ChE211.1: Introduction to Chemical Engineering

Chemical processes, process variables and process flow diagram

Ayoade Kuye

Learning Objectives

- At the end of this module you will learn:
  - Different types of chemical processes and process diagrams
  - How these diagrams represent process views at different scales
  - One consistent method for drawing process flow diagrams
  - The information to be included in a process flow diagram

Introduction

- Chemical engineering deals with conversion of raw materials to more economic products.
  - The operation or a series of operations that causes a physical or chemical transformation in a material or a mixture of materials is called a **process**.
- In general, chemical processes are complex. There is need therefore to present such information in a manner that is least likely to be misinterpreted.
- This module discusses further chemical processes, variables that influence such processes and diagrams for representing such processes.

Chemical Processes – 1 of 3

- The raw materials may be placed in an equipment for some time before being converted to a product or they may flow continuously through the equipment. These processes are classified as batch, continuous, semi-batch or semi-continuous.
- **Batch Process**: Raw materials go into the process at $t = 0$; finished products and waste materials come out of the process at a defined time-point, t^*; no materials go in or out of the process at $0 < t < t^*$. By definition, the process is time-dependent, so all variables (concentrations, reaction rates, productivity, yield, purity…) will be functions of t.
  - Example: baking cookies in a conventional oven

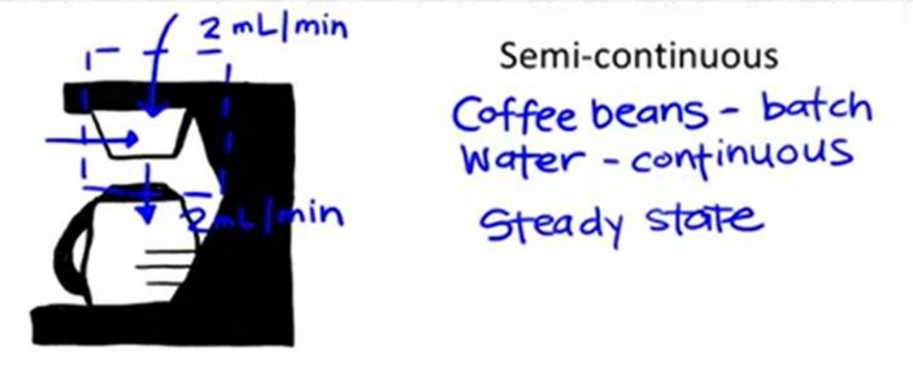
Chemical Processes - 2 of 3

- **Continuous Process:** In this type of process, raw materials continuously flow into the processing equipment, and finished products and waste continuously flow out of the equipment. Holding tanks upstream of the processing equipment are periodically charged with raw materials to keep the process going. If a continuous process is operating at "steady state", all variables (concentrations, reaction rates, productivity, yield, purity…) will be *independent* of time. Continuous processes do not have to operate at steady state. In this course, however, we will assume continuous processes are operating at steady state unless told otherwise.
  - Example: baking break in a conveyer belt oven.

Chemical Processes - 3 of 3

- **Semi-batch Process:** Hybrid between a batch and a continuous process. One or more components are batch, whereas one or more components are continuous (albeit not at steady state).
  - Example: Cooking rice
    - ✓ Rice and water are placed in a pressure cooker. As time goes on, the rice becomes more cooked, while some water escapes as steam. Because water is not going in at the same rate as steam is coming out, the water/steam stream is not at steady state.

- **Semi-continuous** *Process*: Also a hybrid between a batch and a continuous process. One or more components are batch, whereas one or more components are continuous and at steady state.
  - Example: Making coffee
    - ✓ A coffee percolator is charged with coffee grounds. Hot water flows in and out continuously and at steady state.



Exercise 1

Classify the following processes as continuous, batch, semi-continuous, or semi-batch.

a. Slowly discarding solid waste in a garbage basket with running water
b. Smoking a pork shoulder
c. Washing lettuce in a strainer
d. Converting hydrodynamic energy from a waterfall into electricity at a power plant
e. Roasting a chicken while glazing it with butter every hour
f. Blending ingredients to make a milkshake
g. Frying an egg

Process diagrams

- In general, chemical processes are complex. There is need therefore to present such information in a manner that is least likely to be misinterpreted.
  - The most effective way of communicating the information about a process is through the use of flow diagrams.
  - It is essential that chemical engineers be able to formulate appropriate process diagrams and be skilled in analyzing and interpreting diagrams prepared by others.
- The focus is on three diagrams: **block flow**, **process flow**, and piping and instrumentation diagrams.
  - PFD is the most useful to chemical engineers.

Block flow diagram

- Can take one of two forms:
  - Block flow process diagram: drawn for a single process .
  - Block flow plant diagram: drawn for a complete chemical complex involving many different chemical process.
- Both types of block flow diagrams are useful for explaining the overall operation of chemical plants.

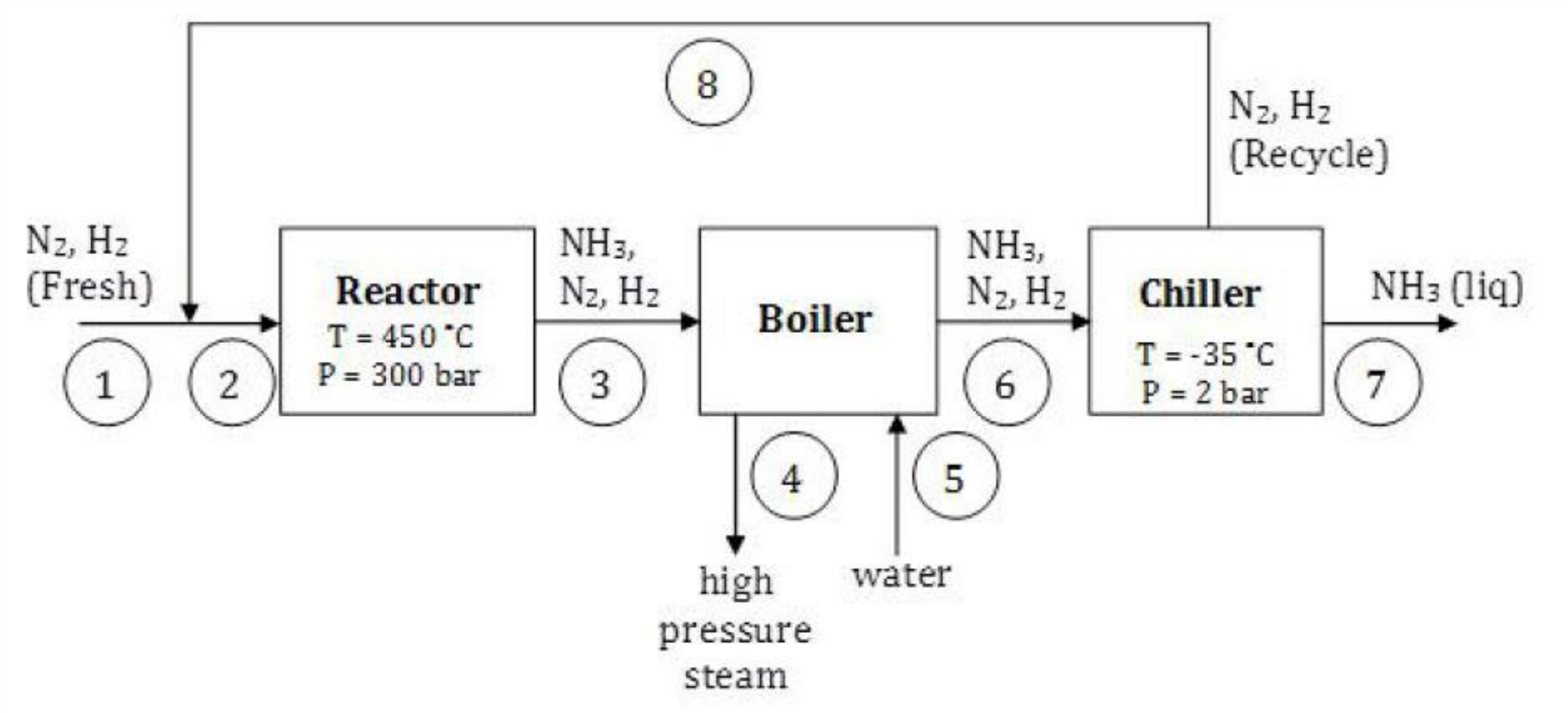
BLOCK FLOW PROCESS DIAGRAM

- Each unit operation is represented by a block
- Each block in the diagram represents a process function and may, in reality, consist of several pieces of equipment.
- It is clear that such a diagram is very useful for “getting a feel“ for the process
- It shows the main features without getting bogged down in the details.

Convections and format recommended for laying out a block flow process diagram.

1. Operations shown by blocks.
2. Major flow lines shown with arrows giving direction of flow.
3. Flow goes from left to right whenever possible.
4. Light stream (gases) toward top with heavy stream (liquids and solids) toward bottom.
5. Critical information unique to process supplied.
6. If lines cross, then the horizontal line is continuous and the vertical line is broken.
7. Simplified material balance provided.

Example: Block flow process diagram for the production of ammonia

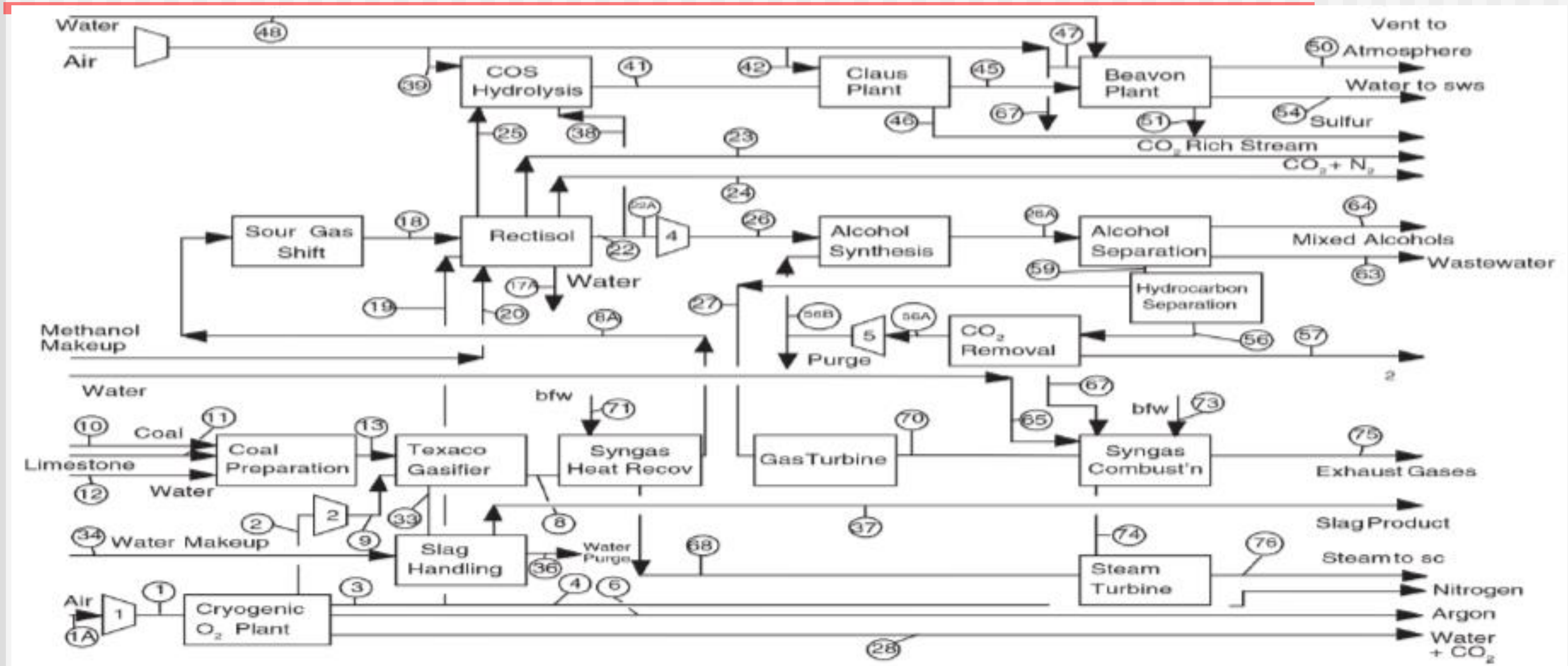


- Block flow process diagrams often form the starting point for developing a PFD.

BLOCK FLOW PLANT DIAGRAM

- Each block in this diagram represents a complete chemical process (compressors and turbines are also shown as trapezoids), and a block flow process diagram could be drawn for each block.
- It allows a complete picture of what this plant does and how all the different processes interact.
- The conventions for drawing block flow plant diagrams are similar to that for block flow process diagram.

Example: Block Flow Plant Diagram of a Coal to Higher Alcohol Fuels Process



- This is a complex process in which a number of alcohol fuel products are produced from a feedstock of coal. Each block in this diagram represents a complete chemical process (compressors and turbines are also shown as trapezoids), and a block flow process diagram could be drawn for each block

PROCESS FLOW DIAGRAM (PFD)

- The PFD contains the bulk of the chemical engineering data necessary for the design of a chemical process.
- A typical commercial PFD will contain the following information:
  - All the major pieces of equipment in the process will be represented on the diagram along with a description of the equipment. Each piece of equipment will have assigned a unique equipment number and a descriptive name.
  - All process flow streams will be shown and identified by a number. A description of the process conditions and chemical composition of each stream will be included. These data will be either displayed directly on the PFD or included in an accompanying flow summary table.
  - All utility streams supplied to major equipment that provides a process function will be shown.
  - Basic control loops, illustrating the control strategy used to operate the process during normal operations, will be shown.

PROCESS FLOW DIAGRAM (PFD)

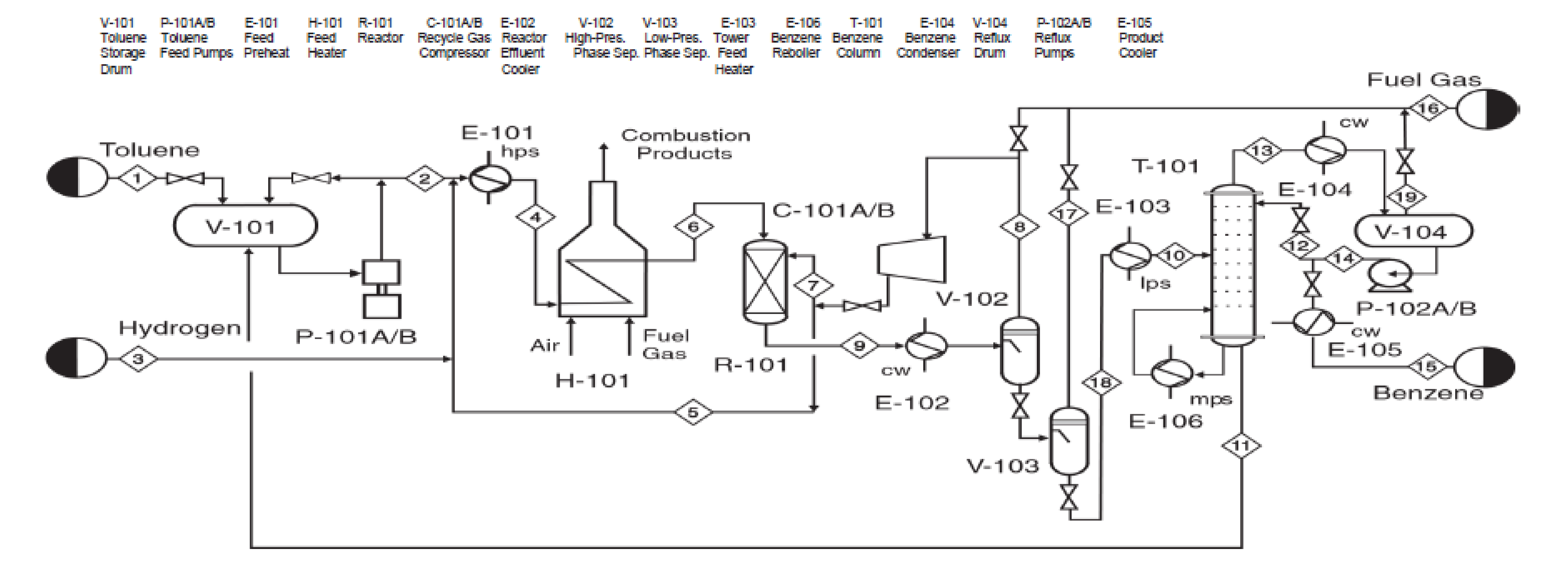
The basic information provided by a PFD can be categorized into one of the following:

- Process topology
- Stream information
- Equipment information

Process Topology

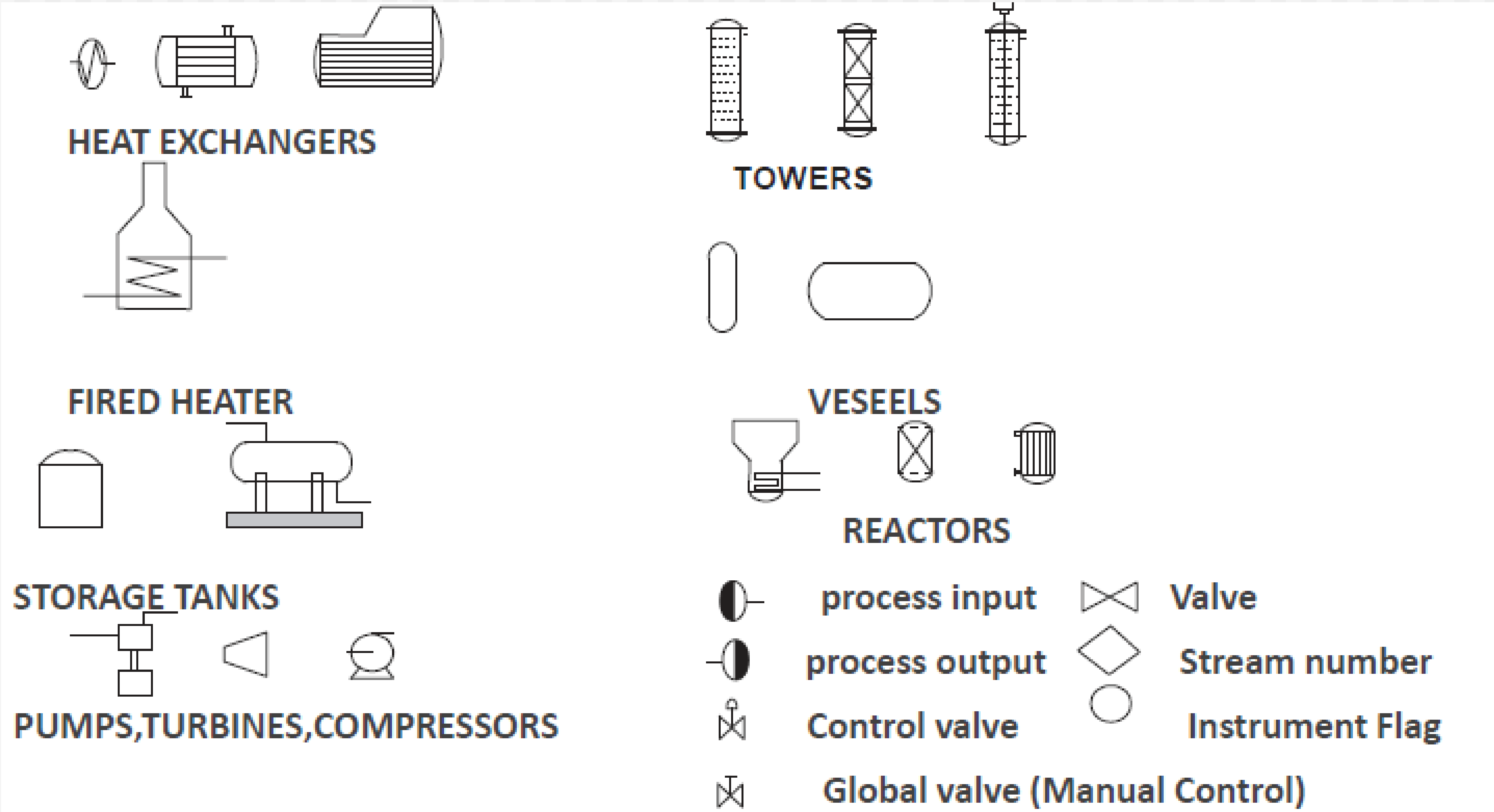
- The location of and interaction between equipment and process streams.
  - Equipment is represented symbolically by “icons” that identify specific unit operations.
  - A list of the equipment numbers along with a brief descriptive name for the equipment is printed along the top of the diagram
  - When a piece of equipment wears out and is replaced by a new unit that provides essentially the same process function as the old unit, then it is not uncommon for the new piece of equipment to inherit the old equipment’s name and number (often an additional letter suffix will be used, e.g., H-101 might become H-101A).
  - On the other hand, if a significant process modification takes place, then it is usual to use new equipment numbers and names

Process Topology



- Skeleton Process Flow Diagram (PFD) for the Production of Benzene via the Hydrodealkylation of Toluene

Process Topology



- Symbols for Drawing Process Flow Diagrams

Process Topology

Conventions Used for Identifying Process Equipment

General Format XX-YZZ A/B
XX are the identification letters for the equipment classification
C – Compressor or Turbine
E – Heat Exchanger
H – Fired Heater
P – Pump
R – Reactor
T – Tower
TK – Storage Tank
V – Vessel
Y designates an area within the plant
ZZ is the number designation for each item in an equipment class
A/B identifies parallel units or backup units not shown on a PFD
Additional description of equipment is given on top of PFD

Process Topology

- As an example of how to use the Table in the slide 15, consider the unit operation P-101A/B. In this example, each number or letter means:
- **P**-101A/B identifies the equipment as a pump.
- P-**1**01A/B indicates that the pump is located in area 100 of the plant.
- P-1**01**A/B indicates that this specific pump is number 01 in unit 100.
- P-101**A/B** indicates that a backup pump is installed. Thus, there are two identical pumps, P-101A and P-101B. One pump will be operating while the other is idle.

Stream Information

- Each of the process streams is identified by a number in a diamond box located on the stream. The direction of the stream is identified by one or more arrowheads. The process stream numbers are used to identify streams on PFD.
  - See slide 18
- Also identified in PFDs are utility streams.
  - Utilities are needed services that are available at the plant. Chemical plants are provided with a range of central utilities that include electricity, compressed air, cooling water, refrigerated water, steam, condensate return, inert gas for blanketing, chemical sewer, wastewater treatment, and flares.
  - See next slide for a list of the common services

Stream Information
Conventions for Identifying Process and Utility Streams

Process Streams	
All conventions shown in Table 1.1 apply.	
Diamond symbol located in flow lines.	
Numerical identification (unique for that stream) inserted in diamond.	
Flow direction shown by arrows on flow lines.	
Utility Streams	
lps	Low-Pressure Steam: 3–5 barg (sat)*
mps	Medium-Pressure Steam: 10–15 barg (sat)*
hps	High-Pressure Steam: 40–50 barg (sat)*
htm	Heat Transfer Media (Organic): to 400°C
cw	Cooling Water: From Cooling Tower 30°C Returned at Less than 45°C †
wr	River Water: From River 25°C Returned at Less than 35°C
rw	Refrigerated Water: In at 5°C Returned at Less than 15°C
rb	Refrigerated Brine: In at -45°C Returned at Less than 0°C
cs	Chemical Wastewater with High COD
ss	Sanitary Wastewater with High BOD, etc.
el	Electric Heat (Specify 220, 440, 660V Service)
bfw	Boiler Feed Water
ng	Natural Gas
fg	Fuel Gas
fo	Fuel Oil
fw	Fire Water

***These pressures are set during the preliminary design stages and typical values vary within the ranges shown.**

†Above 45°C, significant scaling occurs and the usual return temperature is 40°C.

Stream Information

- For small diagrams containing only a few operations, the characteristics of the streams such as temperatures, pressures, compositions, and flowrates can be shown directly on PFD.
- For complex diagrams only the stream number is provided on the diagram.
  - The stream information is normally given in a flow summary table. It is divided into two sections—required information and optional information. See next slide
  - The flow summary table for benzene PFD is shown in slide 21

Information Provided in a Flow Summary

Required Information
Stream Number
Temperature (°C)
Pressure (bar)
Vapor Fraction
Total Mass Flowrate (kg/h)
Total Mole Flowrate (kmol/h)
Individual Component Flowrates (kmol/h)
Optional Information
Component Mole Fractions
Component Mass Fractions
Individual Component Flowrates (kg/h)
Volumetric Flowrates (m /h)
Significant Physical Properties
Density
Viscosity
Other
Thermodynamic Data
Heat Capacity
Stream Enthalpy
K-values
Stream Name

Flow Summary Table for the Benzene PFD

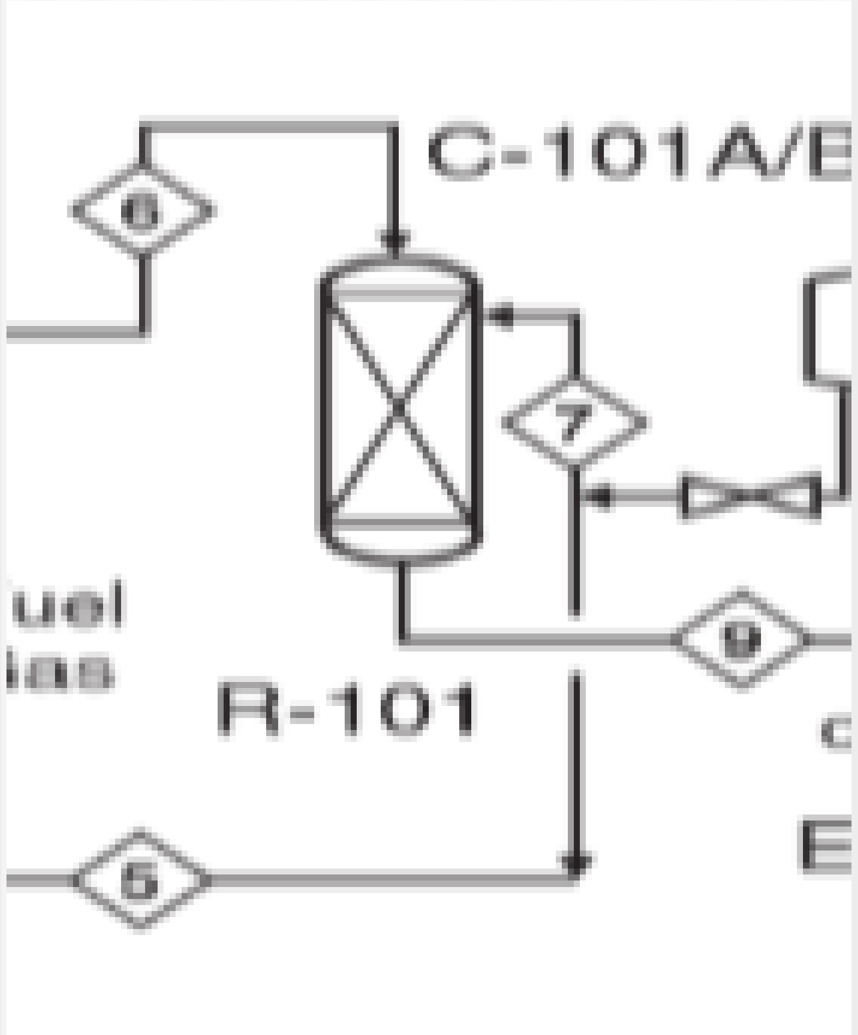
Stream number	1	2	3	4	5	6	7	8
Temperature (˚C)	25	59	25	225	41	600	41	38
Pressure (bar)	1.90	25.8	25.5	25.2	25.5	25.0	25.5	23.9
Vapor fraction	0.0	0.0	1.00	1.0	1.0	1.0	1.0	1.0
Mass flow (tonne/h).	10.0	13.3	0.82	20.5	6.41	20.5	0.36	9.2
Mole flow (Kmol/h).	108.7	144.2	301.0	1204.4	758.8	1204.4	42.6	1100.8
Component flowrates (Kmol/h).								
Hydrogen	0.0	0.0	286.0	735.4	449.4	735.4	25.2	651.9
Methane	0.0	0.0	15.0	317.3	302.2	317.3	16.95	438.3
Benzene	0.0	1.0	0.0	7.6	6.6	7.6	0.37	9.55
Toluene	108.7	143.2	0.0	144.0	7.0	144.0	0.04	1.05

Flow Summary Table for the Benzene PFD

9	10	11	12	13	14	15	16	17	18	19
654	90	147	112	112	112	38	38	38	38	112
24.0	2.6	2.8	3.3	2.5	3.3	2.3	2.5	2.8	2.9	2.5
1.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	1.0
20.9	11.6	3.27	14.0	22.7	22.7	8.21	2.61	0.07	11.5	0.01
1247.0	142.2	35.7	185.2	291.6	290.7	105.6	304.2	4.06	142.2	0.90
652.6	0.02	0.0	0.0	0.02	0.0	0.0	178.0	0.67	0.02	0.02
442.3	0.88	0.0	0.0	0.88	0.0	0.0	123.05	3.10	0.88	0.88
116.0	106.3	1.1	184.3	289.46	289.46	105.2	2.85	0.26	106.3	0.0
36.0	35.0	34.6	0.88	1.22	1.22	0.4	0.31	0.03	35.0	0.0

Example: Determine the conversion per pass of toluene to benzene in R-101 in slide 18

- **Solution:**
  - Conversion X = (benzene produced in reactor)/(total toluene fed to reactor)
  - From the PFD, the input streams to R-101 are Stream 6 (reactor feed) and Stream 7 (recycle gas quench), and the output stream is Stream 9 (reactor effluent stream).
  - From the flow summary table (units are kmol/h):
    - ✓ Toluene fed to reactor = 144 (Stream 6) + 0.04 (Stream 7) = 144.04 kmol/h
    - ✓ Benzene produced in reactor = 116 (Stream 9) – 7.6 (Stream 6) – 0.37 (Stream 7) = 108.03 kmol/h
    - ✓ X = 108.03/144.04 = 0.75



Equipment Information

- The final element of the PFD is the equipment summary.
  - The information necessary to estimate the costs of equipment and furnish the basis for the detailed design of equipment.
    - ✓Such information for most of the equipment encountered in fluid processes is presented in the next slide.
      - Using this information the equipment summary for the benzene process is presented in Slide 26

Equipment Descriptions for PFD and P&IDs

Equipment Type Description of Equipment
Towers Size (height and diameter), Pressure, Temperature Number and Type of Trays Height and Type of Packing Materials of Construction
Heat Exchangers Type: Gas-Gas, Gas-Liquid, Liquid-Liquid, Condenser, Vaporizer Process: Duty, Area, Temperature, and Pressure for Both Streams Number of Shell and Tube Passes Materials of Construction: Tubes and Shell
Tanks and Vessels Height, Diameter, Orientation, Pressure, Temperature, Materials of Construction
Pumps Flow, Discharge Pressure, Temperature, ΔP, Driver Type, Shaft Power, Materials of Construction
Compressors Actual Inlet Flowrate, Temperature, Pressure Inlet and Outlet, Driver Type, Shaft Power, Materials of Construction
Heaters (Fired) Type, Tube Pressure, Tube Temperature, Duty, Fuel, Material of Construction
Other Provide Critical Information

Equipment Summary for Toluene Hydrodealkylation PFD

Heat Exchangers	E-101	E-102	E-103	E-104	E-105	E-106
Type	Fl.H.	Fl.H.	MDP	Fl.H.	MDP	Fl.H.
Area (m^2)	36	763	11	35	12	80
Duty (MJ/h)	15,190	46,660	1055	8335	1085	9045
Shell						
Temp. (°C)	225	654	160	112	112	185
Pres. (bar)	26	24	6	3	3	11
Phase	Vap.	Par. Cond.	Cond.	Cond.	l	Cond.
MOC	316SS	316SS	CS	CS	CS	CS
Tube						
Temp. (°C)	258	40	90	40	40	147
Pres. (bar)	42	3	3	3	3	3
Phase	Cond.	l	l	l	l	Vap.
MOC	316SS	316SS	CS	CS	CS	CS

Equipment Summary for Toluene Hydrodealkylation PFD

Vessels/Tower/ Reactors	V-101	V-102	V-103	V-104	T-101	R-101
Temperature (°C)	55	38	38	112	147	660
Pressure (bar)	2.0	24	3.0	2.5	3.0	25
Orientation	Horizontal	Vertical	Vertical	Horizontal	Vertical	Vertical
MOC	CS	CS	CS	CS	CS	316SS
Size						
Height/Length (m)	5.9	3.5	3.5	3.9	29	14.2
Diameter (m)	1.9	1.1	1.1	1.3	1.5	2.3
Internals		s.p.	s.p.		42 sieve trays	Catalyst
					316SS	packed bed-10m
	P-101	P-102	C-101			
Pumps/Compressors	(A/B)	(A/B)	(A/B)	Heater		H-101
Flow (kg/h)	13,000	22,700	6770	Type		Fired
Fluid Density (kg/m^3)	870	880	8.02	MOC		316SS
Power (shaft) (kW)	14.2	3.2	49.1	Duty (MJ/h)		27,040
Type/Drive	Recip./	Centrf./	Centrf./	Radiant Area (m^2)		106.8
	Electric	Electric	Electric			
Efficiency (Fluid Power/Shaft Power)	0.75	0.50	0.75	Convective Area (m^2)		320.2

Equipment Summary for Toluene Hydrodealkylation PFD

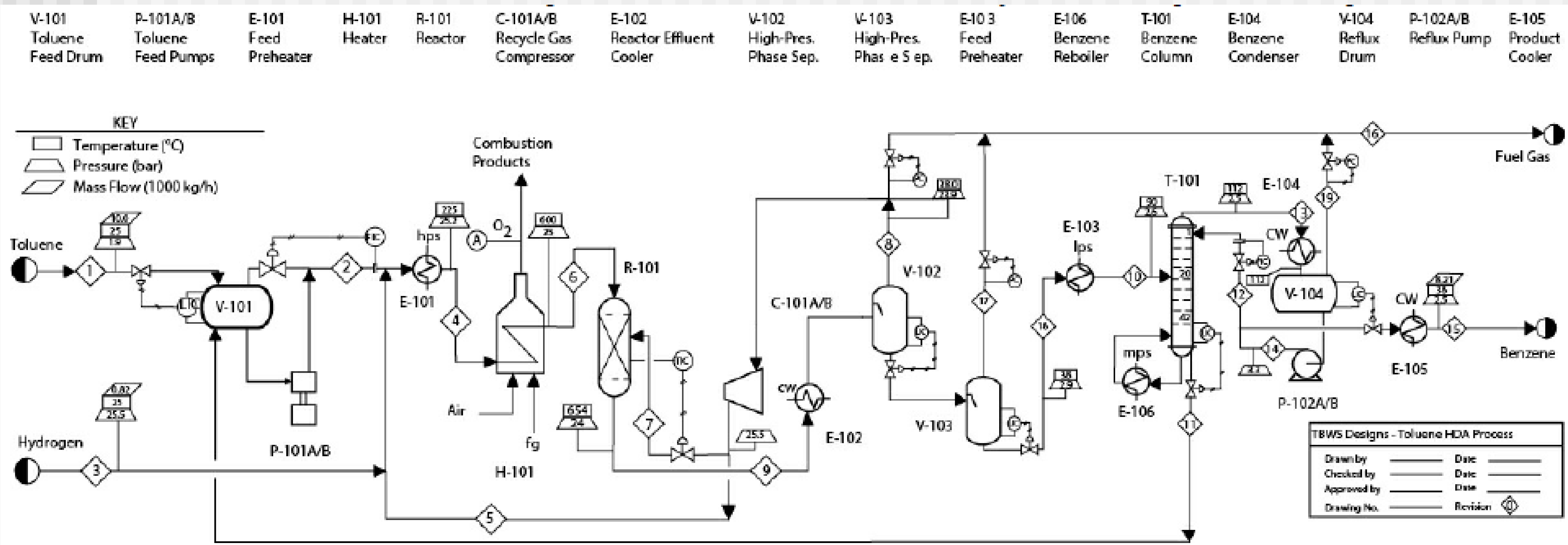
Pumps/Compressors	P-101 (A/B)	P-102 (A/B)	C-101 (A/B)	Heater	H-101
MOC	CS	CS	CS	Tube P (bar)	26.0
Temp. (in) (°C)	55	112	38		
Pres. (in) (bar)	1.2	2.2	23.9		
Pres. (out) (bar)	27.0	4.4	25.5		

Key:

MOC	Materials of construction	Par	Partial
316SS	Stainless steel type 316	F.H.	Fixed head
CS	Carbon steel	Fl.H.	Floating head
Vap	Stream being vaporized	Rbl	Reboiler
Cond	Stream being condensed	s.p.	Splash plate
Recipr.	Reciprocating	l	Liquid
Centrf.	Centrifugal	MDP	Multiple double pipe

Combining Topology, Stream Data, and Control Strategy to Give a PFD

- The amount of process information displayed on the PFD has been kept to a minimum. A more representative example of a PFD for the benzene process is shown. It includes all of the previous elements plus additional information on the major control loops used in the process



PIPING AND INSTRUMENTATION DIAGRAM (P&ID).

- The piping and instrumentation diagram (P&ID), also known as mechanical flow diagram (MFD), provides information needed by engineers to begin planning for the construction of the plant.
- The P&ID includes every mechanical aspect of the plant except:
  1. Operating Conditions *T*, *P*
  2. Stream Flows
  3. Equipment Locations
  4. Pipe Routing
     a. Pipe Lengths
     b. Pipe Fittings
  5. Supports, Structures, and Foundations

PIPING AND INSTRUMENTATION DIAGRAM (P&ID).

- Each PFD will require many P&IDs to provide the necessary data.
- Utility connections are identified by a numbered box in the P&ID. The number within the box identifies the specific utility.
- The circular flags on the diagram indicate where the information is obtained in the process and identify the measurements taken and how the information is dealt with.
- The P&ID is also used to train operators. Once the plant is built and is operational, there are limits to what operators can do.
- The P&ID is particularly important for the development of start-up procedures when the plant is not under the influence of the installed process control systems.

Conventions in Constructing Piping and Instrumentation Diagrams

- **For Equipment—Show Every Piece Including**
  - Spare Units
  - Parallel Units
  - Summary Details of Each Unit
- **For Piping—Include All Lines Including Drains and Sample Connections, and Specify**
  - Size (Use Standard Sizes)
  - Schedule (Thickness)
  - Materials of Construction
  - Insulation (Thickness and Type)
- **For Instruments—Identify**
  - Indicators
  - Recorders
  - Controllers
  - Show Instrument Lines
- **For Utilities—Identify**
  - Entrance Utilities
  - Exit Utilities
  - Exit to Waste Treatment Facilities

Conventions Used for Identifying Instrumentation on P&IDs (ISA standard ISA-S5.1)

Location of Instrumentation

- Instrument Located in Plant
- Instrument Located on Front of Panel in Control Room
- Instrument Located on Back of Panel in Control Room

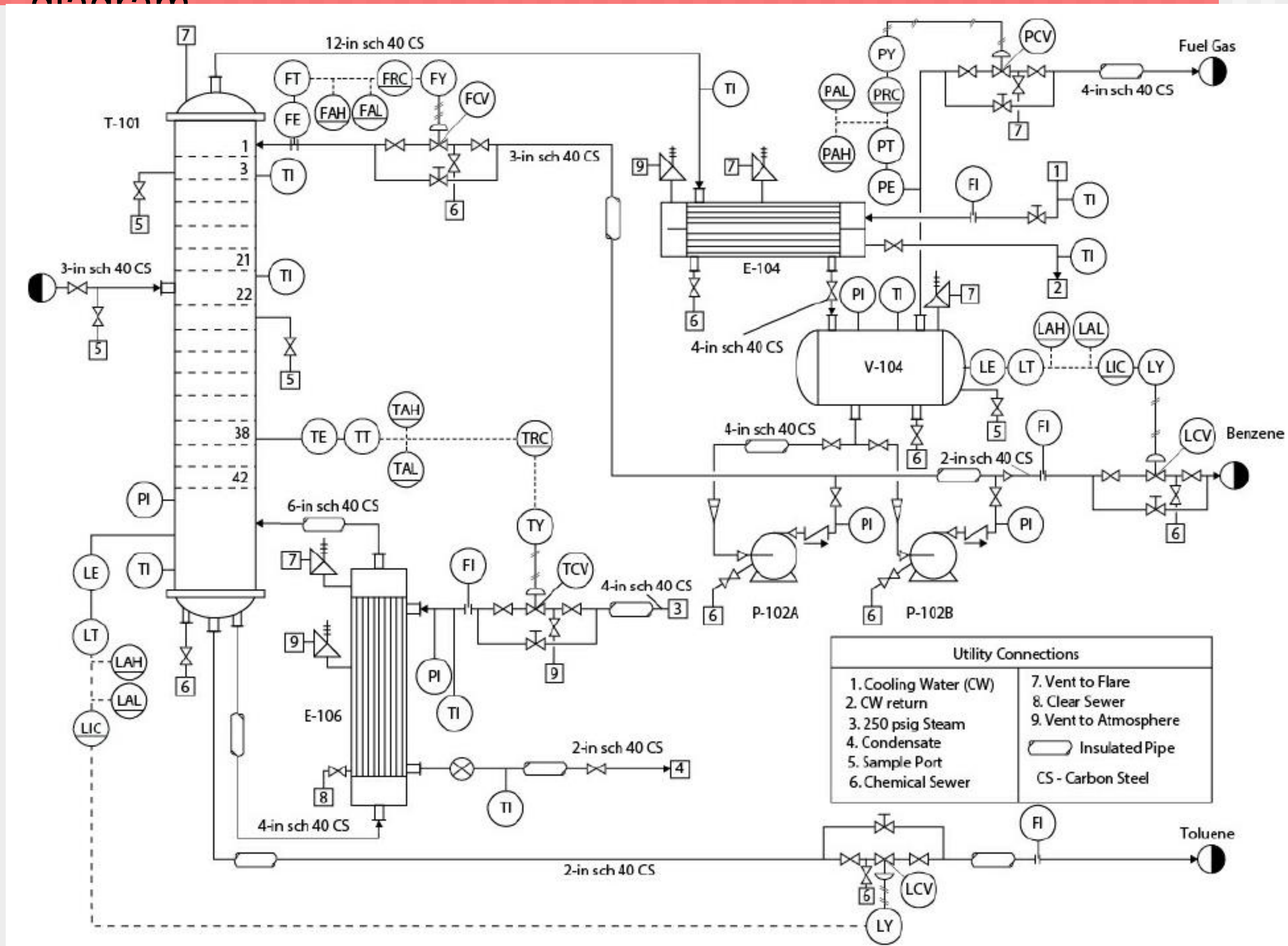
Meanings of Identification Letters XYY

First Letter (X)	Second or Third Letter (Y)
A Analysis	Alarm
B Burner	Flame
C Conductivity	Control
D Density or Specific Gravity	
E Voltage	Element
F Flowrate	
H Hand (Manually Initiated)	High
I Current	Indicate
J Power	
K Time or Time Schedule	Control Station
L Level	Light or Low
M Moisture or Humidity	Middle or Intermediate
O	Orifice
P Pressure or Vacuum	Point
Q Quantity or Event	
R Radioactivity or Ratio	Record or print
S Speed or Frequency	Switch
T Temperature	Transmit
V Viscosity	Valve, Damper, or Louver
W Weight	Well
Y	Relay or Compute
Z Position	Drive

Identification of Instrument Connections

- Capillary
- Pneumatic
- Electrical

- A representative P&ID for the distillation section of the benzene process shown earlier is presented below and this is included as part of the diagram



Exercise 2

- During a retrofit of an existing process, a vessel used to supply the feed pump to a batch reactor has been replaced because of excessive corrosion. The vessel is essentially identical to the original one, except it is now grounded differently to reduce the corrosion. If the function of the vessel (namely, to supply liquid to a pump) has not changed, answer the following questions:
  - Should the new vessel have a new equipment number, or should the old vessel number be used again? Explain your answer.
  - On which diagram or diagrams (BFD, PFD, PI&D) should the change in the grounding setup be noted?

Exercise 3

- Choose one chemical engineering equipment or vessel and download a video from the web showing how the equipment or vessel works. Watch the video and summarize your understanding of the principles governing how it works.
- Notes:
  - No two groups should choose the same equipment or vessel.
  - Once you choose an equipment or vessel please announce it on the Piazza platform for others to see.
  - A link would be provided for you to submit the video & your summary