Water Management in Refineries

M. Colin Arnold & Joshi Samuel

1. Image -- http://www.ge.com/research/grc_2_6.html

Overview

- Background
- Project Goals
- Unit Operations
- Water Treatments
- Results
- Conclusion

1. http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html

Background

Some water uses in refinery[1]

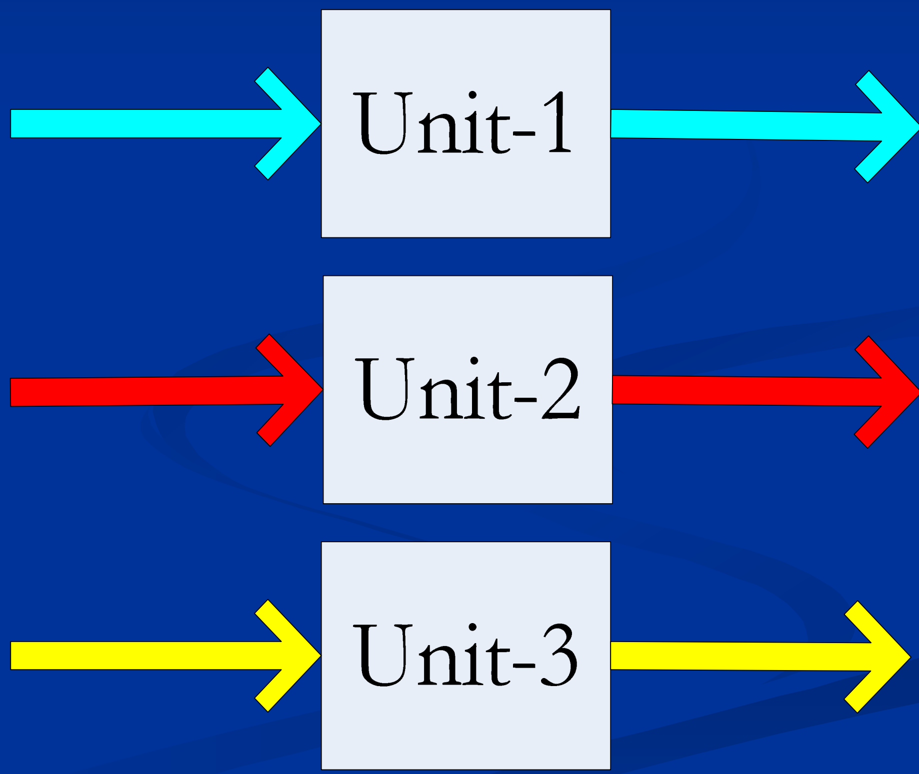
- Caustic treatment
- Distillation
- Sweetening
- Desalting

1. http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html

Background

Traditionally

- Only fresh water feed sources
- No recycle
- Collected into a sink
- Disposed after clean up



1. Koppol, A.P., *et al.* Adv. in Env. Res., V(8), 2003, 151-171.

Background

Recently

- Water reuse
- Minimal or zero discharge
- Minimizing Cost

Reasons

- Stricter EPA regulations
- Water scarcity
- Purchase Cost

1. Koppol, A.P., *et al.* Adv. in Env. Res., V(8), 2003, 151-171.
2. Image -- http://en.wikipedia.org/wiki/Image:Water_pollution.jpg

Project Goals

Reduce

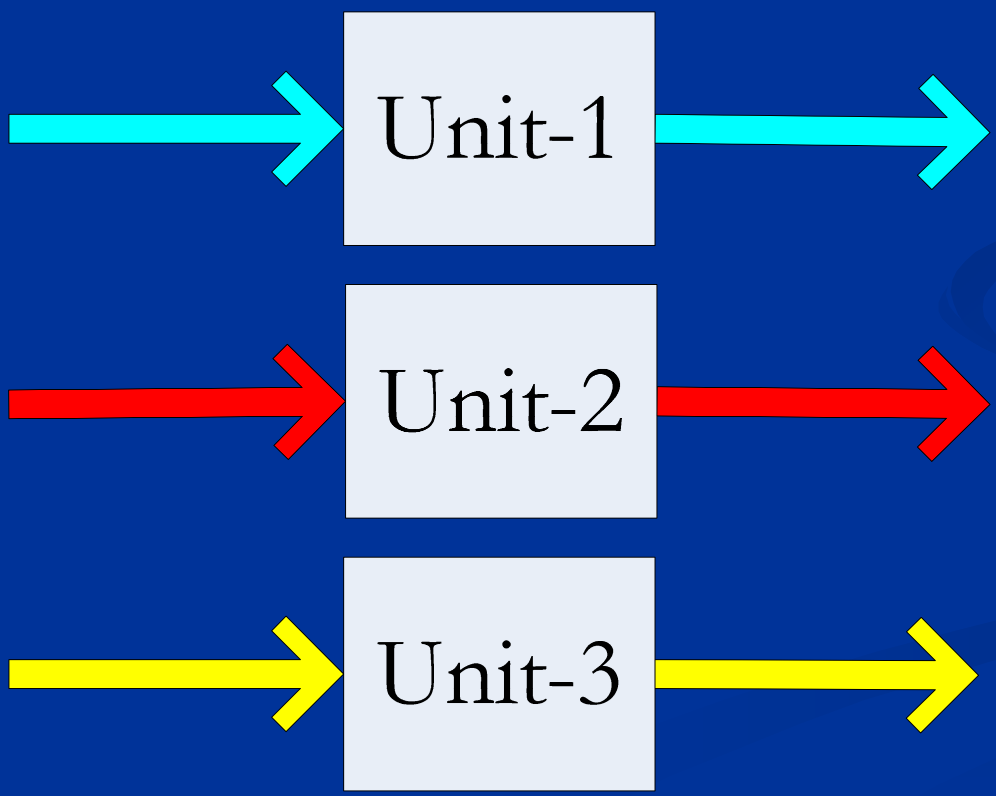
1. Fresh water intake

2. Total operation cost

- Optimizing Waste water treatment
- Minimizing Total discharge
- Maximizing Water reuse

Project Goals

- In other words, we want to change this:



Project Goals

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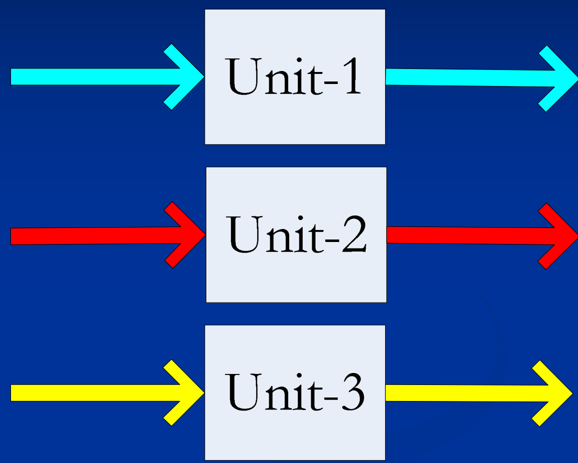

Project Goals

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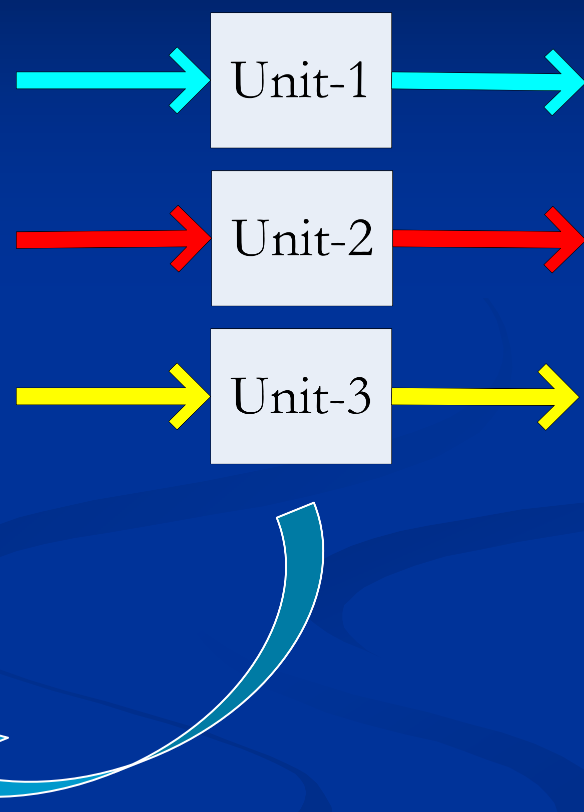
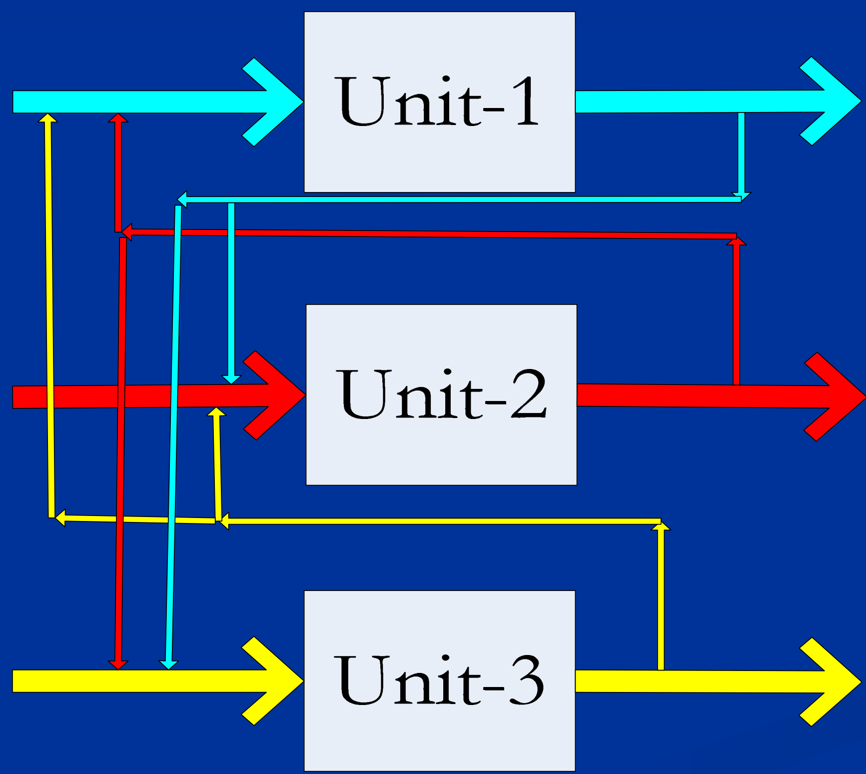


to this:



Unit Operations

Six Units:

- 1: Caustic Treating
- 2: Distillation
- 3: Amine Sweetening
- 4: Merox I Sweetening
- 5: Hydrotreating
- 6: Desalting

Unit Operations

Six Units:

- 1: Caustic Treating

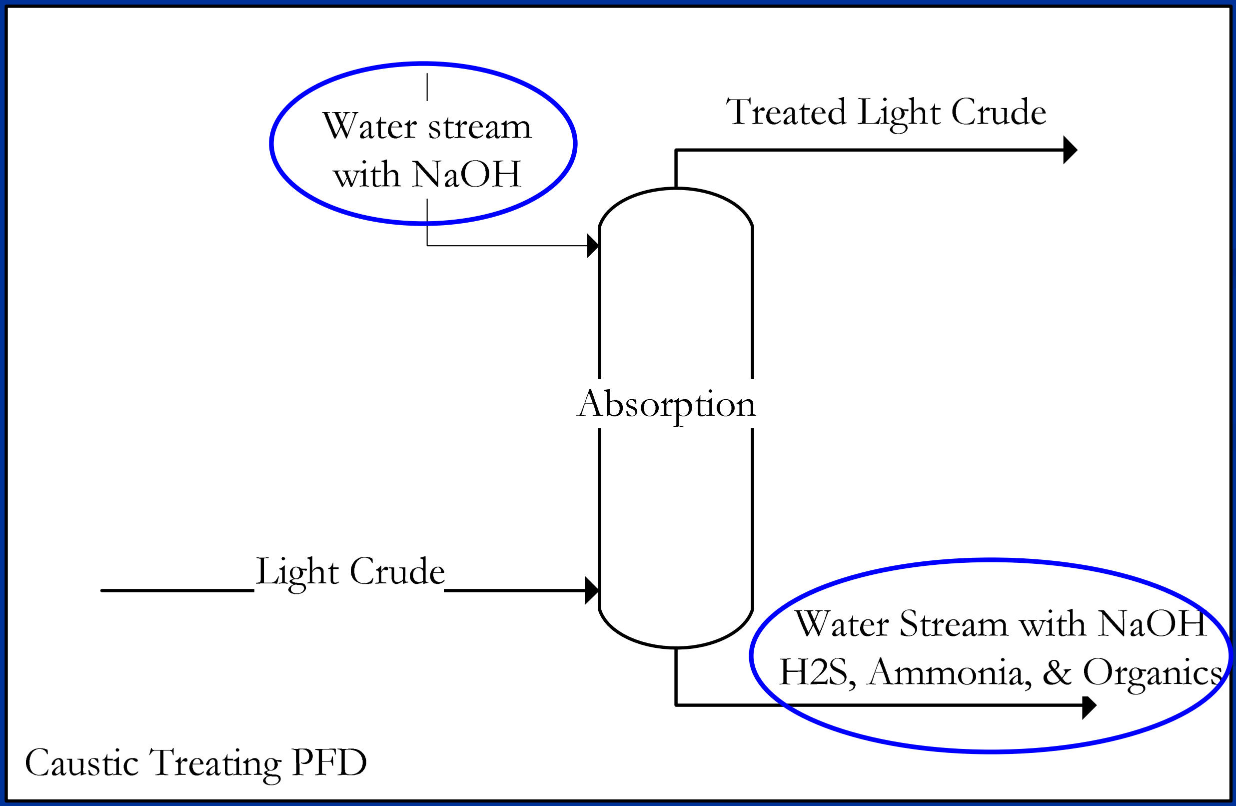
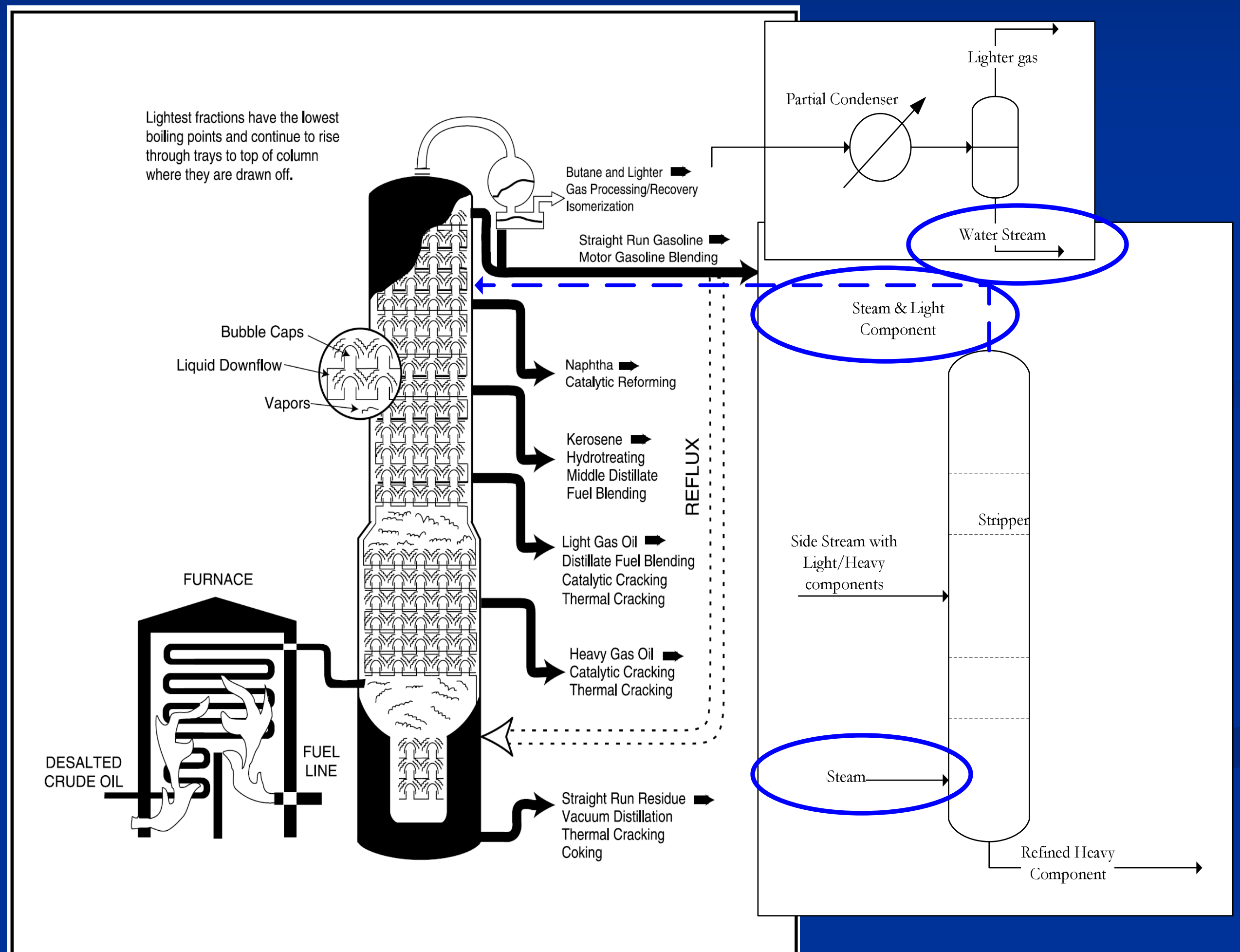


Figure - http://www.pall.com/chemical_5582.asp

Unit Operations

Six Units:

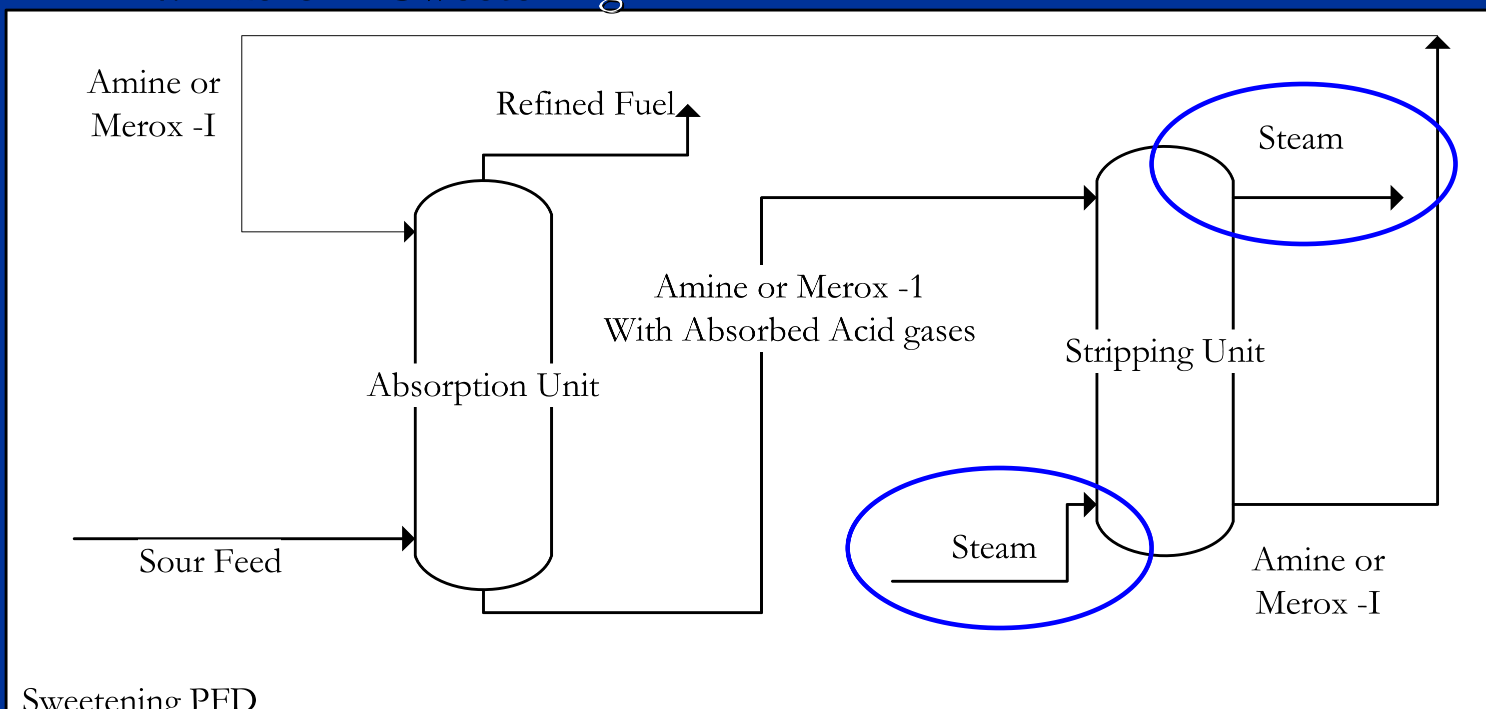
- 2: Distillation



Unit Operations

Six Units:

- 3: Amine Sweetening
- 4: Merox I Sweetening

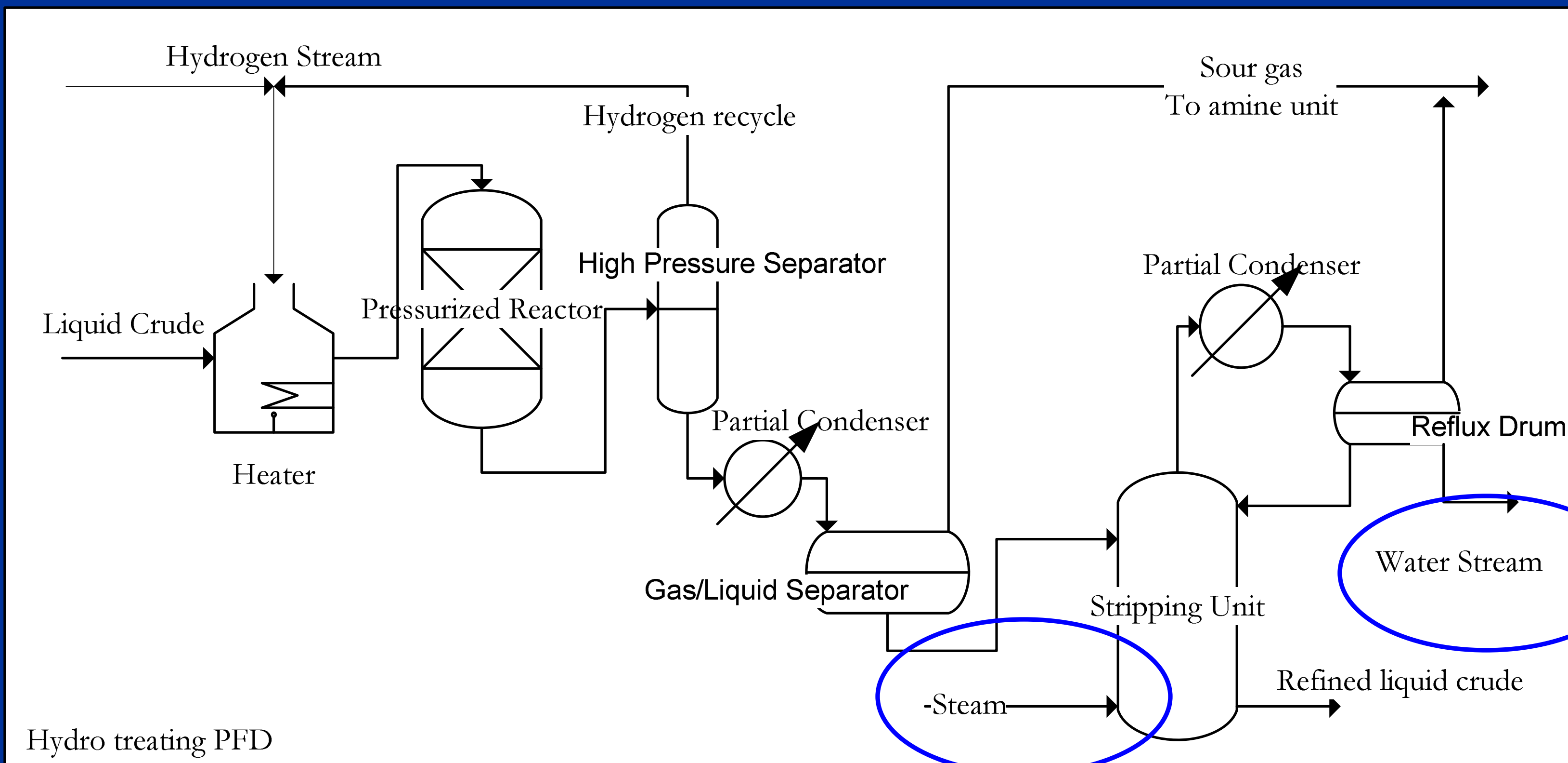


1 - http://www.newpointgas.com/amine_treating.php

Unit Operations

Six Units:

- 5: Hydrotreating

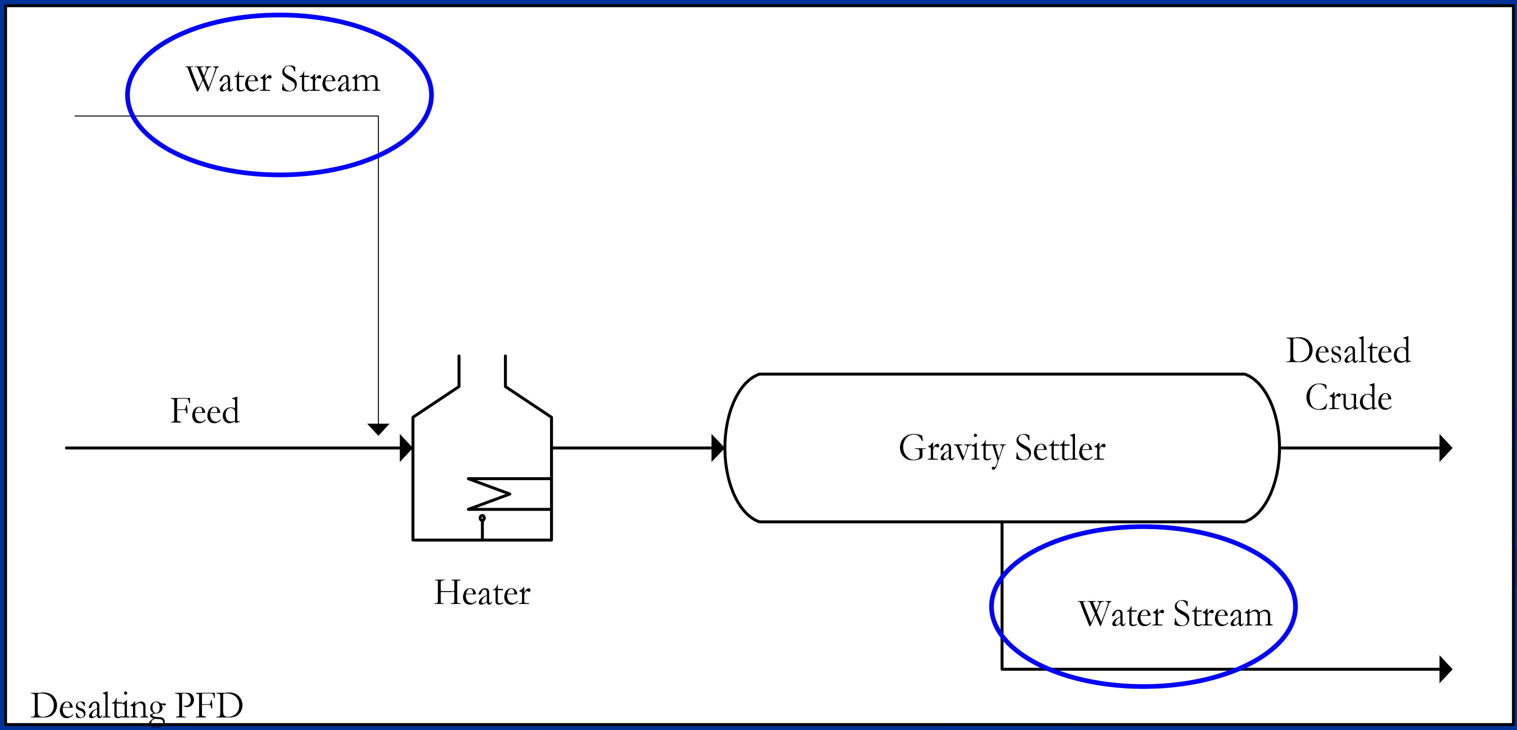


1- http://www.hghouston.com/refining.html

Unit Operations

Six Units:

- 6: Desalting



1- http://www.hghouston.com/refining.html

Unit Operations

Each unit has an inherent values

- $C_{in,max}$
- $C_{out,max}$
- Mass Load

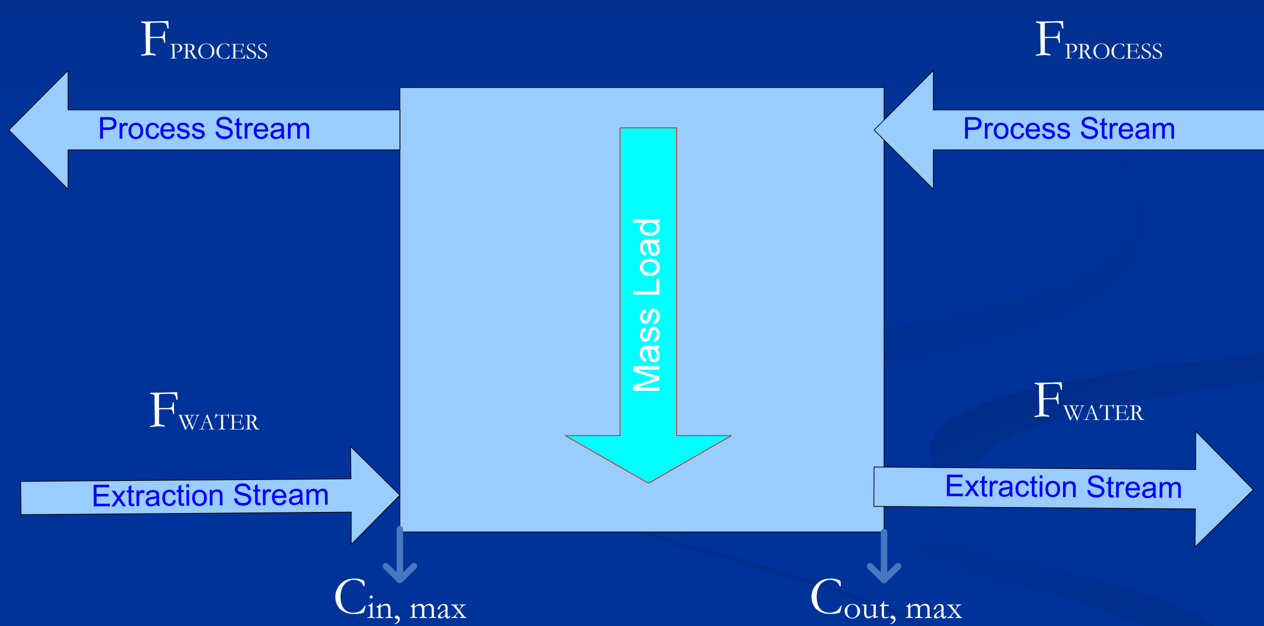
Process	Contaminant	Cin,max (ppm)	Cout,max (ppm)	Mass Load (kg/h)
(1) Caustic Treating	Salts	300	500	0.18
	Organics	50	500	1.2
	H_2S	5000	11000	0.75
	Ammonia	1500	3000	0.1
(2) Distillation	Salts	10	200	3.61
	Organics	1	4000	100
	H_2S	0	500	0.25
	Ammonia	0	1000	0.8
(3) Amine Sweetening	Salts	10	1000	0.6
	Organics	1	3500	30
	H_2S	0	2000	1.5
	Ammonia	0	3500	1
(4) Merox I Sweetening	Salts	100	400	2
	Organics	200	6000	60
	H_2S	50	2000	0.8
	Ammonia	1000	3500	1
(5) Hydrotreating	Salts	85	350	3.8
	Organics	200	1800	45
	H_2S	300	6500	1.1
	Ammonia	200	1000	2
(6) Desalter	Salts	1000	9500	120
	Organics	1000	6500	480
	H_2S	150	450	1.5
	Ammonia	200	400	0

From: Koppol, A.P., *et al.* Adv. in Env. Res., V(8), 2003, 151-171.

Unit Operations

Each unit has an inherent values

- $C_{in,max}$
- $C_{out,max}$
- Mass Load



Water Treatment

TABLE I. WATER CONTAMINANTS	
Class	**Typical examples**
Suspended solids	Dirt, clay, silt, dust, insoluble metal oxides and hydroxides, colloidal materials
Dissolved organics	Trihalomethanes, synthetic organic chemicals, humic acids, fulvic acids
Dissolved ionics (salts)	Heavy metals, silica, arsenic, nitrates, chlorides, carbonates
Microorganisms	Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells
Gases	Hydrogen sulfide, carbon dioxide, methane, radon

TABLE II, EFFECTIVENESS OF WATER PURIFICATION PROCESSES

Treatment Process & Technology	Types of contaminants				
	Suspended Solids	Dissolved Organics	Dissolved Ionics (salts)	Micro-organisms	Gases
Filtration:					
Bed filtration	Very effective	NA	NA	NA	NA
Cartridge filtration	Very effective	NA	NA	NA	NA
Bag filtration	Very effective	NA	NA	NA	NA
Precoat (DE)	Very effective	Partially effective	NA	NA	NA
Adsorption:					
Activated carbon	NR	Very effective	NA	NA	Partially effective
Membrane technologies:					
Microfiltration	Very effective	NA	NA	Partially effective	NA
Ultrafiltration	NR	Very effective	NA	Effective	NA
Nanofiltration	NR	Very effective	Effective	Very effective	NA
Reverse Osmosis	NR	Very effective	Very effective	Very effective	NA
Thermal technologies:					
Distillation	NR	Partially effective	Very effective	Very effective	NA
Freezing	NR	NA	Very effective	NR	NA
Electrical technologies:					
Electrodialysis	NA	NA	Effective	NA	NA
Electrode-ionization	NA	NR	Effective	NR	NA
Chemical technologies:					
Ion exchange	NR	NA	Very effective	NA	NA
Ozonation	NA	Partially effective	Partially effective	Very effective	NA
Use of chlorine compounds	NA	NA	NA	Effective	NA
Irradiation:					
Ultraviolet	NA	Partially effective	NA	Effective	NA

NA= not applicable NR= not recommended (not cost effective)

Tables - Cartwright, Peter. *Process Water Treatment – Challenges and Solutions*. Chemical Engineering Magazine. March 2006.

Water Treatment

Three options for treatment[1]

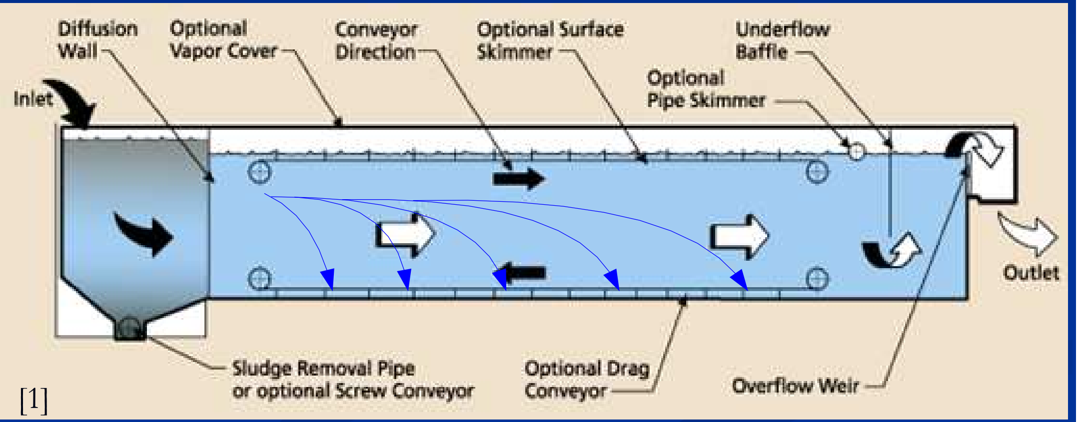
1. Option 1: API separator followed by ACA
2. Option 2: Reverse Osmosis Treatment
3. Option 3: Chevron waste water treatment

1. Koppol, A.P., *et al*. Adv. in Env. Res., V(8), 2003, 151-171.

Water Treatment

- [2] Option 1: API separator followed by ACA

  - Reduces Organics to 50 ppm
  - $0.12 per ton



[1]

1. http://www.monroeenvironmental.com/clarifier-api-separator.htm
2. Koppol, A.P., *et al.* Adv. in Env. Res., V(8), 2003, 151-171.

Water Treatment

[2] Option 1: API separator followed by ACA

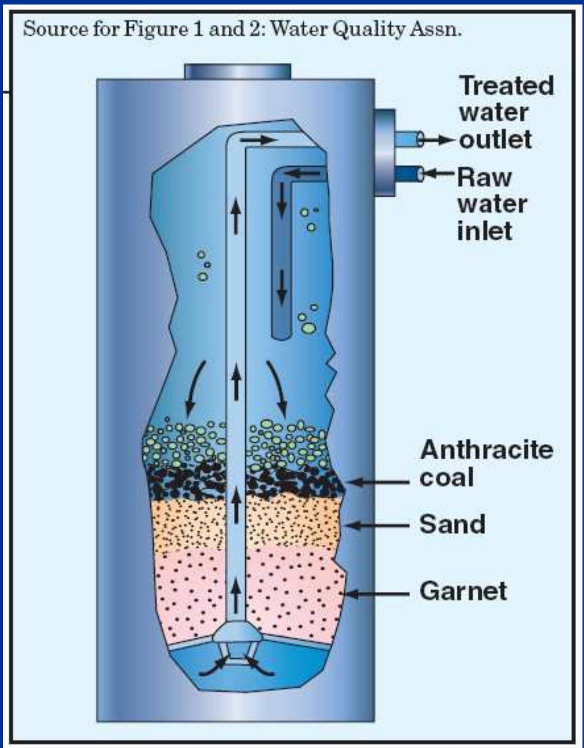


FIGURE 1. Bed filters are effective for removing suspended solids from water

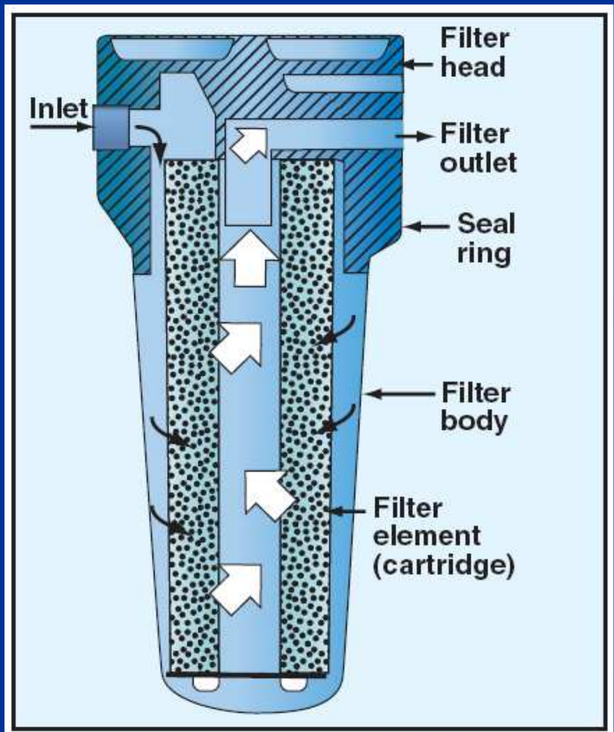


FIGURE 2. Cartridge filters can be fabricated in any of several configurations

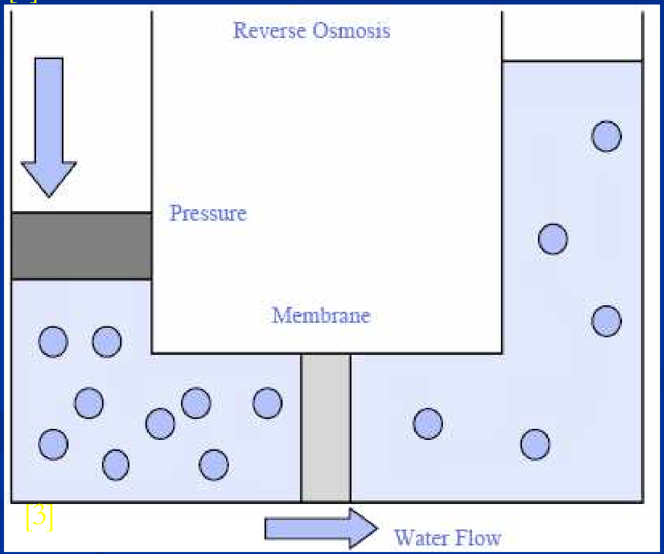
Figures - Cartwright, Peter. *Process Water Treatment – Challenges and Solutions*. Chemical Engineering Magazine. March 2006.

$J = \frac{-kA}{\mu} \times \frac{\Delta P}{\delta}$

Water Treatment

Option 2: Reverse Osmosis Treatment

[2]



- Reduces Salts to 20 ppm
- $0.56 per ton

1. http://www.aquatechnology.net/commercialro.html
2. http://ag.arizona.edu/region9wq/pdf/nv_ROhow.pdf

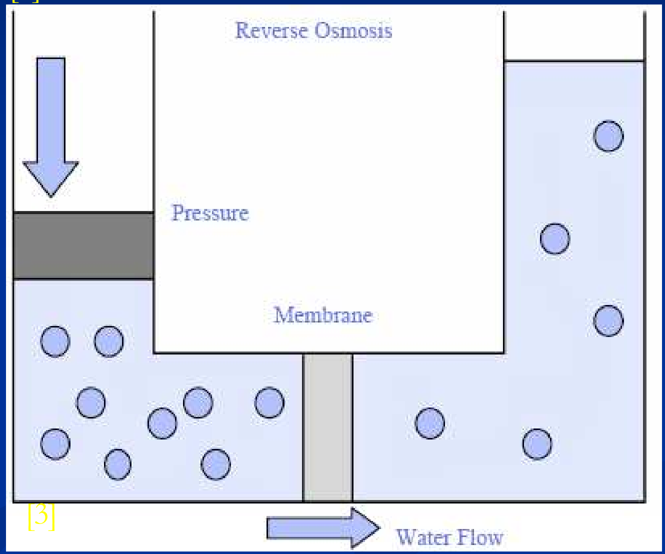
$J = \frac{-kA}{\mu} \times \frac{\Delta P}{\delta}$

Water Treatment

Option 2: Reverse Osmosis Treatment

- Reduces Salts to 20 ppm
- $0.56 per ton

[2]



[3]

$$J = \frac{-kA}{\mu} \times \frac{\Delta P}{\delta}$$

where

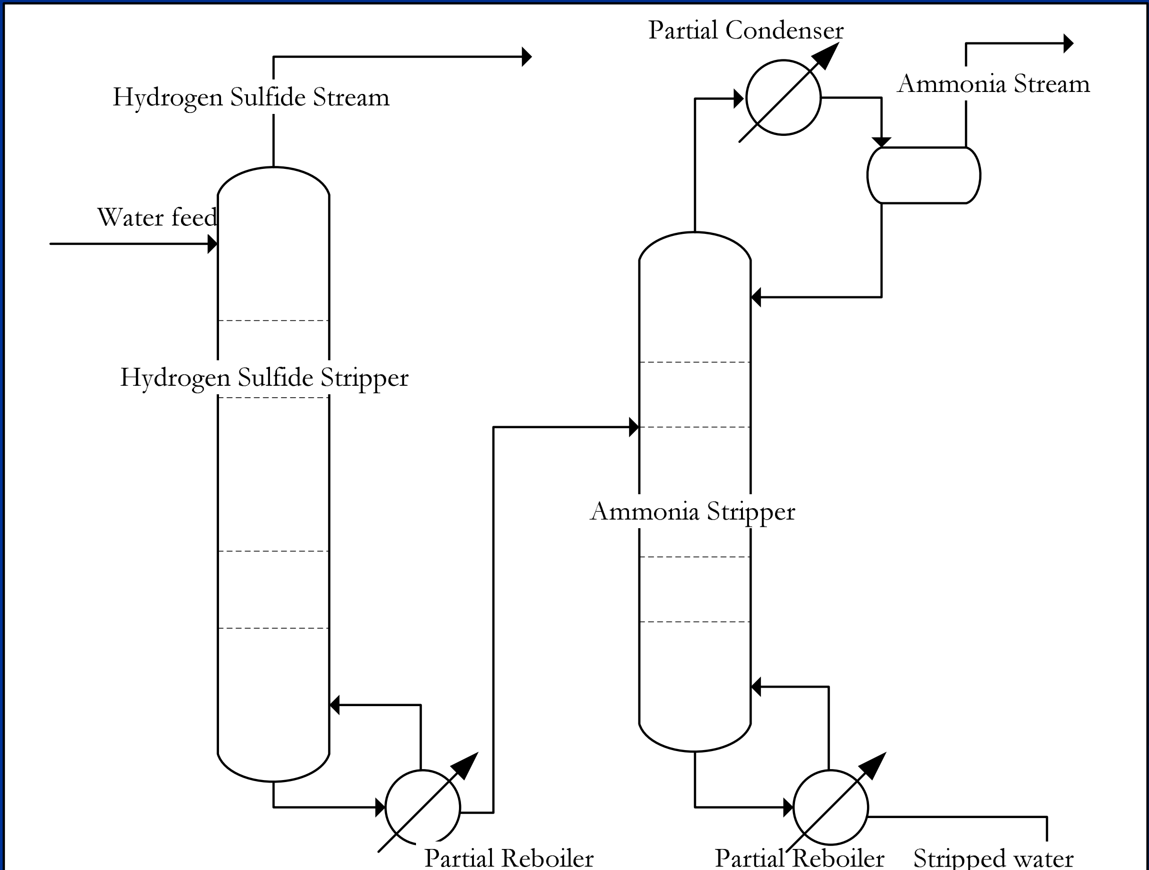
- "J" - Volumetric flux across membrane
- "k" – permeability
- "A" – flux area
- "ΔP" – Pressure drop
- "💻" – viscosity
- "✉" – membrane thickness

1. http://www.aquatechnology.net/commercialro.html
2. http://ag.arizona.edu/region9wq/pdf/nv_ROhow.pdf

Water Treatment

Option 3: Chevron waste water Treatment

- Reduces H_2S to 5 ppm
- Reduces Ammonia to 30 ppm
- $1.00 per ton



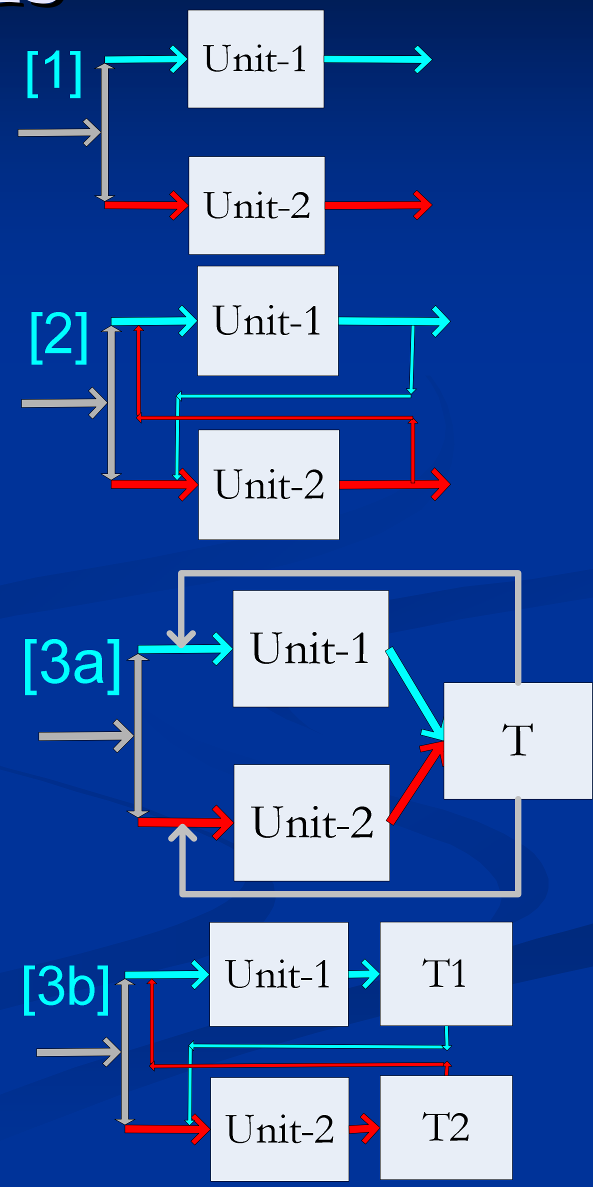
Chevron Waste Water Treatment PFD

http://www.chevron.com/products/prodserv/refiningtechnology/waste_wtr_treat_6a.shtm

Unit Operations

Assumptions

1. Parallel Operation
2. Outlets from a unit may be split and fed to any unit
3 a) Outlets can be combined, treated, and recycled OR
  b) Outlets can be treated separately and recycled
4. No water loss during treatment



GAMS Model

- The Backbone of the Program

```
Set  u  water using units          / 1*6 /
     w  freshwater source          / 1 /
     s  wastewater sink            / 1 /
     c  Contaminant                / 1*4 /;
Alias(u,ua);

Parameters
   CFW(w)  Cost of freshwater in $ per ton
      / 1   .32 /

   CWW(s)  Cost of wastewater treatment $ per ton
      / 1   1.68 /;

Table  ConFW(w,c)  Freshwater source concentration in ppm
        1     2     3     4
   1    0     0     0     0;
```

GAMS Model

- The Backbone of the Program

Table Cinmax(u,c) maximum inlet concentration in the units in ppm

	1	2	3	4
1	300	50	5000	1500
2	10	1	0	0
3	10	1	0	0
4	100	200	50	1000
5	85	200	300	200
6	1000	1000	150	200;

Table Coutmax(u,c) maximum outlet concentration in the units in ppm

	1	2	3	4
1	500	500	11000	3000
2	200	4000	500	1000
3	1000	3500	2000	3500
4	400	6000	2000	3500
5	350	1800	6500	1000
6	9500	6500	450	400;

Table ConWW(s,c) Concentration limits at the sink in ppm

	1	2	3	4
1	10000000000	10000000000	10000000000	10000000000;

GAMS Model

- The Backbone of the Program

Table ML(u,c) Mass Load (transfered to water at unit) in g per hour

	1	2	3	4
1	180	1200	750	100
2	3610	100000	250	800
3	600	30000	1500	1000
4	2000	60000	800	1000
5	3800	45000	1100	2000
6	120000	480000	1500	0;

Variable

FW(w,u)	Flowrates between freshwater sources and units in ton per hour
F(u,u)	Flowrates between units in ton per hour
FS(u,s)	Flowrates between units and sinks in ton per hour
Cout(u,c)	Outlet concentration in the units in ppm
Cost	Cost in $Mil per year
Consu	Consumption in ton per hour;

Positive variable FW,F,FS,Cout;

GAMS Model

- The Backbone of the Program

```
Equations
  waterbalance(u)    Balance of water
  inlet(u,c)         Limit of inlet concentration of the units
  outlet(u,c)        Calculation of outlet concentration of the units
  maxout(u,c)        Limit of outlet concentration of the units
  sink(s,c)          Limit of inlet concentration of the sinks
  ObjCost            Objective function that minimizes cost
  ObjConsu           Objective function that minimizes cosumption
**Linear - Starting points
  inletl(u,c)        Limit of inlet concentration of the units
  outletl(u,c)       Calculation of outlet concentration of the units
  maxoutl(u,c)       Limit of outlet concentration of the units;

  waterbalance(u)    ..sum(w,FW(w,u))+sum(ua,F(ua,u))=e=sum(ua,F(u,ua))+sum(s,FS(u,s));
  inlet(u,c)         ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Cout(ua,c))=L=(sum(ua,F(u,ua))+sum(s,FS(u,s)))*Cinmax(u,c);
  outlet(u,c)        ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Cout(ua,c))+ML(u,c)=E=(sum(ua,F(u,ua))+sum(s,FS(u,s)))*Cout(u,c);
  maxout(u,c)        ..Cout(u,c)=L=Coutmax(u,c);
  sink(s,c)          ..sum(u,FS(u,s)*(Cout(u,c)-ConWW(s,c)))=L=0;
```

GAMS Model

- The Backbone of the Program

```
  ObjCost        ..Cost=e=(sum(w,sum(u,FW(w,u))*cfw(w))+sum(s,sum(u,FS(u,s))*cww(s)))*0.008760;
**This cost assumes constant operation
**The "*0.008760" term comes from 8760 hours opperated per year and divided by 1E6 to get units
    of millions of dollars
  ObjConsu       ..Consu=e=sum(w,sum(u,FW(w,u)));

  inletl(u,c)    ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Coutmax(ua,c))=L=(sum(ua,F(u,ua))+sum(s,FS(u,s)))*Cinmax(u,c);
  outletl(u,c)   ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Coutmax(ua,c))+ML(u,c)=E=(sum(ua,F(u,ua))+sum(s,FS(u,s)))*Coutmax(u,c);
  maxoutl(u,c)   ..Cout(u,c)=e=Coutmax(u,c);

MODEL Reuse / waterbalance,inlet,outlet,maxout,sink,ObjCost,ObjConsu/;
MODEL Start / waterbalance,inletl,outletl,maxoutl,ObjCost,ObjConsu/;
*SOLVE Start using MIP minimizing cost;
SOLVE Start using MIP minimizing consu;
*SOLVE Reuse using MINLP minimizing cost;
SOLVE Reuse using MINLP minimizing consu;

DISPLAY Cost.l,Consu.l,FW.l,F.l,FS.l,Cout.l;
```

GAMS Model

In other words…

- Amount of freshwater was calculated
  - Amount of waste water was calculated and checked to assure a zero mass balance
- The cost of fresh water and treatment was calculated as the total cost
- The program minimizes either the total cost or freshwater required
  - First estimates solution by solving the problem linearly
  - Then uses a non-linear algorithm to find a solution
  - The initial linear guess is necessary because of nature of nonlinear systems

GAMS Model

Important Equations

- waterbalance(u) ..sum(w,FW(w,u))+sum(ua,F(ua,u))=e=sum(ua,F(u,ua))+sum(s,FS(u,s));

$$\sum_{w} FW_{w,u} + \sum_{u_j} F_{u_j,u_i} = \sum_{u_j} F_{u_i,u_j} + \sum_{s} FS_{u,s}$$

- Water balance around each unit
- “FW” → Flow rate of streams from fresh water to units
- “F” → Flow rate of streams between units
- “FS” → Flow rate of streams from units to sinks
- “w” → Fresh water source
- “s” → Waste water sink
- “u”, “u_i”, and “u_j” → Any unit

GAMS Model

Important Equations

- inlet(u,c)
  ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Cout(ua,c))=L=(sum(ua,F(u,ua))+sum(s, FS(u,s)))*Cinmax(u,c);

$$\sum_{w}(FW_{w,u} \times C_{w,c}) + \sum_{u_j}(F_{u_j,u_i} \times C_{u_j,c}) \le (\sum_{u_j} F_{u_i,u_j} + \sum_{s} FS_{ui,s}) \times C_{u_i}^{in,\max}$$

- Sets the mixed inlet concentration of a contaminant less than its allowed maximum
- "C" → Concentration

GAMS Model

Important Equations

- outlet(u,c)
  ..sum(w,FW(w,u)*ConFW(w,c))+sum(ua,F(ua,u)*Cout(ua,c))+ML(u,c)=E=(sum(ua,F(u,ua))+sum(s,FS(u,s)))*Cout(u,c);

$$\sum_{w}(FW_{w,u}\times C_{w,c})+\sum_{u_j}(F_{u_j,u_i}\times C_{u_j,c})+ML_{u,c}=(\sum_{u_j}F_{u_i,u_j}+\sum_{s}FS_{ui,s})\times C_{u_i}^{out}$$

- Finds the outlet concentration of a contaminant once it has picked up a mass load in a unit
- "ML" → Mass Load

GAMS Model

Important Equations

- maxout(u,c) ..Cout(u,c)=L=Coutmax(u,c);

$$C_u^{out} \leq C_u^{out,\max}$$

  - Sets each outlet concentration from a unit to less than or equal to the allowed maximum

GAMS Model

Important Equations

- sink(s,c) ..sum(u,FS(u,s)*(Cout(u,c)-ConWW(s,c)))=L=0;

$$\sum_{s} (F_{u,s} \times (C_{u,c} - C_{s,c})) \leq 0$$

  - Sets the concentration of contaminants going to a sink to not exceed the limits allowed at the sink

GAMS Model

Important Equations

- ObjCost ..Cost=e=(sum(w,sum(u,FW(w,u))*cfw(w))+sum(s,sum(u,FS(u,s))*cww(s)))*0.008760;

$$Cost = \sum_{w}(\sum_{u}(FW_{w,u} \times P_{w}) + \sum_{s}(FW_{u,s} \times P_{s})) \times 0.008760$$

  - Determines the total cost of a given setup
  - P_w → Price of purchasing fresh water
  - P_s → Price of treating waste water
  - Multiplied by 0.008760 to convert from $/hr to $Mil/yr

GAMS Model

Important Equations

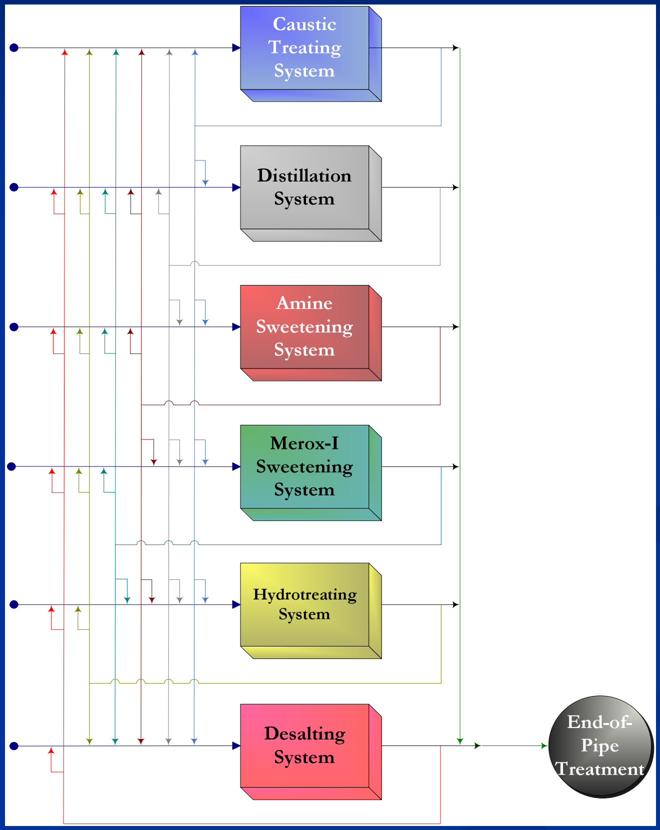
- ObjConsu ..Consu=e=sum(w,sum(u,FW(w,u)));

$$Consu = \sum_{w} \sum_{u} FW_{w,u}$$

  - Calculates the fresh water requirement of a setup

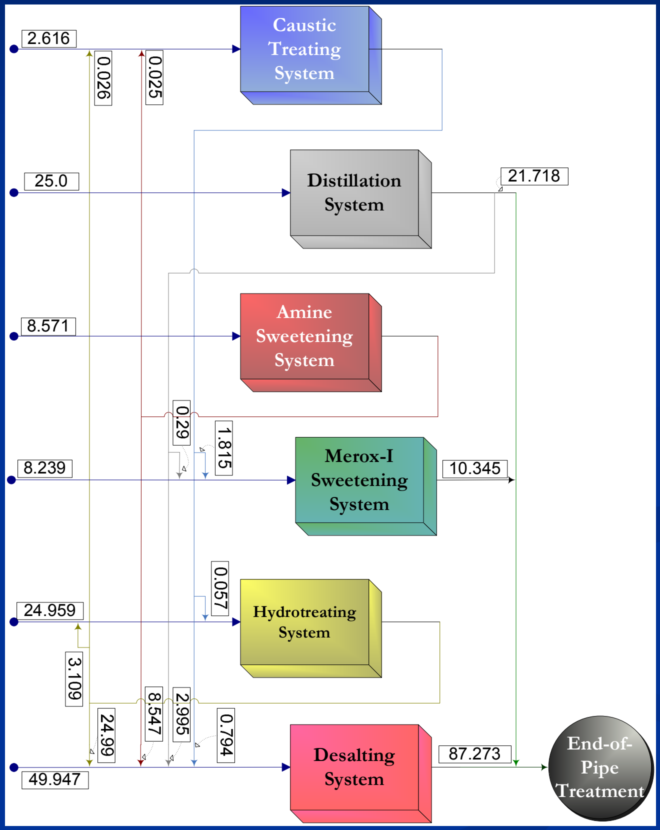
GAMS Model

- The maximum number of streams available are shown schematically as:



GAMS Model

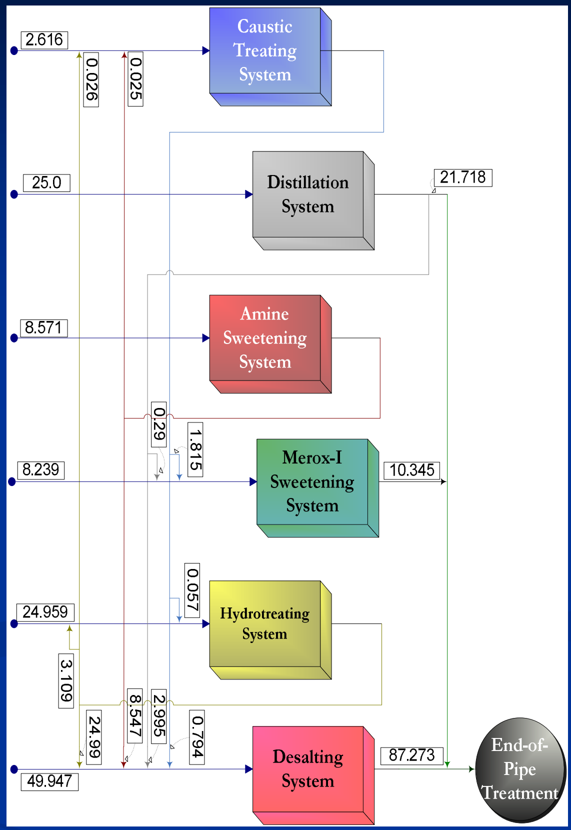
- And the results of the GAMS model minimizing consumption are:



GAMS Model

- Result (all flowrates in ton/hour)

Origin	Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Fresh Water Source	2.616	25	8.571	8.239	24.959	49.947	n/a	119.332
Caustic Treating	0	0	0	1.815	0.057	0.794	0	2.666
Distillation	0	0	0	0.29	0	2.995	21.715	25
Amine Sweetening	0.025	0	0	0	0	8.547	0	8.572
Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
Hydrotreating	0.026	0	0	0	3.109	24.99	0	28.125
Desalting	0	0	0	0	0	0	87.273	87.273
Sum to Destination	2.667	25	8.571	10.344	28.125	87.273	119.333	



- Can compare to published results[1]

Origin	Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Fresh Water Source	2.4	25	8.571	8.388	24.445	50.518	n/a	119.322
Caustic Treating	0	0	0	1.645	0.775	0	0	2.42
Distillation	0	0	0	0.312	0	2.97	21.718	25
Amine Sweetening	0	0	0	0	0	8.571	0	8.571
Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
Hydrotreating	0	0	0	0	0	25.21	0	25.21
Desalting	0	0	0	0	0	0	87.269	87.269
Sum to Destination	2.4	25	8.571	10.345	25.22	87.269	119.332	

- Very similar for the most part
  - Only significant differences are that $F_{1,6}$, $F_{3,1}$, $F_{5,1}$, and $F_{5,5}$ are all zero in the published results

1. Koppol, A.P., *et al*. Adv. in Env. Res., V(8), 2003, 151-171.

GAMS Model Problems

- Minimum flowrates
  - Very low flowrates may be physically unrealizable
  - As an example, a minimum of 0.1 ton per hour is set

- One possible solution is use of a binary marker $Y_{i,i}$

- Set so that $Y_{i,i}*F_{min} \leq F_{i,i} \leq Y_{i,i}*F_{max}$
  - If $F_{i,i} \leq F_{min}$, the model should automatically set $Y_{i,i}$ to zero and reset $F_{i,i}$ to zero
  - Maximum must be included as well so that $Y_{i,i}$ isn't always zero
  - F_{max} is an arbitrarily large number

GAMS Model Problems

Binary Marker, $Y_{i,i}$

- Using this marker works fundamentally

Origin		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
	Fresh Water Source	79.343	3.E+01	8.571	9.828	0	0	n/a	122.742
	Caustic Treating	0	0	0	0	80.478	0	0	80.478
	Distillation	0.1	0	0	0.517	2.847	0	21.536	25
	Amine Sweetening	1.035	0	0	0	0	0	7.536	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0.1	83.325	0	83.425
	Desalting	0	0	0	0	0	0	83.325	83.325
	Sum to Destination	80.478	25	8.571	10.345	83.425	83.325	122.742	

- However, the solver did not guarantee the solution to be the absolute optimum in this case

- Solution still is very close to previous results
  - Consumption = 122.761 ton/hr, Cost = $Mil 2.151/yr

GAMS Model Problems

Binary Marker, $Y_{i,i}$

- Results can be compared to published results

Origin		Destination: Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	79.343	3.E+01	8.571	9.828	0	0	n/a	122.742
	Caustic Treating	0	0	0	0	80.478	0	0	80.478
	Distillation	0.1	0	0	0.517	2.847	0	21.536	25
	Amine Sweetening	1.035	0	0	0	0	0	7.536	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0.1	83.325	0	83.425
	Desalting	0	0	0	0	0	0	83.325	83.325
	Sum to Destination	80.478	25	8.571	10.345	83.425	83.325	122.742	

- Published Results:

Origin		Destination: Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.388	24.445	50.518	n/a	119.322
	Caustic Treating	0	0	0	1.645	0.775	0	0	2.42
	Distillation	0	0	0	0.312	0	2.97	21.718	25
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0	25.21	0	25.21
	Desalting	0	0	0	0	0	0	87.269	87.269
	Sum to Destination	2.4	25	8.571	10.345	25.22	87.269	119.332	

GAMS Model Problems

- Minimum flowrates
  - Using a binary marker uses very many resources
  - Thus, a different process may be desired
- An alternate solution is to set individual flowrates less than the minimum to zero

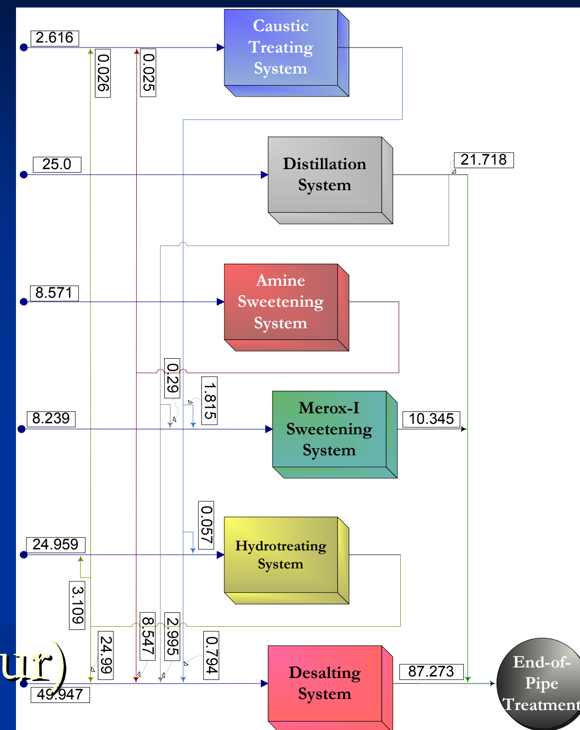
Origin		Destination				
		Caust.	Dist.	Am.Sw.	M1S	Hydr.
	Fresh Water Source	2.616	25	8.571	8.239	24.959
	Caustic Treating	0	0	0	1.815	0.057
	Distillation	0	0	0	0.29	0
	Amine Sweetening	0.025	0	0	0	0
	Merox I Sweetening	0	0	0	0	0
	Hydrotreating	0.026	0	0	0	3.109
	Desalting	0	0	0	0	0

- $F_{3,1} = 0.025 \rightarrow F_{3,1} = 0$

- If another flowrate is less than the minimum after doing this, it is set to zero also
- This process is repeated until none are below the minimum
- Six different combinations of streams set to zero meet the minimum flowrate standards

GAMS Model Problems

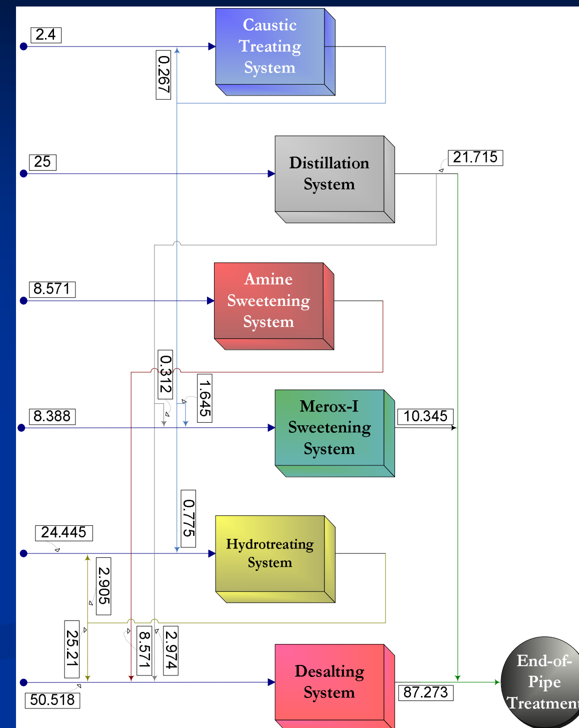
- New Results (flowrates in ton per hour)
  - Before:



		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.616	25	8.571	8.239	24.959	49.947	n/a	119.332
	Caustic Treating	0	0	0	1.815	0.057	0.794	0	2.666
	Distillation	0	0	0	0.29	0	2.995	21.715	25
	Amine Sweetening	0.025	0	0	0	0	8.547	0	8.572
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0.026	0	0	0	3.109	24.99	0	28.125
	Desalting	0	0	0	0	0	0	87.273	87.273
	Sum to Destination	2.667	25	8.571	10.344	28.125	87.273	119.333	

GAMS Model Problems

- New Results (flowrates in ton per hour)
  - After:



- All flowrates are now greater than the arbitrary minimum (0.1)

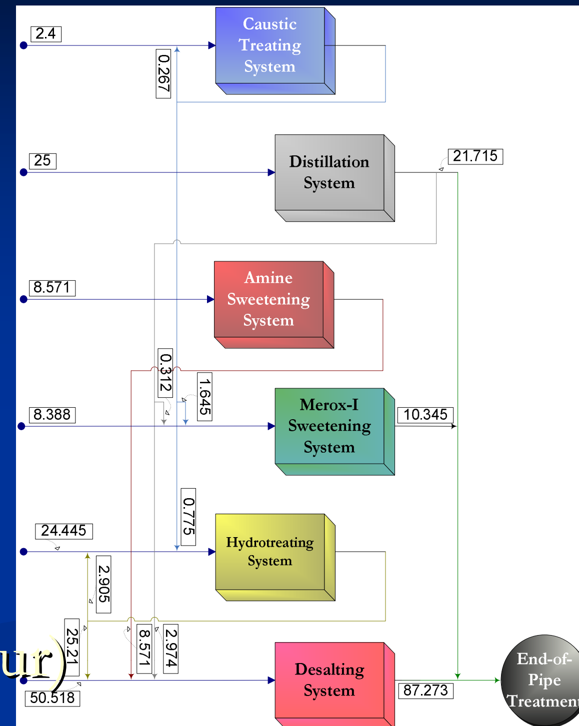
Origin	Destination: Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Fresh Water Source	2.4	25	8.571	8.388	24.445	50.518	n/a	119.322
Caustic Treating	0.267	0	0	1.645	0.775	0	0	2.687
Distillation	0	0	0	0.312	0	2.974	21.715	25.001
Amine Sweetening	0	0	0	0	0	8.571	0	8.571
Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
Hydrotreating	0	0	0	0	2.905	25.21	0	28.115
Desalting	0	0	0	0	0	0	87.273	87.273
Sum to Destination	2.667	25	8.571	10.345	28.125	87.273	119.333	

- Fresh water requirements do not change by use of minimum flowrates

GAMS Model Problems

- New Results (flowrates in ton per hour)

		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.388	24.445	50.518	n/a	119.322
	Caustic Treating	0.267	0	0	1.645	0.775	0	0	2.687
	Distillation	0	0	0	0.312	0	2.974	21.715	25.001
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	2.905	25.21	0	28.115
	Desalting	0	0	0	0	0	0	87.273	87.273
	Sum to Destination	2.667	25	8.571	10.345	28.125	87.273	119.333	



- Published Results (flowrates in ton per hour)

		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.388	24.445	50.518	n/a	119.322
	Caustic Treating	0	0	0	1.645	0.775	0	0	2.42
	Distillation	0	0	0	0.312	0	2.97	21.718	25
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0	25.21	0	25.21
	Desalting	0	0	0	0	0	0	87.269	87.269
	Sum to Destination	2.4	25	8.571	10.345	25.22	87.269	119.332	

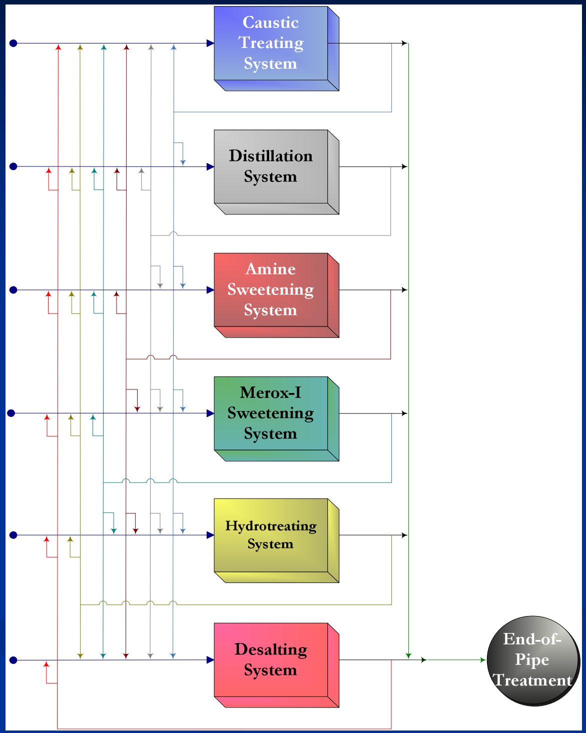
GAMS Model Robustness

- The GAMS model can be used to test other scenarios
- Scenario 1:
  - The Amine sweetening unit (unit 3) is aging early and another has been ordered to replace it; unfortunately, the unit will not arrive and be in operation for another year. A consequence of the early aging of the unit is that it can only handle $C_{in,max}$ one fifth of its previous operation capacity, the $C_{out,max}$ are cut in half and the mass loads triples.

		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.091	24.371	19.394	n/a	87.827
	Caustic Treating	0.267	0	0	1.529	0.871	0	0	2.667
	Distillation	0	0	0	0	0	0	25	25
	Amine Sweetening	0	0	0	0	0	0	8.571	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0.725	1.349	24.242	0.275	26.591
	Desalting	0	0	0	0	0	0	43.636	43.636
	Sum to Destination	2.667	25	8.571	10.345	26.591	43.636	87.827	

GAMS Model Robustness

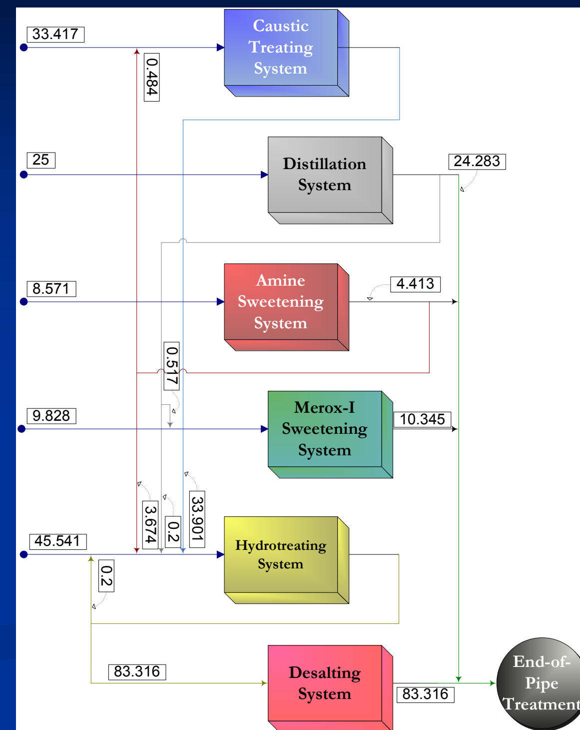
- A more valuable check of robustness is to fix the streams between units as either existent or non-existent once an initial minimization is run
- The mass load can then be changed to test that new solutions are reasonable



GAMS Model Robustness

- New Scenario:
  - Mass loads double, network fixed

- Initial Results:



		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	33.417	25	8.571	9.828	45.541	0	n/a	122.357
	Caustic Treating	0	0	0	0	33.901	0	0	33.901
	Distillation	0	0	0	0.517	0.2	0	24.283	25
	Amine Sweetening	0.484	0	0	0	3.674	0	4.413	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0.2	83.316	0	83.516
	Desalting	0	0	0	0	0	0	83.316	83.316
	Sum to Destination	33.901	25	8.571	10.345	83.516	83.316	122.357	

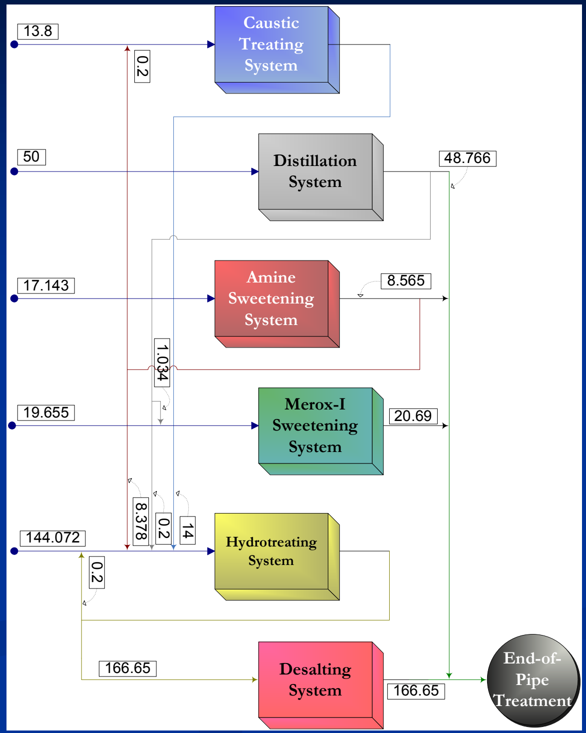
  - Cost = \$Mil 2.144 / yr
  - Consumption = 122.357 ton/hr

GAMS Model Robustness

- New Scenario:
  - Mass loads double, network fixed

- Final Results:

Origin		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
	Fresh Water Source	13.8	50	17.143	19.655	144.072	0	n/a	244.67
	Caustic Treating	0	0	0	0	14	0	0	14
	Distillation	0	0	0	1.034	0.2	0	48.766	50
	Amine Sweetening	0.2	0	0	0	8.378	0	8.565	17.143
	Merox I Sweetening	0	0	0	0	0	0	20.69	20.69
	Hydrotreating	0	0	0	0	0.2	166.65	0	166.85
	Desalting	0	0	0	0	0	0	166.65	166.65
	Sum to Destination	14	50	17.143	20.689	166.85	166.65	244.671	



- Cost = $Mil 4.287 / yr
- Consumption = 244.67 ton/hr

GAMS Model Robustness

- Other modes of the GAMS program can be used find solutions that:

GAMS Model Robustness

- Other modes of the GAMS program can be used find solutions that:
  - Minimize cost

Origin		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	16.68	25	8.571	0	24.774	44.307	n/a	119.332
	Caustic Treating	0	0	0	9.852	0.243	7.062	0	17.157
	Distillation	0	0	0	0	0	3.285	21.715	25
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0.477	0	0	0.493	3.109	24.047	0	28.126
	Desalting	0	0	0	0	0	0	87.273	87.273
	Sum to Destination	17.157	25	8.571	10.345	28.126	87.272	119.333	

GAMS Model Robustness

- Other modes of the GAMS program can be used find solutions that:
  - Minimize cost, then minimize the consumption with the initial solutions fixed

		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.422	25.572	49.367	n/a	119.332
	Caustic Treating	0.265	0	0	1.606	0.794	0	0	2.665
	Distillation	0	0	0	0.316	0.937	2.032	21.715	25
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.344	10.344
	Hydrotreating	0	0	0	0	0.822	27.303	0	28.125
	Desalting	0	0	0	0	0	0	87.273	87.273
	Sum to Destination	2.665	25	8.571	10.344	28.125	87.273	119.332	

GAMS Model Robustness

- Other modes of the GAMS program can be used find solutions that:
  - Minimize consumption, then minimize the cost with the initial solutions fixed

		Destination							
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	Sink	Sum from Source
Origin	Fresh Water Source	2.4	25	8.571	8.388	26.058	48.914	n/a	119.331
	Caustic Treating	0.267	0	0	1.645	0.755	0	0	2.667
	Distillation	0	0	0	0.312	1.312	1.662	21.715	25.001
	Amine Sweetening	0	0	0	0	0	8.571	0	8.571
	Merox I Sweetening	0	0	0	0	0	0	10.345	10.345
	Hydrotreating	0	0	0	0	0	28.125	0	28.125
	Desalting	0	0	0	0	0	0	87.273	87.273
	Sum to Destination	2.667	25	8.571	10.345	28.125	87.272	119.333	

GAMS Model & Regeneration

- Treatment units can be added mid-process to regenerate streams
- Equations must be updated to include flow from units to regenerators and cost of regeneration

- Calculation of outlet concentrations
  - Mixing Streams: $C_{mix} = \Sigma_i(C_{in,unit\text{-}i} * F_{in,unit\text{-}i})/F_{out,total}$
  - Outlet Concentration: $C_{out} = C_{mix} * X + C_{regen}$
  - If contaminant is not reduced in regenerator, $C_{regen} = 0$ and $X = 1$;
  - If contaminant *is* reduced in regenerator C_{regen} is its specified outlet concentration and $X = 0$

GAMS Model & Regeneration

- Results:

		Destination										
		Caust.	Dist.	Am.Sw.	M1S	Hydr.	Desalt	API/ACA	RO	CWWT	Sink	Sum from Source
Origin	Fresh Water Source	0	25	8.571	0	0	0	n/a	n/a	n/a	n/a	33.571
	Caustic Treating	0	0	0	0.014	0	0	2.55	0	0	0.1	2.664
	Distillation	0	0	0	0	0.016	0.013	19.814	0	0	5.156	24.999
	Amine Sweetening	0	0	0	0	0	0	8.471	0	0	0.1	8.571
	Merox I Sweetening	0	0	0	0	0	0	0	0	0	10.085	10.085
	Hydrotreating	0	0	0	0	0	0	29.893	0	0	0.1	29.993
	Desalting	0	0	0	0	0	0	56.396	0	0	18.03	74.426
	API and ACA	0	0	0	0	0	0	n/a	88.838	28.289	n/a	117.127
	Reverse Osmosis	1.333	0	0	2.187	10.905	74.413	n/a	n/a	0	n/a	88.838
	Chevron WWT	1.333	0	0	7.885	19.072	0	0	n/a	n/a	n/a	28.29
	Sum to Destination	2.666	25	8.571	10.086	29.993	74.426	117.124	88.838	28.289	33.571	

- Consumption = 33.571 ton/hr, Cost: = $Mil 1.301/yr
- Published consumption is the same:
  - Consumption = 33.571 ton/hr, Cost = $Mil 1.110/yr
  - Cost is somewhat higher

GAMS Summary

- Conclusions
  - GAMS model values are very close to published results
  - Model maintains effectiveness with use of regeneration
  - Model is robust enough to predict results in other cases

Future Work

- Include price of piping in GAMS model
  - Extensive piping networks may save in water cost compared to simpler networks, but cost more to construct
  - Cost of network, length and type of pipe required could all be variables in model

- Include maximum flowrates
  - Need to include minimum flowrates previously explained
  - Reasoning for using maximum flowrates is similar

- Continue study with fixed initial setup and changing mass loads
  - This setup better models the cost over time, so extending time period and increasing number of periods makes model more useful

Thank You!

Questions?