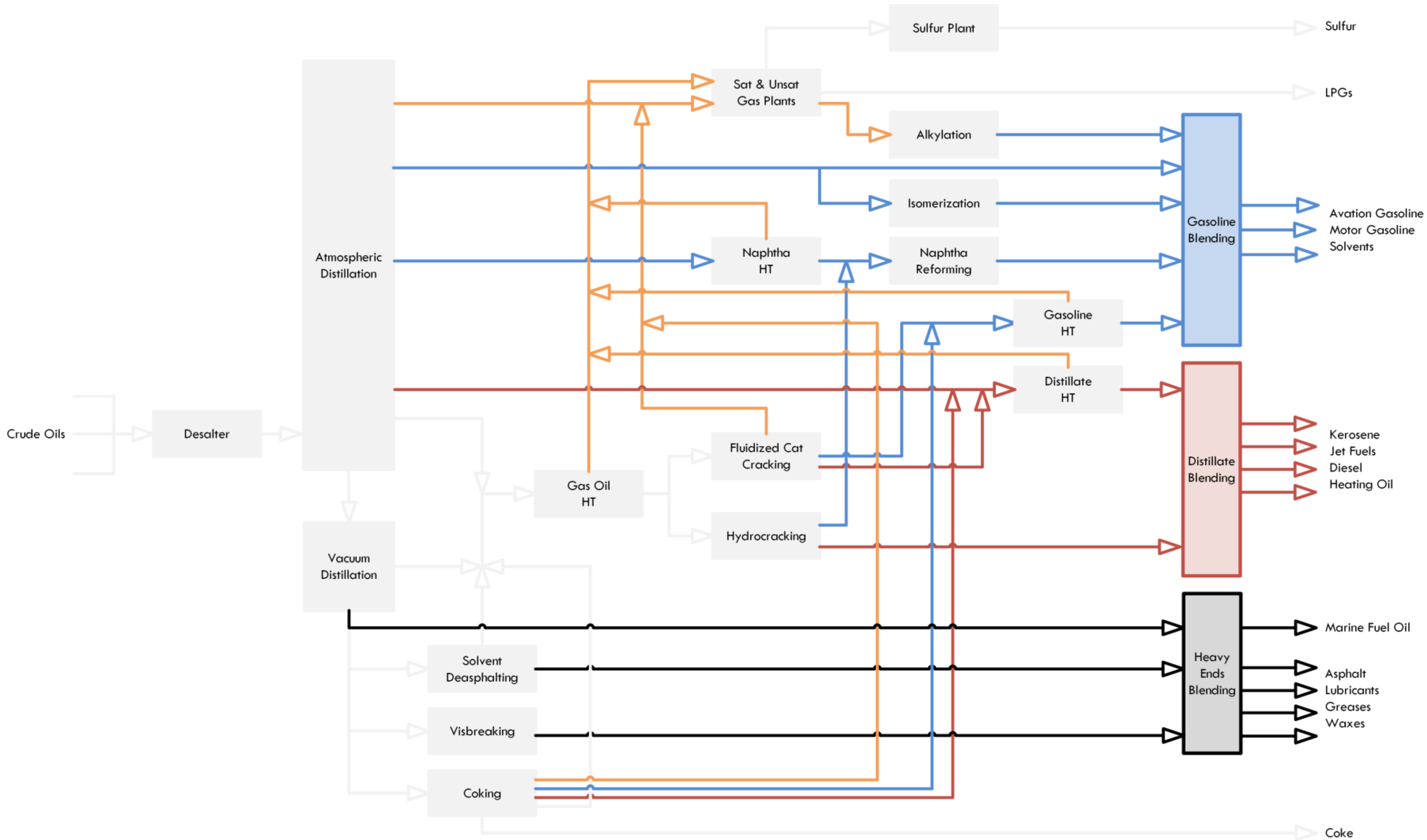
Product Blending & Optimization Considerations

Chapters 12 & 14

COLORADO SCHOOL OF MINES

Petroleum Refinery Block Flow Diagram



Updated: July 1, 2019

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

Topics

Blending

- Blending equations
- Specifications / targets
- Typical blend stock properties

Optimization

- Economics & planning applications
- Optimization tools
  - Linear programming
  - Non-linear (geometric) programming

Adjusting upstream operations to meet downstream targets

Blending

Updated: July 1, 2019

Blending Equations

Volume blending equations

- Specific gravity
- Aromatics & olefins content (vol%)

$$X_{mix} = \sum v_i X_i = \frac{\sum V_i X_i}{\sum V_i}$$

Mass blending equations

- Sulfur & nitrogen content (wt% or ppm)
- Nickel & vanadium (ppm)
- Carbon residue (CCR, MCRT, …)

$$X_{mix} = \sum w_i X_i = \frac{\sum V_i \gamma_{oi} X_i}{\sum V_i \gamma_{oi}}$$

Reid Vapor Pressure (RVP)

$$(\text{RVP})_{mix}^{1.25} = \frac{\sum V_i (\text{RVP})_i^{1.25}}{\sum V_i}$$

Octane numbers – Simple, by volume

$$(RON)_{mix} = \frac{\sum V_i (RON)_i}{\sum V_i}$$

$$(MON)_{mix} = \frac{\sum V_i (MON)_i}{\sum V_i}$$

Viscosity

$$\log(\log(\nu_{mix} + 0.7)) = \frac{\sum V_i \log(\log(\nu_i + 0.7))}{\sum V_i}$$

Updated: July 1, 2019

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Non-Linear Octane Blending Formula

Developed by Ethyl Corporation using a set of 75 & 135 blends

$$R = \bar{R} + a_1\left[\overline{RJ} - \bar{R}\times\bar{J}\right] + a_2\left[\overline{\left(O^2\right)} - \bar{O}^2\right] + a_3\left[\overline{\left(A^2\right)} - \bar{A}^2\right]$$

$$M = \bar{M} + b_1\left[\overline{MJ} - \bar{M}\times\bar{J}\right] + b_2\left[\overline{\left(O^2\right)} - \bar{O}^2\right] + b_3\left[\frac{\overline{\left(A^2\right)} - \bar{A}^2}{100}\right]^2$$

$$\text{"Road" Octane} = \frac{R+M}{2}$$

$$\text{Sensitivity} = J \equiv R - M$$

$$\text{Volume Average} = \bar{X} \equiv \frac{\sum V_i \times X_i}{\sum V_i}$$

	75 blends	135 blends
a_1	0.03224	0.03324
a_2	0.00101	0.00085
a_3	0	0
b_1	0.04450	0.04285
b_2	0.00081	0.00066
b_3	-0.00645	-0.00632

Petroleum Refinery Process Economics, 2nd ed. ,
by Robert E. Maples, PennWell Corp., 2000

Typical Gasoline Blend Stock Properties

No.	Component	RVP, psi	(R+M)/2	MON	RON	°API
1	iC4	71.0	92.5	92.0	93.0	
2	nC4	52.0	92.5	92.0	93.0	
3	iC5	19.4	92.0	90.8	93.2	
4	nC5	14.7	72.0	72.4	71.5	
5	iC6	6.4	78.8	78.4	79.2	
6	LSR gasoline (C5-180°F)	11.1	64.0	61.6	66.4	78.6
7	LSR gasoline isomerized once-through	13.5	82.1	81.1	83.0	80.4
8	HSR gasoline	1.0	60.5	58.7	62.3	48.2
9	Light hydrocrackate	12.9	82.6	82.4	82.8	79.0
10	Hydrocrackate, C5-C6	15.5	87.4	85.5	89.2	86.4
11	Hydrocrackate, C6-190°F	3.9	74.6	73.7	75.5	85.0
12	Hydrocrackate, 190-250°F	1.7	77.3	75.6	79.0	55.5
13	Heavy hydrocrackate	1.1	67.5	67.3	67.6	49.0
14	Coker gasoline	3.6	63.7	60.2	67.2	57.2
15	Light thermal gasoline	9.9	76.8	73.2	80.3	74.0
16	C6+ light thermal gasoline	1.1	72.5	68.1	76.8	55.1
17	FCC gasoline, 200-300°F	1.4	84.6	77.1	92.1	49.5
18	Hydrog. light FCC gasoline, C5+	13.9	82.1	80.9	83.2	51.5
19	Hydrog. C5-200°F FCC gasoline	14.1	86.5	81.7	91.2	58.1
20	Hydrog. light FCC gasoline, C6+	5.0	80.2	74.0	86.3	49.3
21	Hydrog. C5+ FCC gasoline	13.1	85.9	80.7	91.0	54.8
22	Hydrog. 300-400°F FCC gasoline	0.5	85.8	81.3	90.2	48.5
23	Reformate, 94 RON	2.8	89.2	84.4	94.0	45.8
24	Reformate, 98 RON	2.2	92.3	86.5	98.0	43.1
25	Reformate, 100 RON	3.2	94.1	88.2	100.0	41.2
26	Aromatic concentrate	1.1	100.5	94.0	107.0	
27	Alkylate, C3=	5.7	89.1	87.3	90.8	
28	Alkylate, C4=	4.6	96.6	95.9	97.3	70.3
29	Alkylate, C3=, C4=	5.0	93.8	93.0	94.5	
30	Alkylate, C5=	1.0	89.3	88.8	89.7	
31	Polymer	8.7	90.5	84.0	96.9	59.5

Table 12.1 Blending Component Values for Gasoline Blending Streams
Petroleum Refining Technology & Economics – 5th Ed. by James Gary, Glenn Handwerk, & Mark Kaiser, CRC Press, 2007

Gasoline Blending Considerations

What is available?

- Amounts
- Properties
  - Appropriate to determine product properties
- Associated costs / values

What are you trying to make?

- Amount(s)
- Properties
  - Volatility / RVP (maximum)
  - Octane number (minimum)
  - Drivability Index
  - Distillation
    - T10 (minimum)
    - T50 (range)
    - T90 (maximum)
  - Composition
    - Sulfur (maximum)
    - Benzene & total aromatics (maximums)
    - Olefins (maximum)
- Value

Gasoline Blend Example – 3 Blend Stocks, 2 Specs

Use 3 blend stocks to make regular gasoline (87 road octane) for both summer (9 psi RVP) & winter (15 psi RVP)

$$\left(\frac{R+M}{2}\right)=(92.5)v_{nC4}+(64.0)v_{LSR}+(94.1)v_{Ref}$$

$$(RVP)^{1.25}=(52.0)^{1.25}v_{nC4}+(11.1)^{1.25}v_{LSR}+(3.2)^{1.25}v_{Ref}$$

$$1=v_{nC4}+v_{LSR}+v_{Ref}$$

	Blend Stocks			Regular, no nC4	Regular Summer	Regular Winter
Volume Fractions:						
n-Butane	1				0.056	0.160
LSR (C5 - 180°F)		1		0.236	0.233	0.227
Reformate, 100 RON			1	0.764	0.711	0.613
RVP [psi]	52.0	11.1	3.2	5.3	9.0	15.0
RON	93.0	66.4	100.0	92.1	91.8	91.2
MON	92.0	61.6	88.2	81.9	82.2	82.8
(R+M)/2	92.5	64.0	94.1	87.0	87.0	87.0
Volume Ratios:						
Total:LSR				4.2	4.3	4.4
Reformate:LSR				3.2	3.1	2.7

Diesel Blending Considerations

Available blend stocks

- Amounts
- Properties
  - Appropriate to determine product properties
- Associated costs / values

Specification of final product(s)

- Amount(s)
- Properties
  - Cetane index (minimum)
  - Flash Point (minimum)
  - Distillation
    - T90 (minimum & maximum)
  - Cold properties
    - Cloud point (minimum)
    - Pour point (minimum)
  - Composition
    - Sulfur (maximum)
    - Aromaticity (maximum)
    - Carbon residue (maximum)
  - Color
- Value

Optimization

Optimization for Economics & Planning

What ***should*** be done rather than what ***can*** be done

Optimization

- Combines models to…
  - Describe operations
  - Constraints to operations
- Economics added to define costs & benefits to all actions
- "Optimal" is best of the "feasible" possibilities

Optimization models tend to be data-driven rather than mathematical model driven.

Economics & Planning Applications

Crude oil evaluation
- Incremental value of an opportunity crude compared to base slate
- Take into account change in products produced

Production planning

Day-to-day operations optimization

Product blending & pricing
- May have opportunity to separately purchase blend stocks

Shutdown planning
- Multi time periods, must take into account changes in inventories

Multirefining supply & distribution

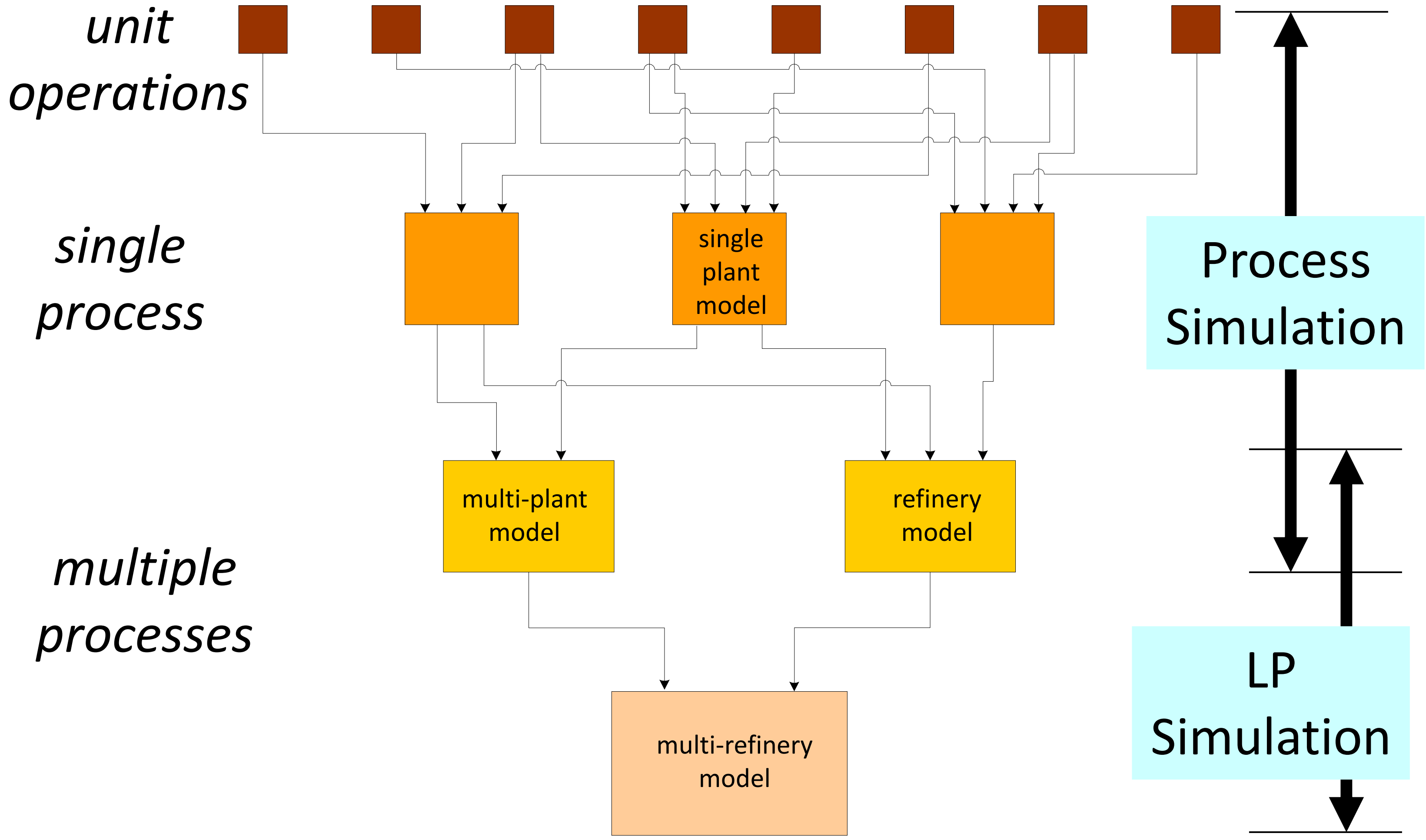
Yearly budgeting

Investment studies

Environmental studies

Technology evaluation

Modeling Hierarchy



Unit Representations

Simple vector model

	Yield Vector
Feedstock	
Butylene	-1.0000
Isobutane	-1.2000
Product	
n-Butane	0.1271
Pentane	0.0680
Alkylate	1.5110
"Alky Bottoms	0.1190
Tar	0.0096
Utilities	
Steam, lb	7.28
Power, kWh	2.45
Cooling Water, M gal	2.48
Fuel, MMBtu	0.69

For every unit of Butylene consumed, must also consume the relative amount of isobutane, produce the shown amounts of products, & use the shown amounts of utilities

Delta-Base model

	Feed	Base Yield	Delta K_W	Delta API
Feed	1.0	-1.0		
Hydrogen		-1500		
C5-180		8.1	1.0	3.6
180-400		28.0	-5.5	11.0
Kw	-12.1	10.9	1.2	
API	-22.0	20.0		4.0
Relative Activity	1	1	1	0.5

Relative activities calculated from actual properties – the Kw & API rows are zero

$$\text{API} = -\frac{1\times(-22.0)+1\times 20.0}{4.0} = 0.5$$

Correct base yields to take into account actual properties & relative activities

$$\text{C5-180} = \frac{1\times 8.1 + 1\times 1.0 + 0.5\times 3.6}{1} = 10.9$$

What is “Linear Programming”?

Word “programming” used here in the sense of “planning”

For N independent variables (that can be zero or positive) **maximize**

$$z = a_{01}x_1 + a_{02}x_2 + \cdots + a_{0N}x_N$$

subject to M additional constraints (all bn positive)

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{iN}x_N \le b_i$$
$$a_{j1}x_1 + a_{j2}x_2 + \cdots + a_{jN}x_N \ge b_j$$
$$a_{k1}x_1 + a_{k2}x_2 + \cdots + a_{kN}x_N = b_k$$

Terminology

- Objective Function – function z to be maximized
- Feasible Vector – set of values x_1, x_2, …, x_N that satisfies all constraints
- Optimal Feasible Vector – feasible vector that maximizes the objective function

Solutions

- Will tend to be in the “corners” of where the constraints meet
- May not have a solution because of incompatible constraints or area unbounded towards the optimum

Change Blending Equations to Fit Linear Form

Sum of blending factors must be removed from the denominator

- Volume blending equations

$$X_{mix} = \sum v_i X_i = \frac{\sum V_i X_i}{\sum V_i} \quad \Rightarrow \quad 0 = \sum V_i \left(X_i - X_{mix} \right)$$

- Mass blending equations

$$X_{mix} = \sum w_i X_i = \frac{\sum V_i \gamma_{oi} X_i}{\sum V_i \gamma_{oi}} \quad \Rightarrow \quad 0 = \sum V_i \left[\gamma_{oi} \left(X_i - X_{mix} \right) \right]$$

Non-Linear Programming

Non-linear blending rules can more closely match the physics of the problem

- Example: octane blending models

$$R = \bar{R} + 0.03324\left[\overline{RJ} - \bar{R}\cdot\bar{J}\right] + 0.00085\left[\overline{\left(O^2\right)} - \bar{O}^2\right]$$

$$M = \bar{M} + 0.04285\left[\overline{MJ} - \bar{M}\cdot\bar{J}\right] + 0.00066\left[\overline{\left(O^2\right)} - \bar{O}^2\right] - 6.32\times10^{-7}\left[\overline{\left(A^2\right)} - \bar{A}^2\right]$$

Guarantees of solutions are more tenuous

- Not necessarily at constraints
- Discontinuous feasible regions possible

Types of optimization algorithms

- Local optimization
  - Based on following gradients
    - Excel's Solver based on GRG2
- Global optimization
  - Randomly search overall region before switching to local optimization technique
    - Simulated annealing

Gasoline Blending Considerations

What is available?

- Amounts
- Properties
  - Appropriate to determine product properties
- Associated costs / values

What are you trying to make?

- Amount(s)
- Properties
  - Volatility / RVP (maximum)
  - Octane number (minimum)
  - Drivability Index
  - Distillation
    - T10 (minimum)
    - T50 (range)
    - T90 (maximum)
  - Composition
    - Sulfur (maximum)
    - Benzene & total aromatics (maximums)
    - Olefins (maximum)
- Value

Gasoline Blending Example – All Into Regular

Raw Materials

	Properties for Blending Calculations							
	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

	Cost & Availability			*Usage*				
	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**30,000**	**0**	30,000	**30,000**	**0**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**35,000**	**0**	35,000	**35,000**	**0**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**60,000**	**60,000**	**0**	60,000	**60,000**	**0**
Reformate (Low Benzene)	**2.75**	**0**	**0**	**0**	**0**	0	**0**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**70,000**	**0**	70,000	**70,000**	**0**
Alkylate	**2.75**	**0**	**40,000**	**40,000**	**0**	40,000	**40,000**	**0**

Products

Lower & Upper Limits on Properties

		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1,000,000**
Premium	**2.85**	**1**	**1**

Cost & Revenue

Revenue ($)	$646,250	$1	$646,251
Cost($)	$557,250	$1	$557,251
Profit ($)	$89,000	$0	**$89,000**

Product Calculations
Volumes & Properties

	Regular	Premium	Total
Produced	**235,000**	**0**	235,000
RON	93.02	83.24	
MON	84.87	81.59	
(R+M)/2	**88.9**	**82.4**	
RVP	**12.9**	**28.0**	
$RVP^{1.25}$	24.43	64.46	
Benzene	**0.90**	**0.48**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**234,999**	**765,000**
	Vol*Octane	**457,000**	**4,948,000**
	Vol*$RVP^{1.25}$	**5,741,488**	**1,195,675**
	Vol*Benzene	**210,750**	**47,750**
Premium	Volume	**-1**	**1**
	Vol*Octane	**-3**	**11**
	Vol*$RVP^{1.25}$	**25**	**-14**
	Vol*Benzene	**0**	**0**

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Gasoline Blending Example – Only Regular (Optimized)

Raw Materials — *Properties for Blending Calculations*

	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

Cost & Availability / *Usage*

	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**30,000**	**0**	30,000	**30,000**	**0**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**35,000**	**0**	35,000	**35,000**	**0**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**60,000**	**12,628**	**0**	12,628	**12,628**	**47,372**
Reformate (Low Benzene)	**2.75**	**0**	**0**	**0**	**0**	0	**0**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**70,000**	**0**	70,000	**70,000**	**0**
Alkylate	**2.75**	**0**	**40,000**	**39,999**	**1**	40,000	**40,000**	**0**

Products — *Lower & Upper Limits on Properties*

		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1,000,000**
Premium	**2.85**	**1**	**1**

Cost & Revenue

Revenue ($)	$515,973	$3	$515,976
Cost($)	$424,605	$2	$424,607
Profit ($)	$91,368	$1	**$91,369**

Product Calculations
Volumes & Properties

	Regular	Premium	Total
Produced	**187,627**	**1**	187,628
RON	91.25	91.75	
MON	84.03	90.25	
(R+M)/2	**87.6**	**91.0**	
RVP	**15.0**	**15.0**	
$RVP^{1.25}$	29.52	29.52	
Benzene	**0.66**	**0.19**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**187,626**	**812,373**
	Vol*Octane	**120,652**	**4,194,760**
	Vol*$RVP^{1.25}$	**5,538,708**	**0**
	Vol*Benzene	**123,111**	**83,278**
Premium	Volume	**0**	**0**
	Vol*Octane	**0**	**19**
	Vol*$RVP^{1.25}$	**30**	**0**
	Vol*Benzene	**0**	**1**

Gasoline Blending Example – Only Premium (Optimized)

Raw Materials — *Properties for Blending Calculations*

	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

	Cost & Availability			*Usage*				
	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**0**	**30,000**	30,000	**30,000**	**0**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**0**	**17,433**	17,433	**17,433**	**17,567**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**60,000**	**0**	**60,000**	60,000	**60,000**	**0**
Reformate (Low Benzene)	**2.75**	**0**	**0**	**0**	**0**	0	**0**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**0**	**32,959**	32,959	**32,959**	**37,041**
Alkylate	**2.75**	**0**	**40,000**	**0**	**40,000**	40,000	**40,000**	**0**

Products — *Lower & Upper Limits on Properties*

		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1**
Premium	**2.85**	**1**	**1,000,000**

Cost & Revenue

Revenue ($)	$3	$514,115	$514,118
Cost($)	$2	$424,930	$424,932
Profit ($)	$0	$89,186	**$89,186**

Product Calculations

Volumes & Properties

	Regular	Premium	Total
Produced	**1**	**180,391**	180,392
RON	90.90	94.67	
MON	83.10	87.33	
(R+M)/2	**87.0**	**91.0**	
RVP	**15.0**	**15.0**	
$RVP^{1.25}$	29.52	29.52	
Benzene	**1.10**	**0.88**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**0**	**0**
	Vol*Octane	**0**	**23**
	Vol*$RVP^{1.25}$	**30**	**0**
	Vol*Benzene	**1**	**0**
Premium	Volume	**180,390**	**819,609**
	Vol*Octane	**0**	**3,427,436**
	Vol*$RVP^{1.25}$	**5,325,125**	**0**
	Vol*Benzene	**158,662**	**39,769**

Updated: July 1, 2019

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Gasoline Blending Example – Combined (Optimized)

Raw Materials

	Properties for Blending Calculations							
	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

	Cost & Availability			*Usage*				
	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**17,925**	**12,075**	30,000	**30,000**	**0**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**35,000**	**0**	35,000	**35,000**	**0**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**60,000**	**43,599**	**16,401**	60,000	**60,000**	**0**
Reformate (Low Benzene)	**2.75**	**0**	**0**	**0**	**0**	0	**0**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**24,226**	**45,774**	70,000	**70,000**	**0**
Alkylate	**2.75**	**0**	**40,000**	**0**	**40,000**	40,000	**40,000**	**0**

Products

	Lower & Upper Limits on Properties		
		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**15.0**
	$RVP^{1.25}$	0.0	29.5
	Benzene	**0.0**	**1.1**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1,000,000**
Premium	**2.85**	**1**	**1,000,000**

Cost & Revenue

Revenue ($)	$332,063	$325,613	$657,675
Cost($)	$272,051	$285,199	$557,250
Profit ($)	$60,011	$40,414	**$100,425**

Product Calculations
Volumes & Properties

	Regular	Premium	Total
Produced	**120,750**	**114,250**	235,000
RON	91.00	95.15	
MON	83.00	86.85	
(R+M)/2	**87.0**	**91.0**	
RVP	**15.0**	**10.6**	
$RVP^{1.25}$	29.52	19.05	
Benzene	**1.09**	**0.69**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**120,749**	**879,250**
	Vol*Octane	**0**	**2,777,250**
	Vol*$RVP^{1.25}$	**3,564,521**	**0**
	Vol*Benzene	**131,888**	**937**
Premium	Volume	**114,249**	**885,750**
	Vol*Octane	**0**	**2,170,750**
	Vol*$RVP^{1.25}$	**2,176,967**	**1,195,675**
	Vol*Benzene	**78,862**	**46,813**

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Gasoline Blending Example – Lower RVP & Benzene

Raw Materials

Properties for Blending Calculations

	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

	Cost & Availability			*Usage*				
	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**8,187**	**0**	8,188	**8,188**	**21,812**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**28,305**	**0**	28,305	**28,305**	**6,695**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**60,000**	**0**	**0**	0	**0**	**60,000**
Reformate (Low Benzene)	**2.75**	**0**	**0**	**0**	**0**	0	**0**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**60,824**	**0**	60,824	**60,824**	**9,176**
Alkylate	**2.75**	**0**	**40,000**	**40,000**	**0**	40,000	**40,000**	**0**

Products

Lower & Upper Limits on Properties

		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**9.0**
	$RVP^{1.25}$	0.0	15.6
	Benzene	**0.0**	**0.62**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**9.0**
	$RVP^{1.25}$	0.0	15.6
	Benzene	**0.0**	**0.62**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1,000,000**
Premium	**2.85**	**1**	**1,000,000**

Cost & Revenue

Revenue ($)	$377,618	$3	$377,621
Cost($)	$333,125	$3	$333,127
Profit ($)	$44,493	$0	**$44,493**

Product Calculations

Volumes & Properties

	Regular	Premium	Total
Produced	**137,316**	**1**	137,317
RON	90.76	95.03	
MON	83.24	86.97	
(R+M)/2	**87.0**	**91.0**	
RVP	**9.0**	**9.0**	
$RVP^{1.25}$	15.59	15.59	
Benzene	**0.62**	**0.62**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**137,315**	**862,684**
	Vol*Octane	**0**	**3,158,261**
	$Vol*RVP^{1.25}$	**2,140,540**	**0**
	Vol*Benzene	**85,136**	**0**
Premium	Volume	**0**	**999,999**
	Vol*Octane	**0**	**19**
	$Vol*RVP^{1.25}$	**16**	**0**
	Vol*Benzene	**1**	**0**

Updated: July 1, 2019

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Gasoline Blending Example –Low Benzene Reformate

Raw Materials

	Properties for Blending Calculations							
	RON	MON	(R+M)/2	RVP	$RVP^{1.25}$	Aromatics	Olefins	Benzene
Butane	93.0	92.0	92.5	54	146.4	0.0	0.0	0.00
Straight Run Naphtha	78.0	76.0	77	11.2	20.5	2.2	0.9	0.73
Isomerate	83.0	81.1	82.05	13.5	25.9	1.6	0.1	0.00
Reformate (High Octane)	100.0	88.2	94.1	3.2	4.3	94.2	0.6	1.85
Reformate (Low Benzene)	93.7	84.0	88.85	2.8	3.6	61.1	1.0	0.12
FCC Naphtha	92.1	77.1	84.6	1.4	1.5	35.2	32.6	1.06
Alkylate	97.3	95.9	96.6	4.6	6.7	0.5	0.2	0.00

	Cost & Availability			*Usage*				
	Cost ($/gal)	Minimum Required	Maximum Available	Regular	Premium	Total	Minimum Slack	Maximum Slack
Butane	**0.85**	**0**	**30,000**	**13,552**	**1,355**	14,907	**14,907**	**15,093**
Straight Run Naphtha	**2.05**	**0**	**35,000**	**35,000**	**0**	35,000	**35,000**	**0**
Isomerate	**2.20**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (High Octane)	**2.80**	**0**	**0**	**0**	**0**	0	**0**	**0**
Reformate (Low Benzene)	**2.75**	**0**	**65,400**	**53,656**	**11,744**	65,400	**65,400**	**0**
FCC Naphtha	**2.60**	**0**	**70,000**	**70,000**	**0**	70,000	**70,000**	**0**
Alkylate	**2.75**	**0**	**40,000**	**35,854**	**4,146**	40,000	**40,000**	**0**

Products

Lower & Upper Limits on Properties

		Lower	Upper
Regular	Octane	**87**	**110**
	RVP	**0.0**	**9.0**
	$RVP^{1.25}$	0.0	15.6
	Benzene	**0.0**	**0.62**
Premium	Octane	**91**	**110**
	RVP	**0.0**	**9.0**
	$RVP^{1.25}$	0.0	15.6
	Benzene	**0.0**	**0.62**

Price & Production Requirements

	Price ($/gal)	Minimum Required	Maximum Allowed
Regular	**2.75**	**1**	**1,000,000**
Premium	**2.85**	**1**	**1,000,000**

Cost & Revenue

Revenue ($)	$572,172	$49,147	$621,318
Cost($)	$511,423	$44,848	$556,271
Profit ($)	$60,749	$4,299	**$65,048**

Product Calculations
Volumes & Properties

	Regular	Premium	Total
Produced	**208,062**	**17,244**	225,307
RON	91.10	94.51	
MON	82.90	87.49	
(R+M)/2	**87.0**	**91.0**	
RVP	**9.0**	**9.0**	
$RVP^{1.25}$	15.59	15.59	
Benzene	**0.51**	**0.08**	

Linear-Form Product Constraints

		Lower Slack	Upper Slack
Regular	Volume	**208,061**	**791,938**
	Vol*Octane	**0**	**4,785,436**
	Vol*$RVP^{1.25}$	**3,243,372**	**0**
	Vol*Benzene	**106,189**	**22,810**
Premium	Volume	**17,243**	**982,756**
	Vol*Octane	**0**	**327,645**
	Vol*$RVP^{1.25}$	**268,815**	**0**
	Vol*Benzene	**1,409**	**9,282**

Adjusting operations to meet targets

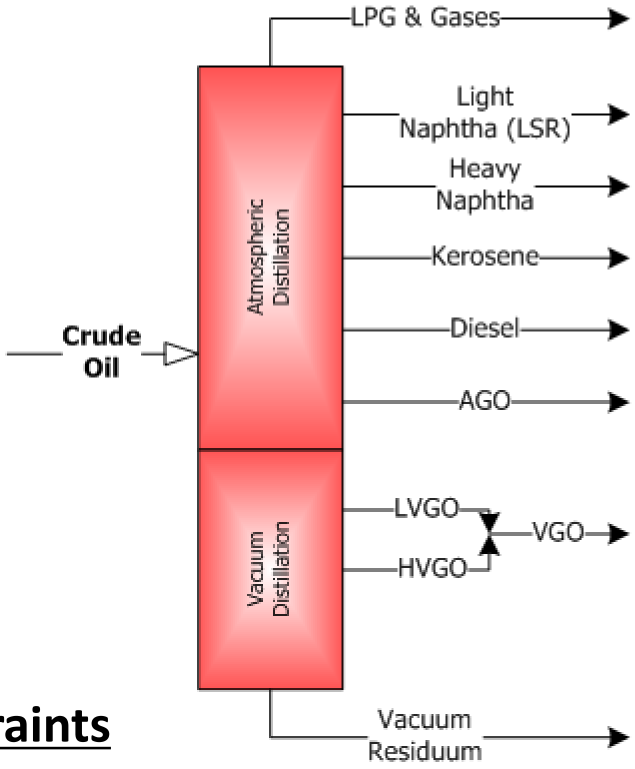
Updated: July 1, 2019

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

Cutpoint Economics

Adjust upstream cutpoints to meet needs in the downstream blending

- Heavy LSR…value as blending component versus Reformer feed
- Heavy Naphtha…value as Reformer feed versus kerosene blend stock
- Heavy Kerosene…value as kerosene blend stock versus diesel blend stock
- Heavy Diesel…value as diesel blend stock versus FCC feed
- Heavy Gas Oil…value as FCC feed versus resid/asphalt production or coker feed

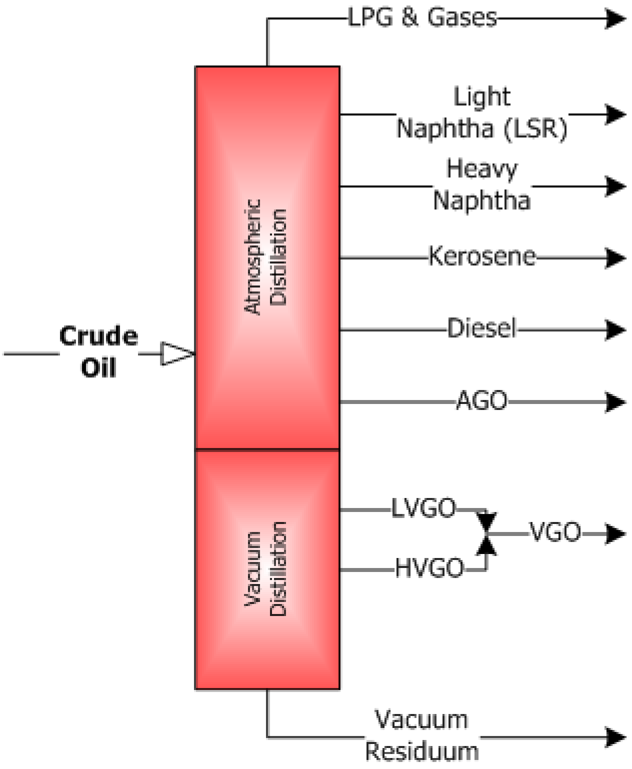


<u>The refinery LP can determine the optimum cut point for each of these given any set of constraints</u>

Cutpoints To Meet Operating Economies

TBP Cut Points (°F) for Various Crude Oil Fractions

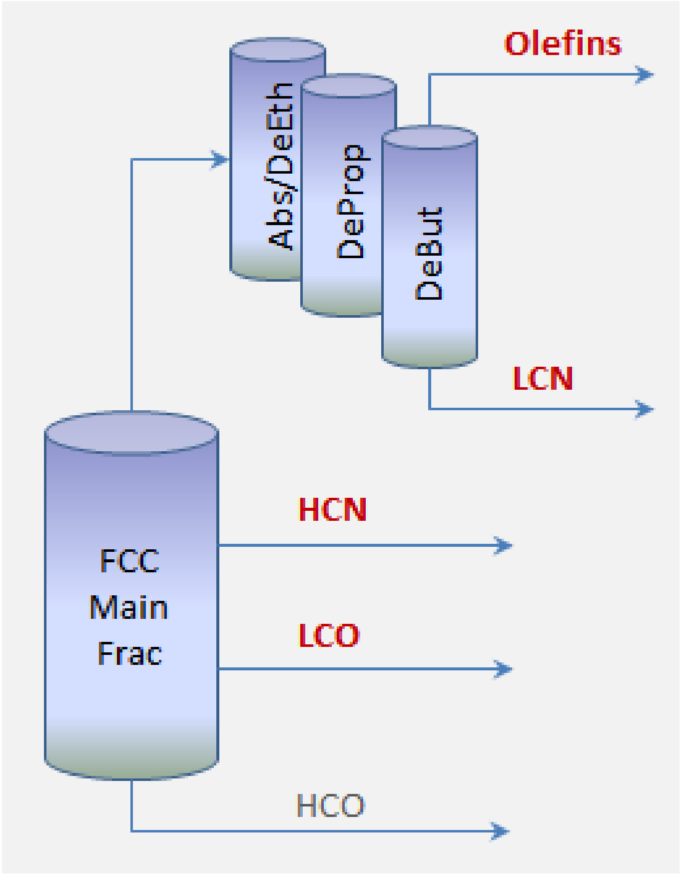
Cut	IBP	EP	Processing Use
LSR	90	180	Min LSR cut
	90	190	Normal LSR cut
	80	220	Max LSR cut
Naphtha	180	380	Max reforming cut
	190	330	Max jet fuel
	220	330	Min reforming cut
Kerosene	330	520	Max kerosene cut
	330	480	Max Jet A cut
	380	520	Max gasoline
Diesel	420	650	Max diesel cut
	480	610	Max jet fuel cut
	520	610	Min diesel cut
Gas Oil	610	800	Cat cracker feed
VGO	800	1050	Cat cracker feed
Resid	1050+		Coker feed, asphalt



Optimize FCC Gasoline Distillation

Frame the analysis

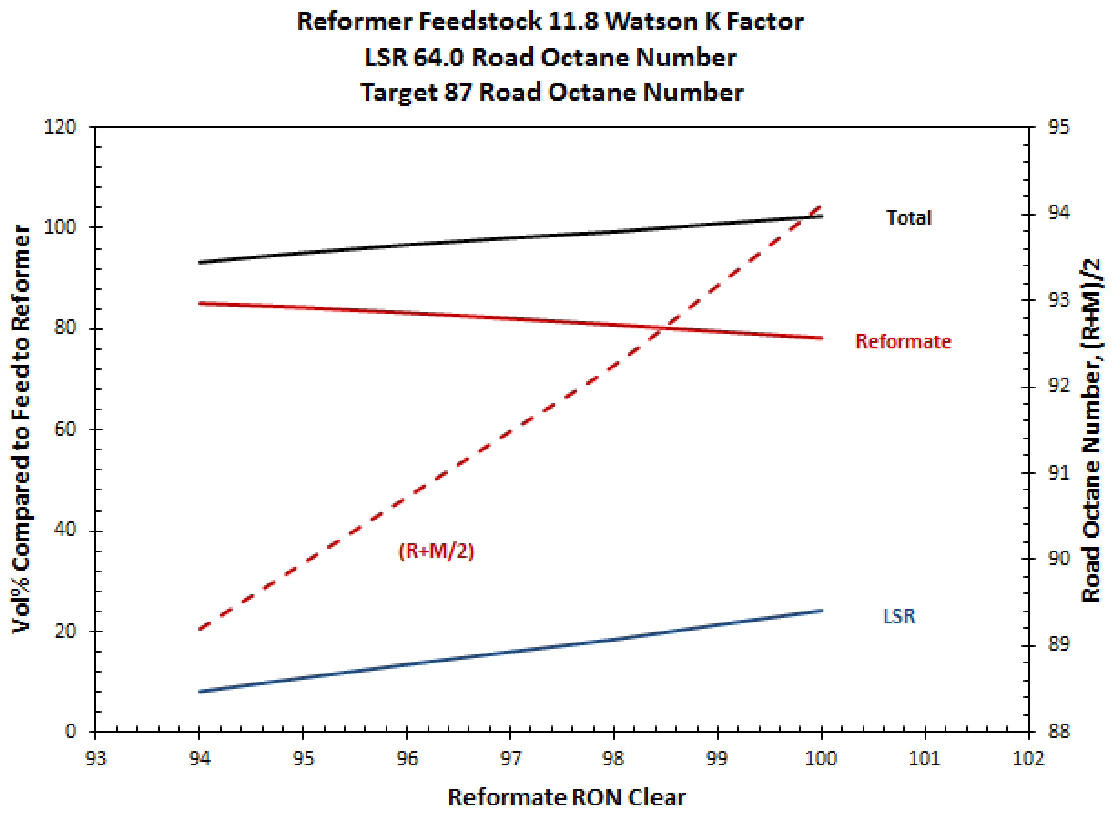
- What is the value of the molecules in the ***stream above***?
- What is the value of the molecules in the ***stream below***?
- What ***upstream unit*** operations affect the stream value?
- What ***downstream unit*** operations affect the stream value?
- What ***unit specific*** operations affect the stream value?
- What ***product blending*** constraints affect the stream value?



Ref: http://www.refinerlink.com/blog/Truly_Optimize_FCC_Gasoline_Distillation

Gasoline Blending – Modify Upstream Operations

How much gasoline can be produced by blending Reformate+LSR with respect to the Reformer's severity?



COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Summary

Updated: July 1, 2019

Summary

Equations for the blending of intermediate stocks to meet final product specifications

Equation forms have been developed to be used with optimization tools (such as linear programming)

Proper optimization of a facility will include adjusting upstream operations to meet downstream targets