Crude Oil Distillation

Chapter 4
Light Naphtha

Crude Oil

Desalter

Gas Separation & Stabilizer

Atmospheric Distillation

Vacuum Distillation

Vacuum Residuum

Coking

Light Naphtha

Heavy Naphtha

AGO

LVGO

HVGO

Solvent Deasphalting

Visbreaking

Fluid Catalytic Cracking

Hydrocracking

Naphtha Reforming

Naphtha Alkylation

Polymerization

Alkylation

Polymers

Polymerization Naphtha

Reformate

Isomerate

Naphtha

Coker Naphtha

Heavy Coker Gas Oil

Light Coker Gas Oil

SDA

Coker Bottoms

Cycle Oils

Fuel Oil

Distillates

Fuel Gas

LPG

Jet Fuels

Kerosene

Residual Fuel Oils

Asphalts

Lubricant

Greases

Waxes

Solvent Dewaxing

Lube Oil

Waxes
Atmospheric & Vacuum Distillation in U.S.

EIA, Jan. 1, 2018 database, published June 2018
http://www.eia.gov/petroleum/refinerycapacity/

Updated: July 12, 2018
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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
Atmospheric & Vacuum Tower Complex
Atmospheric & Vacuum Tower Complex

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

Updated: July 12, 2018
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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 550°F, outlet 600 to 750°F.
    - Heavier crudes cannot be heated to the higher temperatures

Desalter

- Temperature carefully selected — do not let water vaporize
  - Lighter crudes (> 40°API) @ 250°F
  - Heavier crudes (< 30°API) @ 300°F

- 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

Desalting - One Stage

Desalting - Two Stages

Cross-sectional view of Electrostatic crude oil desalter

Drawing by Milton Beychok

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


“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

“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

Example Crude Preheat Trains

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

Ref: “Energy savings in preheat trains with preflash”
Bealing, Gomez-Prado, & Sheldon, PTQ, Q2 2016
Example – Existing Preheat Train

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 prefash”
Bealing, Gomez-Prado, & Sheldon, PTQ, Q2 2016
Product Yield Curves
## Typical “Cut Point” Definitions

<table>
<thead>
<tr>
<th>Cut</th>
<th>TBP IBP (°F)</th>
<th>TBP EP (°F)</th>
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<tr>
<td>Light Naphtha (LSR Gasoline)</td>
<td>80 to 90</td>
<td>180 to 220</td>
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<tr>
<td>Heavy Naphtha</td>
<td>180 to 220</td>
<td>330 to 380</td>
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<tr>
<td>Middle Distillate (Kerosene)</td>
<td>330 to 380</td>
<td>420 to 520</td>
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<tr>
<td>AGO (Atm Gas Oil)</td>
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<td>LVGO (Light Vac Gas Oil)</td>
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<td>HVGO (Heavy Vac Gas Oil)</td>
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<td>Vacuum Resid</td>
<td>950 to 1100</td>
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Industrial distillation columns do not provide perfectly sharp separations

- Initial calculations using crude oil assays assume that all materials at a certain boiling point go 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

Example – Atmospheric Tower Products

<table>
<thead>
<tr>
<th>Yield [vol%]</th>
<th>Raw Crude</th>
<th>Naphtha</th>
<th>Kerosene</th>
<th>Diesel</th>
<th>AGO</th>
<th>Residue</th>
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<td>TBP vol% &amp; °F</td>
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**Diagram:**
- Raw Crude
- Residue
- AGO
- Diesel
- Kerosene
- Naphtha

**Updated:** July 12, 2018

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Example – Scale to Fraction of Crude Charge

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Inc vol% 23.00% 9.30% 19.24% 4.50% 43.97%
Scale to Fraction of Crude Charge

![Graph showing the relationship between cumulative yield and temperature for different crude fractions.](image)

**Table: Scaled Yield Values**

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<td>53.3%</td>
</tr>
<tr>
<td>66.0%</td>
<td>233.0%</td>
<td>13.8%</td>
<td>28.6%</td>
<td>729</td>
<td>54.2%</td>
</tr>
<tr>
<td>70.0%</td>
<td>263.0%</td>
<td>16.1%</td>
<td>29.5%</td>
<td>744</td>
<td>54.7%</td>
</tr>
<tr>
<td>86.0%</td>
<td>293.0%</td>
<td>18.4%</td>
<td>30.4%</td>
<td>761</td>
<td>55.1%</td>
</tr>
<tr>
<td>88.0%</td>
<td>308.0%</td>
<td>19.3%</td>
<td>30.8%</td>
<td>770</td>
<td>55.3%</td>
</tr>
<tr>
<td>90.0%</td>
<td>324.0%</td>
<td>19.7%</td>
<td>31.4%</td>
<td>783</td>
<td>55.6%</td>
</tr>
<tr>
<td>95.0%</td>
<td>345.0%</td>
<td>21.8%</td>
<td>31.8%</td>
<td>803</td>
<td>55.8%</td>
</tr>
<tr>
<td>99.0%</td>
<td>372.0%</td>
<td>23.9%</td>
<td>33.3%</td>
<td>841</td>
<td>56.0%</td>
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<tr>
<td>100.0%</td>
<td>381.0%</td>
<td>25.0%</td>
<td>32.3%</td>
<td>850</td>
<td>56.4%</td>
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</tbody>
</table>

*Incremental volume*  

- Naphtha: 23.00%  
- Kerosene: 9.30%  
- Diesel: 19.26%  
- AGO: 4.56%  
- Residue: 43.57%
Cut Points & Overlaps for Example

<table>
<thead>
<tr>
<th>Yield [vol%]</th>
<th>Raw Crude</th>
<th>Naphtha</th>
<th>Kerosene</th>
<th>Diesel</th>
<th>AGO</th>
<th>Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBP vol% &amp; °F</td>
<td>100%</td>
<td>23.00%</td>
<td>9.30%</td>
<td>19.24%</td>
<td>4.50%</td>
<td>43.97%</td>
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<tr>
<td>1.0%</td>
<td>33</td>
<td>-32</td>
<td>303</td>
<td>372</td>
<td>514</td>
<td>499</td>
</tr>
<tr>
<td>5.0%</td>
<td>96</td>
<td>35</td>
<td>343</td>
<td>442</td>
<td>584</td>
<td>635</td>
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<tr>
<td>10.0%</td>
<td>176</td>
<td>58</td>
<td>357</td>
<td>467</td>
<td>620</td>
<td>713</td>
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<tr>
<td>15.0%</td>
<td>248</td>
<td>83</td>
<td>366</td>
<td>482</td>
<td>642</td>
<td>766</td>
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<tr>
<td>20.0%</td>
<td>312</td>
<td>90</td>
<td>375</td>
<td>493</td>
<td>657</td>
<td>807</td>
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<tr>
<td>30.0%</td>
<td>435</td>
<td>134</td>
<td>390</td>
<td>513</td>
<td>682</td>
<td>874</td>
</tr>
<tr>
<td>40.0%</td>
<td>525</td>
<td>167</td>
<td>403</td>
<td>532</td>
<td>699</td>
<td>938</td>
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<tr>
<td>50.0%</td>
<td>621</td>
<td>202</td>
<td>416</td>
<td>551</td>
<td>715</td>
<td>991</td>
</tr>
<tr>
<td>60.0%</td>
<td>741</td>
<td>233</td>
<td>429</td>
<td>572</td>
<td>729</td>
<td>1,032</td>
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<tr>
<td>70.0%</td>
<td>886</td>
<td>283</td>
<td>442</td>
<td>595</td>
<td>744</td>
<td>1,074</td>
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<tr>
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<td>1,011</td>
<td>293</td>
<td>456</td>
<td>622</td>
<td>761</td>
<td>1,128</td>
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<tr>
<td>85.0%</td>
<td>1,056</td>
<td>308</td>
<td>464</td>
<td>637</td>
<td>770</td>
<td>1,164</td>
</tr>
<tr>
<td>90.0%</td>
<td>1,111</td>
<td>324</td>
<td>473</td>
<td>656</td>
<td>783</td>
<td>1,213</td>
</tr>
<tr>
<td>95.0%</td>
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<td>345</td>
<td>485</td>
<td>680</td>
<td>803</td>
<td>1,288</td>
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<tr>
<td>99.0%</td>
<td>1,361</td>
<td>372</td>
<td>506</td>
<td>718</td>
<td>841</td>
<td>1,428</td>
</tr>
</tbody>
</table>

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, 32.90%, 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
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>
<thead>
<tr>
<th>Provider</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foster Wheeler</td>
<td>Complex of atmospheric &amp; vacuum distillation for initial separation of crude oil. May include pre-flash column.</td>
</tr>
<tr>
<td>Shell Global Solutions</td>
<td>Vacuum distillation</td>
</tr>
<tr>
<td>TECHNIP</td>
<td></td>
</tr>
<tr>
<td>Uhde GmbH</td>
<td>Vacuum distillation</td>
</tr>
</tbody>
</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 & modified by Milton Beychok:

Updated: July 12, 2018
Copyright © 2017 John Jechura (jjechura@mines.edu)
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

## Typical Overall Efficiencies

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

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<th>Drickamer &amp; Bradford in Ludwig</th>
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<td>cP</td>
<td>Ave Viscosity of liquid on plates</td>
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<td>50</td>
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<td>1.70</td>
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**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