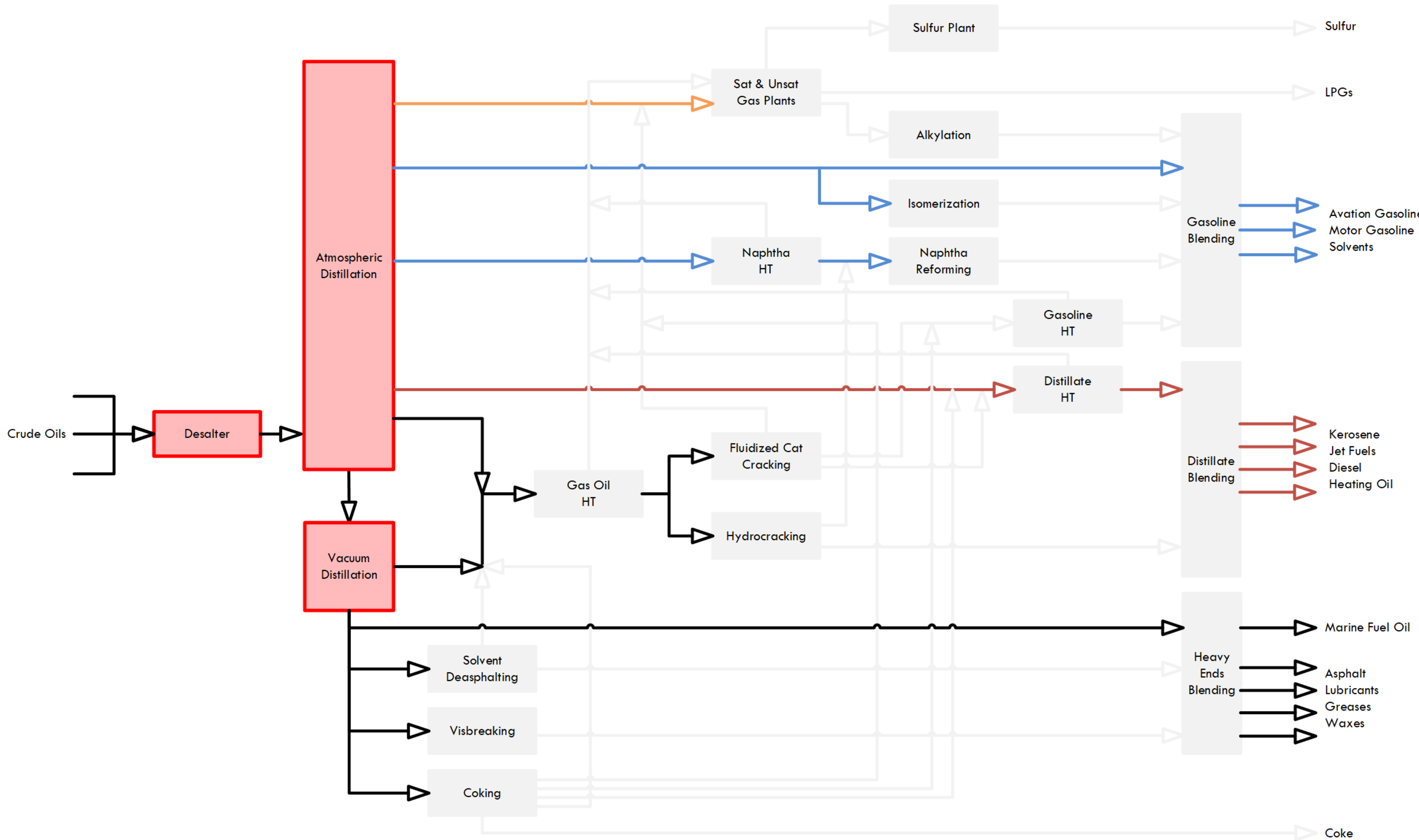
Crude Oil Distillation

Chapter 4

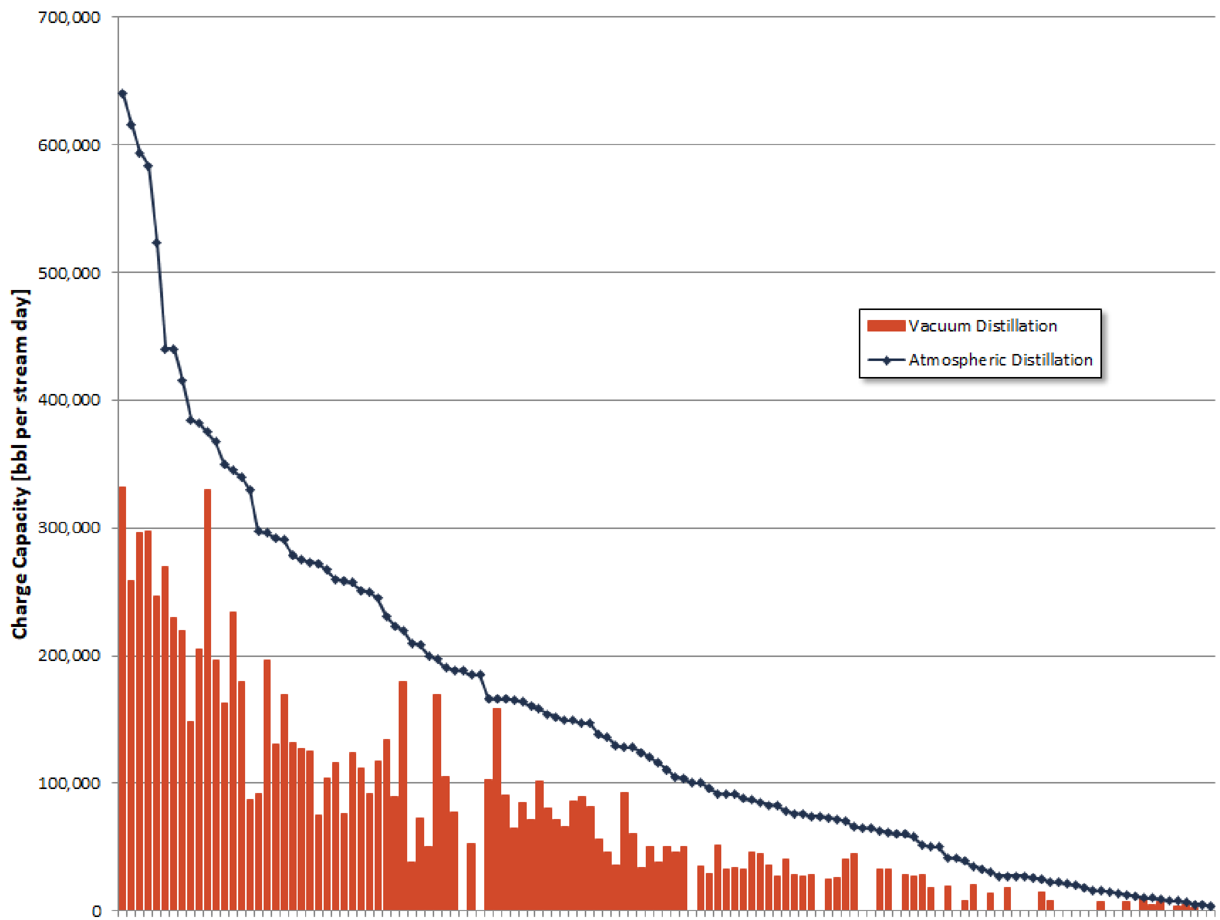
COLORADO SCHOOL OF MINES

Petroleum Refinery Block Flow Diagram



Updated: July 2, 2019

Atmospheric & Vacuum Distillation in U.S.



EIA, Jan. 1, 2019 database, published June 2019
http://www.eia.gov/petroleum/refinerycapacity/

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:
Preflash
Atmospheric
Vacuum

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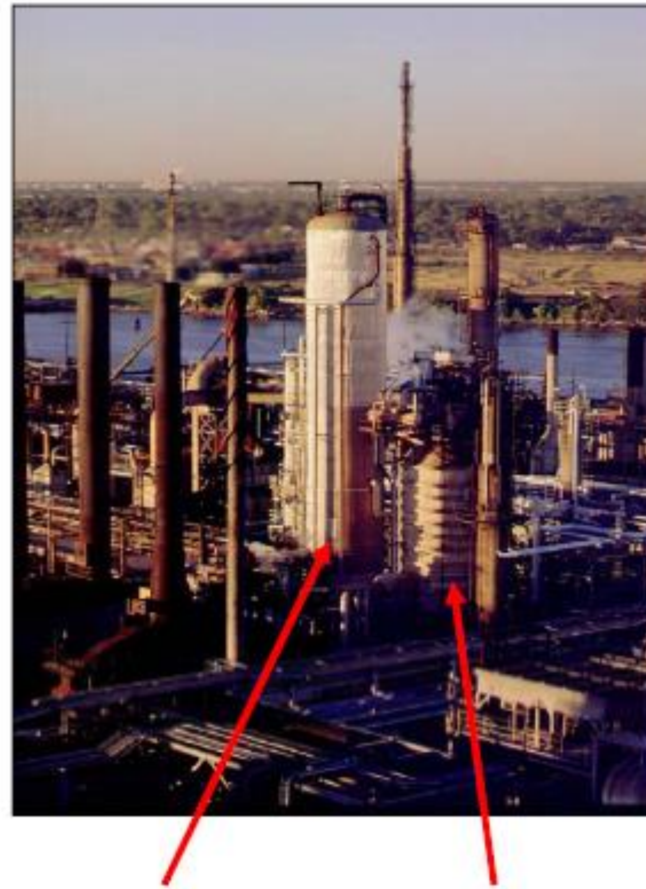
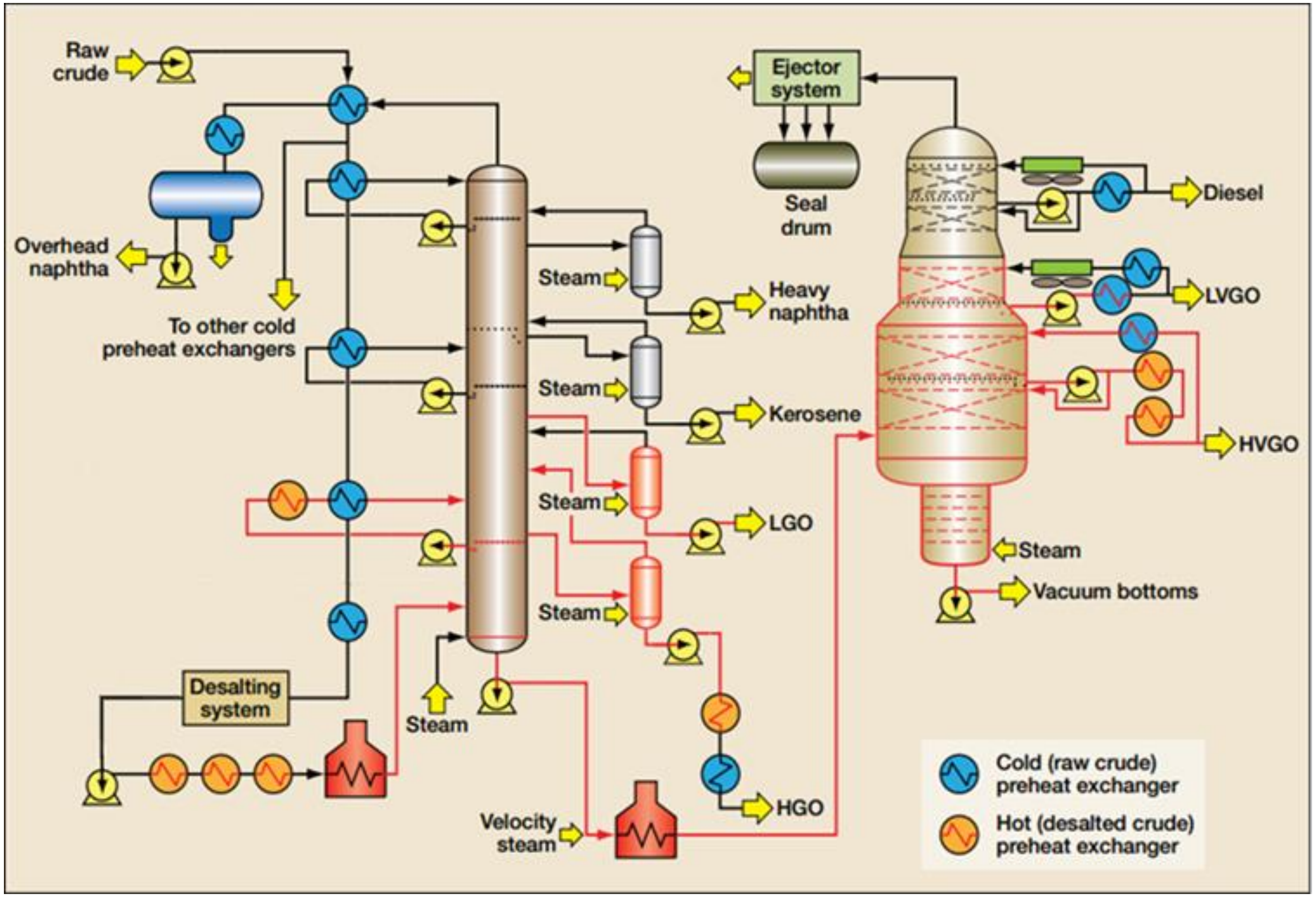
Atmospheric & Vacuum Tower Complex

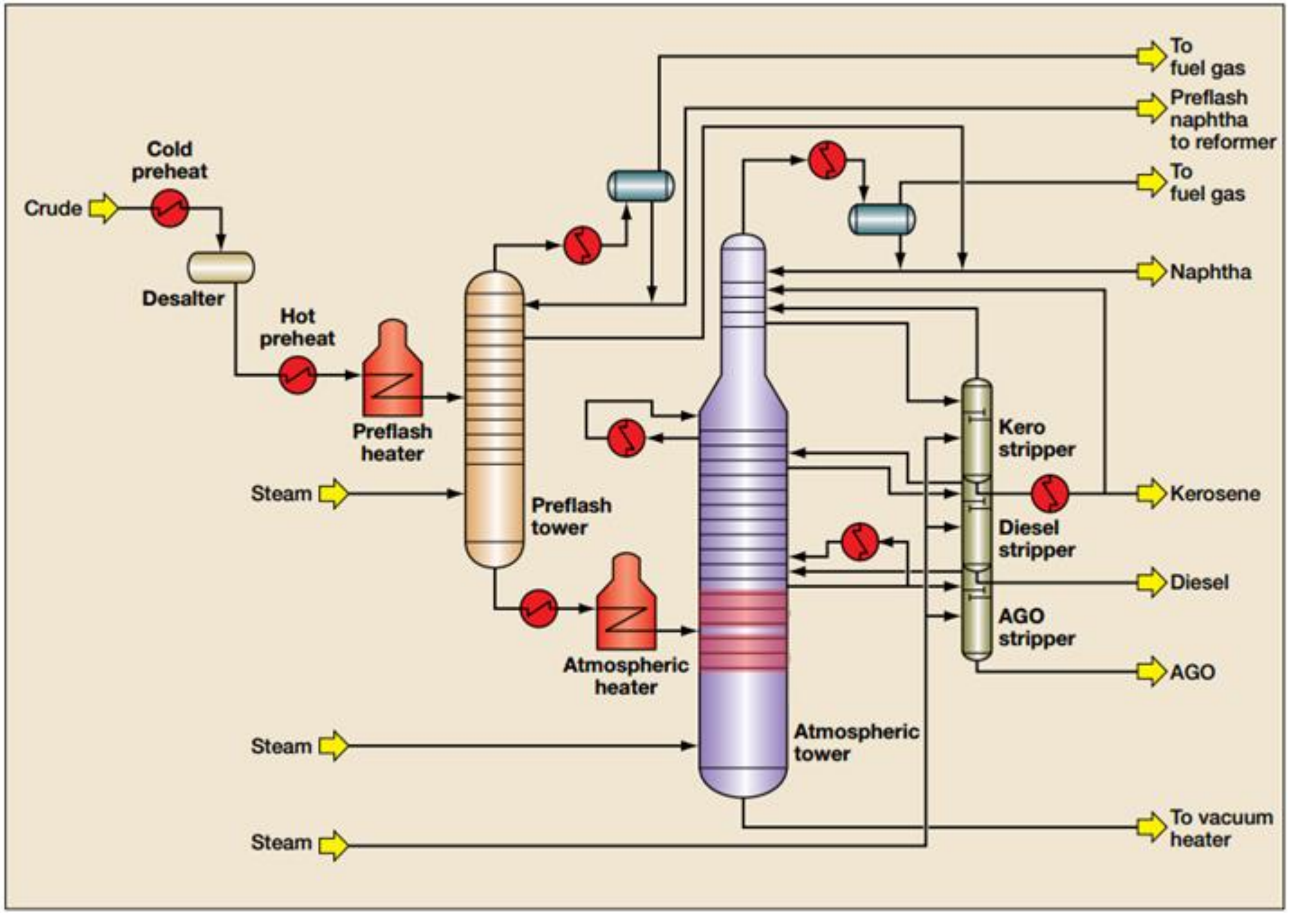


Atmospheric & Vacuum Tower Complex



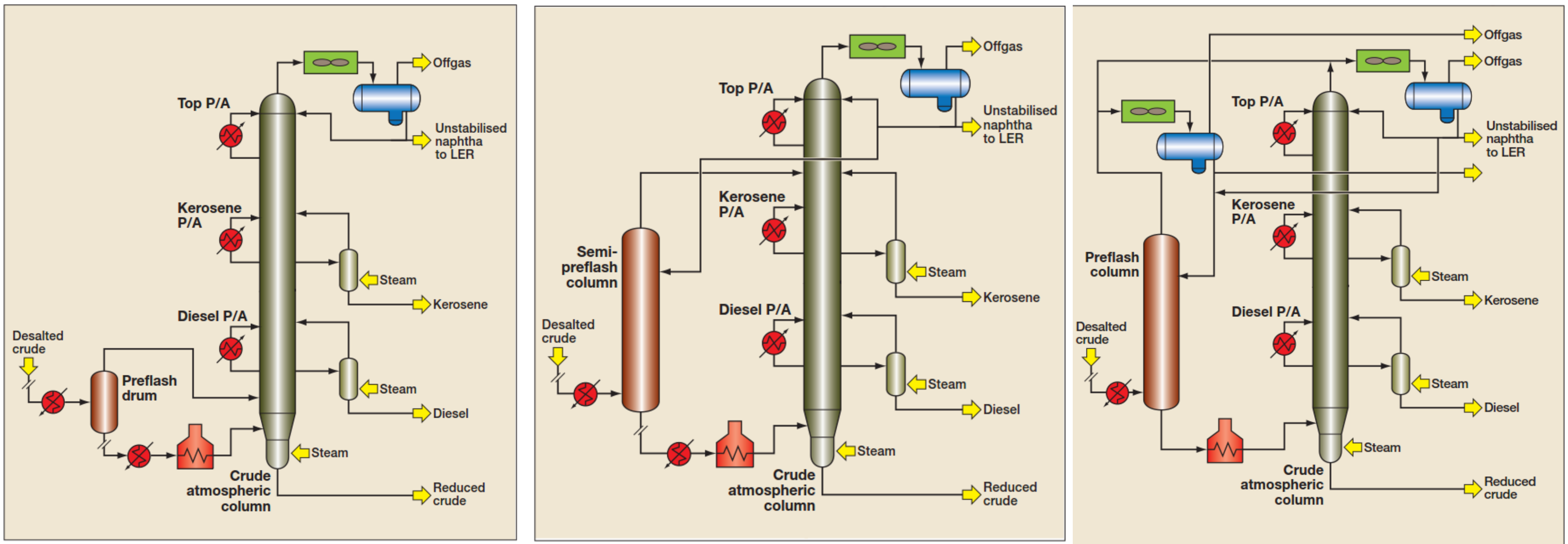
Modified drawing from:
"Revamping crude and vacuum units to process bitumen," Sutikno, *PTQ* ,Q2 2015

Atmospheric Column with Preflash



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

Preflash Options – Tight Oil Example with no AGO



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

Feed Preheat Train & Desalter

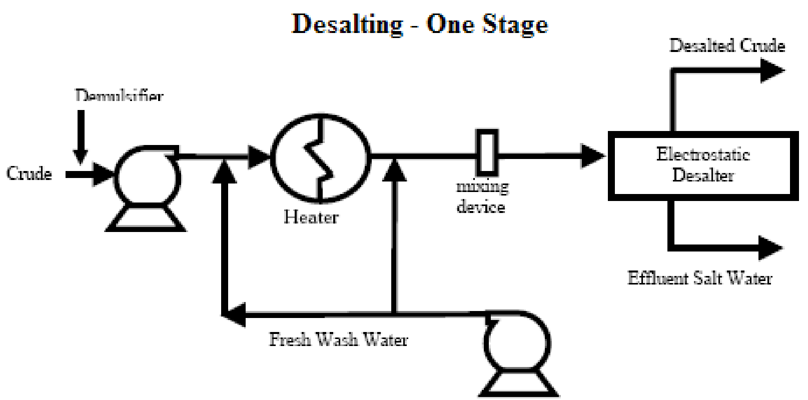
Feed Preheat Train

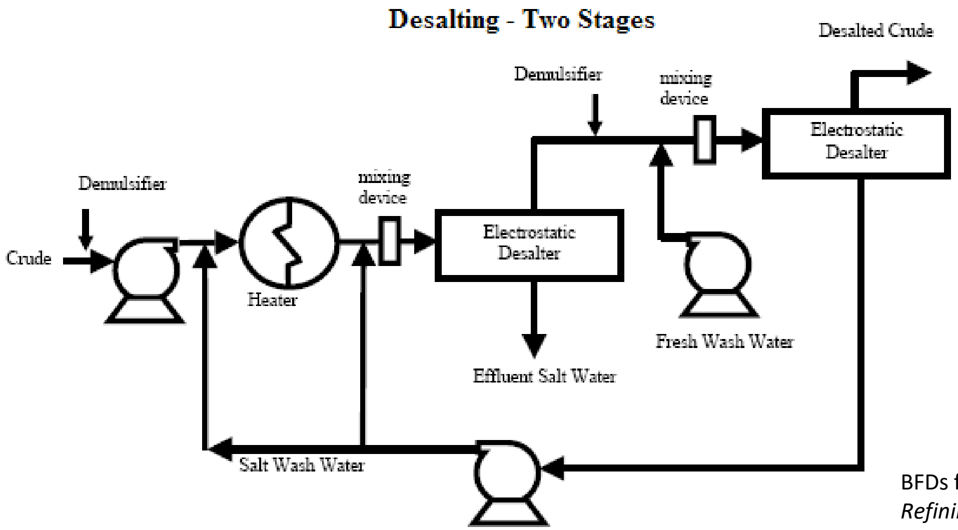
- Initial heat exchange with streams from within the tower
  - Heat recovery important to distillation economics!
    - First absorb part of the overhead condensation load
    - Exchange with one or more of the liquid sides streams, beginning with the top (coldest) side stream
  - Require flexibility
    - 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

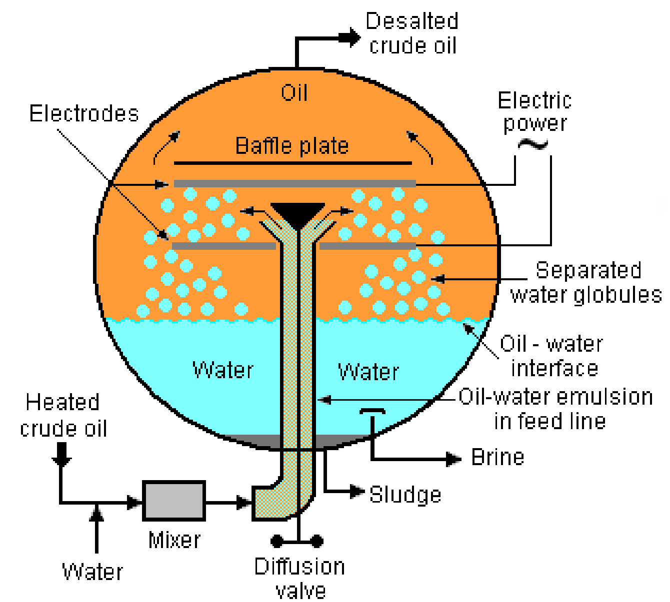
Desalter

- 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

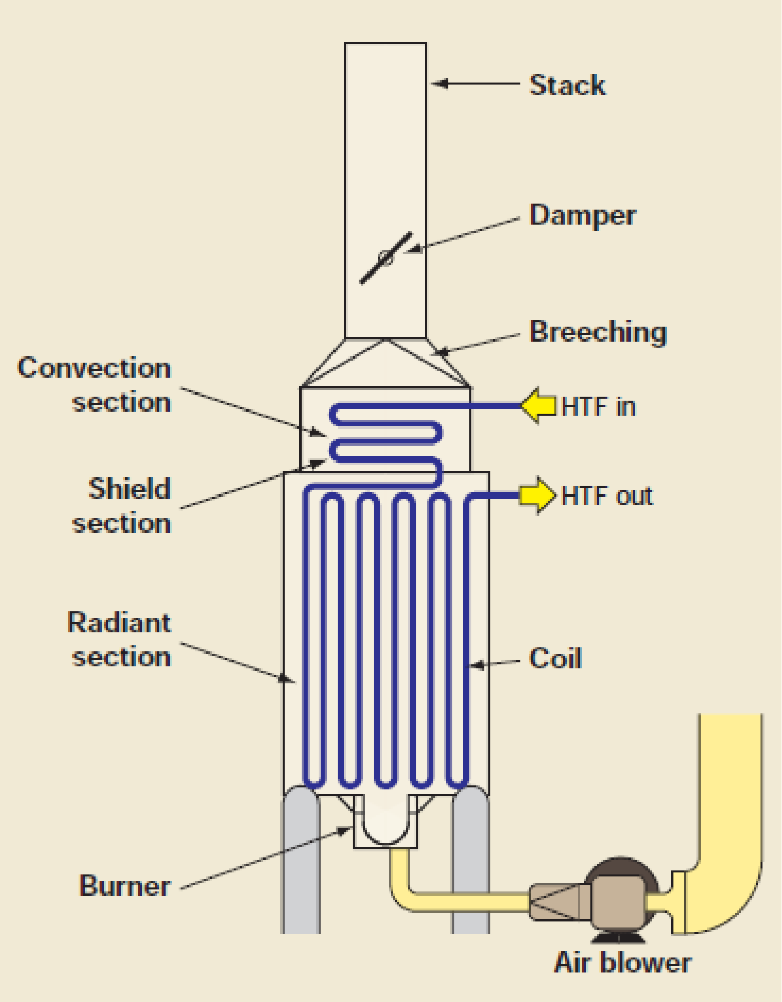
Breaking the crude oil/water emulsion important to minimize downstream problems

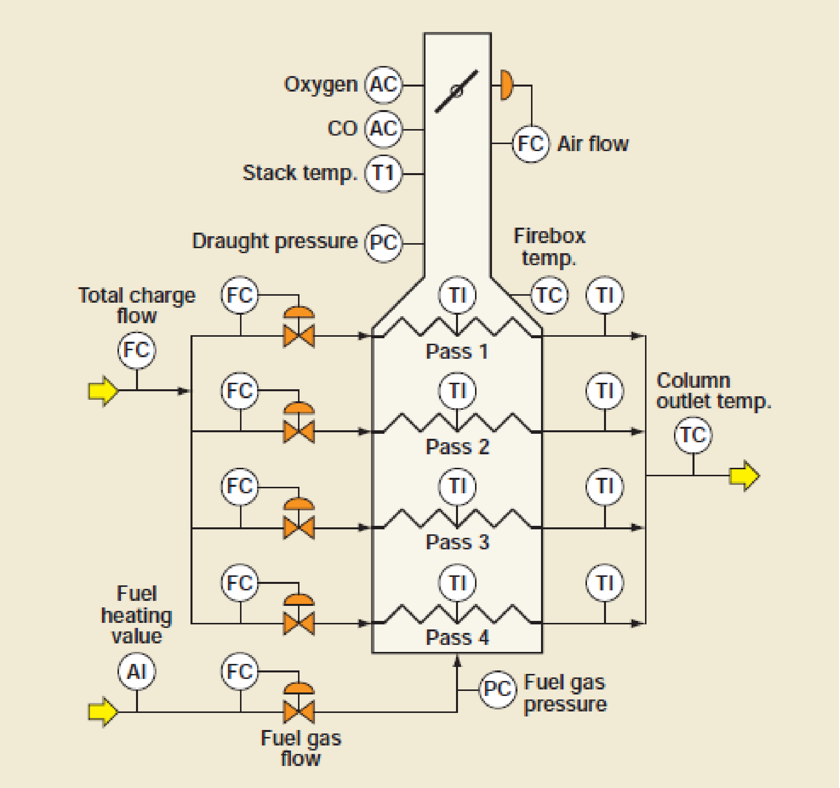
Performance of additives may be crude specific

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

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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

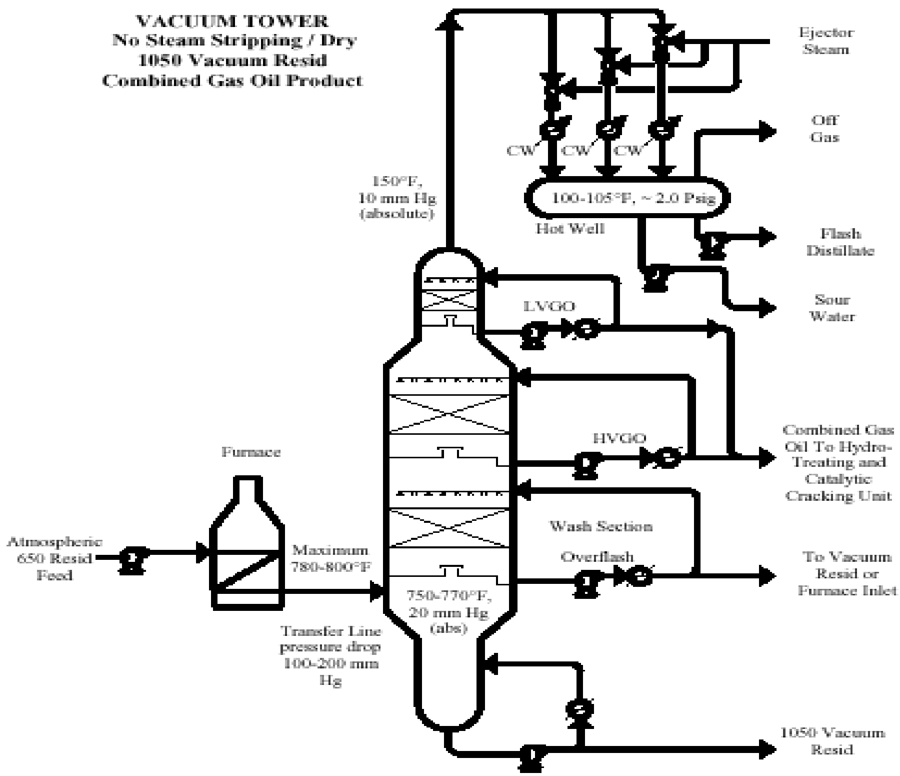
Side Draws & Strippers

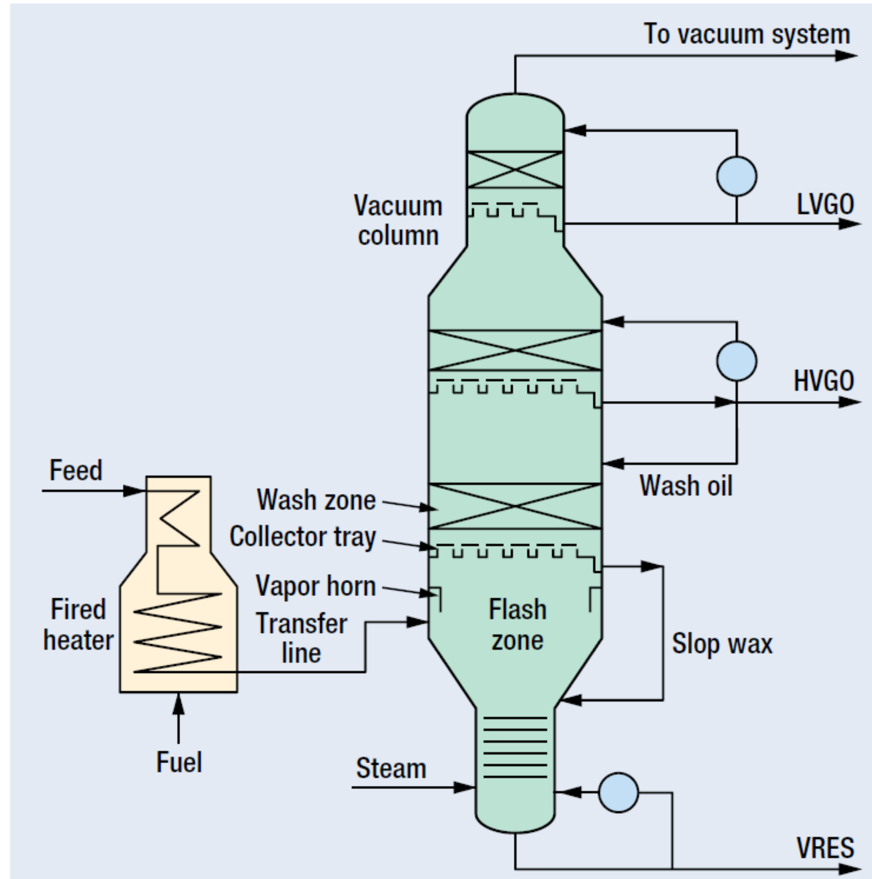
- Side strippers remove light component "tail" & return to main column
- Steam strippers traditional
  - Reboiled strippers reduce associated sour water & may reduce steam usage

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

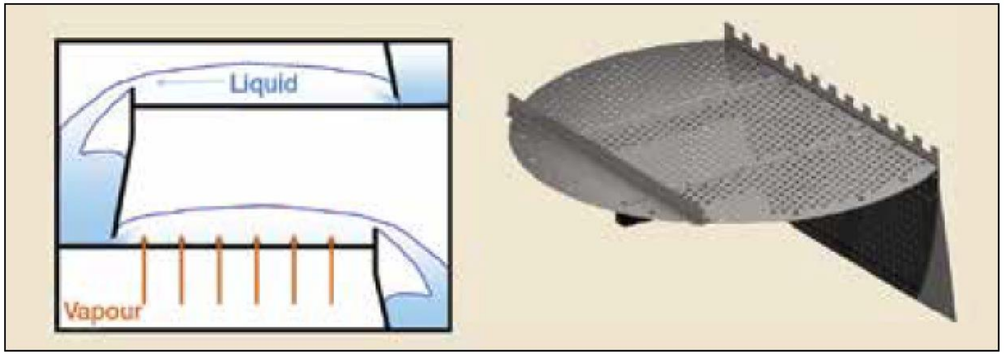


Figure 3 Vapour and liquid flows on trays

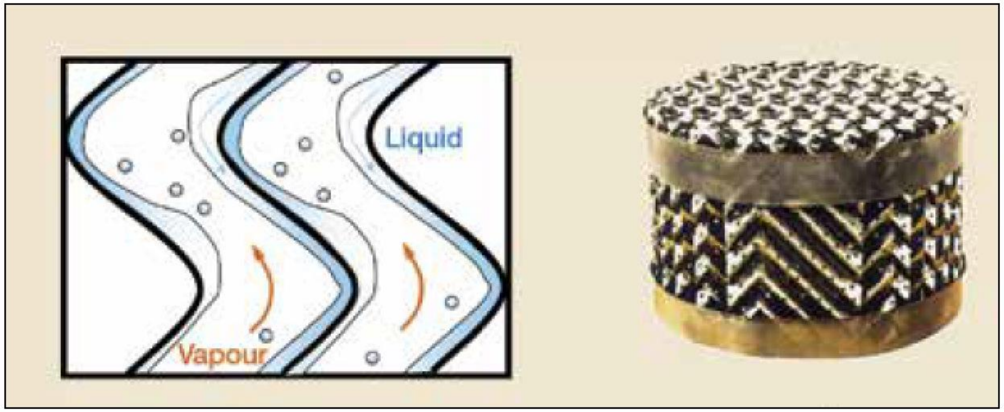


Figure 4 Vapour and liquid flows in structured packing

"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

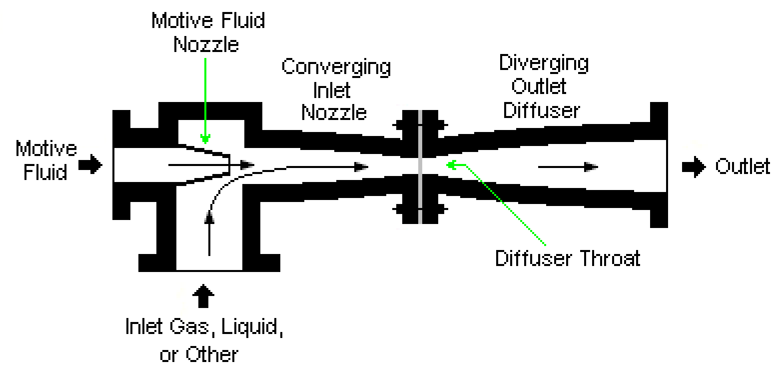
- 1050°F+ cut temperature & no stripping steam
- Smaller tower diameters
- Reduced sour water production
- Pressure profile
  - Flash zone: 20-25 mmHg abs & 750 to 770°F.
  - Top of tower: 10 mmHg abs

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

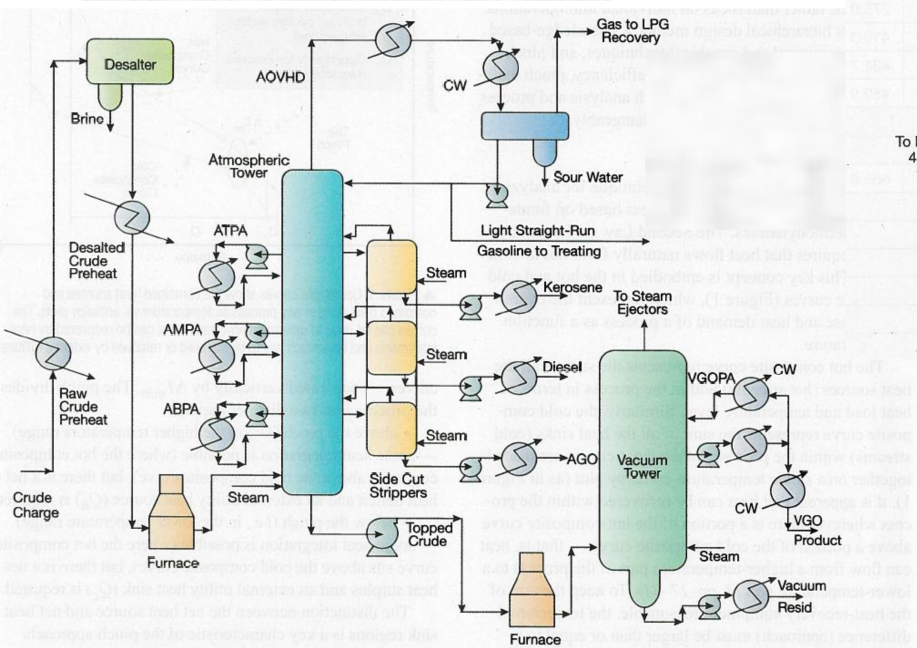
- Vacuum maintained on tower overhead
- Steam systems considered more reliable
- Waste steam is sour & must be treated
- Combinations systems — Last steam stage replaced with a vacuum pump

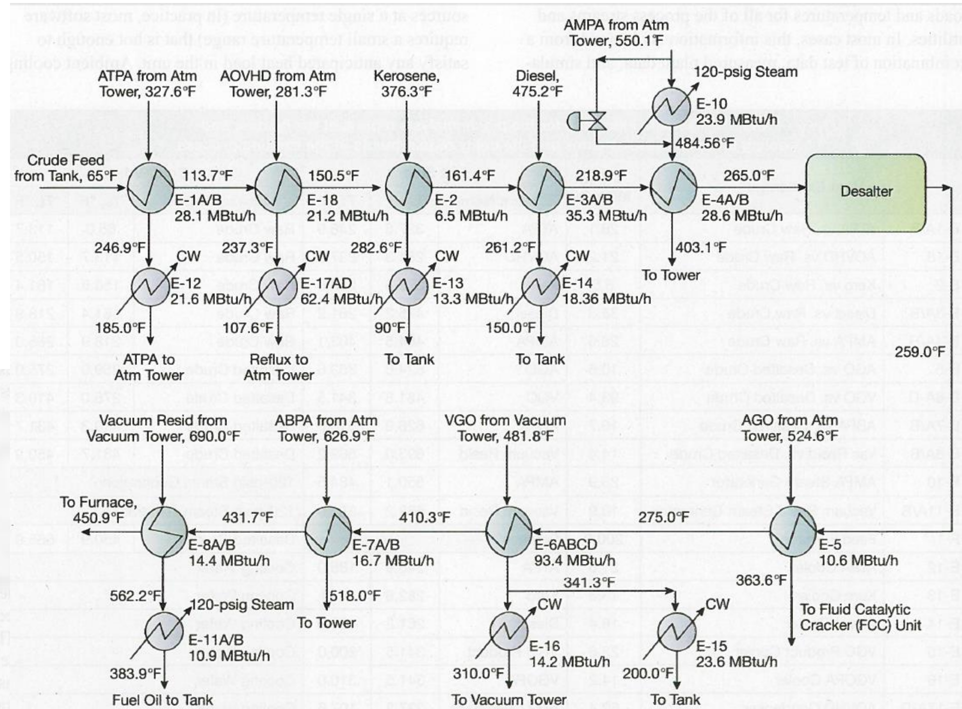


Drawing from http://www.enotes.com/topic/Injector

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

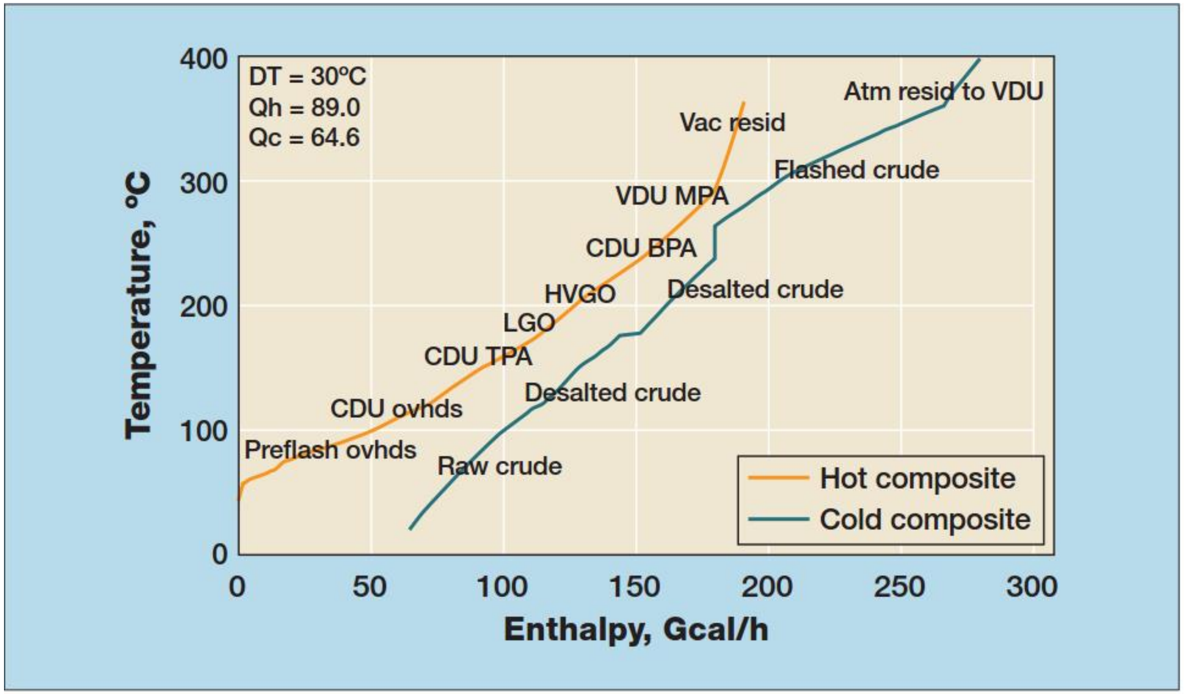


Figure 1 Composite curves

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

Example – Existing Preheat Train

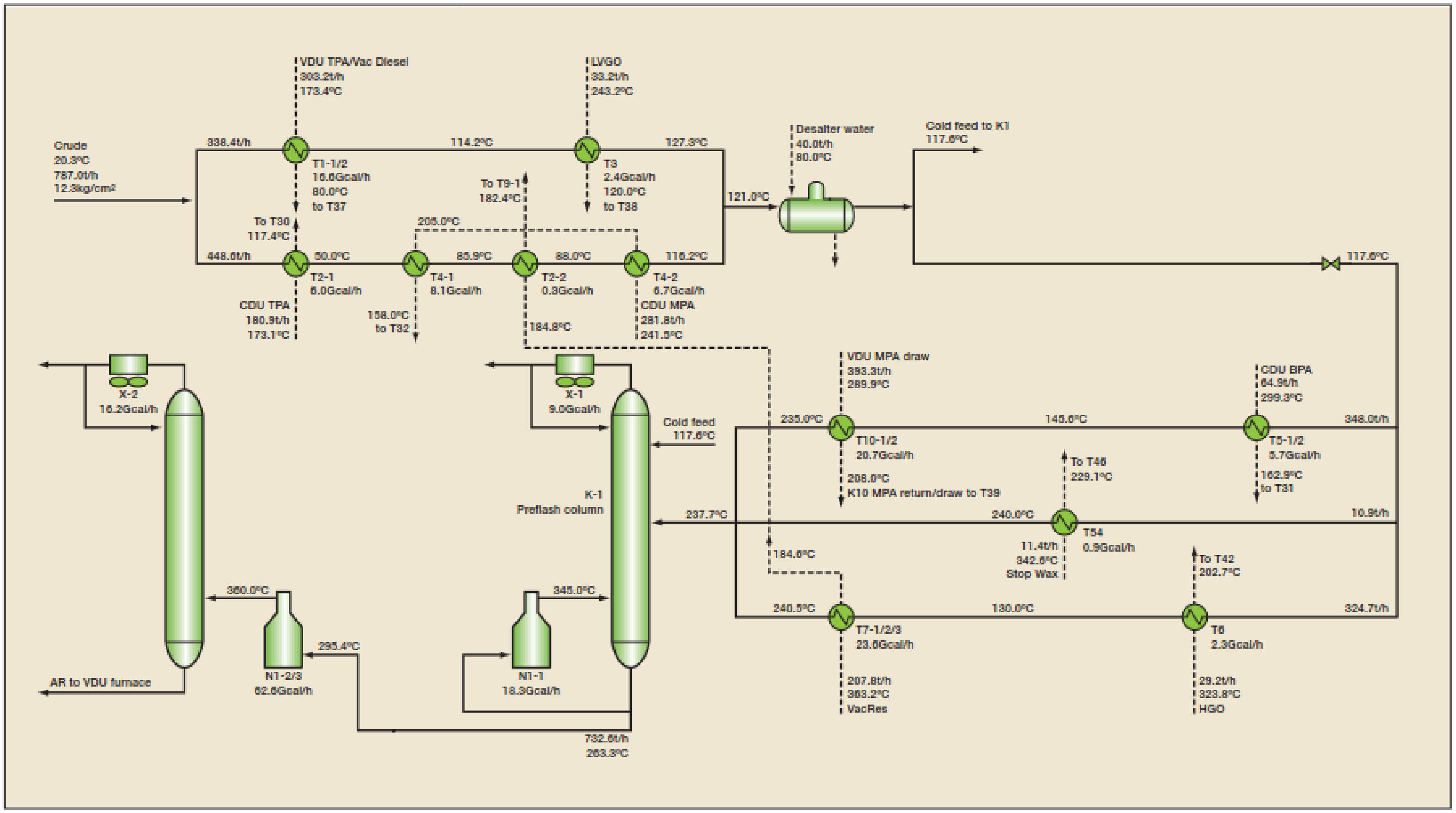


Figure 2 Preheat train configuration

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

Example – Improved Preheat Train

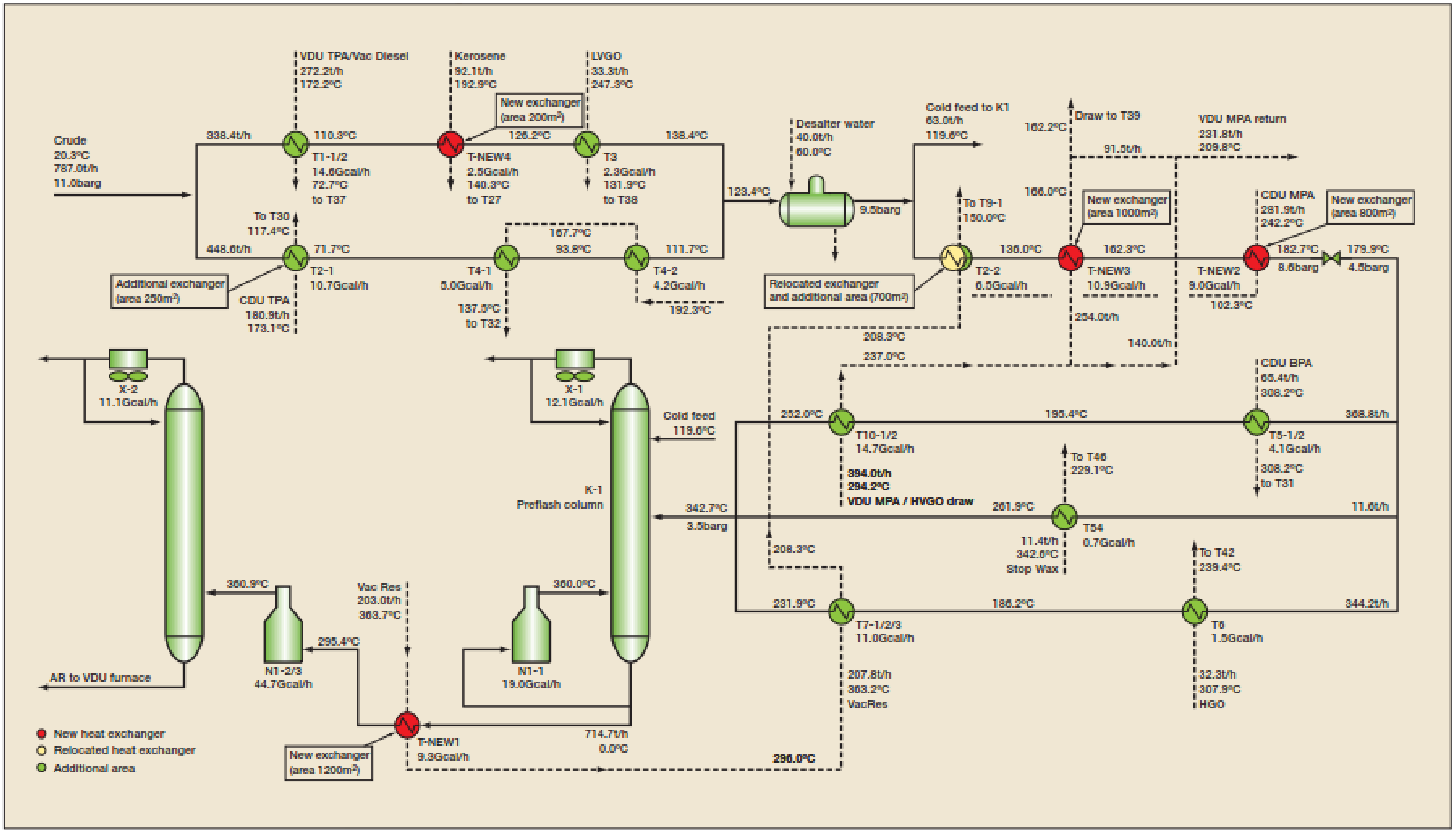


Figure 4 The most cost effective solution

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

Product Yield Curves

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Typical "Cut Point" Definitions

Cut	TBP IBP (ºF)	TBP EP (ºF)
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
Diesel / 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	

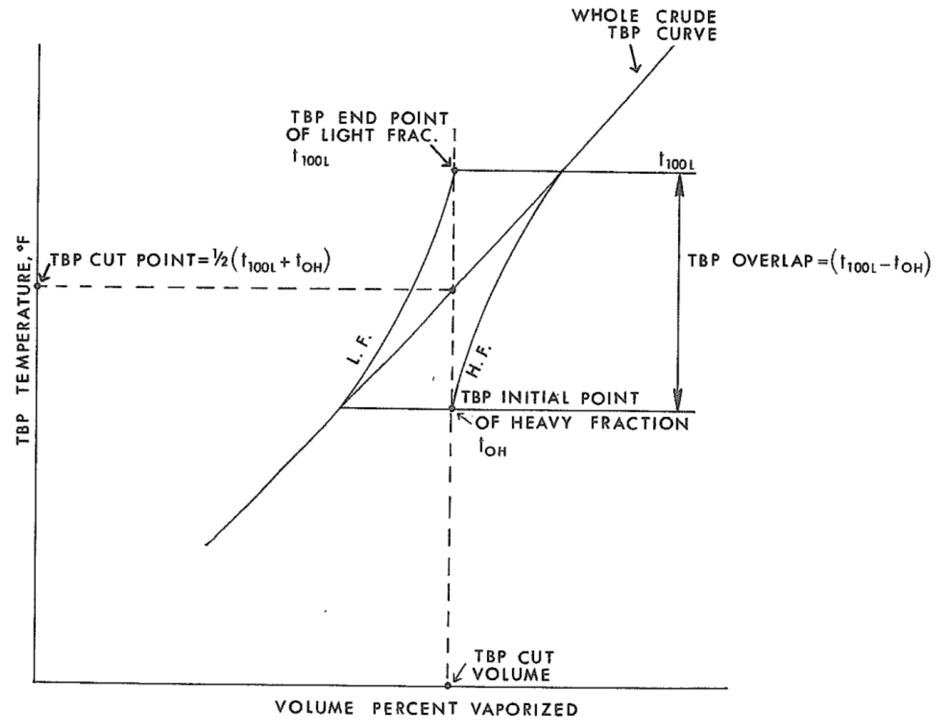
Product Yield Curves – Cut Point, Overlap, & "Tails"

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%	25.38%	9.42%	17.55%	2.11%	45.54%
TBP vol% & °F						
1.0%	42	9	282	346	522	456
5.0%	143	59	327	425	577	589
10.0%	206	99	342	462	609	652
15.0%	257	128	357	483	630	694
20.0%	299	144	366	497	644	728
30.0%	397	182	384	520	669	784
40.0%	509	208	395	541	687	838
50.0%	608	231	407	563	703	900
60.0%	703	260	420	585	717	976
70.0%	806	282	434	610	730	1,075
80.0%	943	305	451	638	746	1,206
85.0%	1,045	318	456	653	757	1,287
90.0%	1,178	337	471	673	768	1,387
95.0%	1,364	356	493	701	780	1,556
99.0%	1,649	365	503	728	789	1,746

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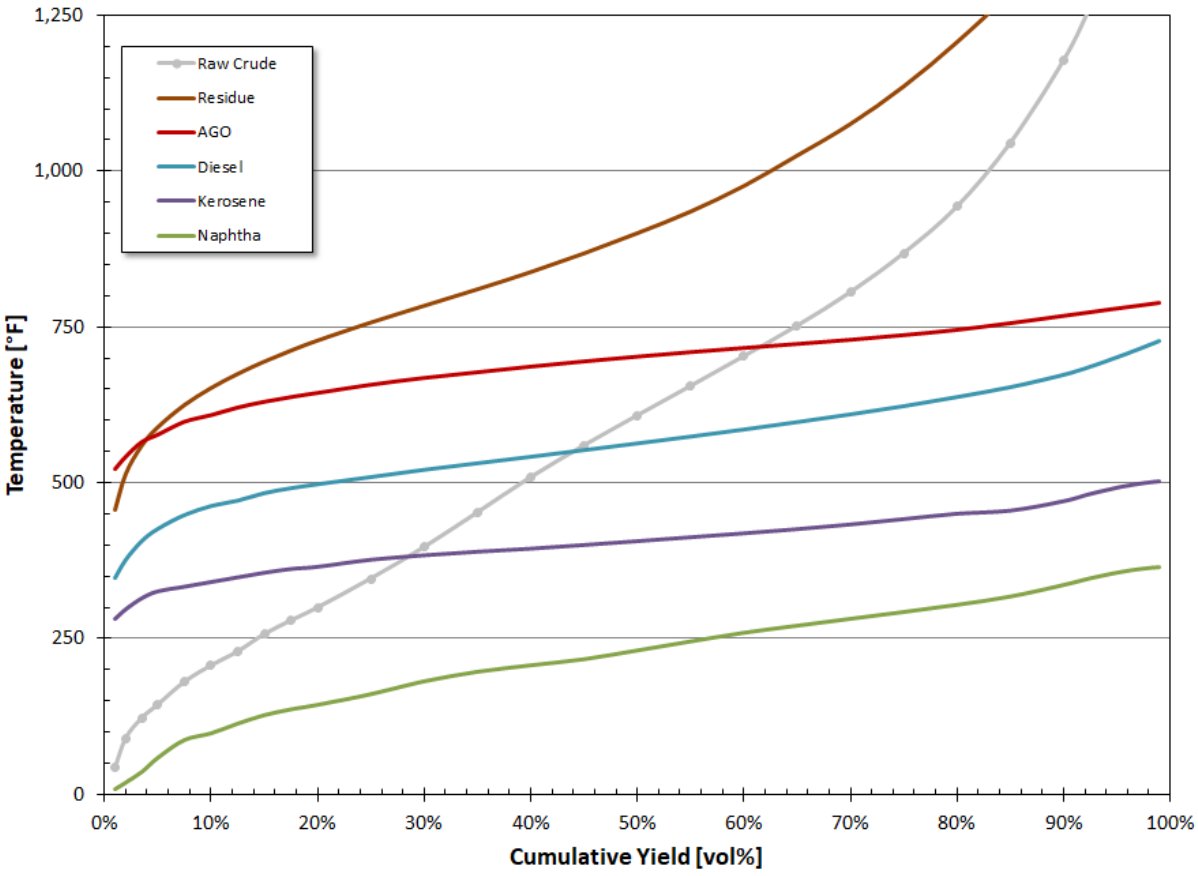

Example – Scale to Fraction of Crude Charge

Scaled Yield Values

Individual	Naphtha		Kerosene		Diesel		AGO		Residue	
vol%	°F	vol%	°F	vol%	°F	vol%	°F	vol%	°F	vol%
0.0%		0.0%		25.4%		34.8%		52.3%		54.5%
1.0%	9	0.3%	282	25.5%	346	35.0%	522	52.4%	456	54.9%
5.0%	59	1.3%	327	25.9%	425	35.7%	577	52.5%	589	56.7%
10.0%	99	2.5%	342	26.3%	462	36.6%	609	52.6%	652	59.0%
15.0%	128	3.8%	357	26.8%	483	37.4%	630	52.7%	694	61.3%
20.0%	144	5.1%	366	27.3%	497	38.3%	644	52.8%	728	63.6%
30.0%	182	7.6%	384	28.2%	520	40.1%	669	53.0%	784	68.1%
40.0%	208	10.2%	395	29.1%	541	41.8%	687	53.2%	838	72.7%
50.0%	231	12.7%	407	30.1%	563	43.6%	703	53.4%	900	77.2%
60.0%	260	15.2%	420	31.0%	585	45.3%	717	53.6%	976	81.8%
70.0%	282	17.8%	434	32.0%	610	47.1%	730	53.8%	1,075	86.3%
80.0%	305	20.3%	451	32.9%	638	48.8%	746	54.0%	1,206	90.9%
85.0%	318	21.6%	456	33.4%	653	49.7%	757	54.1%	1,287	93.2%
90.0%	337	22.8%	471	33.9%	673	50.6%	768	54.2%	1,387	95.4%
95.0%	356	24.1%	493	34.3%	701	51.5%	780	54.4%	1,556	97.7%
99.0%	365	25.1%	503	34.7%	728	52.2%	789	54.4%	1,746	99.5%
100.0%		25.4%		34.8%		52.3%		54.5%		100%
Inc vol%	25.38%		9.42%		17.55%		2.11%		45.54%	

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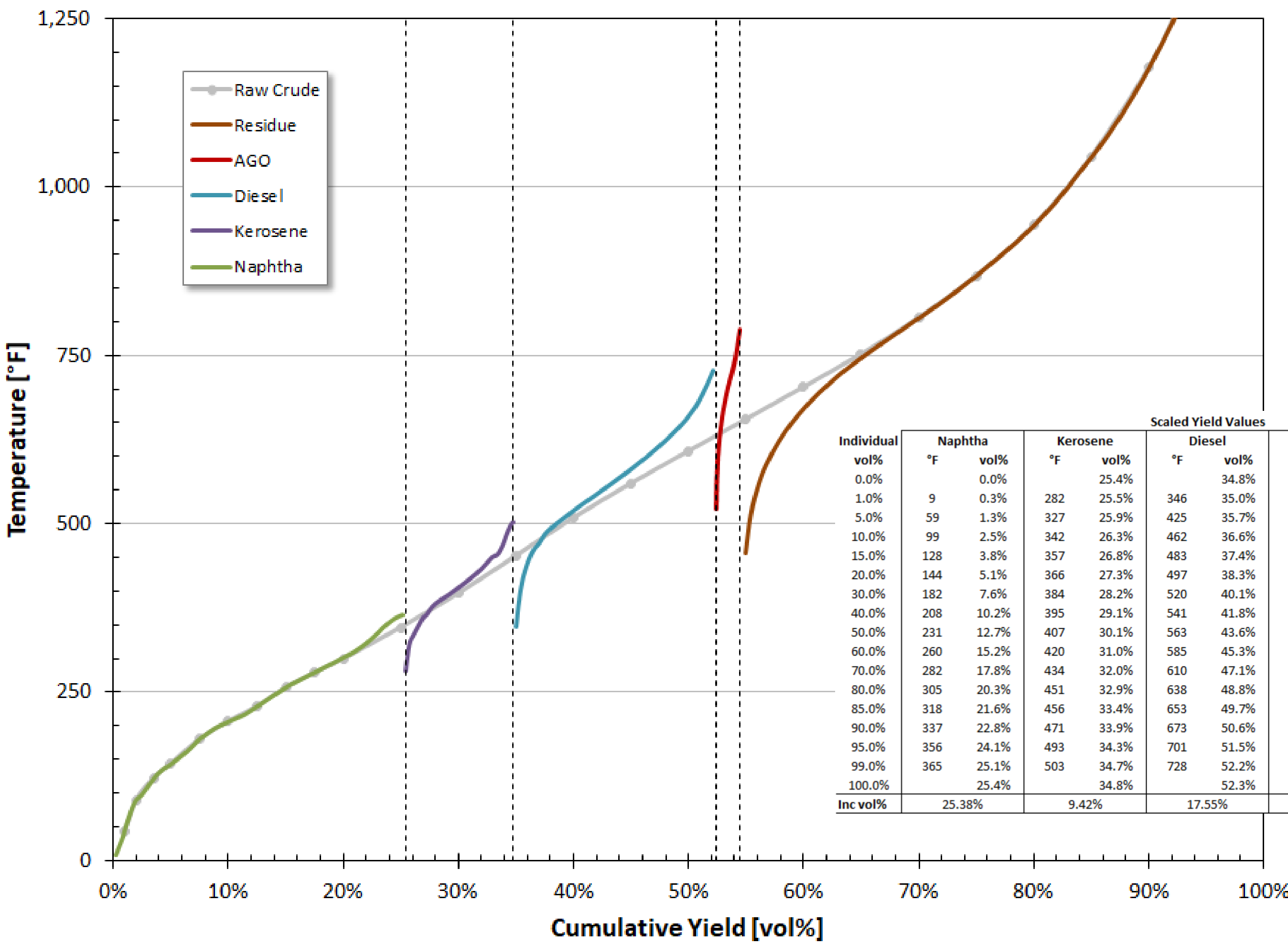
Scale to Fraction of Crude Charge



Scaled Yield Values

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40.0%	208	10.2%	395	29.1%	541	41.8%	687	53.2%	838	72.7%
50.0%	231	12.7%	407	30.1%	563	43.6%	703	53.4%	900	77.2%
60.0%	260	15.2%	420	31.0%	585	45.3%	717	53.6%	976	81.8%
70.0%	282	17.8%	434	32.0%	610	47.1%	730	53.8%	1,075	86.3%
80.0%	305	20.3%	451	32.9%	638	48.8%	746	54.0%	1,206	90.9%
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Inc vol%	25.38%		9.42%		17.55%		2.11%		45.54%	

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Cut Points Based on Volumetrics

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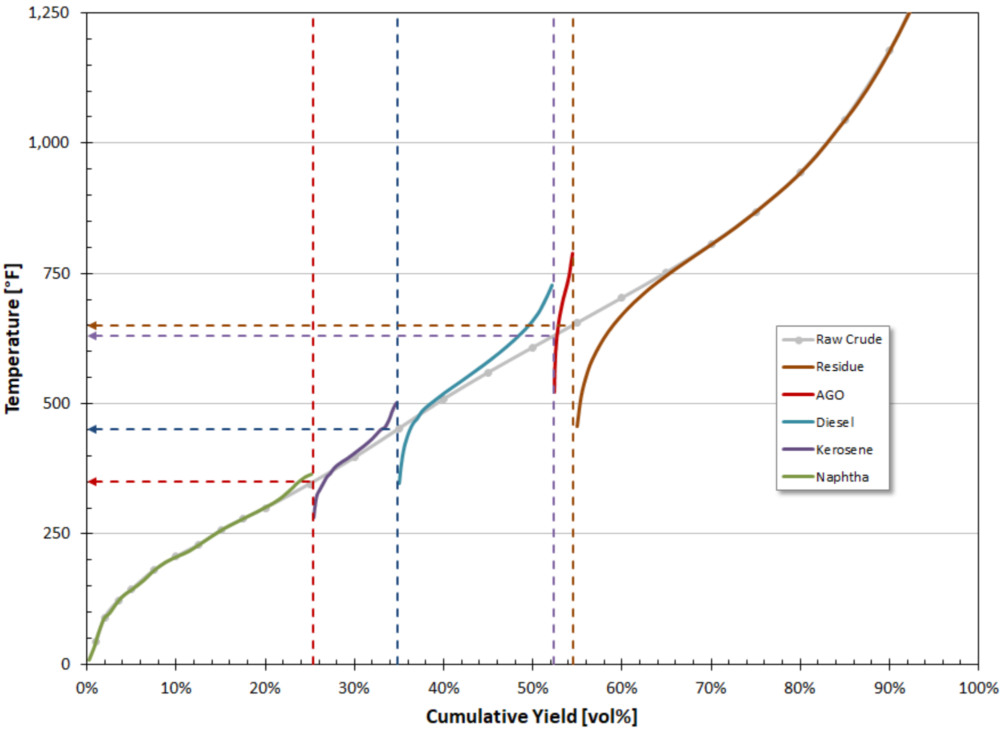
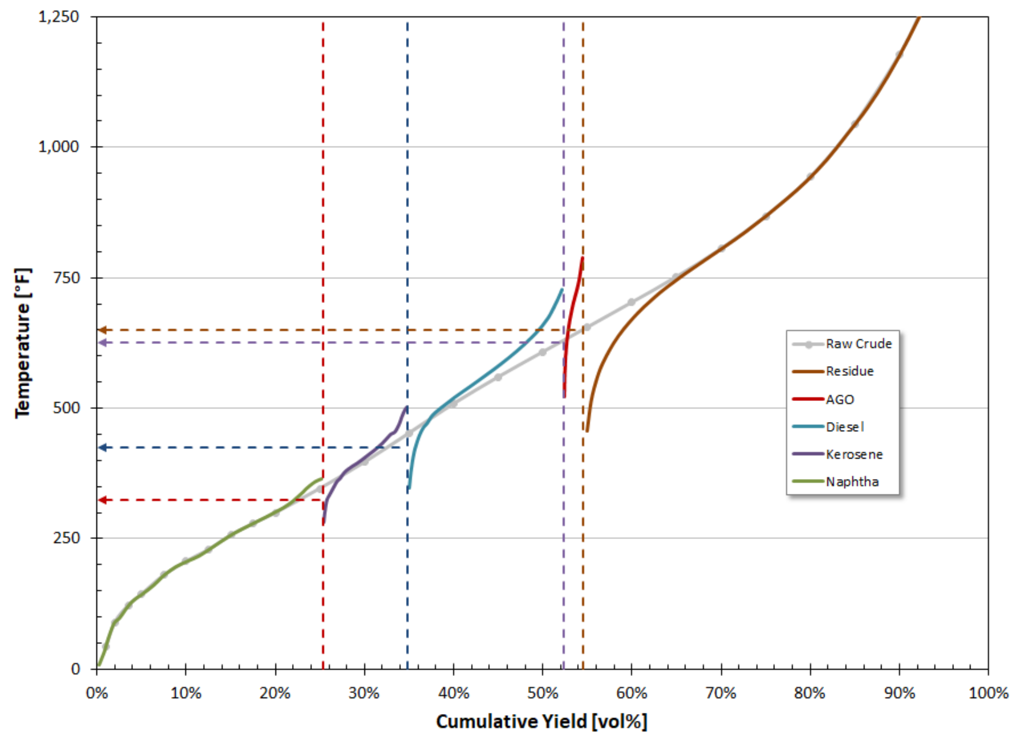
80.0%	943	305	451	638	746	1,206
85.0%	1,045	318	456	653	757	1,287
90.0%	1,178	337	471	673	768	1,387
95.0%	1,364	356	493	701	780	1,556
99.0%	1,649	365	503	728	789	1,746
Cut Point Based on Distillation Curve of the Raw Crude						
Cut [vol%] & [°F]		25.38%	350			
			34.80%	450		
				52.35%	630	
					54.46%	650



Cut Points Based on Volumetrics

	Raw Crude	Naphtha	Kerosene	Diesel	AGO	Residue
Yield [vol%]	100%	25.38%	9.42%	17.55%	2.11%	45.54%
TBP vol% & °F						
1.0%	42	9	282	346	522	456
5.0%	143	59	327	425	577	589
10.0%	206	99	342	462	609	652
15.0%	257	128	357	483	630	694
20.0%	299	144	366	497	644	728
30.0%	397	182	384	520	669	784
40.0%	509	208	395	541	687	838
50.0%	608	231	407	563	703	900
60.0%	703	260	420	585	717	976
70.0%	806	282	434	610	730	1,075
80.0%	943	305	451	638	746	1,206
85.0%	1,045	318	456	653	757	1,287
90.0%	1,178	337	471	673	768	1,387
95.0%	1,364	356	493	701	780	1,556
99.0%	1,649	365	503	728	789	1,746
Cut Point Based on Distillation Curves of the Products						
T01 [°F]			282	346	522	456
T99 [°F]		365	503	728	789	
Mid [°F]		324				
			425			
				625		
					623	
Cut Point Based on Distillation Curve of the Raw Crude						
Cut [vol%] & [°F]		25.38%	350			
			34.80%	450		
				52.35%	630	
					54.46%	650



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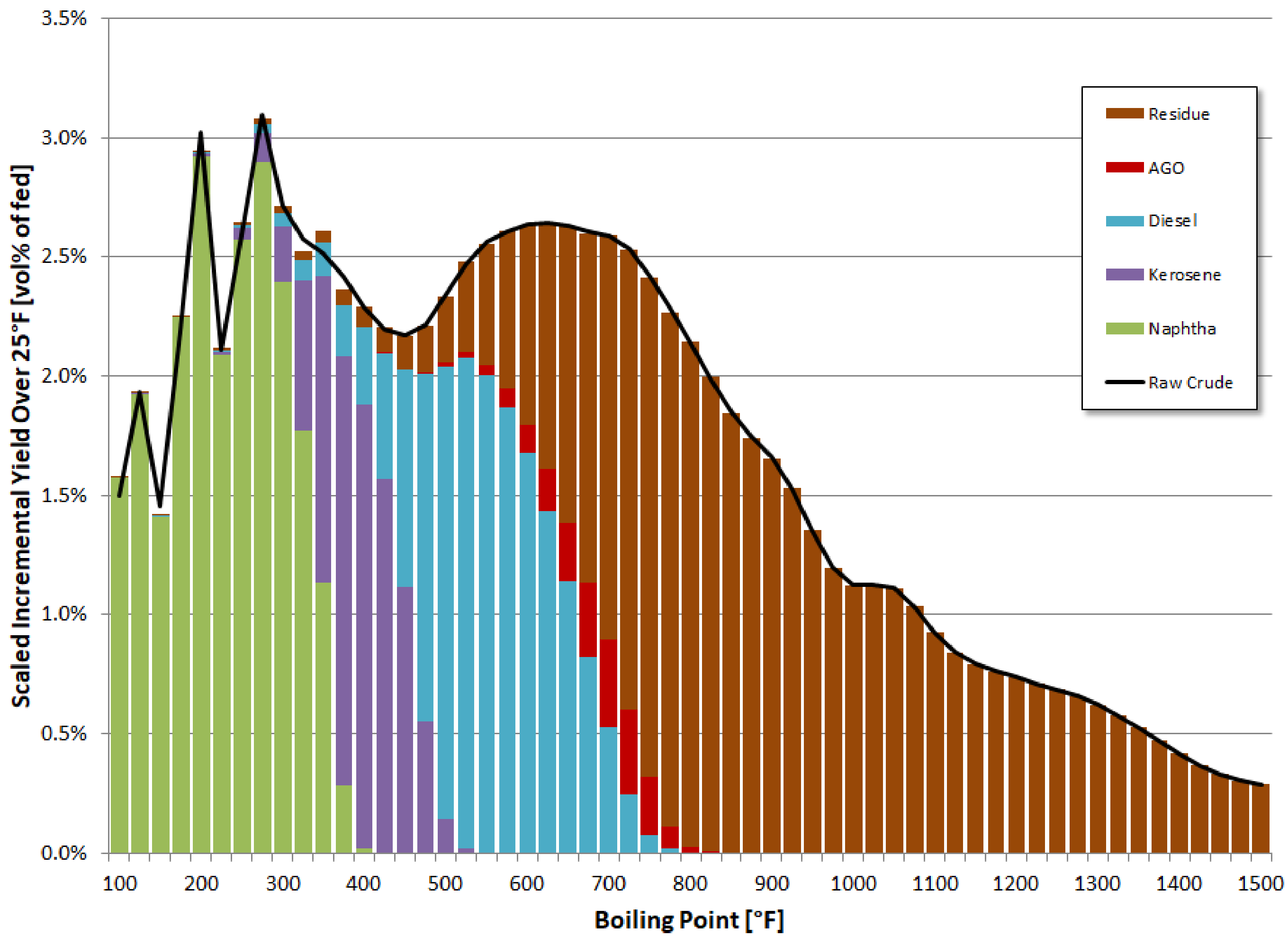
Boiling Point Ranges for Example



How Much Overlap?

	Ideal Fractions							
	LPGs + Naphtha	Kerosene	Diesel	AGO	Atm Resid	Total	API Gravity	Sulfur [wt%]
IBP [F]:		350	450	630	650			
FBP [F]:	350	450	630	650				
Volumetric Rates [bpd]								
Actual Streams: LPGs + Naphtha	23,946	1,434	0	0	0	25,380	62.34	0.003
Actual Streams: Kerosene	1,064	6,522	1,833	0	0	9,419	43.03	0.041
Actual Streams: Diesel	203	1,211	12,174	1,127	2,834	17,549	34.81	0.249
Actual Streams: AGO	0	2	321	145	1,645	2,112	29.23	0.477
Actual Streams: Atm Resid	134	300	3,199	847	41,060	45,539	20.07	0.926
Total	25,347	9,469	17,527	2,119	45,539	100,000		
API Gravity	62.57	43.74	35.52	31.25	19.60			
Sulfur [wt%]	0.003	0.032	0.206	0.385	0.945			

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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

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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

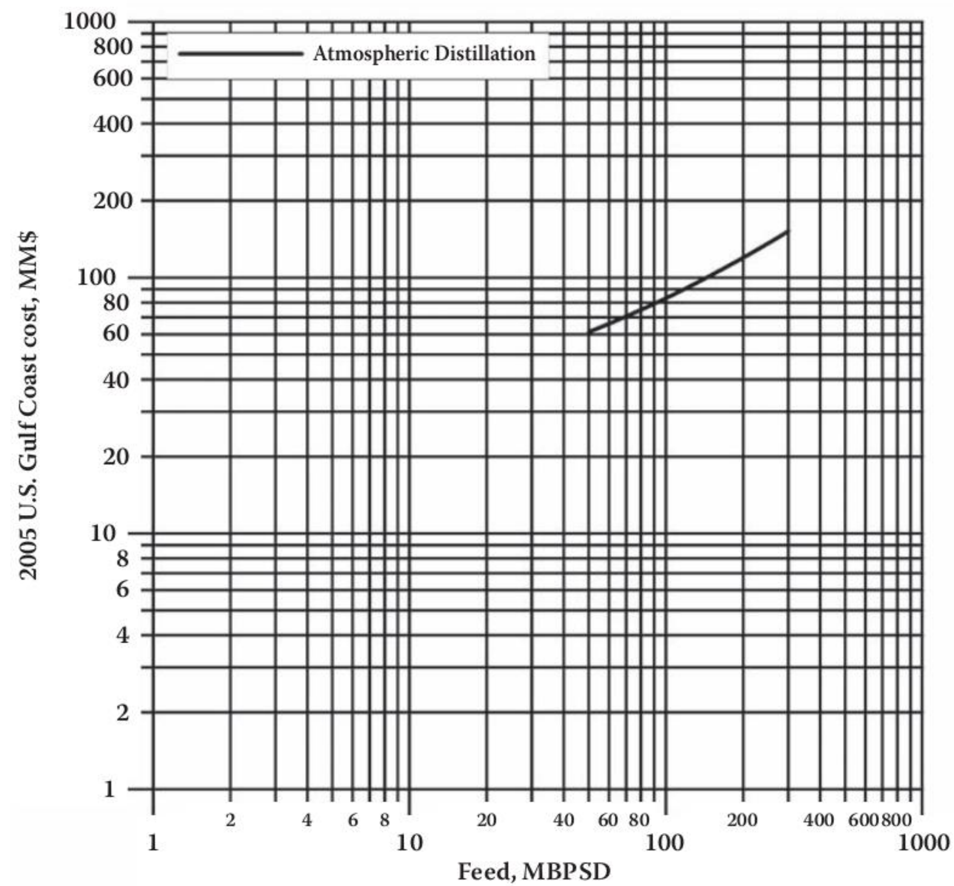


FIGURE 4.9 Atmospheric crude distillation units investment cost: 2005 U.S. Gulf Coast (see Table 4.4).

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

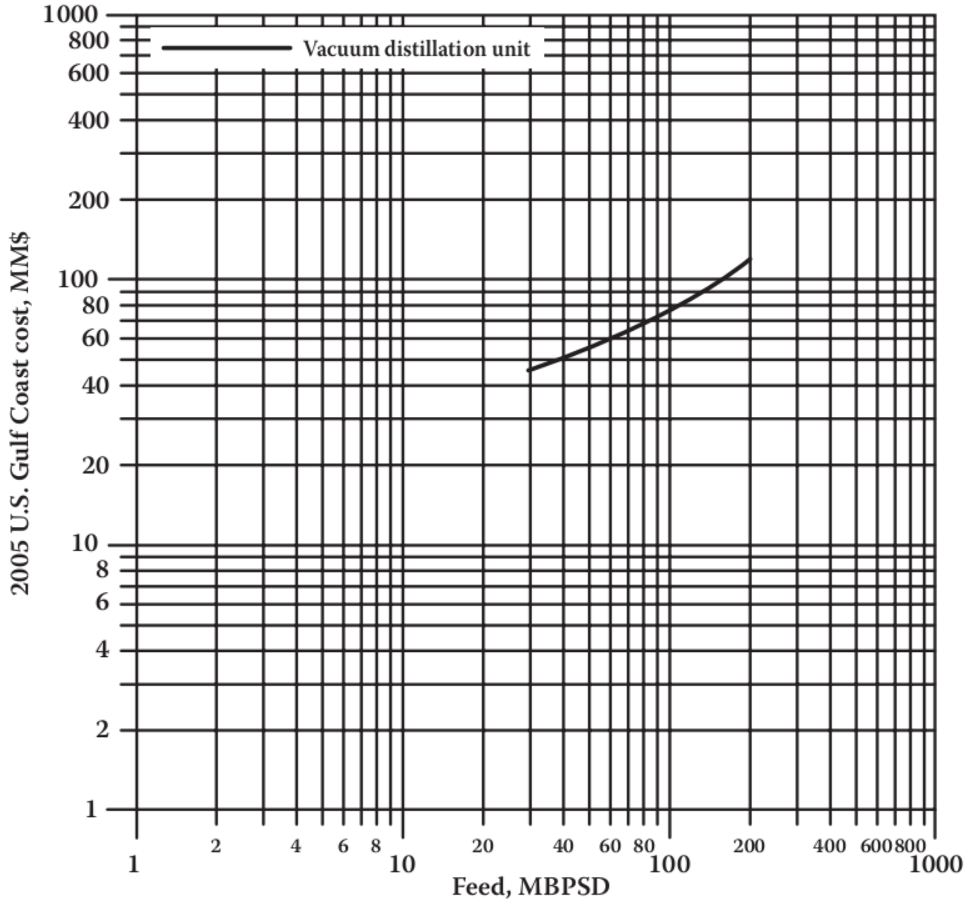


FIGURE 4.11 Vacuum distillation units investment cost: 2005 U.S. Gulf Coast (see Table 4.5).

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

Crude Distillation Unit Costs

Desalter includes

- Conventional electrostatic desalting unit
- Water injection
- Caustic injection
- Water preheating and cooling

Costs not included

- Wastewater treating and disposal
- Cooling water and power supply

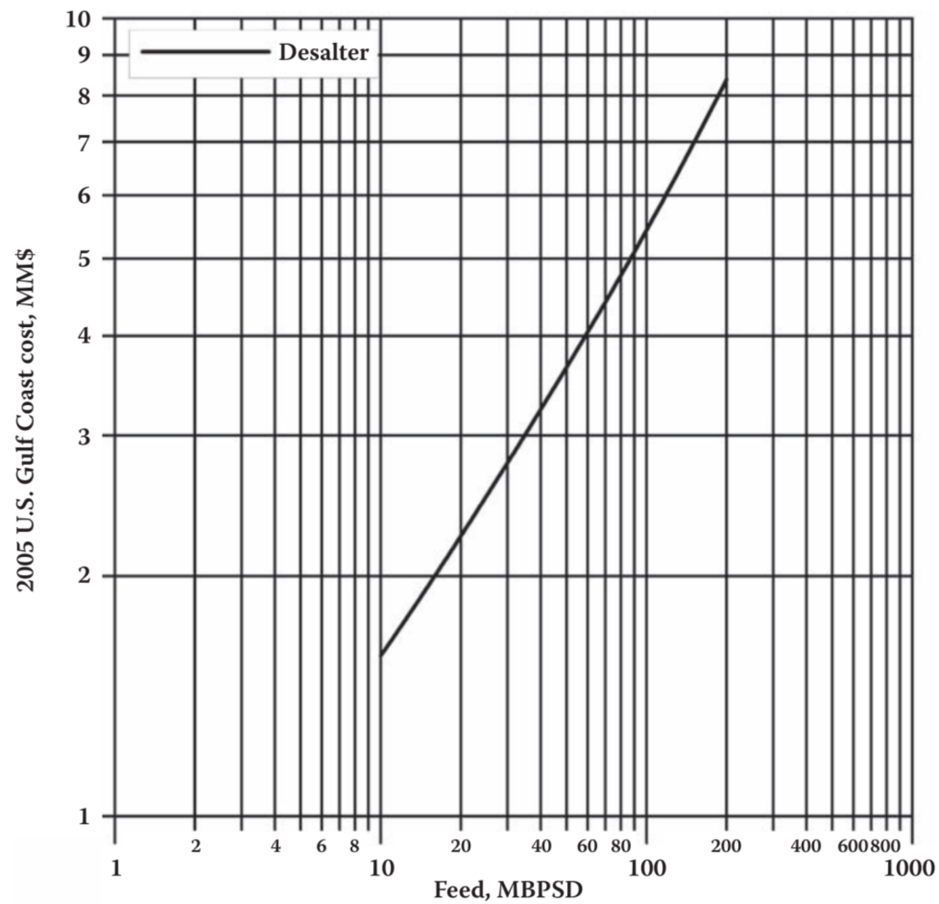


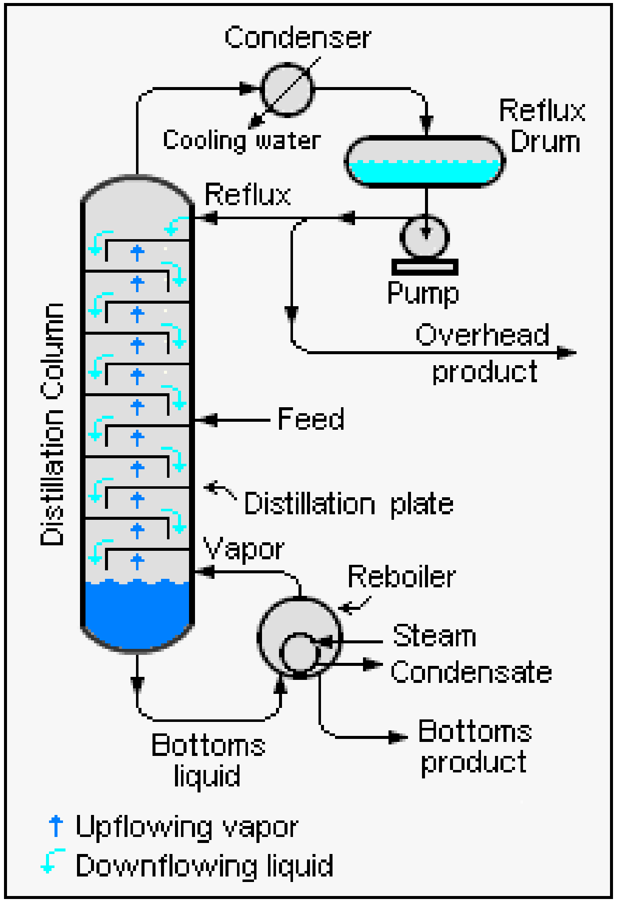
FIGURE 4.7 Crude oil desalting units investment cost: 2005 U.S. Gulf Coast (see Table 4.3).

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

Crude Distillation Technologies

Provider	Features
Foster Wheeler	Complex of atmospheric & vacuum distillation for initial separation of crude oil. May include pre-flash column.
Shell Global Solutions	
TECHNIP	
Uhde GmbH	Vacuum distillation

"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

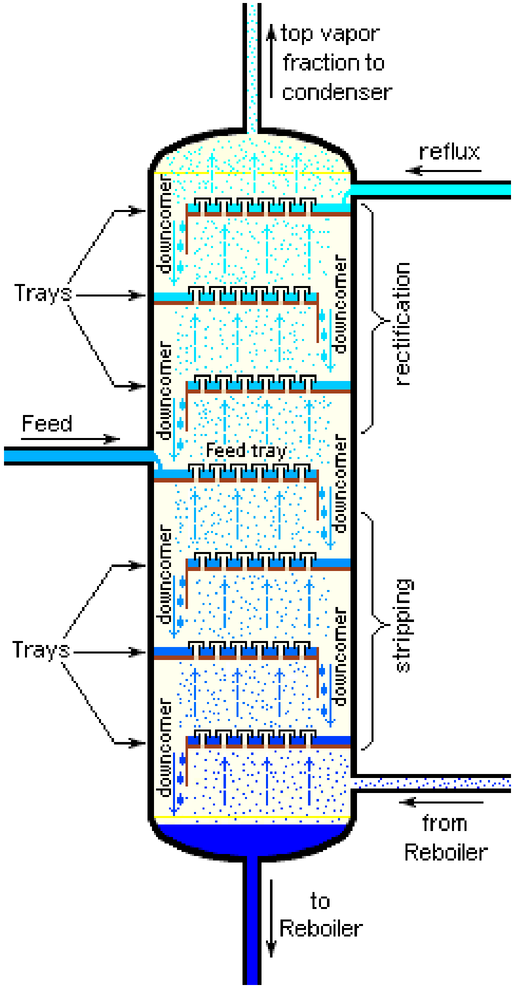
- Trays to contact rising vapors with falling liquids
- Pressure drop across trays – overcome static head of liquid on tray, …

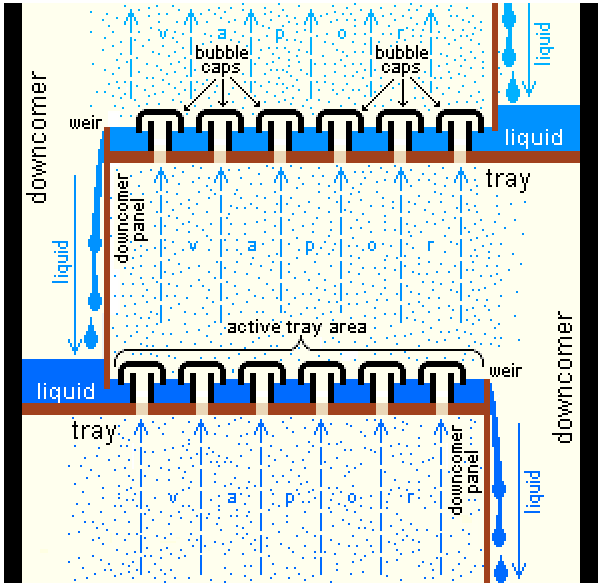
Bottom of column – reboiler to add heat

- 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

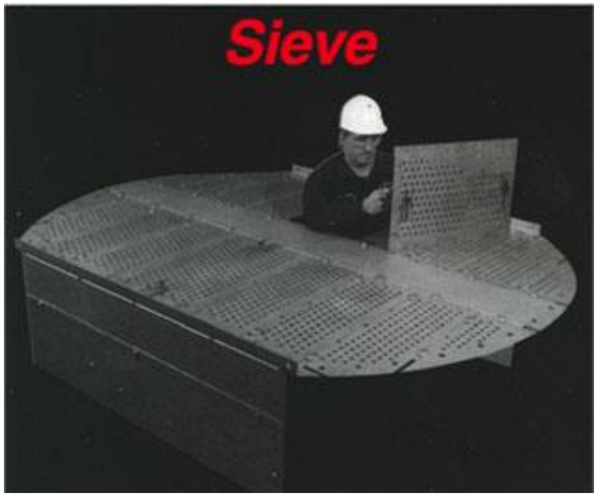
Fractionation Columns & Trays

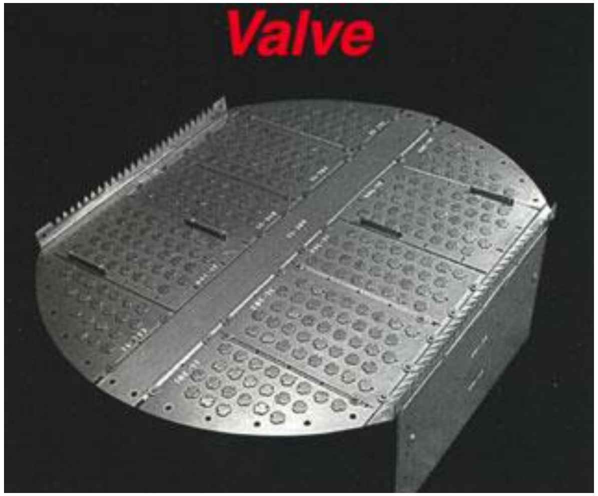




Drawings by Henry Padleckas
http://en.wikipedia.org/wiki/Fractionating_column

Fractionation Tray Types





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

Trays & Packing

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

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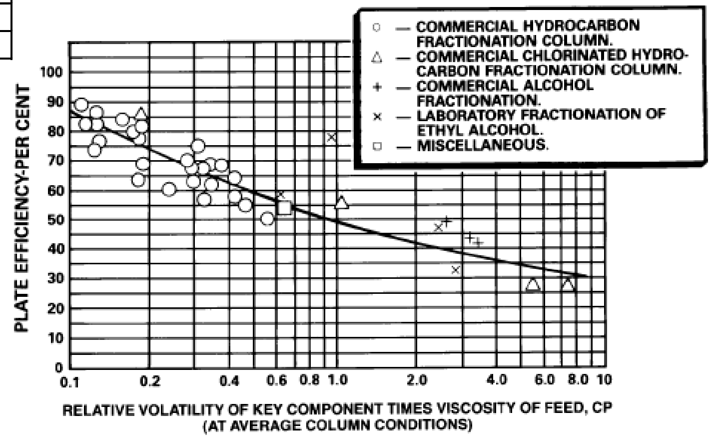
Typical Overall Efficiencies

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

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

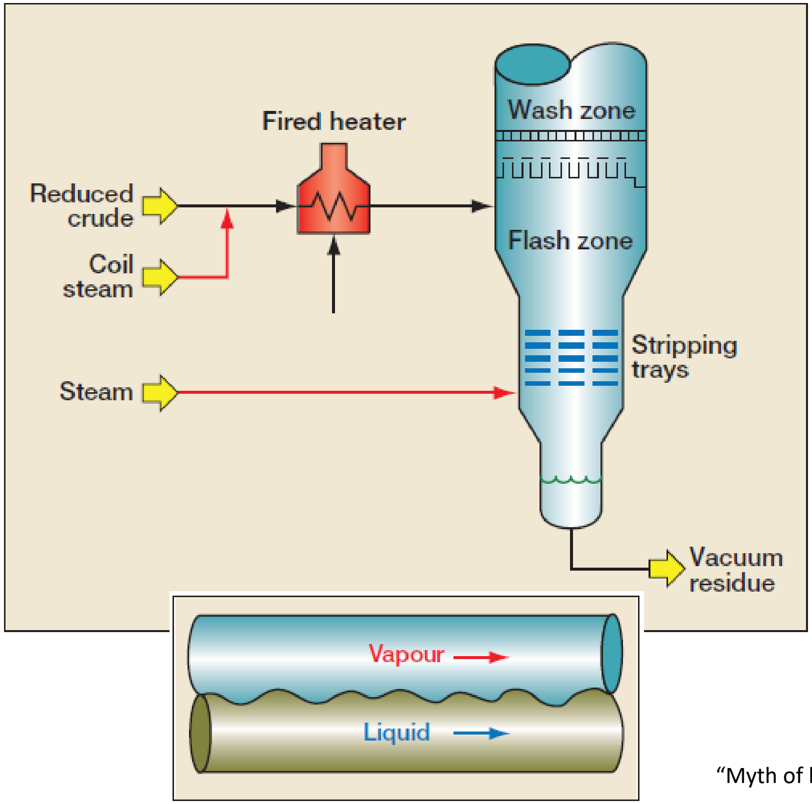
Engineering Data Book, 12th ed.
Gas Processors Association, 2004

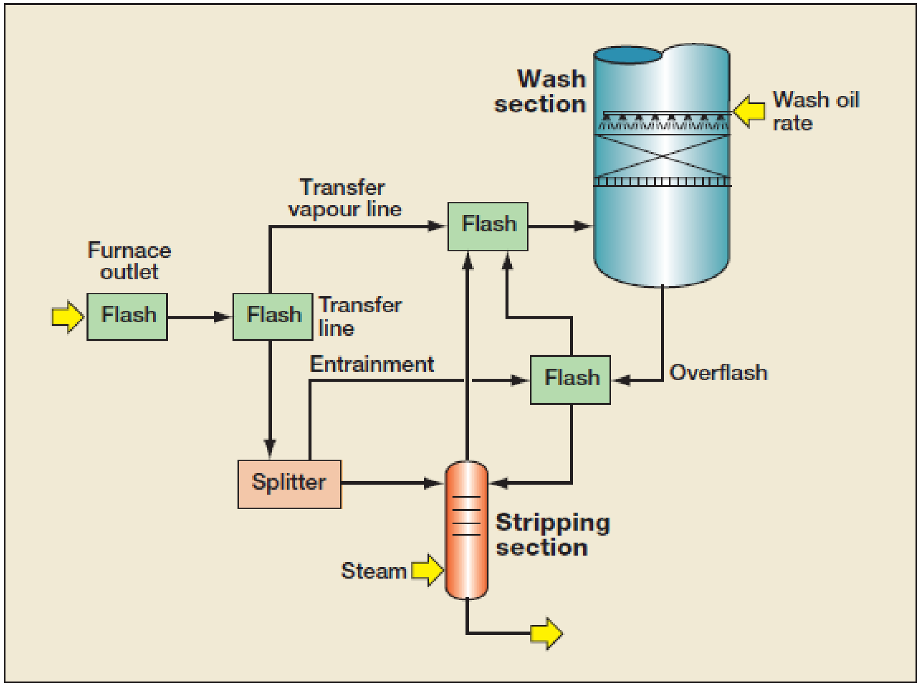


Refinery Process Modeling
Gerald Kaes, Athens Printing Company, 2000, pg. 32

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