

ENGINEERING DESIGN SEMINAR

SEPTEMBER 6, 1994 – NOVEMBER 11, 1994

PROCESS ENGINEERING

PROCESS ENGINEERING

Process engineering can also be called Chemical Engineering since it utilizes the basic chemical engineering fundamentals of:

- Equilibrium
- Thermodynamics
- Mass and energy transfer
- Material balance and energy balance
- Economic balance

The process engineer utilizes equilibrium to determine the vapor-liquid phase distribution in the various parts of a plant. He uses thermodynamics for determining the availability of and predicting the energy and other properties of the substances he is processing, usually with a minimum amount of experimental data. He makes use of mass and energy transfer extensively in his calculations of the many unit operations he performs. The mass and energy balance principles are then used to develop the process specifications covering the overall plant design. The economic balance is utilized many times during and after completion of the design to determine the feasibility of operations, for evaluation of the design of heat exchangers and for energy recovery and the degree of distillation requirements.

One additional fundamental should be the "Judgment Balance", since none of the other engineering disciplines make so much use of empiricism and trial-and-error methods. Many of our calculations are not completely rigorous, such as fractionator sizing, and judgment must be applied to the final answer.

Process engineering also makes use of most of the standard chemical engineering unit operations such as:

- Fluid flow
- Heat transfer
- Distillation
- Evaporation
- Absorption and Adsorption
- Extraction
- Drying
- Filtration

The process design engineer deals also with most of the chemical processes which involve many forms of chemical reaction including:

- Oxidation
- Reduction
- Combustion
- Hydrogenation and Dehydrogenation
- Isomerization, Alkylation and Dealkylation
- Hydrolysis, etc.

The various phases or steps in the process engineering design of a plant are as follows:

- Establish the design basis
- Develop schematic flow diagram
- Develop mass balance
- Use V/L equilibrium for phase conditions
- Make recycle calculations
- Make fractionation, extraction, etc., reflux and equilibrium stage calculations
- Develop energy balance
- Determine fractionator and extractor internal loadings and the size of the vessels
- Develop a comprehensive process flow diagram and controls
- Issue the process design to project engineering

The process engineering phase of a project takes about 5-10 pct of the man-hours required to produce the complete project specification for a plant. This small percentage of engineering man-hours expended in producing the process design will have a much greater effect on the economics and operability of the plant than any other phase of the design. The process design will affect the number of pieces of equipment used, the size and arrangement of the equipment, the materials of construction and the degree of instrumentation and control; all of which bear substantially on the cost and operability of the plant.

The process engineer works with the development engineers in the early phase of his work and then he works closely with the project engineers after his specifications are completed in order to develop the complete project specification of the plant.

PROCESS ENGINEERING

DEFINITION OF ENGINEERING

"The art and science by which the properties of matter and the sources of power in nature are made useful to mankind"

The art is a skill, acquired by performance and experience, of knowing when to apply science and when to use empiricism to the tasks at hand.

Chemical engineering is defined in terms of unit operations and chemical processes.

Process engineering is the essence of chemical engineering since it deals with both unit operations, chemical processes and the basic fundamentals.

A process engineer must have one essential ingredient, "common sense", since process engineering is as much as "art" as it is a science.

PROCESS ENGINEERING

Uses Most Standard Unit Operations

- Fluid flow
- Heat transfer
- Distillation
- Absorption and adsorption
- Extraction
- Drying and evaporation

Deals With Most Chemical Processes

- Oxidation
- Reduction
- Combustion
- Hydrogenation & Dehydrogenation
- Isomerization, Alkylation & Dealkylation
- Hydrolysis

Design Steps of Project

- Establish basis of design
- Develop schematic flow
- Develop mass balance
- Calculate V/L phase conditions
- Calculate fractionators & extractors
- Develop energy balance
- Calculate vessel V/L loadings
- Develop comprehensive flow & controls

THE FIVE BASIC FUNDAMENTALS ARE:

- Material balance
- Energy balance
- Heat and mass transfer
- Equilibrium
- Economic balance

The sixth fundamental should be judgment balance, since none of the other engineering disciplines make so much use of empiricism and trial-and-error methods.

HEAT AND WEIGHT BALANCES

Pounds in = pounds out

Btu's in = Btu's out

Must always check!

HEAT TRANSFER ART

- Installed cost ÷ value of utilities = payout
- Normal payout 2-5 years (before taxes)

VAPOR/LIQUID EQUILIBRIUM ART

Process designers bread-and-butter; recognize limitations of data.

$$Y = KX$$

$$\text{Dew Point} = \frac{Y}{K}$$

$$\text{Bubble Point} = KX$$

$$\text{Flash } Y = \frac{FK}{K + \frac{L}{V}}$$

TRIAL-AND-ERROR CALCULATIONS

- Equilibrium flashes
- Cycle calculations
- Cycle factors

FRACTIONATION ART

- McCabe/Thiele diagrams
- Permissible mass velocity
- Head over the weir
- Downcomer velocity
- Fenske's equation
- Barrel factors

THE ECONOMIC BALANCE

- Save customers money
- Safety and operability
- Use safety margins wisely
- Healthy skepticism

THE AGE OF COMPUTERS

- Art aspects overlooked
- Designers best tool
- Know limitations of programs
- Do not use sledgehammer for tacks
- Do not violate fundamentals
- Remember Gibbs, $F = 2 + C - P$

ART OF CHECK FACTORS

- Properties of hydrocarbons
- Thermodynamics
- Fractionator calculations
- Absorption/stripping
- Heat transfer
- Hydraulic calculations
- Economics

PROPERTIES OF HYDROCARBONS

- Critical temperature, °F

$$T_C = T_B + 350 \pm 50^\circ$$

$$T_B = \text{Normal boiling point, } ^\circ\text{F}$$

Specific Heat Range (100-600°F)

- Liquids 0.4-0.8
- Vapors 0.35-0.75
- Steam ~ 0.5
- Water 1.0
- Air ~ 0.25
- Hydrogen ~ 3.5

V/L Equilibrium Constants

$$K \equiv P^o/\pi$$

$$K_2 = \frac{P_2^o}{\pi} \left(\frac{(1 - X_1)}{X_2} \right)$$

Where X_2 is solubility of 2 in 1

$$\alpha = P_1^o/P_2^o = K_1/K_2$$

= *Relative Volatility*

PROPERTIES OF HYDROCARBONS

— Latent Heat Range, Btu/lb

Hydrocarbons	100-200 (at B/P.)
Steam	100-200 (@100° – 500°F)
At critical temperature	0

THERMODYNAMICS – THREE LAWS

Equations of State

$$PV = NZRT$$

$$\left(P + \frac{A}{V^2}\right)(V - B) = RT \text{ (Van der Waals' equation)}$$

Heat Balance

$$H = U + PV$$

Entropy

$$\Delta S = \frac{Q}{T}$$

FRACTIONATOR CALCULATIONS

Minimum Reflux – Ideal Binary

$$\text{Reflux/Feed} \left(\frac{R}{F} \right)_M = \left(\frac{R}{D} \right) \left(\frac{D}{F} \right)$$

$$\frac{L}{V} = \frac{R/D}{1 + R/D}$$

$$(R/F)_M = 1/(\alpha - 1), \text{ bubble point feed}$$

$$= \left[\left(\alpha / (\alpha - 1) \right) \right] - X_F, \text{ dew point feed}$$

$$\text{Actual } R/F = 1.1 \text{ to } 1.3 (R/F)_{\min}$$

Minimum Stages – Fenske

$$n = \log \left(\frac{X_{LD}}{X_{LB}} \right) \left(\frac{X_{HB}}{X_{HD}} \right) / \log \alpha$$

$$\alpha^n = \left(\frac{X_{LD}}{X_{LB}} \right) \left(\frac{X_{HB}}{X_{HD}} \right)$$

All at total reflux

Actual stages = 2 – 3n

Tray Efficiency (F(α))

$$\alpha = 1.05 \quad \text{eff} \cong 90 + \text{pct}$$

$$\alpha = 1.8 \quad \text{eff} \cong 80 \text{ pct}$$

$$\alpha = 3^+ \quad \text{eff} \cong 50 \text{ pct}$$

Immiscible Systems $\text{eff} \cong 15\%$

$$\text{Strippers} \quad \text{eff} \cong 60 \text{ pct}$$

$$\text{Absorbers} \quad \text{eff} \cong 25 \text{ pct}$$

FRACTIONATOR SIZING

Permissible Mass Velocity (Brown & Souders)

$$PMV = C\sqrt{D_V}(D_L - D_V), lb/h \cdot ft^2$$

Tray Space

<u>Inches</u>	<u>C</u>
12	235
18	460
24	592
30	662

Max. Rates:

2.0(PMV) on Low Pressure towers

1.5(PMV) on High Pressure towers

Weir Rates – Francis Equation

$$H_{OW} = 0.48(gpm/inch)^{2/3}, inches$$

- Minimum H_{OW} about 0.48 inches
- Maximum H_{OW} about 2.0 inches
- Maximum downcomer velocity 0.5 ft/s

Fractionator Sizing

Barrel Factors

$$\frac{R+F}{D^2} \leq 240$$

R = Reflux, bbl/d

F = Feed, bbl/d

D = ID, feet

Bottom Heat Flux

$$\frac{Q}{D^2} \leq 350,000$$

Q = Reboiler duty, Btu/h

ABSORPTION AND STRIPPING

Kremser Method

$$pct\ Absorbed = \left(\frac{A^{n+1} - A}{A^{n+1} - 1} \right) 100$$

$$\text{Where } A = \frac{L}{KV} \quad n = \text{theoretical stages}$$

$$pct\ stripped = \left(\frac{S^{n+1} - S}{S^{n+1} - 1} \right) 100$$

$$\text{Where } S = \frac{KV}{L} \quad n = \text{theoretical stages}$$

HEAT TRANSFER

$$Q = UA\Delta T$$

$$A = \frac{Q}{U\Delta T}$$

Q = Heat transferred, Btu/h

A = Surface area, ft²

U = Overall heat transfer coefficient

ΔT = Log mean temperature difference, °F

Range $100 \geq U > 10$

HYDRAULIC CALCULATIONS

$$\text{Pump bhp} = \text{gpm}(\Delta\text{psi}/1714)$$

$$\text{Compressors bhp} \cong 70 \left(\frac{\text{std ft}^3/\text{d}}{10^6} \right) @ \text{CR} = 3$$

$$\cong 30 \left(\frac{\text{std ft}^3/\text{d}}{10^6} \right) @ \text{CR} = 1.5$$

Adiabatic Compression

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}}$$

$$n = \frac{C_p}{C_v} \quad n \text{ Range: } 1.2 \text{ to } 1.4$$

GRAPHICAL ANALYSIS

Linear Plot

$$Y = AX + B$$

Log/Log Plot

$$Y = AX^B + C$$

Semi-Log Plot

$$\text{Log } Y = AX +$$

ESTIMATING ECONOMICS

Capital Cost

- Plat Cost, \$/bbl Capacity
- Fractionator Cost, \$/ft of Diameter
- Heater Cost, \$/10⁶ Btu/h
- Exchanger Cost, \$/ft²
- Compressor Cost, \$/bhp
- Erected vs. Fabricated Cost
- Revamp Cost

Utilities

- Fuel Cost

Fuel Oil $\cong$ 6 10⁶ Btu/bbl.
- Electric Cost
- Steam Cost
- Cost bhp at \$0.05/kWh $\cong$ \$300/bhp·a

ENGINEERING DESIGN SEMINAR

SEPTEMBER 6, 1994 – NOVEMBER 11, 1994

PROCESS FLOW DIAGRAMS

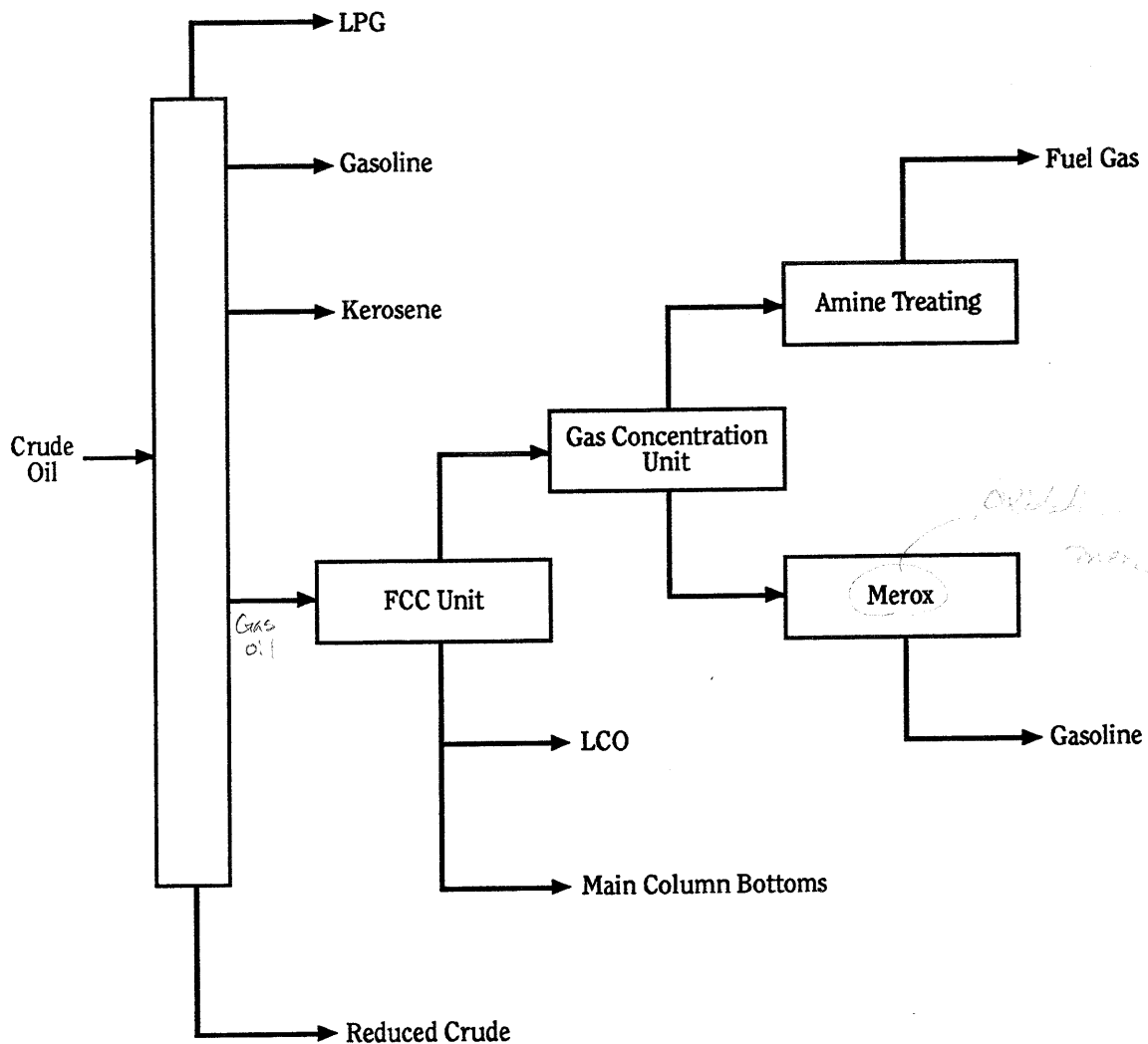
TYPES OF FLOW DIAGRAMS

- Block Flow Diagrams
- Process Flow Diagrams
- Piping & Instrument Flow Diagrams
- Mechanical Flow Diagram

BLOCK FLOW DIAGRAMS

- Overview of processing scheme
- Simple information format
 - No instrumentation
 - Selective equipment shown
 - No process information
- Inter-relationships highlighted
- Used for presentations and proposals

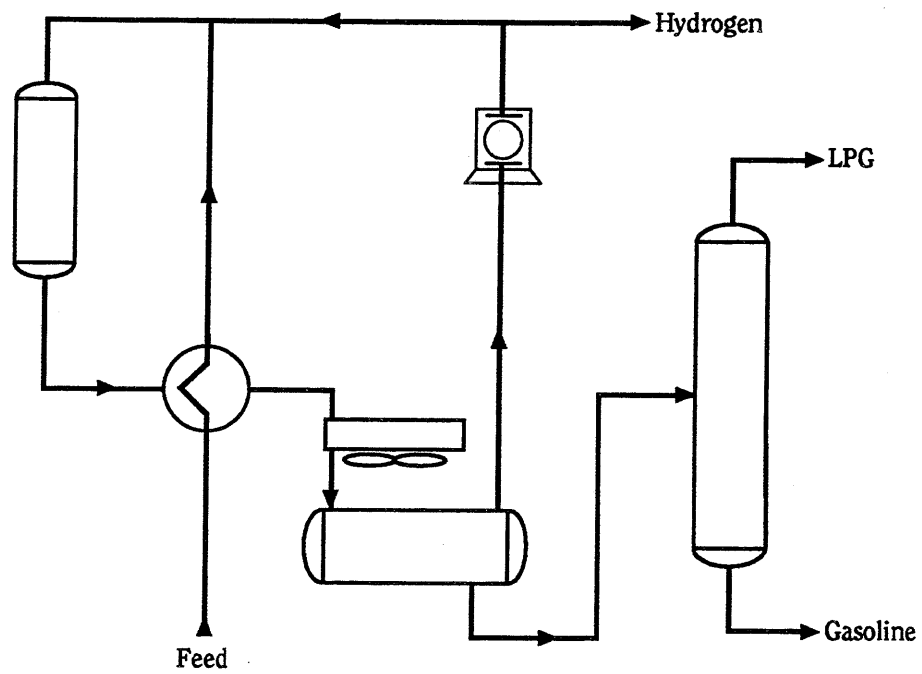
Process Units



Block Flow for Gas Oil Draw

EDS-R00-3001

Unit Operations



Block Flow Diagram for Reformer

EDS-R00-3002

PROCESS FLOW DIAGRAM

Normal Process Flow Configuration

- Reasonable size
- Minimum details
- Heat & weight balance corresponds to process flow

Control Instrumentation

- Required for normal operation
- Non-essential instrumentation not shown
- No start-up or shutdown instrumentation

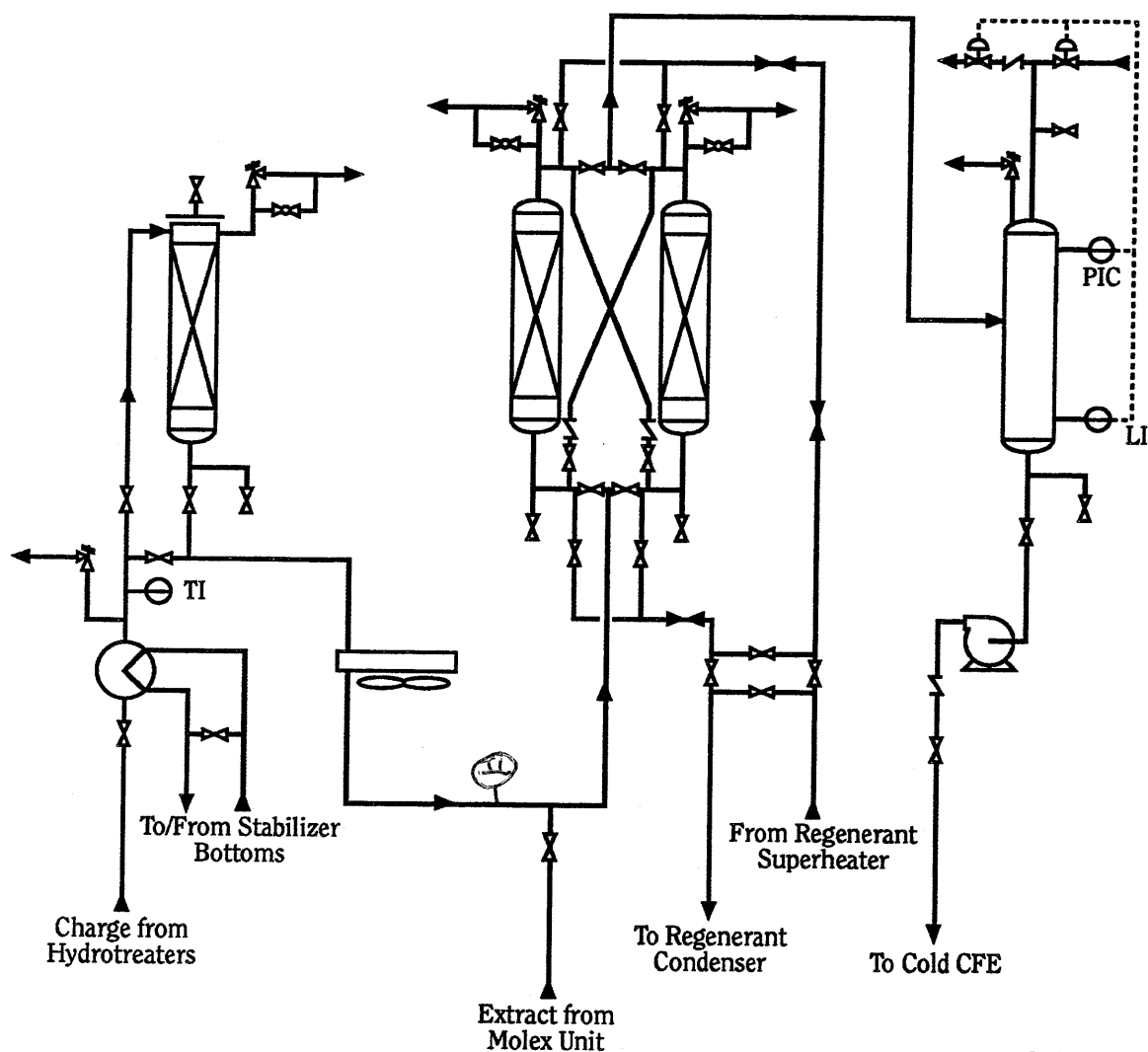
Major Equipment

- Number of reactor beds
- Reboiler & condenser type
- Number of trays and feed location

Flagging

- Overall mol balance of terminal streams
- Internal temperature, pressure, enthalpy, and flow rates

PFD Example



EDS-R00-3003

PIPING & INSTRUMENT DIAGRAMS

Basic Equipment Arrangement

Coordination of Design Effort

- Input by equipment and instrumentation specialists
- Contractor
- Prestart-up checkout
- Operator training

Notes and Details

- Items not included in project specifications
- Piping details
- Warnings for hazardous materials
- Identifies start-up, shutdown, and special use piping
- Identifies winterizing needs

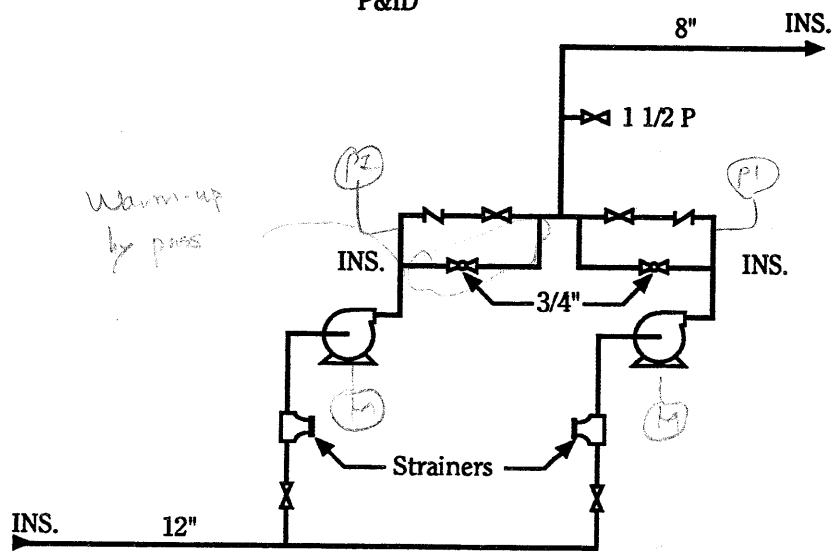
Control, Monitoring, Alarm, and Special Use Instrumentation

Pumps

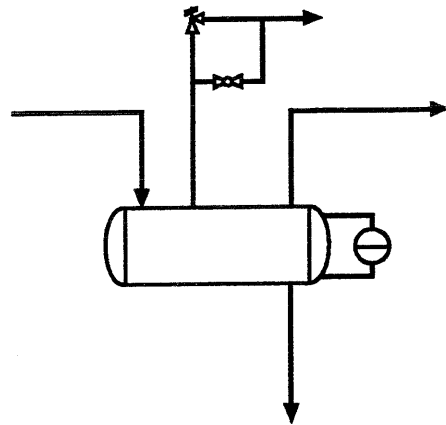
PFD



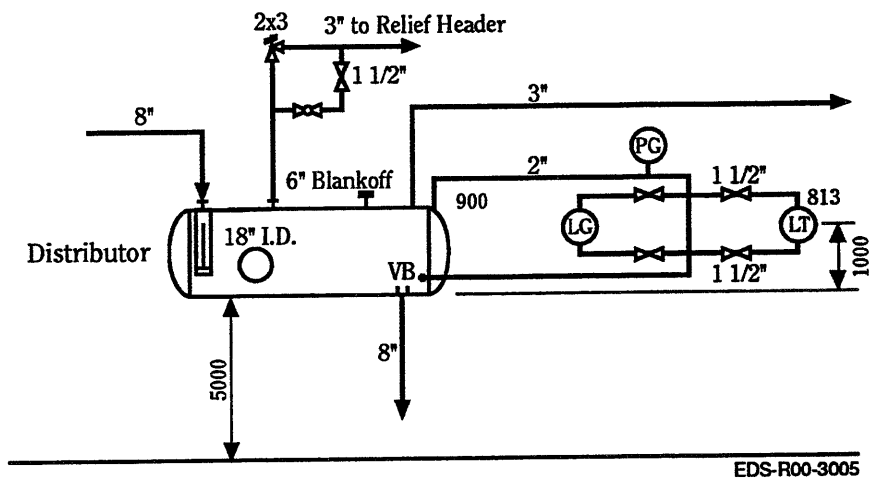
P&ID



PFD



Relief Header



PROCESS FLOW DIAGRAMS

CONCEPT & EVOLUTION

- Conceptual or New Process Technology
- Mature Process Technology
- Process Revamps

NEW PROCESS TECHNOLOGY

- Define product(s) and feed(s)
- Determine unit operations required
- Generate heat and mass balances
- Perform a heat transfer analysis
- Material and energy balances
- Add control instrumentation

MATURE TECHNOLOGY

- Feed quality (feed preparation)
- Operating flexibility
- Process improvements
- Energy utilization
- Utility availability and cost
- Ambient conditions
- Product requirements (post treatment)
- Battery limit conditions

REVAMP CONSIDERATIONS

- **Revamp Objectives**

 - Higher capacity**

 - Different feedstock**

 - More efficient process**

 - Updating technology**

 - Minimum change/cost**

 - Loosening constraints (debottlenecking)**

- **Determine What Equipment Actually Present and Its Suitability for The New Service**
- **Rate Equipment for New Process Conditions**
- **Consider Changes in Codes and Design Practice**

CRUDE UNIT DESIGN

Building the Process Flow Diagram

PROCESS DESIGN BASIS

Feed

- Quantity
- Properties

Bases/Goals

- Economic
- Operational
- Environmental

- Safety

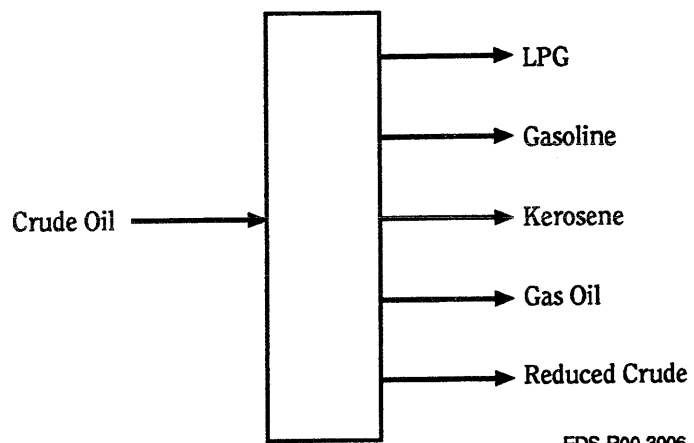
Products

- Distribution
- Yields
- Properties

Utilities

- Steam
- Water
- Fuel

Feed & Products



EDS-R00-3006

SEPARATION PROCESSES

- Filtration
- Distillation
- Crystallization
- Liquid Extraction
- Absorption
- Adsorption
- Electrophoresis

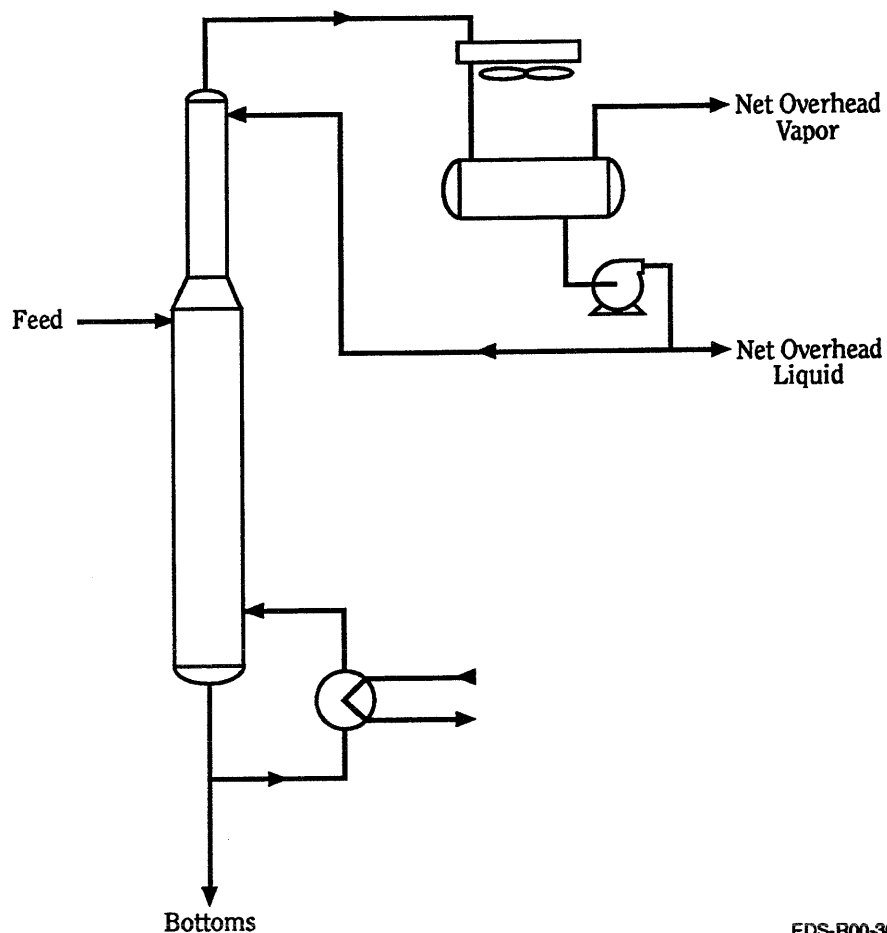
Order of Separation.

DISTILLATION REQUIREMENTS

- Heat or energy source
- Heat or energy removal
- Vapor liquid contacting
- Equilibrium stages

- n-1 Fractionating Towers

Basic Flow Scheme



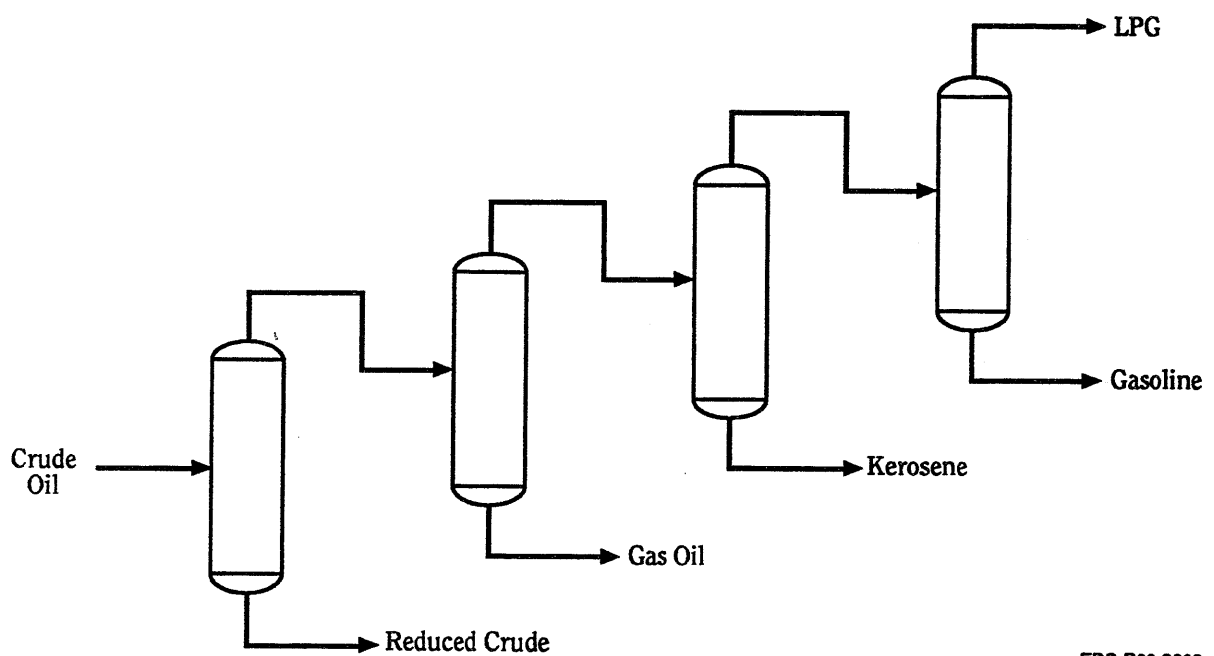
EDS-R00-3007

CONFIGURATION

Five products require four columns

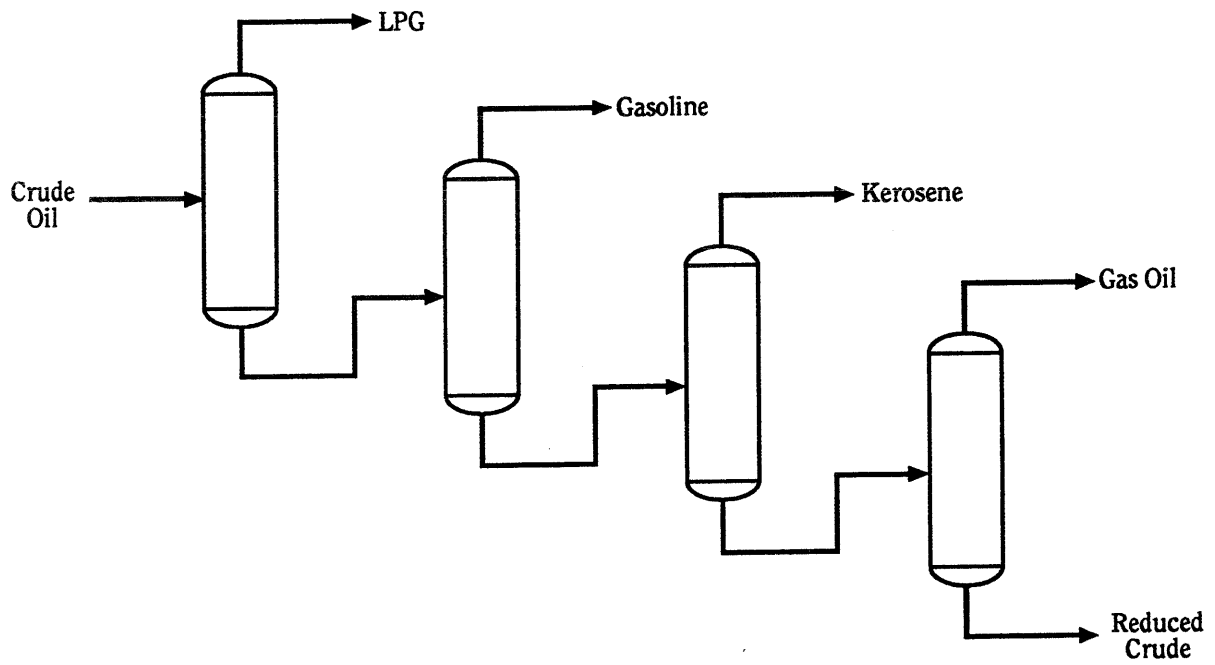
But in what order should the separation be made?

Products at Bottom



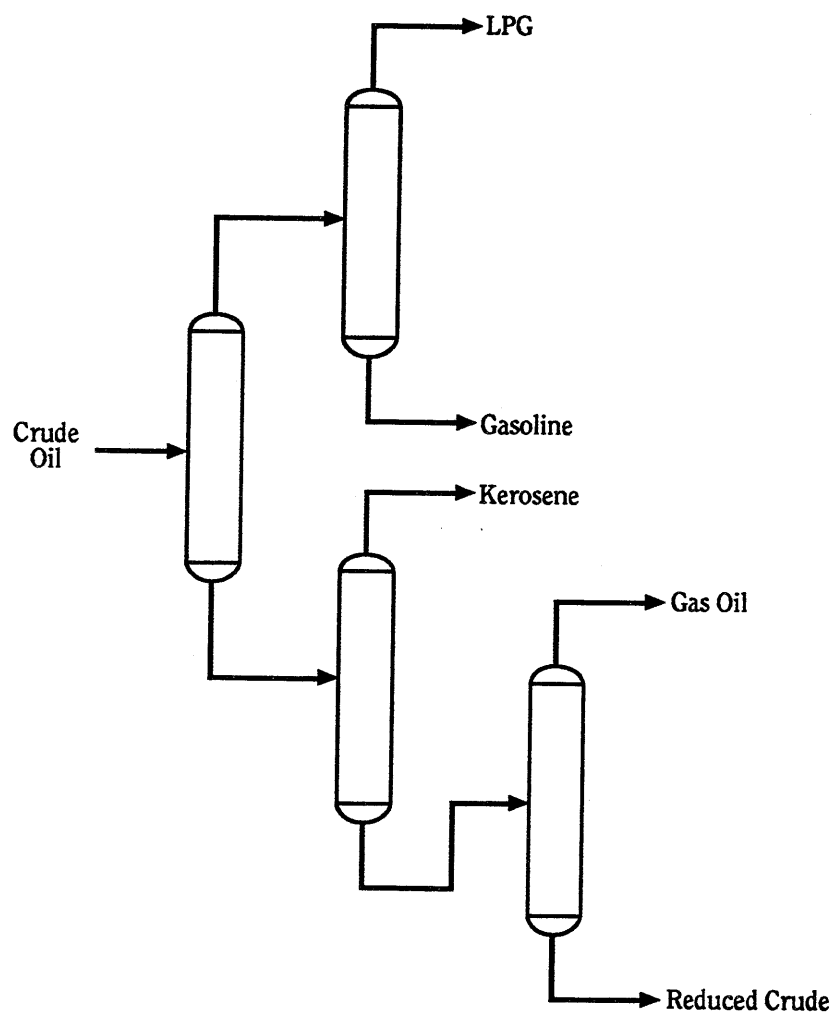
EDS-R00-3008

Products at Overhead



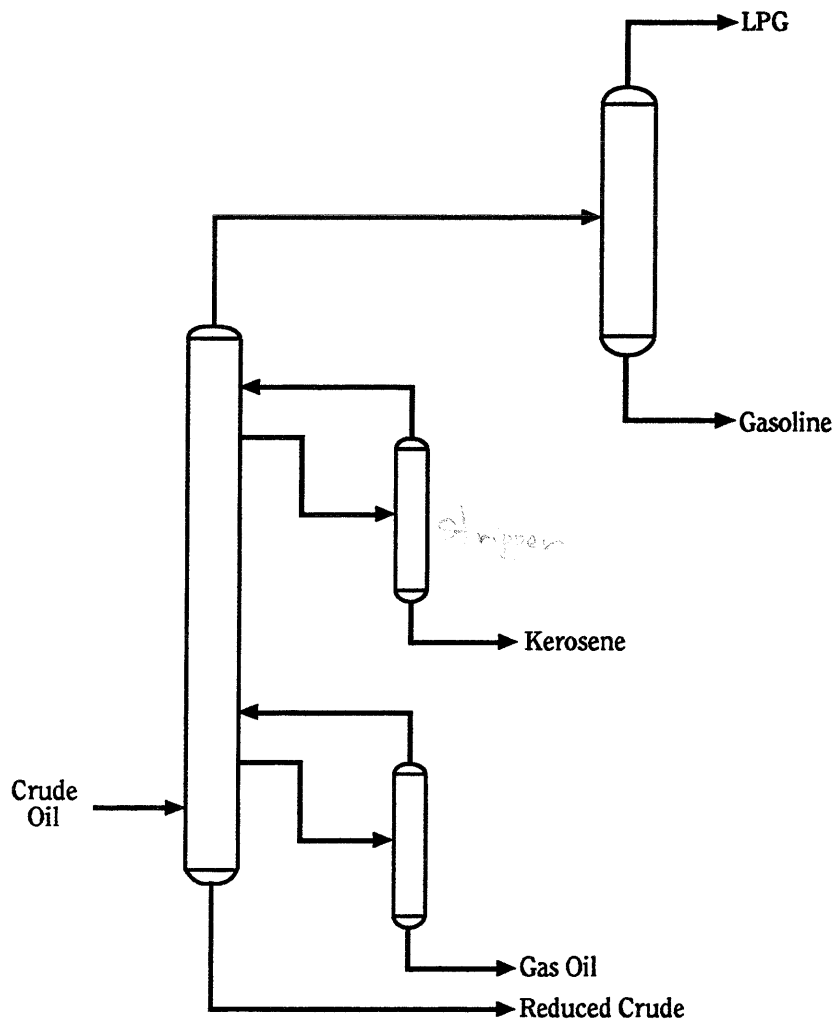
EDS-R00-3009

Permutations



EDS-R00-3010

Typical Configuration



EDS-R00-3011

ADDING TO BASIC FLOW SCHEME

- Overhead system
- Heat input
- Feed preparation
- Battery limit conditions

OVERHEAD SYSTEM

- Lowest pressure (practical)

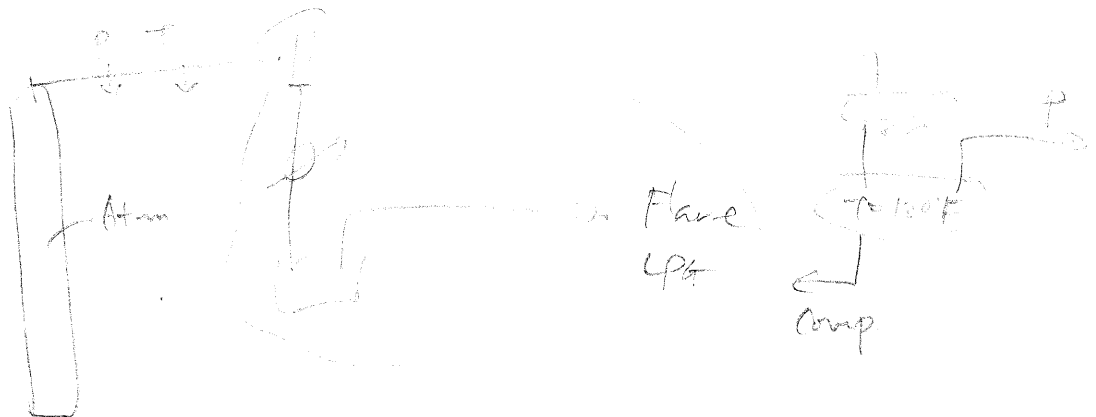
No compressor

Net gas compressor

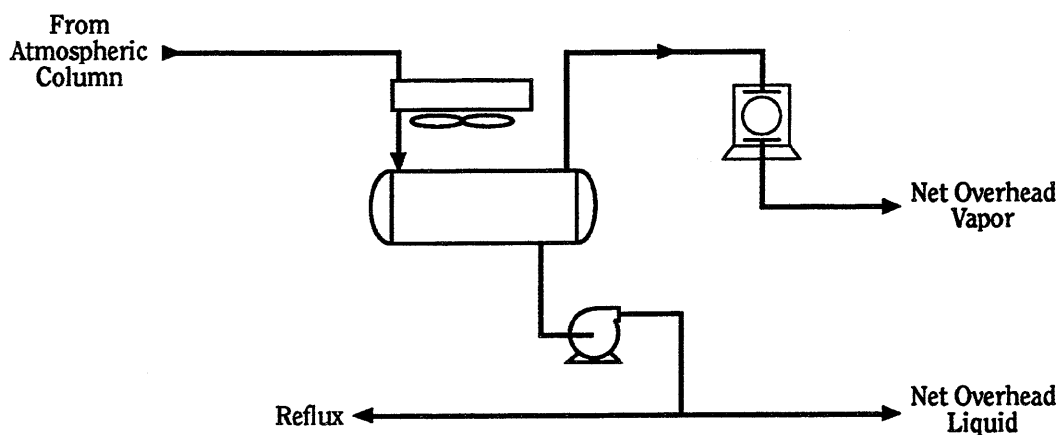
- Lowest temperature (practical)

Air cooled condenser 130 ~ 120° F

Water cooled condenser 100 ~ 90° F

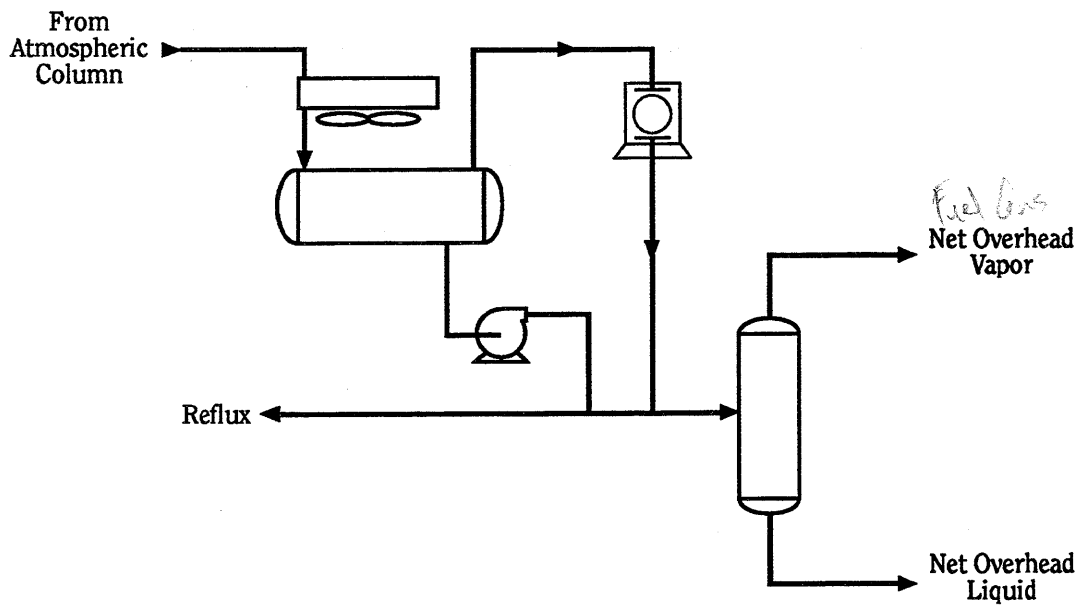


Partial Condensing System



EDS-R00-3012

Recontacting System



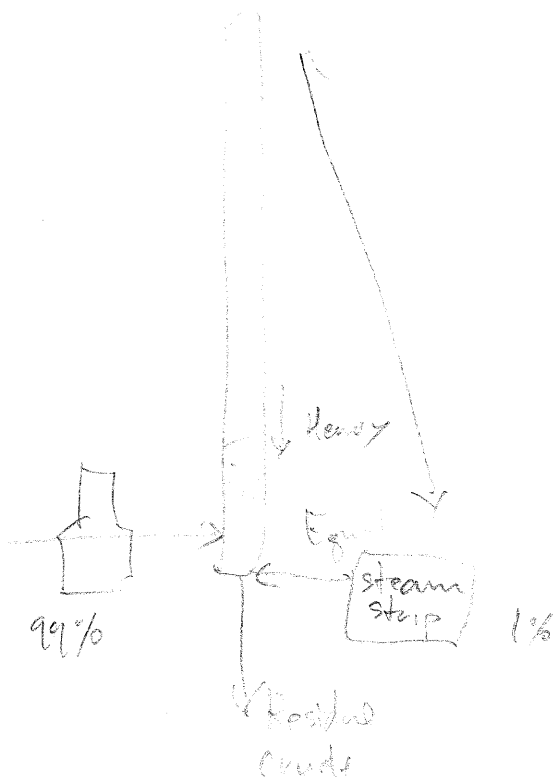
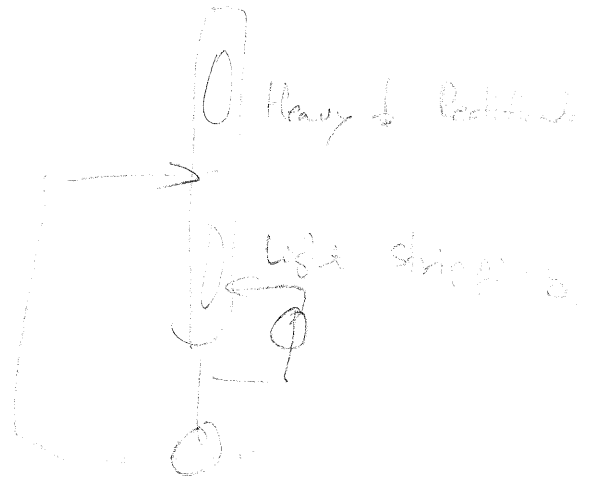
EDS-R00-3013

Gas Cond

HEAT INPUT

Heat Input Locations

- Feed
- Bottoms
- Upper reboiler/Interheater
- Combination of above

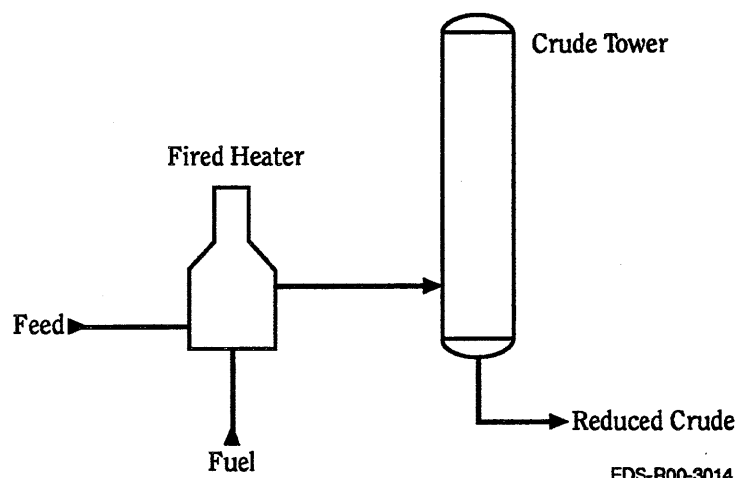


HEAT INPUT TO CRUDE COLUMN

Note: Feed composition is fixed

- Temperature required is based on:
 - Amount vaporized
 - Vaporization pressure
- Feed susceptible to thermal degradation
- High temperature requires a fired heater

Heat Input to Feed



FEED PREPARATION

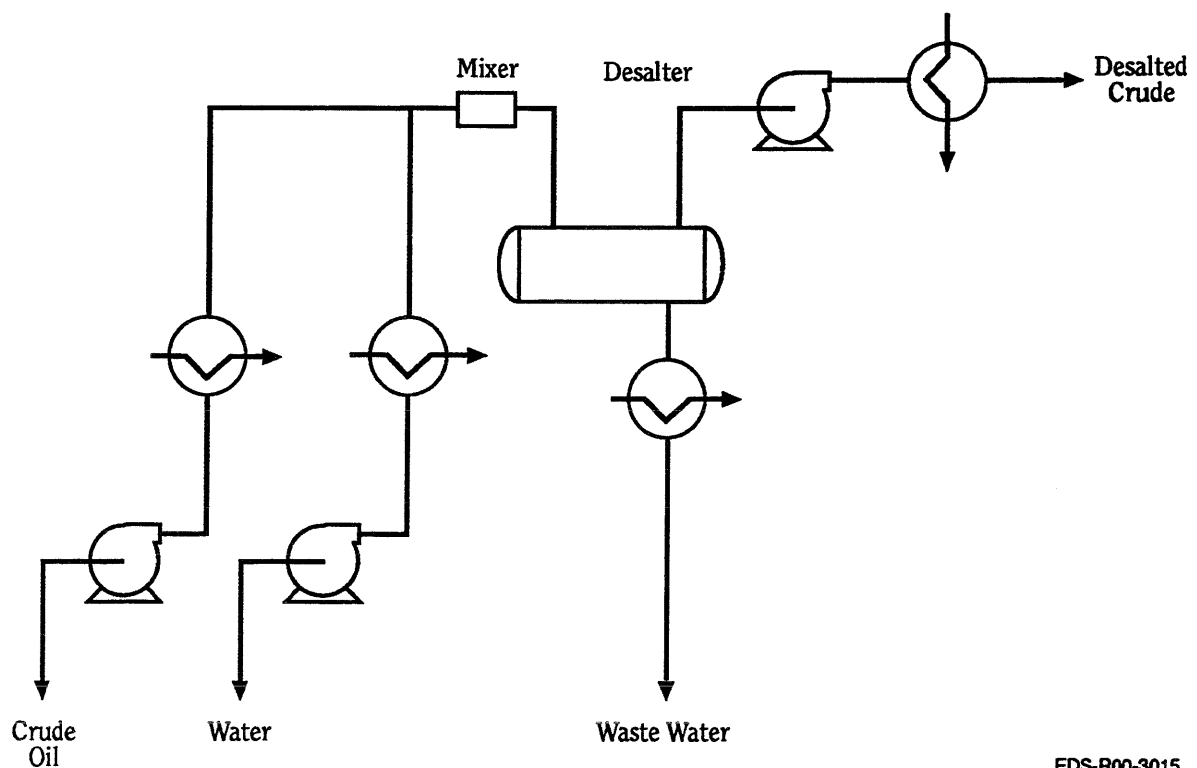
Design Principle

Provide contacting of crude oil with water at a temperature of 230–250 °F and at a pressure sufficient to keep water in the liquid phase

Equipment Required

- Pumps
- Heat exchangers
- Mixer
- Desalter vessel

Desalter Flow Diagram



EDS-R00-3015

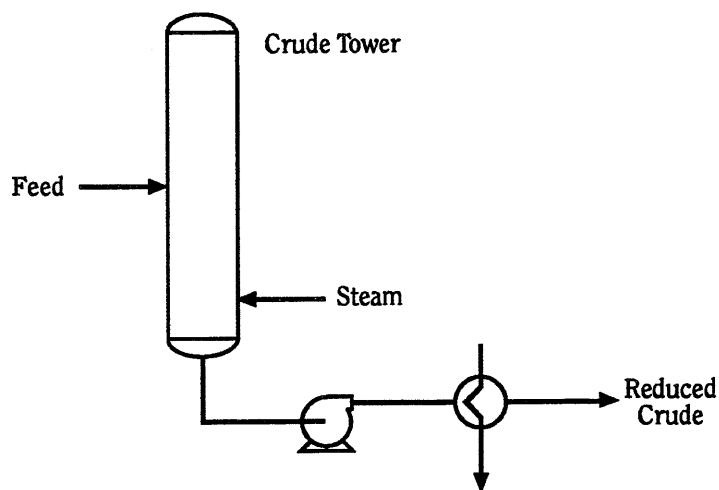
BATTERY LIMIT CONDITIONS

Design Criteria

- Cool below atmospheric boiling point
- Cool below flash point
- Cool below 175–180 °F
- Do not cool over viscous streams
- Provide sufficient pressure to get to destination

pressure drop at hydrocarbon
plugging at the end

Battery Limit Requirements



EDS-R00-3016

HEAT AND MASS BALANCE CALCULATIONS

FRACTIONATION CALCULATIONS

Quantify Energy Requirements

- Overhead Condenser
- Reboiler

Determine Reflux Required

- Pump
- Column Diameter

Determine Number of Trays

DESIGN APPROACHES

Two Approaches

- Rigorous calculations
- Empirical design

- Short cut.

RIGOROUS CALCULATIONS

- Simultaneous solution of:

 - Component balance

 - Enthalpy balance

 - Tray balance

 - Overall balance

- Using:

 - Equation of state

 - Equilibrium relationships

 - Convergence algorithms

FCC = Hysim

ADVANTAGES & DISADVANTAGES

- Theoretical approach
- Thermodynamically consistent

But

- Requires precise knowledge of components
- Accuracy dependent on equation of state
- Requires a computer solution
- Convergence problems

EMPIRICAL CALCULATIONS

– Distillation design based on:

Experience

Correlating parameters

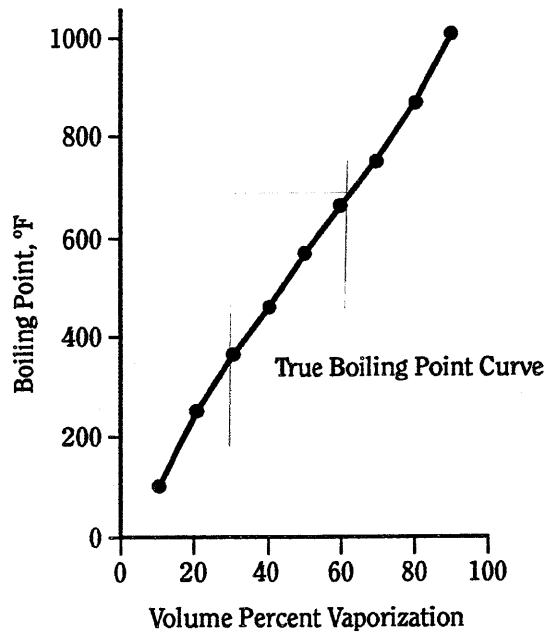
Fundamental nature of problem

Heat and mass balances

DESIGN APPROACH

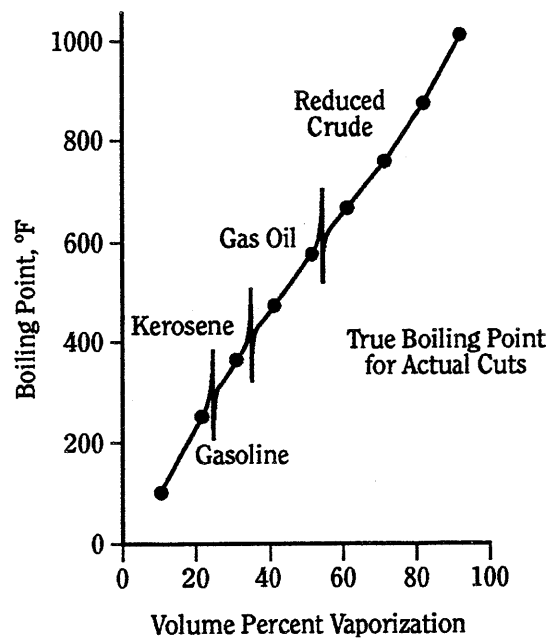
- TBP & ASTM distillations
- Flash calculations
- Product recoveries assumed
- Draw temperatures estimated
- Stripping steam rate fixed
- Number of trays required determined
- Excess heat calculated
- Reflux rate calculated

Feed Characterization



EDS-R00-3017

True Boiling Point of Products

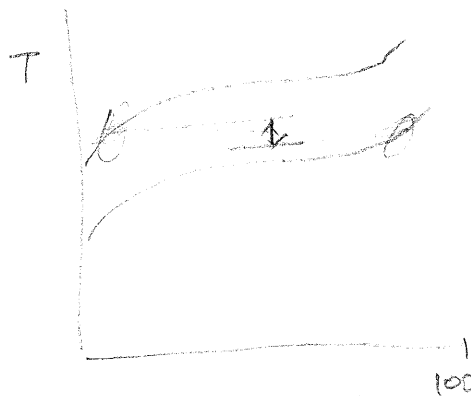


EDS-R00-3018

NUMBER OF TRAYS

Function of:

- Degree of separation difficulty
- Required separation
- Reflux ratio
- Location of draw



HEAT EXCHANGE ANALYSIS

- Determine quantity of heat at each location
- Note temperature available/required
- Provide sufficient approach temperature for exchanger
Pure Component *fouling*
- Perform economic evaluation

But

- Consider operating flexibility
- Mechanical difficulties
- *Other factor : safety*

INSTRUMENTATION

PURPOSE

- To permit smooth operation of process
- To restore process to normal conditions after upset
- To maintain product quality
- To operate process unit safely

CONTROL PROBLEM

- Which variables to control?
- Is the control scheme stable?
- What is the minimum control necessary?
- Type of control : feedforward
 feedback
 advanced control = multi variable control.

MEASURED QUANTITIES

Direct Measurements

- Temperature
- Pressure
- Composition

Indirect Measurements

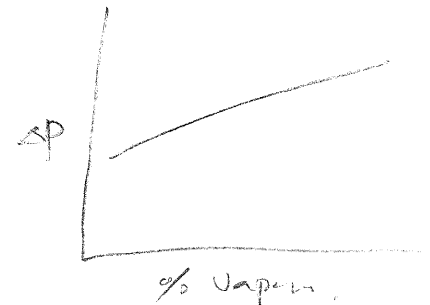
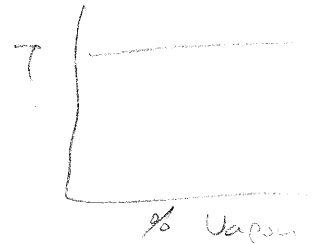
- Flow
- Level
- Composition
- Heat Input

HEAT INPUT CONTROL

To maintain constant heat input:

Process Variables

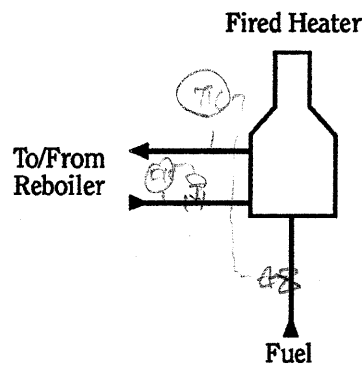
- Process flow
- Fuel flow
- Incoming temperature
- Outlet temperature
- Outlet pressure



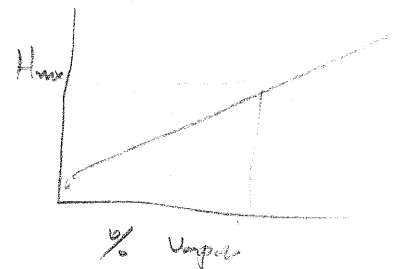
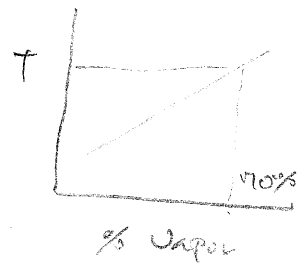
~~Debutanizer Reboiler~~

$$Q = m_1 c_p \Delta T + \dot{m}_2 \lambda$$

$$= UA \Delta T$$



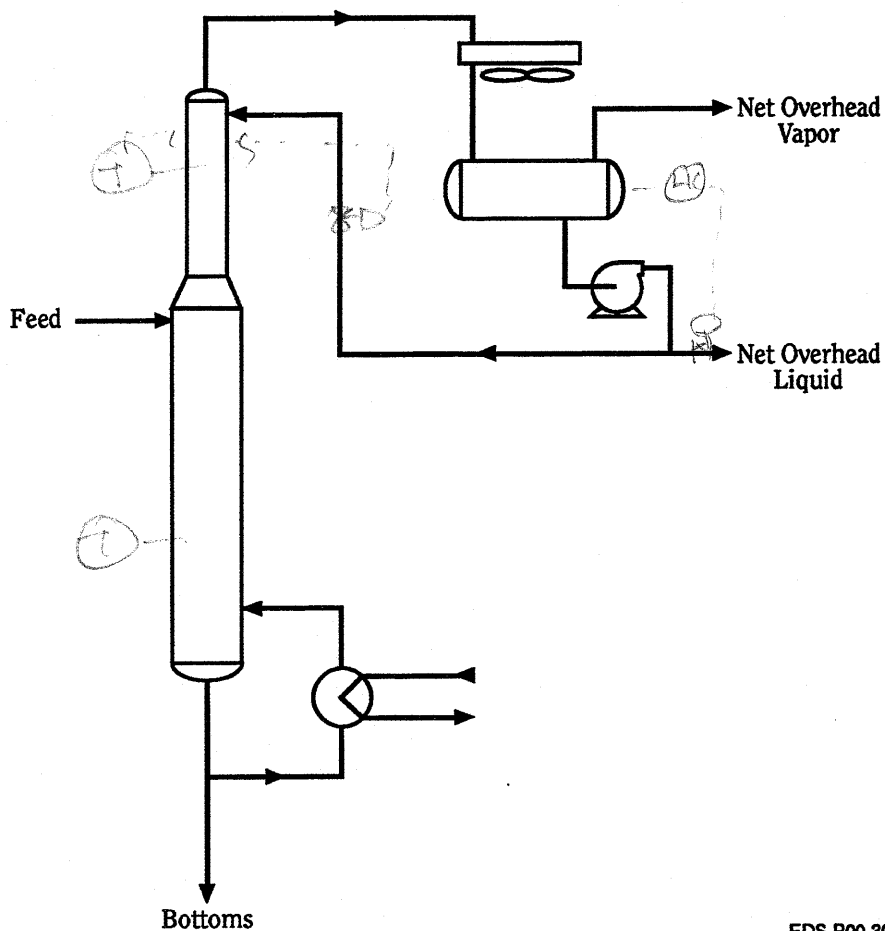
EDS-R00-3019



$$Q = (h_m - h_L) \dot{m}_T$$

↓
FRC

Composition Control

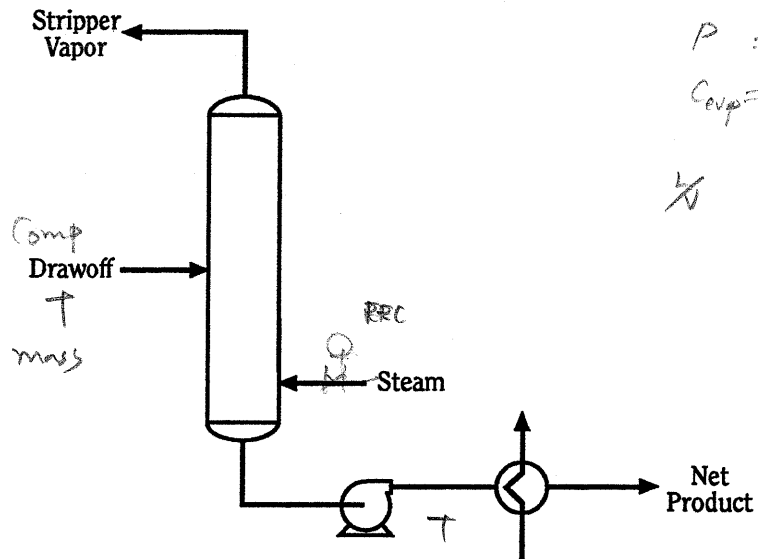


EDS-R00-3020

- 1) Analysis & expansion & maintenance is required.
- 2) Temperature



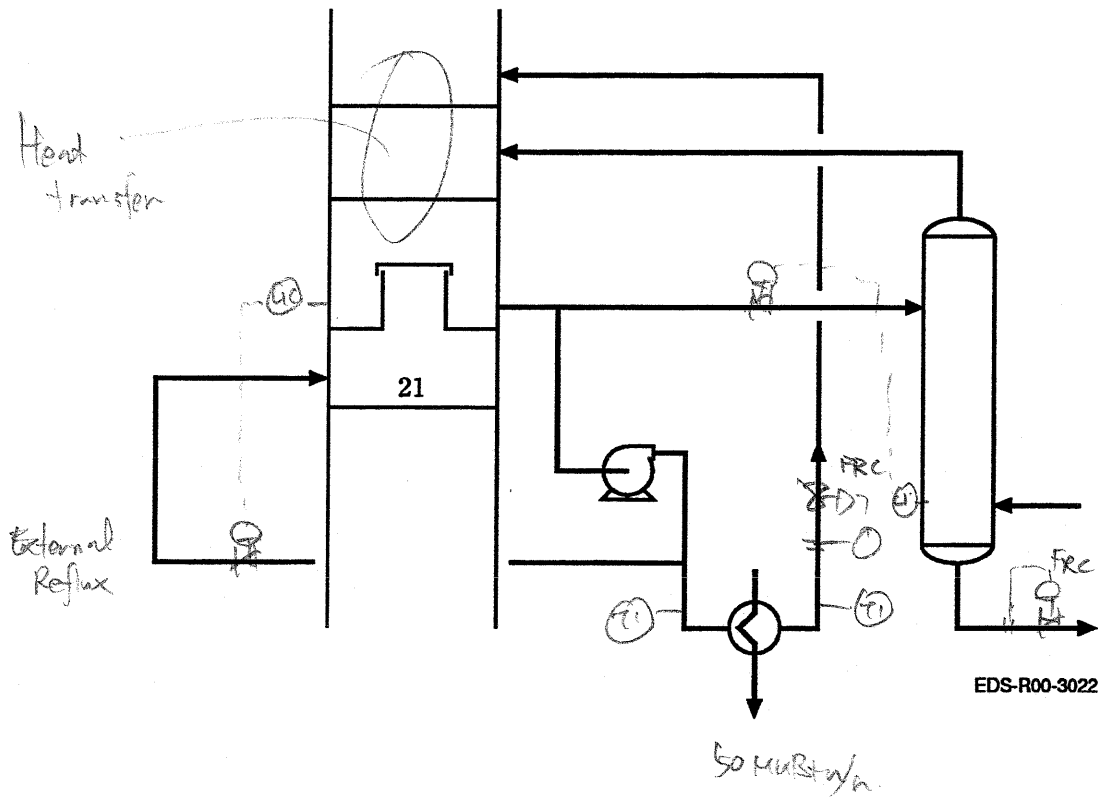
Control of Sidecut Stripper



EDS-R00-3021

T = not important
P = by Crude column
Comp
4

Control of Pumparound Loop



EDS-R00-3022