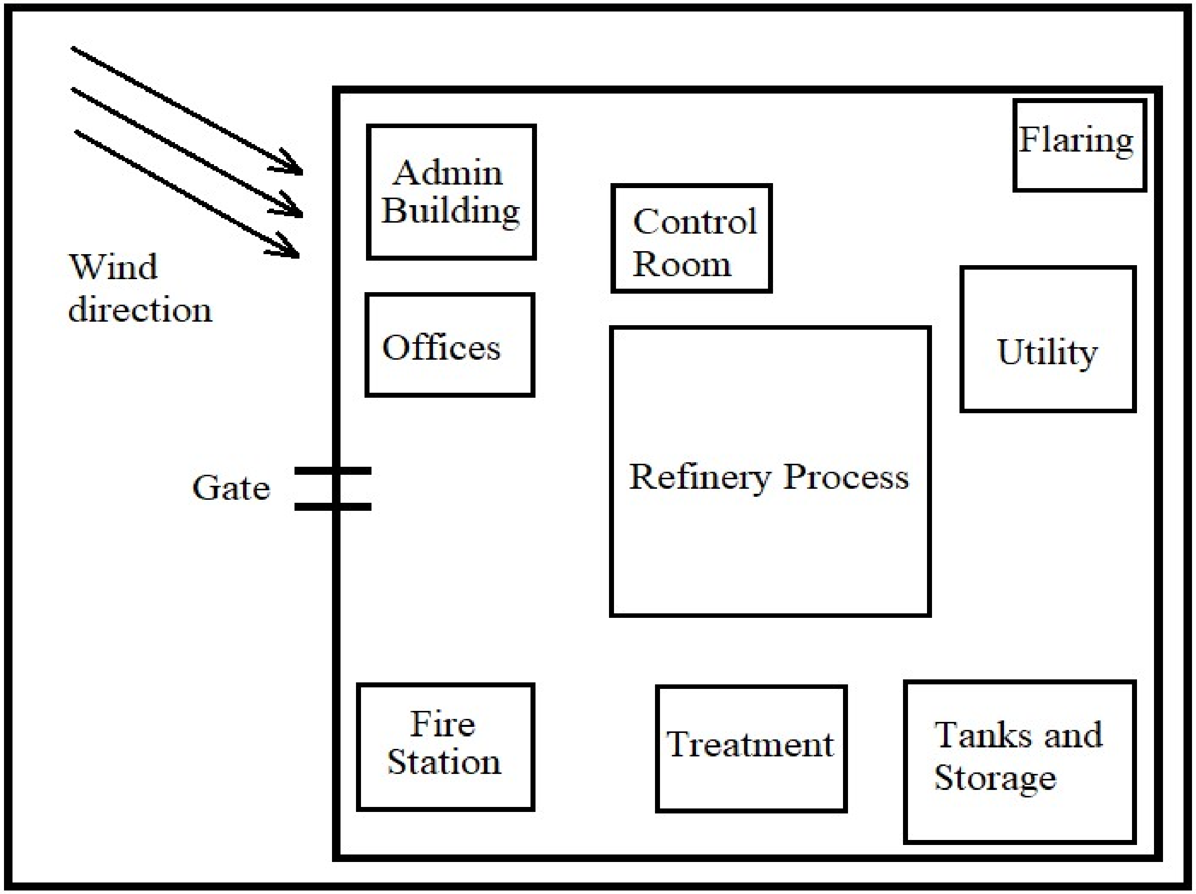
- Cooling towers should be cited so that, under the prevailing wind, the plume of condensate spray drifts away from the plant area and adjacent properties.
- The main storage areas should be placed between the loading and unloading facilities and the process units they serve.
- Storage tanks containing hazardous materials should be cited, at least 70 meter from the site boundary.
- Storage tanks needed to be far when they contain gases under pressure, liquids with high vapor pressure or explosive fluids. Acid tanks usually do not take long distance.

Site Layout

- Flares are important safety devices used in the refineries and petrochemical facilities to burn excess hydrocarbon gases, which cannot be recovered or recycled.
- Safety and control systems might vent some compounds to avoid explosions.
- Flare should be away from other flammable materials.



A Simple Site Layout for a Refinery



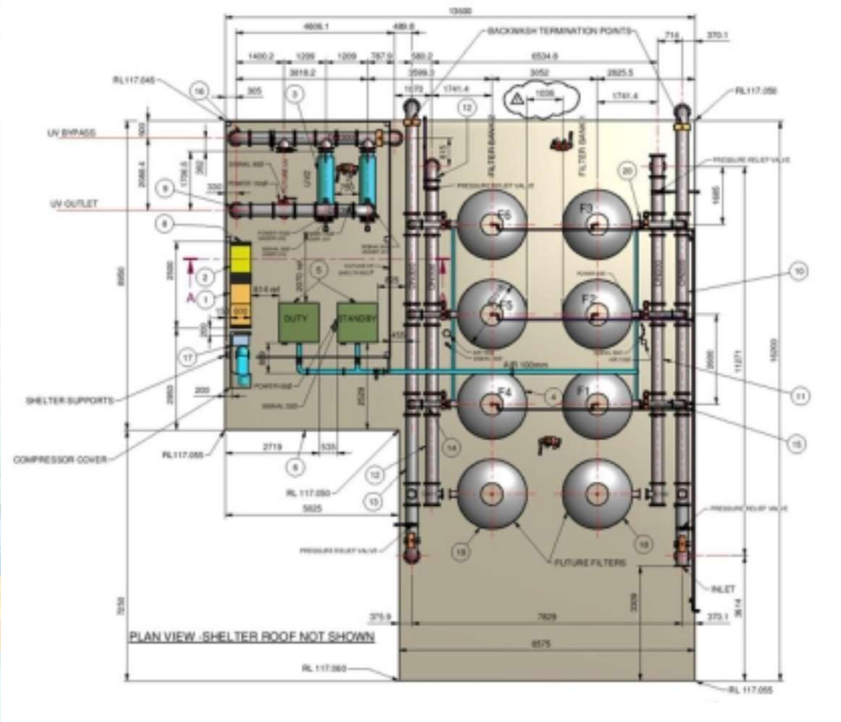
Plant Layout: General Consideration

Layout for the main processing area:

(1) Grouped layout

(2) Flow line layout.

- The Grouped layout places all similar pieces of equipment adjacent to each other.
- Advantage: Ease of operation and supervision also it is easy to switch from one unit to another.
- This is best for large plants.



Plant Layout: General Consideration

- The flow line layout scheme uses the train or line system, which locates all the equipment according to their position in the flows-sheet.
- Advantage: minimizes the length of transfer lines and thereby it reduces energy needed to transport materials. Extensively used in pharmaceutical industry where each batch of produced drug must be kept separate from all other batches.

- A combination of group layout scheme and flow line layout schemes will be used that base suits the specific situation you have in hand.

Plant Layout: Factors to Consider

- The economic construction and efficient operation of a process unit depends on how well the plant and equipment specified on the process flow series lay out.
- The principal factors to be considered are:

1- Economic consideration: construction and operating costs 2- The process requirements 3- Convenience of operation 4- Convenience of maintenance	5- Safety 6- Future expansion 7- Modular or flexible or integrated construction

Plant Layout: Some General Consideration

- Structural steel work buildings are normally used for process equipment because they are good for ventilation and heat release.
- Closed buildings are used for:
  - ✓ Process operations that require protection from the weather,
  - ✓ Small plants, or
  - ✓ Processes that require ventilation with scrubbing of the vain gas.
- The arrangement of the major items of equipment often follows the sequence given on the process flow sheet; with the columns and vessel arranged in rows and the ancillary equipment, such as heat exchangers and pumps, positioned along the outside.

Plant Layout: Cost and Future Expansion

- The cost of construction can be minimized by selecting a layout that gives the shortest run of connecting pipe between equipment and the least amount of structural steel work.
- However, these may not necessarily be the best arrangement for operation and maintenance.
- Equipment should be located so that it can be conveniently tied in/fitted with any future expansion of the process.
- Space should be left for future needs, service pipes should be oversized to allow for future requirements.

Plant Layout: Operation

- Equipment that needs frequent attention of operators should be located convenient to the control room.
- Valves, sample points, and instruments should be located at convenient positions and heights for easy access.
- Sufficient working space and headroom must be provided to allow easy access to equipment. If it is anticipated that equipment will need replacement, then sufficient space must be allowed to permit access to lifting equipment.

Plant Layout: Maintenance and Safety

- *Locate heat exchangers such that the tube bundles can be easily withdrawn for cleaning and tube replacement.*
- *Vessels and reactors that require frequent replacement of catalyst or packing should be located on the outside of buildings.*
- *Equipment that requires dismantling for maintenance, such as compressors and large pumps, should be placed under shades.*
- *Blast walls maybe provided to isolate potentially hazardous equipment and to confine the effects of an explosion.*
- *Provide at least two escape routes for operators from each level in process buildings.*


ARTIS

Storage Facilities

- Non-hazardous, non-flammable and non-explosive materials: Locate upwind of plant.
- Materials which do not fit the above:
  - Do not locate upwind nor downwind.
  - Locate to the side of processing area (at least ~75 m).

Spacing of items

- Refer to Tables
  - Ref.: Baasel
  - Ref.: GAPS Guidelines GAP:
    - Publication of Global Asset Protection Services.
    - Oil and Chemical Plant Layout and Spacing.

	Service Buildings	Motor Control Centers And Electrical Substations	Utilities Areas	Cooling Towers	Control Rooms	Compressor Buildings	Large Pump Houses	Process Units Moderate Hazard	Process Units Intermediate Hazard	Process Units High Hazard	Atmospheric Storage Tanks	Pressure Storage Tanks	Refrigerated Storage Tanks Dome Roof	Flares	Unloading And Loading Racks	Fire Water Pumps	Fire Stations
Service Buildings	/																
Motor Control Centers And Electrical Substations	/	/															
Utilities Areas	50	50	/														
Cooling Towers	50	50	100	50 (1)													
Control Rooms	/	/	100	100	/												
Compressor Buildings	100	100	100	100	100	30											
Large Pump Houses	100	100	100	100	100	30	30										
Process Units Moderate Hazard	100	100	100	100	100	30	30	50									
Process Units Intermediate Hazard	200	100	100	100	200	50	50	100	100								
Process Units High Hazard	400	200	200	200	300	100	100	200	200	200							
Atmospheric Storage Tanks	250	250	250	250	250	250	250	250	300	350	*						
Pressure Storage Tanks	350	350	350	350	350	350	350	350	350	350	*	*					
Refrigerated Storage Tanks Dome Roof	350	350	350	350	350	350	350	350	350	350	*	*	*				
Flares	300 (2)	300	300	300	300	300	300	300	300	300	300	400	400	/			
Unloading And Loading Racks	200	200	200	200	200	200	200	200	200	300	250	350	350	300	50		
Fire Water Pumps	50	50	50	50	50	200	200	200	300	300	350	350	350	300	200	/	
Fire Stations	50	50	50	50	50	200	200	200	300	300	350	350	350	300	200	/	/

1 ft = 0.305 m
/ = no spacing requirements
* = spacing given in Table 3

Examples:

(1) 50 ft separation between two cooling towers
(2) 300 ft separation between service building and flare

TABLE 1. Inter-Unit Spacing Recommendations For Oil And Chemical Plants.

	Compressors	Intermediate Hazard Pumps	High Hazard Pumps	High Hazard Reactors	Intermediate Hazard Reactors	Moderate Hazard Reactors	Columns, Accumulators, Drums	Rundown Tanks	Fired Heaters, Incineraors, Oxidizers	Air Cooled Heat Exchanger	Heat Exchangers	Pipe Racks	Emergency Exchangers	Unit Block Valves	Analyzer Rooms
Compressors	30														
Intermediate Hazard Pumps	30	5													
High Hazard Pumps	50	5	5												
High Hazard Reactors	50	10	15	25											
Intermediate Hazard Reactors	50	10	15	25	15										
Moderate Hazard Reactors	50	10	15	25	15	15									
Columns, Accumulators, Drums	50	10	15	50	25	25	15								
Rundown Tanks	100	100	100	100	100	100	100	100							
Fired Heaters, Incineraors, Oxidizers	50	50	50	50	50	50	50	100	25						
Air Cooled Heat Exchanger	30	15	15	25	15	15	15	100	50	/					
Heat Exchangers	30	10	15	25	15	10	10	100	50	15	5				
Pipe Racks	30	10	15	25	15	10	10	100	50	/	10	/			
Emergency Exchangers	50	50	50	100	50	50	50	100	50	50	50	50	/		
Unit Block Valves	50	50	50	100	50	50	50	100	50	50	50	50	/	/	
Analyzer Rooms	50	50	50	50	50	50	50	100	50	50	50	50	/	/	/

1 ft = 0.305 m
/ = no spacing requirements

TABLE 2. Intra-Unit Spacing Recommendations For Oil And Chemical Plants.

	FLOATING & CONE ROOF TANKS < 3000 BARRELS	FLOATING & CONE ROOF TANKS > 3000 < 10,000 BARRELS	FLOATING ROOF TANKS > 10,000 < 300,000 BARRELS	JUMBO FLOATING ROOF TANKS > 300,000 BARRELS	CONE ROOF TANKS CLASS II, III PRODUCT > 10,000 < 300,000 BARRELS	CONE ROOF TANKS INERTED CLASS I PRODUCT** > 10,000 < 150,000 BARRELS	PRESSURE STORAGE VESSELS SPHERES AND SPHEROIDS	PRESSURE STORAGE VESSELS DRUMS AND BULLETS	REFRIGERATED DOME ROOF STORAGE TANKS
FLOATING & CONE ROOF TANKS < 3000 BARRELS	0.5 D*								
FLOATING & CONE ROOF TANKS > 3000 < 10,000 BARRELS	0.5 D	0.5 D							
FLOATING ROOF TANKS > 10,000 < 300,000 BARRELS	1 X D	1 X D	1 X D						
JUMBO FLOATING ROOF TANKS > 300,000 BARRELS	1 X D	1 X D	1 X D	1 X D					
CONE ROOF TANKS CLASS II, III PRODUCT > 10,000 < 300,000 BARRELS	0.5 D	0.5 D	1 X D	1 X D	0.5 D				
CONE ROOF TANKS INERTED CLASS I PRODUCT** > 10,000 < 150,000 BARRELS	1 X D	1 X D	1 X D	1 X D	1 X D	1 X D			
PRESSURE STORAGE VESSELS SPHERES AND SPHEROIDS	1.5 D 100' MIN	1.5 D 100' MIN	1.5 D 100' MIN	2 X D	1.5 D 100' MIN	1.5 D 100' MIN	1 X D 50' MIN		
PRESSURE STORAGE VESSELS DRUMS AND BULLETS	1.5 D 100' MIN	1.5 D 100' MIN	1.5 D 100' MIN	2 X D	1.5 D 100' MIN	1.5 D 100' MIN	1 X D 100' MIN	1 X D	
REFRIGERATED DOME ROOF STORAGE TANKS	2 X D 200' MIN	2 X D 200' MIN	2 X D 200' MIN	2 X D	2 X D 200' MIN	2 X D 200' MIN	1 X D 100' MIN	1 X D 100' MIN	1 X D 100' MIN

D = Largest Tank Diameter
1 barrel = 42 gallons = 159 L
°C = (°F-32) x 0.555
1 ft = 0.305 m

*For Class II, III products, 5 ft spacing is acceptable.
**Or Class II or III operating at temperatures > 200°F.

TABLE 3. Storage Tank Spacing Recommendations For Oil And Chemical Plants.

Placing of Equipment

1) Divide the processing area into unit areas such as:

- Feed storage
- Feed preparation
- Reaction
- Product purification
- Product packaging and storage
- Pollution control (waste preparation for disposal)

2) Apply the previously mentioned guidelines

Placing of Equipment

3) Try to group the units so that the number of operating personnel is minimized

4) "Maximum Loss" concept

- Some companies place a limit on the maximum loss that can be expected if a fire or explosion occurs: This means only a certain amount of equipment can be placed in any given area, which must be physically separated from other areas (by using, for example, fire walls).

Elevation

- If there is no special reason for elevating equipment, it should be placed at the ground level.
- Possible reasons to elevate some equipment:
  - To simplify plant operation
    - Example: Gravity feed of reactors from elevated tanks
  - To enable the system to operate.
    - Example: Steam jet ejector with an inter-condenser.
  - For safety.
    - Example: Reactors making explosive materials (TNT) usually are located above a large tank of water.

Maintenance

- Equipment which need cranes for maintenance should be located at plant perimeter or on a roadway (wide enough).
- Leave adequate space around equipment to allow for maintenance requirements (example: taking out the tubes of heat exchanger).

Railroads and Roadways

- Raw materials and/or product storage should be close to railroads/roadways.
- Road around perimeter of the site.
- There should be two ways to reach every location (for safety purposes).
- Minimize traffic congestion in the plant (by locating loading/unloading facilities plant offices, warehouses, personnel facilities near the main road).

Pipe Racks

- Place all pipes together:
  - ✓ This simplifies their construction
  - ✓ This simplifies locating problems

- Do not locate anything under pipe racks, because, if they leak, then they damage the underneath equipment.

Planning for future expansion (improvements)

- If linear distance between all parts was increased by 25%, the initial cost would increase only by 3% !!!
- Expansion and improvement of existing facilities
  - Get copies of engineering flowsheets and plot plans of existing site.
  - Check if they are correct
  - May want to photograph the plant area from an airplane.

Techniques Used in Preparing Site and Plant Layout

- Simple physical models of plant layouts can be made using cardboard or rectangular and cylindrical blocks. A scale of 1:30 may be used for major projects.
- Currently Computer Aided Design tools are being increasingly used for plant layout studies. Such models are replacing previously used physical models.
- Several proprietary software are available for the generation of 3D models of plant layout and piping.
- One can zoom in on a section of a plant and view it from various angles.
- A virtually 3D walk through the plant is also now possible.

Computer Generated 3D Plant Layout Model

- Advantage:

  Ease of information transfer.

- Expert systems and optimization algorithms can be incorporated in the package to assist the designer to find the best practical layout.

Footprint Universal Quick Estimator

Base Formula:

- Total Footprint = Base Area × Multiplier
- Where Base Area = Actual equipment footprint

1. Distillation/Absorption Columns:

Footprint (m^2) = $\pi \times (D + A)^2$

Where: D = Column diameter (m)

A = Access allowance (m)

Access Allowance (A):

- Indoor: 1.5-2.0m
- Outdoor: 2.0-3.0m
- Hazardous service: 3.0-4.0m

Quick: Footprint ≈ $5 \times \pi \times (D/2)^2$

Equipment Type	Multiplier	Notes
Columns/Towers	4-8	Height dependent
Reactors	5-10	Hazard dependent
Tanks (atmospheric)	2-4	Maintenance access
Heat Exchangers	3-6	Bundle removal
Pumps/Compressors	4-8	Vibration isolation
Furnaces/Heaters	8-15	Safety zones
Filters/Centrifuges	5-9	Material handling

2. Horizontal Vessels:

Footprint (m^2) = $(L + 3) \times (D + 2)$

Where: L = Vessel length (m)

D = Vessel diameter (m)

Quick: Footprint $\approx 1.5 \times (L \times D)$

3. Storage Tanks:

Atmospheric tanks: Footprint $\approx 2 \times \pi \times (D/2)^2$

Pressure vessels: Footprint $\approx 3 \times \pi \times (D/2)^2$

4. Shell & Tube Exchangers:

Footprint (m^2) = $(L + 2) \times (D + 1.5)$

Where: L = Tube length (m)

D = Shell diameter (m)

Quick: Footprint $\approx 0.05 \times$ Area (m^2)

Example: 200 m^2 exchanger → 10 m^2 footprint

5. Air Coolers:

Footprint (m^2) = 1.2 × (L × W)

Where: L = Bundle length

W = Bundle width

Add 3m clearance for fan maintenance

6. Plate Heat Exchangers:

Footprint ≈ 2 × (Frame area)

7. Pumps:

Footprint (m^2) = 4 × (L × W)

Where L,W = Pump baseplate dimensions

Centrifugal pumps: 3-6 m^2 per pump

Positive displacement: 4-8 m^2 per pump

8. Compressors:

Reciprocating: Footprint ≈ 8 × (L × W)

Centrifugal: Footprint ≈ 6 × (L × W)

Add 2m all around for maintenance

9. Agitators/Mixers:

$$\text{Footprint} \approx \pi \times (D + 3)^2$$

Where D = Tank diameter

10. Stirred Tank Reactors:

$$\text{Footprint } (m^2) = \pi \times (D + M)^2$$

Where: M = 3m (non-hazardous), 5m (hazardous), 8m (highly hazardous)

Quick: $\text{Footprint} \approx 7 \times \pi \times (D/2)^2$

11. Fixed Bed Reactors:

$$\text{Footprint} \approx 5 \times \pi \times (D/2)^2$$

12. Fluidized Bed Reactors:

$\text{Footprint} \approx 8 \times \pi \times (D/2)^2$ (due to ancillaries)

13. Filters:

Plate & frame: Footprint ≈ 3 × (L × W)

Rotary drum: Footprint ≈ π × (D + 3) × (L + 2)

14. Centrifuges:

Basket type: Footprint ≈ $(2.5D)^2$

Decanter: Footprint ≈ (L + 4) × (D + 3)

15. Dryers:

Rotary: Footprint ≈ (L + 4) × (D + 3)

Spray: Footprint ≈ π × $(D + 4)^2$

16. Fired Heaters:

Footprint ≈ 10 × (Radiant section area)

Or: Footprint ≈ 0.5 × Duty (MW)

Example: 10 MW heater → 50 m^2 footprint

Ethics in Engineering Design

- Ethics is a branch of philosophy that addresses the moral principles which govern a person's behaviour or the conducting of an activity. Ethics is a tool that enables a moral person to determine the right conduct in a situation.
- Professional ethics are principles that govern the behavior of a person or a group of persons in a business environment.
- Professional ethics addresses the concern for moral issues that arise because of the specialized knowledge of a professional and how the use of this knowledge should be governed when providing service affecting all stakeholders such as individuals, organizations and the public in general.

Ethics in Engineering Design

- Engineering is an important profession and has a direct and vital impact on the quality of life on mankind.
- The services provided by the engineers require honesty, impartiality, fairness and equity and must be dedicated to the production of the public health, safety and welfare.
- Engineering design ethics concerns issues that arise during the design of technological products processes systems and services. This includes issues such as safety, sustainability and clients and users privacy.

Advantages/Disadvnatages of Modular Construction

- Modular construction:

  Assemble sections of a plant at the plant manufacture's (EPC) site and then transported to the plant site.

- Advantage of modular construction are:
  1. Improved quality control,
  2. Reduce construction cost
  3. Less need for skilled labour on site
- Some of the disadvantages are:
  1. Higher design cost
  2. More structural steel work
  3. More flanged connections

Example 1: Reflux Drum for a Liquid-Liquid Extractor Footprint

Consider a separation process involving a mixture of an aqueous phase and an organic solvent (e.g., Toluene) in a decanter following a reaction. The objective is to calculate the drum's footprint using the provided data:

Operating Conditions: Pressure: Atmospheric (vented). Temperature: 40°C. Phase Densities: Organic Phase (Light): 865 kg/m^3 Aqueous Phase (Heavy): 990 kg/m^3

Flow Rates: Organic Phase: 8,000 kg/hr Aqueous Phase: 12,000 kg/hr Total Feed: 20,000 kg/hr

Heuristics:

- *Required Holdup Time: 5 minutes for each phase. This is the time from the interface level to allow for proper settling and to dampen flow fluctuations.*
- *Vessel Fullness: Typically 50% full of liquid to provide ample vapor space and a stable interface. The liquid volume is split between the two phases.*
- *Liquid drums usually are horizontal*
- *Drums for gas-liquid separation are vertical*
- *A length-to-diameter ratio of 3 is considered optimal*

1. Calculate Liquid Volumetric Flow:

- Organic Vol. Flow = 8,000 kg/hr / 865 kg/m³ = 9.25 m³/hr
- Aqueous Vol. Flow = 12,000 kg/hr / 990 kg/m³ = 12.12 m³/hr
- Total Liquid Flow = 9.25 + 12.12 = 21.37 m³/hr

2. Calculate Required Liquid Holdup Volume:

- We need 5 minutes of holdup for each phase within the vessel's separation section.
- Volume = Flow Rate × Time
- Organic Holdup Volume = 9.25 m³/hr × (5 min / 60 min/hr) = 0.77 m³
- Aqueous Holdup Volume = 12.12 m³/hr × (5 min / 60 min/hr) = 1.01 m³
- Total Liquid Holdup Volume = 0.77 + 1.01 = 1.78 m³

3. Determine Vessel Length (Based on Holdup):

For a horizontal vessel, the liquid volume is a function of the diameter and the length of the cylindrical section.

- For a drum that is 50% full, the cross-sectional area occupied by liquid is half of the total cross-sectional area.
- Total V = $\pi*(D/2)^2$ L = $\pi*(D/2)^2$ 3D = ¾ π D^3
- Actual volume = 2*1.78 = 3.56 m^2
- The required diameter of the drum D = 1.147 m
- Length of the cylindrical drum = 3*1.47 = 3.44 m
- We must also add space for inlet distributors, mist eliminators, and outlet weirs. Let's add ~1.5 m to the length for these internals
- Cylindrical Length: 3.44 m (for holdup) + 1.5 m (for internals) = 4.94 m
- Final Vessel Dimensions: Diameter (D): 1.2 m and Straight Length (T/T): 4.94 m

- $L/D = 4.94/1.2 = 4.12$ which is acceptable
- Total Length: Add the space for two 2:1 elliptical heads. Depth of one head = D/4 = 0.3 m.
- Total Overall Length (L): 4.94 m + (2 * 0.3 m) = 5.54 m

4- Estimate the Footprint

- A horizontal vessel's footprint is dominated by its length and the required maintenance access.
- Base Footprint:
  - The vessel itself has a diameter of 1.2 m and a total length of 5.54 m.
  - It will be supported by two saddles. The spacing of the saddles will be roughly the length of the vessel, so the base area is approximately 1.2 m x 5.54 m.

- *Add Maintenance Access Area:*
  - *We need access to manways (typically on both ends or on top), instruments, and valves.*
  - *We need space to pull the internal components (like the inlet distributor or weir plates).*
  - *A typical rule is to add 1.5 meters around the entire vessel.*
  - *Required Length Side: 5.54 m + (2 × 1.5 m) = 8.54 m*
  - *Required Width Side: 1.2 m + (2 × 1.5 m) = 4.2 m*
- *Calculate Footprint Area:*
  - *Footprint Area ≈ 8.54 m x 4.2 m = 35.87 m²*

Summary:

Parameter	Value	Notes
Function	Liquid-Liquid Separation Drum	
Holdup Time	5 min per phase	
Liquid Fill %	50%	
Diameter (D)	1.2 m	Dictated by settling
Total Length (L)	5.54 m	Includes heads & internals
L/D Ratio	4.94 / 1.2 = 4.12	Acceptable for separators
Vessel Footprint	1.2 m x 5.54 m	Vessel only
Required Layout Area	8.54 m x 4.2 m	Includes access
Area (m^2)	~35.87 m^2	For plot plan

Footprint Sketch

```
+------------------------------------------------------------+
|                                                            |
|                   Maintenance Access Way                   |
|    +----------------------------------------------------+  |
|    |                                                    |  |
|    |              (Weirs & Manways)                     |  | 4.2 m
|    |       +--------------------------------+           |  |
|    |       |================================|           |  |
|    |       |    HORIZONTAL VESSEL (1.2m Ø) |           |  |
|    |       |================================|           |  |
|    |       |  AQ. Out  | Interface | Org. Out |         |  |
|    |       +--------------------------------+           |  |
|    |                                                    |  |
|    +----------------------------------------------------+  |
|                   Maintenance Access Way                   |
+------------------------------------------------------------+
                        8.54 m
```

Example 2: Pharmaceutical Intermediate Plant (Layout Calculation)

Using the project specifications for a manufacturing facility that will produce 5,000 tons per year of Acetylsalicylic Acid (ASA) intermediate using a batch process operated in 3 shifts, and given that the available site area is 200 m × 150 m (a total of 30,000 m²), use the values from the provided table of design parameters to determine the final plant layout parameters for the proposed plant.

Equipment	Qty	Dimensions (m)	Area Required (m²)	Notes
Reactor R-101	3	3.0 × 4.5	28.3 each	Glass-lined
Storage Tank T-201	4	4.0 × 6.0	50.3 each	Raw material
Centrifuge C-301	2	3.5 × 2.5 × 2.8	8.75 each	
Dryer D-401	2	2.5 × 4.0	19.6 each	
Heat Exchanger E-101	3	2.0 × 1.5 × 3.0	3.0 each	
Pump P-101	6	1.5 × 1.0	1.5 each	
Control Room	1	15 × 10	150	
Warehouse	1	40 × 30	1,200	

A. Process Unit Area Calculation (Gross Equipment Area Method)

Base equipment area:

- Reactors: 3 × 28.3 = 84.9 m²
- Tanks: 4 × 50.3 = 201.2 m²
- Centrifuges: 2 × 8.75 = 17.5 m²
- Dryers: 2 × 19.6 = 39.2 m²
- Heat Exchangers: 3 × 3.0 = 9.0 m²
- Pumps: 6 × 1.5 = 9.0 m²
- Total equipment footprint = 360.8 m²

Add maintenance access (factor of 2.5-4.0, using 3.0):

- Process area required = 360.8 × 3.0 = 1,082.4 m²

Add piping/electrical space (30%):

- Total process area = 1,082.4 × 1.3 = 1,407 m²

B. Building & Structure Areas

- Control room: 150 m²
- Warehouse: 1,200 m²
- Utilities area (estimated): 500 m²
- Administration: 300 m²
- Laboratory: 200 m²
- Substation: 100 m²
- Total building area = 2,450 m²

C. Safety Distance Calculations

Fire Protection Distances

- Using NFPA 30 guidelines for Class IB flammable liquids:

Equipment Type	Minimum Separation (m)
Between reactors	3.0 m
Reactor to property line	15.0 m
Flammable storage to control room	22.5 m
Tank to tank (flammable)	Diameter/2 = 2.0 m (Rule of thump)

Blast Distance Calculation

For pressure equipment (8 bar design):

- Blast distance = K × (P × V) $^{(1/3)}$

  Where: K = 6 (for populated areas)

  P = 8 bar

  V = Reactor volume = 32 m^3

- Blast distance = 6 × (8 × 32)$^{(1/3)}$ = 6 × (256)$^{(1/3)}$ = 6 × 6.35 = 38.1 m

Therefore, place reactors > 38m from control room.

D- Site Utilization Calculation

- Total site area = 30,000 m^2
- Process area = 1,407 m^2
- Building area = 2,450 m^2
- Roads & pathways (20% of TA) = 6,000 m^2
- Green belt/safety buffer (30% of TA) = 9,000 m^2

  Total used = 1,407 + 2,450 + 6,000 + 9,000 = 18,857 m^2

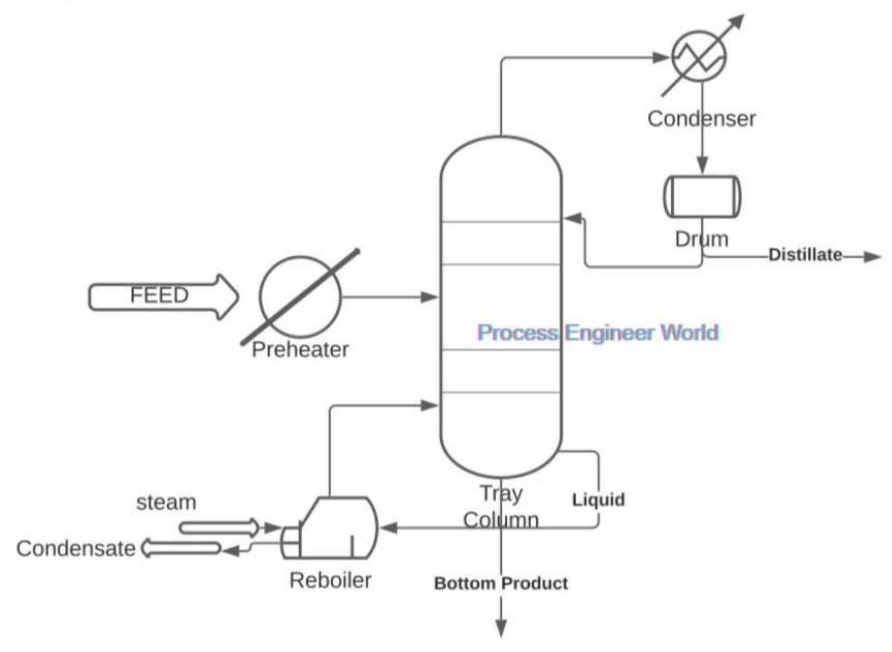
  Site utilization = 18,857 / 30,000 = 62.9% ✓ (Acceptable: 60-70%)

Final Layout Parameters

Parameter	Value	Standard
Process area	1,407 m^2	4.7% of site
Building coverage	8.20%	< 15% (local code)
Green area	9,000 m^2	30% (required)
Safety distances	All meet NFPA	Verified
Road width	6.0 m main, 4.0 m access	OSHA compliant

Example 3: Distillation Column System Footprint Calculation

How would you calculate the total required footprint area for the complete distillation column system, given the equipment specifications (distillation column: diameter 2.5 m and height 30 m; reboiler: shell diameter 2.2 m and length 4.5 m; condenser: shell diameter 1.8 m and length 4.0 m; reflux drum: diameter 1.8 m and length 3.6 m; plus two centrifugal pumps), and incorporating adequate spacing for equipment installation, maintenance access, and safety clearances?



1: Base Equipment Footprint

1. Column footprint:

   Area = $\pi \times (D/2)^2 = 3.14 \times (1.25)^2 = 4.91\ m^2$

2. Reboiler footprint: Shell & tube dimensions:

   For 200 m^2 area, typical size: 2.2m × 4.5m long

   Area = $2.2 \times 4.5 = 9.90\ m^2$

3. Condenser footprint:

   For 150 m^2 area: 1.8m × 4.0m long

   Area = $1.8 \times 4.0 = 7.20\ m^2$

4. Reflux drum footprint:

   Area = $\pi \times (0.9)^2 = 2.54\ m^2$

5. Pump footprint (each):

   Size: $1.5m \times 0.8m = 1.20\ m^2$

   Two pumps: $2.40\ m^2$

Total base footprint = $4.91 + 9.90 + 7.20 + 2.54 + 2.40 = 26.95\ m^2$

2: Add Operational & Maintenance Access

A. Maintenance zones:

1. Column:
   - Tray removal: Need space for 4m long trays
   - Access one side: 3.0m minimum
   - Area increase = $(2.5 + 3.0) \times 3.0 = 16.50\ m^2$
2. Heat exchangers:
   - Tube bundle removal: [Length + 3m]
   - Reboiler: $[4.5 + 3.0] \times 2.2 = 16.50\ m^2$
   - Condenser: $[4.0 + 3.0] \times 1.8 = 12.60\ m^2$

B. Operational access:

- Walkways: 1.2m wide around equipment
- Pipe racks: 3.0m wide corridor

Step 3: Structural Requirements

Column foundation:

- Baseplate size: 3.5m × 3.5m = 12.25 m^2
- Skirt access: +1.0m all around
- Foundation area = $(3.5 + 2.0)^2 = 5.5^2 = 30.25\ m^2$

4: Final Footprint Calculation

Component	Dimensions	Area (m^2)
Base equipment		26.95
Maintenance zones		45.6
Walkways (1.2m)		28.8
Pipe rack corridor	3m × 8m	24
Column foundation	5.5m × 5.5m	30.25
Instrumentation		8
Contingency (15%)		24.84

Total footprint = 188.44 m^2 ≈ 190 m^2

Chemical Plant Design

Plant Location

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

Outlines

- Plant Location: how to select
- General Considerations
- Factors to Consider

Introduction

- When a new project has been approved, it is necessary to:
  - Choose the location where the plant will be constructed.
  - Provide many additional diagrams that are needed during the planning and construction phases. Although these diagrams do not provide additional process information, they are essential to the successful completion of the project. Some of these are the utility flow sheet, plot plans, elevation diagrams, piping isometrics, etc.
- In other words, it is desired to know where facilities should be located and how facilities should be arranged.

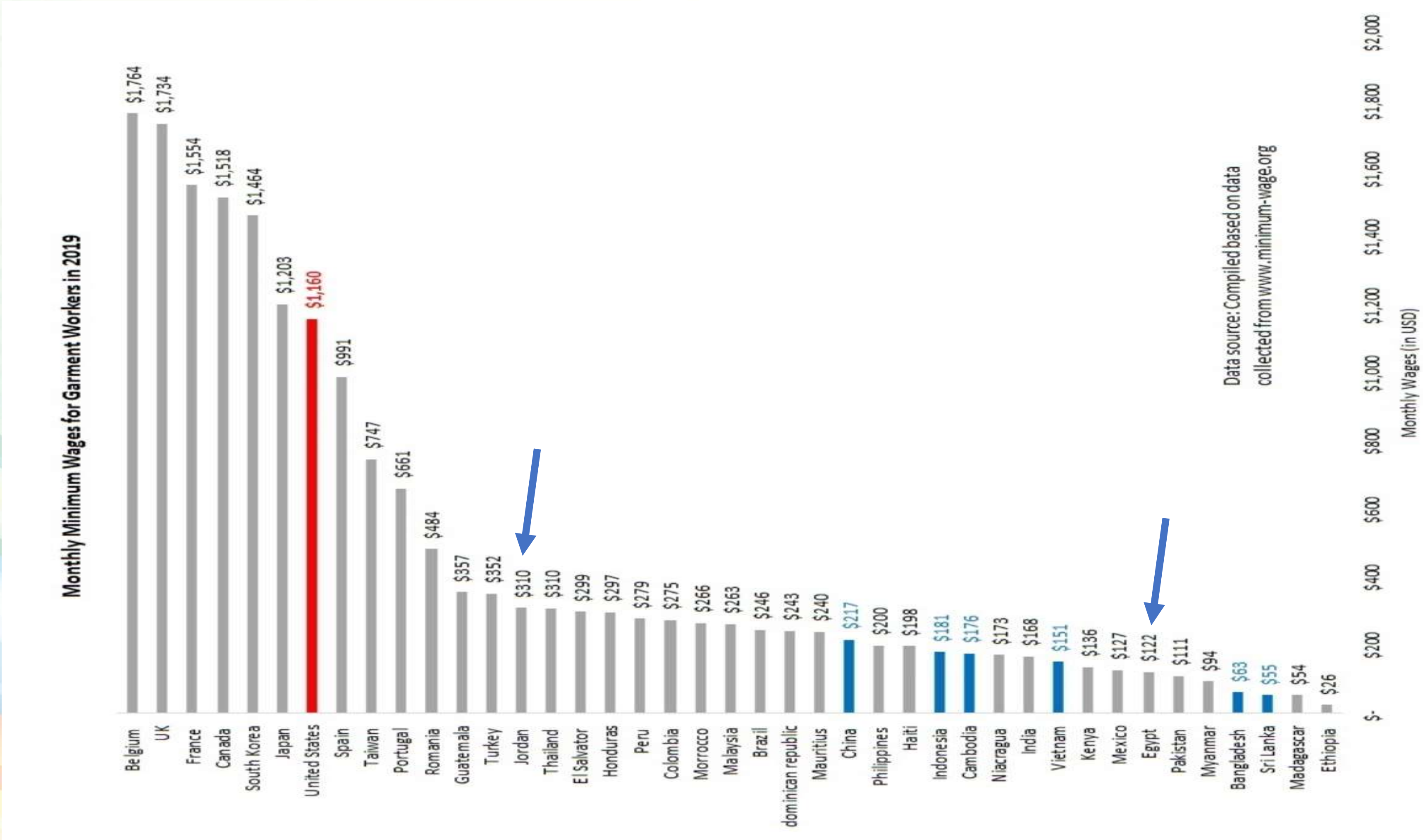
Choosing a Location

- Choosing a location must be made with the objective to maximize benefit. Remember that choosing a location
  - ✓ Is a long-term decision
  - ✓ Is difficult to reverse
  - ✓ Affects the fixed and variable costs
  - ✓ Dictates transportation costs
  - ✓ Is subject to other costs: taxes, wages, etc.
- There is a fierce competition amongst all countries to attract companies by providing them with many incentives. Until a global and ethical attitude is put in place for the benefit of all human beings, this competition will dictate the market.

- Ranking of the Business Environment
  - Political Stability: Risk of government collapse, corruption, etc.
  - Economic Policy: Tax rates, trade openness, fiscal policy.
  - Regulatory Environment: Ease of starting a business, property rights, legal framework.
  - Infrastructure: Quality of transportation, telecommunications, and utilities.
  - Macroeconomic Conditions: Inflation, exchange rate stability, interest rates.

1997 – 2001

1 Netherlands	11 Finland
2 Britain	12 Belgium
3 Canada	13 New Zealand
4 Singapore	14 Hong Kong
5 U.S.	15 Austria
6 Denmark	16 Australia
7 Germany	17 Norway
8 France	18 Ireland
9 Switzerland	19 Italy
10 Sweden	20 Chile


Monthly Minimum Wages for Garment Workers in 2019
Belgium $1,764
UK $1,734
France $1,554
Canada $1,518
South Korea $1,464
Japan $1,203
United States $1,160
Spain $991
Taiwan $747
Portugal $661
Romania $484
Guatemala $357
Turkey $352
Jordan $310
Thailand $310
El Salvator $299
Honduras $297
Peru $279
Colombia $275
Morrocco $266
Malaysia $263
Brazil $246
dominican republic $243
Mauritius $240
China $217
Philippines $200
Haiti $198
Indonesia $181
Cambodia $176
Niacragua $173
India $168
Vietnam $151
Kenya $136
Mexico $127
Egypt $122
Pakistan $111
Myanmar $94
Bangladesh $63
Sri Lanka $55
Madagascar $54
Ethiopia $26
Data source: Compiled based on data collected from www.minimum-wage.org
$- $200 $400 $600 $800 $1,000 $1,200 $1,400 $1,600 $1,800 $2,000
Monthly Wages (in USD)

Chemical Process Location

- The geographic location of the plant can have a crucial effect on the success of an industrial project and the scope for future expansion.
- Considerable care must be exercised in selecting a suitable site for a new project. Otherwise, the competitive advantage of the process can be lost.
- Provision must be made for the ancillary buildings and services needed for the plant operation and for the environmentally acceptable disposal of effluent.
- Key factors to consider:

low cost of production/distribution of products, scope for future expansion, safe living conditions, environmental and political issues.

Plant Location: Factors to Consider

The location of a new plant should be established when we complete the detailed estimate design. The key factors to be considered are:

❑ Availability and Price of Raw Materials, ❑ Prospective Markets for Products ❑ Energy Availability- Power and Fuel ❑ Transportation Facilities ❑ Environmental Impact and Effluent Disposal ❑ Taxation, Legal restrictions and Strategic Issues	❑ Climate ❑ Labor Supply ❑ Water supply ❑ Site or Land Characteristics ❑ Flood and Fire Protection ❑ Local Community Factors

1- Availability and Price of Raw Materials

- One of the most important factors that influences the selection of a plant site.
- Plants producing bulk chemicals are generally built near the source of major raw materials.
- Consider: purchased price of raw materials, Transportation expenses, Purity of raw materials, Reliability of supply and Storage requirements.
  - ✓ Ethylene plants: Many are located in the Middle East. The reason being the cheap source of ethane from natural gas is available there.
  - ✓ Oil refineries: tend to be located near ports and in regions of dense population or where there are clusters of industries, oil refinery produces many grades of fuel and a good market is required

- *When the quantity of the product is small compared with the amount of raw materials, the site is placed near the source of raw material.*
- *If a plant is to recover bromine from sea water, it will obviously be placed next to the sea, the bromine concentration of Dead sea water is about 5206 parts per million. So it is obviously more expensive to transport one million kg of water than 5200 kg or bromine.*

2- Prospective Markets for Products

- Proximity to the major market is an important consideration.
- The proximity of the market will affect the cost of product distribution, buyers tend to purchase from the nearby sources.
- Markets are needed for major final products as well as saleable by-products

- For Bulk Commodity Products such as cement, mineral acids, fertilizers, etcetera and Consumer Products, the production cost per metric ton is relatively low, but the cost of transport is a significant fraction of the sales price. Such plants should be located close to the primary market.
- This consideration is less important for low-volume production and high-priced products, such as pharmaceuticals

3- Energy Availability - Power and Fuel

- Electrical power is needed at all sites, electrolytic and electrometallurgical processes require cheap sources of electricity, they may be located near hydroelectric stations.
- If the plant requires large quantities of coal or oil, locate the plant near such a source. Ensure continuity of operation with tie-up by long-period contract.
- If gas is a basic raw material such as ammonia synthesis, synthetic gasoline, then availability of gas is the controlling factor as it is raw material, as well as source of heat and power.
- We have to consider the local cost of power. Then you can decide on whether to purchase power or you need to generate power on site.

4- Transportation Facilities

- The transport of materials and products to and from the plant is an important consideration for selection of plant location.
- Common Means of Transportations are water, railroads and highways.
- The kind and amount of materials or products will determine the convenient mode.
- Plant sites should preferably be close to at least two major forms of transport.
  - ✓ Road transport is suitable for local distribution from a central warehouse.
  - ✓ Rail transport is cheaper for long-distance transport of bulk chemicals.
  - ✓ Air transport is convenient for movement of personnel between plant and the company headquarters.

5- Climate

- Extreme Temperatures and Excessive Humidity at a site will increase cost and can badly influence the economic operation of a plant.
- Abnormally Low Temperatures require additional insulation and special heating for equipment and pipe runs.
- High Temperature will require special cooling towers or air conditioning equipment.
- Stronger structures are needed at locations subject to high winds such as cyclone prone areas or areas which have a history with earthquakes or prone to earthquakes.

6- Labour Supply

- Labour Supply is another very important factor that must be considered for plant location.
- The type and supply of workers available in the vicinity of a proposed plant site must be examined.
- Both skilled and unskilled workers are required for construction of the plant and its operation.
- Skilled craft workers such as electricians, welders and pipefitters will be needed for plant maintenance.

7- Water Supply

- *In general, process industries use large quantities of water for cooling, washing, steam generation and also as raw material.*
- *Reliable supply of water is required, a large river or lake is preferable. Deep wells or artesian wells will be satisfactory, if less amount of water is required in your plant.*
- *The level of the existing water table should be checked. If the water supply shows seasonal fluctuations, cost of constructing reservoir or standby wells should be considered.*
- *Quality of water and cost of purification treatment should also be considered.*

8- Environmental Impact and Effluent Disposal

- Almost all industrial processes produce waste products. The difficulties and cost of their disposal should be considered.
- There are legal restrictions on the disposal of toxic and harmful effluents.
- The permissible tolerance levels for various methods of waste disposal should be considered very carefully.
- We have to see whether we need additional waste treatment facilities for the plant or not.
- If needed then this will add to your cost the sites selected for a plan should have adequate capacity and facilities for correct waste disposal.
- An environmental impact assessment should be made for each project.

9- Taxation, Legal restrictions and Strategic issues

- Tax rates on income, local building codes, law and order situation should be considered.
- Capital grants, tax concessions and other incentives are often given by the government to direct new investment to preferred locations (areas of high unemployment).
- Special Economic Zone where if you invest you can enjoy Duty free export, Tax incentive, Government also gives Seed Funding Support.
- In today's globalized economy, the determination of the plant location is even a more difficult problem.

10- Site or Land characteristics

- The characteristics of the land at a proposed plant site may strongly affect construction cost. The land should ideally be flat, well drained and have suitable load-bearing characteristics.
- The cost of the land is important as well as local building costs and living conditions.
- Sufficient suitable land must be available for the proposed plant and also for future expansion.
- Particular care must be taken for reclaimed land near the ocean in earthquake zones because of the poor seismic character of such land.

11- Flood and Fire protection

- Many industrial plants are located along rivers or large water bodies. So there is a risk of flood.
- Local flooding history should be examined and the consequences of such occurrences should be considered.
- Protection from losses by fire is another important factor in selecting a plant location. Assistance from the outside fire department should be available.
- Fire hazards in the immediate area surrounding the plant side should also be considered.

12- Local Community Factors

- The proposed plant should be acceptable to the local community. The plant should not be seen as a risk to the local population.
- Some communities welcome new plant construction as a source of new job opportunity and economic prosperity. More affluent communities may actively discourage chemical plant construction.
- The local communities should have adequate facilities for satisfactorily living of plant personnel: schools, banks, housing, recreational and cultural facilities.

Plant Location: Factors to Consider: Conclusion

- In most cases, it is not possible to select plant location considering one or two factors.
- We can pick few promising sites and perform a weighted-score analysis of the various plant location factors.
- We may start with say 20 possible sites, then after careful analysis of various factors, we may bring down the list to 4 to 5 equally attractive sites.
- The final choice usually involves a very detailed consideration of economic factors for such equally attractive sites.
- Quantitative methods are used for consideration at the final stage such methods are: Factor Rating Method, Cost-Profit-Volume Analysis, Centroid Method, Linear Programming method, etcetera.

Example 1: Plant Location: Factor Rating Method

- The plant locations A, B and C are assigned ratings with respect to three factors.
- The weight to the factors, W1, W2 and W3 are also mentioned. We have to find the best plant location among A, B and C.

Location	Factors		
	Availability of skilled labor ($W_1 = 0.4$)	Availability of raw materials ($W_2 = 0.35$)	Proximity to the markets ($W_3 = 0.25$)
A	65	60	55
B	70	45	90
C	60	95	50

- find the sum of weighted scores for each location. The site with the highest weighted score is selected as the best choice.

Plant Location: Factor Rating Method: Example

- *Find the sum of weighted score for each location. The site with the highest weighted score is selected as the best choice.*

Location	Factors			Total
	Availability of skilled labor ($W_1 = 0.4$)	Availability of raw materials ($W_2 = 0.35$)	Proximity to the markets ($W_3 = 0.25$)	
A	*(65)(0.4) = 26*	*(60)(0.35) = 21*	*(55)(0.25) = 13.75*	*60.75*
B	*(70)(0.4) = 28*	*(45)(0.35) = 15.75*	*(90)(0.25) = 22.5*	*66.25*
C	*(60)(0.4) = 24*	*(95)(0.35) = 33.25*	*(50)(0.25) = 12.5*	*69.75*

Then the best location is C

Plant Location: Cost-Profit-Volume Analysis

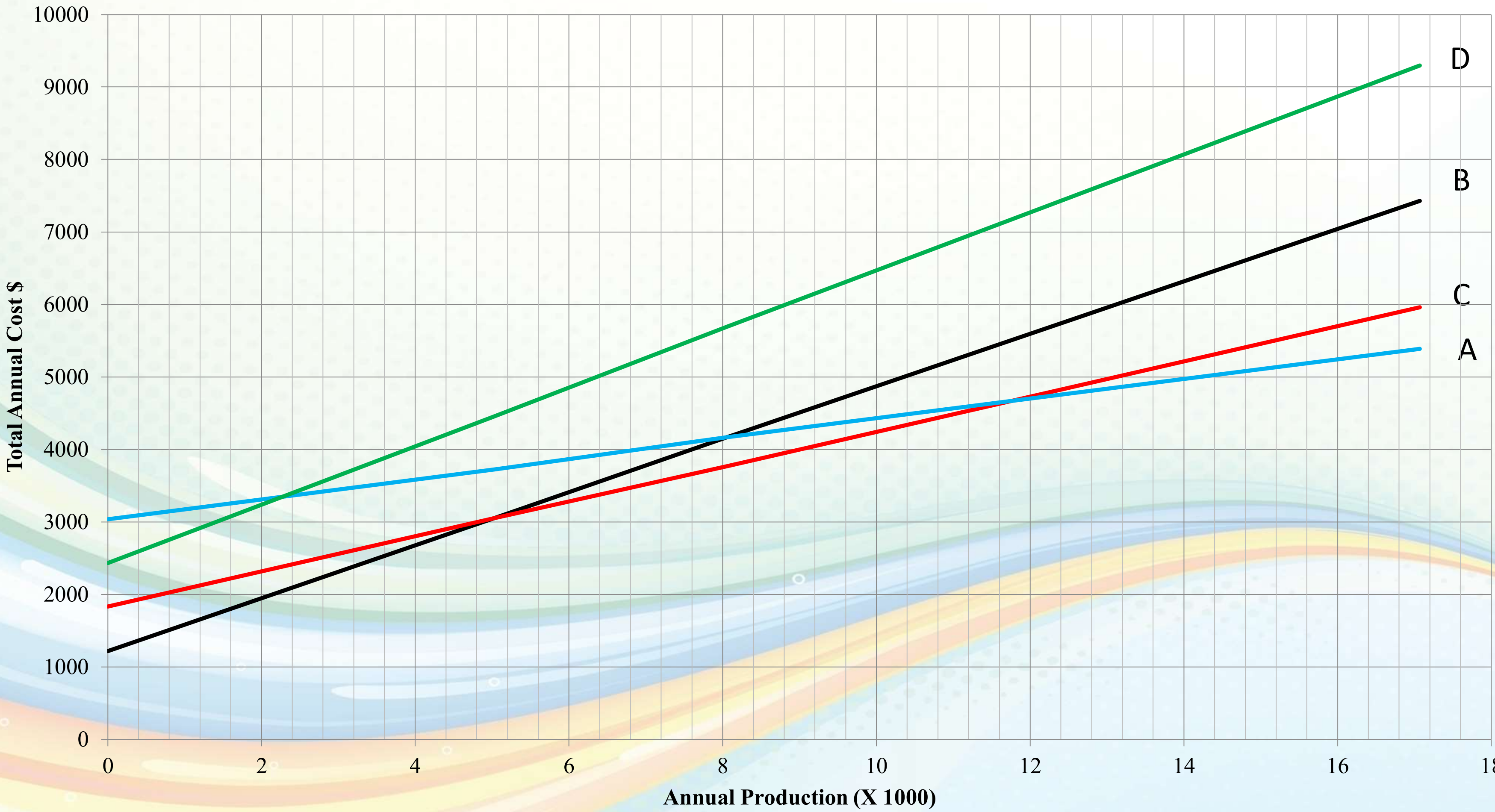
1. Determine the fixed cost and the variable cost associated with each possible location.
2. Plot the total cost lines for all location alternatives on the same graph.
3. Determine which location will have the lowest total cost for the expected level of production output.

- Alternatively determine which location will have the highest profit.
- Assumptions:
  - ✓ Fixed costs are constant for the range of probable output
  - ✓ Variable costs are linear to the range of probable output
  - ✓ The required level of output can be estimated well
  - ✓ Only one product is involved.

Plant Location: Cost-Profit-Volume Analysis: Example

Location	Annual fixed cost ($)	Variable Cost / unit ($)	Total Cost ($)
A	3000	0.1320	4320
B	1200	0.3600	4800
C	1800	0.2400	4200
D	2400	0.4200	6600

- The expected output (Q) at the selected locations = 10000 units.
- Which location would be best?


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Total Annual Cost $
0
2
4
6
8
10
12
14
16
18
Annual Production (X 1000)
D
B
C
A

Example 2: Site Selection for a New Acrylic Acid Plant

Build a new, world-scale plant to produce 200,000 metric tons per year of Acrylic Acid, a key ingredient for paints, adhesives, and superabsorbent polymers.

Solution:

Based on the requirements, the team identifies three potential regions:

1. Gulf Coast, USA (e.g., Texas/Louisiana)
2. Rotterdam Area, Netherlands
3. Singapore

Factor	Weight	Gulf Coast, USA	Score	Weighted Score	Rotterdam, EU	Score	Weighted Score	Singapore	Score	Weighted Score
Raw Material (Propylene) Proximity	10	Abundant from local refineries	10	100	Good supply via pipeline	8	80	Must be imported; higher cost	6	60
Utility & Energy Cost	9	Low-cost natural gas & electricity	10	90	Moderate energy costs	7	63	High energy costs	6	54
Labor Availability & Cost	8	Skilled pool; moderate cost	8	64	Skilled pool; high cost	7	56	Skilled pool; very high cost	6	48
Transportation & Logistics	8	Good (ports, rails, pipelines)	9	72	Excellent (major global hub)	10	80	Excellent (major global hub)	10	80
Environmental Regulations	7	Well-understood but strict	7	49	Stringent EU laws; slower permits	6	42	Very strict but efficient	8	56
Political & Economic Stability	7	High	9	63	Very High	10	70	Very High	10	70
Water Availability	6	Abundant	9	54	Good (from Rhine)	8	48	Limited; requires desalination	5	30
Incentives & Tax Breaks	5	Attractive local incentives	8	40	Moderate EU incentives	6	30	Very attractive government packages	9	45
Total Weighted Score				532			469			443

Recommendation: Select the Gulf Coast, USA site.

Justification:

- *Overwhelming Economic Advantage: highest scores on the two most critical factors.*
- *Balanced Strengths: While it may not be the absolute best in every category (like logistics), it is strong across the board. It has abundant water, a skilled labor force, and good infrastructure.*
- *Manageable Risks: The regulatory environment is well-known to the company, and the political risk is low. The initial cost advantage provides a buffer against market fluctuations.*

Why not the other sites?

- *Rotterdam: Its strategic position and superior logistics infrastructure make it an ideal hub for European market operations, but higher energy costs and stricter, slower regulatory processes reduce its overall attractiveness.*
- *Singapore: A world-class logistics hub with fantastic stability and incentives. However, the lack of local raw materials and the very high costs of energy and water make it the most expensive.*

Chemical Plant Design

Process Utilities

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

Outlines

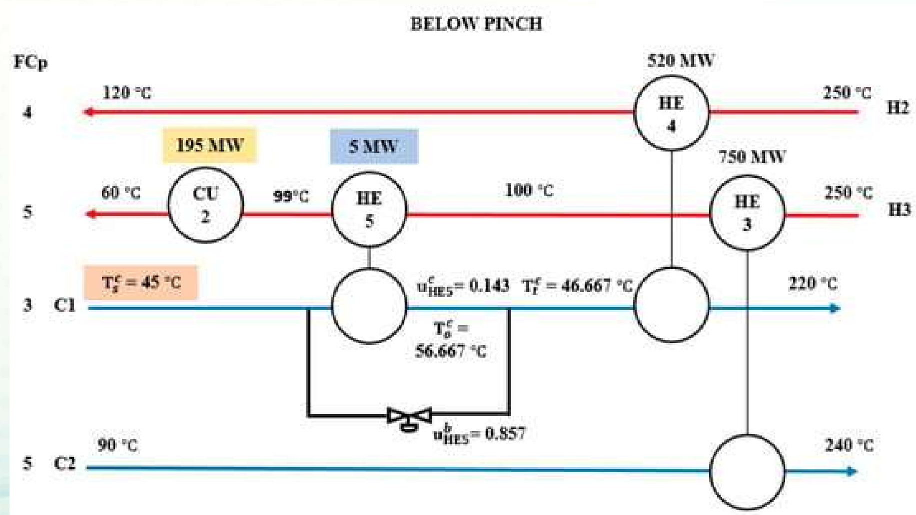
- *Process utilities*
- *Utility flow diagram*
- *Numerical examples*

Chemical Process Utilities

- Not many chemical processes are carried out entirely at ambient temperature. They are carried out at various temperatures depending on what temperature will be the optimum temperature for the particular process.
- So routinely process streams need to be heated up or pulled down to reach the desired operating temperature to add or remove heat of reaction, to sterilize feed streams or to cause vaporization or condensation etc.
- Solids are usually heated or cooled by direct heat transfer.

Chemical Process Utilities

- *Gas and liquid streams are usually heated or cooled by indirect heat exchanger with another fluid-either a process steam or utility stream such as steam, hot oil, cooling water, refrigerant*



- *The consumption of energy is a significant cost in many processes. Energy cost can be reduced by recovering waste heat from hot process streams and by making use of the fuel value of waste streams*

Chemical Process Utilities

- Utilities refer to the ancillary services needed in the operation of any production process. These services are normally supplied from a central site facility and include:

➢ Fuel for fired heaters ➢ Fluids for process heating : ✓ Steam ✓ Hot oil or specialized heat transfer fluids ➢ Process water: ✓ Water for general use ✓ Demineralized water	➢ Fluids for process cooling ✓ Cooling water ✓ Chilled water ✓ Refrigeration systems ➢ Compressed air ➢ Inert-gas supplies which is usually nitrogen ➢ Electricity

Chemical Process Utilities

- Many plants generate utility at site or get supply from company-owned central station facility.
- The price charged for a particular utility is mainly determined by the operating cost of generating and transmitting the utility stream.
- The utility is generated at site, this must be included as part of capital cost.
- Some smaller plants purchase utilities from a supplier (utility company).
- In such cases the utility prices are set by contract between these two companies and generally depend on the price of natural gas, fuel oil, electricity etc.

Chemical Process Utilities

- The utility consumption of a process cannot be estimated accurately without you complete material balance, energy balance as well as heat integration.

Chemical Process Utilities: Energy

- The most common sources of energy are:
  - Petroleum oil
  - Natural gas
  - Coal, coke
  - Nuclear energy
  - Alternate sources which we must think to use more and more in future.
- In the chemical industries, power is supplied primarily in the form of electrical energy and steam energy.
- Some of the intensive energy intensive companies are Bulk Chemicals Manufacturer, Refineries, Mining etc.

Chemical Process Utilities: Electricity

- The electricity demand in chemical plants is mainly for electrochemical processes, Agitators, Blowers, Pumps, Compressors, Air coolers, Solids-handling operations, Motor drives, Instrumentation, Lighting etc.
- The power required may be generated on site or may be purchased from the local supply company.
- Some plants generate their own electricity using a gas-turbine cogeneration plant with a heat recovery system generator; waste- heat boiler to raise steam.
- The overall thermal efficiency of such systems can be in the range of 70 to 80% compared with the 30 to 40% obtained from a conventional power station.

Process Utilities: Use Electricity for Heating?

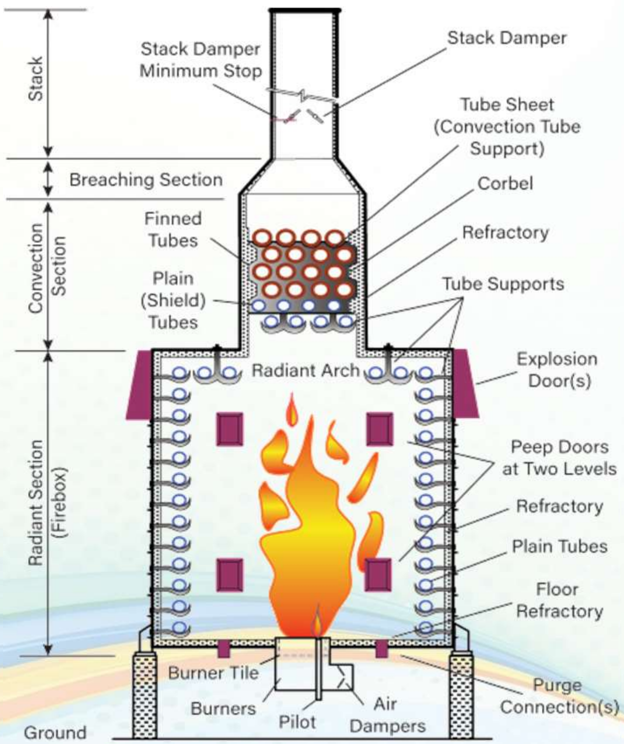
- Industrial power rates are a critical pre-investment consideration for manufacturers because electric heating is expensive.
- When the cost of heating is small fraction of overall process costs and there is need for rapid on/off heating, the electric heating may be used.
- For example, small scale batch operations.
- For large scale chemical plants, better we should use steam instead of electricity.

Process Utilities: Disadvantages of Electric Power

- Heat from electricity is much more expensive than heat from fuels because of the thermodynamic inefficiency of power generation.
- Electric heating requires very high power draws. This substantially increases the electrical infrastructure cost of the plant site.
- Electric heating apparatus are expensive, requires high maintenance and must comply with very stringent safety requirements.
- Steam heaters are intrinsically safer than electric heaters. If control fails, electric heaters have a higher probability of overheating.

Process Utilities: Fired Heat

- Fired heaters are used for process heating duties above the highest temperature that can be reached using high pressure steam typically above 250 °C using steam at 40 bar.
- Process streams may be heated directly in the furnace tubes or indirectly using a hot oil circuit or heat transfer fluid.



- The cost of fired heat can be calculated from the price of the fuel fired.
- Most fired process heaters use natural gas as fuel because natural gas as fuel is cleaner; it has low maintenance of burners and fuel lines.

Chemical Process Utilities: Steam

- Steam is the most widely used heat sources in most chemical plants.
- The heat of condensation of steam is high giving a high heat output per unit amount of utility at constant temperature compared to hot oil and flue gas that release sensible heat over a broad range of temperature.
- The temperature at which heat is released can be controlled by controlling the pressure of the steam.
- Condensing steam has very high heat transfer coefficients, so this will lead to low cost heat exchanger.
- Nontoxic, non-flammable and also inert to many process fluids

Chemical Process Utilities: Steam

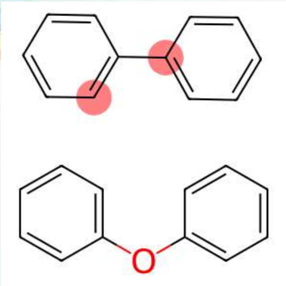
- The steam for process heating is usually generated in water tube boilers using the most economical fuel that is available.
- High pressure steam is typically available at above 40 bar corresponding to a condensing temperature up to 250 °C. High pressure steam is used for process heating at high temperatures.
- High pressure steam is expanded through steam turbines to form medium pressure steam, typically at 20 bar, corresponding to a condensing temperature of 212 °C.
- Medium pressure steam is used for intermediate temperature heating or expanded to form low pressure steam, typically at about 3 bar, condensing at 134 °C.

Chemical Process Utilities: Steam

- The low pressure steam can be used for process heating, dissolve non-condensable gases, stripping vapour, purging etc.
- High pressure steam, medium pressure steam or low pressure steam can also be expanded in condensing turbines to generate shaft work for process drives or electricity production.
- The prices of medium and low pressure steam are usually less than the price of high pressure steam.

Chemical Process Utilities: Hot Oil and Heat Transfer Fluids

- Where fired heat or steam are not suitable, circulating systems of hot oil or specialized heat transfer fluids are often used as heat sources.
- Heat transfer fluids and mineral oils are typically used for heating in the range of 50 to 400 °C.
- While using hot oil, the upper temperature limit is determined by thermal decomposition of the oil, fouling or coking of heat-exchanger tubes.
- Most common heat transfer fluids are mineral oils and Dowtherm A.
- Dowtherm A is an eutectic mixture of two stable organic compounds: biphenyl and diphenyl oxide.



Chemical Process Utilities: Cooling Water

- When a process stream requires cooling at high temperature, you must consider various heat recovery techniques such as transferring heat to a coold process stream, raising steam, preheating boiler feed water etc.
- Cooling water is the most commonly used cold utility in the temperature range of 120 to 40 ^{o}C.
- Air cooling is preferred in regions where water is expensive or the ambient humidity is too high for cooling water systems to operate effectively.

Chemical Process Utilities: Cooling Water

- If a process stream is to be cooled below 40 °C, cooling water or air cooling would be used to cool down up to 40 or 50 °C and then it will be followed by chilled water or a refrigeration down to the target temperature.
- Natural and forced-draft cooling towers are generally used to provide the cooling water required on a site.
- The minimum temperature that can be reached with cooling tower will depend on ambient temperature and humidity.
- When cooling tower is not efficient, air coolers or refrigeration are used.

Chemical Process Utilities: Cooling Water

- Refrigeration is needed for processes where cooling water cannot produce the target temperature.
- Vapor compression refrigeration machines are normally used.
- To cool down a process stream for temperatures down to around 10 degree Celsius, chilled water can be used.
- For further lower temperatures, say down to -30 °C, salt brines, sodium chloride, calcium chloride are commonly used.
- Large refrigeration duties are usually supplied by a standalone packaged refrigeration system.

Chemical Process Utilities: Water

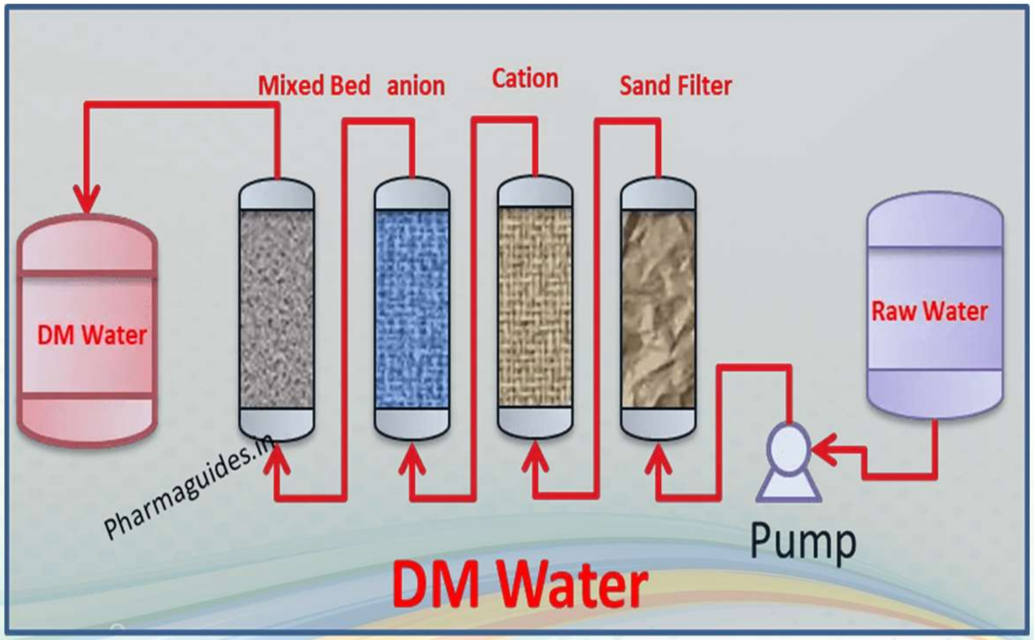
- Water is used in many process of processing operations such as chemical reactions, extracting, dissolving etc.
- It is also used for drinking, sanitary facilities, general cleanup, washing in fire hydrant etc.
- Water for industrial purposes can be obtained from one of the two general sources: first the plant's own source or second a municipal supply.
- If the demands for water are large, it is more economical for the plant to provide its own water source:
  - ✓ Drilled wells, Rivers, Lakes, Dammed streams etc.

Chemical Process Utilities: Water

- When municipal water is used, the price of water varies strongly by location depending on fresh water availability.
- The bulk water tariff for industries that use water as raw materials such as bottled water, soft drinks, etc. may be substantially higher as compared to other industries.

Chemical Process Utilities: Demineralized Water

- Demineralized water, from which all the minerals have been removed by ion exchange, is used where pure water is needed for process use.
- This is also used for boiler feed water.



- Mixed and multiple-bed ion-exchange units are used, one resin converting the cations to hydrogen and the other removing the anions.
- Water with less than 1 ppm of dissolving solids can be produced.

Chemical Process Utilities: Compressed Air

- Compressed air is needed for general use and for the pneumatic controllers that are usually used for chemical plant control.
- Rotary and reciprocating single-stage or two-stage compressors are used to generate compressed airs.
- Instrument air must be dry and clean and it should also be free from oil.
- Compressed air is also needed for oxidation reactions, air strippers, aerobic fermentations
- Air is normally distributed at a pressure of 6 bar.
- Large process air requirements are typically met with standalone air blowers or compressors.

Chemical Process Utilities: Cooling Air

- Ambient air is used as a coolant in many process operations: air cooled heat exchanger, cooling towers, prilling towers.
- Cooling air flow caused by natural draft is free, but the air velocity will generally be quite low.
- Fans or blowers are commonly used to ensure higher air velocities.

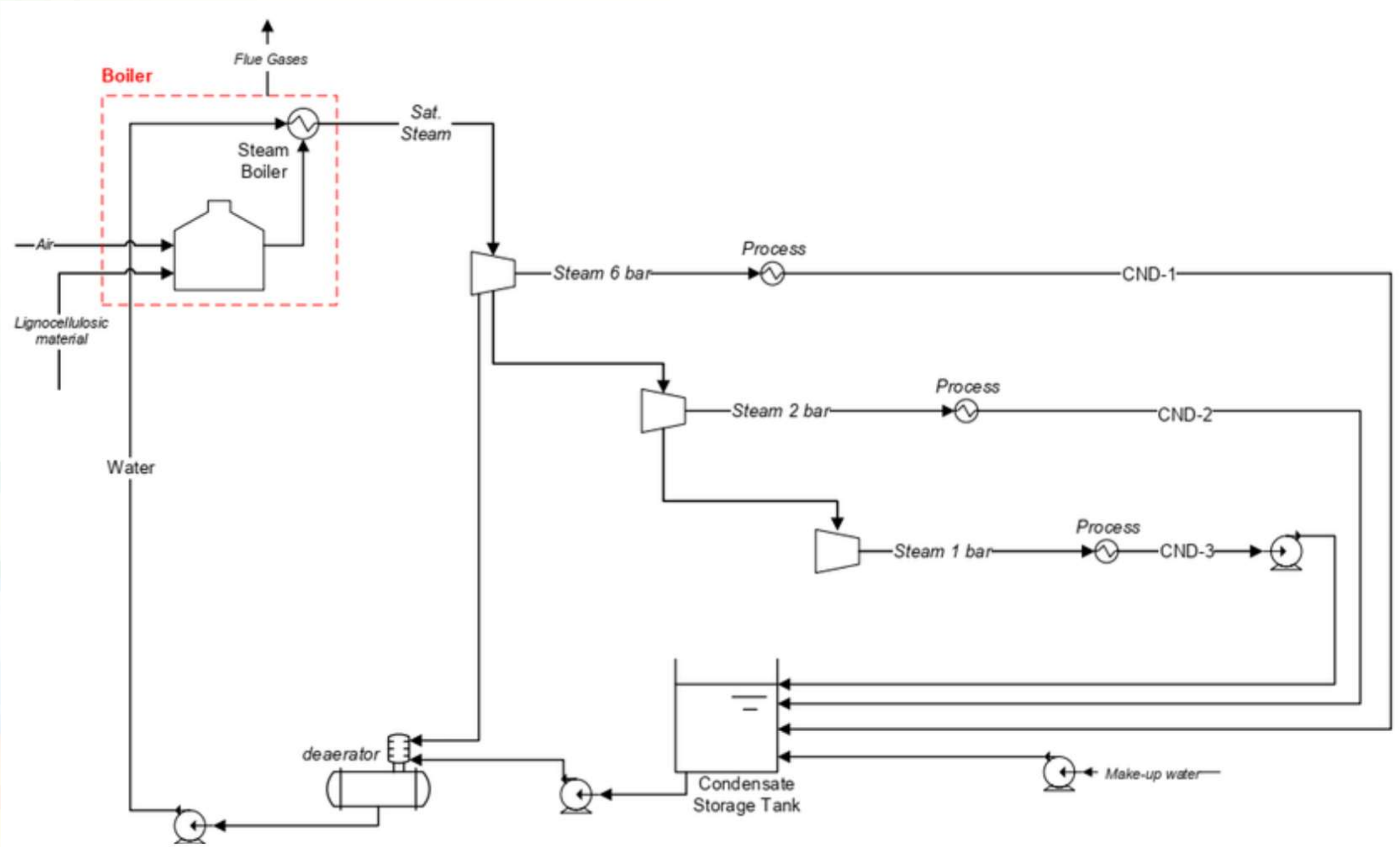
- The cost of cooling air may be computed from the cost of operating the fan, which can be determined from the fan power consumption.
- Cooling fans typically operate with very high flow rates and very low pressure drops about few inches of water.

Chemical Process Utilities: Inert Gases

- Where a large quantity of inert gas is required for the inert blanketing of tanks and for purging, this will usually be supplied from central facility.
- Nitrogen is normally used and can be manufactured on site in an air liquefaction plant or it may also be purchased as liquid nitrogen in tankers from utility supply companies.

Utility Flow Diagram

- Utility flow diagram provides information on the flows and characteristic of all the utilities used by the plant.
- It summarizes the interrelationship of utilities such as air, water, steam, heat transfer media, process vents and purges, safety relief blow-down etc. to the basic process.
- Utility flow diagram are prepared as a separate sheet when the amount of detail is too great to include on the process flow-sheet.
- Utility flow diagram is a useful diagram for optimization of the system to reduce consumption of both material and energy.



Flue Gases
Boiler
Sat. Steam
Steam Boiler
Air
Lignocellulosic material
Steam 6 bar
Process
CND-1
Steam 2 bar
Process
CND-2
Steam 1 bar
Process
CND-3
Water
deaerator
Condensate Storage Tank
Make-up water

Example 1:

Two design options (A and B) for a distillation system and these two options are being compared based on the total annual cost. The following information is available:

	Option A	Option B
Installed cost of the system	180000	144000
Cost of cooling water for condenser	7200	9600
Cost of steam for reboiler	19200	24000

The annual fixed charge amounts to 12% of the installed cost.

What is the total annual cost of the better option?

Example 1:

Example 2:

Estimate the annual cost of providing heat to a process from a fired heater using natural gas as fuel if the process duty is 5 MW and the price of natural gas is 1.5$ per Million BTU. Assume heater efficiency to be 85%, operating hours available in a year 8000 and also it is given that 1 BTU per hour is equal to 0.293071 watt.

Solution:

Example 3 (Sizing a Hot Oil Heater):

In a chemical plant, we are producing a specialty solvent. We need to heat a stream of this solvent before it enters a distillation column. The heating will be done using a shell and tube heat exchanger with a hot thermal oil on the shell side.

1. Process Stream Data (Tube Side - The Product to be Heated)

Fluid: Specialty Solvent (assume properties similar to Toluene for calculation)

- Mass Flow Rate = 15,000 kg/h
- Inlet Temperature = 25°C
- Outlet Temperature = 120°C
- Operating Pressure: 5 bar

Physical Properties of the Solvent (at average temperature):

- Average Temp = (25 + 120)/2 = 72.5°C
- Specific Heat Capacity (Cp_product) = 1.80 kJ/kg·°C (or 1800 J/kg·°C)

2. Utility Stream Data (Shell Side - The Heating Medium)

- Fluid: Therminol 66 (a common heat transfer oil)
- Inlet Temperature = 180°C (This is fixed by the heater)
- Outlet Temperature = 140°C (This is a design choice; we must not let the oil cool too much to avoid high viscosity)
- Operating Pressure: 3 bar

Physical Properties of Therminol 66 (at average temperature):

- Average Temp = (180 + 140)/2 = 160°C
- Specific Heat Capacity (Cp_{oil}) = 2.40 kJ/kg·°C (or 2400 J/kg·°C).

Example 4 (Multistage Compression of a Reactor Feed Gas):

In a petrochemical plant, a waste gas stream from a refining process is being repurposed. This gas, rich in ethylene, is fed to a polymerization reactor. The reactor operates at 30 bar (g), but the gas is available at near atmospheric pressure. Your task is to design the compression system.

1. Stream Data and Properties

- *Gas Composition:*
  - *Ethylene (C_2H_4): 85 mol%, Nitrogen (N_2): 10 mol%, and Methane (CH_4): 5 mol%*
- *Flow Rate: n_dot = 450 kg-mol/h (0.125 kg-mol/s)*
- *Source Conditions:*
  - *Pressure (P_1): 1.1 bar (a) and Temperature (T_1): 35°C (308 K)*
- *Destination Conditions:*
  - *Pressure (P_{2final}): 31 bar (a) (30 bar(g) + 1 atm)*

- *Gas Properties (Calculated from Composition):*
  - *Average Molecular Weight: ~28.2 kg/kg-mol*
  - *Specific Heat Ratio ($k = C_p/C_v$) = 1.18 (Ethylene-dominated)*

Chemical Plant Design

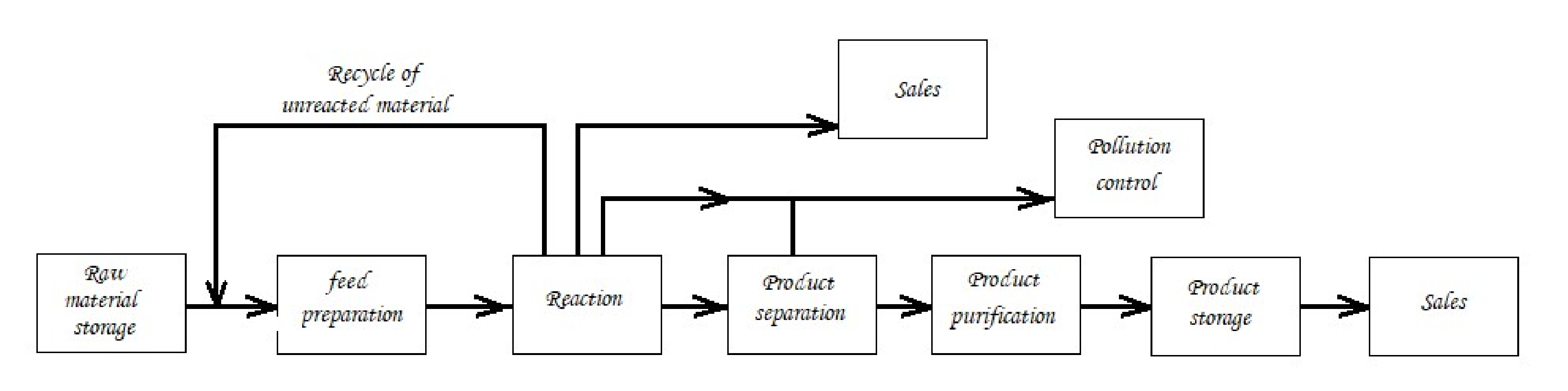
Selection of Process Equipment

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

Outlines

- Selection of process equipment
- Single Train or Dual Trains
- Buy or Build
- Proprietary and Non-proprietary
- Scale-up of Equipment in Design
- Process Equipment: Safety Factors
- Equipment specification
- Materials of construction
- Economics Involved in Selection
- Heuristics Rules for Process Equipment

Chemical Process Equipment



- A chemical engineering process is an assembly of several units. Each unit performs a specific operation.
- Plant design is concerned with the selection specification and design of equipment, so that each unit can perform specified functions.
- A logical step after Flow-sheet preparation is selection of:
  - ✓ Process equipment and
  - ✓ Suitable materials of construction for all parts of the plant.

Chemical Process Equipment

- For construction of plant, we need detailed design specifications and fabrication drawings for all equipment, including instruments wiring, piping and auxiliaries.
- Consider this: very few new ideas about processes ever actually materialize (< 1%, Douglas). Money spent to design such discarded proposals is lost forever.
- Thus we have to quickly identify appropriate equipment cost, so that the economic promise of future efforts can be predicted.
- Shortcut design techniques are used to obtain inexpensive answers with reasonable accuracy. Remember that, shortcut designs are no substitute for more rigorous designs required to actually build equipment, shortcut designs are adequate for the purpose of cost estimation.

Continuous Process: Single Train or Dual Trains

- *Decide whether the plant will be built as a single train or dual train plant.*

Single Train:

- ✓ *All the materials go through each unit*
- ✓ *Lower cost to build, but failure of any item in the plant will cause the shutdown of the entire plant*

Continuous Process: Single Train or Dual Trains

Dual trains:

- ✓ Two identical plants built side by side, and half the flow will go through each.
- ✓ More expensive to build but one we need will remain operative if the other one unit fails.

To avoid unplanned shutdown many items particularly valves control valves are purchased as spares and often installed in parallel with the operating ones

Chemical Process Equipment: Buy or Build

- Two roles played by engineers: Buyers and builders
- If you wish to acquire an automobile:
  - ✓ Build a car from scratch?
  - ✓ Buy a car made by specialist manufacturer?
- In both cases experience and judgment are valuable, but the levels of expertise and detailed knowledge required are very different.

Chemical Process Equipment: Terminology

Cookers, Coolers, Economizers, Kettles, Preheaters, Reboilers, Superheaters, Thermosyphons	All are heat exchangers and they are often identical in designs
Fume collections, Stripping, Scrubbing, Humidification, and Fractionation	Carried out in packed towers or tray towers: Distillation columns Absorption columns

Chemical Process Equipment: Generic Groups

- A large number of chemical process equipment found in chemical engineering catalogs can be combined into a smaller set of generic groups.

❑ Evaporators, vaporizer	▪ Process vessels
❑ Conveyors	▪ Pumps
❑ Crushers, millers, grinders	▪ Reactors
❑ Furnaces	▪ Separators
❑ Gas movers, compressors	▪ Size enlargement equipment
❑ Gas solid contacting equipment	▪ Storage vessels
❑ Heat exchangers	
❑ Mixers	

- Coolers, heaters etcetera all may come under heat exchangers
- Furnaces will be put separately

Process Equipment: Proprietary and Non-proprietary

- Broadly there are two types of equipment that are used in chemical process industries.

Proprietary equipment: These are designed and manufactured by specialist manufacturers and sold as standard catalogue items.

- ✓ Example: pumps, compresses, filters, centrifuges, dryers

Non-proprietary equipment: These are designed specifically for particular process.

- ✓ These are custom built for a company by specialist fabricators.
- ✓ Examples: reactors, distillation columns, heat exchangers

- If you are not working with specialist equipment manufacturers a chemical engineer is not normally involved in the detailed design of proprietary equipment.

Proprietary Equipment: Role of Chemical Engineers

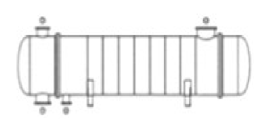
- Specify the process duty (temperature, pressure, flow rate, etc.) and select the appropriate equipment needed for the particular process.
- Proprietary items are generally available in certain standard sizes. Which size will be most suitable? Consult with the vendors.
- Is modification of standard equipment necessary for the particular application?
  - ✓ Example: A standard tunnel dryer designed to handle particulate solids may be adapted to dry synthetic fibers.
- Use of standard off the shelf equipment will always reduce the cost.

Non-proprietary Equipment: Role of Chemical Engineers

- Selection and sizing of the equipment.
- Design data must be developed, giving sizes, operating conditions, number and location of openings, types of flanges and heads, codes, variation allowances, and other information.
- Example: For construction of a distillation column, determine the number, type, and design of plates, column diameter, position of inlet, outlet, and instrument nozzles.
- This information is then supplied, in the form of sketches and specification sheets, to the specialist mechanical design groups of an engineering procurement and construction company (EPC) for detailed design.
- Whenever possible standard specifications should be used.

Heat Exchanger Specification Sheet / Engineering Data Sheet

1	Company:					
2	Location:					
3	Service of Unit:	Our Reference:				
4	Item No.:	Your Reference:				
5	Date: Rev No.:	Job No.:				
6	Size 949--4150	mm	Type BEM	Hor	Connected in	1 parallel
7	Surf/unit(eff.) 268.5	m²	Shells/unit 1		Surf/shell (eff.)	268.5 m²
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		Overheads		Cooling Water	
11	Fluid quantity, Total	kg/s	12.5075		105.1389	
12	Vapor (In/Out)	kg/s	12.5075	0	0	0
13	Liquid	kg/s	0	12.5075	105.1389	105.1389
14	Noncondensable	kg/s	0	0	0	0
15						
16	Temperature (In/Out)	°C	46	43.75	20	29.76
17	Dew / Bubble point	°C	46	43.75		
18	Density Vapor/Liquid	kg/m³	10.82 /	/ 564	/ 998.83	/ 997.39
19	Viscosity	mPa s	0.0085 /	/ 0.125	/ 1.0164	/ 0.8043
20	Molecular wt, Vap		58.6			
21	Molecular wt, NC					
22	Specific heat	kJ/(kg K)	1.76 /	/ 2.47	/ 4.194	/ 4.19
23	Thermal conductivity	W/(m K)	0.0174 /	/ 0.102	/ 0.5937	/ 0.6067
24	Latent heat	kJ/kg	337.4	338.4		
25	Pressure (abs)	bar	4.9	4.81683	5	4.91813
26	Velocity	m/s	9.86		0.87	
27	Pressure drop, allow./calc.	bar	0.2	0.08317	0.7	0.08187
28	Fouling . . (min)	m² K/W	0.00009		0.00018	
29	Heat exchanged 4300	kW			MTD corrected	19.9 °C
30	Transfer rate, Service		Dirty 930.7	Clean 1273.8		W/(m² K)
31	CONSTRUCTION OF ONE SHELL				Sketch	
32			Shell Side	Tube Side		
33	Design/vac/test pressure:g	bar	6/ /	6/ /		
34	Design temperature	°C	85	85		
35	Number passes per shell		1	2		
36	Corrosion allowance	mm	3.18	3.18		
37	Connections In	mm	1 437.95/ -	1 304.8/ -		
38	Size/rating Out		1 154.05/ -	1 254.51/ -		
39	ID Intermediate		/ -	/ -		
40	Tube No. 1108 OD 19.05		Tks-Avg 1.2 mm	Length 4150 mm	Pitch 23.81	mm
41	Tube type Plain	#/m	Material Carbon Steel		Tube pattern 60	
42	Shell Carbon Steel ID 950		OD 974 mm	Shell cover	-	
43	Channel or bonnet Carbon Steel			Channel cover	-	
44	Tubesheet-stationary Carbon Steel		-	Tubesheet-floating	-	
45	Floating head cover -			Impingement protection	None	
46	Baffle-crossing Carbon Steel		Type Single segmental	Cut(%d) 34.96 V	Spacing: c/c 395	mm
47	Baffle-long -		Seal type		Inlet 570	mm
48	Supports-tube	U-bend		Type		
49	Bypass seal		Tube-tubesheet joint	Exp.		
50	Expansion joint	-	Type None			
51	RhoV2-Inlet nozzle	637	Bundle entrance 1346		Bundle exit 17	kg/(m s²)
52	Gaskets - Shell side	-	Tube Side		Flat Metal Jacket Fibe	
53	Floating head	-				
54	Code requirements	ASME Code Sec VIII Div 1			TEMA class	R - refinery service
55	Weight/Shell	5266.6	Filled with water 8719.6		Bundle 3044.3	kg
56	Remarks					
57						
58						



DISTILLATION COLUMN DATA SHEET		Tag. No	T-100
		Sheet No	1 of 1
		Function	Removal of cyclohexane
Operating Data			
COLUMN INSIDE DIAMETER (m)	2.080	STRIPPING TRAYS	10 TRAYS
COLUMN OUTSIDE DIAMETER (m)	2.086	RECTIFYING TRAYS	6 TRAYS
COLUMN HEIGHT (m)	11	NO OF TRAYS	16 TRAYS
TRAY SPACING (m)	0.45		
Internal Condition			
	FEED	TOP	BOTTOM
TEMPERATURE (°C)	96.5	80.95	164
PRESSURE (kPa)	101.3	106.3	111.3
MOLAR FLOW (kmol/hr)	183522.820	118201.286	65321.530
MASS FLOW (kg/hr)	16394400	9949210	6445190
MOLECULAR WEIGHT (kg/kmol)	89.33167003	84.1731	98.665
DENSITY (kg/m^3)	839.253	716.519	812.366
VISCOSITY (kg/ms)	0.624	0.406	0.364
VOLUMETRIC FLOW (m^3/hr)	5.426	3.857	2.203
Technical / Mechanical Data			
FEED NOZZLE THICKNESS (mm)	9.8	BOLT AREA (mm)	0.0186
VAPOR NOZZLE THICKNESS (mm)	7.603	DEAD WEIGHT (kN)	425.432
LIQUID NOZZLE THICKNESS (mm)	6.319	PLATE THICKNESS (m)	0.005
COLUMN INSIDE DIAMETER (m)	2.080	GASKET INSIDE DIAMETER (m)	2.096
COLUMN OUTSIDE DIAMETER (m)	2.086	GASKET OUTSIDE DIAMETER (m)	2.100
CORROSION ALLOWANCE (mm)	2.00	SIEVE TRAY HOLE DIAMETER (m)	0.006
VESSEL MATERIALS	STAINLESS STEEL	WEIR LENGTH (m)	1.560
TRAY MATERIALS	STAINLESS STEEL	WEIR HEIGHT (m)	0.75
SKIRT MATERIAL	STAINLESS STEEL	HOLE AREA (m^2)	0.000113
TRAYS FROM TOP TO BOTTOM	16 TRAYS	DOWNCOMER AREA (m^2)	0.408
NET AREA (m^2)	2.990	NO OF HOLES	3008
Date of enquiry			
Manufacturer			

Scale-up of Equipment in Design

- Common Design Basis:
  - ✓ Accurate data available in the literature
  - ✓ Past experience
- In case the above are not adequate, pilot plant tests may be necessary to design effective plant equipment.
- The results of the pilot plant test must be scaled up to the plant capacity.
- Note that pilot plant test may not be necessary always.
- A chemical engineer should be acquainted with the limitations of scale up methods and should know how to select the essential design variables.

Scale-up of Equipment in Design: Examples

Equipment	Is Pilot Plant Test Necessary	Major Variables for Operational Design	Major Variables Characterizing Size or Capacity	Maximum Scale-up Ratio
Batch reactor	Yes	Reaction Rate, Equilibrium State	Volume, Residence Time	100:1
Continuous reactor	Yes	Reaction Rate, Equilibrium State	Flow Rate, Residence Time	100:1
Crystallizer	Yes	Solubility Data	Flow Rate, Heat Transfer Area	100:1
Rotary filters	Yes	Cake Resistance, Bulk Density	Flow Rate, Filtration Area	100:1, 25:1

Scale-up of Equipment in Design: Examples

Equipment	Is Pilot Plant Test Necessary	Major Variables for Operational Design	Major Variables Characterizing Size or Capacity	Maximum Scale-up Ratio
Centrifugal Pump	No	Discharge Head	Flow rate, Power Input, Impeller Diameter	100:1, 100:1 , 10:1
Shell-and-Tube Heat Exchanger	No	Temperature, Viscosity, Thermal Conductivity	Flow Rate, Heat Transfer Area	100:1, 100:1
Plate Column	No	Equilibrium Data, Superficial Vapor Velocity	Flow Rate, Diameter	100:1, 10:1
Spray Column	No	Gas Solubility	Flow Rate, Power Input	10:1

Factors in equipment scale-up and design

Type of equipment	Is pilot plant usually necessary?	Major variables for operational design (other than flow rate)	Major variables characterizing size or capacity	Maximum scale-up ratio based on indicated charac-terizing variable	Approximate recommended safety or over-design factor, %
Agitated batch crystallizers	Yes	Solubility–temperature relationship	Flow rate Heat-transfer area	>100 : 1	20
Batch reactors	Yes	Reaction rate Equilibrium state	Volume Residence time	>100 : 1	20
Centrifugal pumps	No	Discharge head	Flow rate Power input Impeller diameter	>100 : 1 >100 : 1 10 : 1	10
Continuous reactors	Yes	Reaction rate Equilibrium state	Flow rate Residence time	>100 : 1	20
Cooling towers	No	Air humidity Temperature decrease	Flow rate Volume	>100 : 1 10 : 1	15
Cyclones	No	Particle size	Flow rate Diameter of body	10 : 1 3 : 1	10
Evaporators	No	Latent heat of vaporization Temperatures	Flow rate Heat-transfer area	>100 : 1 >100 : 1	15
Hammer mills	Yes	Size reduction	Flow rate Power input	60 : 1 60 : 1	20
Mixers	No	Mechanism of operation System geometry	Flow rate Power input	>100 : 1 20 : 1	20
Nozzle-discharge centrifuges	Yes	Discharge method	Flow rate Power input	10 : 1 10 : 1	20 20
Packed columns	No	Equilibrium data Superficial vapor velocity	Flow rate Diameter Height/diameter ratio	>100 : 1 10 : 1	15
Plate columns	No	Equilibrium data Superficial vapor velocity	Flow rate Diameter	>100 : 1 10 : 1	15

Plate-and-frame filters	Yes	Cake resistance or permeability	Flow rate Heat-transfer area	>100 : 1 >100 : 1	20
Reboilers	No	Temperatures Viscosities	Flow rate Heat-transfer area	>100 : 1 >100 : 1	15
Reciprocating compressors	No	Compression ratio	Flow rate Power input Piston displacement	>100 : 1 >100 : 1 >100 : 1	10
Rotary filters	Yes	Cake resistance or permeability	Flow rate Filtration area	>100 : 1 25 : 1	20
Screw conveyors	No	Bulk density	Flow rate Diameter Drive horsepower	90 : 1 8 : 1	20
Screw extruders	No	Shear rate	Flow rate Power input	100 : 1 100 : 1	20 10
Sedimentation centrifuges	No	Discharge method	Flow rate Power input	10 : 1 10 : 1	20 20
Settlers	No	Settling velocity	Volume Residence time	>100 : 1	15
Spray columns	No	Gas solubilities	Flow rate Power input	10 : 1	20
Spray condensers	No	Latent heat of vaporization Temperatures	Flow rate Height/diameter ratio	70 : 1 12 : 1	20
Tube-and-shell heat exchangers	No	Temperatures Viscosities Thermal conductivities	Flow rate Heat-transfer area	>100 : 1 >100 : 1	15

Process Equipment: Safety Factors

- A reasonable safety factor for selection and designer equipment should be applied.
- Safety factors represent the amount of over design that would be used to account for:
  - ✓ The changes in the operating performance with time
  - ✓ The uncertainties in the design process.
- The indiscriminate application of safety factors should be avoided.
- Otherwise the process or equipment would never prove its economic value.
- Typical safety factors are given here batch reactor 20%, continuous reactor 20%, crystallizers 20%, cyclone 10%, plate columns 15%, shell and tube heat exchanger 15%, reciprocating compressor 10%,

Process Equipment: Safety Factors

- Generally the magnitudes of safety factors are determined by:
  - ✓ Economic or market considerations
  - ✓ Accuracy of the design data and calculations
  - ✓ Potential changes in the operating conditions
  - ✓ Background information available on the overall process
  - ✓ Amount of safety factors used in other components of the design

Standard vs. Special Process Equipment

Chemical Engineering Axiom:

- ✓ Standard equipment should be selected whenever possible. Standard equipment has stored the rigorous taste of service.
- ✓ A new design thus a special equipment is a new experiment equipment for both user and designer.

- ➢ Use of standard equipment reduces cost;
  - ✓ Duplication will be easy.
  - ✓ If the equipment is standard, manufacturer may have the desired size in stock
  - ✓ Better guarantee of satisfactory performance may be obtained for standard equipment
  - ✓ Easy to repair

Process Equipment: Specifications

- Before an equipment manufacturer is contacted, the chemical engineer should prepare a preliminary specification sheet for the equipment.
- The following information must be included in the specification sheet so that the cost of purchasing and installing each piece of equipment can be determined.

❑ Specific type of equipment	❑ Insulation required
❑ Size and or capacity	❑ Corrosion allowances if it is large
❑ Material of constructions	❑ Special features such as jackets on heat exchangers
❑ Operating pressure	❑ Duplication of plant items for safety and or reliability
❑ Maximum and Minimum operating temperature	❑ Delivery date, support
❑ Essential controls	

Process Equipment: Specifications

- The heat exchangers and pumps cannot be sized until the energy balance for the plant is completed.
- The final energy balance depends upon the energy conservation measures to be employed and the plant layout.
- Other equipment can be sized reasonably accurately at this stage.
- Many approximate methods or equivalent sizing are available in textbooks.

Process Equipment Specifications: Example 1

Size a methanol storage tank for a plant which produces 10,000 tonnes of a particular product per year. Given:

- ✓ *0.3 kg of methanol is required for each kg of product.*
- ✓ *A 15 day storage capacity specified for methanol.*
- ✓ *The plant will operate 8,300 hours*

Solution:

Kg of methanol used per day:

$$\frac{0.3kg\ Methanol}{kg\ product} \times \frac{10000000\ kg\ product}{year} \times \frac{1\ year}{8300\ h} \times \frac{24\ h}{day} = 8675$$

Kg of methanol that must be stored: $\frac{8675\ kg}{day} \times 15\ days = 130000\ kg$

Volume (m³) of methanol that must be stored: $\frac{13000\ kg}{792\ kg/m^3} = 165\ m^3$

Assume the length of the storage tank is 3 times the diameter and it will only be filled to a maximum 90% of the capacity.

So the size of the tank is:

$$\frac{\pi D^2}{4} L = \frac{3\pi D^3}{4} = 165 m^3 \times \frac{1}{0.9} = 183.33 m^3$$

$$\rightarrow D = 4.27\ m$$

$$\rightarrow L = 3D = 12.81\ m$$

Process Equipment: Materials of Construction

- A good understanding of the process and all process related information is required for selecting materials of construction.
- Final choice of raw materials must be made first
- Consider the effects of corrosion and erosion, perform laboratory testing if necessary
- The materials of construction should have good chemical resistance; it should be resistant to the corrosion action of any chemicals that may contact the exposed surfaces.
- The materials of construction should have good structural strength, resistance to physical or thermal shock, favorable cost, ease of fabrication and maintenance.

Materials of Construction: Selection Guidlines

Preliminary Selection	Final Selection
1. Experience	1. Fabrication method
2. Manufacturers data	2. Effect of temperature pressure agitation
3. Literature	3. Possibility of impurity
4. Availability	4. Material cost
5. Laboratory testing	5. Production cost
6. Mechanical and physical properties	6. Probable life of equipment
7. Tensile strengths, stiffness	7. Product degradation
8. Toughness, hardness	8. Liability of special hazards
9. Fatigue resistance	
10. Corrosion, erosion resistance	

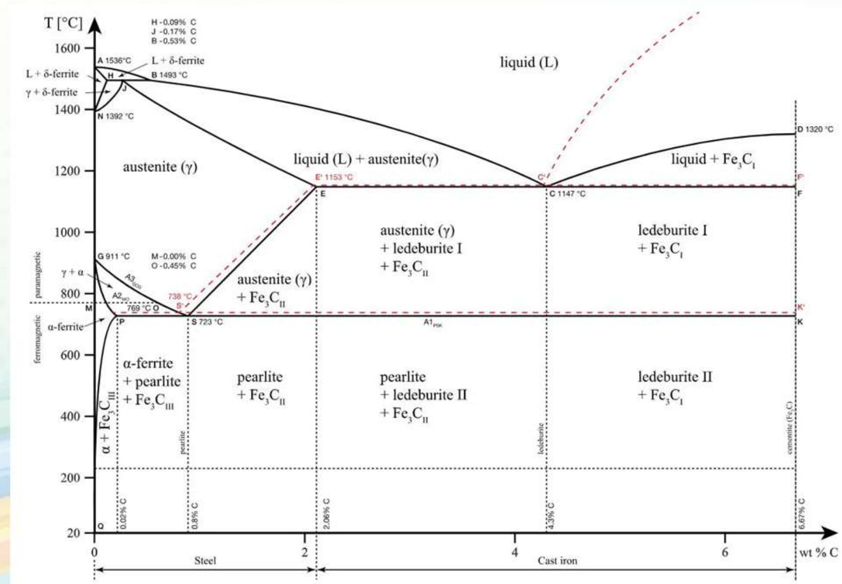
Economics Involved in Selection

First cost of equipment or material often is not a good economic criterion for comparing alternate materials of construction for chemical process equipment. Any cost estimation should include the following items:

1. Total equipment or materials costs
2. Installation costs
3. Maintenance costs, amount and timing
4. Service life
5. Replacement costs
6. Cost of inhibitors, control facilities required to achieve estimated service life
7. Depreciation and taxes
8. Time value of money
9. Inflation

Classification of stainless steels by alloy content and microstructure

Stainless steels	Chromium types	Martensitic	Hardenable (types 403, 410, 414, 416, 416Se, 420, 431, 440A, 440B, 440C)
		Ferritic	Nonhardenable (types 405, 430, 430F, 430Se, 442, 446)
	Chromium-nickel types	Austenitic	Nonhardenable, except by cold working (types 201, 202, 301, 302, 302B, 303, 303Se, 304, 304L, 305, 308, 309, 309S, 310, 310S, 314, 316, 316L, 317, 321, 347, and 348)
			Strengthened by aging or precipitation-hardening (types 17-14 CuMo, 17-10P, HNM)
		Semiaustenitic	Precipitation-hardening (PH 15-7 Mo, 17-7 PH, AM 355)
		Martensitic	Precipitation-hardening (17-4 PH, 15-5 PH, stainless W)



Stainless steels most commonly used in the chemical process industries

Type[a]	Composition, % Cr	Ni	C max.	Other significant elements[b]	Major characteristics	Properties	Applications
301	16.00–18.00	6.00–8.00	0.15		High work-hardening rate combines cold-worked high strength with good ductility	Good structural qualities	Structural applications, bins and containers
302	17.00–19.00	8.00–10.00	0.15		Basic, general-purpose austenitic type with good corrosion resistance and mechanical properties	General-purpose	Heat exchangers, towers, tanks, pipes, heaters, general chemical equipment
303	17.00–19.00	8.00–10.00	0.15	S 0.15 min	Free-machining modification of type 302; contains extra sulfur	Type 303Se is also available for parts involving extensive machining	Pumps, valves, instruments, fittings
304	18.00–20.00	8.00–12.00	0.08		Low-carbon variation of type 302, minimizes carbide precipitation during welding	General-purpose. Also available as 304L with 0.03% carbon to minimize carbide precipitation during welding	Perforated blow-pit screens, heat exchanger tubing, preheater tubes
305	17.00–19.00	10.00–13.00	0.12		Higher heat and corrosion resistance than type 304	Good corrosion resistance	Funnels, utensils, hoods
308	19.00–21.00	10.00–12.00	0.08		High Cr and Ni produce good heat and corrosion resistance. Used widely for welding rod	In order of their numbers, these alloys show increased resistance to high-temperature corrosion. Types 308S, 309S, and 310S are also available for welded construction (types 308, 309, 310)	Welding rod, more ductile welds for type 430
309	22.00–24.00	12.00–15.00	0.20		High strength and resistance to scaling at high temperatures		Welding rod for type 304, heat exchangers, pump parts
310	24.00–26.00	19.00–22.00	0.25		Higher alloy content improves basic characteristics of type 309		Jacketed high-temperature, high-pressure reactors, oil-refining still tubes
314	23.00–26.00	19.00–22.00	0.25	Si 1.5–3.0	High silicon content	Resistant to oxidation in air to 1100°C	Radiant tubes, carburizing boxes, annealing boxes
316	16.00–18.00	10.00–14.00	0.08	Mo 2.00–3.00	Mo improves general corrosion and pitting resistance and high-temperature strength over that of type 302	Resistant to high pitting corrosion. Also available as 316L for welded construction	Distillation equipment for producing fatty acids, sulfite paper processing equipment
317	18.00–20.00	11.00–15.00	0.08	Mo 3.00–4.00	Higher alloy content improves basic advantages of type 316	Type 317 has the highest aqueous corrosion resistance of all AISI stainless steels	Process equipment involving strong acids or chlorinated solvents
321	17.00–19.00	9.00–12.00	0.08	Ti 5 × C, min.	Stabilized to permit use in 420–870°C range without harmful carbide precipitation	Stabilized with titanium and columbium-tantalum, respectively, to permit their use for large welded structures which cannot be annealed after welding (types 321, 347)	Furnace parts in presence of corrosive fumes
347	17.00–19.00	9.00–13.00	0.08	Cb-Ta 10 × C, min.	Characteristics similar to type 321. Stabilized by Cb and Ta		Like 302 but used where carbide precipitation during fabrication or service may be harmful, welding rod for type 321

Stainless steels most commonly used in the chemical process industries

Type[a]	Composition, % Cr	Ni	C max.	Other significant elements[b]	Major characteristics	Properties	Applications
403	11.50–13.50		0.15	Si 0.50 max.	Version of type 410 with limited hardenability but improved fabricability	Not highly resistant to high-temperature oxidation in air	Steam turbine blades
405	11.50–14.50		0.08	Al 0.10–0.30	Version of type 410 with limited hardenability but improved weldability	Good weldability and cladding properties	Tower linings, baffles, separator towers, heat exchanger tubing
410	11.50–13.50		0.15		Lowest-cost general-purpose stainless steel	Wide use where corrosion is not severe	Bubble-tower parts for petroleum refining, pump rods and valves, machine parts, turbine blades
416	12.00–14.00		0.15	S 0.15 min.	Sulfur added for free-machining version of type 410. Type 416Se also available	The most free-machining type of martensitic stainless	Valve stems, plugs, gates, useful for screws, bolts, nuts, and other parts requiring considerable machining during fabrication
420	12.00–14.00		0.15 min.		Similar to type 410 but higher carbon produces higher strength and hardness	High-spring temper	Utensils, bushings, valve stems, and wear-resisting parts
430	14.00–18.00		0.12		Most popular of nonhardening chromium types. Combines good corrosion resistance (to nitric acid and other oxidizing media)	Good heat resistance and good mechanical properties. Also available in type 430F	Chemical and processing towers, condensers. Furnace parts such as retorts and low stressed parts subject to temperatures up to 800°C. Type 430 nitric acid storage tanks, furnace parts, fan scrolls. Type 430F pump shafts, instrument parts, valve parts
431	15.00–17.00	1.25–2.50	0.20		High yield point	Very resistant to shock	Products requiring high yield point and resistance to shock
442	18.00–23.00		0.25		High-chromium nonhardenable type	High-temperature uses where high-sulfur atmospheres make presence of nickel undesirable	Fume furnaces, fire stacks, materials in contact with high-sulfur atmospheres
446	23.00–27.00		0.20		Similar to type 442 but Cr increased to provide maximum resistance to scaling. Especially suited to intermittent high temperatures	Excellent corrosion resistance to many liquid solutions; fabrication difficulties limit its use primarily to high-temperature applications. Useful in high-sulfur atmospheres	Burner nozzles, stack dampers, boiler baffles, furnace linings, glass molds

Heuristics Rules for Process Equipment

- Heuristics rules based upon experience, also referred to as rules of thumb, can be useful for the design, specifying and operation of several kinds of equipment used in process plants.
- The first and foremost heuristic rule is that the engineer should not shy away from using heuristics - and the second rule is that he or she should not rely blindly upon them.
- Heuristics like these can make life much easier during project scoping, process design, equipment specification and similar tasks provided that they are updated.
- Check the PDF uploaded via Moodle for these heuristics.

Heuristics Rules for Process Equipment

Heat Exchangers; Refrigeration

- In a shell-and-tube exchanger, the tube side is for corrosive, fouling, scaling and/or high-pressure fluids; the shell side is for viscous and/or condensing fluids
- Typical minimum temperature approaches are 20°F with normal coolants, or 10°F or less with refrigerants
- Ordinarily, the maximum heat transfer area for shell and tube heat exchangers is about 5,000 ft^2
- When refrigerating to temperatures below about - 80°F, it is customary to use cascades of two or more refrigeration stages

Corrosion

Typical property and chemical resistance data for selected plastics

Plastics[a]	Specific gravity	Tensile strength MPa	Modulus of elasticity, tension MPa × 10^2	Impact strength, Izod[b] J	Maximum temp. (no load) ¡C	HDT[c] at 1.75 MPa ¡C	Chemical resistance[d] Weather resistance	Weak acid	Strong acid	Weak alkali	Strong alkali	Solvents
Epoxies (*bis*-A)												
No filler	1.06–1.40	28–90	15–36	0.3–1.4	120–260	15–260	R	R	A	R	S	R–S
Graphite-fiber	1.37–1.38	1280–1380	814–827				S	R	R	R	R	R–S
Mineral-filled	1.6–2.0	34–103		0.4–0.5	150–260	120–260	S	R	R	R	R	R–S
Glass-filled	1.7–2.0	69–207	207	14–41	150–260	120–[illegible]60	S	R	R–S	R	R	R–S
Epoxies (novolac): no filler	1.12–1.24	34–76	15–36	0.4–0.9	200–260	230–[illegible]50	R	R	R	R	R	R
Epoxies (cycloaliphatic), no filler	1.12–1.18	69–121	34–48		250–290	260–[illegible]0	R	R	R–A	R	R–A	R
Melamines												
Cellulose-filled	1.45–1.52	34–62	76	0.3–0.5	120	[illegible]	S	R–S	D	R	D	R
Flock-filled	1.50–1.55	48–62		0.5–0.7	120	[illegible]30	S	R–S	D	R	D	R–S
Asbestos-filled	1.70–2.0	34–48	138	0.4–0.5	120–200	130	S	R–S	D	S	S	R
Fabric-filled	1.5	55–76	97–110	0.8–1.4	120	150	S	R	D	R	A	R–S
Glass-filled	1.8–2.0	34–69	165	0.8–24	150–200	200	S	R	D	R	R–S	R
Polyesters												
Glass-filled BMC	1.7–2.3	28–69	110–172	2.0–22	150–180	200–230	R–E	R–A	S–A	S–A	S–D	A–D
Glass-filled SMC	1.7–2.1	55–138	110–172	11–30	150–180	200–230	R–E	R–A	S–A	S–A	S–D	A–D
Glass-cloth reinforced	1.3–2.1	172–345	131–310	7–41	150–180	200–230	R–E	R–A	S–A	S–A	S–D	A–D
Silicones												
Glass-filled	1.7–2.0	28–45	69–103	4–20	320	320	R–S	R–S	R–S	S	S–A	R–A
Mineral-filled	1.8–2.8	28–41	90–124	0.4–0.5	320	320	R–S	R–S	R–S	S	S–A	R–A
Nylons												
6/6	1.13–1.15	62–83	27	27	80–150	65–105	R	R	A	R	R	R–D
6	1.14	86		1.6	80–170	60–70	R	R	A	R	R	R–A[i]
6/10	1.07	49	19	2.2	80		R	R	A	R	R	R–A[i]
8	1.09	27		>22			R	R	A	R	R	R–A[i]
12	1.01	45–59	12–14	1.6–5.7	80–125	50–55	R	R	A	R	R	R–A[i]
Copolymers	1.08–1.14	52–76		2–26	80–120	55–180	R	R	A	R	R	R–A[i]
Polyesters												
PET	1.37	72		1.1	80	85	R	R	A[e]	R	A	R–A[i]
PBT	1.31	55–57	25	1.6–1.8	140	55	R	R	R	R	A	R
PTMT	1.31	57		1.4	130	50	R	R	R	R	A	R
Copolymers	1.2	50		1.4		70						
Polycarbonate	1.2	62	24	16–22	120	130–140	R	R	A[e]	A	A	A
PC-ABS	1.14	57	26	14	105	105	R–E	R	A[e]	R	S	A
Polyethylenes												
LD	0.91–0.93	6–17	1.4–1.9		80–100	30–40	E	R	A[e]	R	R	R
HD	0.95–0.96	20–37		0.5–19	80–120	45–55	E	R	R–A[e]	R	R	R
HMW	0.95	17	7			40–80	E	R	A[e]	R	R	R
Polypropylenes												
GP	0.90–0.91	33–38	11–15	0.5–3.0	105–150	50–60	E	R	A[e]	R	R	R
High-impact	0.90–0.91	21–34	9	2–16	95–120	50–60	E	R	A[e]	R	R	A
Polystyrenes												
GP	1.04–1.07	41–50	31	0.4	65–80	80–105	S	R	A[e]	R	R	D
High-impact	1.04–1.07	20–32	20–28	0.9–1.4	60–80	80–100	S	R	A[e]	R	R	D
Polysulfone	1.24	70	25	1.6	150	175	S	R	R	R	R	R–A
Polyurethanes	1.11–1.25	31–58	0.7–24		90		R–S	S–D	S–D	S–D	S–D	R
Vinyl, rigid	1.3–1.5	34–55	21–34	0.7–27	65–80	55–80	R	R	R–S	R	R	R–A
Vinyl, flexible	1.2–1.7	7–28		0.7–27	60–80		S	R	R–S	R	R	R–A
Rigid CPVC	1.49–1.58	52–62	25–32	1.4–7.6	110	95–115	R	R	R	R	R	R
PVC-acrylic	1.30–1.35	38–45	19–23	20		80	R	R	S	R	R	A
PVC-ABS	1.10–1.21	18–41	6–23	14–20			S	R	R–S	R	R	R–D
SAN	1.08	69–83	34–39	0.5–0.7	60–95	90–105	S–E	R	A	R	R	A

[a] All values at room temperature unless otherwise listed
[b] Notched samples
[c] Heat deflection temperature
[d] R = resistant; A = attacked; S = slight effects; E = embrittles; D = decomposes
[e] By oxidizing acids
[f] By ketones, esters, and chlorinated and aromatic hydrocarbons
[g] Halogenated solvents cause swelling
[h] By fuming sulfuric
[i] Dissolved by phenols and formic acid
[†] Modified from *Plastics Engineering Handbook of the Society of the Plastics Industry,* 5th ed., Kluwer Academic Publishers, Dordrecht, The Netherlands, 1991, and P. A. Schweitzer, *Mechanical and Corrosion Resistant Properties of Plastics and Elastomers,* Marcel Dekker, New York, 2001.

Corrosion resistance of construction materials

Code designation for corrosion resistance

A = Acceptable, can be used successfully
C = Caution, resistance varies widely depending on conditions; used when some corrosion is permissible
X = Unsuitable
Blank = Information lacking

Code designation for gasket materials[‡]

a = Asbestos, white (compressed or woven)
b = Asbestos, blue (compressed or woven)
c = Asbestos (compressed and rubber-bonded)
d = Asbestos (woven and rubber-frictioned)
e = GR-S or natural rubber
f = Tefln

	Metals								Nonmetals					
			Stainless steel											
Chemical	Iron and steel	Cast iron (Ni-resist)	18-8	18-8 Mo	Nickel	Monel	Red brass	Aluminum	Industrial glass	Carbon (Karbate)	Phenolic resins (Haveg)	Acrylic resins (Lucite)	Vinylidene chloride (Saran)	Acceptable nonmetallic gasket materials
Acetic acid, crude	C	C	C	C	C	C	C	A	A	A	A	A	C	b, c, d, f
Acetic acid, pure	X	X	C	A	C	A	X	A	A	A	A	X	X	b, c, d, f
Acetic anhydride	C	C	A	A	A	A	X	A	A	A	A	X	C	b, c, d, f
Acetone	A	A	A	A	A	A	A	A	A	A	C	X	C	a, e, f
Aluminum chloride	X	C	X	X	C	C	A	A	A	A	A	...	A	a, c, e, f
Aluminum sulfate	X	C	C	A	C	C	X	A	A	A	A	A	A	a, c, d, e, f
Alums	X	C	C	A	C	A	X	A	A	A	A	A	A	a, c, d, e, f
Ammonia (gas)	A	A	C	A	A	A	X	C	A	...	A	...	C	a, f
Ammonium chloride	C	A	C	C	A	A	C	C	A	A	A	A	A	b, c, d, e, f
Ammonium hydroxide	A	A	A	A	C	C	X	C	A	...	A	A	C	a, c, d, f
Ammonium phosphate, monobasic	X	C	A	A	...	C	X	X	A	A	A	...	...	b, c, d, e, f
Ammonium phosphate, dibasic	C	A	A	A	...	A	C	C	A	A	A	...	...	a, c, d, e, f
Ammonium phosphate, tribasic	A	A	A	A	A	A	X	C	A	A	A	...	...	a, c, d, e, f
Ammonium sulfate	C	A	C	C	A	A	C	A	A	A	A	A	A	b, c, d, e, f
Aniline	A	A	A	A	...	A	X	...	A	A	C	...	C	a, f
Benzene, benzol	A	A	A	A	A	A	A	A	A	A	A	...	C	a, f
Boric acid	X	C	A	A	A	A	C	A	A	A	A	...	A	a, c, d, e, f
Bromine	X	C	C	C	C	C	C	...	A	C	X	...	X	b, f

Low- and High-Temperature Materials

- The extremes of low and high temperatures used in many recent chemical processes have created some unusual problems in fabrication of equipment.
- For example, some metals lose their ductility and impact strength at low temperatures, although in many cases, yield and tensile strengths increase as the temperature is decreased.
- It is important in low-temperature applications to select materials resistant to shock.
- Among the most important properties of materials at the other end of the temperature spectrum are creep, rupture, and short-time strengths.
- Stress rupture is another important consideration at high temperatures since it relates stress and time to produce rupture.
- Ferritic alloys are weaker than austenitic compositions, and in both groups molybdenum increases strength.

Metals and alloys for low-temperature process use

ASTM specification and grade	Recommended minimum service temperature, °C
Carbon and alloy steels:	
T-1	−45
A 201, A 212, flange or firebox quality	−45
A 203, grades A and B (2.25% Ni)	−60
A 203, grades D and E (3.50% Ni)	−100
A 353 (9% Ni)	−195
Copper alloys, silicon bronze, 70-30 brass, copper	−195
Stainless steel types 302, 304L, 304, 310, 347	−255
Aluminum alloys 5052, 5083, 5086, 5154, 5356, 5454, 5456	−255

Alloys for high-temperature process use

Alloys	Nominal composition, % Cr	Ni	Fe	Other	Max. temp., °C
Ferritic steels:					
Carbon steel			bal.		480
$2\frac{1}{4}$ chrome	$2\frac{1}{4}$		bal.	Mo	
Type 502	5		bal.	Mo	620
Type 410	12		bal.		700
Type 430	16		bal.		850
Type 446	27		bal.		1100
Austenitic steels:					
Type 304	18	8	bal.		900
Type 321	18	10	bal.	Ti	
Type 347	18	11	bal.	Cb	
Type 316	18	12	bal.	Mo	
Type 309	24	12	bal.		1100
Type 310	25	20	bal.		1100
Type 330	15	35	bal.		
Nickel-base alloys:					
Nickel		bal.			
Incoloy	21	32	bal.		1100
Hastelloy B		bal.	6	Mo	
Hastelloy C	16	bal.	6	W, Mo	
60/15	15	bal.	25		
Inconel	15	bal.	7		1100
80/20	20	bal.			
Hastelloy X	22	bal.	19	Co, Mo	
Multimet	21	20	bal.	Co	
Rene 41	19	bal.	5	Co, Mo, Ti	
Superalloys:					
Inconel X	15	bal.	7	Ti, Al, Cb	
A 286	15	25	bal.	Mo, Ti	
Stellite 25	20	10	Co-base	W	1100
Stellite 21 (cast)	27.3	2.8	Co-base	Mo	
Stellite 31 (cast)	25.2	10.5	Co-base	W	

Example 2: Material Selection for a Heat Exchanger

Material of Construction (MOC) Selection for a Condenser in an Acetic Acid Recovery Unit.

1. Process Description and Duty

- Unit: Acetic Acid Recovery Unit, downstream of an oxidation reactor.

➢ Streams:

  - Shell Side (Cooling): Cooling Water (CW). Inlet: 30°C, Outlet: 40°C. Standard plant cooling water with chlorides (~150-200 ppm), slightly basic (pH ~7.5-8.5).
  - Tube Side (Process Fluid): Vapor mixture from a reactor.
    - Composition: 85% Acetic Acid (CH_3COOH), 10% Water (H_2O), 5% Formic Acid ($HCOOH$) and other trace organic byproducts.
    - Phase Change: Saturated Vapor at 115°C to a saturated liquid at 110°C.
    - Pressure: 2 bar (g) and the flow Rate: 5,000 kg/h.

➢ Heat Exchanger Type: Shell and Tube, fixed tube sheet.

➢ Duty: 250 kW.

2. The Engineering Problem

We are to select the most appropriate material for the tubes and the tubesheet of this condenser. The shell, exposed to relatively benign cooling water, can be made from Carbon Steel. The process side is highly corrosive, making the tube material selection critical for safety, reliability, and economics.

3. Material Selection Analysis

- Candidate Materials:
  - Type 316 Stainless Steel (SS 316)
  - Type 304 Stainless Steel (SS 304)
  - Hastelloy C-276 (a Nickel-Chromium-Molybdenum alloy)
  - Graphite (Impervious)
  - Tantalum

Criteria	SS 304	SS 316	Hastelloy C-276	Graphite	Tantalum
1. Corrosion Resistance	**Poor.** Susceptible to pitting and stress corrosion cracking (SCC) from chlorides (CW side) and general corrosion from acetic/formic acid, especially at elevated temps.	**Fair/Good for acids, but a major risk.** Excellent resistance to acetic acid. However, the presence of **chlorides** on the cooling water side at elevated temperatures (>60°C) makes it highly susceptible to **Chloride-Induced Stress Corrosion Cracking (CISCC)**. A major safety risk.	**Excellent.** Highly resistant to all three components: acetic acid, formic acid, and chlorides. No risk of CISCC.	**Excellent.** Inert to acetic and formic acids and immune to chloride attack.	**Outstanding.** One of the most corrosion-resistant metals. Perfect for this service.
2. Mechanical & Thermal	Good strength, easy to fabricate.	Good strength, easy to fabricate.	High strength, excellent fatigue resistance, more difficult to fabricate.	Brittle, low tensile strength, poor thermal shock resistance. Good thermal conductivity.	Very high strength but extremely ductile and expensive to fabricate.
3. Fouling	Low fouling tendency.	Low fouling tendency.	Very low fouling tendency.	Surface can be prone to fouling but is easy to clean.	Very low fouling tendency.
4. Initial Cost	**Low**	**Moderate** (~2x CS)	**Very High** (~5-7x SS 316)	**Moderate/High**	**Extremely High** (~10x SS 316)
5. Fabricability	Excellent	Excellent	Good (requires specialized welders)	Fair (specialized manufacturers)	Poor (very specialized)
6. Longevity / Reliability	Unacceptable. Likely to fail prematurely.	**High Risk.** CISCC could lead to catastrophic failure within 1-3 years. Not recommended.	**Excellent.** 20+ year service life expected.	**Good.** Can last 10-15 years if not mechanically damaged.	**Exceptional.** Will likely outlast the plant.

4. *Evaluation and Decision-Making*

- *Elimination of Poor Candidates:*
  - *SS 304 and SS 316 are eliminated due to the high risk of corrosion failure. SS 316 fails primarily due to the cooling water chloride content combined with the high process temperature, which heats the tube wall. This is a classic failure mode in chemical plants.*
  - *Tantalum is eliminated on the basis of cost. It is overkill for this service and not economically justifiable.*
- *Final Shortlist:*
  - *Hastelloy C-276*
  - *Graphite*

	Hastelloy C-276	Graphite
Pros	• Superior mechanical integrity & reliability.	• Lower initial capital cost.
	• Excellent for high-pressure service.	• Excellent corrosion resistance.
	• Low fouling, easy to clean.	• High thermal conductivity.
	• Long, predictable service life.	
Cons	• Very high initial cost.	• Brittle - risk of damage during transport, installation, or operation (water hammer).
		• Limited pressure and temperature rating.
		• Porous (requires impervious grade).
		• Shorter and less predictable service life.

5. Final Recommendation

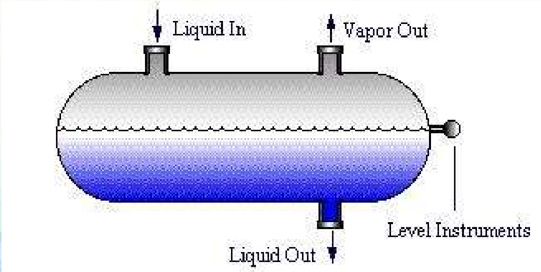
For a chemical plant design course, the recommended choice would be:

1. *Tubes & Tubesheet: Hastelloy C-276*
2. *Shell: Carbon Steel*

Example 3: Designing a Horizontal Reflux Drum (Liquid-Liquid Separation)

We need to size a reflux drum for a distillation column separating Benzene and Toluene. The total liquid flow from the condenser is 50 m^3/h. The drum will hold the reflux and the distillate product.

Heuristics Applied:



- Liquid drums usually are horizontal.
- In liquid-liquid separation, reflux drums are usually kept about half full…
- …holdup time of about 5 min. (or 5 to 10 min if the drum liquid is fed to a downstream separation tower)
- A length-to-diameter ratio of 3 is considered optimal…

Step 1: Determine Liquid Holdup Volume

We'll choose a holdup time of 5 minutes (0.0833 hours) as it's a standard value.

- Liquid Flow Rate, $Q = 50\ m^3/h$
- Required Liquid Volume, $V_{liq} = Q \times t = 50\ m^3/h \times (5/60)\ h = 4.17\ m^3$

Step 2: Determine Total Drum Volume

Since the drum is half full (a common heuristic for level control), the total drum volume is twice the liquid volume.

- Total Drum Volume, $V_{total} = V_{liq} \times 2 = 4.17\ m^3 \times 2 = 8.33\ m^3$

Step 3: Calculate Drum Dimensions

We use the optimal L/D ratio of 3. The volume of a horizontal cylinder is given by:

$V_{total} = (\pi/4) \times D^2 \times L$ and Substitute $L = 3D$:

$V_{total} = (\pi/4) \times D^2 \times (3D) = (3\pi/4) \times D^3$

$D^3 = V_{total} \times (4/(3\pi)) = 8.33 \times (4/(3\pi)) = 3.536\ m^3$

$D = \sqrt[3]{(3.536)} \approx 1.52$ meters

$L = 3 \times D = 3 \times 1.52\ m = 4.56$ meters

Step 4: Check against Practical L/D Range

Our calculated L/D is exactly 3.0, which falls perfectly within the common range of 2.5 to 5.0.

Final Proposal for Reflux Drum:

- Type: Horizontal Drum
- Function: Reflux Drum / Liquid-Liquid Surge
- Total Volume: 8.3 m^3
- Dimensions: Diameter = 1.5 m, Length = 4.6 m (L/D = 3.06)
- Operating Liquid Level: 50% of diameter
- Holdup Time: 5 minutes at design flow

Example 4: Designing a Slurry Mixing Tank

Design an agitator for a tank that will keep a solid catalyst suspended in a liquid reactant. The catalyst particles have a settling velocity of 0.1 ft/s. We must select the type of agitator, its size, and its operating speed.

Given Data:

- *Tank Geometry: Vertical cylindrical tank*
- *Tank Diameter (T): 2 meters (6.56 ft)*
- *Liquid Height (H): 2 meters (equal to diameter)*
- *Liquid Volume: ~6.3 m^3 (~1,660 gallons)*
- *Solid Properties: Settling velocity = 0.1 ft/s*
- *Liquid Properties: Similar to water ($\rho \approx 1000$ kg/m^3, $\mu \approx 1$ cP)*

•

Heuristic Applied:

"Solids with a low settling velocity (such as 0.03 ft/s) can be successfully suspended with either turbine or propeller agitators; suspension of solids with settling velocities greater than 0.15 ft/s requires vigorous agitation with a propeller."

- *Our settling velocity is 0.1 ft/s.*
- *This is higher than the "low" threshold (0.03 ft/s) but lower than the "vigorous agitation" threshold (0.15 ft/s).*

Decision: *A standard turbine agitator should be sufficient. It is a versatile choice for this intermediate settling velocity and is common in chemical processes.*

Heuristics Applied:

- *A length-to-diameter ratio of 3 is considered optimal..." (This is a general vessel heuristic we'll use for the impeller).*
- *(From standard mixing practice): For a radial-flow turbine, the impeller diameter (D_a) is typically 1/3 of the tank diameter (D_T).*

1. Impeller Diameter:

- $D_a = D_T / 3 = 2.0\ m / 3 \approx 0.67\ m$ *(or about 0.66 ft)*

2. Impeller Speed (RPM):

- *We need a rotational speed that will keep the solids suspended. A common heuristic for minimum power for suspension is to use a peripheral (tip) speed as a criterion. For solids suspension with a turbine, a tip speed of 400-600 ft/min is often effective. Let's select a target tip speed of 500 ft/min.*
  - *Tip Speed (TS) =* $\pi \times D_a \times N$*, where N is the rotational speed in RPM.*
  - $N = TS / (\pi \times D_a) = 500\ ft/min / (\pi \times 2.2\ ft) \approx 72\ RPM$

Estimate Power Requirement

- We can use the Power Number (N_p) method. For a standard 6-blade disk turbine, $N_p \approx 5.0$.

1. Calculate Reynolds Number (Re):

- $Re = (\rho \times N \times D_a{}^2) / \mu$
- First, convert N from RPM to Rev/sec: $N = 72 / 60 = 1.2$ rev/s
- $Re = (1000\ kg/m^3 \times 1.2\ s^{-1} \times (0.67\ m)^2) / 0.001\ Pa{\cdot}s$
- $Re \approx 540{,}000$ (This is in the turbulent regime, so using $N_p = 5$ is correct).

2. Calculate Power (P):

- $P = N_p \times \rho \times N^3 \times D_a{}^5$
- $P = 5.0 \times 1000\ kg/m^3 \times (1.2\ s^{-1})^3 \times (0.67\ m)^5$
- $P \approx 5.0 \times 1000 \times 1.728 \times 0.135$
- $P \approx 1{,}166$ Watts ≈ 1.56 hp

Check Power per Unit Volume:

- Liquid Volume = 1,660 gallons
- Power/Volume = 1.56 hp / 1,660 gal ≈ 0.00094 hp/gal
- This is significantly lower than the 0.1-0.2 hp/gal mentioned for intense inline blending, which makes sense.

Final Design Specification and Summary

- Application: Solid-Liquid Suspension (Catalyst in Reactor)
- Agitator Type: 6-Blade Disk Turbine (Radial Flow)
- Impeller Diameter: 0.67 m (≈ 1/3 of Tank Diameter)
- Operating Speed: 72 RPM
- Installed Power: 1.6 hp (A standard 2 hp motor would be selected for safety factor).
- Tip Speed: 500 ft/min (Adequate for 0.1 ft/s settling velocity).
- Baffles: The tank should be equipped with 4 standard baffles (width = T/12 ≈ 0.17 m) to prevent vortexing and ensure effective mixing

Chemical Plant Design

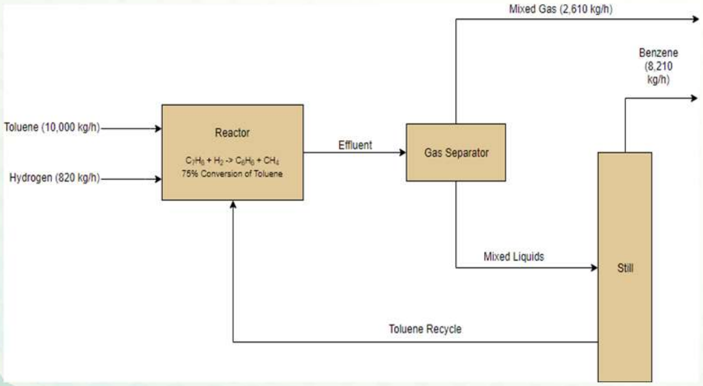
Piping and Instrumentation Diagram

The University of Jordan
Chemical Engineering Department
Prof. Yousef Mubarak

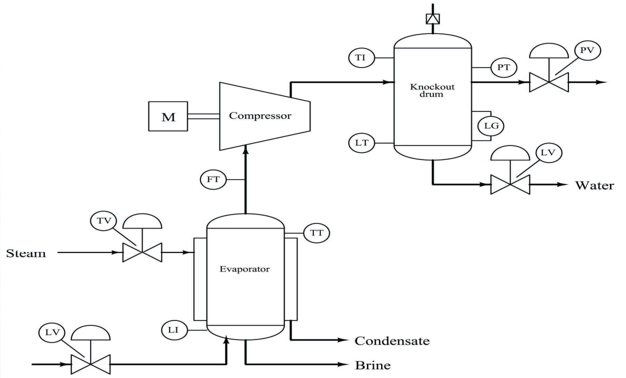
Chemical Engineering Flow Diagram

- *Process flow diagram: emphasis is on process flows.*
- *Piping and instrumentation diagram: emphasis is on process control*
- *Process flow diagram and P&ID diagram are close, but they are not the same.*

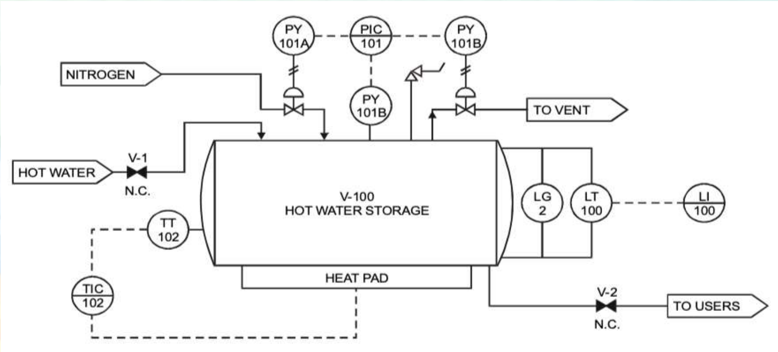
Chemical Engineering Flow Diagram



Block Flow Diagram (BFD)



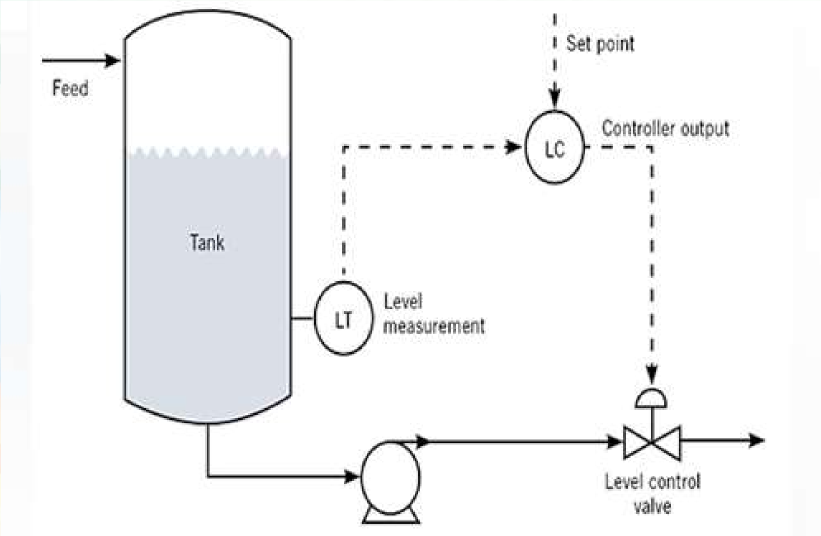
Process Flow Diagram

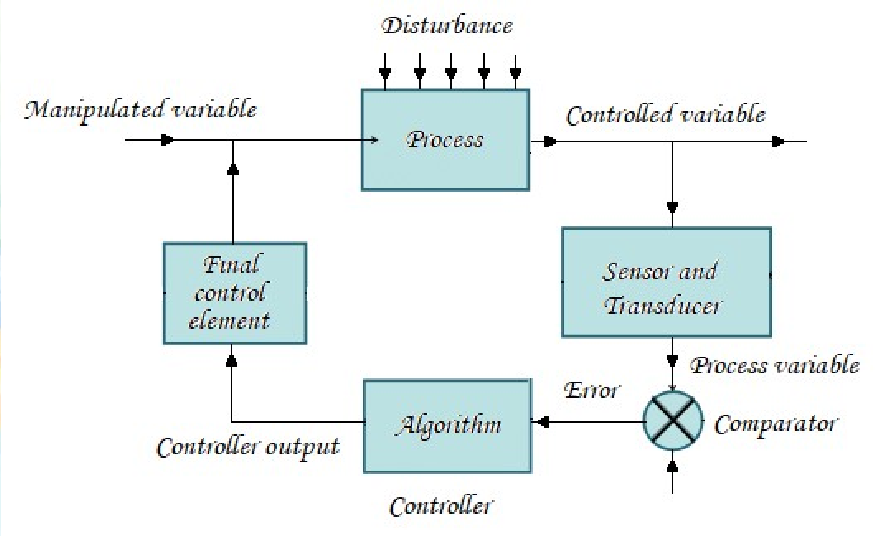


Piping and Instrumentation Diagram (P&ID)

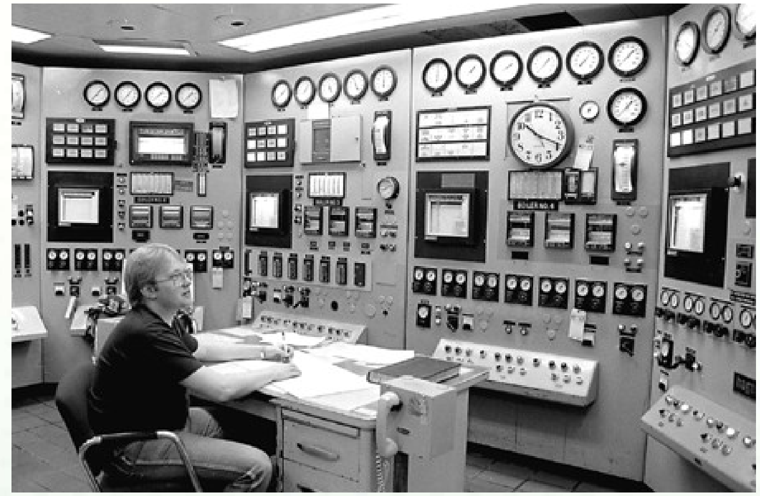
Basic Control Loop

- *Process control deals with the problem of maintaining the main process variable close to its desired values in spite of disturbances by means of an automatic system.*





Control Room



- *Modern processes use automatic process control to ensure consistent quality and quantity of products as well as it ensures safe and economic operation.*

- *Use of programmable logic control, distributed control system and centralized operation from control room are common*

PFD and P&ID

- The process flow sheet shows the arrangement of the major pieces of equipment and their interconnection. It is a description of the nature of the process.
- The piping and instrumentation diagram shows the engineering details of the equipment, instruments, piping, valves and fittings and their arrangement. It is also called the engineering flow sheet or engineering line diagram.
- Piping and instrumentation diagram usually does not show:

The process information	Equipment rating or capacity
Pressure, temperature, flow data	Manual switches

P&ID: A Key Document

- The piping and instrumentation diagram acts as a directory to all failed instrumentation and control that will be installed on a process and thus is a key document to the control engineer.
- The piping and instrumentation diagram plays an important role in the design, installation and to day to day maintenance of the control system.
- It is a key piece of information in terms of understanding what is currently being used in the plant for process control and safety.

P&ID: A Key Document

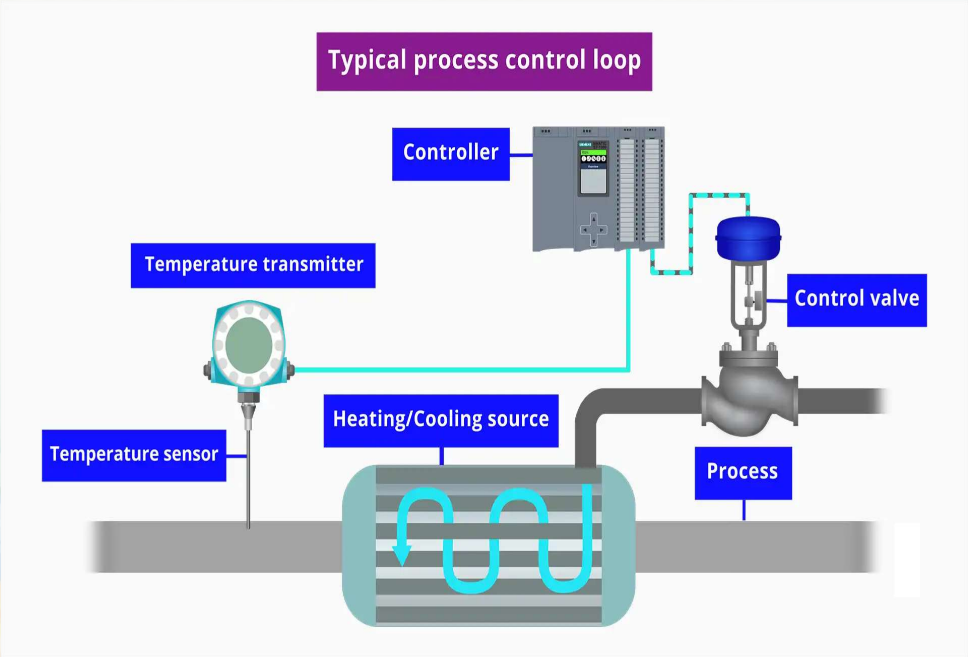
Example:

Plant operator: sees some malfunctioning with a piece of valve and reports to maintenance department that a valve on a piece of equipment is not functioning correctly.

Maintenance person: consults the piping and instrumentation diagram to identify the valve. Then he or she can learn how the valve is used in the control of the process.

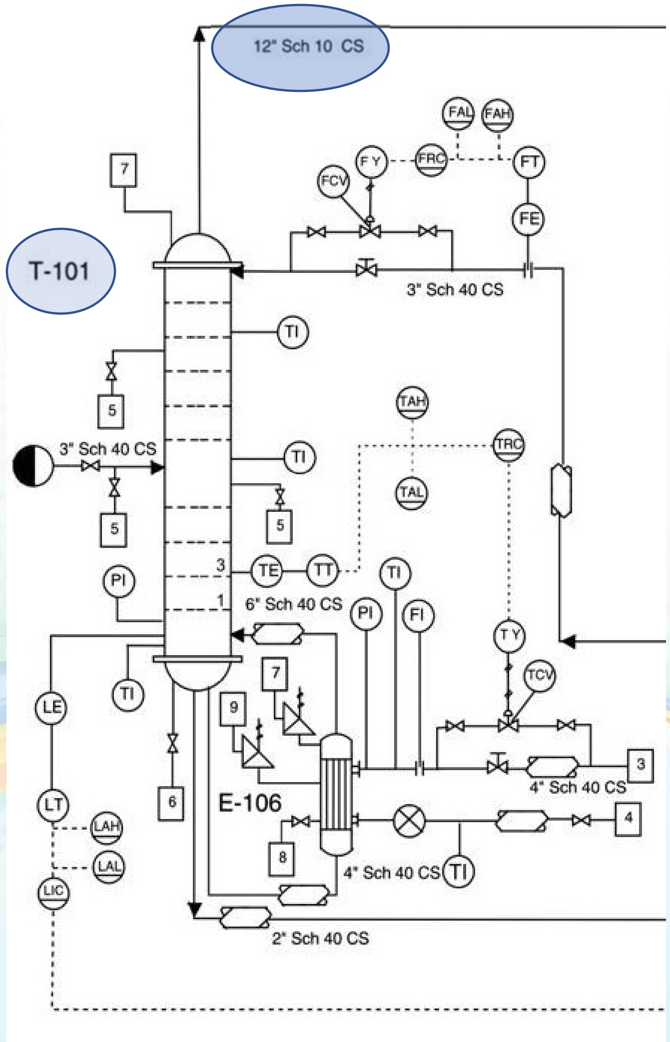
P&ID Representation

- Schematics where process units and instruments are represented using special symbols
- Control and measurement instruments are represented by specific symbols and circles with letters and numbers



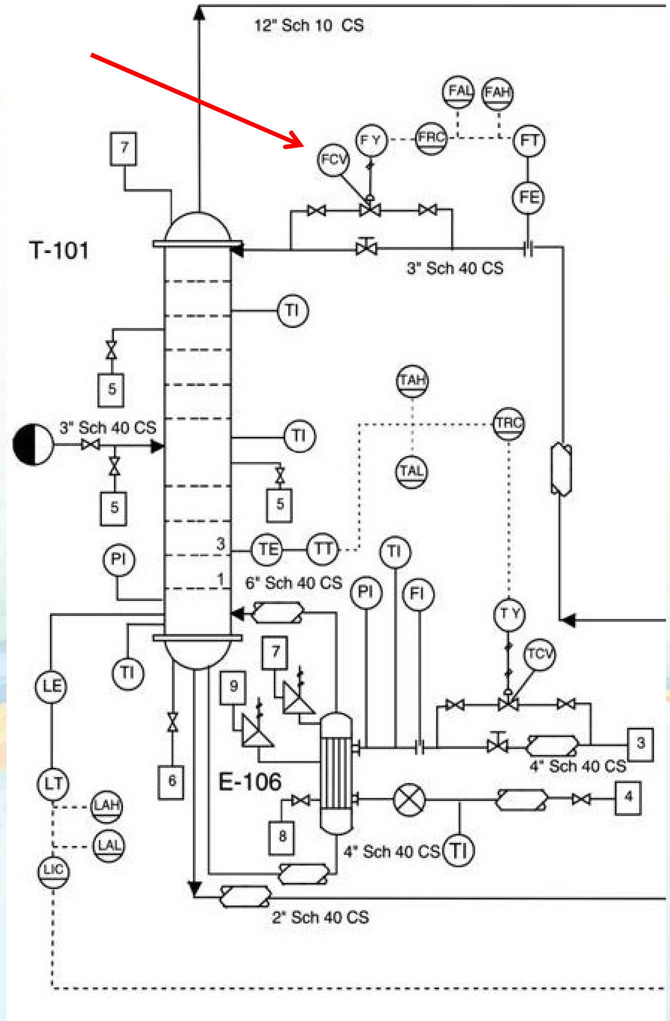
P&ID: It Should Show

- All process equipment identified by equipment number.
- The equipment are usually drawn in proportion. The location of nozzles are shown.
- All pipes are identified by line number.
- The pipe size and material of construction should be shown. The material may be included as part of the line identification number.



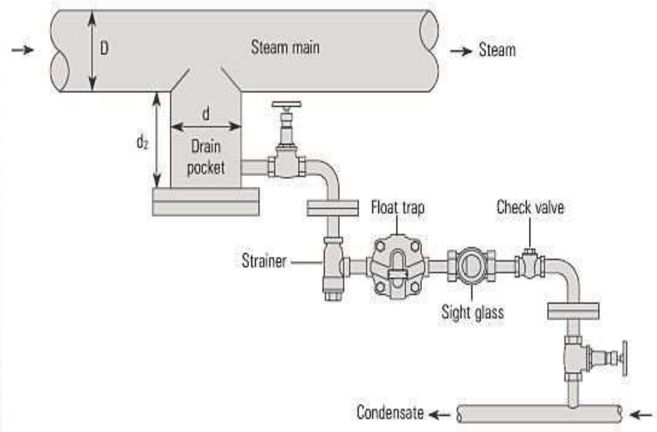
P&ID: It Should Show

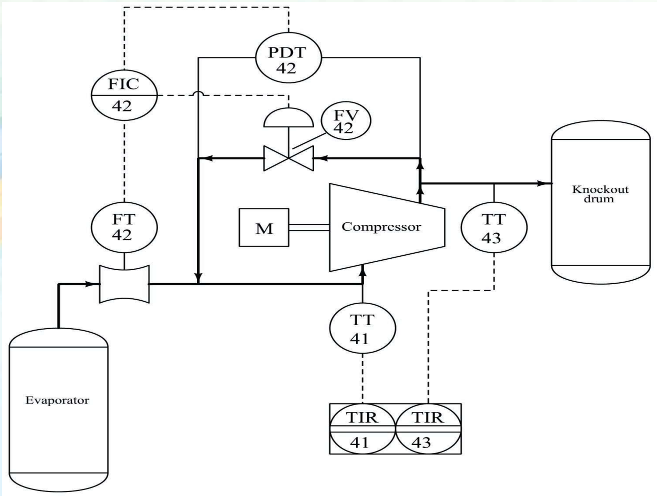
- All valves, control valves, block valves are shown with identification number.
- The type and size should also be shown. The type may be shown by the symbol used for the valve or included in the code used for the valve number.



P&ID: It Should Show

- Ancillary fittings that are part of the piping system (such as inline sight glasses, strainers and steam traps) with an identification number. Cold and hot insulation are marked.
- All pumps are shown with suitable code number
- All control loops and instruments are shown with an identification number.



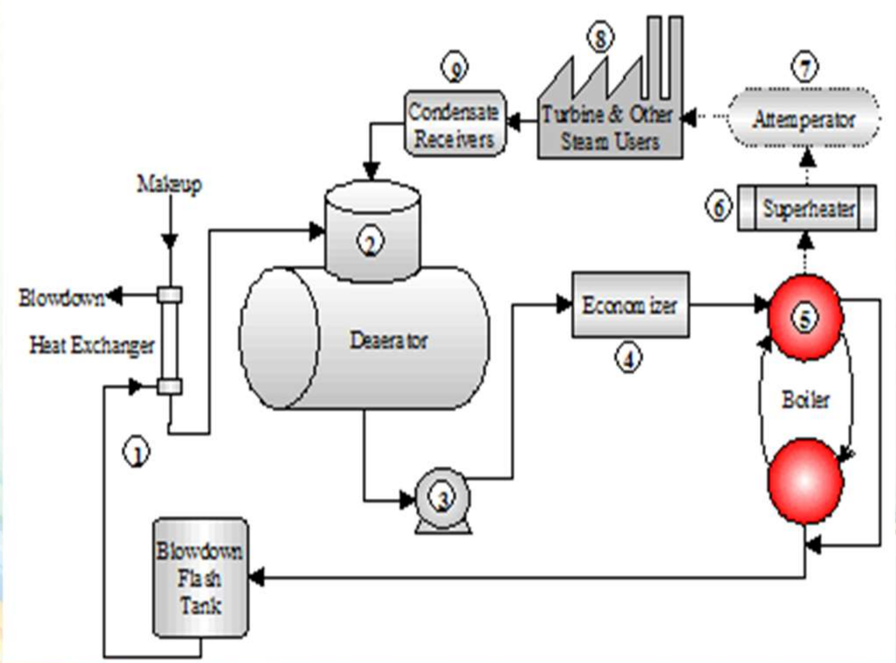


P&ID: It Should Show

- For simple processes, the utility lines (service lines) can be shown on the P&ID. Utility connections are identified by a numbered box in the P&ID.
- The number within the box identifies the specific utility. The key identifying the utility connections is shown in a table on the P&ID.
- For complex processes, separate diagrams would be used to show the utility lines. Then the service connections to each unit should be shown on the P&ID.
- The same equipment identification number should be used on both diagrams.

P&ID: Equipment Elevation

- A deaerator is a device that is commonly used in steam generating boilers to remove oxygen and other dissolved gases from feed-water for boilers to avoid corrosion.
- Most deaerators remove oxygen down to levels 7 ppb by weight and essentially eliminate carbon dioxide from the water.



P&ID: Equipment Elevation

- In a typical steam power plant, the boiler feed water (BFW) pump takes suction from the deaerator and discharges high pressure water to the boiler through the feed water heaters.
- The deaerator is installed at some elevation above the BFW pump to provide the net positive suction head required (NPSHr) by the pump.
- For complete drainage of a vessel, a specific pipeline, maybe sloped. This can also be indicated on P&D in a symbolic manner.

Codes and Standards: PFD and P&ID

US Standards

- ✓ ANSI Y32.2.3: Graphical Symbols for pipe fittings, valves and piping
- ✓ ANSI Y32.2.11: Graphical Symbols for process flow diagrams
- ✓ ISA 5.5: Graphical Symbols for process displays

British Standards

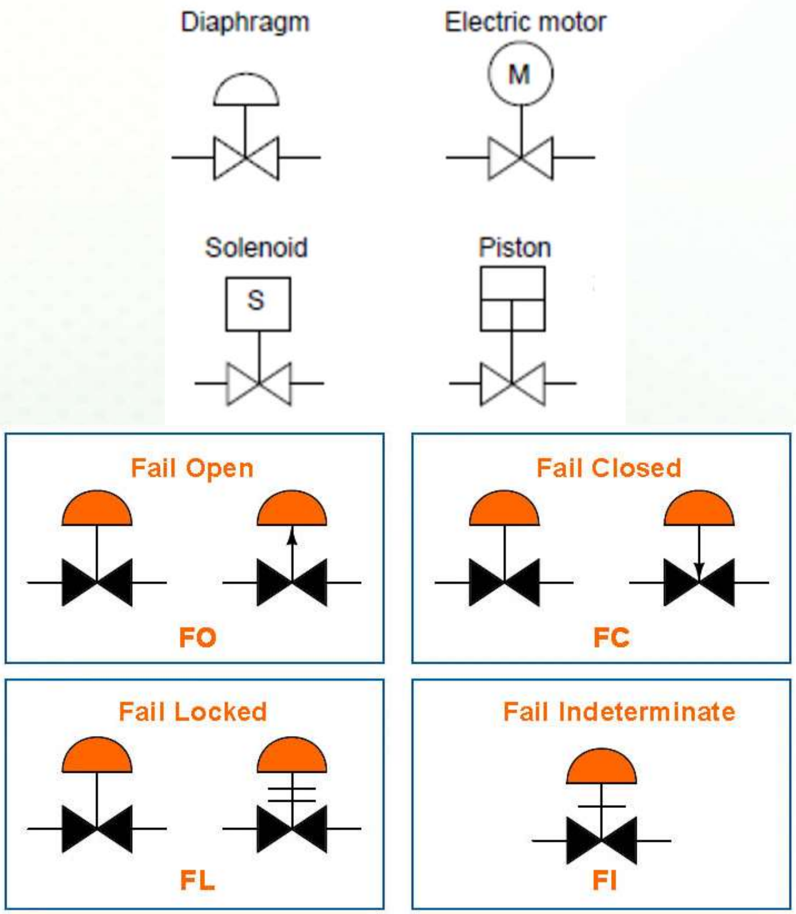
- ✓ BS: 1646 1 to 4: Symbols representation for process measurement, control function and instrumentation

German Standards

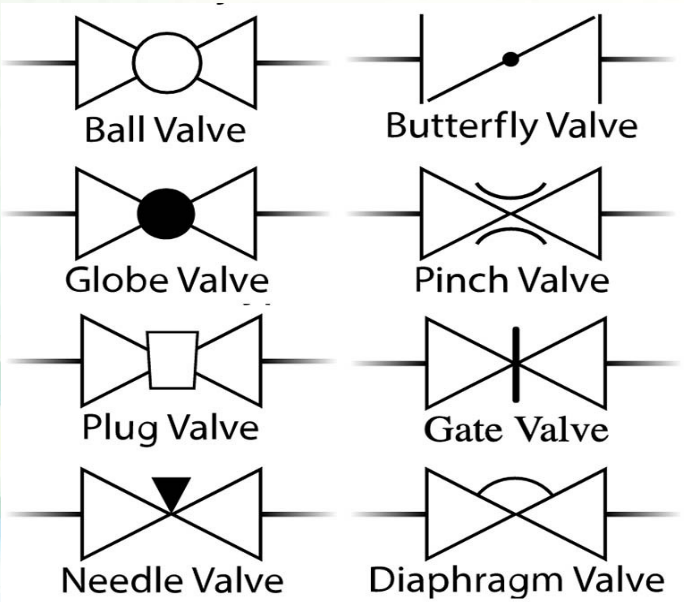
- ✓ DIN 19227 P1 to P3: Graphical Symbols and identifying letters for process measurement and control functions.

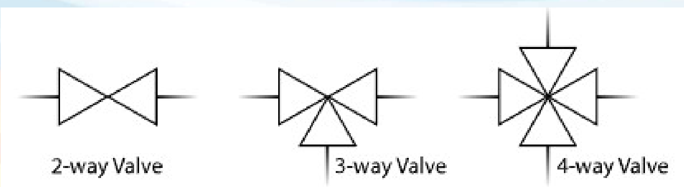
P&ID: Common Symbols

- *Representation of all types of control valves, both pneumatic and electric actuators.*
- *Fail locked" means when the control valve loses power, the valve stem stays in the last position*
- *The direction of the arrow shows the position of the valve when the power supply fails.*



P&ID: Symbols for Valve





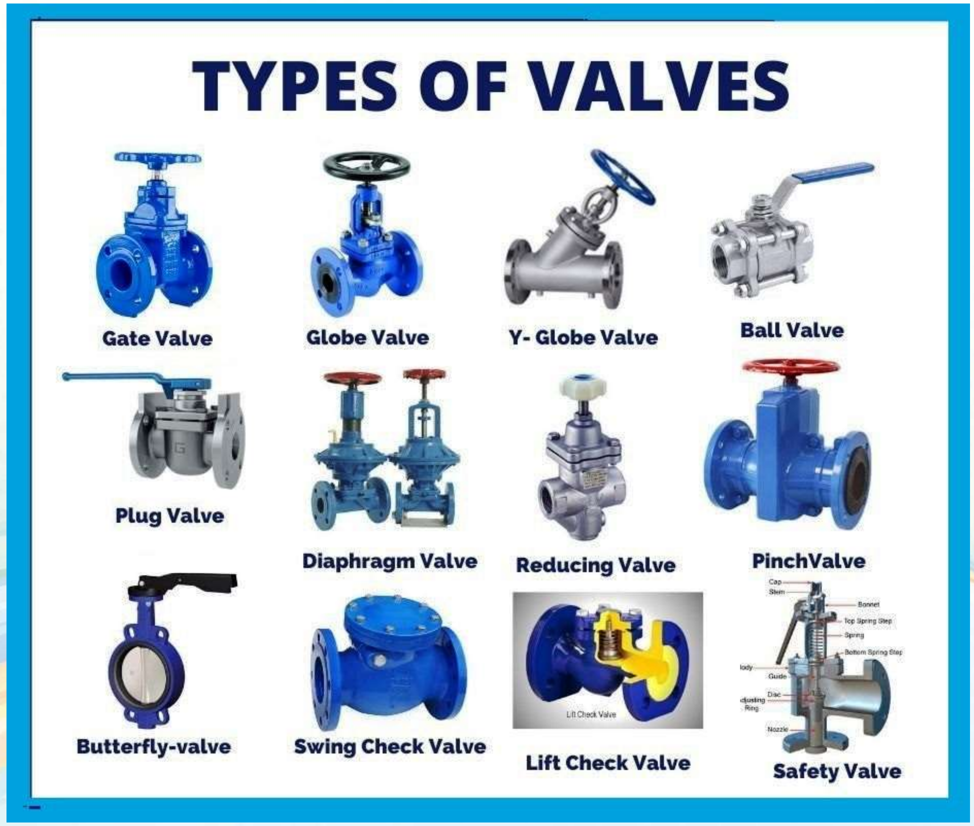
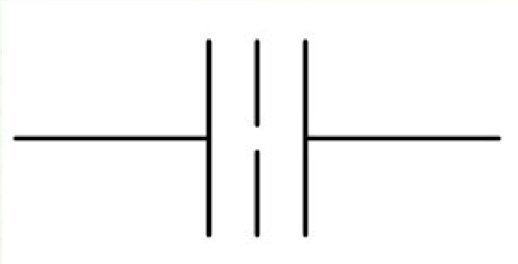
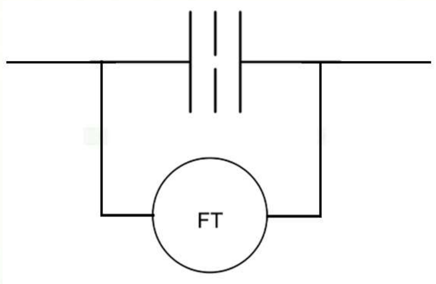


Image	Valves	Butt weld Symbol	Flanged Symbol	Socket or Threaded Symbol	Valves	Image
	Gate				Gate	
	Globe				Globe	
	Ball				Ball	
	Plug				Plug	
	Butterfly			...	Butterfly	
	Control straight	...		...	Control straight	
	Control angle	...		...	Control angle	

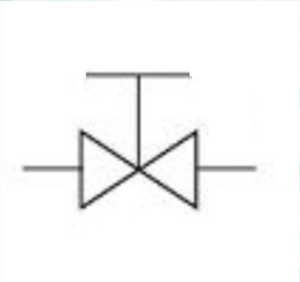
Image	Valves	Butt weld Symbol	Flanged Symbol	Socket or Threaded Symbol	Valves	Image
	Y-type				Y-type	
	Three way				Three way	
	Check				Check	
	Bottom	...		...	Bottom	
	Relief	...		...	Relief	
	Needle				Needle	
	Diaph	...			Diaph	

P&ID: Common Symbols

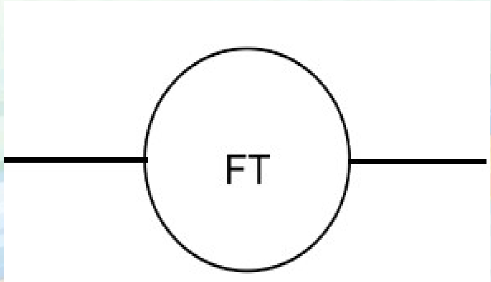




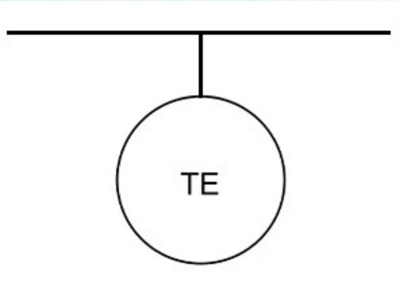
Orifice with transmitter



Hand Valve

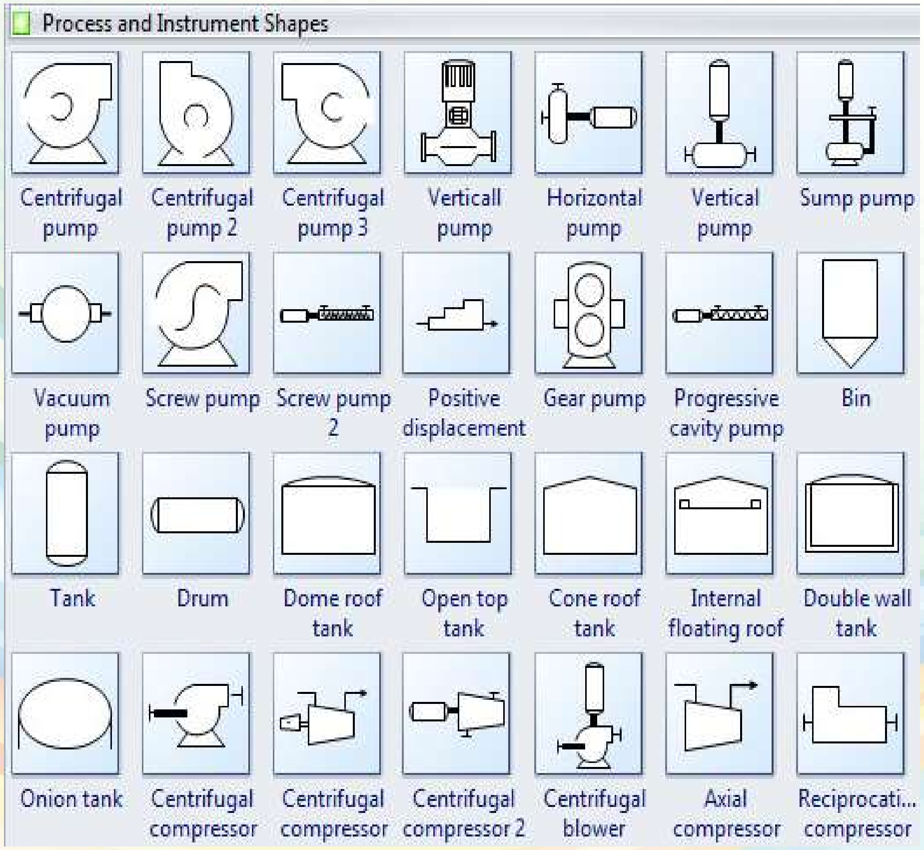


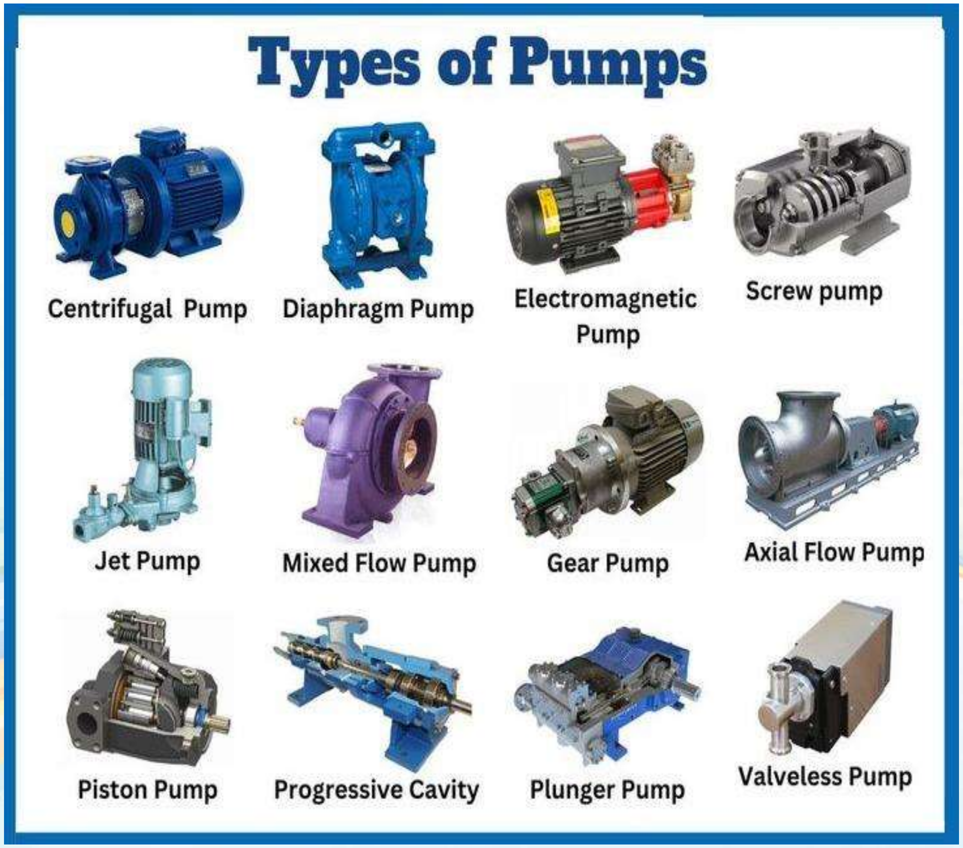
Inline measurement



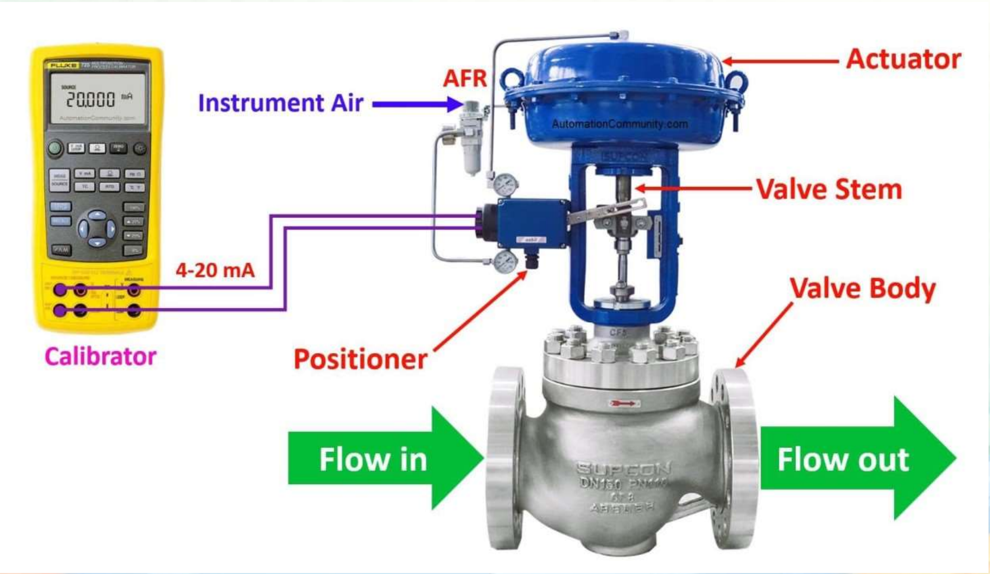
Measurement element

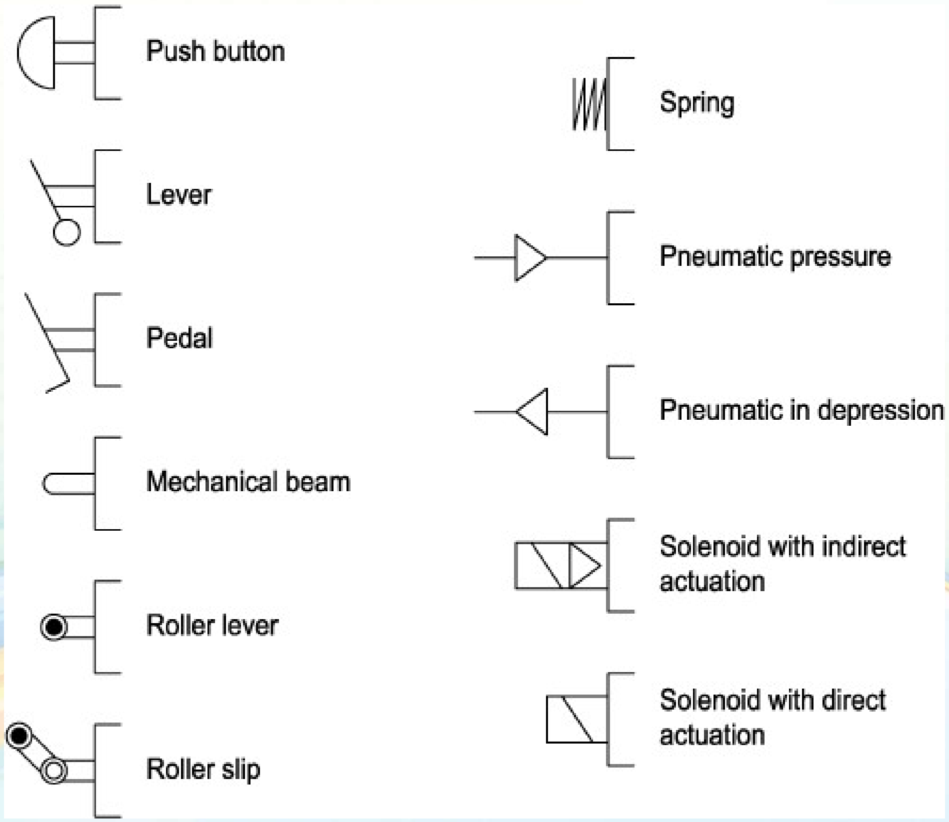
P&ID: Pump Symbol





P&ID: Actuator Symbol





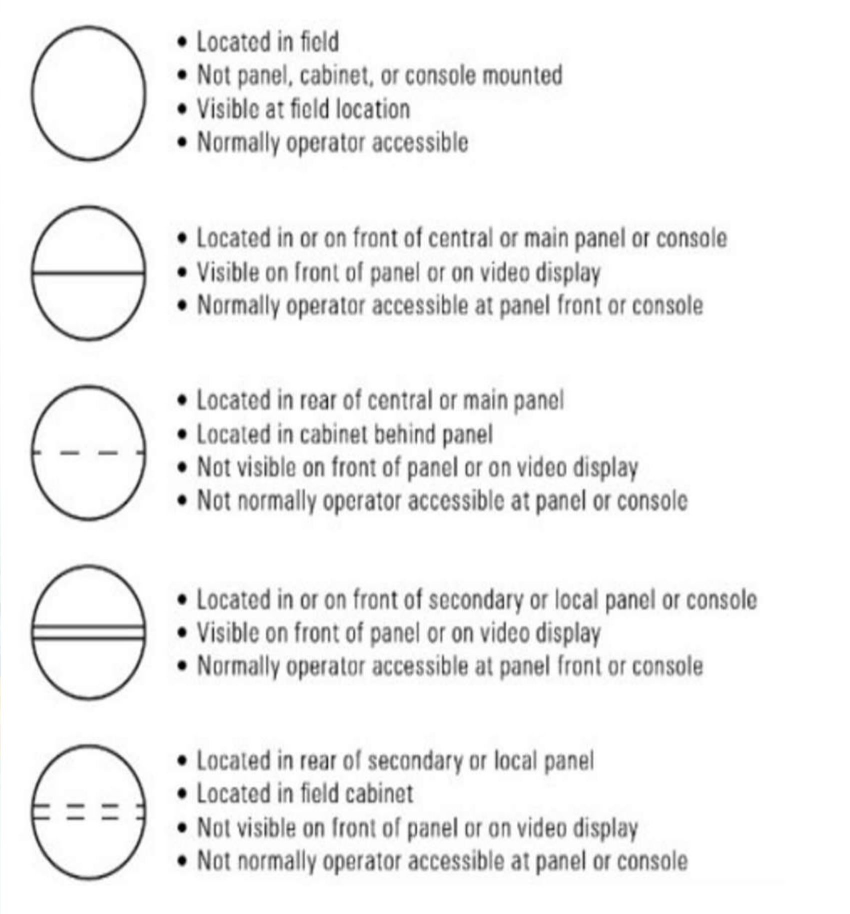
P&ID: Definitions

Locally mounted:

The instrument and the display when located on the plant, near the location of the measuring or sensing instrument.

Main panel:

Instruments located on a panel in the control room (more common)



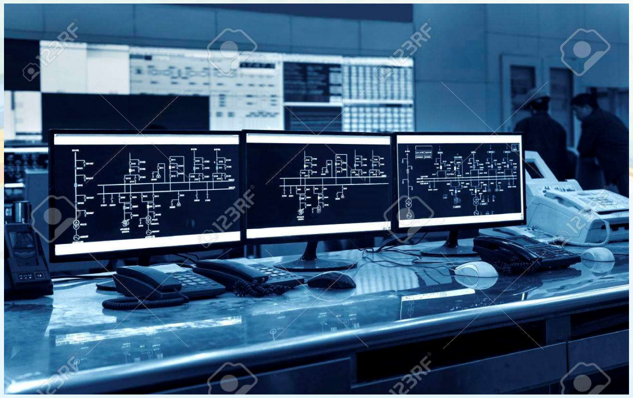
P&ID: Definitions

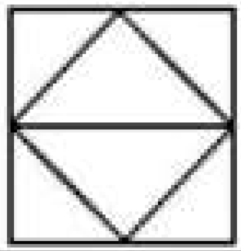
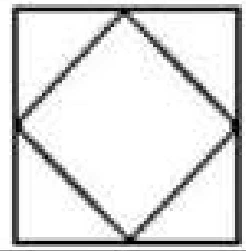
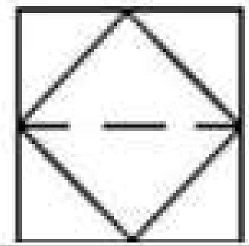
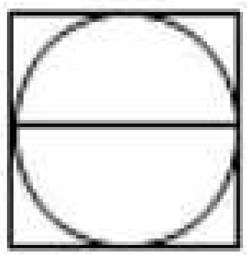
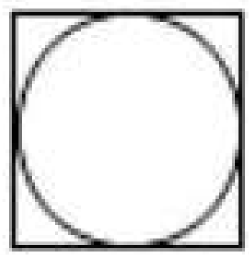
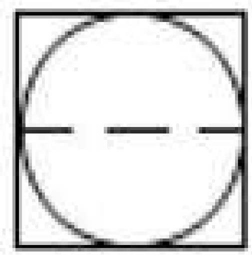
Distributed control system:

Is functionally integrated, but consists of subsystems that may be physically separated and remotely located from one another.

Shared display:

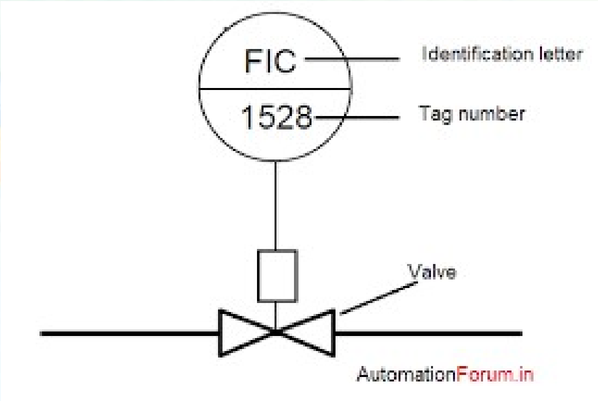
An operator interface device such as computer screen, video screen that is used to display process control information from a number of sources. Modern plants use shared display instead of instrument panels.



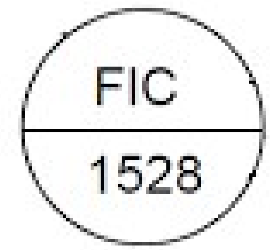
	Accessible to the Operator; Primary Location on the Main Control Panel	Mounted in the Field	Not Normally Accessible to Operator, Behind the Panel
Programmable Logic Control			
Shared Display Shared Control in Distributed Control System			

P&ID: Instrument Representation

- The piping and instrumentation diagram will use symbols and circles to represent each instrument and how they are interconnected in the process.
- The type and the function of the instrument is indicated on the circle by a letter code and tag number.
- The first letter is used to designate the measured variable.
- The succeeding letters second and third letters are used to designate the function of the component or to modify the meaning of the first letter.
- 1528 is a loop number.



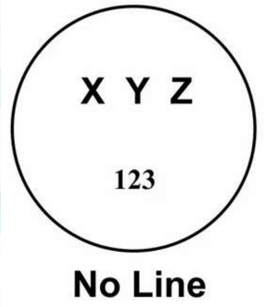
P&ID: Instrument Representation: Conention



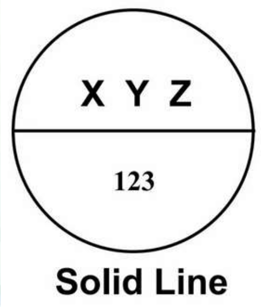
- FIC 1528 Instrument identification or tag number
- F 1528 Loop identifier
- 1528 Loop number
- TIC Function identification
- T First letter
- IC Succeeding letters
- P: Pressure, L: level, F: Flow, T: Temperature
- I will stand for indicator, R for recorder, C for controller, T for transmitter, S for switch, E for element, G for gage

P&ID: Instrument Representation

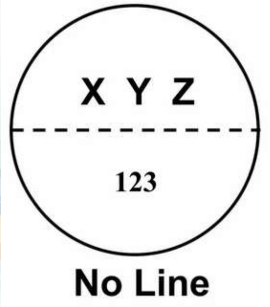
- *The presence or absence of a line determines the location of the physical device.*
- *For example, no line means the instrument is installed in the field near the process or we call it locally mounted.*



the instrument is installed in the field near the process (close to the operator)



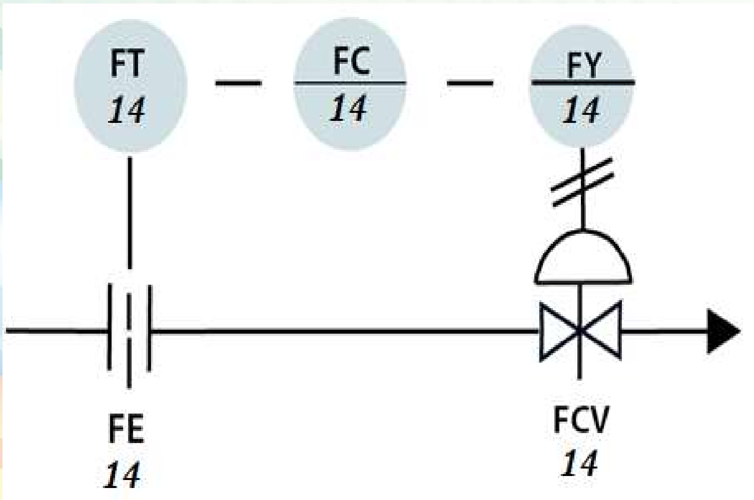
the instrument is mounted in the control panel and it is accessible to the operator

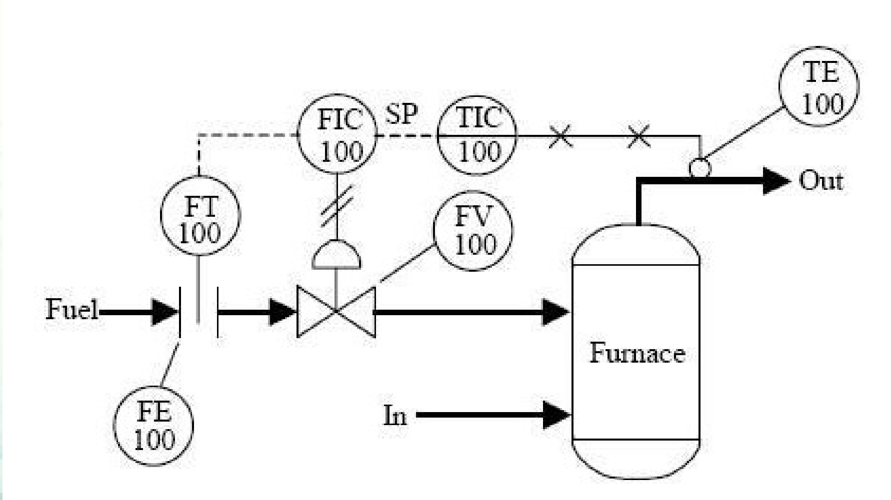


the instrument is mounted out of sight. It is not accessible to the operator

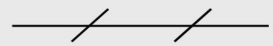
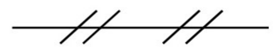
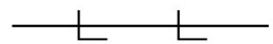
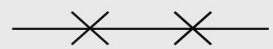
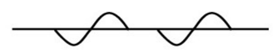
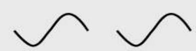
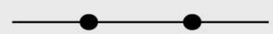
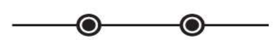
P&ID: Same number in a Control Loop

- *Same number will be used in all instruments of a particular control loop*

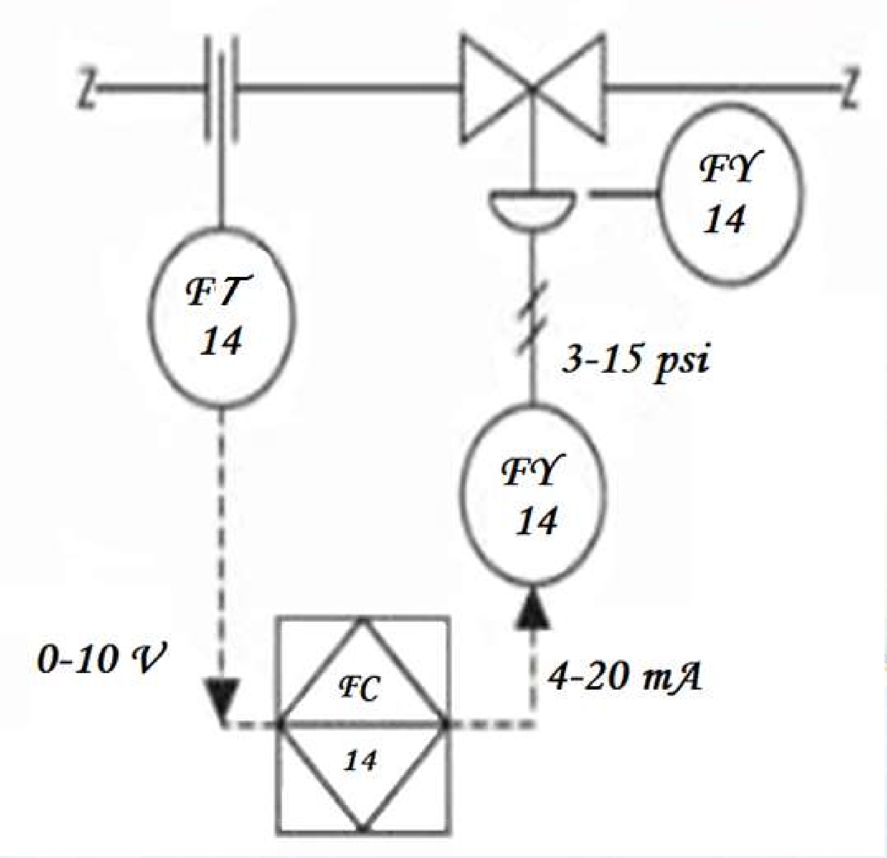




P&ID: Instrument Line Symbols

Piping (Major Projcess)		
Connection to Process (Minor Process)		• Functional diagram continuously variable signal. • Electrical schematic ladder diagram signal and power rails.
Undefined Signal		• Use for Process Flow Diagrams and diagrams where type of signal is not of concern
Pneumatic Signal		• Filled thermal element capillary tube. • Filled sensing line between pressure seal and instrument.
Electric Signal		• Electronic or electrical continuously variable or binary signal. • Functional diagram binary signal.
Hydraulic Signal		• Hydraulic Signal
Capillary Tube		• Filled thermal element capillary tube. • Filled sensing line between pressure seal and instrument.
Electromagnetic or Sonic Signal (Guided)		• Guided electromagnetic signal / sonic signal. • Fiber optic cable.
Electromagnetic or Sonic Signal (Not Guided)		• Unguided electromagnetic signals, light, radiation, radio, sound, wireless, etc. • Wireless instrumentation signal / communication link.
Internal System Link (Software or Data Link)		• Communication link and system bus, between devices and functions of a shared display, shared control system. (DCS, PLC, or PC communication link and system bus.)
Internal System Link (Software or Data Link)		• Communication link or bus connecting two or more independent microprocessor or computer-based systems. (DCS-to-DCS, DCS-to-PLC, PLC-to-PC, DCS-to-Fieldbus, etc.)
Mechanical Link		• Mechanical Link

- *This represents pneumatic flow control valve.*
- *There is a control loop, which is showing presence of both pneumatic signal as well as electric signal.*
- *So if your control system uses pneumatic control valve as well as transmitters which transmits say 4 to 20 milliampere current your diagram will have both electrical lines as well as pneumatic lines.*



P&ID: Line Code

Example 1:

2" AARX-304 S/S 1" F

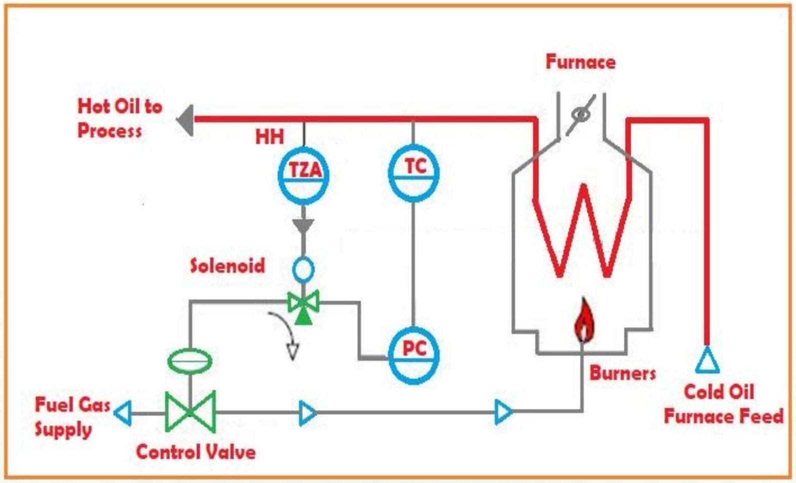
2 inch diameter, type 304 stainless steel pipe in acetic acid reactor discharge service, insulated with 1 inch of fiberglass insulation.

Example 2:

- 2" AARX-304 S/S 1" F → 2" AARX-304 S/S
- The fluid has cooled enough to eliminate the insulation.

Alarm and Safety Trips

- Audible and visual alarms are used to alert operators of serious and potentially hazardous deviations in process conditions.
- Some key instruments are fitted with a trip system to take action automatically to avoid hazardous situation such as shutting down pumps, closing valves, operating emergency systems



On high temperature, the high temperature alarm will operate a solenoid valve to release the air on the pneumatic activator and thus close the valve

False Alarm

- *Alarms that actuate because of faulty sensors, or because the alarm limit is set too close to normal operating conditions frequently provide false alarms.*
- *It is difficult to tell when these unreliable alarms are warning of a real deviation that requires action.*
- *If a display is crowded with many such nuisance alarms operators may fail to notice a real alarm that requires action.*
- *Never ignore safety alarms.*
- *If your plant has alarms that do not require a response, evaluate the need for the alarms.*

CONTROL SYSTEM DESIGN

- The design of a control system for a chemical plant is guided by the objective to maximize profits by transforming raw materials into useful products while satisfying:
  - ✓ Product specifications,
  - ✓ Safety and operational constraints,
  - ✓ Environmental regulations.

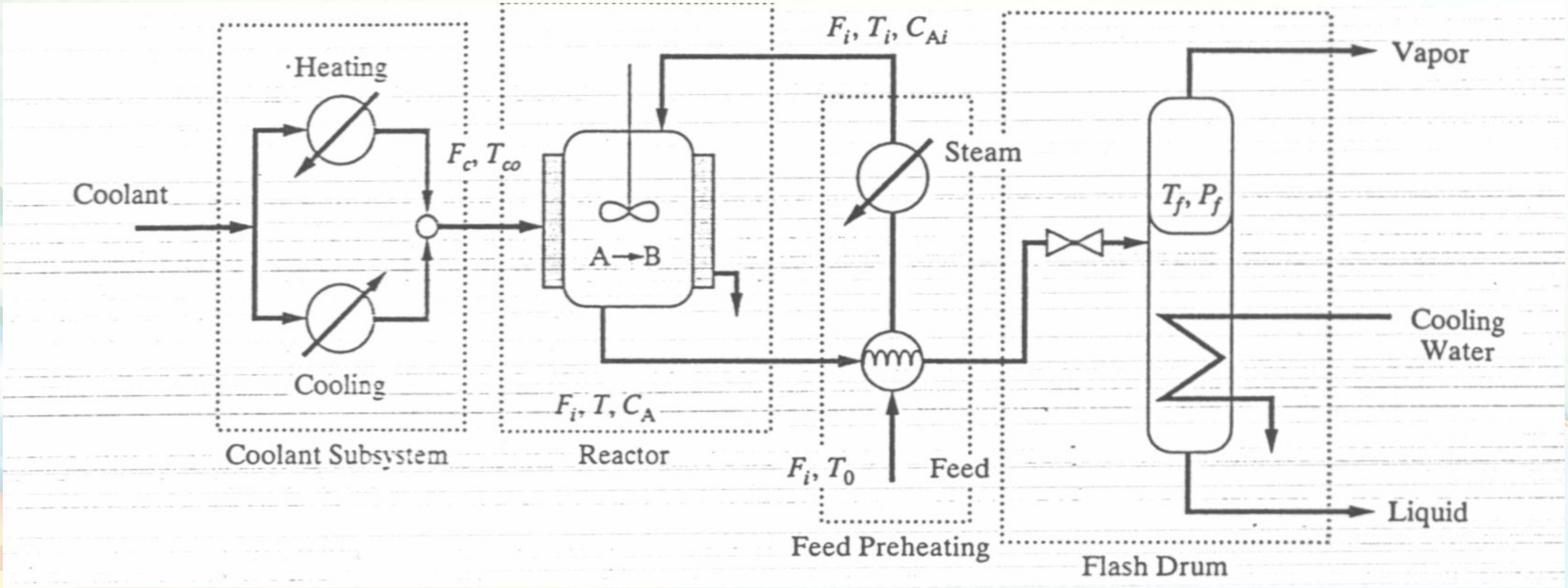
Product specifications

- To satisfy customer expectations, it is important that product quality and rate meet specifications.
- This has been the driving force for the implementation of on-line, optimal process control in the chemical industry.

Safety

- The plant must be operated safely to protect the well-being of plant personnel and nearby communities.
- As an example, a typical safety-driven constraint requires that the temperature and pressure of a steel vessel not exceed upper limits dictated by metallurgy

Conceptual Control Configuration for a Chemical Process

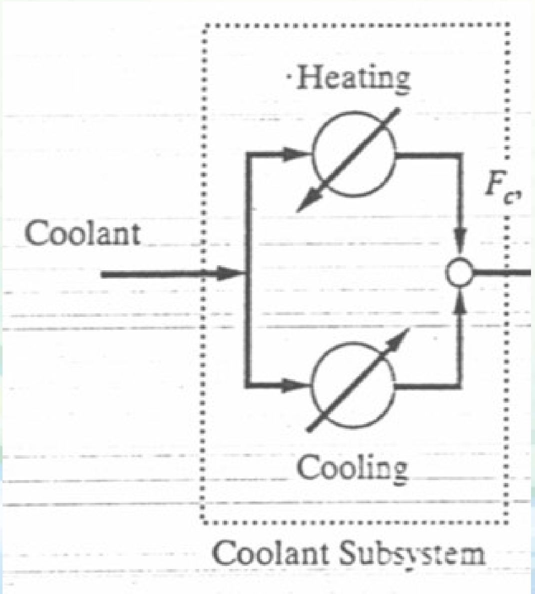


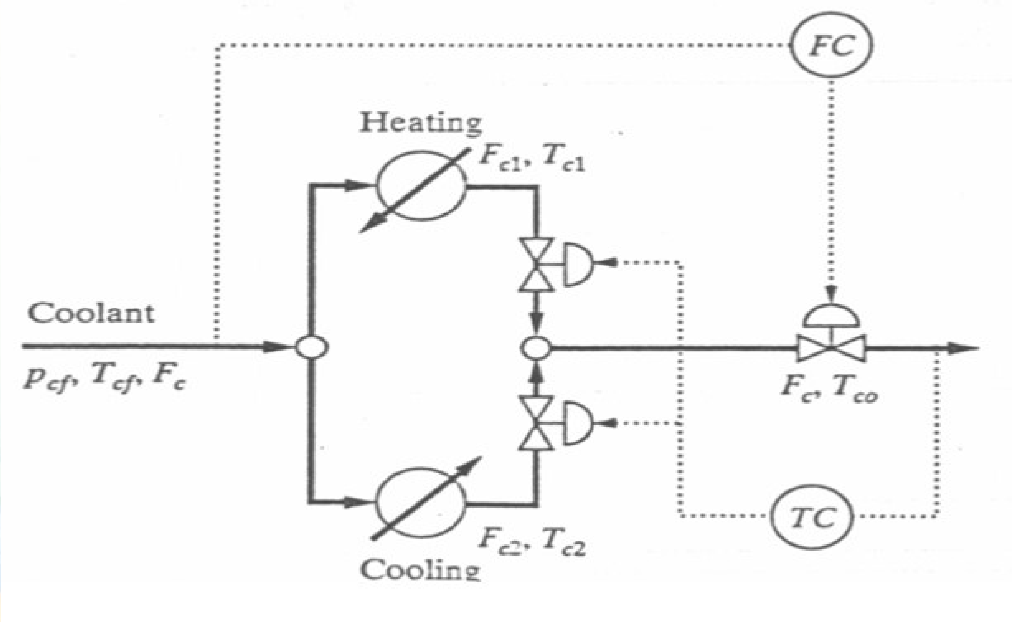
Control Objectives

The control system is designed to:

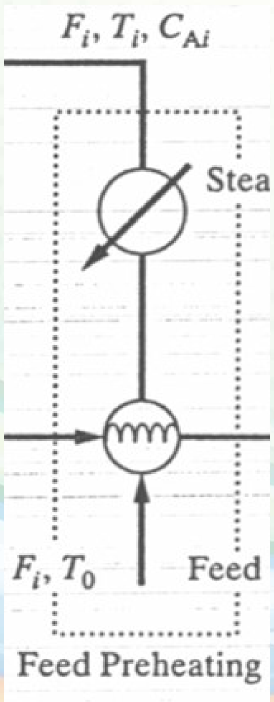
- ✓ Keep the conversion of the plant at its highest permissible value
- ✓ Maintain a constant production rate
- ✓ Achieve constant composition in the liquid effluent from the flash drum

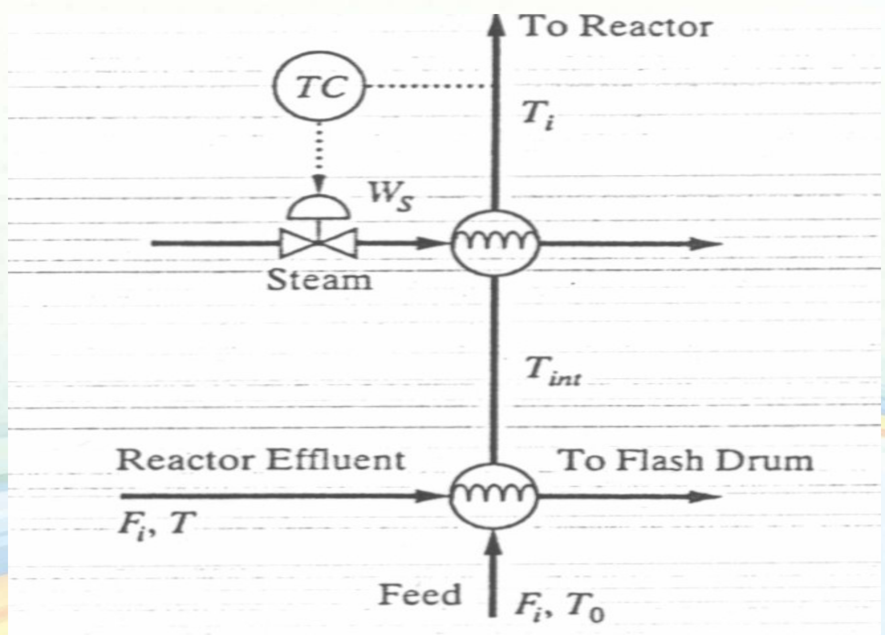
Coolant Subsystem





Feed Preheating Subsystem

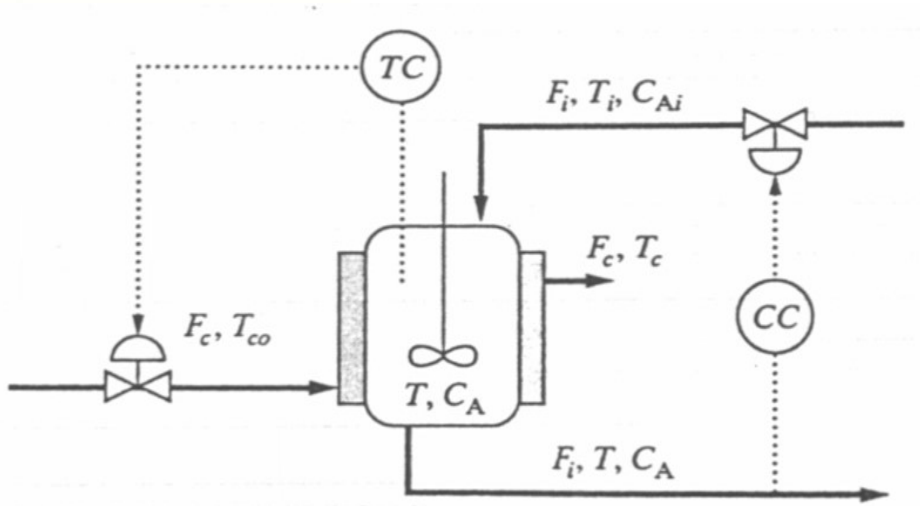




Reactor

Selection of controlled variables

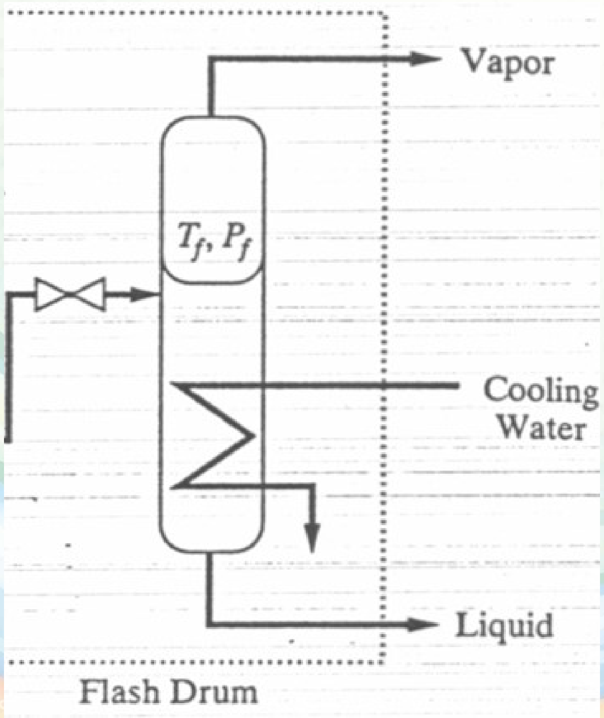
- C_A is selected because it affects the product quality directly. T is selected to avoid safety problems and because it interacts with C_A.



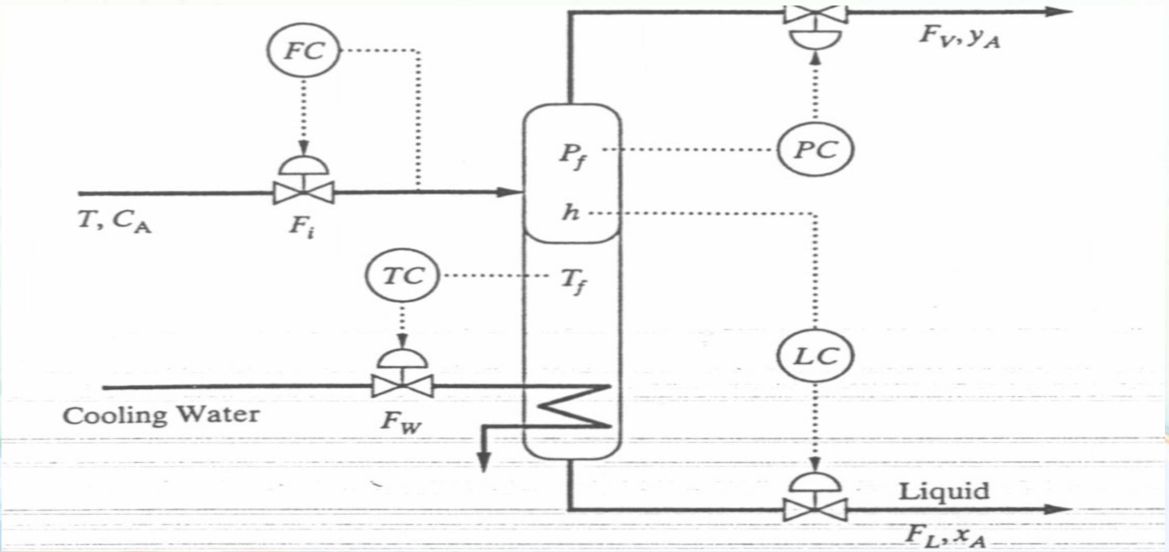
Selection of manipulated variables

- The feed flow rate, F_i, is selected because it directly and rapidly affects the conversion.
- Using the same reasoning, either T_{co} or F_c (whichever is not considered to be a disturbance) is selected to control the reactor temperature, T.
- There are several opportunities to improve on this configuration.

Flash Drum

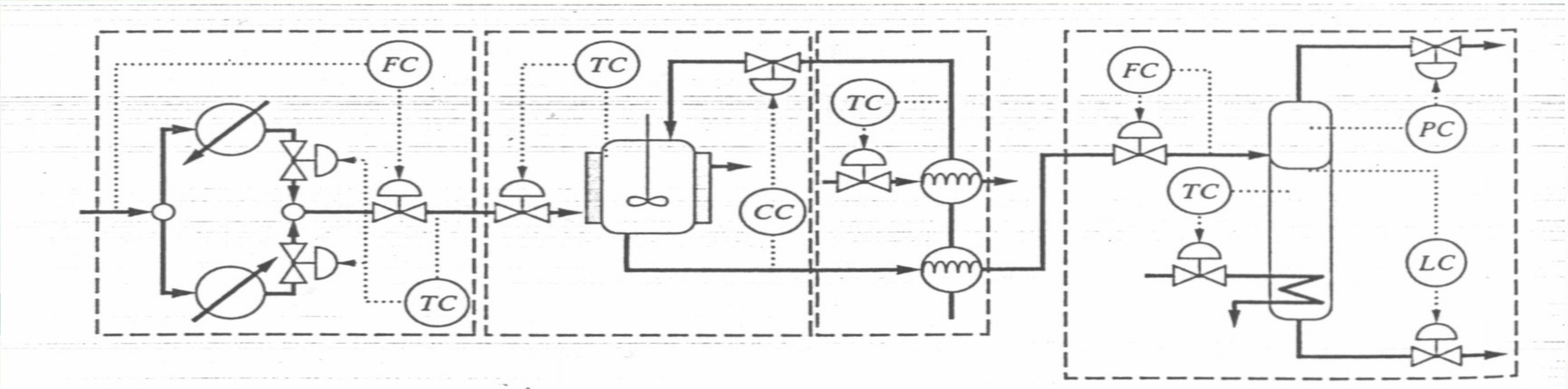


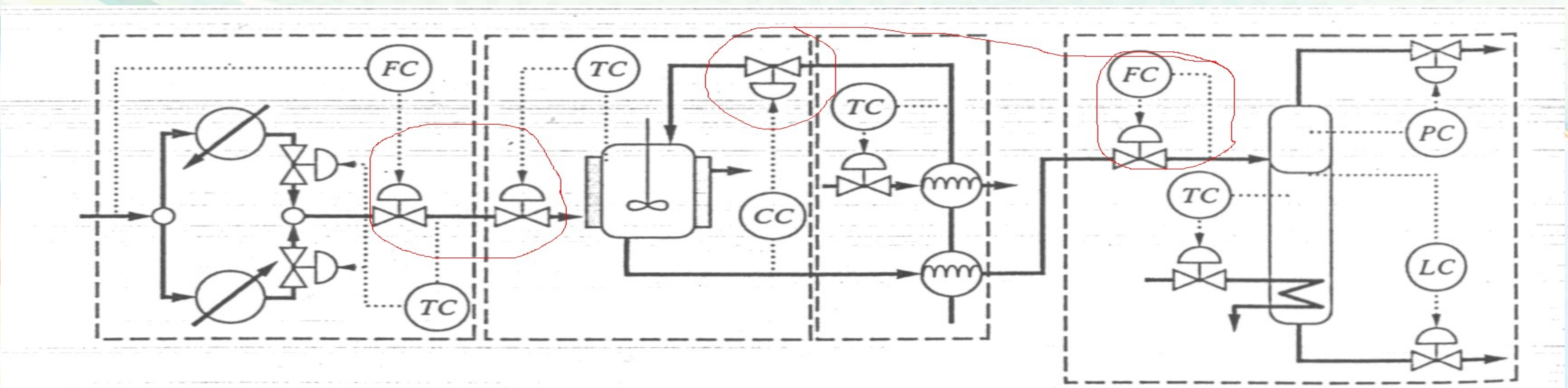
Vapor
T_f, P_f
Cooling
Water
Liquid
Flash Drum



FC
PC
F_V, y_A
P_f
h
T, C_A
F_i
TC
T_f
LC
Cooling Water
F_W
Liquid
F_L, x_A

Recombination





Refined