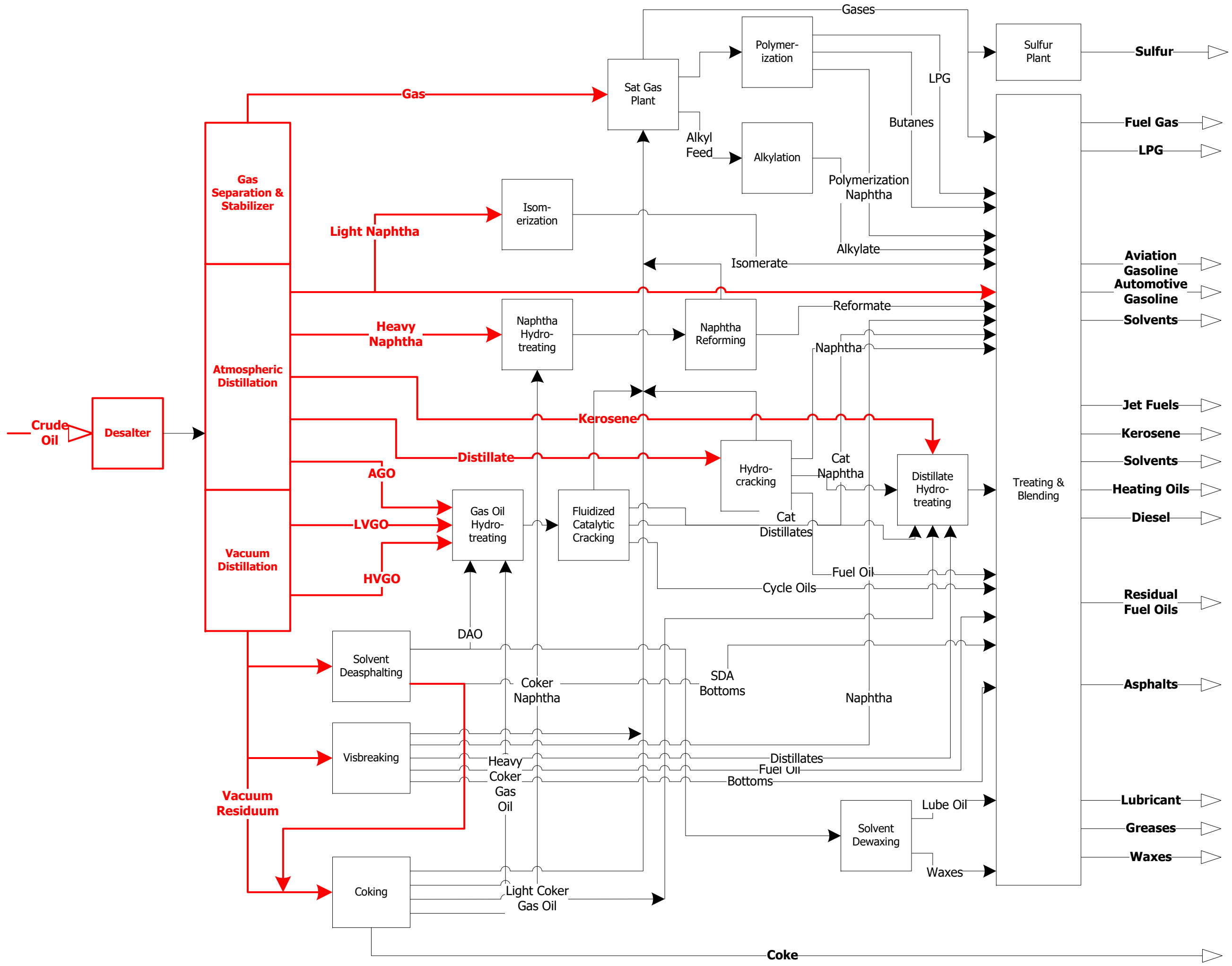
Crude Oil Distillation

Chapter 4



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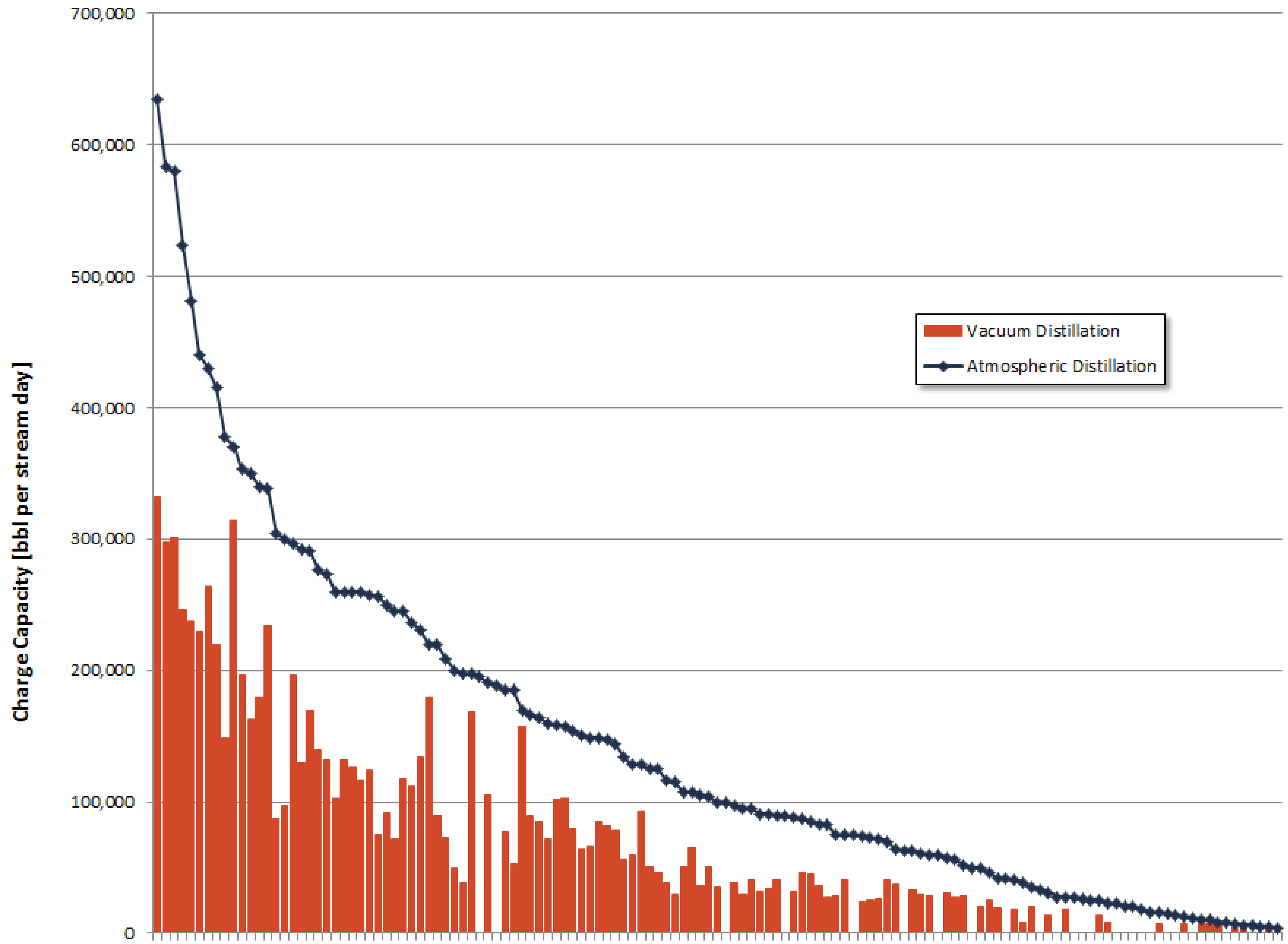
Atmospheric & Vacuum Distillation in U.S.



EIA, Jan. 1, 2017 database, published June 2017
http://www.eia.gov/petroleum/refinerycapacity/

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Topics

Crude Stills

- Historically the oldest refining process
- Only the first step in crude oil processing

Purpose

- To recover light materials
- Fractionate into sharp light fractions

Configuration — May be as many as three columns in series

- Crude Stabilizer/Preflash Column
  - Reduce traffic in the Atmospheric Column
- Atmospheric Column
- Vacuum Column
  - Reduced pressure to keep blow cracking temperatures

Product Yield Curves – Cut Point, Overlap, & Tails

Configuration:

Atmospheric
Vacuum
Preflash

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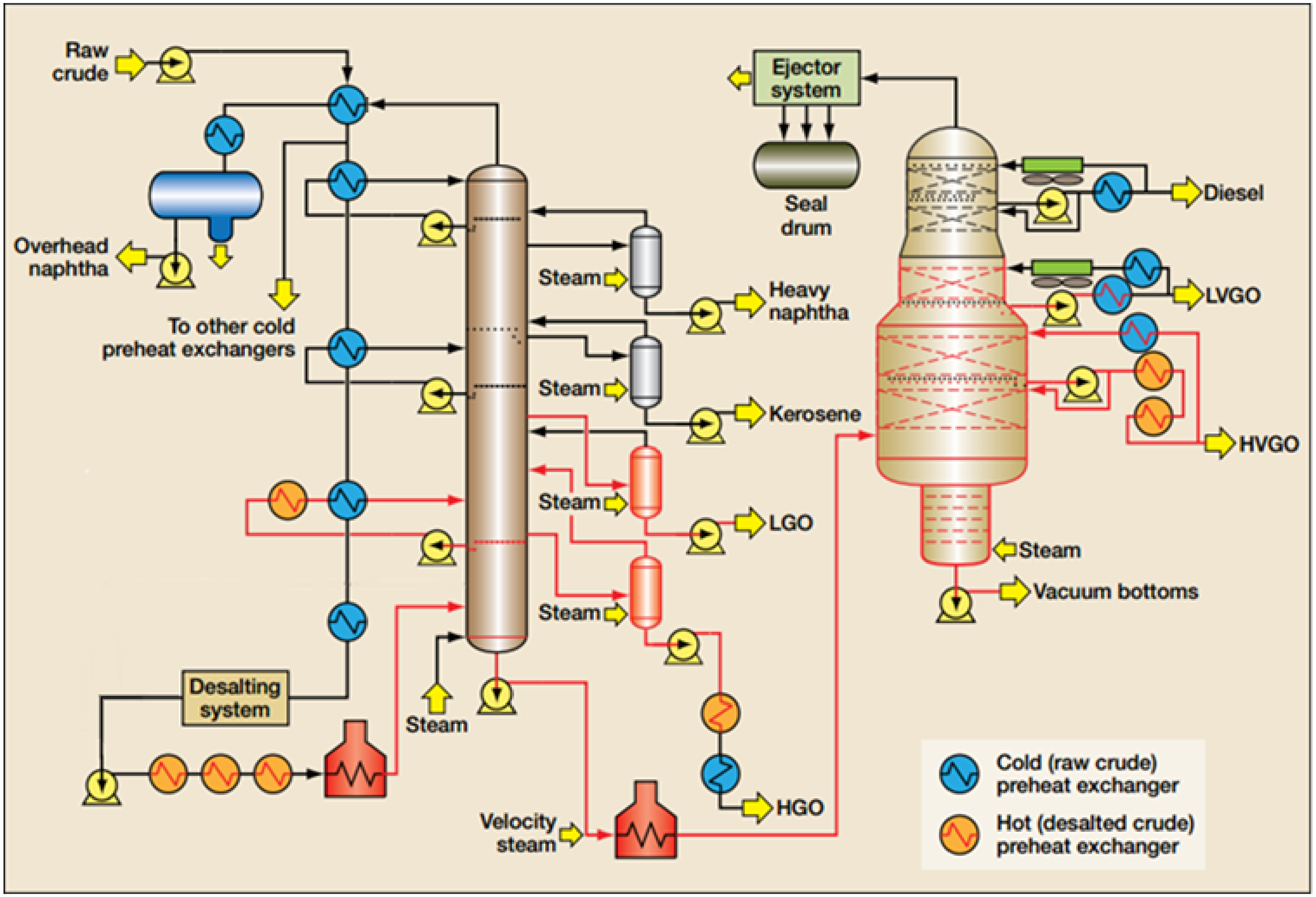
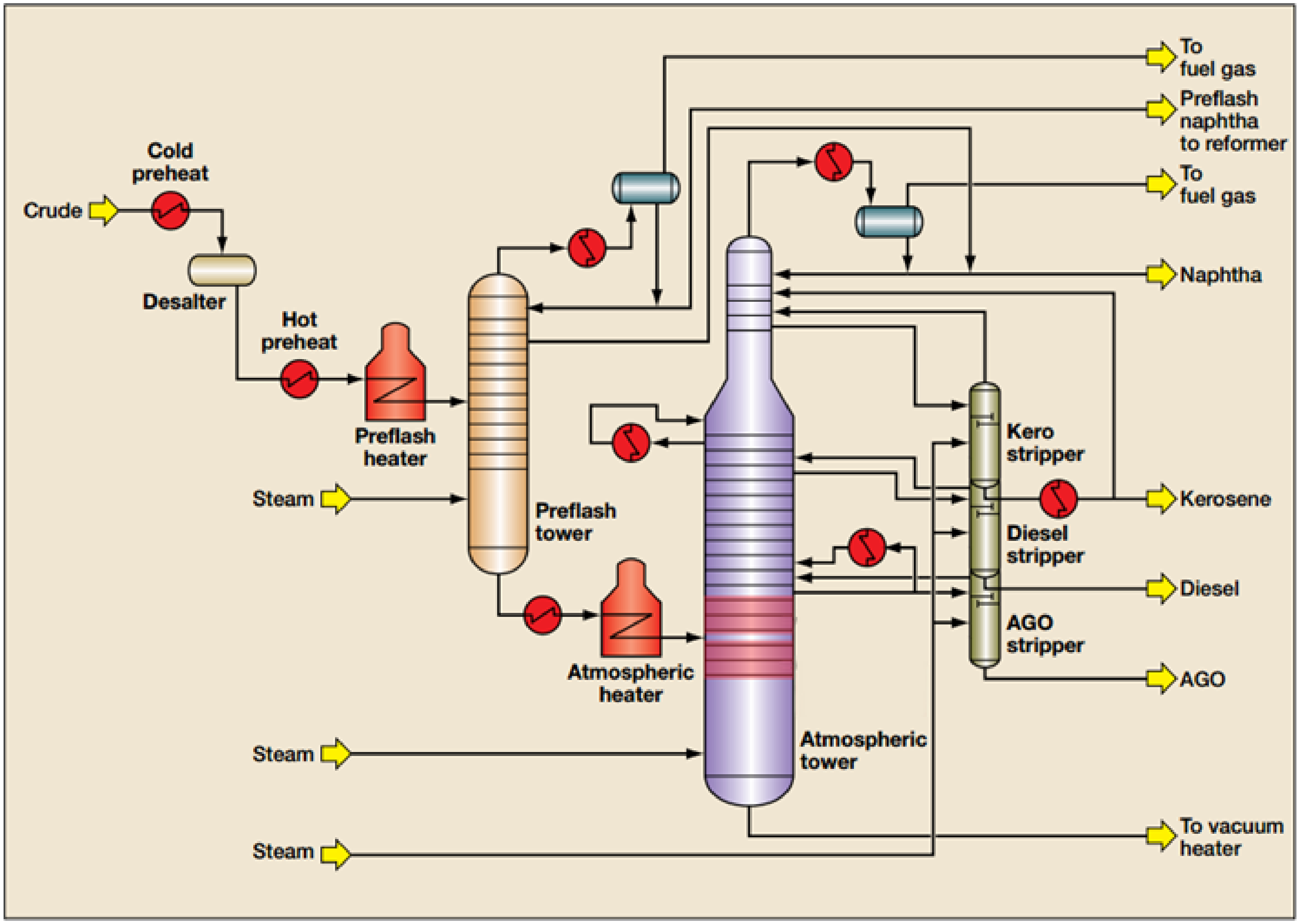
Atmospheric & Vacuum Tower Complex

Atmospheric & Vacuum Tower Complex



Modified drawing from:
"Revamping crude and vacuum units to process bitumen," Sutikno, *PTQ* ,Q2 2015

Atmospheric Column with Preflash



Modification of figure in "Increasing distillate production at least capital cost," Musumeci, Stupin, Olson, & Wendler, *PTQ*, Q2 2015

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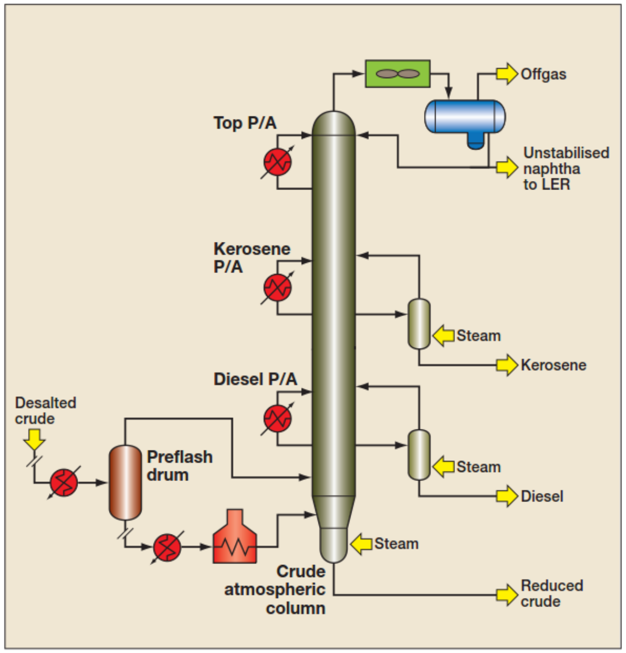
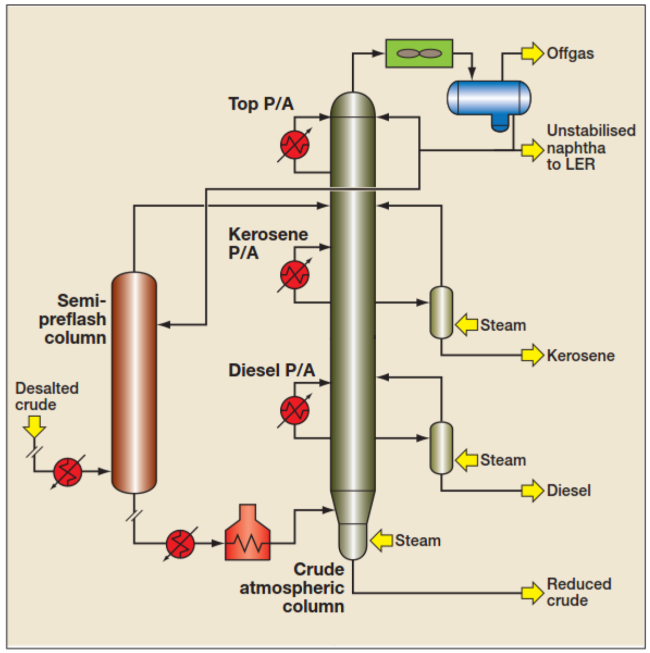
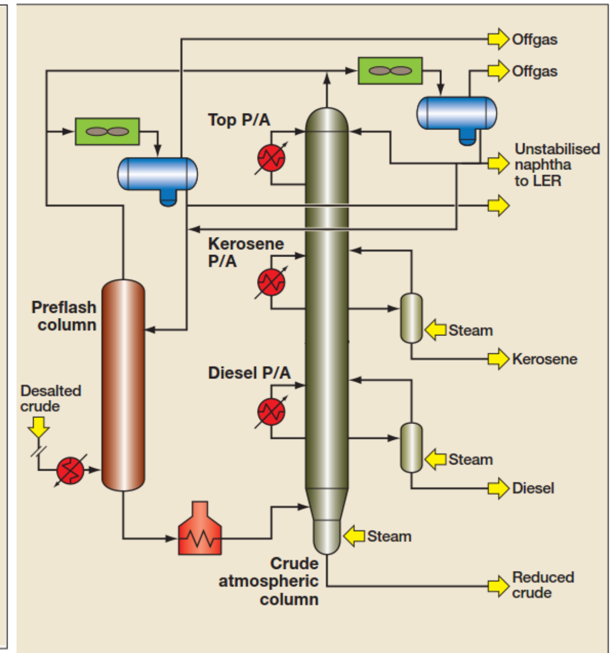
Preflash Options – Tight Oil Example with no AGO







"Optimising preflash for light tight oil processing," Lee, *PTQ*, Q3 2015

Feed Preheat Train & Desalter

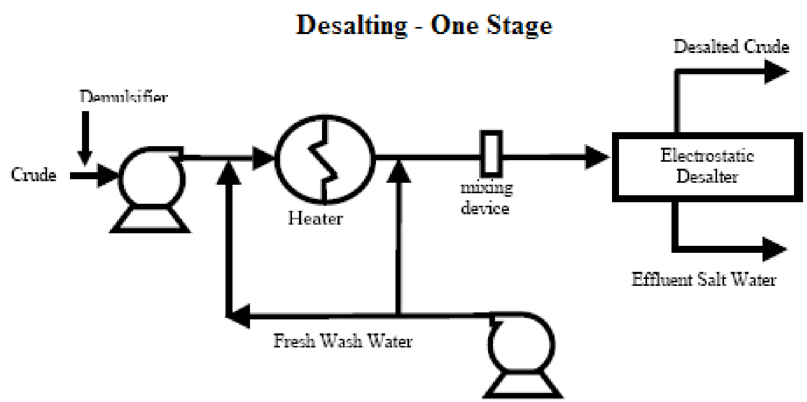
Feed Preheat Train

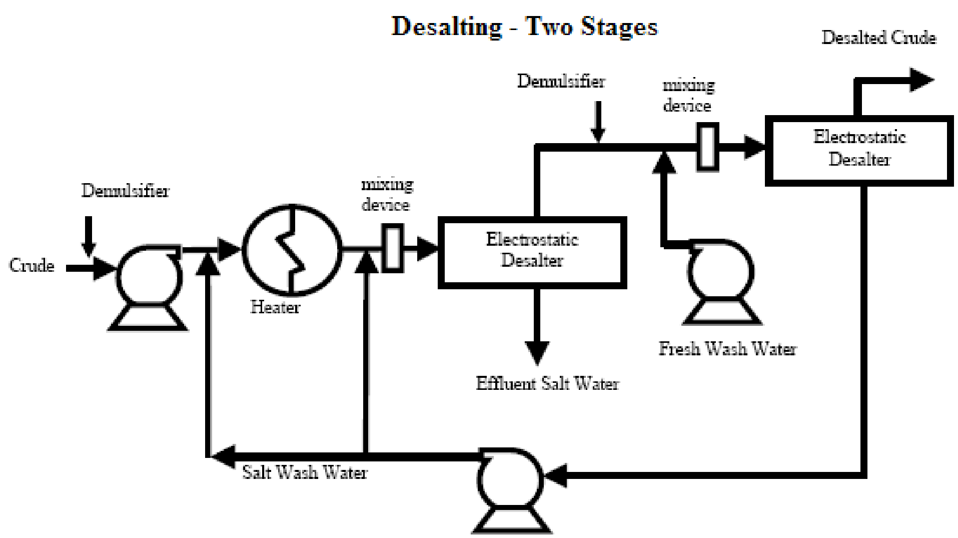
- Initial heat exchange with streams from within the tower
  - Heat recovery important to distillation economics!
    - First absorb part of the overhead condensation load
    - Exchange with one or more of the liquid sides streams, beginning with the top (coldest) side stream
  - Require flexibility
    - Changes in crude slate
    - Temperature at desalter
    - Limits on two-phase flow through network
- Final heating in a direct fired heater
  - Heat enough to vaporize light portions of the crude but temperature kept low to minimize thermal cracking
    - Inlet typically 550ºF, outlet 600 to 750ºF.
    - Heavier crudes cannot be heated to the higher temperatures

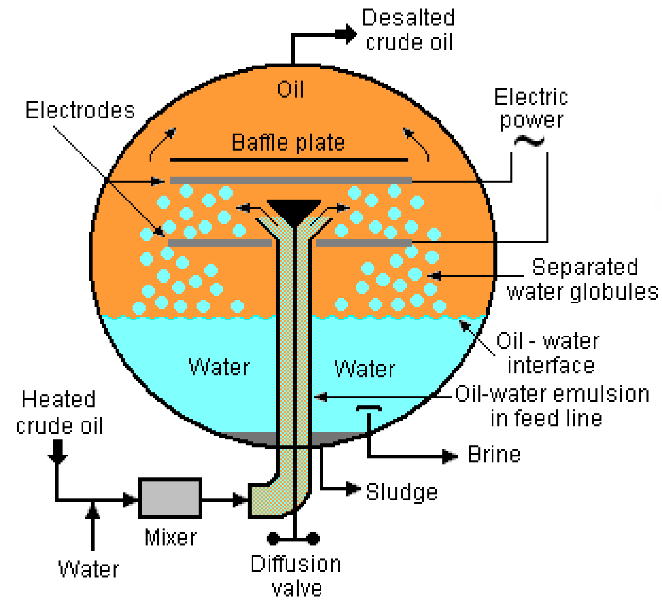
Desalter

- Temperature carefully selected — do not let water vaporize
  - Lighter crudes (> 40ºAPI) @ 250ºF
  - Heavier crudes (< 30ºAPI) @ 300ºF
- All crudes contain salts (NaCl, MgCl, …)
  - Salt present in the emulsified water
  - Treated in the field with heat & chemicals to break oil water emulsions.
  - Salt can cause damage to equipment
    - Scale in heat exchangers
    - HCl formation can lead to corrosion
    - Metals can poison refinery catalysts
- Remove salts & dissolved metals & dirt
  - Oil mixed with fresh wash water & demulsifiers.
- Separation in electrostatic settling drum
- Wash water up to 10% of crude charge
  - ~ 90% of the water can be recovered
- Effluent water treated for benzene

Crude Electrostatic Desalting







Cross-sectional view of Electrostatic crude oil desalter

Drawing by Milton Beychok
http://en.citizendium.org/wiki/File:Desalter_Diagram.png

BFDs from:
Refining Overview – Petroleum Processes & Products,
by Freeman Self, Ed Ekholm, & Keith Bowers, AIChE CD-ROM, 2000

Crude Desalting

Breaking the crude oil/water emulsion important to minimize downstream problems

Performance of additives may be crude specific

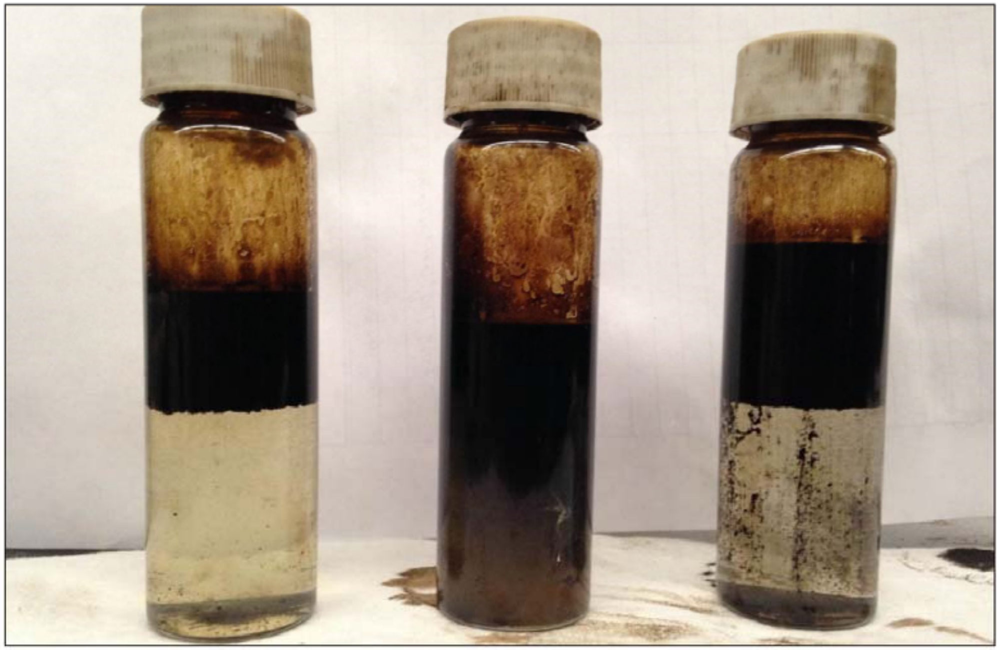
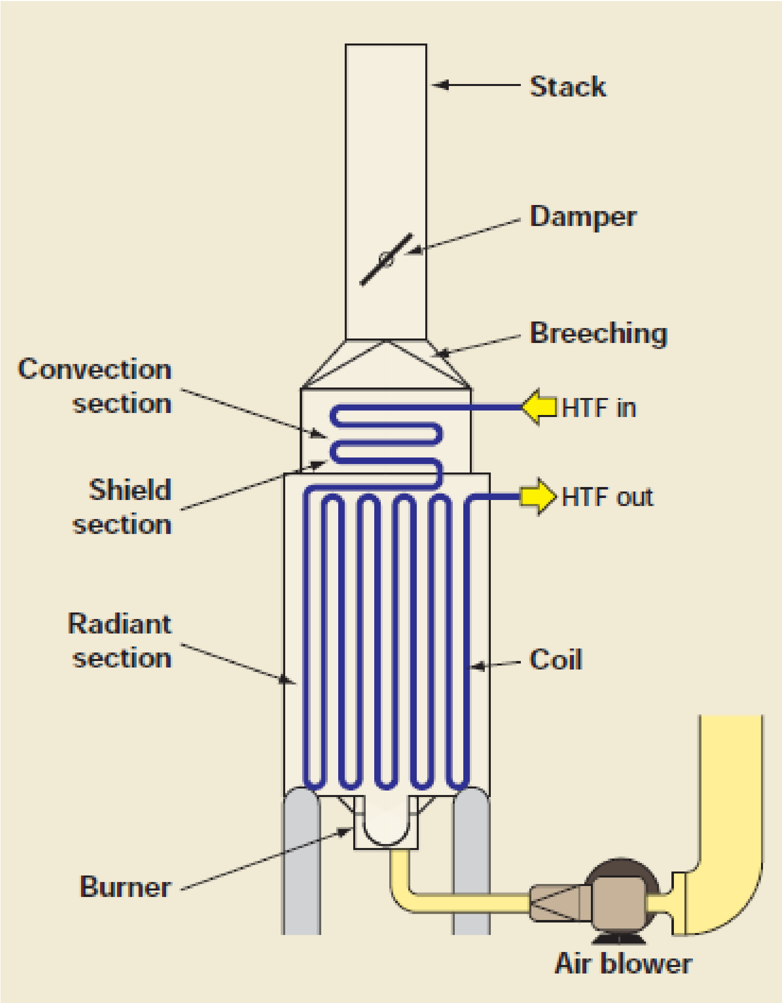
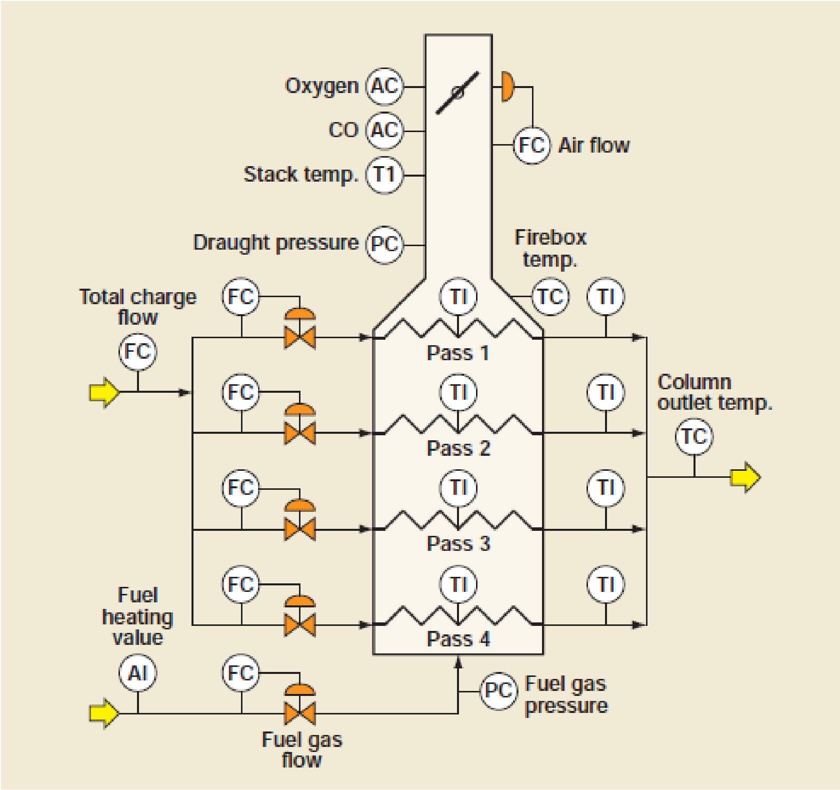


Figure 5 From left to right: an emulsion treated with caustic, no chemistry, and a standard emulsion breaker

Picture from:
"Removing contaminants from crude oil"
McDaniels & Olowu, *PTQ* Q1, 2016

Direct Fired Heater





Ref: "Useful tips for fired heater optimisation"
Bishop & Hamilton, *Petroleum Technology Quarterly*, Q2 2012

Atmospheric Distillation Summary

Condenser …

- Partial condenser if no Stabilizer Column.
- Total condenser if Stabilizer Column to remove light ends.

… but no reboiler.

Feed preheat exchanger train

- All of the heat to drive the column comes from the hot feed.
  - As much as 50% of the incoming crude may be flashed.
  - “Overflash”
    - Extra amount of material vaporized to ensure reflux between flash zone & lowest side draw
    - Typically 2 vol% of feed

Pumparounds

- Move cooling down column.
- Liquid returned above draw tray

Side draws

Side strippers

- “Clean up” side products

Stripping steam

- Reduce hydrocarbon partial pressure
- Condensed & removed as a second liquid phase.
  - Conditions set so it doesn’t condense within the column – can lead to foaming
  - Must be treated as sour water

Atmospheric Distillation Summary

Wash Zone

- Couple trays between flash zone & gas oil draw.
- Reflux to wash resins & other heavy materials that may contaminate the products.

Condenser

- Typically 0.5 to 20 psig.
- Balancing act
  - Low pressures reduce compression on overhead system
  - High pressures decrease vaporization but increase flash zone temperatures & furnace duty; affects yields

Pumparounds

- Reduces overhead condenser load & achieves more uniform tower loadings
- Provides liquid reflux below liquid draws

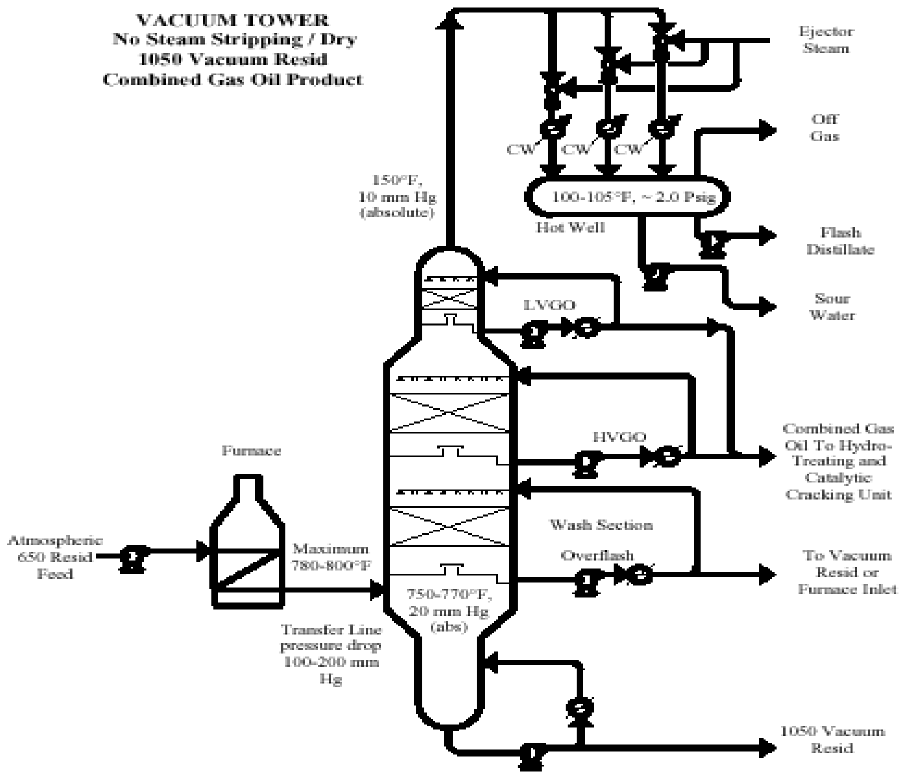
Side Draws & Strippers

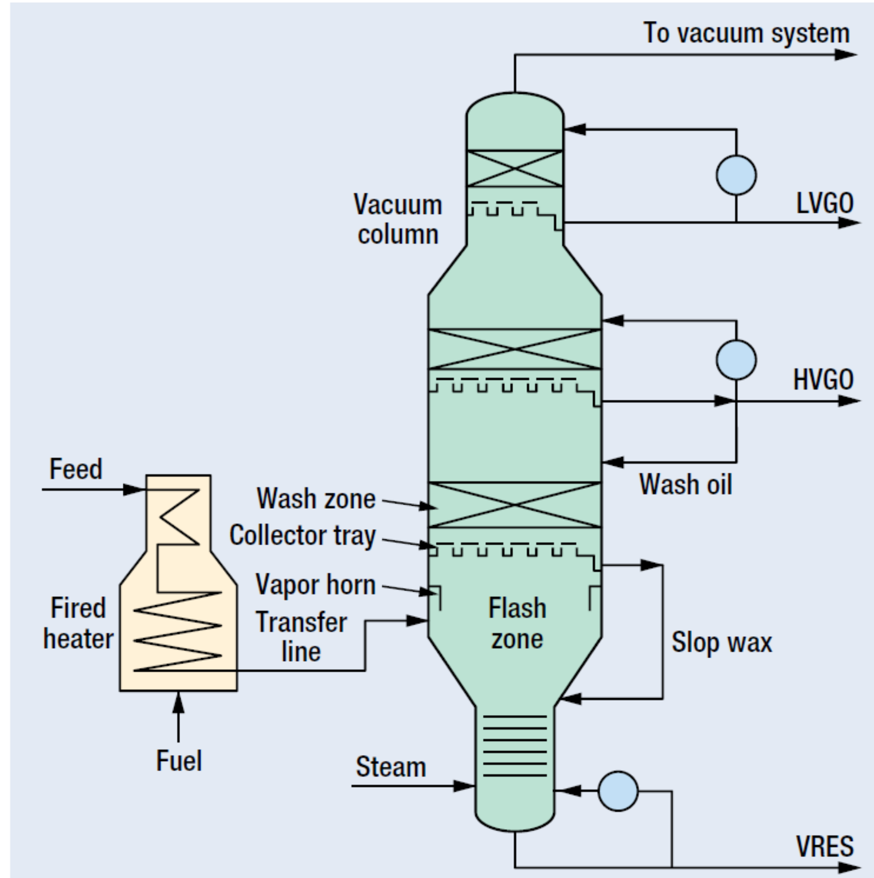
- Side strippers remove light component "tail" & return to main column
- Steam strippers traditional
  - Reboiled strippers reduce associated sour water & may reduce steam usage

Trays & Pressure Profile

- Typically 32 trays in tower
- 0.1 psi per tray for design & target for operation
  - May find as high as 0.2 psi per tray, but probably flooding!
- Condenser & accumulator
  - 3 to 10 psi across condenser
  - Liquid static head in accumulator
- Typically 6 to 16 psi across entire column.

Vacuum Distillation





Refining Overview – Petroleum Processes & Products,
by Freeman Self, Ed Ekholm, & Keith Bowers, AIChE CD-ROM, 2000

"Consider practical conditions for vacuum unit modeling"
R. Yahyaabadi, *Hydrocarbon Processing*, March 2009

Vacuum Distillation – Trays vs. Packing

Packing used in vacuum towers instead of trays

- Lower pressure drops across the tower – vapor "slides by" liquid instead of pushing through the layer on the tray
- Packing also helps to reduce foaming problems

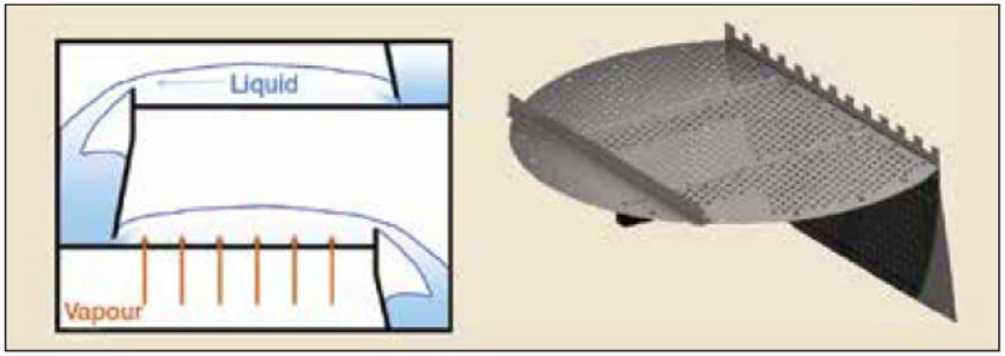


Figure 3 Vapour and liquid flows on trays

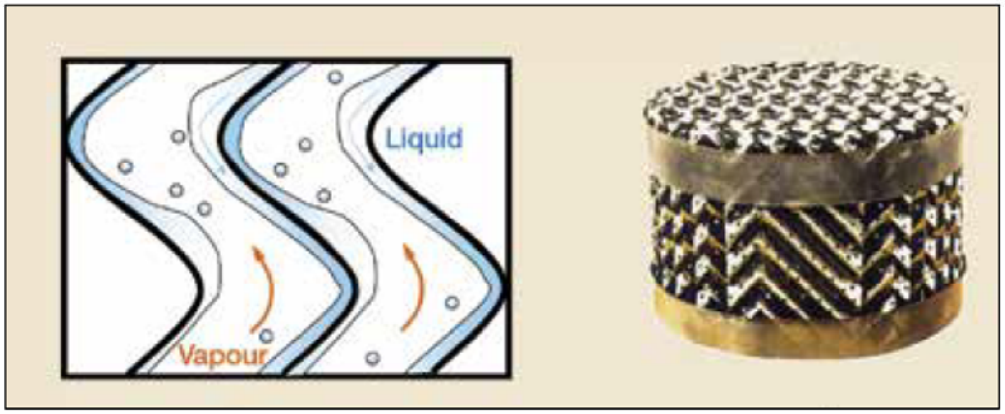


Figure 4 Vapour and liquid flows in structured packing

"Foaming in fractionation columns"
M. Pilling, *PTQ*, Q4 2015

Vacuum Distillation Summary

Column Configuration

- Vacuum conditions to keep operating temperatures low
- Large diameter column
- Very low density gases
- Condenser only for water vapor
- Liquid reflux from pumparounds
- No reboiler
- Stripping steam may be used
  - Needed for deep cuts (1100°F)
- Common problem – coking in fired heater & wash zone
  - Fired heater – high linear velocities to minimize coke formation
  - Wash zone – sufficient wash oil flow to keep the middle of the packed bed wet

Feed

- Atmospheric residuum
- All vapor comes from the heated feed
- Under vacuum (0.4 psi)
- Separate higher boiling materials at lower temperatures
  - Minimize thermal cracking

Products

- May have multiple gas oils
  - Usually recombined downstream to FCCU after hydrotreating
- Vacuum resid
  - Blended — asphalt, heavy fuel oil
  - Further processing — thermal, solvent
    - Depends on products & types of crude

Vacuum Distillation Summary

Dry System

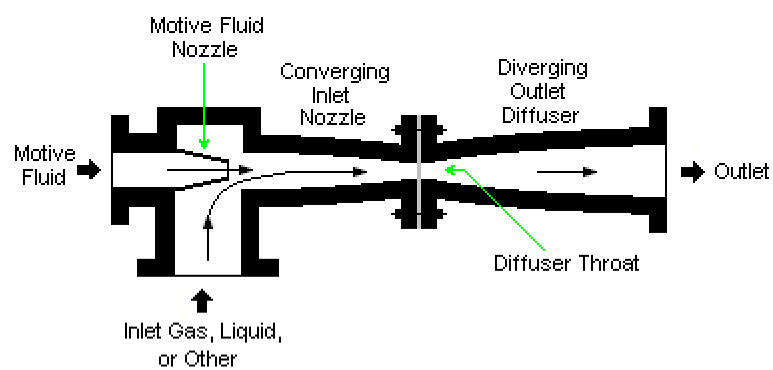
- 1050°F+ cut temperature & no stripping steam
- Smaller tower diameters
- Reduced sour water production
- Pressure profile
  - Flash zone: 20-25 mmHg abs & 750 to 770°F.
  - Top of tower: 10 mmHg abs

Deep Cut System

- 1100°F+ cut temperature & stripping steam
- Steam reduces hydrocarbon partial pressures
- Pressure profile
  - Flash zone: 30 mmHg abs
  - HC partial pressure 10-15 mmHg abs
  - Top of tower: 15 mmHg abs

Steam Ejectors & Vacuum Pumps

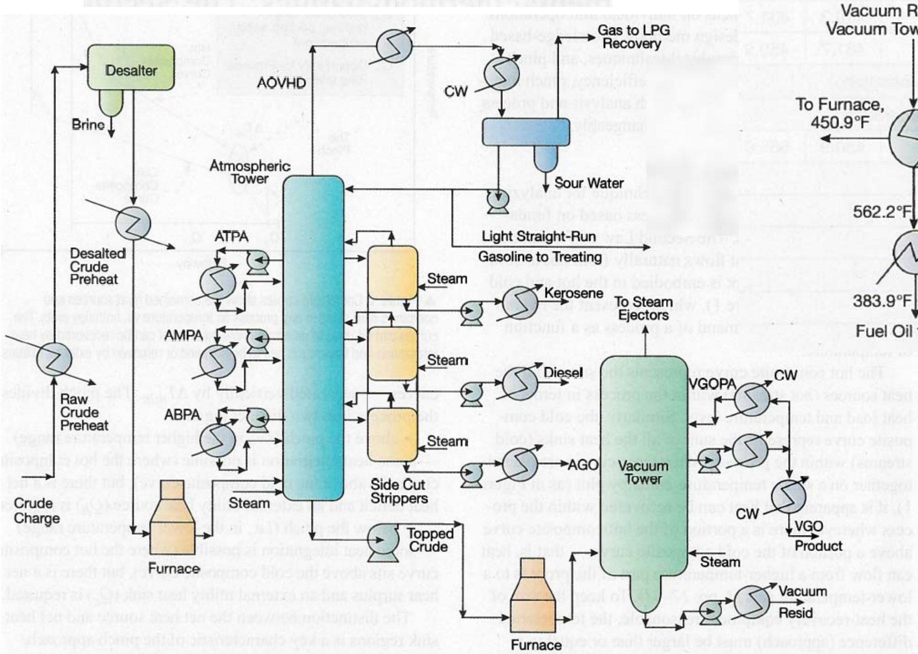
- Vacuum maintained on tower overhead
- Steam systems considered more reliable
- Waste steam is sour & must be treated
- Combinations systems — Last steam stage replaced with a vacuum pump

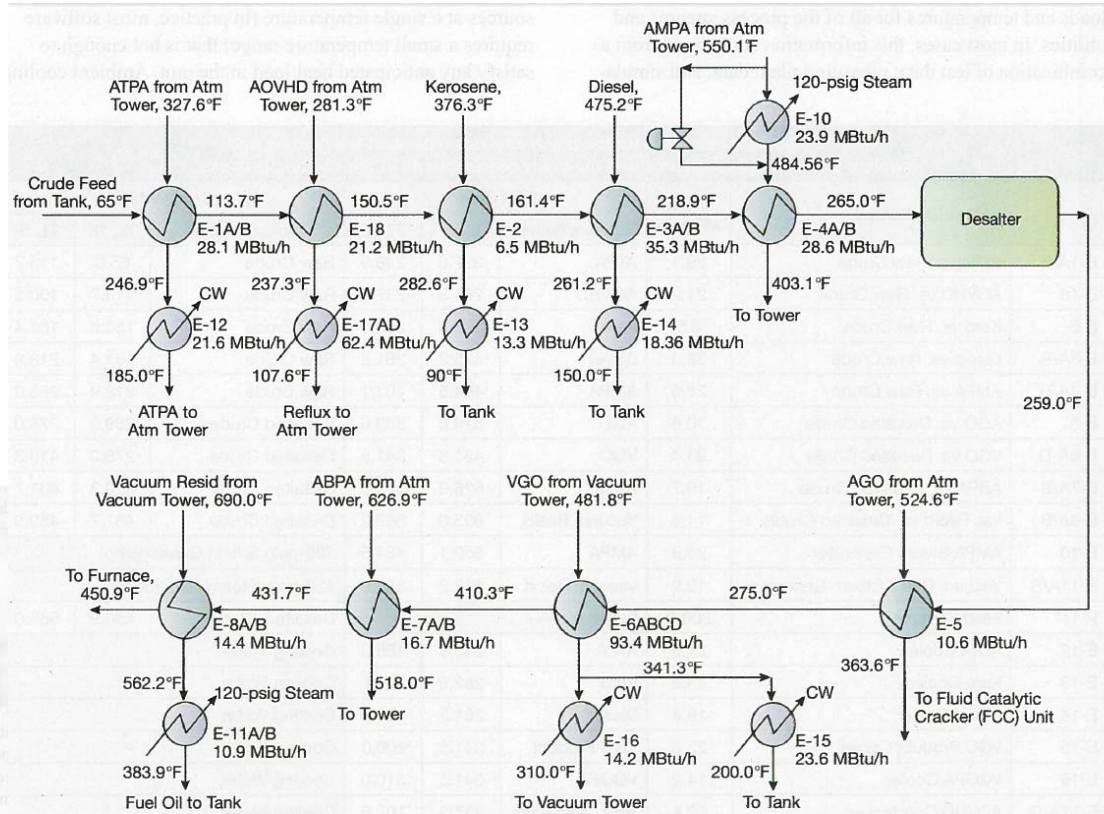


Drawing from http://www.enotes.com/topic/Injector

Example Crude Preheat Trains

Atmospheric Bottom Pumparound (ABPA)
Atmospheric Gas Oil (AGO)
Atmospheric Mid Pumparound (AMPA)
Atmospheric Top Pumparound (ATPA)
Atmospheric Tower Overheads (AOVHD)
Cooling Water (CW)
Kerosene (Kero)
Vacuum Gas Oil (VGO) Product
Vacuum Gas Oil Pumparound (VGOPA)
Vacuum Residuum (Resid)





Ref: "Improve energy efficiency via Heat Integration"
Rossiter, *Chemical Engineering Progress*, December 2010

"Composite Curve" for Preheat Train

Compare amount of heat available & at what temperatures

Goal is to shift the hot & cold composite curves as close as possible

- "Pinch" technology
- This will reduce the amount of "excess" heat to be "thrown away" to the environment
- This will also reduce the amount of "fresh" heat added to the system

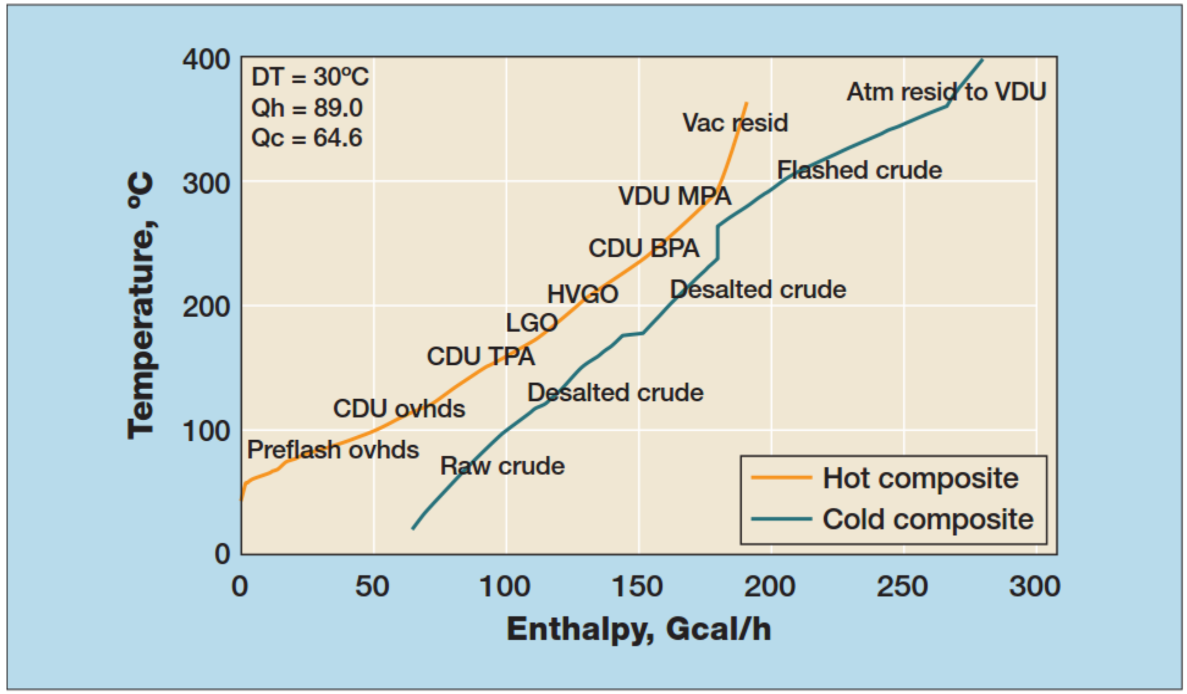


Figure 1 Composite curves

Ref: "Energy savings in preheat trains with preflash" Bealing, Gomez-Prado, & Sheldon, *PTQ*, Q2 2016

Example – Existing Preheat Train

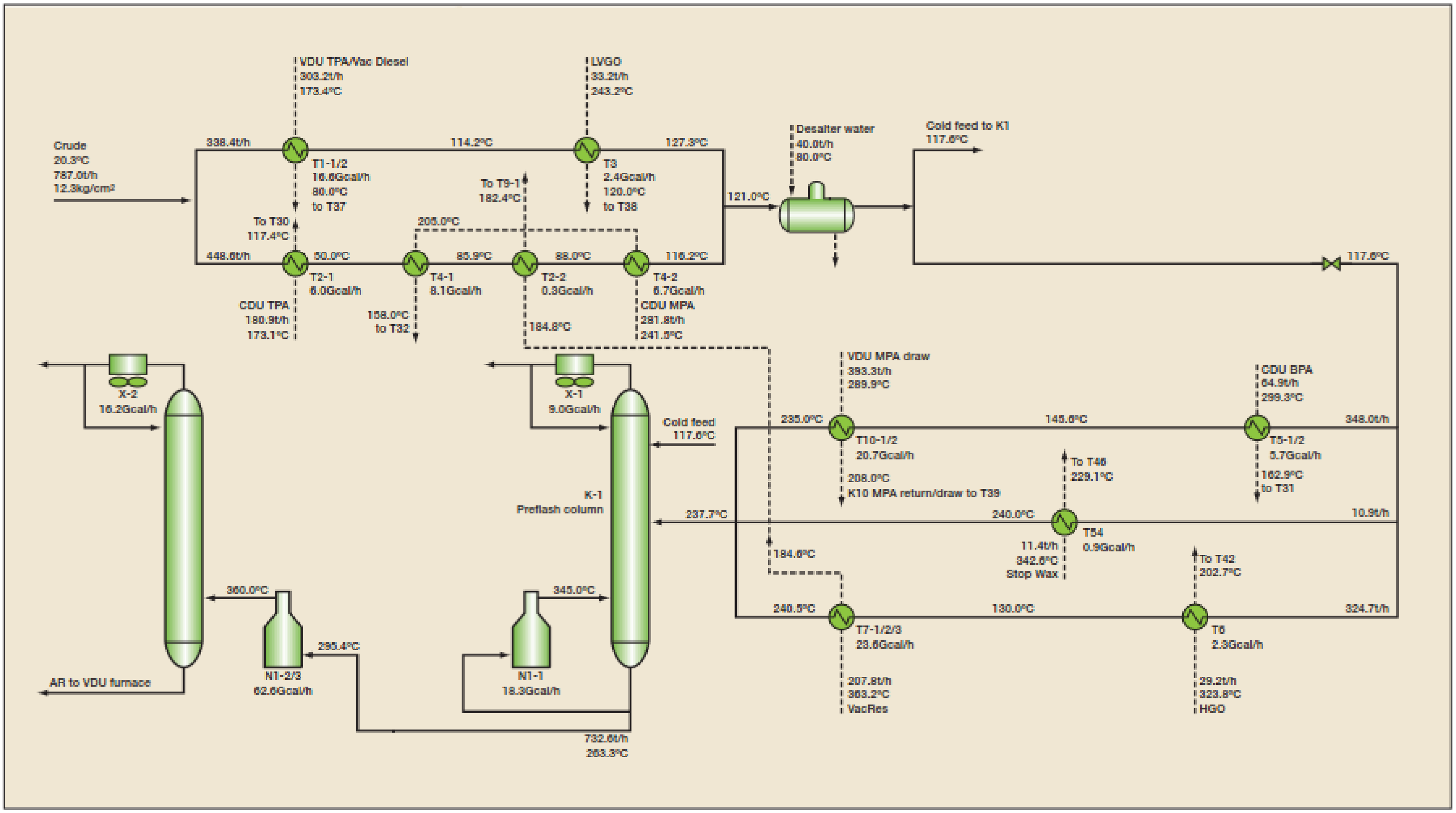


Figure 2 Preheat train configuration

Ref: "Energy savings in preheat trains with preflash"
Bealing, Gomez-Prado, & Sheldon, *PTQ*, Q2 2016

Example – Improved Preheat Train

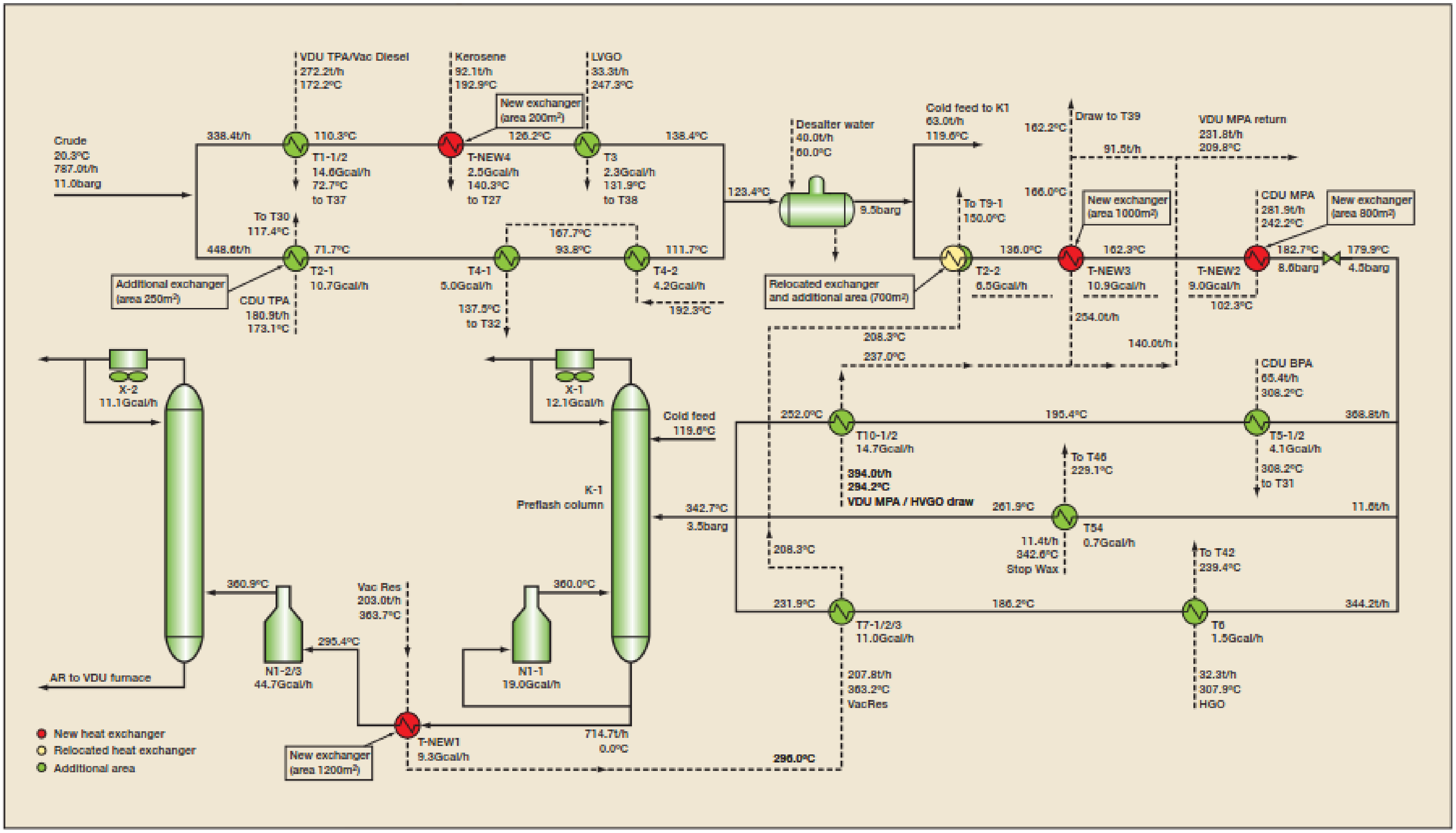


Figure 4 The most cost effective solution

Ref: "Energy savings in preheat trains with preflash"
Bealing, Gomez-Prado, & Sheldon, *PTQ*, Q2 2016

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Product Yield Curves

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Typical “Cut Point” Definitions

Cut	TBP IBP (°F)	TBP EP (°F)
Light Naphtha (LSR Gasoline)	80 to 90	*180 to 220*
Heavy Naphtha	*180 to 220*	330 to 380
Middle Distillate (Kerosene)	330 to 380	420 to 520
AGO (Atm Gas Oil)	420 to 520	650
LVGO (Light Vac Gas Oil)	650	800
HVGO (Heavy Vac Gas Oil)	800	950 to 1100
Vacuum Resid	950 to 1100	

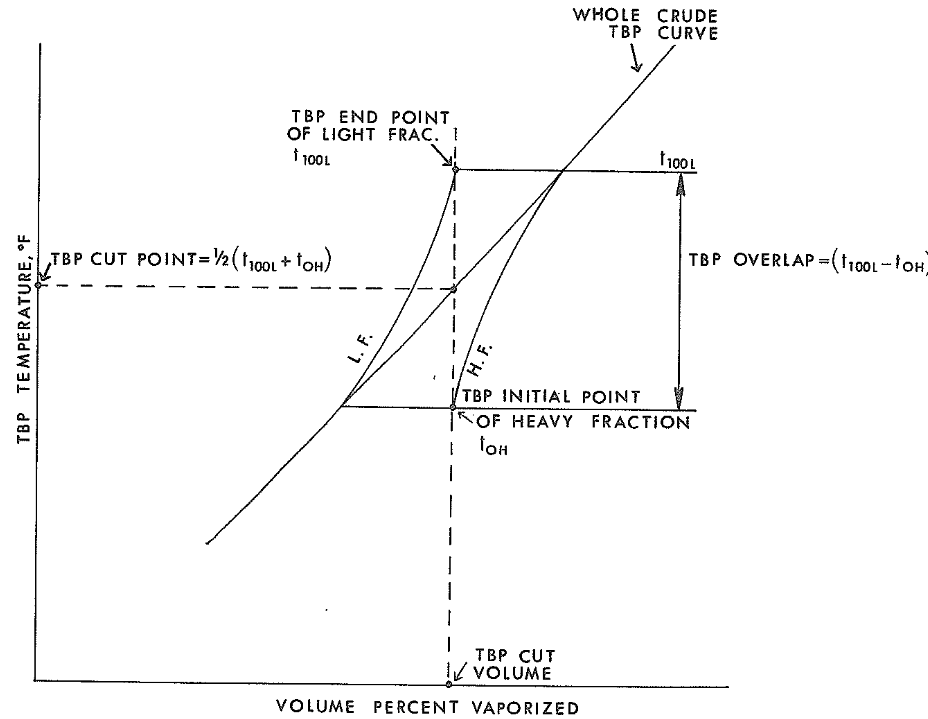
Product Yield Curves – Cut Point, Overlap, & "Tails"

Industrial distillation columns do not provide perfectly sharp separations

- Initial calculations using crude oil assays assume that all materials at a certain boiling point goes to one product or another
- Imperfect separations result in light-ends & heavy-ends "tails" in adjacent products
- Presence of tails complicate the definition of "cut point"

Analysis

- Scale distillation curves to represent the volume removed
- "Cut point" temperature represents the feed's TBP corresponding the cumulative volume removed
- "Tail" represents the light fraction's amount above the cut point & the heavy fraction's amount below the cut point



Ref: R.N. Watkins, *Petroleum Refinery Distillation*, 2nd ed., 1979

Example – Atmospheric Tower Products

	Raw Crude	Naphtha	Kerosene	Diesel	AGO	Residue
Yield [vol%]	100%	23.00%	9.30%	19.24%	4.50%	43.97%
TBP vol% & °F						
1.0%	33	-32	303	372	514	499
5.0%	96	35	343	442	584	635
10.0%	176	58	357	467	620	713
15.0%	248	83	366	482	642	766
20.0%	312	90	375	493	658	807
30.0%	435	134	390	513	682	874
40.0%	525	167	403	532	699	938
50.0%	621	202	416	551	715	991
60.0%	741	233	429	572	729	1,032
70.0%	886	263	442	595	744	1,074
80.0%	1,011	293	456	622	761	1,128
90.0%	1,111	324	473	656	783	1,213
95.0%	1,197	345	485	680	803	1,288
99.0%	1,361	372	506	718	841	1,428

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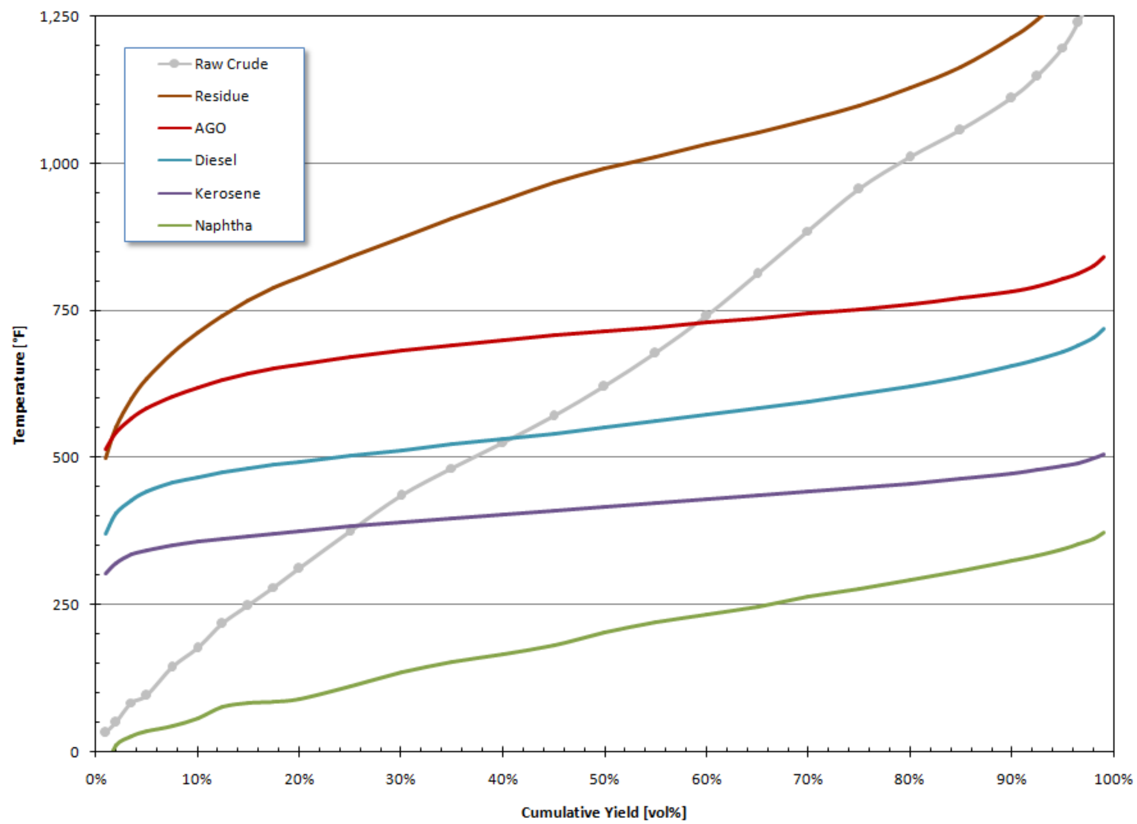

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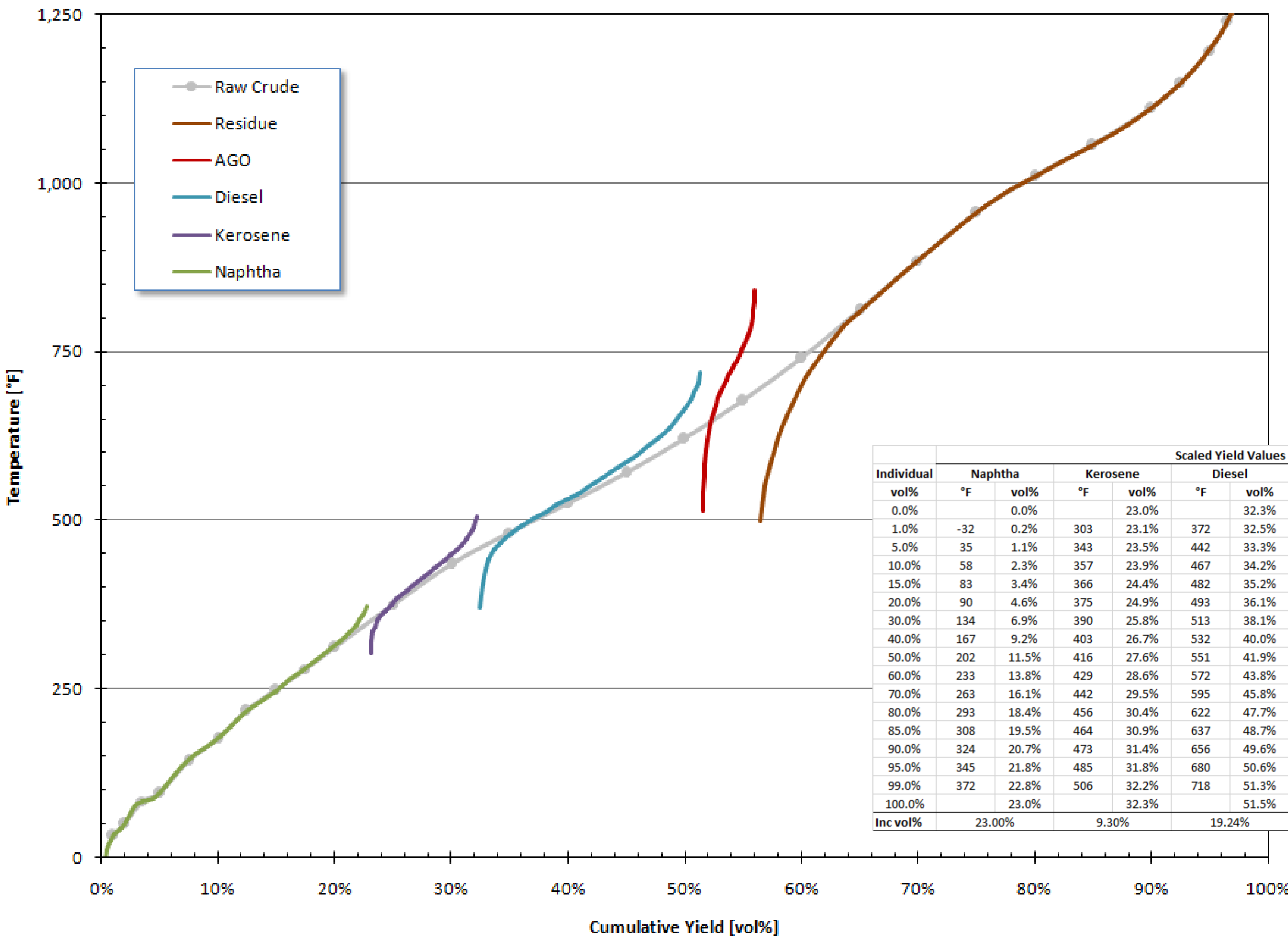
Example – Scale to Fraction of Crude Charge

	Scaled Yield Values									
Individual	Naphtha		Kerosene		Diesel		AGO		Residue	
vol%	°F	vol%	°F	vol%	°F	vol%	°F	vol%	°F	vol%
0.0%		0.0%		23.0%		32.3%		51.5%		56.0%
1.0%	-32	0.2%	303	23.1%	372	32.5%	514	51.6%	499	56.5%
5.0%	35	1.1%	343	23.5%	442	33.3%	584	51.8%	635	58.2%
10.0%	58	2.3%	357	23.9%	467	34.2%	620	52.0%	713	60.4%
15.0%	83	3.4%	366	24.4%	482	35.2%	642	52.2%	766	62.6%
20.0%	90	4.6%	375	24.9%	493	36.1%	658	52.4%	807	64.8%
30.0%	134	6.9%	390	25.8%	513	38.1%	682	52.9%	874	69.2%
40.0%	167	9.2%	403	26.7%	532	40.0%	699	53.3%	938	73.6%
50.0%	202	11.5%	416	27.6%	551	41.9%	715	53.8%	991	78.0%
60.0%	233	13.8%	429	28.6%	572	43.8%	729	54.2%	1,032	82.4%
70.0%	263	16.1%	442	29.5%	595	45.8%	744	54.7%	1,074	86.8%
80.0%	293	18.4%	456	30.4%	622	47.7%	761	55.1%	1,128	91.2%
85.0%	308	19.5%	464	30.9%	637	48.7%	770	55.4%	1,164	93.4%
90.0%	324	20.7%	473	31.4%	656	49.6%	783	55.6%	1,213	95.6%
95.0%	345	21.8%	485	31.8%	680	50.6%	803	55.8%	1,288	97.8%
99.0%	372	22.8%	506	32.2%	718	51.3%	841	56.0%	1,428	99.6%
100.0%		23.0%		32.3%		51.5%		56.0%		100%
Inc vol%	23.00%		9.30%		19.24%		4.50%		43.97%	

Scale to Fraction of Crude Charge



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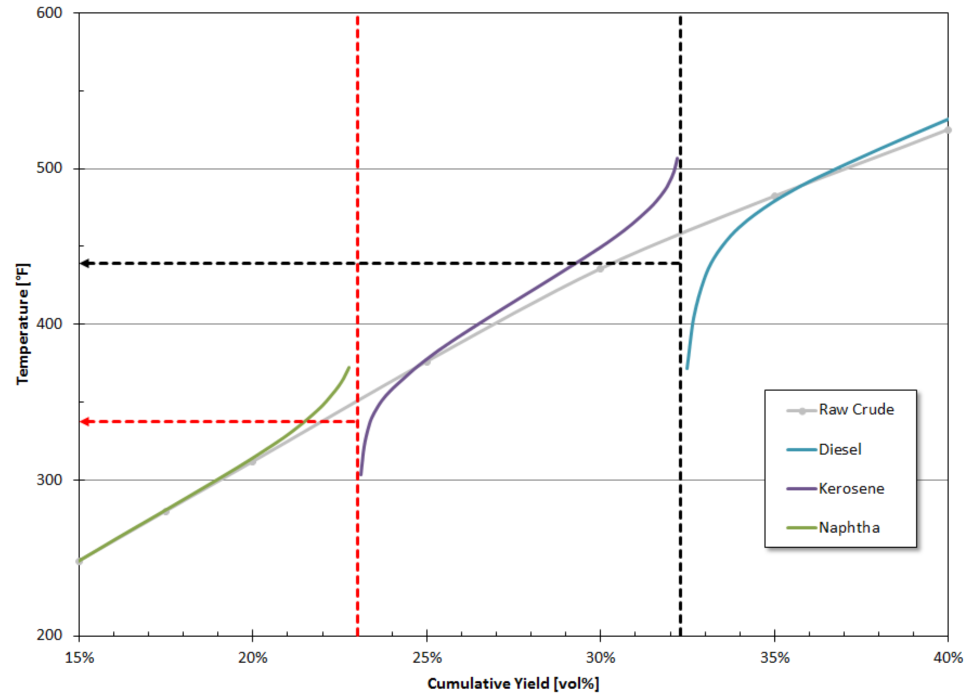
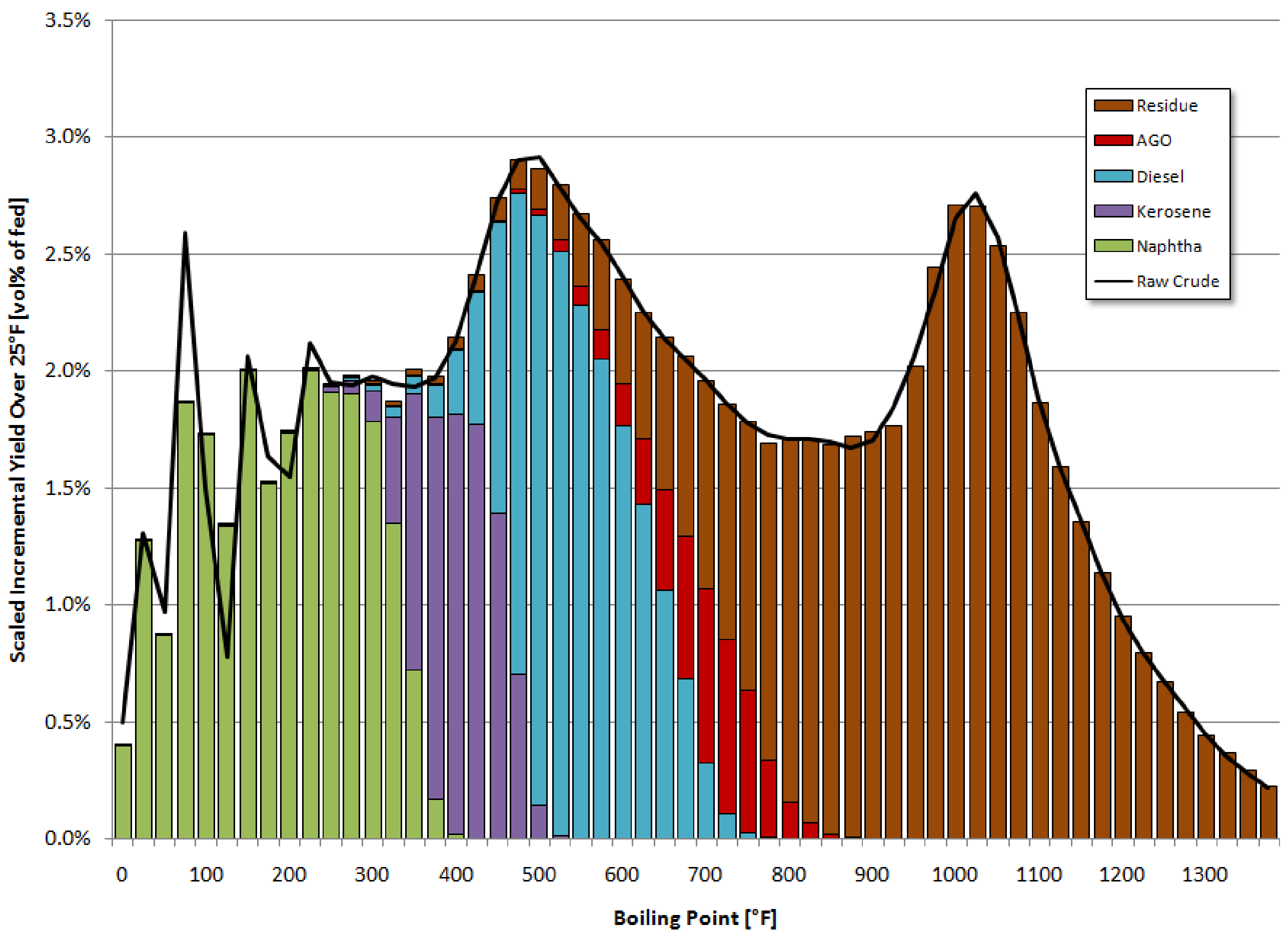
15.0%	83	3.4%	366	24.4%	482	35.2%	642	52.2%	766	62.6%
20.0%	90	4.6%	375	24.9%	493	36.1%	658	52.4%	807	64.8%
30.0%	134	6.9%	390	25.8%	513	38.1%	682	52.9%	874	69.2%
40.0%	167	9.2%	403	26.7%	532	40.0%	699	53.3%	938	73.6%
50.0%	202	11.5%	416	27.6%	551	41.9%	715	53.8%	991	78.0%
60.0%	233	13.8%	429	28.6%	572	43.8%	729	54.2%	1,032	82.4%
70.0%	263	16.1%	442	29.5%	595	45.8%	744	54.7%	1,074	86.8%
80.0%	293	18.4%	456	30.4%	622	47.7%	761	55.1%	1,128	91.2%
85.0%	308	19.5%	464	30.9%	637	48.7%	770	55.4%	1,164	93.4%
90.0%	324	20.7%	473	31.4%	656	49.6%	783	55.6%	1,213	95.6%
95.0%	345	21.8%	485	31.8%	680	50.6%	803	55.8%	1,288	97.8%
99.0%	372	22.8%	506	32.2%	718	51.3%	841	56.0%	1,428	99.6%
100.0%		23.0%		32.3%		51.5%		56.0%		100%
Inc vol%	23.00%		9.30%		19.24%		4.50%		43.97%	

Cut Points & Overlaps for Example

	Raw Crude	Naphtha	Kerosene	Diesel	AGO	Residue
Yield [vol%]	100%	23.00%	9.30%	19.24%	4.50%	43.97%
TBP vol% & °F						
1.0%	33	-32	303	372	514	499
5.0%	96	35	343	442	584	635
10.0%	176	58	357	467	620	713
15.0%	248	83	366	482	642	766
20.0%	312	90	375	493	658	807
30.0%	435	134	390	513	682	874
40.0%	525	167	403	532	699	938
50.0%	621	202	416	551	715	991
60.0%	741	233	429	572	729	1,032
70.0%	886	263	442	595	744	1,074
80.0%	1,011	293	456	622	761	1,128
85.0%	1,056	308	464	637	770	1,164
90.0%	1,111	324	473	656	783	1,213
95.0%	1,197	345	485	680	803	1,288
99.0%	1,361	372	506	718	841	1,428
Cut Point Based on Distillation Curves of the Products						
T01 [°F]			303	372	514	499
T99 [°F]		372	506	718	841	
Mid [°F]		338				
			439			
				616		
					670	
Cut Point Based on Distillation Curve of the Raw Crude						
Cut [vol%] & [°F]		23.00%	351			
			32.30%	457		
				51.54%	638	
					56.03%	690



Boiling Point Ranges for Example



Summary

Summary

Reported refinery capacity tied to charge to crude distillation complex

- Increase capacity with Pre-flash column

Complex column configurations

- No reboilers, heat from feed furnaces
  - Reuse heat via heat exchange between feed & internal column streams
- Side draws, pumparounds, side strippers
  - Pumparounds ensure proper liquid reflux within the column
- Stripping steam
- 3-phase condensers
  - Condensed water will have hydrocarbons & dissolved acid gases
- Pre-heat train recycles heat
  - Products & internal streams heat the feed
  - Feed cools the internal streams & products

Vacuum column to increase the effective cut points

- Vacuum columns large diameter to keep vapor velocities low
- Vacuum gas oils recombined – only separated for operating considerations

Pressure drops are important, especially in the vacuum column

Steam stripping aids in separation without cracking

Metals are undesirable. Can remove some metals via desalters.

Supplemental Slides

Updated: July 5, 2017

COLORADO SCHOOL OF MINES
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Crude Distillation Unit Costs

Atmospheric column includes

- Side cuts with strippers
- All battery limits process facilities
- Heat exchange to cool products to ambient temperature
- Central control system

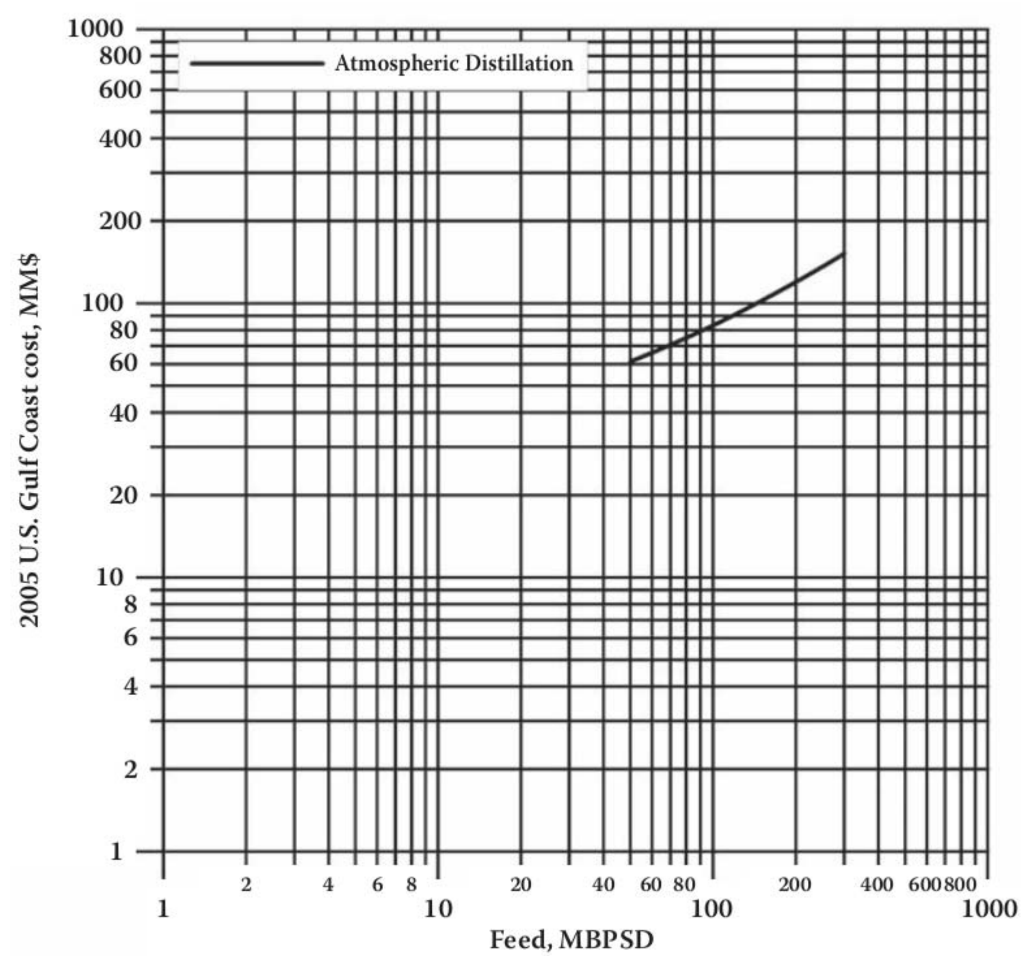


FIGURE 4.9 Atmospheric crude distillation units investment cost: 2005 U.S. Gulf Coast (see Table 4.4).

Petroleum Refining Technology & Economics, 5th ed.
Gary, Handwerk, & Kaiser
CRC Press, 2007

Crude Distillation Unit Costs

Vacuum column includes

- Facilities for single vacuum gas oil
- 3-stage vacuum jet system at 30 – 40 mmHg
- Heat exchange to cool VGO to ambient temperature

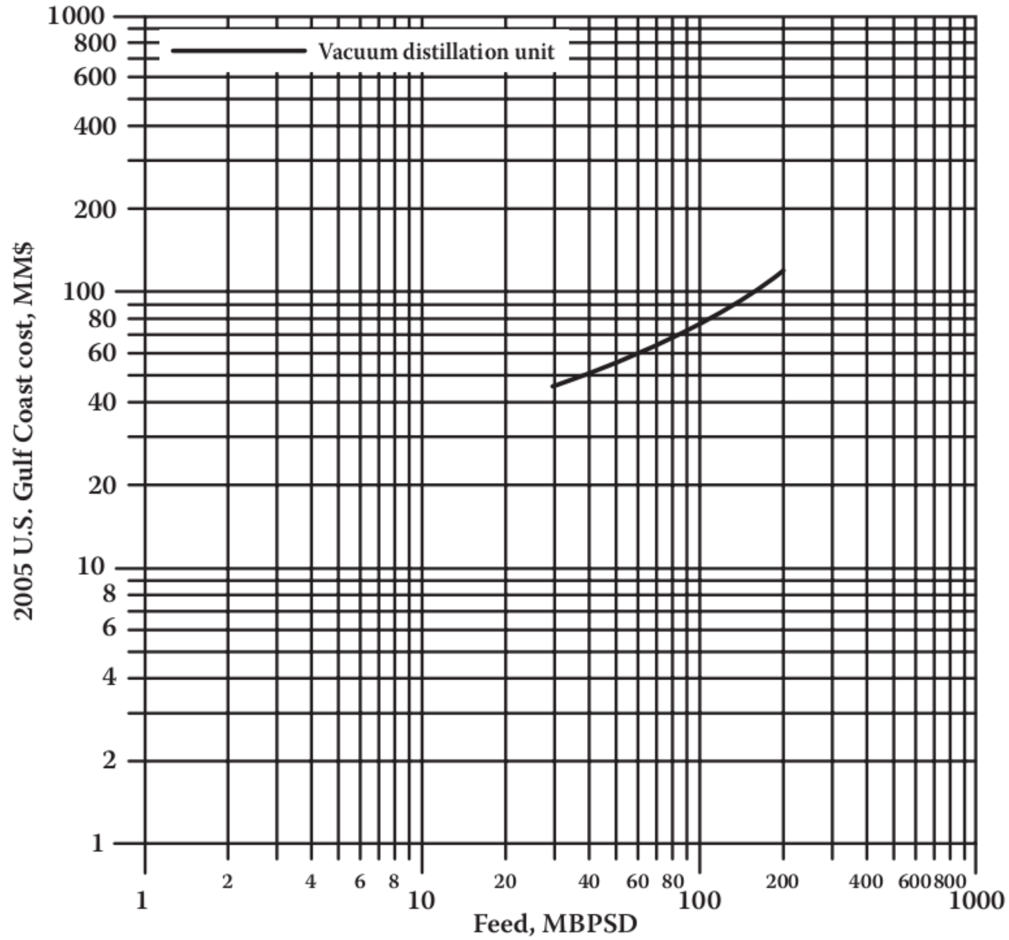


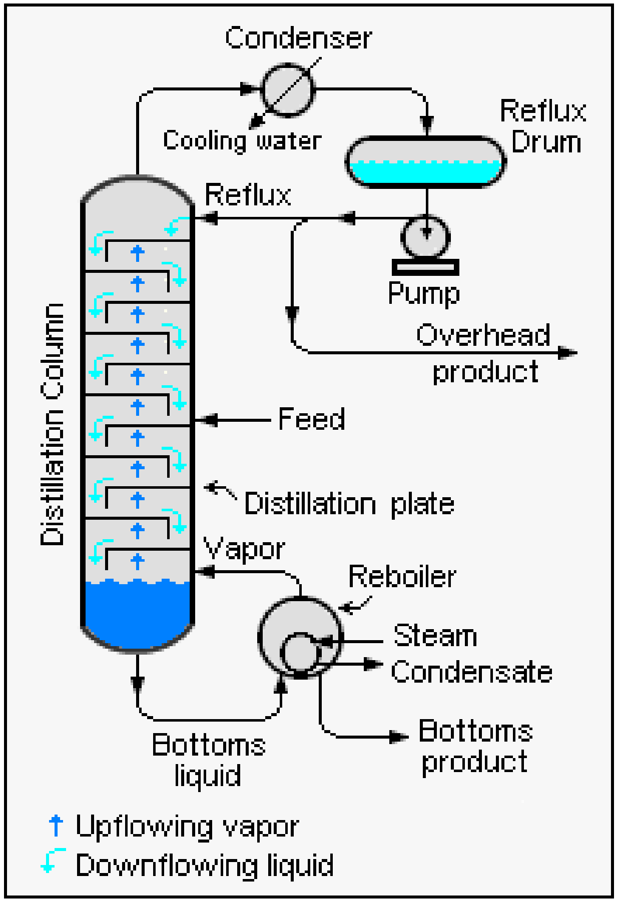
FIGURE 4.11 Vacuum distillation units investment cost: 2005 U.S. Gulf Coast (see Table 4.5).

Petroleum Refining Technology & Economics, 5th ed.
Gary, Handwerk, & Kaiser
CRC Press, 2007

Crude Distillation Technologies

<table>
<tr><th>Provider</th><th>Features</th></tr>
<tr><td>Foster Wheeler</td><td rowspan="3">Complex of atmospheric & vacuum distillation for initial separation of crude oil. May include pre-flash column.</td></tr>
<tr><td>Shell Global Solutions</td></tr>
<tr><td>TECHNIP</td></tr>
<tr><td>Uhde GmbH</td><td>Vacuum distillation</td></tr>
</table>

“Typical” Distillation Column



Top of column – condenser to remove heat

- Provides liquid reflux through top of column
- Partial condenser may have vapor but no liquid distillate product
- Coldest temperature – cooling media must be even colder
- Lowest pressure
- Top section strips heavy components from the rising vapors

Feed

- Vapor, liquid, or intermediate quality
- Introduced in vapor space between trays

Internals

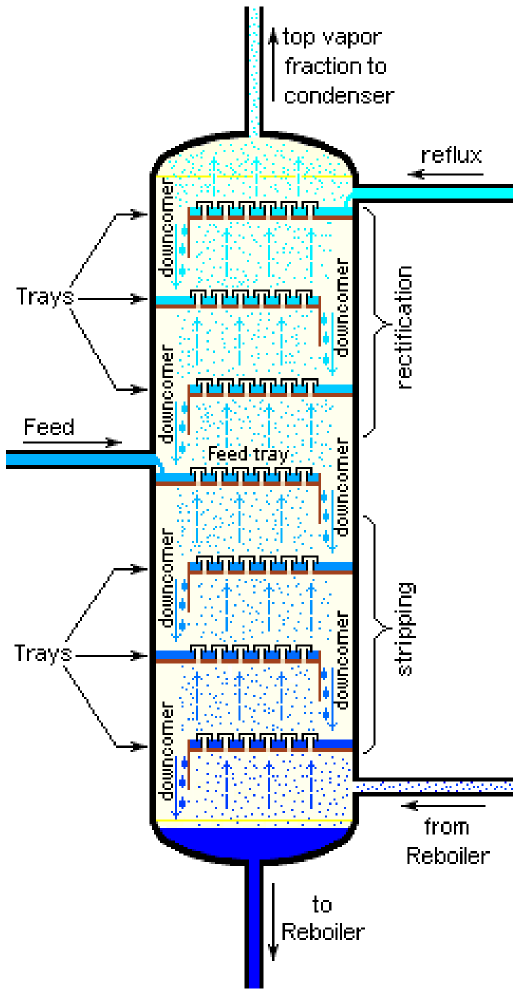
- Trays to contact rising vapors with falling liquids
- Pressure drop across trays – overcome static head of liquid on tray, …

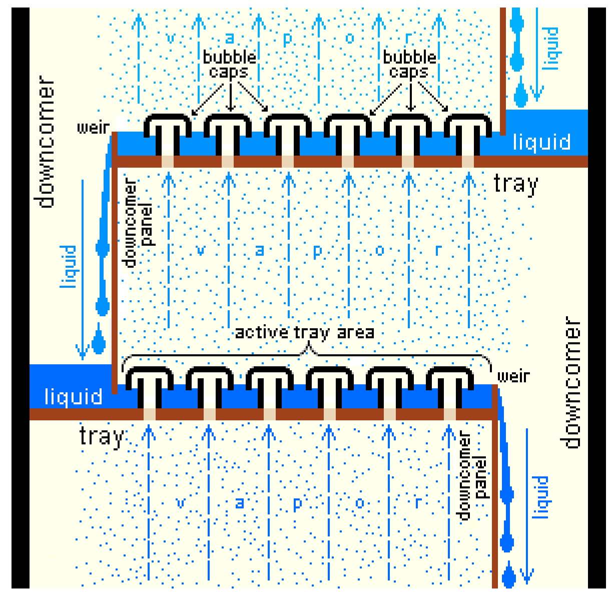
Bottom of column – reboiler to add heat

- Provides vapor traffic in bottom of column
- Highest temperature – heating media must be even hotter
- Highest pressure
- Bottom section strips light components from the falling liquid

Drawing by Henry Padleckas & modifed by Milton Beychok:
http://en.wikipedia.org/wiki/File:Continuous_Binary_Fractional_Distillation.PNG

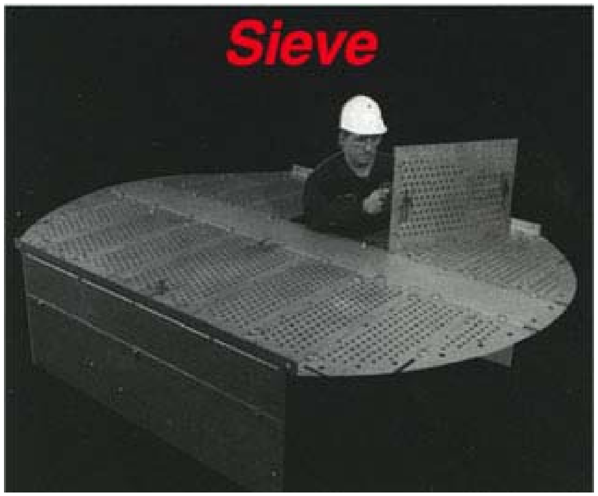
Fractionation Columns & Trays

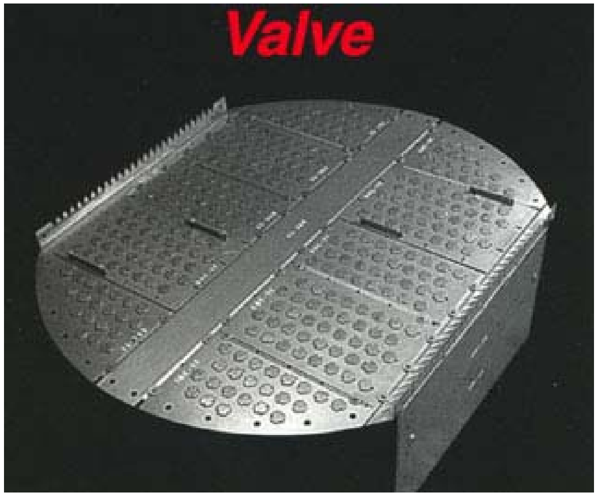




Drawings by Henry Padleckas
http://en.wikipedia.org/wiki/Fractionating_column

Fractionation Tray Types





http://www.termoconsult.com/empresas/acs/fractionation_trays.htm

Trays & Packing

http://www.ec21.com/product-details/Tower-Internals--3942077.html

Typical Overall Efficiencies

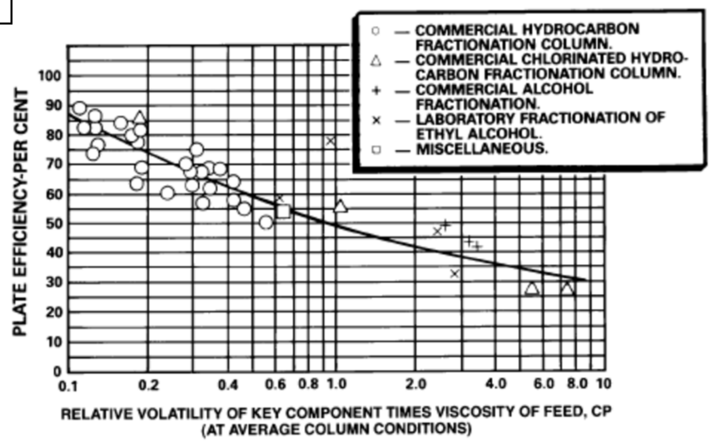
Column Service	**Typical No. of Actual Trays**	**Typical Overall Efficiency**	**Typical No. of Theoretical Trays**
Simple Absorber/Stripper	20 – 30	20 – 30	
Steam Side Stripper	5 – 7		2
Reboiled Side Stripper	7 – 10		3 – 4
Reboiled Absorber	20 – 40	40 – 50	
Deethanizer	25 – 35	65 – 75	
Depropanizer	35 – 40	70 – 80	
Debutanizer	38 – 45	85 – 90	
Alky DeiC4 (reflux)	75 – 90	85 – 90	
Alky DeiC4 (no reflux)	55 – 70	55 – 65	
Naphtha Splitter	25 – 35	70 – 75	
C2 Splitter	110 – 130	95 – 100	
C3 Splitter	200 – 250	95 – 100	
C4 Splitter	70 – 80	85 – 90	
Amine Contactor	20 – 24		4 – 5
Amine Stripper	20 – 24	45 - 55	9 – 12
Crude Distillation	35 – 50	50 – 60	20 – 30
Stripping Zone	5 – 7	30	2
Flash Zone – 1st draw	3 – 7	30	1 – 2
1st Draw – 2nd Draw	7 – 10	45 – 50	3 – 5
2nd Draw – 3rd Draw	7 – 10	50 – 55	3 – 5
Top Draw – Reflux	10 – 12	60 – 70	6 – 8
Vacuum Column (G.O. Operation)			
Stripping	2 – 4		1
Flash Zone – HGO Draw	2 – 3		1 – 2
HGO Section	3 – 5		2
LGO Section	3 – 5		2
FCC Main Fractionator	24 – 35	50 – 60	13 – 17
Quench Zone	5 – 7		2
Quench – HGO Draw	3 – 5		2 – 3
HGO – LCGO	6 – 8		3 – 5
LCGO – Top	7 – 10		5 – 7

Refinery Process Modeling
Gerald Kaes, Athens Printing Company, 2000, pg. 32

Viscosity	**Maxwell**	**Drickamer & Bradford in Ludwig**
cP	**Ave Viscosity of liquid on plates**	**Molal Ave Viscosity of Feed**
0.05	…	98
0.10	104	79
0.15	86	70
0.20	76	60
0.30	63	50
0.40	56	42
0.50	50	36
0.60	46	31
0.70	43	27
0.80	40	23
0.90	38	19
1.00	36	17
1.50	30	7
1.70	28	5

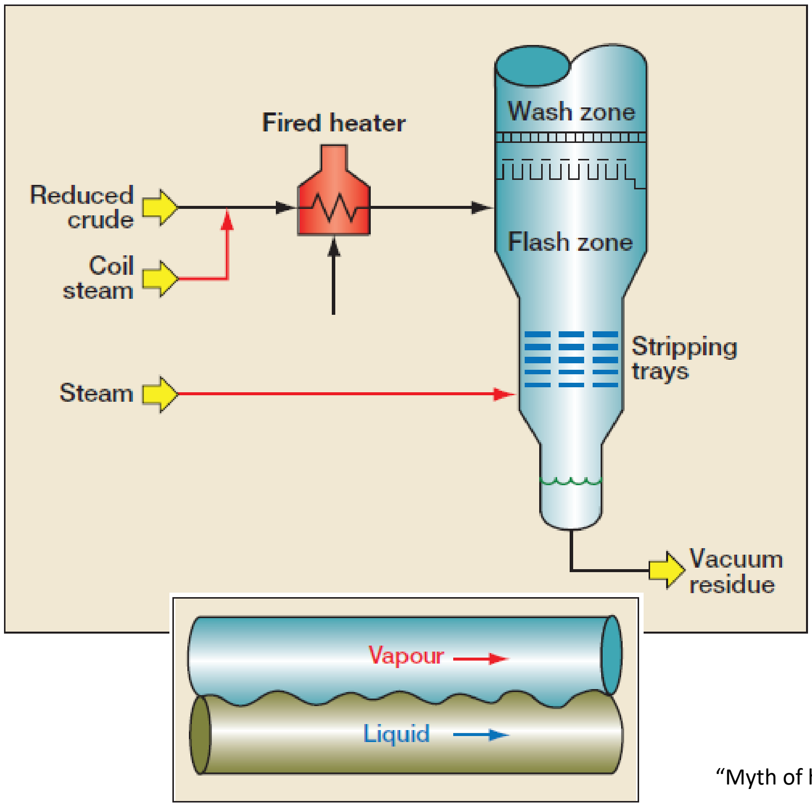
Rules of Thumb for Chemical Engineers, 4th ed.
Carl Branan, Gulf Professional Publishing, 2005

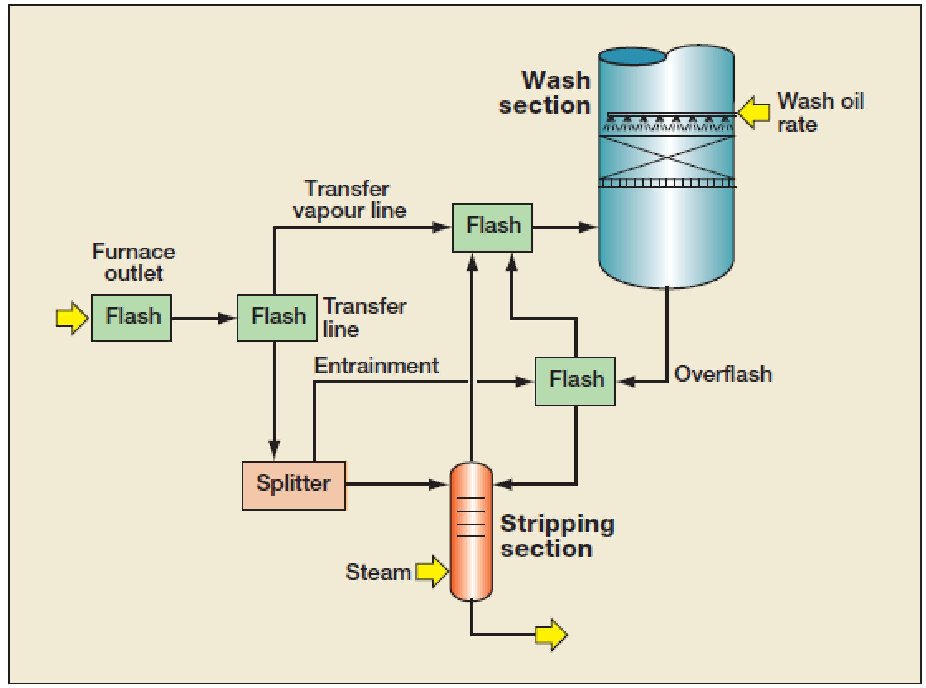
Engineering Data Book, 12th ed.
Gas Processors Association, 2004



Vacuum Tower Transfer Lines

Mass transfer effects in the transfer line complicate the effects at the bottom of the Vacuum Tower





“Myth of high cutpoint in dry vacuum units ,” S. Golden, T. Barletta, & S. White, *PTQ*, Q2 2014