Hydrocarbon Fractionation

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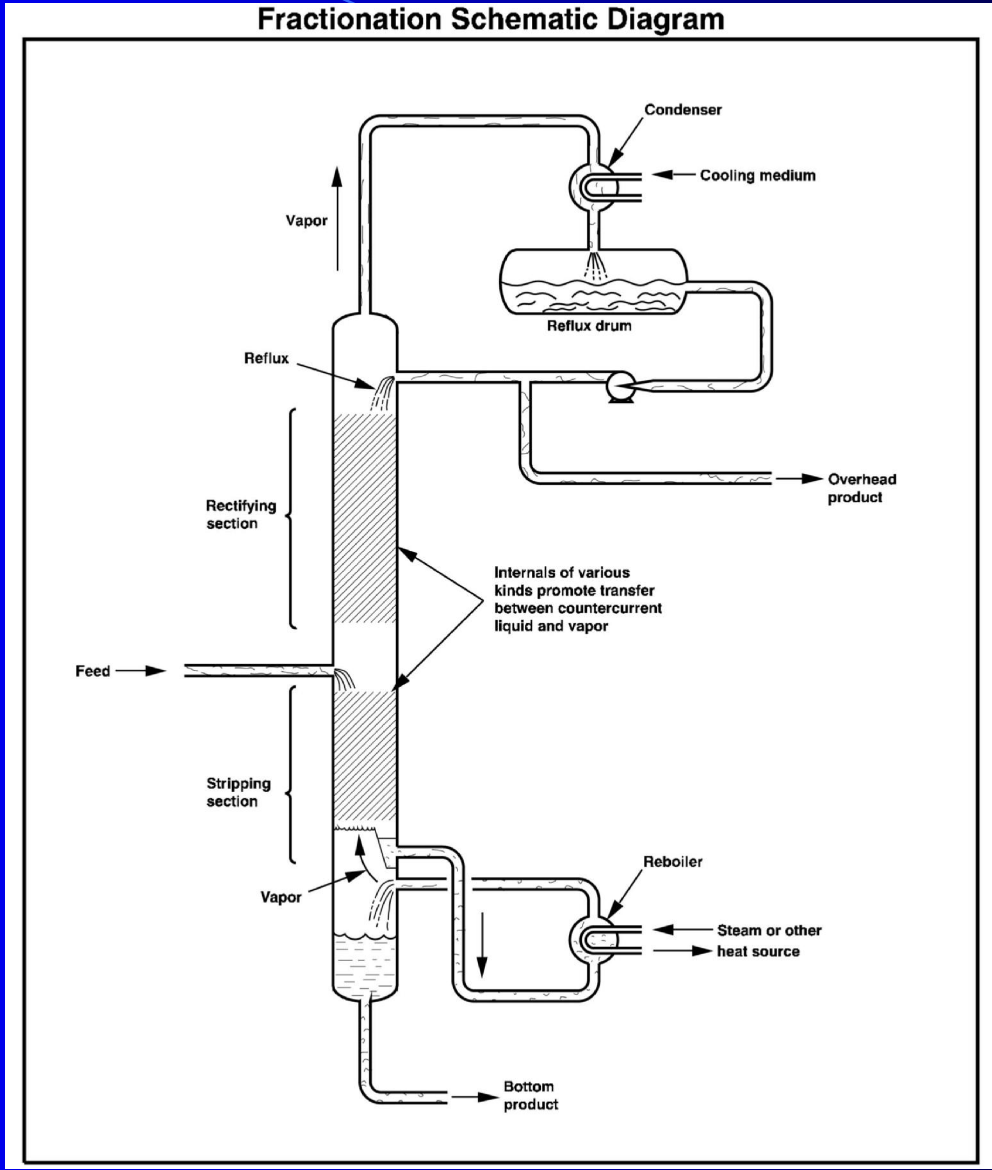
Virtually every gas plant, process system, and refinery uses at least one type of fractionation.

Fractionation is the splitting or purification of a single component or mixture of hydrocarbon components.

A fractionator is a device for separating a mixture into two or more parts; at least one of which will have a controlled composition or vapour pressure.

Fractionation, by definition, is a chemical engineering unit operation that is utilized to separate components (or mixtures of components) by their relative volatility (α). The difficulty of the separation and ultimately the product purity is directly related to the relative volatility of the components.

Hydrocarbon Fractionation



Hydrocarbon Fractionation

Types of fractionators include the following:

- **Demethanizers (C_{2+} liquid product)**
- **Deethanizers (C_{3+} liquid product)**
- **Depropanizers (C_3 overhead product)**
- **Debutanizers/stabilizer (C_4 overhead product, C_{5+} bottoms product)**
- **Frac Oil towers (C_6 liquid product)**

Butane splitters (iso and normal butane separation)

Fractionation - Definitions

Fractionator: a device for separating a mixture into two or more parts, at least one of which will have a controlled composition or vapour pressure specification.

Reboiler: a heat exchanger with an external heat source for fractionation towers and/or strippers designed to vaporize liquid and produce a stripping vapour stream.

Condenser: a heat exchanger with the extraction of heat for the purposes of condensing vapours, and/or subcooling liquids.

Fractionation - Definitions

Reflux: a liquid stream that has been condensed from the tower overhead vapour and is re-introduced into the tower to aid in reducing product losses, enriching product quality, and enhancing performance. Reflux is usually expressed as a ratio of the molar rate of reflux liquid divided by the molar rate of the net overhead product.

Equilibrium Stage: Each theoretical stage of the tower is represented by two product streams and two feed streams. While the liquid feed and vapour feed enter the stage at different temperatures, heat and mass transfer occur such that the resulting liquid phase and the resulting vapour phase exist in equilibrium with each other. In essence, liquid exits the stage at its bubble point, while vapour exits the stage at its dewpoint. This is basis for all fractionation designs.

Fractionation - Definitions

Heavy Key: Generally referred to as the component with lower volatility. Should constitute the majority of the bottoms product.

Light Key: The more volatile component or the one that should predominantly appear within the overhead stream.

Fractionation - Definitions

Absorber: any device where liquid flows counter-current to a gas stream for the purpose of removing one or more components from that gas.

Stripper: any device where gas flows counter-current to a liquid for the purpose of removing one or more components from that liquid.

Distillation – Basic Principles

Distillation – Basic Principles

The phase behavior principles and the thermodynamic properties of enthalpy and entropy are used extensively in solving fractionation based systems.

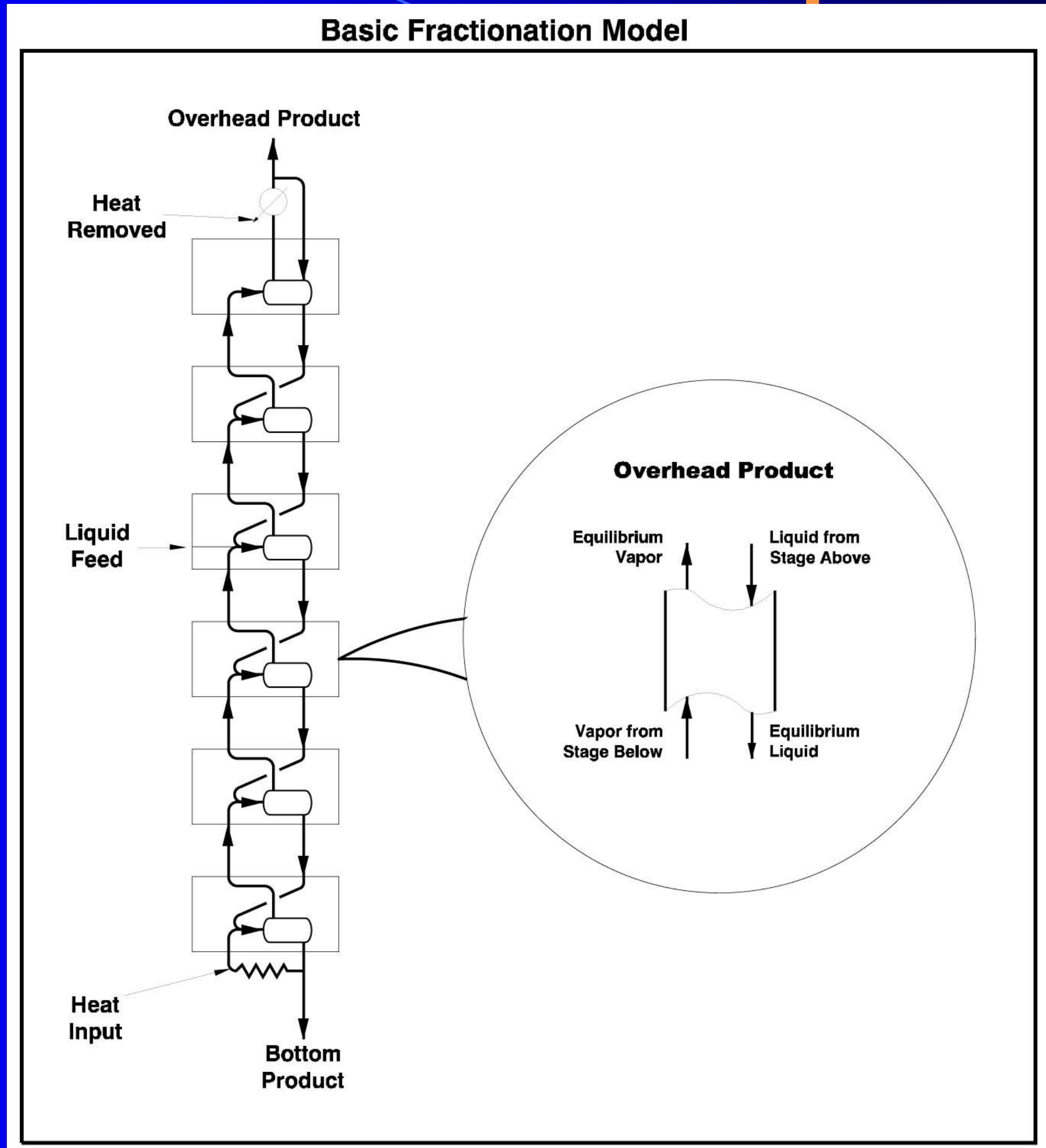
Each tower stage represents a single equilibrium separation stage requiring complex enthalpy and mass balance calculations.

One key parameter to remember is that liquid product exiting the tower at the bottom must be at its bubble point, while vapour exiting the condenser will be at it's dewpoint.

Reboiler temperature must be the bubble point of the product stream.

Overhead condensing temperature must the dewpoint of the overhead product or reflux stream.

Distillation – Basic Principles



T-X Diagram

T-X Diagram

The basic and underlying principle of distillation is that the light key is significantly more volatile than the heavy key.

The measure of the ease of separation is defined as α:

$$\alpha = K_{LK}/K_{HK}$$

where K is the equilibrium k-value of the pure component.

T-X Diagram

For example, when separating ethane and iso-pentane, the relative volatility can be shown to be:

$$\alpha = K_{C2}/K_{i\text{-}C5}$$

$$\alpha = 2.83/0.1537 = 18.4$$

while if we examine the ethane/heptane system, the ratio is:

$$\alpha = 3.103/1.561e^{-2} = 198$$

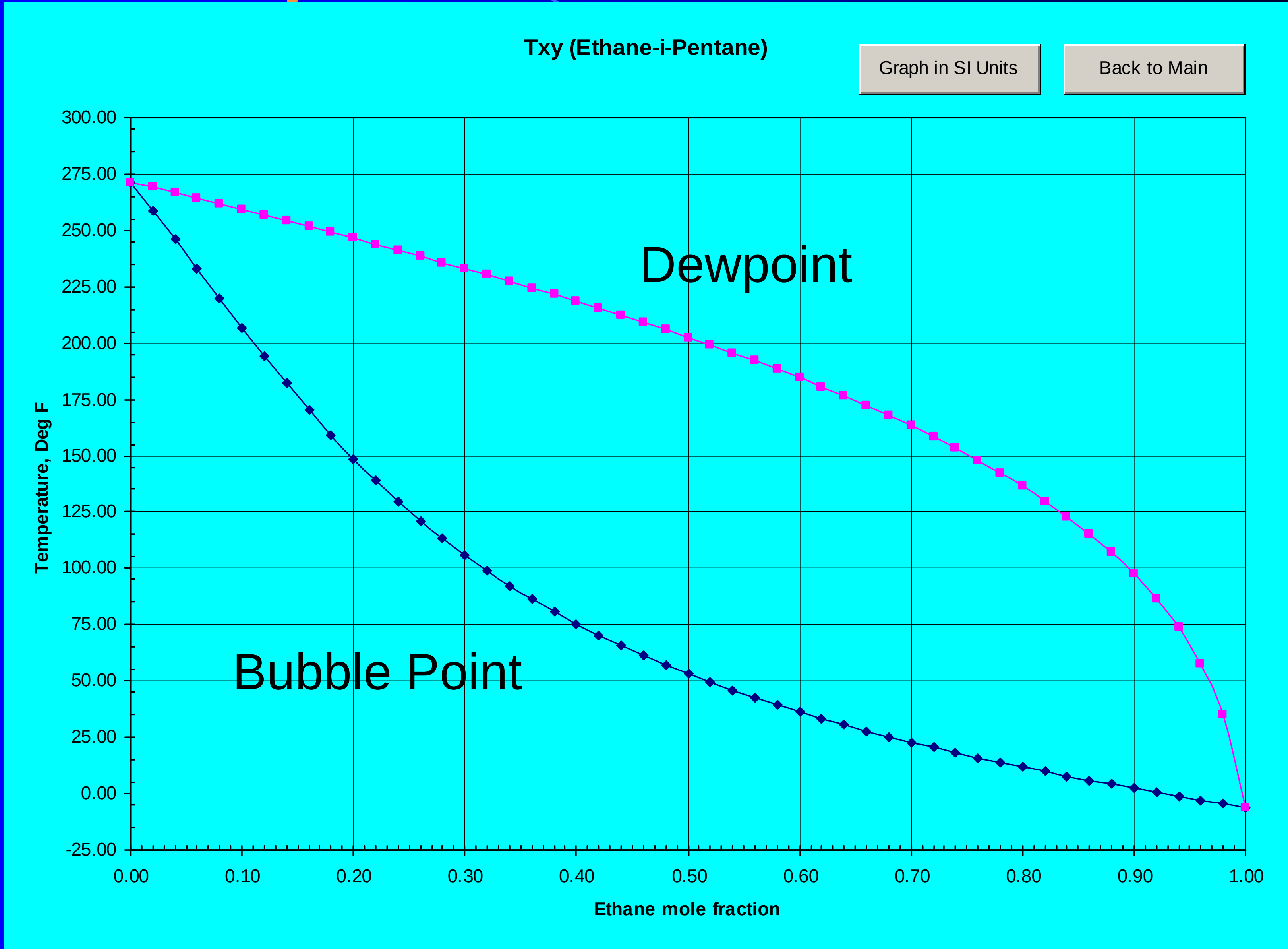
this correctly shows that the ethane/heptane system is substantially easier to separate than the ethane/i-pentane system.

T-X Diagram

The phase behavior of binary systems is very important to the understanding of fractionation. Even though most distillation systems involve multi-component systems, the separation we are concerned with normally occurs between two components.

One of the tools to allow this to happen is the use of the T-x diagram; a graphical prediction of phase behavior within a two component system for a given pressure.

T-X Diagram



Txy (Ethane-i-Pentane)
Graph in SI Units
Back to Main
Dewpoint
Bubble Point
Temperature, Deg F
300.00
275.00
250.00
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00
-25.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Ethane mole fraction

T-X Diagram

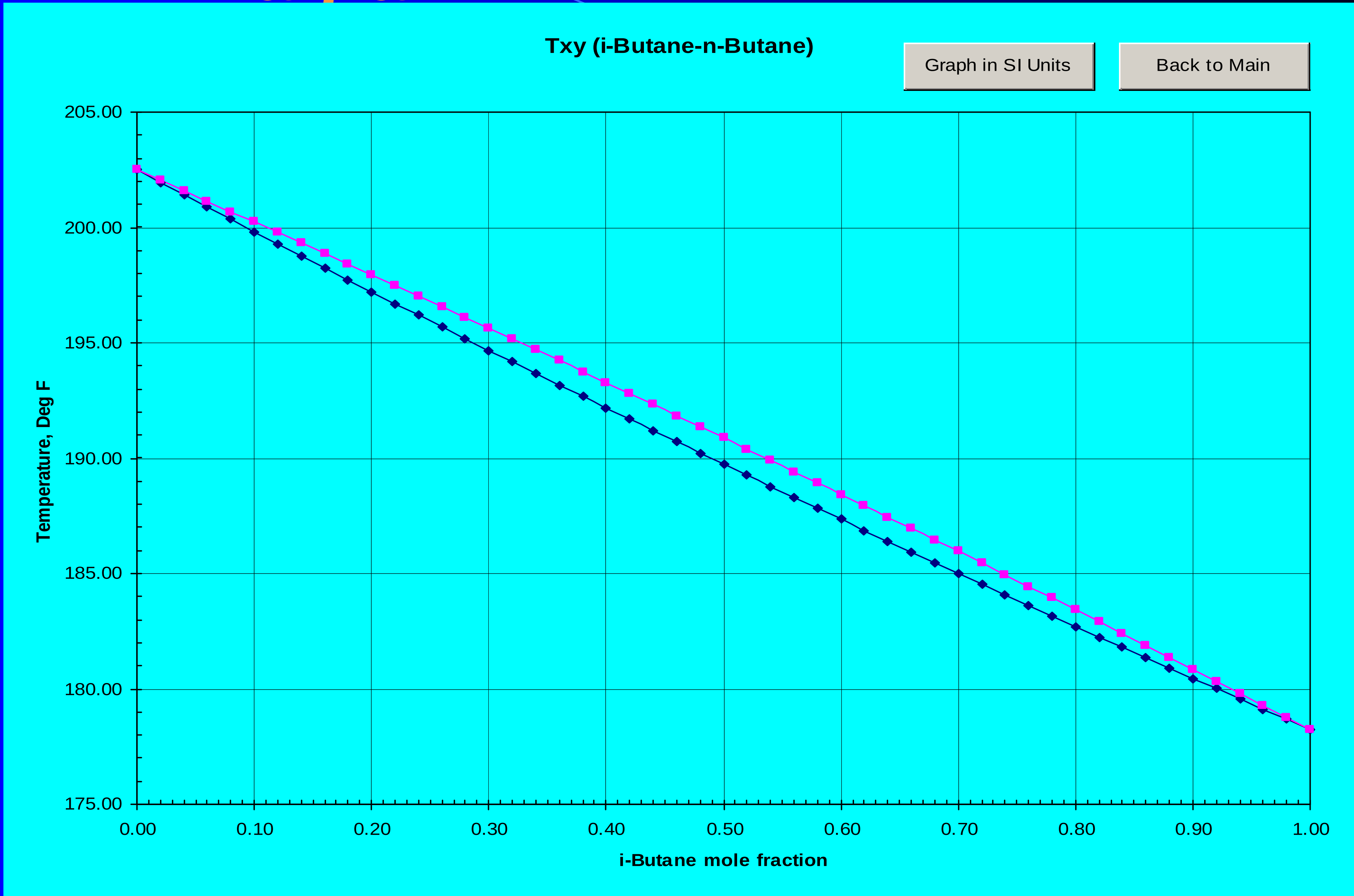
The diagram represents a phase envelope of dewpoint and bubble point lines for the binary system.

For a given composition of 50 mole % ethane, the bubble point is roughly 53°F and the dewpoint is roughly 202°F.

The use of an ethane/i-C_5 system is relatively simplistic due to the large difference in relative volatility of the two components.

The T-x diagram for the i-C4/n-C4 system is a much tougher separation

T-X Diagram



Txy (i-Butane-n-Butane)
Graph in SI Units
Back to Main
205.00
200.00
195.00
190.00
185.00
180.00
175.00
Temperature, Deg F
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
i-Butane mole fraction

T-X Diagram

Wider envelopes represent a larger relative volatility while narrow envelopes like the i-C4/n-C4 system represent smaller relative volatilities.

The smaller the relative volatility, the smaller the composition change that will occur in any equilibrium separator.

In most of the hydrocarbon fractionation systems, the relative volatility is less than 3; in some cases like the butane splitter example, it is less than 1.5.

T-X Diagram - Azeotrope

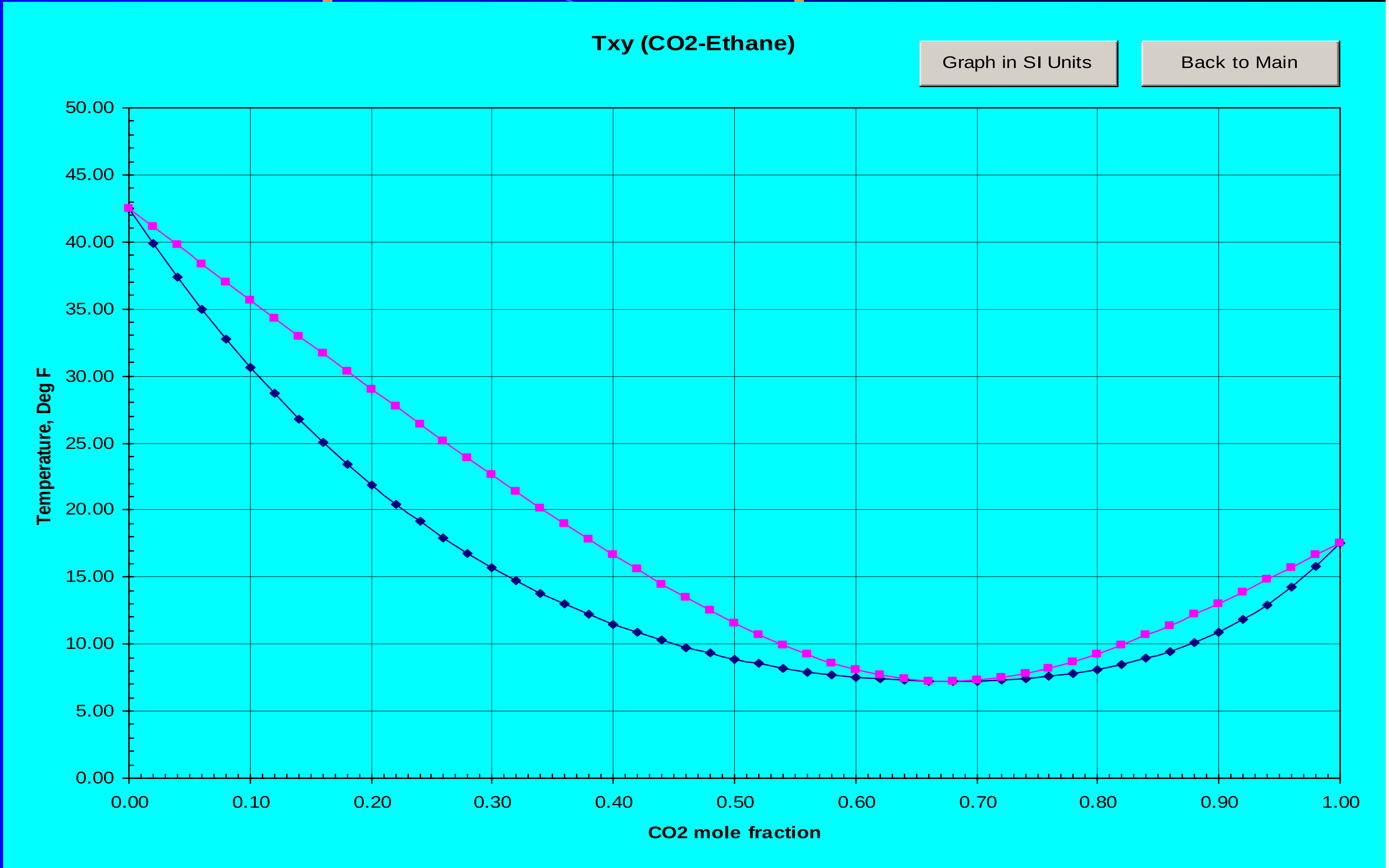
Some binary systems exhibit a relative volatility of 1.0 at certain compositions.

These systems are referred to as azeotropes.

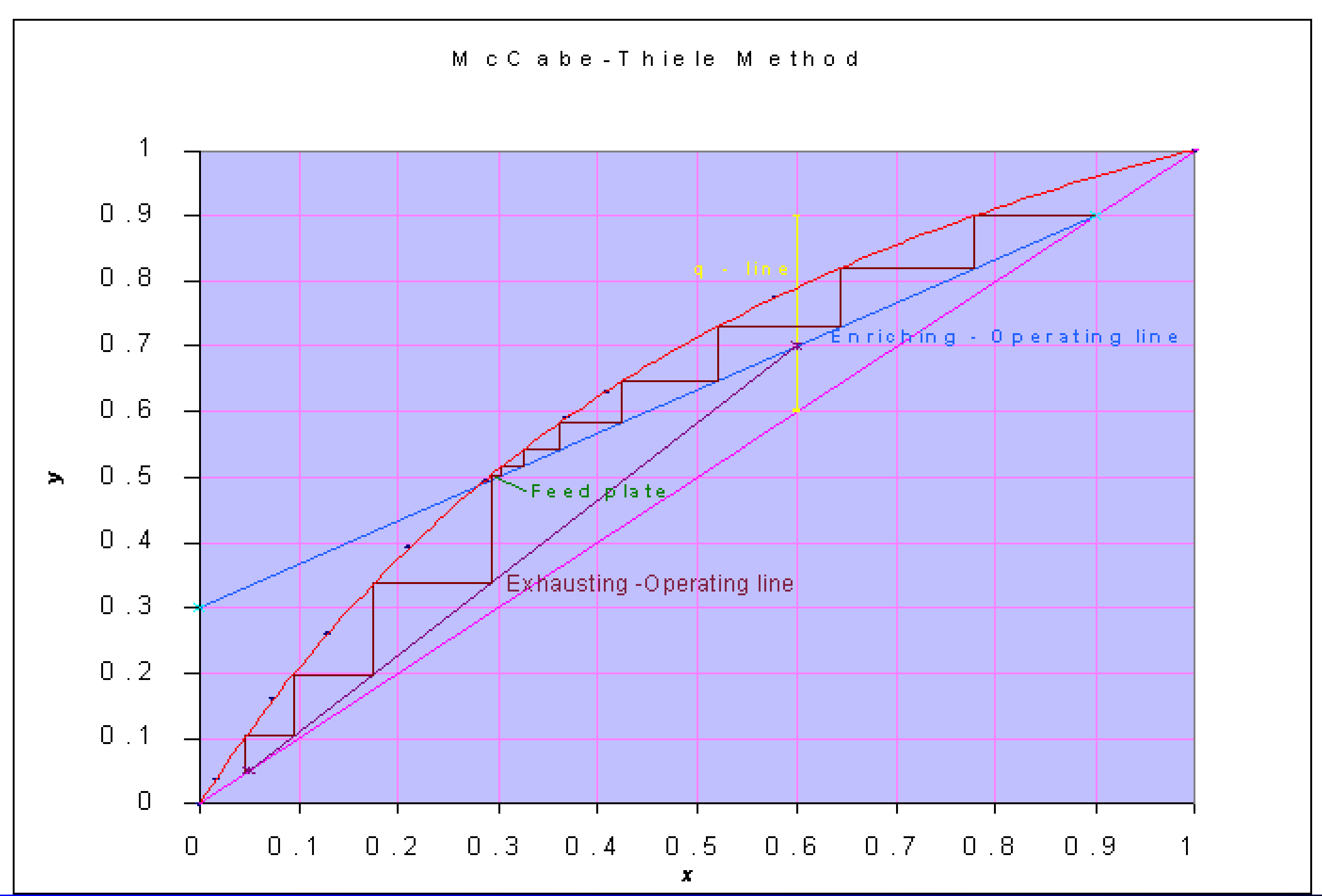
An azeotrope boils like a pure component, i.e.; the vapour phase composition is identical to the liquid phase composition.

Azeotropes are not common in the gas processing industry, but they do occur. An example is the T-x diagram for a CO_2/ethane system at 400 Psia.

T-X Diagram - Azeotrope



T-X Diagram – McCabe-Thiele



Design Considerations

Design Considerations – Design Basis

Establish feed rate, composition, temperature and pressure.

Temperatures feeding a column may be higher or lower than design due to changes in process, ambient effects, and slight upstream process quirks.

Establish required product purity and vapour pressure requirements.

Establish available utilities.

Establish cooling medium such as air, water, refrigerant, and/or process fluid.

Design Considerations – Design Basis

Perform a material balance around the column to establish the distillate and bottoms product rates and compositions.

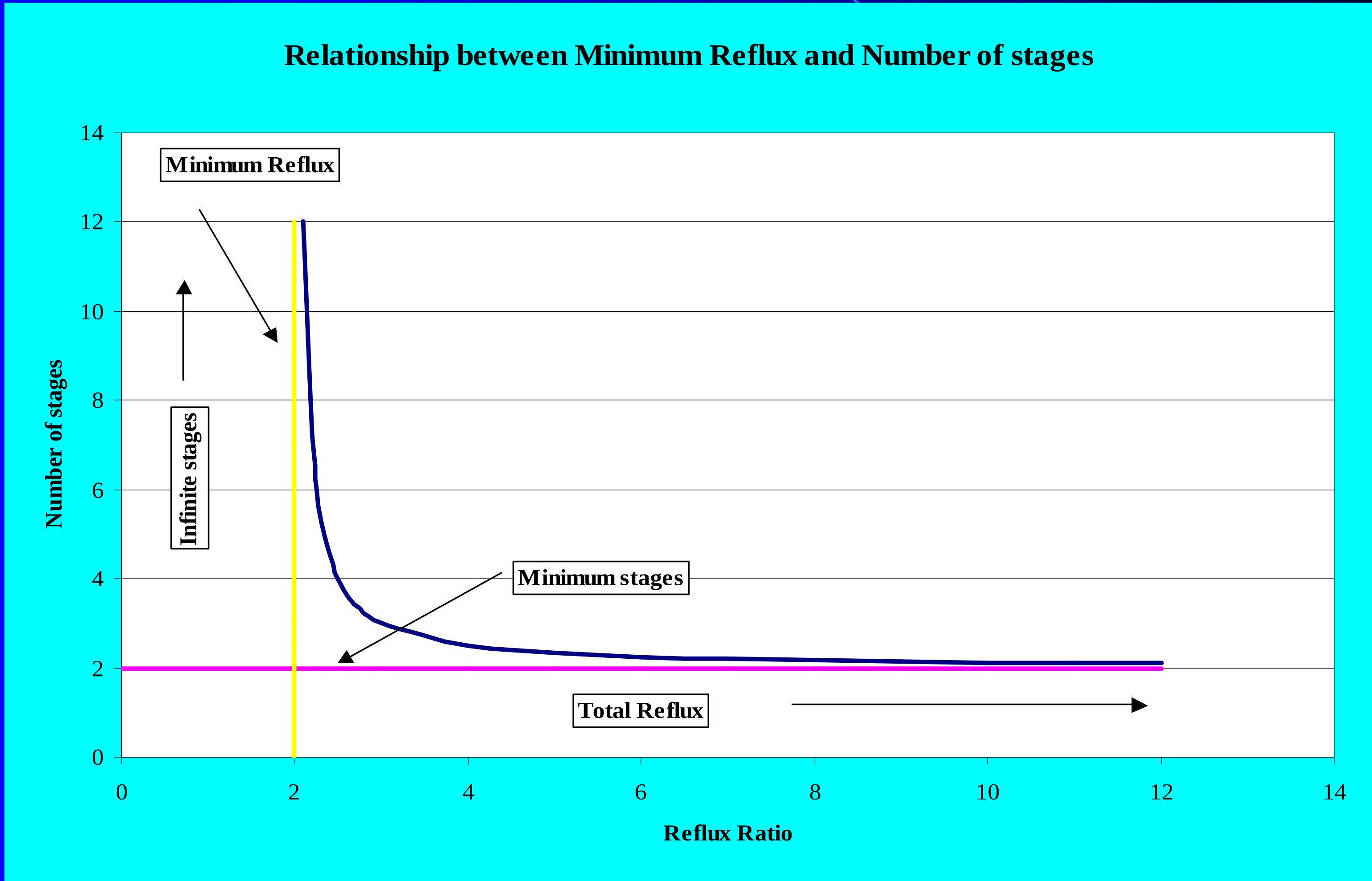
Establish light and heavy keys for the distillation process.

Establish operating pressure.

Establish whether the condenser should be a partial or a total condenser

Design Considerations – Design Basis

Establish reflux ratio and number of stages.



Design Considerations – Minimum Stages

Minimum stages can be calculated by the Fenske equation as follows:

$$S_m \equiv \frac{\log\left[\left(\frac{X_D}{X_B}\right)_{LK}\left(\frac{X_B}{X_D}\right)_{HK}^{b}\left(\frac{B}{D}\right)^{1-b}\right]}{\log \beta_{ij}}$$

Design Considerations – Minimum Reflux

Minimum reflux can be calculated by the Underwood method as follows:

$$1 - q = \sum_{i=1}^{n} \frac{X_{Fi}}{(\alpha - \phi)/\alpha_i}$$

$$\left({}^{L_o}\!/\!{}_{D} \right)_m + 1 = R_m + 1 = \sum_{i=1}^{n} \frac{X_{Di}}{(\alpha_i - \phi)/\alpha_i}$$

Design Considerations – Design Basis

• Most hydrocarbon fractionators operate at an actual reflux of 1.05 to 1.25X the minimum – this is primarily an economic issue.

• Condenser load is a direct function of reflux rate – as this increases, the reboiler load must also increase to maintain the energy balance around the tower.

• Increasing reflux ratio will increase tower liquid/vapour traffic and increase tower size.

Design Considerations – Typical

	Operating Pressure, Psig	Number of actual trays	Reflux Ratio	Tray efficiency, %
Demethanizer	200-400	18-26	Top Feed	45-60 %
Deethanizer	175-350	25-35	0.9 – 2.0*	50-70 %
Depropanizer	185-270	30-40	1.8 – 3.5	50-70 %
Debutanizer	70-90	25-35	1.2 – 1.5	50-70 %
Butane Splitter	80-100	60-80	6.0 - 14.0	50-70 %
Rich Oil Fractionator	130-160	20-30	1.75 – 2.0	Top 67 % Bottom 50 %
Rich Oil Demethanizer	200-400	40	-	Top 25-40 % Bottom 40-60%
Condensate Stabilizer	50-400	16-24	Top Feed	40-60 %

Design Considerations – Efficiency

- **Many factors affect tray efficiency:**
  - **Relative vapour and liquid loading of the tray**
  - **Physical characteristics of the liquid (foaming, viscosity, surface tension, etc.)**
  - **Characteristics of the tray**
  - **mechanical design and installation of the tray**
  - **Thermodynamic properties used to determine the number of theoretical trays**

Design Considerations – Efficiency

- **Predicting tray efficiency:**
  - **Can utilize published FRI data in Hydrocarbon Processing**
  - **Can use O'Connell correlation that relates viscosity, Henry's Law Constant, tower pressure, mole weight, density, and equilibrium constant for overall efficiency.**
  - **Be cautious when estimating tray efficiencies – if in doubt, guess low…**

Design Considerations – Feed Point

- Establishing feed tray location is critical to optimize operation of the tower

- If the feed is too high, it can create excessive reflux.

- If the feed point is too low, excessive reboiler heat is required to meet the bottoms product specification

- Improper feed point location is usually manifested by a sharp discontinuity in the tower temperature profile.

Design Considerations – Stabilizer

- This tower is a non-refluxed absorber – traditional short-cut methods are not effective.

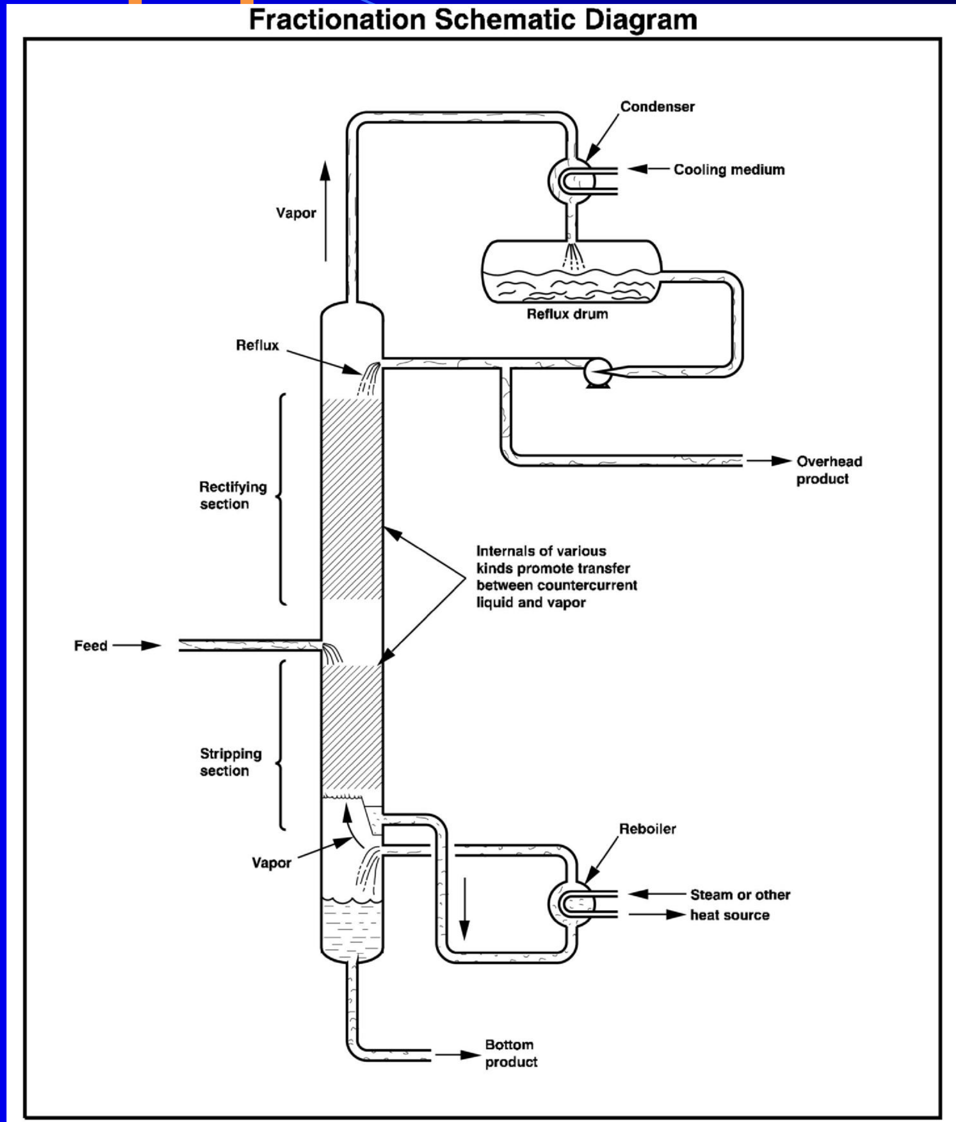
- Usual method is to choose an operating pressure and calculate the temperature necessary to achieve the bottoms specification – this is normally an RVP spec.

- Stabilizers are relatively immune to poor performance – that is, the tray efficiency is not critical to tower performance.

- Reboiler heat may be an indirect salt bath heater, a steam heater, or even a hot TEG glycol bath.

Process Equipment

Process Equipment - Schematic



Process Equipment - Tower

- The stripping section is usually located below the feed point of the tower.

- The upper section of the tower is the rectification section where the reflux is doing most of the work to enrich the composition.

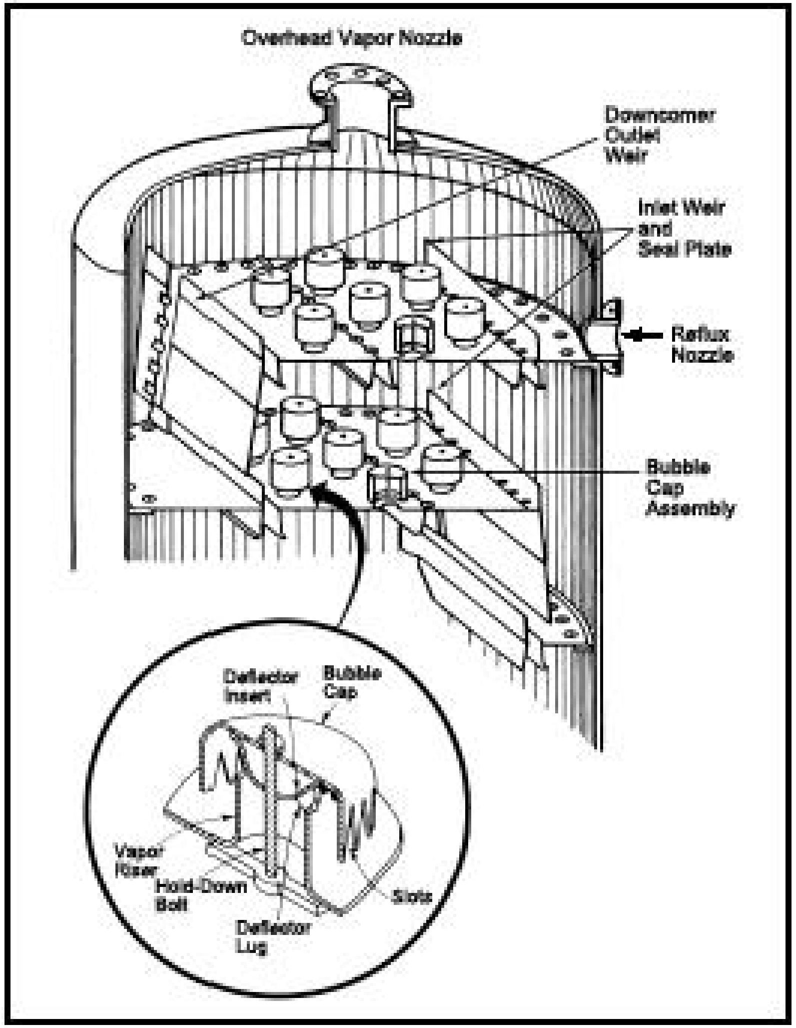
- Internals to the distillation column can be either trays or packing.

- Trays, while most common in larger diameter towers can be sieve type, valve type, bubble cap, or other.

- Bubble caps maintain a constant liquid height on the tray. Bubble caps are relatively simplistic and are used to a large degree on glycol absorbers

Process Equipment – Bubble Cap Tower

Top Two Trays of a Bubble-cap Column[28]



Process Equipment - Trays

- Valve trays are simply small steel caps with clips that will lift once the gas starts to push up through the column.

- Sieve trays are the most simplistic and can offer the highest capacity, but at lower rates are susceptible to liquid weeping.

- Sizing of trayed towers, while usually within the realm of tray vendors can often be simplified using as modified Souders/Brown equation where the "C" factor is a function of tray spacing and surface tension.

- Tray efficiency remains a matter of heated discussion among process designers; typical published tray efficiencies range from 45-60% for demethanizers to as high as 80-90% for depropanizers.

Process Equipment - Trays

Type	Sieve tray	Valve tray	Bubble Cap tray	Dual Flow tray
Capacity	High	High to very high	Moderately high	Very high
Efficiency	High	High	Moderately high	Lower than other types
Turndown	About 2:1	About 4-5:1	Excellent	Low, even lower than sieve
Entrainment	Moderate	Moderate	High	Low to moderate
Pressure Drop	Moderate	Moderate	High	Low to moderate
Cost	Low	About 20% higher	High, 2-3X	Low
Maintenance	Low	Low to moderate	Relatively high	Low
Fouling	Low	Low to moderate	High	Extremely low
Effects of corrosior	Low	Low to moderate	High	Very low

Process Equipment - Trays

- Tray flooding mechanisms:
  - Spray entrainment flooding – at low liquid flow rates. Trays operate in the spray regime where most of the liquid on the tray is in the form of liquid drops. As vapour velocity is increased, a condition is reached where the bulk of the these drops are entrained into the tray above.

  - Froth entrainment flooding – at higher liquid flow rates, the dispersion on the tray is in the form of a froth. When vapour velocity is increased, froth height increases. When tray spacing is short, the froth envelope reaches the tray above. Entrainment increases rapidly resulting in flooding.

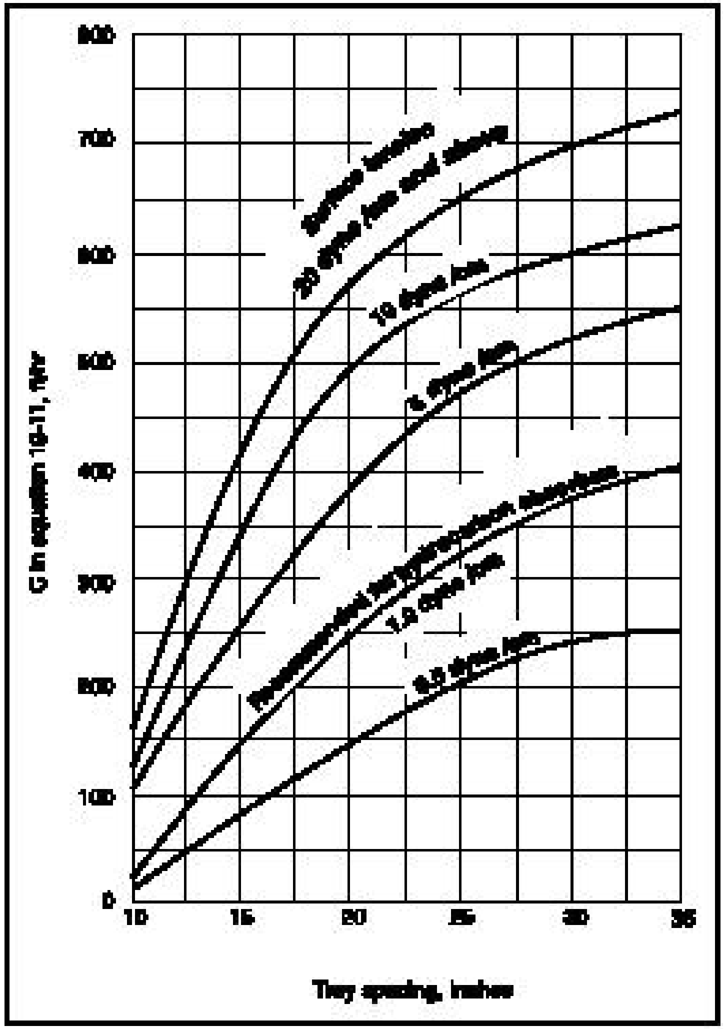
  - Downcomer backup flooding – aerated liquid is backed up into the downcomer because of high tray pressure drop. As liquid flows are increased, downcomer backup increases until it is full of liquid.

Process Equipment - Packing

- In order to maximize efficiency
  - maximize specific surface area – i.e., surface area per unit
  - spread the surface area uniformly
  - promote uniform distribution of vapour and liquid throughout the packed bed
  - to freely drain and liquid so that stagnant liquid pockets are minimized
  - maximize wetting of packing surfaces
- In order to maximize capacity:
  - maximize void space per unit column volume
  - minimize friction
  - minimize fouling
  - ensure uniform resistance to vapour and liquid flow
  - permit easy disengagement of vapour from liquid

Process Equipment – Souders/brown

Souders-Brown Correlation for Approximate Tower Sizing[9]



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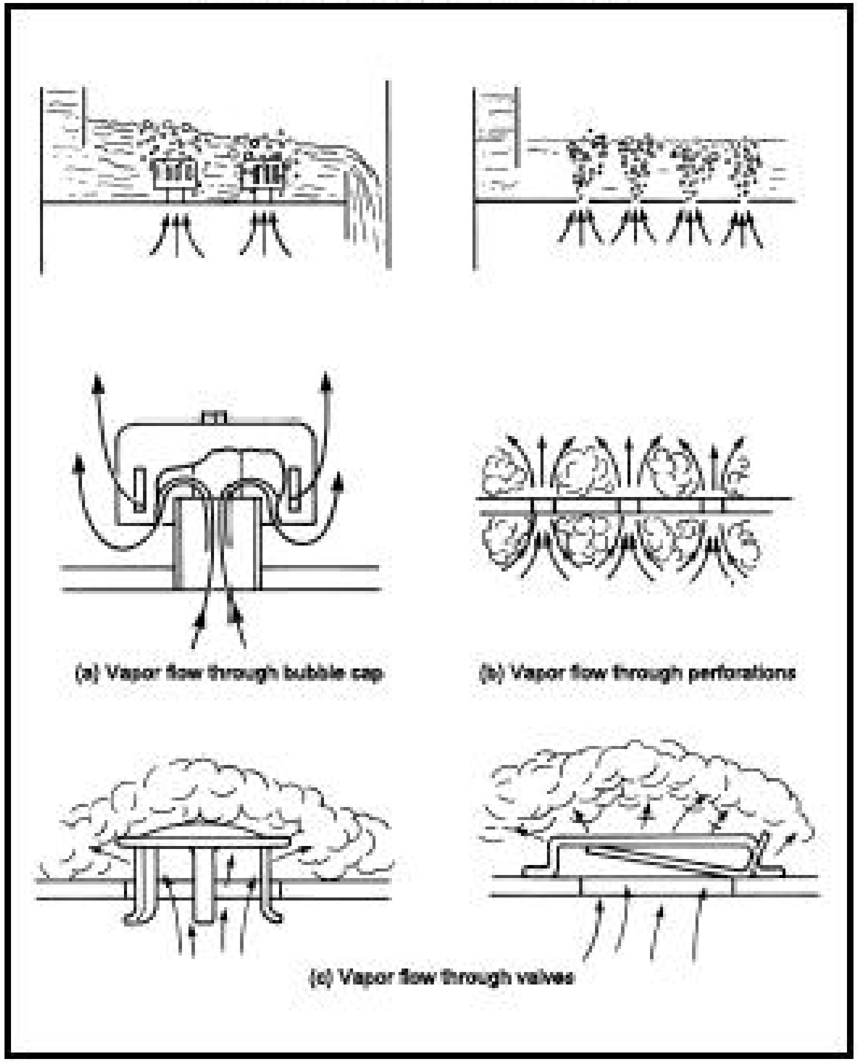
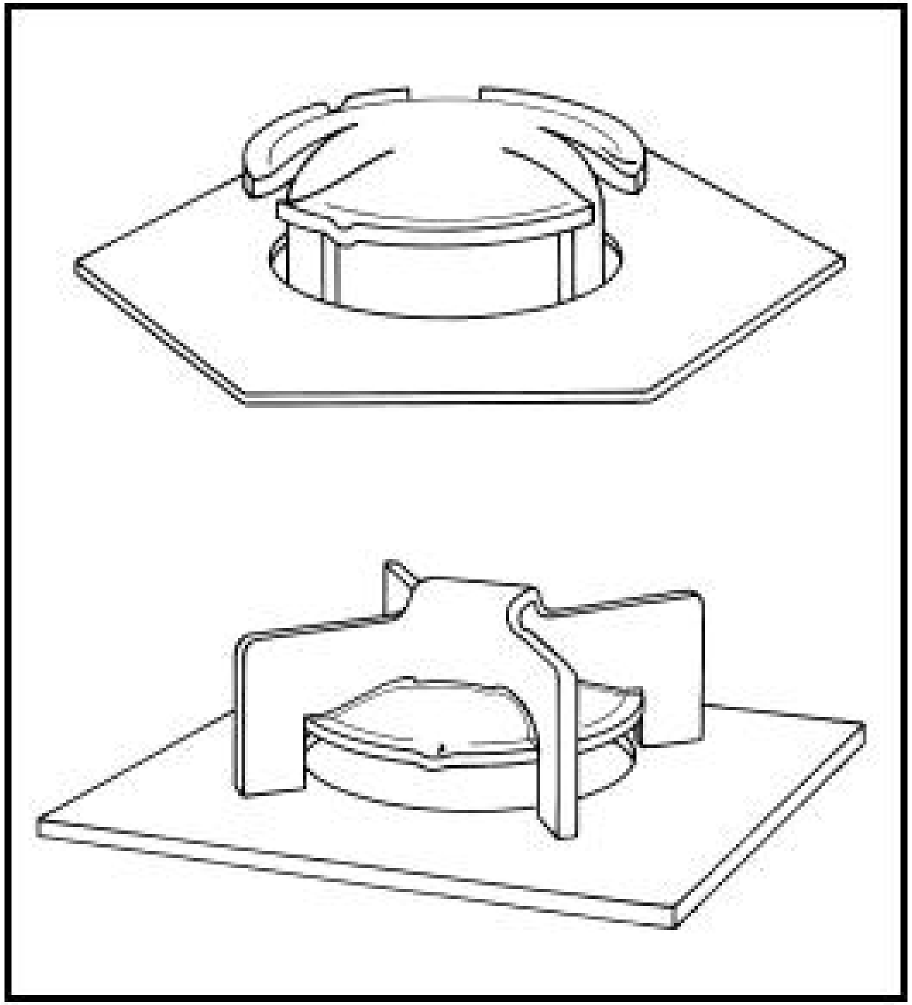
Process Equipment - Trays

Flow Through Vapor Passages[28]

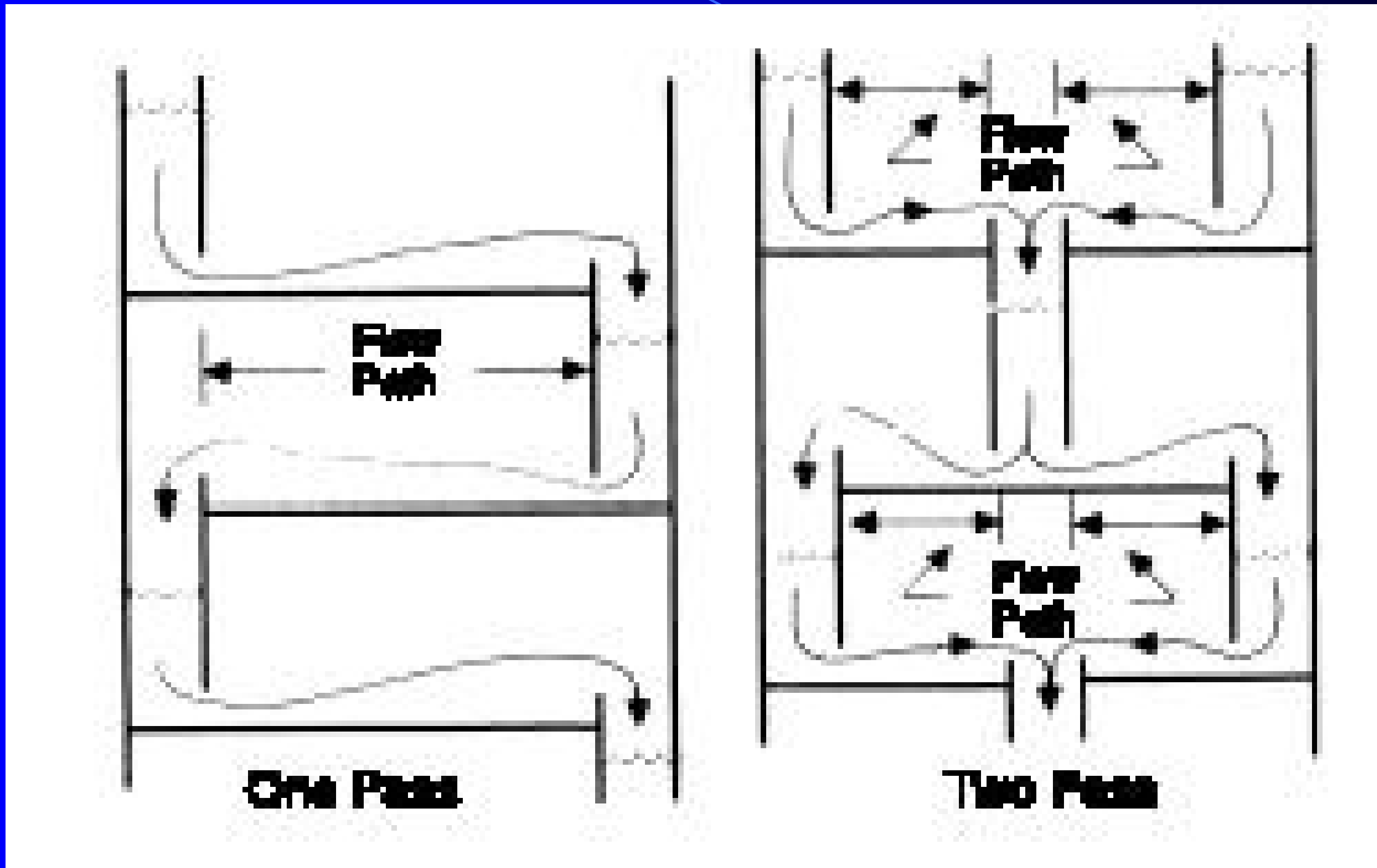


Process Equipment - Trays

Valve Types[28]



Process Equipment - Trays



Process Equipment - Packing

- Smaller diameter towers, typically less than 20-24”, often use random dumped packings. Three basic generations include:
  - Raschig rings/Berl Saddles, Lessing Rings
  - Pall rings/Intalox saddles/Super Intalox/Hy-Pak
  - New geometries of Pall Rings and Intalox saddles, Cascade Mini-rings, Chempak, Nutter Rings,

- There are three types of packed towers: Random or dumped packing. Stacked packing. Structured packing.

- Tower sizing for packed towers often uses the Eckert method, which is a pressure drop/capacity correlation – also termed the GPDC or Generalized Pressure Drop correlation

Process Equipment - HETP

- **Height of the tower must be adequate to provide sufficient contact between the vapour and the liquid.**

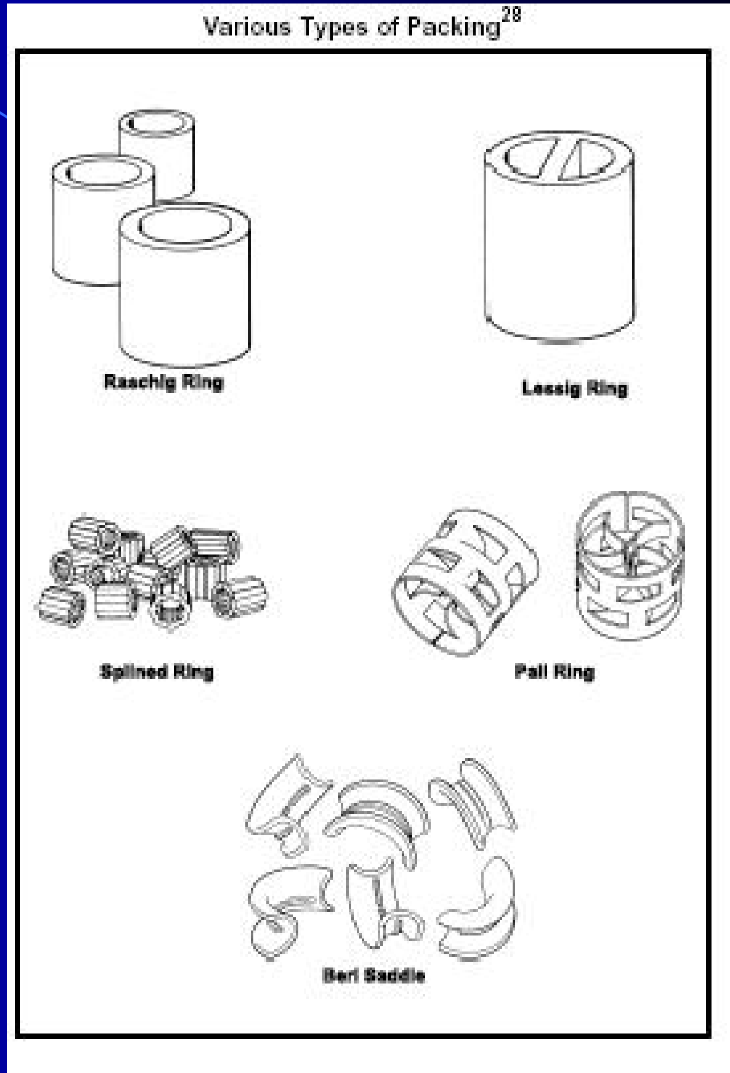
$$h = (HETP) * (N)$$

Where HETP is the height of an equivalent theoretical plate and N is the number of stages

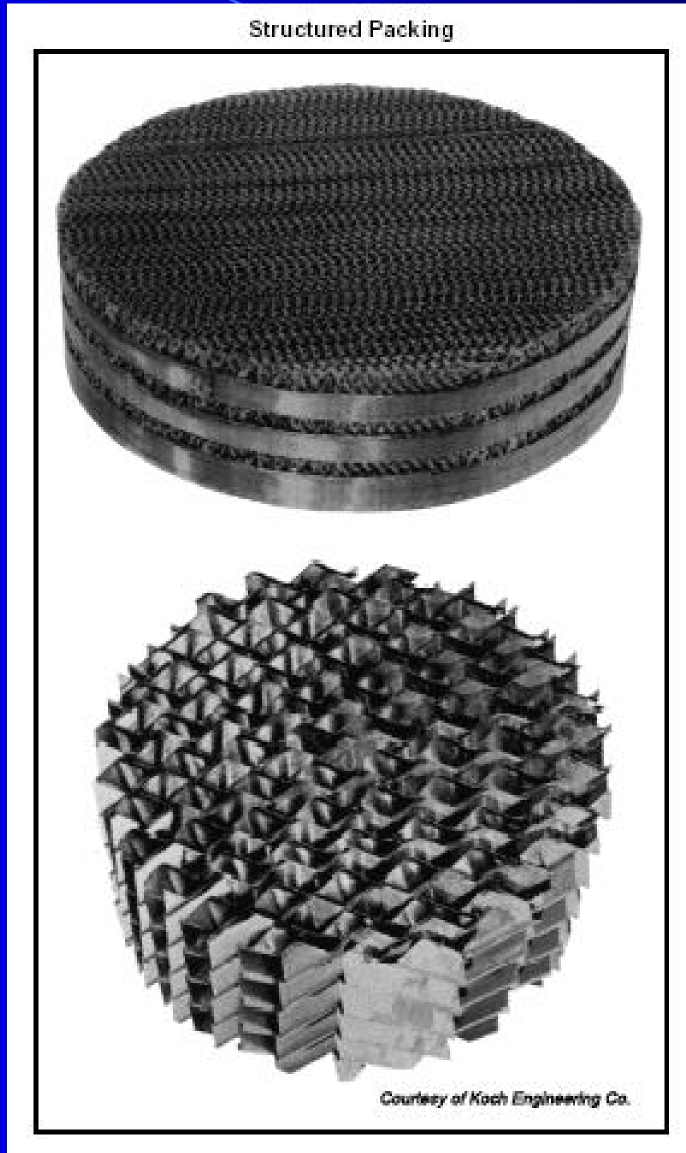
- **Establishing an HETP can be difficult – check with packing mfr's or use the following "rough" guidelines**

Packing Size	HETP
1" dia	18"
1.5" dia	26"
2" dia	35"

Process Equipment - Packing



Process Equipment - Packing



Process Equipment - Packing

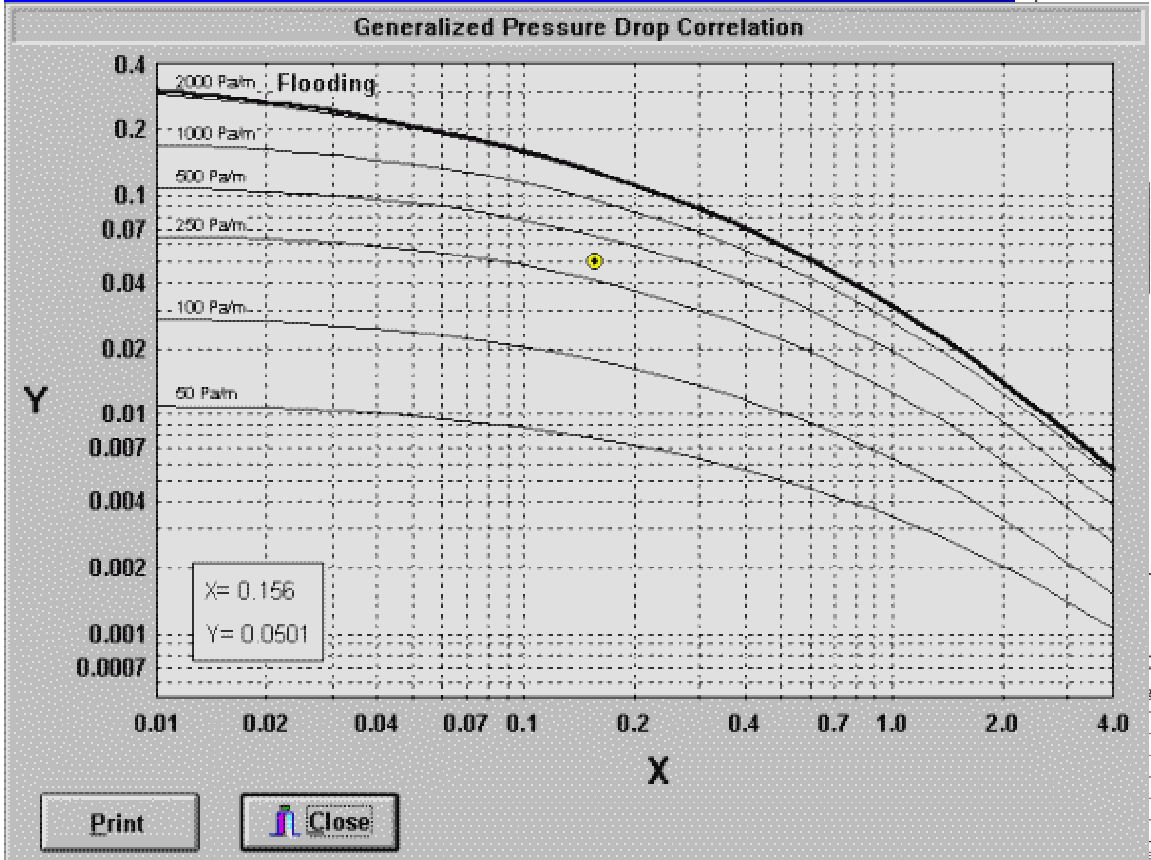


FIG. 19-22

Packed Column Pressure Drop Correlation

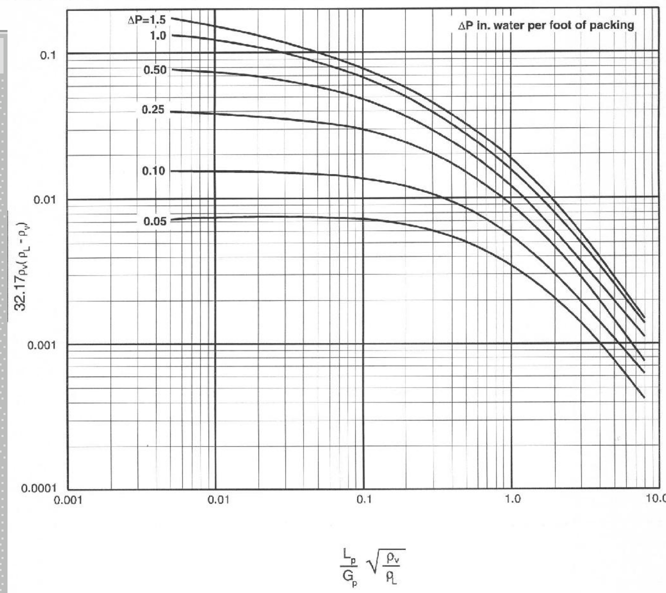


FIG. 19-23

Packing Factors (F_P)
(Dumped Packing)

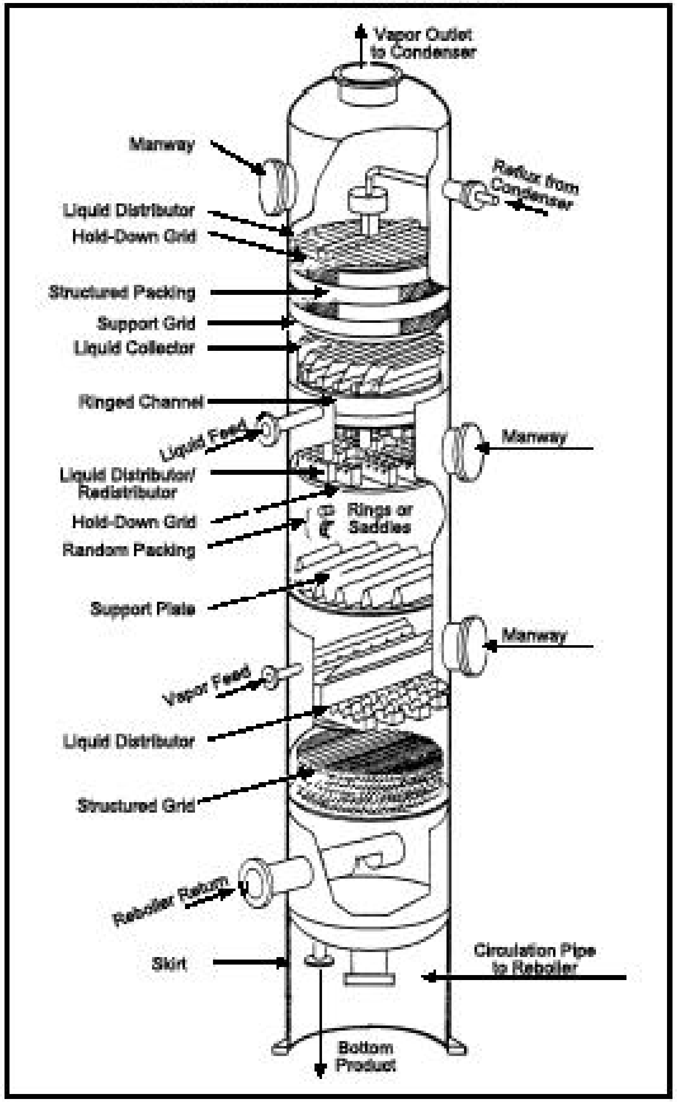
Type	Material	Nominal Packing Size (Inches)										
		1/4	3/8	1/2	5/8	3/4	1	1.25	1.50	2	3	3.5
	Metal				51		40		24	18	12	
	Metal						45		29	26		16
Saddles®	Ceramic						60			30		
Saddles®	Plastic						40			28		18
	Plastic				75		55		40	26		17
	Metal				70		56		40	27		18
es®	Ceramic	725	330	200		145	92		52	40	22	
Raschig Rings	Ceramic	1600	1000	580	380	255	155	125	95	65	37	
Raschig Rings	1/32" Metal	700	390	300	170	155	115					
Raschig Rings	1/16" Metal			410	300	220	144	110	93	62	32	
Berl Saddles	Ceramic	900		240		170	110		65	45		

Courtesy of Norton Co.

19-17

Process Equipment - Internals

Example Packed Column Internals[29]



Process Equipment – Reboiler

- Forced Circulation
  - utilizes a pump to force the product through the exchanger – pump rate is quite high – good for remote reboilers.
  - pump NPSH is a design issue – flashing hot liquid

- Once-through Circulation
  - Low cost, although no method of recovery if off-spec

- Vertical thermosyphon
  - highest heat transfer but technically difficult – requires careful piping design
  - small footprint

- Horizontal thermosyphon
  - same issues – better access for tubes

Process Equipment – Reboiler

- Flooded bundle or kettle type
  - most forgiving type of reboiler
  - tolerant of liquid surges and resistant to off-spec jumps.
  - best used for stabilizers, and heavy liquid fractionators.

- Can utilize thermal heat transfer oils, Dowtherm, Paratherm, steam, glycols, etc.

- Temperature control methods are important - over sizing is not recommended.

- Avoid temperature differences higher than 72°F and limit design flux to 10,000 Btu/hrft^2.

- Consider fouling, access, service, and possible design fluctuations.

Process Equipment – Reboiler

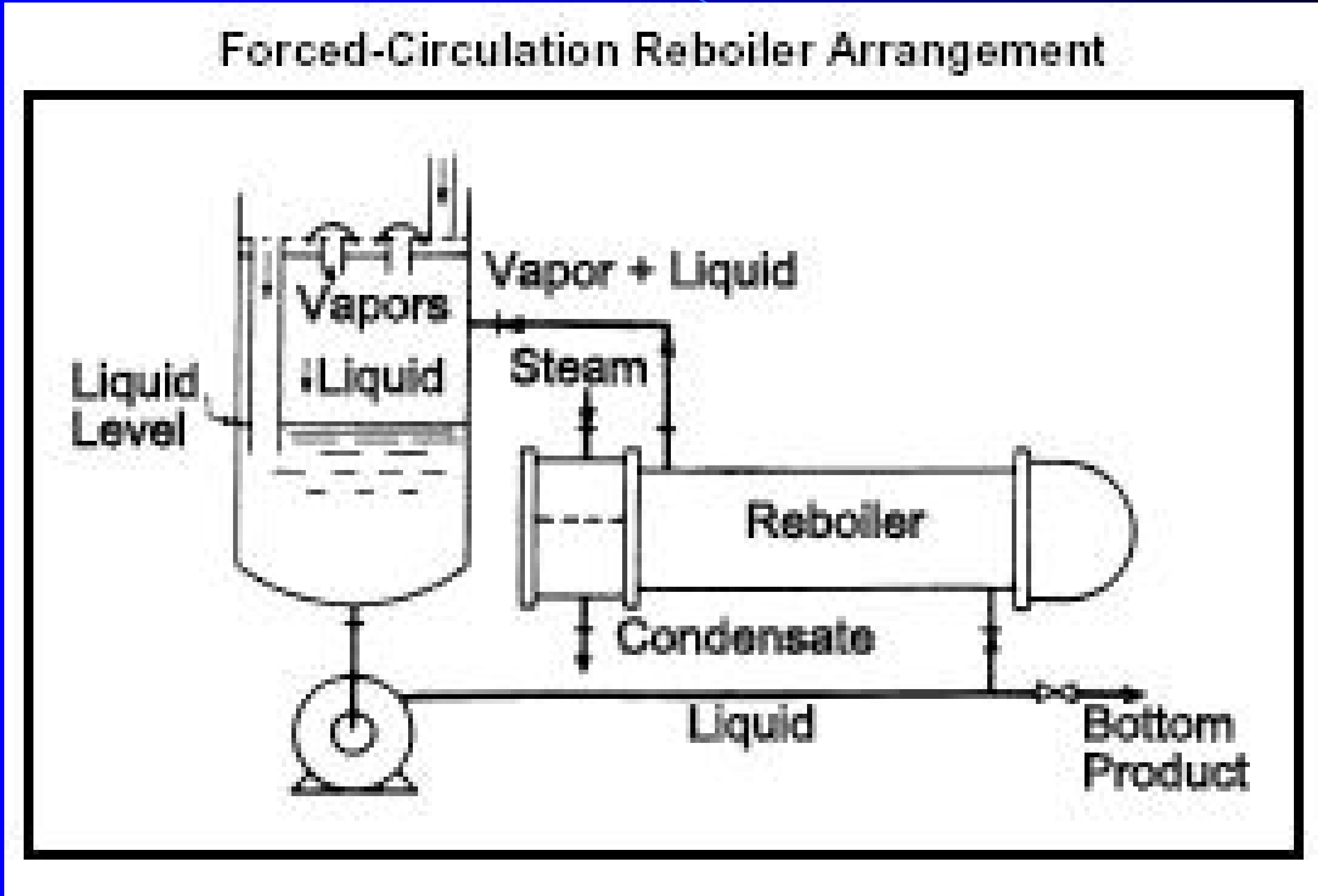
- Reboiler piping design is critical – must incorporate rigorous pressure drop and velocity calculations

- Under sizing reboiler vapour return lines is a typical design oversight.

- Consider variations in liquid composition in reboiler design – especially in stabilizers.

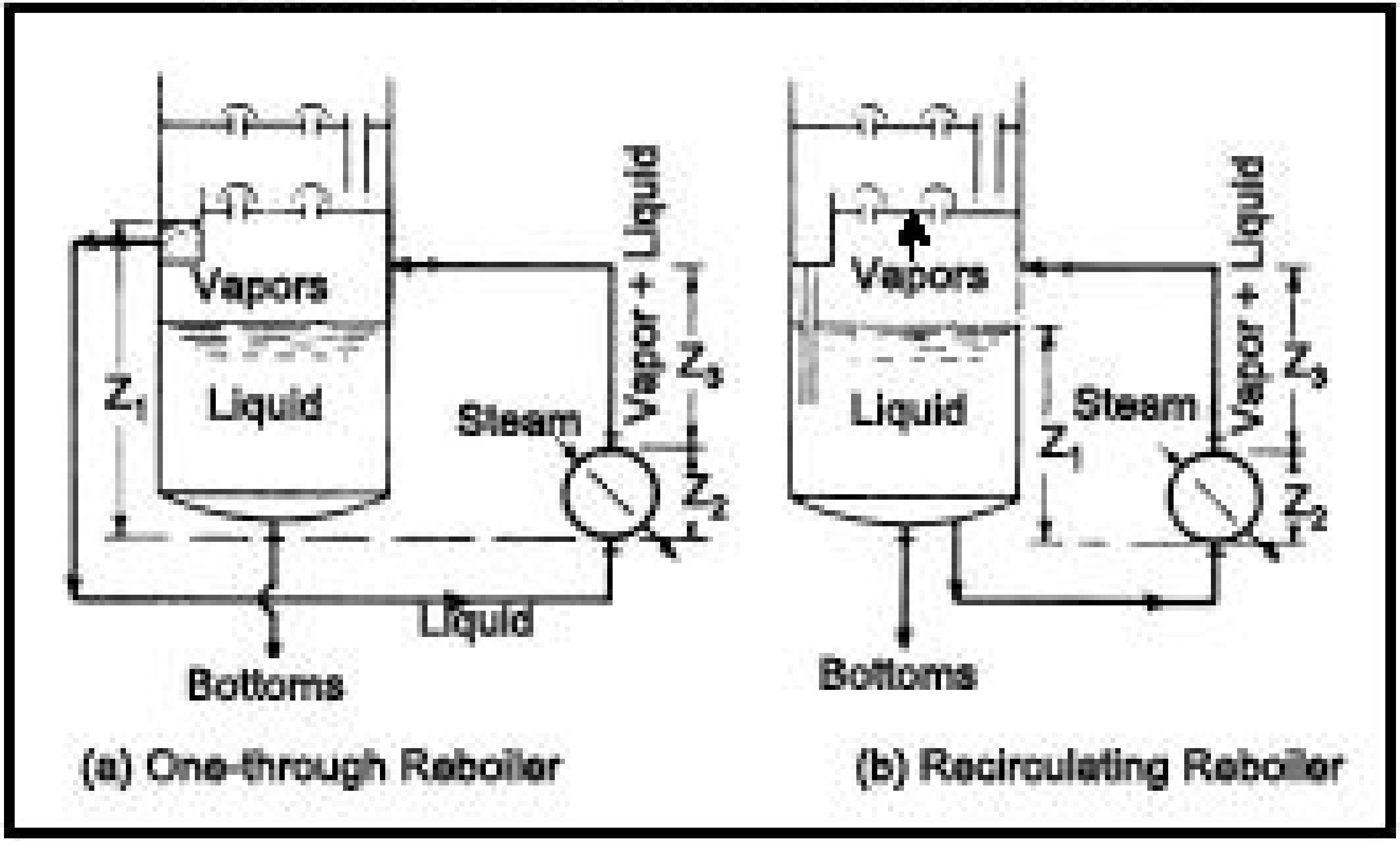
- Steam systems often benefit from a flow control loop combined with a temperature control system.

Process Equipment – Forced Circulation



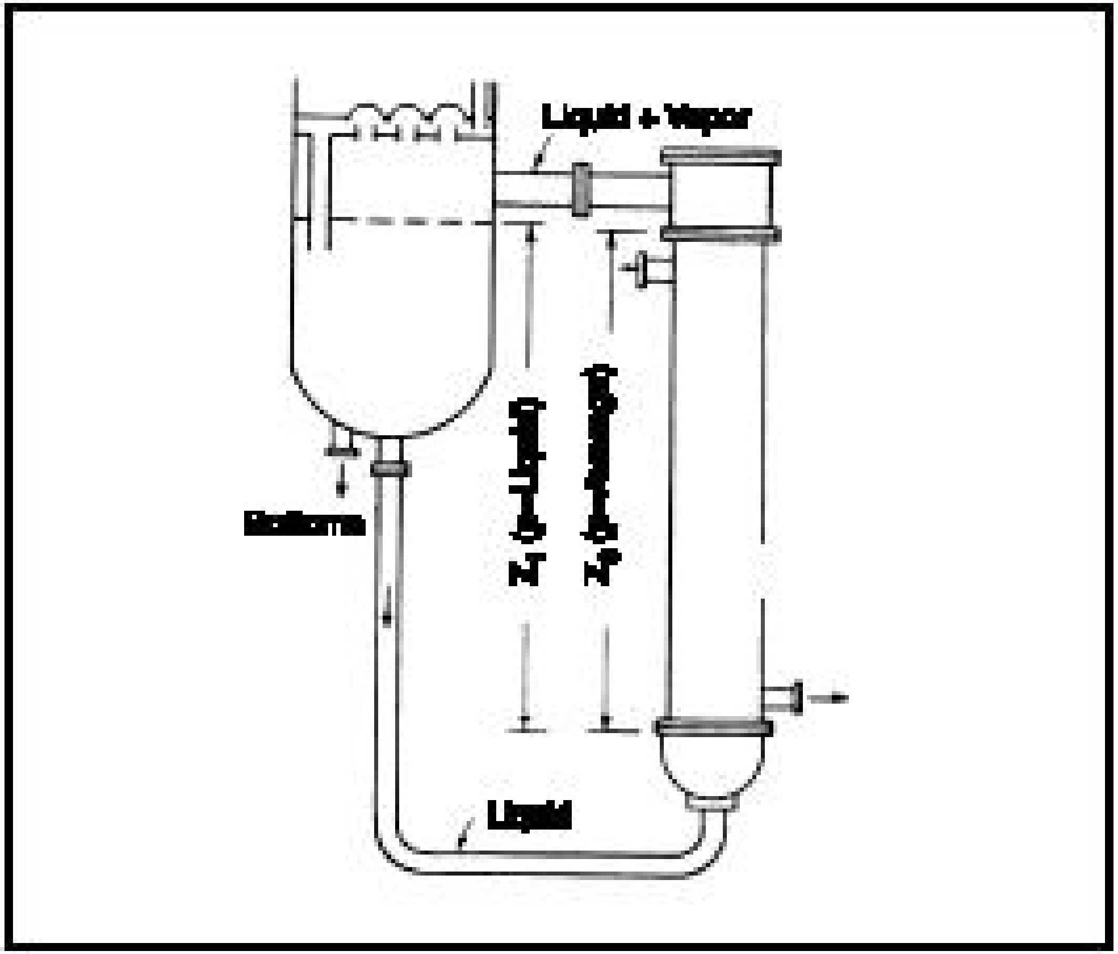
Process Equipment – Natural Circulation

Natural-Circulation Reboiler Arrangements

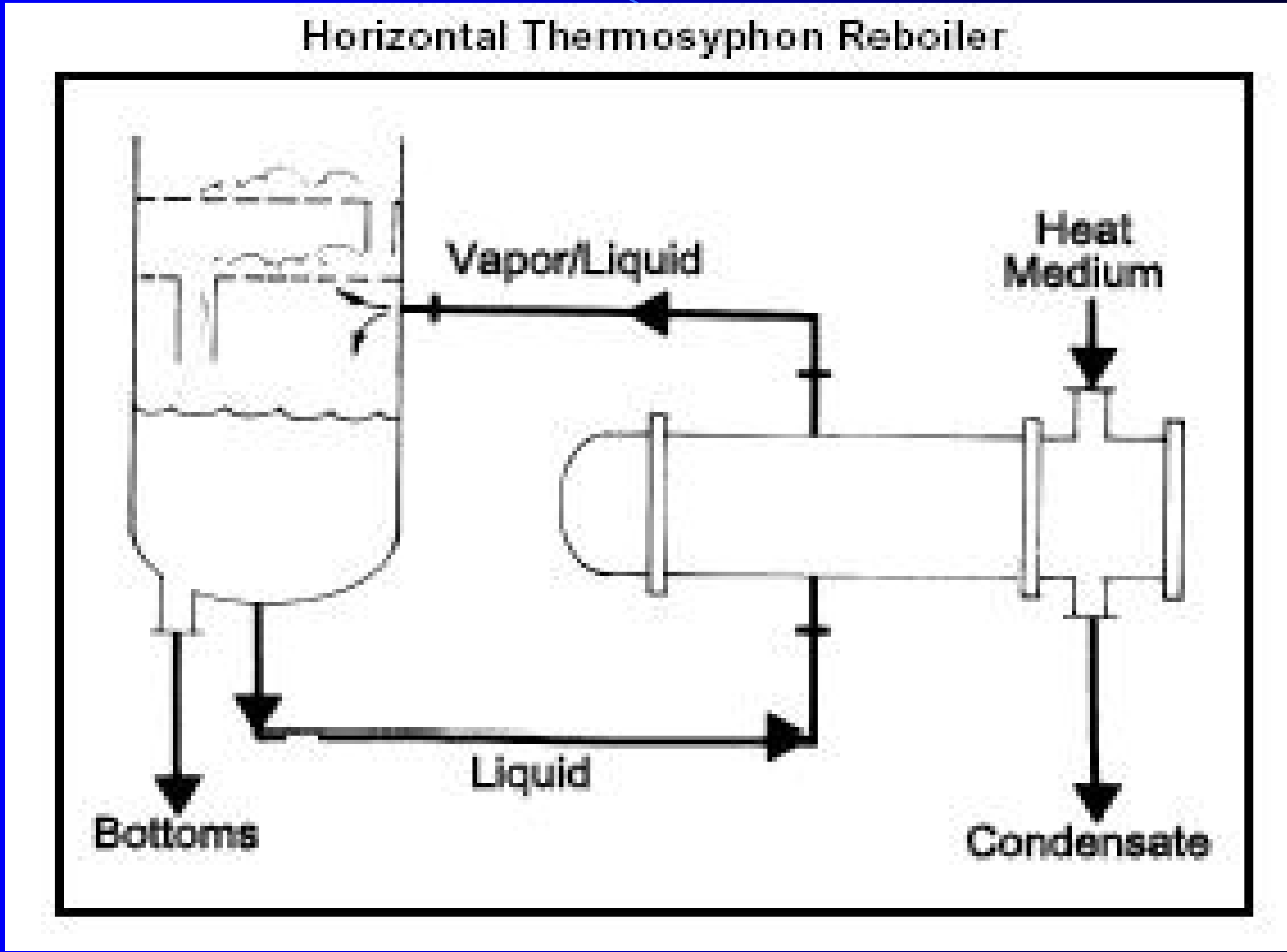


Process Equipment – Vertical Thermosyphon

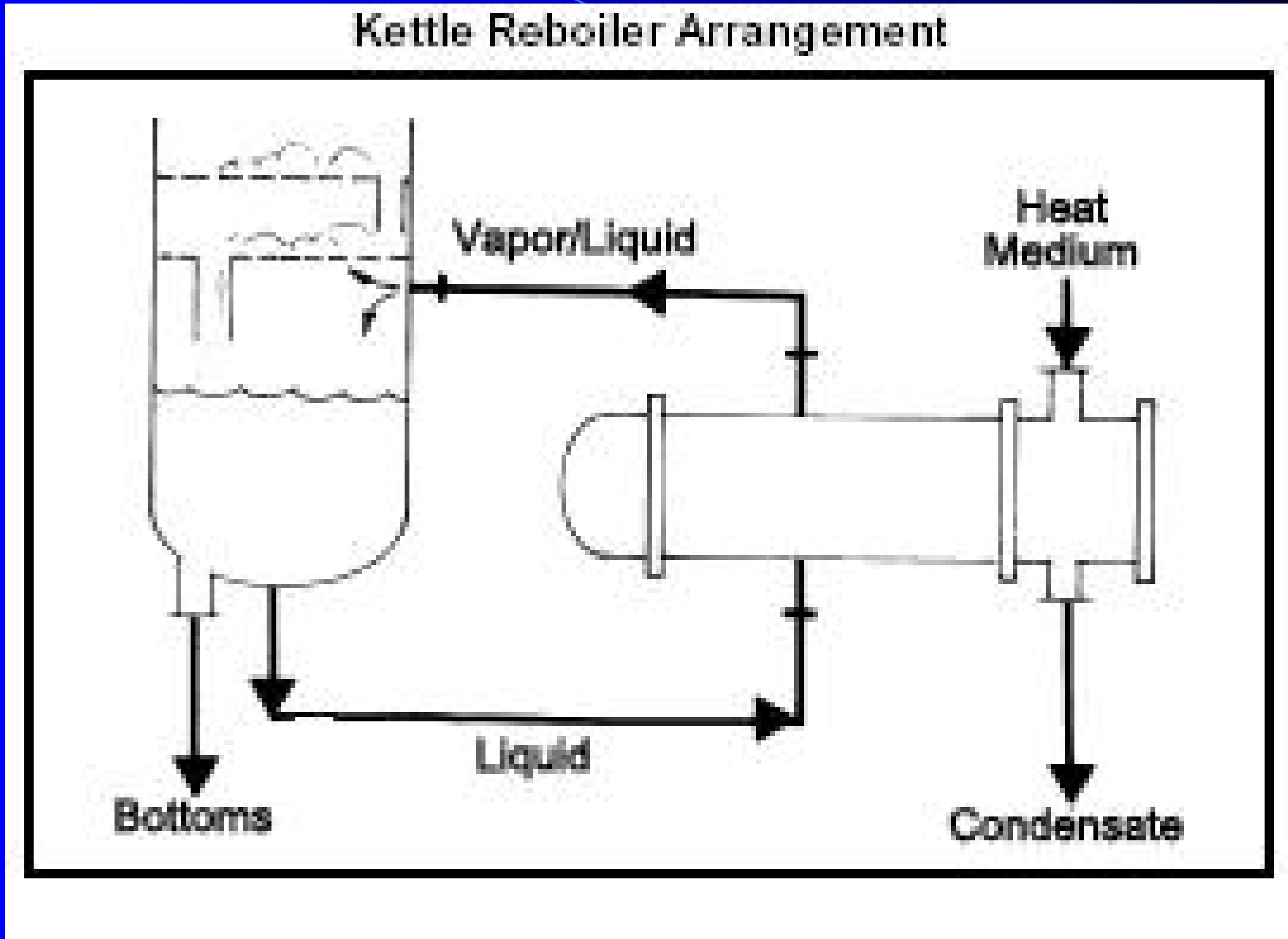
Vertical Thermosyphon Reboiler Connected to Tower



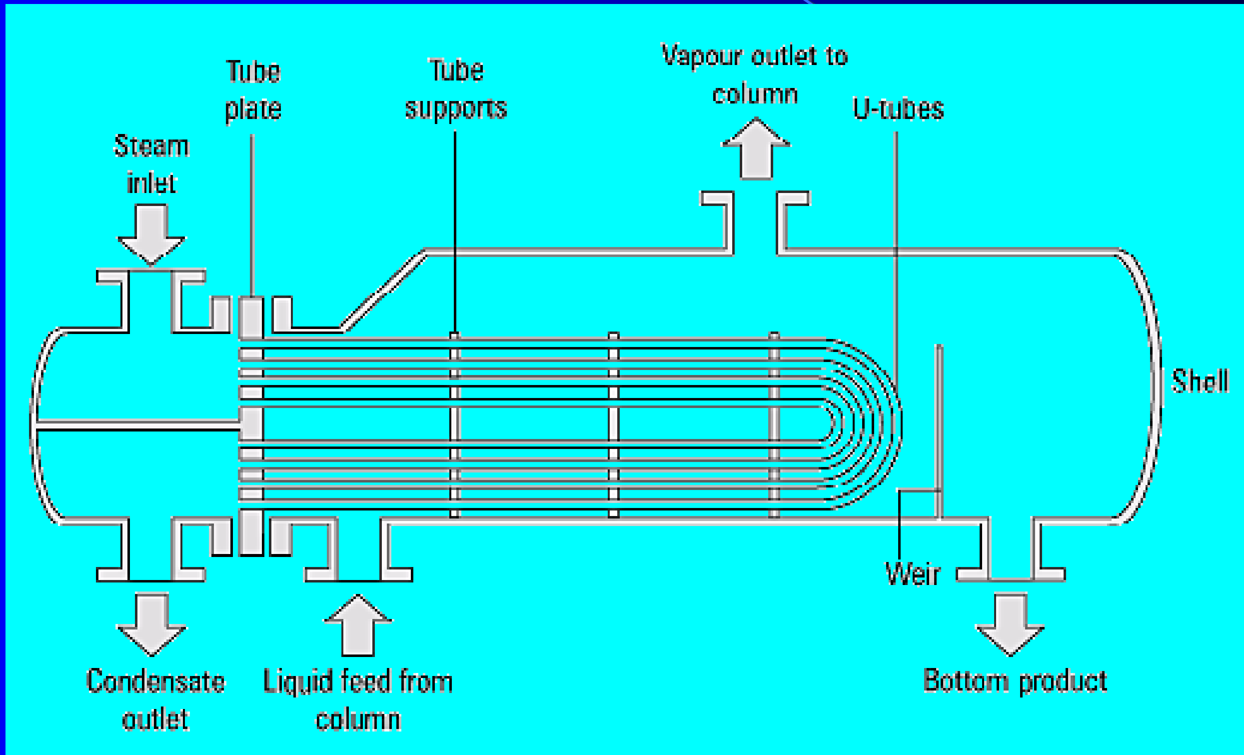
Process Equipment – Horizontal Thermosyphon



Process Equipment – Kettle



Process Equipment – Kettle



Process Equipment – Condenser

- Air Cooled
  - can be forced draft or induced draft
  - may require ambient temperature protection
  - can require extensive controls to prevent over-cooling
- Water Cooled
  - choice of materials is critical
  - Water velocity of about 5 ft/sec is considered optimum
  - average "U" of roughly 100 Btu/hrft^2°F
- Refrigeration Cooled
  - can use same refrigerant as main process cooling
  - can adapt temperatures to intermediate levels

Process Equipment – Reflux Drum

- provides some time for the fluid to accumulate and eliminates minor or temporary swings in flows and levels. Often set as 5-10 minutes. Too large a reflux drum will cause sluggish delays in the system controls.

- provides a suction reservoir for the reflux pumps to ensure sufficient suction and adequate NPSH for the reflux pumps.

- provides a way for non-condensables to separate out of the system

- usually horizontal with gas dome and possible water boot

- provides a separation vessel for two phase condensers.

- Must provide adequate reflux pump NPSH

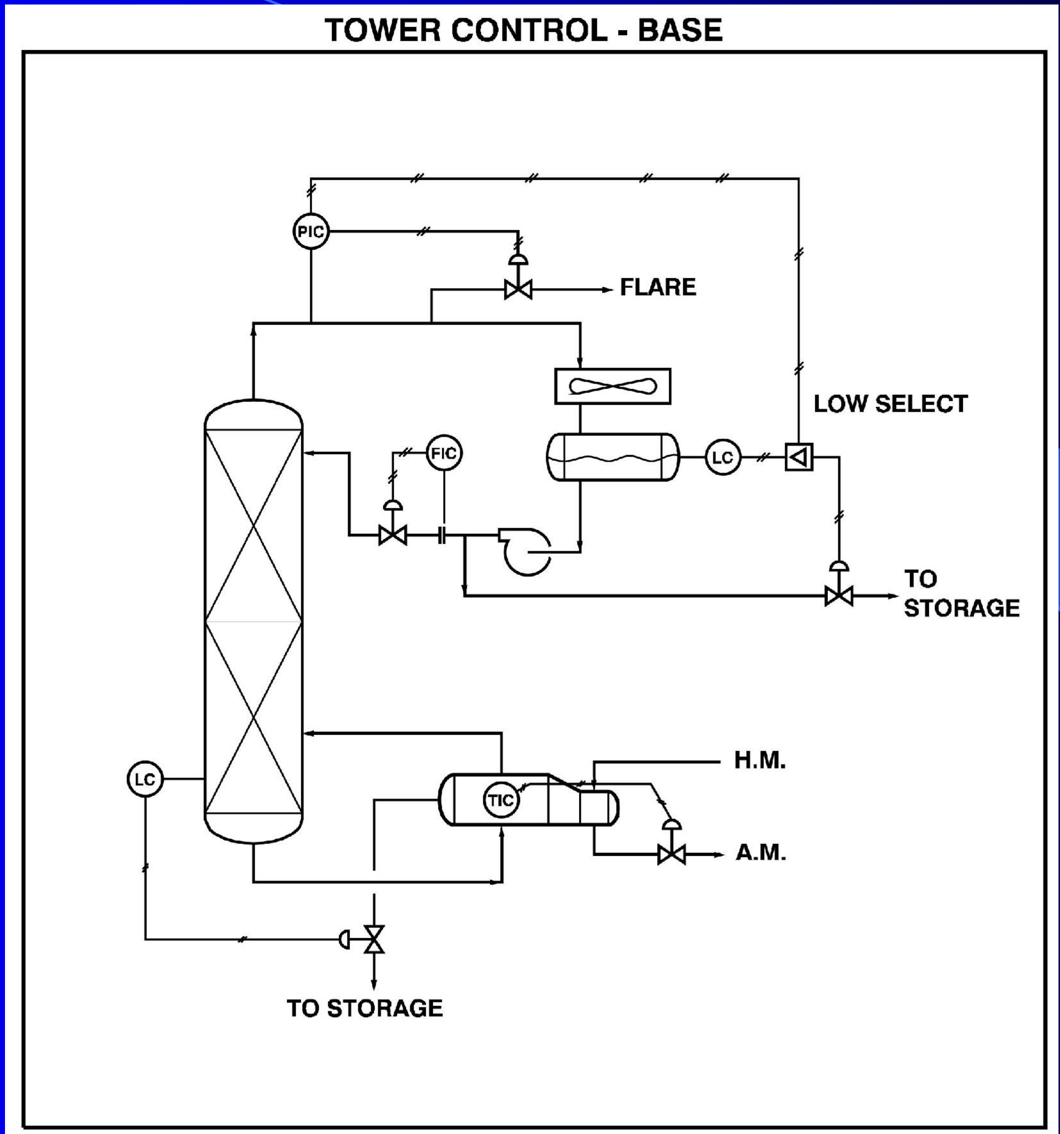
Process Equipment

Process Equipment

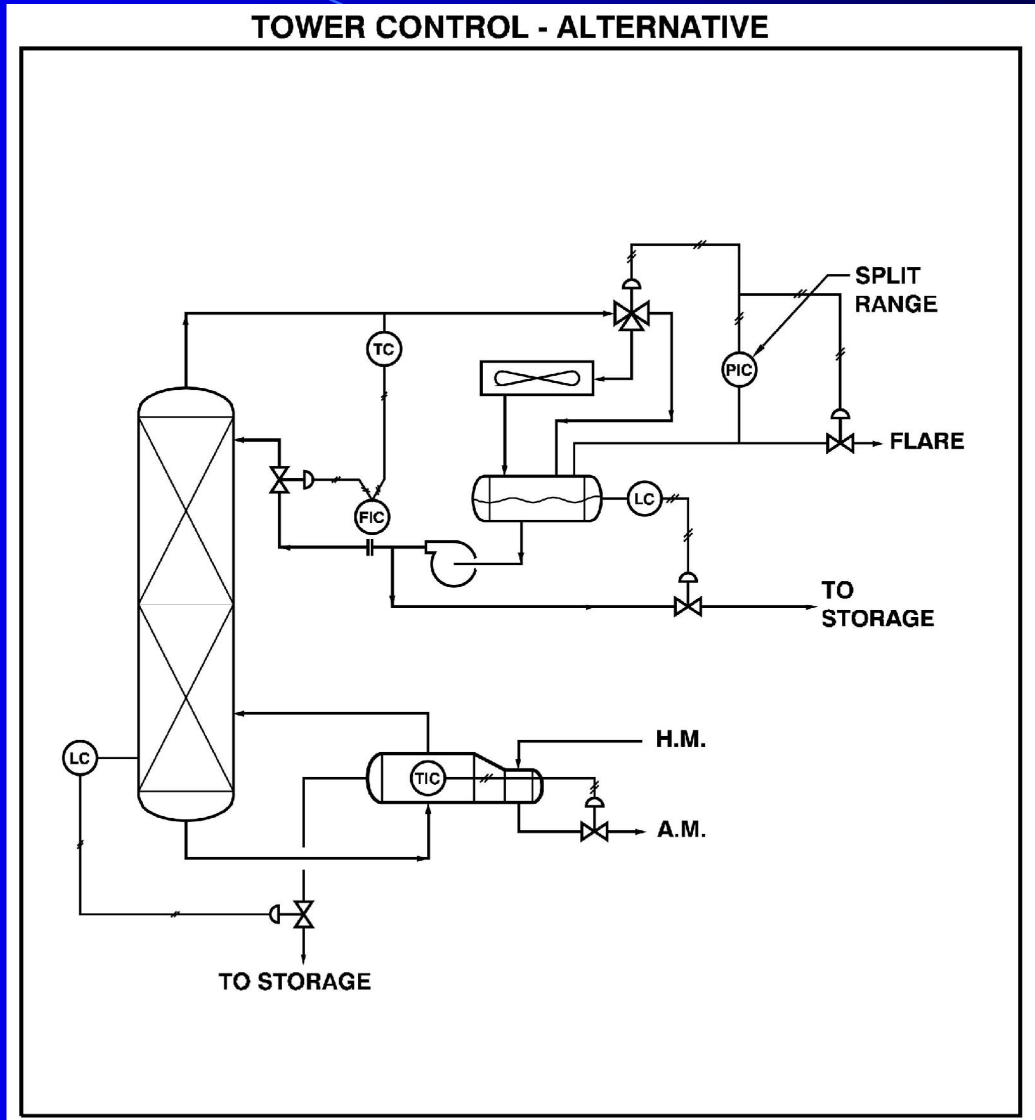
Process Equipment – Column Controls

Controlled Variable	Manipulated variable
Bottoms composition (temperature)	Heat input to the reboiler
Distillate composition	Reflux rate
Tower pressure	Heat removal (condenser)
Liquid level in the tower/reboiler	Bottoms rate
Liquid level in the accumulator	Distillate rate

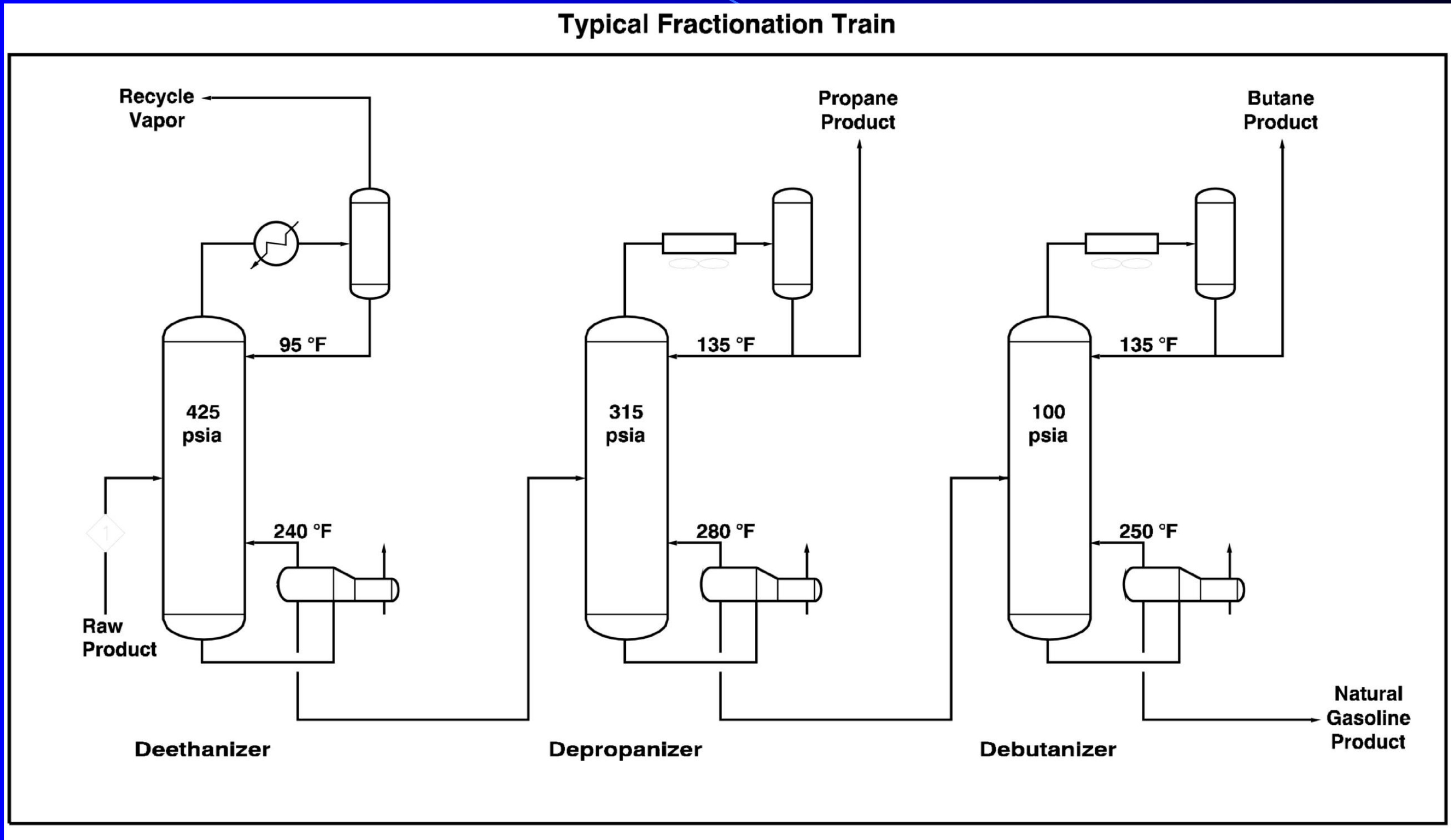
Process Equipment – Column Controls



Process Equipment – Column Controls



Process Equipment – Train



Process Equipment – Storage

- Stable liquid, that is, liquid that does not flash under normal atmospheric conditions, is usually stored in above ground vented storage tanks.

- Tanks often incorporate some type of vapour control using either VRU (vapour recovery unit) or vapour bleed to flare systems. Vapour control is often for control of odours as well as preventing hydrocarbon losses.

- Liquid that requires higher pressure or lower temperature to remain liquid, must be stored in:
  - pressurized storage bullets
  - Pressurized liquid storage spheres
  - Refrigerated storage tanks designed to ensure that the liquid remains below it's flash point at storage pressures.

Process Equipment – Storage

- Pressurized storage tanks should NOT be connected to a plant or facility flare system – there is a considerable risk of overwhelming a flare system with highly flammable hydrocarbons at rates that may far exceed design.

- Liquids can be pumped into pipelines, or transferred into trucks, ships and railcars. Accurate metering is required with computerized mass metering being very common.

- Be aware of local requirements with respect to Fire Codes. Most areas require storage tank dykes or berms for 110% containment of the largest tank to contain fires.

Process Equipment – Storage

The decision to use refrigerated storage in lieu of pressurized storage is generally a function of the volume of the liquid to be stored, the fill rate, the physical and thermodynamic properties of the liquid to be stored, and the capital investment and operating expenses of each type of system.

The parameters involved in selecting the optimum refrigerated storage facility are:

· Quantity and quality of product to be stored.

· Fill rate, temperature, and pressure of incoming stream.

· Shipping conditions for the product.

· Composition of the product.

· Cooling media (air, water, etc.) available.

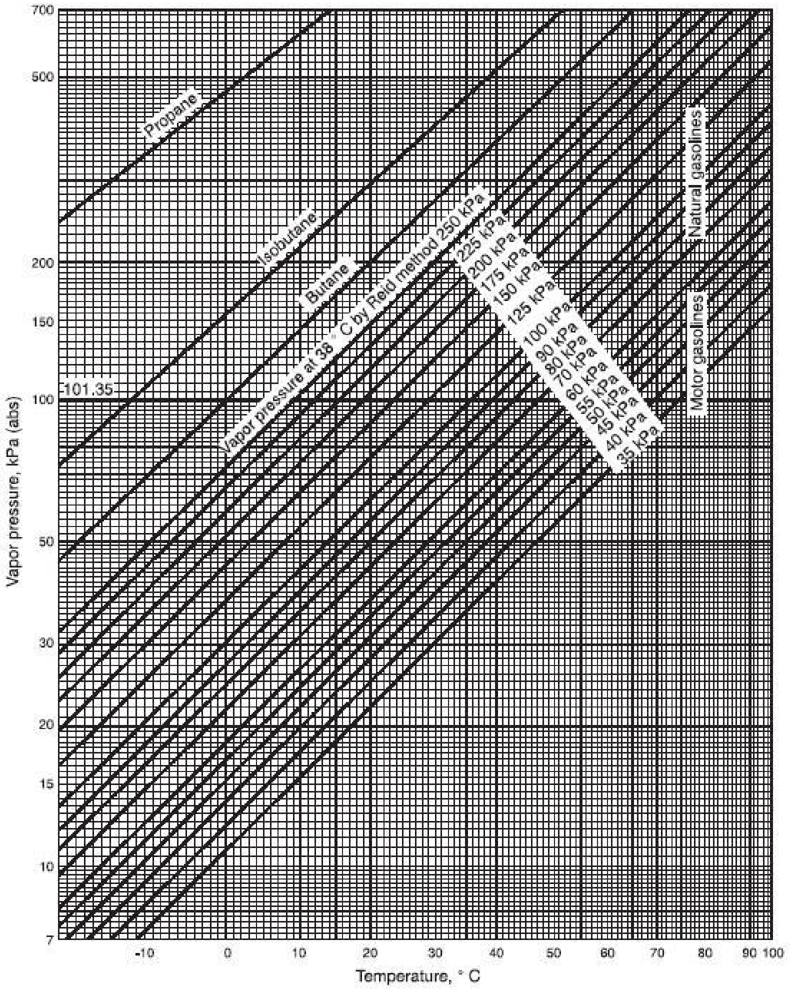
· Availability and cost of utilities.

· Load bearing value of soil.

Process Equipment – Storage

FIG. 6-4

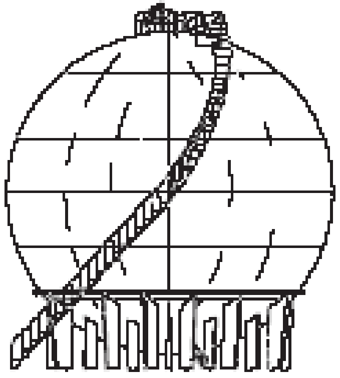
True Vapor Pressures vs. Temperatures for Typical LPG, Motor, and Natural Gasolines



CAUTION: This chart cannot be used to determine crude oil vapor pressure. Refer to API Technical Data Book Fig. 5B1.2

FIG. 6-6

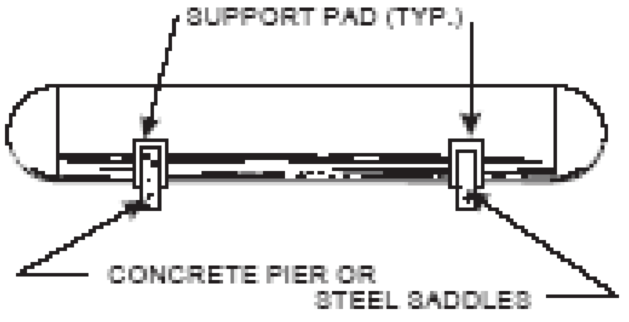
Typical Spherical Storage Tank



Courtesy of C-E Natco

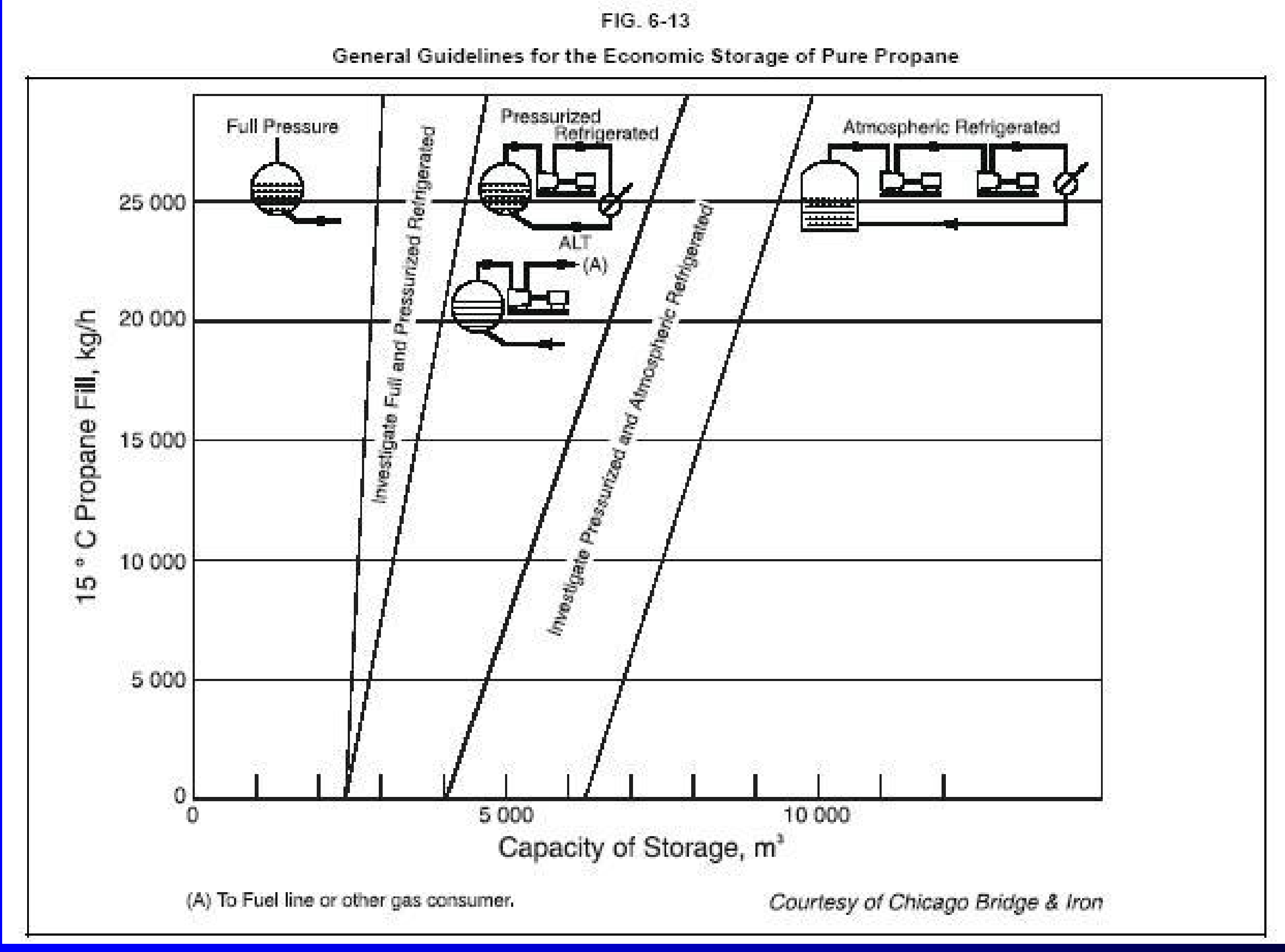
FIG. 6-7

Horizontal-Cylindrical Type Vessel



Courtesy of C-E Natco

Process Equipment – Storage



Process Equipment – Storage

- Tanks dykes are not typically utilized for LPG storage tanks due to the volatility of the liquids and the desire to prevent a BLEVE.

- Dykes are often either concrete or clay or a combination with liners, sumps, and water removal systems.

- Most pressurized liquid storage tanks for C_3/C_4 are a 1.7 barg (250 Psig) design that utilizes ANSI 150# equipment.

- Be aware of possible situations involving uncontrolled flow of hydrocarbons from the tank.

Process Equipment – Storage