Water Management in Refining Processes

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5/8/2009

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Background

Water serves many purposes in an oil refinery, including but not limited to cooling high-temperature refining operations, equipment washing, steam generation, unit hydrotests, and fire fighting[i]. In the process of generating a system modeling water use in a refinery, six units will be explored that use water to absorb contaminants from the crude oil that is processed in the plant. These six processes are caustic treating, distillation, amine sweetening, Merox I sweetening, hydrotreating, and the desalter unit. The contaminants that are removed during the processes are salts, organics, H_2S, and ammonia. Table 1 below lists the maximum inlet and outlet concentrations for the six water-using units.

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

Table 1. Maximum inlet, outlet concentrations (ppm) for six water-using units[ii]

Figure 1 below gives a schematic of a typical refinery. The water-using units are cirled in red and the wastewater treatment processes are circled in green.

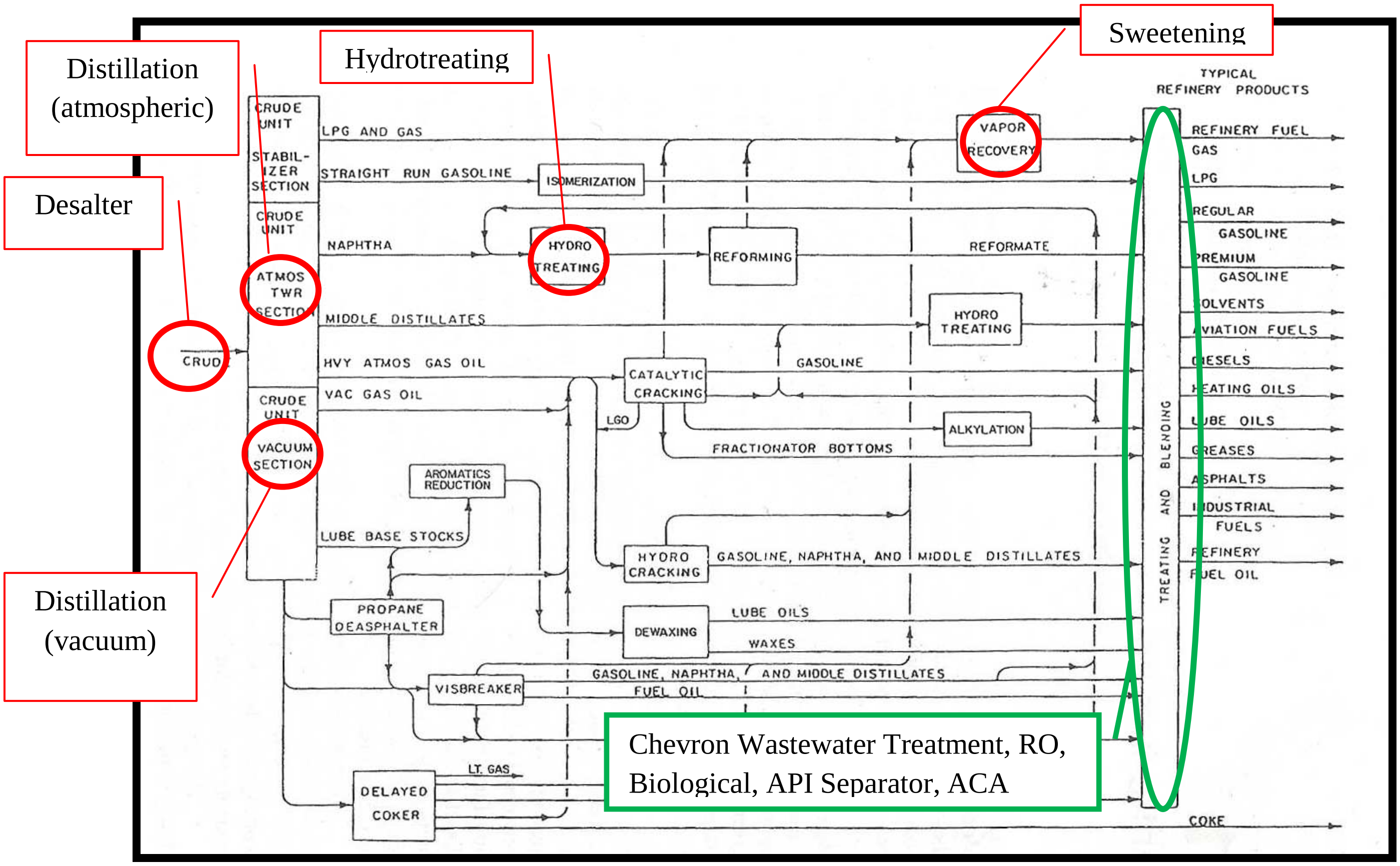


Figure 1. Refinery schematic[iii]

Crude desalting is usually the first step in a petroleum refining process. Crude oil enters into the refining unit from outside storage tanks and contains heavy amounts of contaminants, including water with dissolved or suspended salt crystals. It is heated by heat exchangers in order to increase the viscosity[iv]. A separate water stream is then introduced to the system and comes into contact with the crude oil, after which the two streams are vigorously mixed over a mixing valve. Water and crude oil are immiscible solvents and since salt has a higher solubility in water, the aforementioned salt particles will partition into the water. A schematic of the desalting process is shown on the following page.

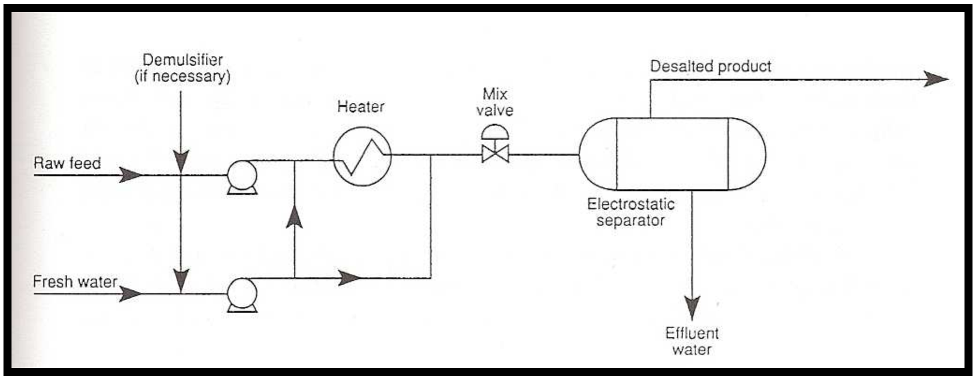


Figure 2. Single-stage electrostatic desalting system[v]

There are two types of distillation: atmospheric and vacuum. After the desalting stage, the crude oil is heated in heat exchangers and heated to about 750 degrees Fahrenheit before it enters into an atmospheric distillation unit. Atmospheric distillation separates light end products like natural gas, naphtha, and gas oil from crude oil. The crude is partially vaporized in a fired heater before entering the distillation unit flash zone. Superheated steam is introduced through the column bottom to strip any remaining gas oil from the flash zone liquid. The steam reduces the hydrocarbon partial pressure thereby reducing vaporization temperature. An atmospheric column is shown below:

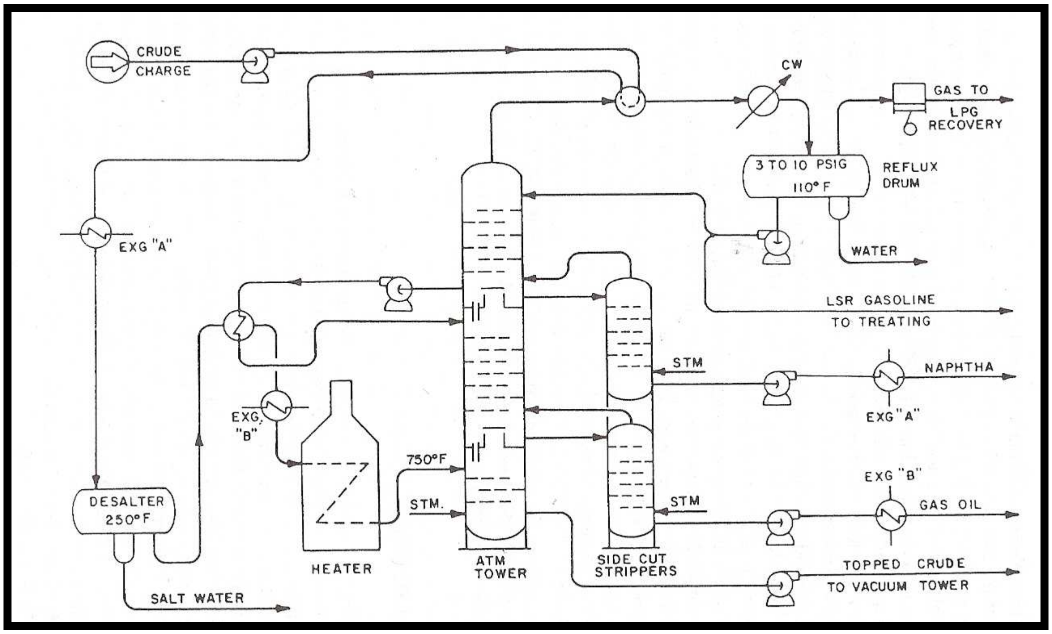


Figure 3. Atmospheric distillation unit[vi]

Following atmospheric distillation, the heavy bottoms product containing heavier fractions of crude oil is sent to a vacuum distillation tower where distillation under very low pressures (usually 25 to 40 mmHg[vii]) is carried out. Temperatures required for atmospheric distillation of heavier components would be too high and would result in cracking of hydrocarbons. By lowering the distillation pressure and introducing steam to the system (to improve vaporization), heavier products can be distilled. Prior to entering the distillation column, the topped crude is heated in a furnace to temperatures of about 750-850 degrees Fahrenheit. After distillation, different fractions of heavy components exiting the system pass through pumps and heat exchangers. A vacuum distillation column is shown below:

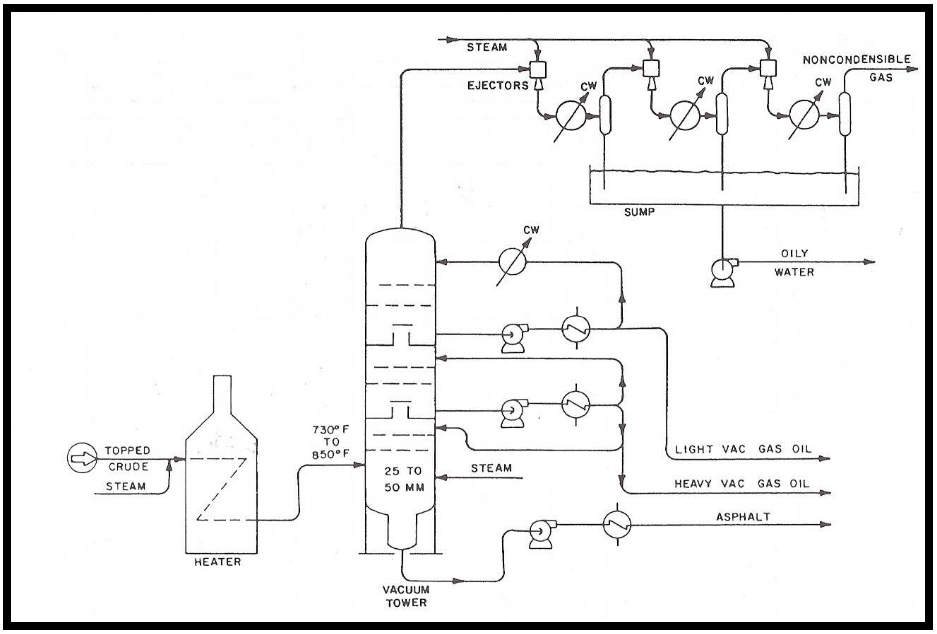


Figure 4. Vacuum distillation unit[viii]

Caustic treating is a refining process that uses an aqueous solution of NaOH to absorb acid gas compounds, like H_2S, CO_2, and mercaptans, found in natural gas or liquid hydrocarbon streams. Crude oil fractions that exit from the vapor stream in a distillation tower contain sulfur-based compounds, which are odiferous and corrosive. Following distillation, this light crude stream goes through amine treatment, which removes many of the mercaptans and helps to reduce the load that is sent to caustic treatment[ix]. A caustic solution of normally 15 wt% NaOH and higher is then introduced into an absorption tower where it comes into contact with the passing stream of light crudes and extracts the contaminants[x]. Caustic treating is normally used to clean liquefied natural gas (LNG) and diesel fuels. A diagram of a caustic treatment unit is shown below.

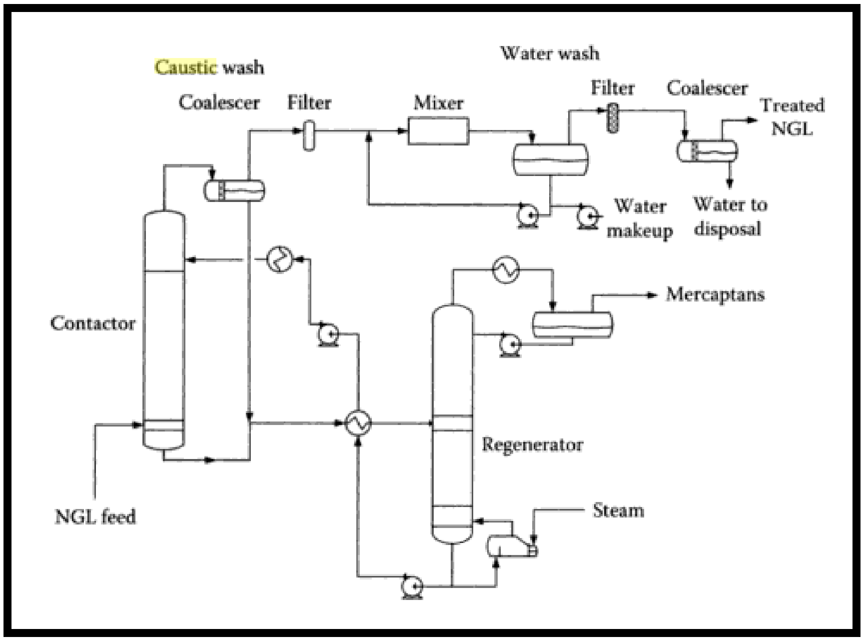


Figure 5. Caustic treating process[xi]

Amine sweetening is a process whereby aqueous solutions of alkanolamines (such as monoethanolamine or diethanolamine) absorb contaminants like hydrogen sulfide (H_2S), carbon dioxide (CO_2), and mercaptans from a passing stream of natural gas. The absorption process is called sweetening because it eliminates the bitter odor coming from the sour feed making the clean gas smell "sweet". The acid gas contents are removed through chemical reactions with the amines in the amine solution and come out of the absorber in the rich amine liquid solution. A flash tank is usually installed at the absorber outlet to reduce flash any hydrocarbons that may be in the feed, thereby removing them from the acid gas product[xii]. A process flow diagram of an amine-sweetening unit is shown in Figure 6.

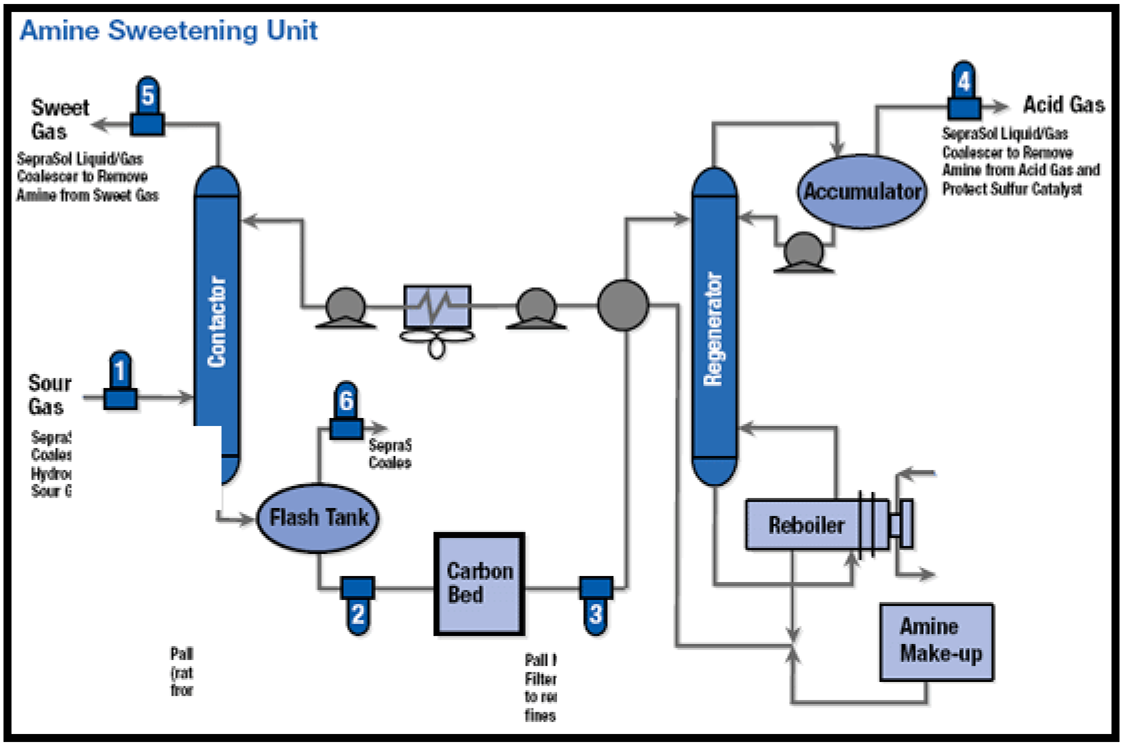


Figure 6. Amine-sweetening unit[xiii]

Hydrotreating is a process that removes elemental sulfur, nitrogen, oxygen, halides, and trace metals from crude oil in order to improve the quality of its constituents, such as gasoline, diesel fuel, and jet fuels. Hydrotreating is used to convert olefins and unstable diolefins into paraffins by reacting them with hydrogen. A schematic of the hydrotreating process is shown in Figure 7. Hydrogen is mixed with feed liquids and heated in a heating furnace. The heated crudes, at about 700-800°F, are passed through a catalytic reactor where chemical reactions convert organic sulfur and nitrogen compounds to hydrogen sulfide and ammonia. The reactor effluent is cooled in a heating exchanger and condensed hydrocarbons are sent to a stripper, where a desulfurized bottoms product exits.

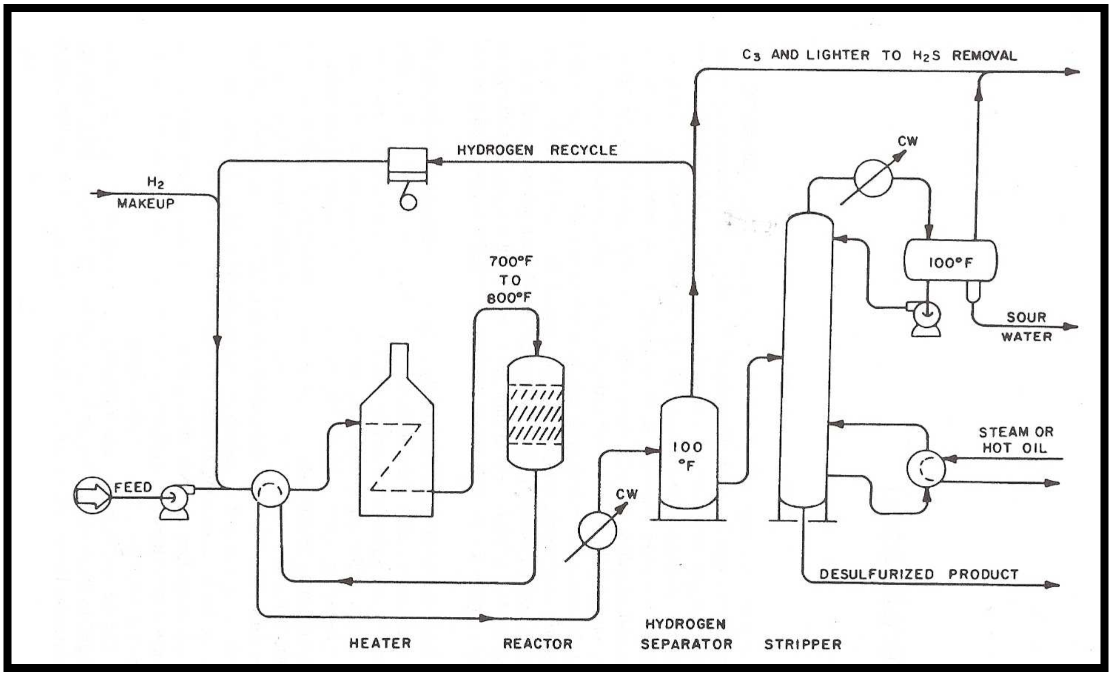


Figure 7. Hydrotreatment unit[xiv]

API separators separate suspended solids and oil from wastewater streams based on differences in specific gravities between the oil and the wastewater. The differential density is much smaller for oil and wastewater than for suspended solids and wastewater. Thus, the oil globules will rise through the water, suspended solids will sink to the bottom, and the wastewater containing some small amounts of oil particles will exit as the middle layer. After separation, the oil in the top layer is skimmed off and re-processed and the sedimentation from the bottom of the separator is removed using a sludge pump.

The particles settling in an API separator operate on the basis of Stokes Law: the contaminant particles fall through the viscous fluid by their own weight due to a gravitational force. The upward drag of the small particles (which are assumed to be spheres) combine with the buoyancy force balances the gravitational force thereby creating a settling velocity, which is the velocity at which the particles settle. The settling velocity, also termed the terminal velocity, is given by:

$$V_t = \frac{2}{9\mu}(\rho_W - \rho_O)gR^2 \qquad \text{Equation 1}$$

where V_t is the settling velocity in cm/s, μ is the fluid viscosity in poise, ρ_W is the density of water at the design temperature in g/cm^3, ρ_O is the density of oil at the design temperature in g/cm^3, g is the gravitational constant (981 cm/s^2), and R is the radius of the particle which will be removed in cm. Typically, a particle with a radius no smaller than 0.015 cm, will settle out of the water. A schematic of an API separator is shown below.

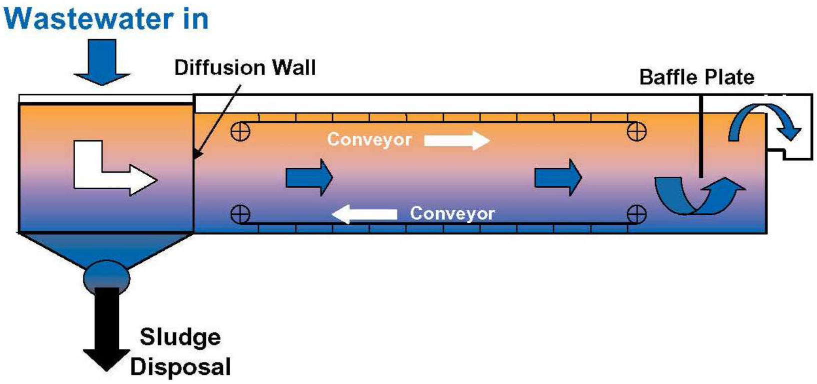


Figure 8. API Separator^{xv}

Reverse osmosis

Theory of reverse osmosis

Reverse osmosis is a process by which dissolved solutes are separated from a solution by a pressure-driven membrane that applies the preferential diffusion for separation. The solution to be separated on one side of the membrane known as the feed is separated by a membrane filled with pure water on the other side. Due to difference in the concentrate between the feed and permeate side instability is created, water then flows from the pure side to the feed to equilibrate the system. The water level in the solution will rise to a point, which is equal to the osmotic pressure, π, of the concentrated solution. When this occurs, the water flux across the membrane to the permeate is equal to that to the feed and equilibrium is reached. At this point of equilibrium, the driving force generated to move the water molecules is then terminated. This process is known as the osmosis process.

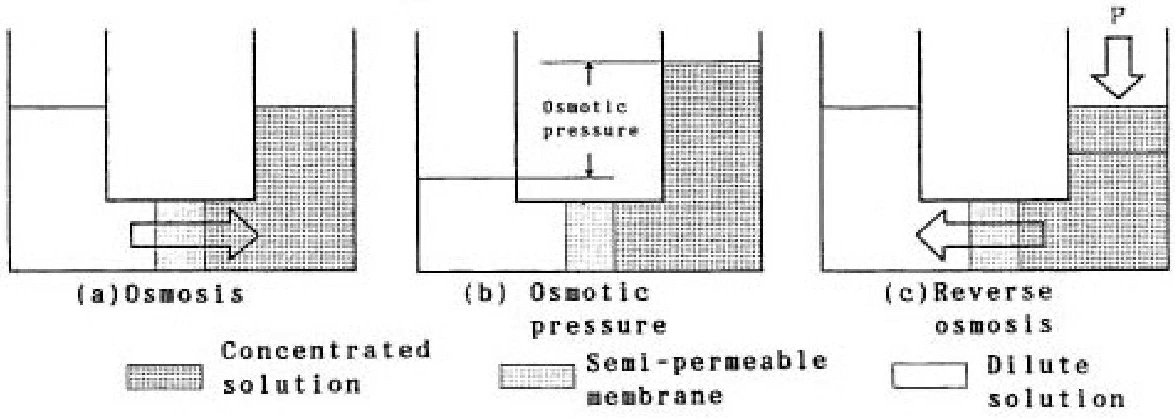


Figure 9. Osmosis and reverse osmosis processes

In reverse osmosis, high pressure is applied at the feed and a differential pressure is created between the permeate and feed sides of the membrane. This results into a pressure change, the system then becomes unstable allowing the flow of water from the feed stream through the membrane to the pure water side (permeate). As water passes through the membrane, the solutes are rejected at the membrane surface increasing the concentration of the feed stream which flows out of the process as a stream called the concentrate. The permeate exits the process at atmospheric pressure, while the concentrate stream leaves the membrane element at high pressure is approximately equal to the feed pressure.

The rate of flow of water molecules in a unit area of the membrane (also known as the water flux) through the membrane is the product of the driving force and the transfer rate as defined by the below equation:

$$J_W = k_w \cdot (\Delta P - \Delta\pi) \qquad \text{Equation 2}$$

where: J_W = volumetric flux of water ($L/m^2 \cdot s$)

k_W = mass transfer coefficient of water flux ($L/m^2 \cdot s \cdot atm$)

$\Delta P = (P_F - P_P)$ = hydraulic pressure change (atm)

$\Delta\pi = (\pi_F - \pi_P)$ = change in osmotic pressure in the feed and permeate (atm)

The flow of the solutes (salt) through the membrane is given by the equation below:

$$J_S = k_S \cdot (\Delta C) \qquad \text{Equation 3}$$

where: J_S = mass flux of solute ($kg/m^2 \cdot s$)

k_S = mass transfer coefficient of solute ($L \cdot S/m^2$)

The osmotic pressure of the feed is calculated using van’t Hoff law for dilute solutions as in the expression below:

$$\pi = cRT \qquad \text{Equation 4}$$

where : c = concentration of solute in feed/permeate (mol/L)
R = gas constant ~0.0820578 (L·atm)/(g-mol·K)
T = temperature of solution (K)

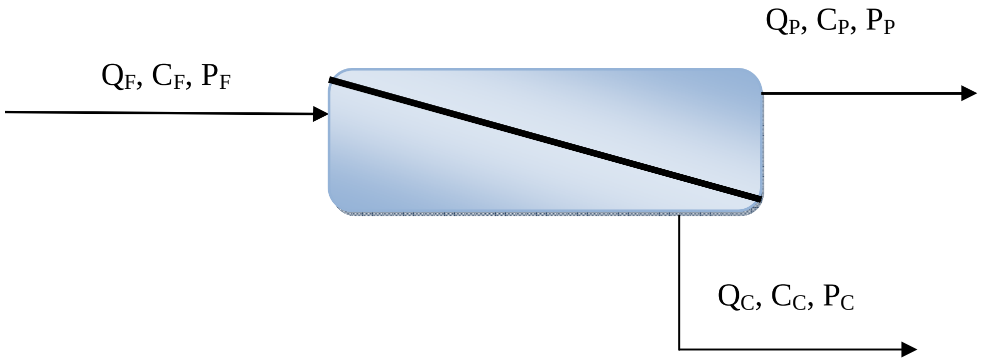
Membrane material

The force directed towards the membrane for the separation of solutes from water based on the physical and chemical properties of the solutes to be removed and the material of the membrane. The resistance to flow through the membrane is inversely related to the thickness which means that for high efficiency, the membrane has to be extremely thin. For a reverse osmosis, the thickness of the membranes ranges from about 0.1 to 2 μm. This extreme size of the material makes the membrane lack structural reliability as a result, membranes usually comprise of several layers with low porosity. The ideal material is one that can produce a high flux without clogging or fouling and is physically durable and chemically inactive. The materials most widely used in reverse osmosis are the cellulosic derivatives and polyamide derivatives (Crittenden).

Process application in wastewater treatment

In wastewater treatment process, reverse osmosis is a technology used for the removal of various inorganic contaminants. However, the main problem with the reverse osmosis technologies in the waste water treatment industry is the disposal of the concentrates and fouling that occurs on the membrane over a period of time as pressure is increased. However, to prevent this from occurring, the wastewater is pretreated by scaling which adjust the PH value, changing the solubility of the precipitates of inorganic contaminants that could be formed during operation (Hendricks).

Mathematical model



A mass balance around the membrane pressure vessel process results to the following equations:

Membrane mass balance

$$Q_F = Q_C + Q_P \qquad \text{Equation 5}$$

$$C_F Q_F = C_C \cdot Q_C + C_P \cdot Q_P \qquad \text{Equation 6}$$

where:

C_C = concentrate of solute in concentrate water (kg/m^3)
C_P = solute concentrate in permeate water (kg/m^3)
C_F = solute concentrate in feed water (kg/m^3)
Q_P = permeate flow (m^3/s)
Q_F = feed flow (m^3/s)
Q_C = concentrate flow (m^3/s)

The flow rate of water molecules in the permeate is related to the water flux by the equation shown below:

$$Q_P = J_W \text{ x Area of membrane} \qquad \text{Equation 7}$$

The flux of the solutes is also related to the flux of water by the equation below:

$$J_S = C_P \cdot J_W \qquad \text{Equation 8}$$

The combination of the solute flux in equations 2 and 8, and rearranging the equation, the concentration of salts in the treated water (permeate) C_P, was determined. The final equation that relates the concentration out at the permeate was found to be:

$$C_P = C_F - B \cdot N \qquad \text{Equation 9}$$

where N: the number of membranes

B (found using Mathcad):

$$B = \frac{((C_F RTk_w)^{2} + 2C_F RTk_w(\;\; 3k_S \quad k_w P_F \quad k_w P_P) + k_S^{2} + 2k_S k_W (P_F \quad P_P) + k_w^{2}(P_F^{2} \quad 2P_F P_P + P_P^{2})) \quad \frac{k_S}{2} \quad \frac{k_W P_F}{2} + \frac{k_W P_P}{2} + \frac{C_F RTk_W}{2}}{RTk_W}$$

The effect of the design parameters, N, k_W, and k_S, and the feed conditions T and P_F are summarized in the table below:

Increase in variables	**Increase/ decrease**
Feed temperature, T (K)	increases
Number of membranes, N	decreases
Salt permeability, k_S (L/m2-atm-s)	increases
Water permeability, k_W (L/m2-atm-s)	decreases
Feed pressure, P_F (atm)	decreases

Table 2. Effect of feed conditions and design parameter on effluent concentration

From the above table, it can be seen that the operating temperature has to be low in order to obtain a high degree of wastewater purity. Also, the salt permeability which is the ability of the salt to pass through the membrane to the permeate has to be low. As expected, the salt permeability affects the purity of water showing that if the porous membrane used for the process is liable to absorb the salt molecules, then the amount of salt in the permeate will be high. This renders the treatment system inefficient, and therefore the material of the membrane used for the process is highly important. An increase in the number of membranes used, will give a reduction in the contaminants found in the effluent stream as desired. Therefore, a high number of membranes should be used for the treatment process. This is highly recommended because the membrane (whichever type) has the ability to foul if the amount of contaminants in the feed is high and therefore gets attached to the surface.

The table below summarizes the optimum conditions and design parameters to achieve high degree of purity in the wastewater.

Parameters and effects	
Feed temperature, T (K)	Decrease temperature, negligible effect at extreme low temperature
Number of membranes, N	Increase the number used, high degree of purity can be attained
Salt permeability, Ks (L/m2-atm-s)	Choose material with low salt permeability, possibly zero
Water permeability, Kw(L/m2-atm-s)	Choose material with high water permeability
Feed pressure, PF (atm)	Increase the pressure at the feed to allow high degree of diffusion at membrane

Table 3. Feed conditions and design parameters to be considered for process design

Activated Carbon Adsorption

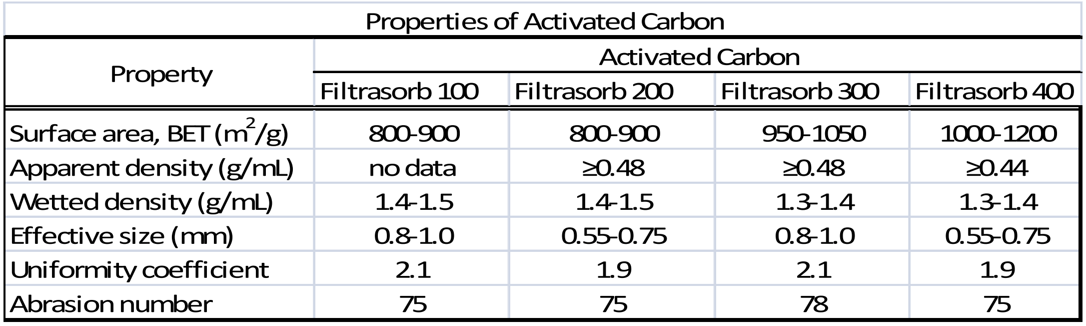
Theory of adsorption

Adsorption is a process by which molecules of substances present in a liquid phase are attached on the surface of a solid matter and removed from the liquid phase. The process involves the molecules in the gas or liquid phase diffuse to the surface of the solid and stay there by chemical bonding or weak intermolecular forces. The solid phase particle which provides the bonding sites is known as the adsorbent and the substance in the adsorbed state is called the adsorbate.

There are two main types of adsorption which are the physisorption and the chemisorption. The physisorption is when the adhesive forces are of physical nature and adsorption is relatively weak and the amount of heat evolved for a mole of gas adsorbed is usually less than 20 kJ (Laidler). For the chemisorption, the adsorbed molecules are bonded to the surface by covalent forces which are stronger than intermolecular forces between the molecules of the adsorbate. In chemisorption which is usually applied in industries, after the surface has been covered with a monolayer of adsorbed molecules, it is said to be saturated and additional adsorption occurs on the layer that already exists. However, Langmuir emphasized that adsorption formation is of unimolecular layer and once formed adsorption ceases but multilayer can exist for physisorption.

Adsorbent

Adsorbents used in industries are generally synthetic microporous solids: activated carbon, molecular sieve carbon, activated alumina, silica gel, zeolites and bleaching clay. The most important characteristics of adsorbents are pore volume, the pore distribution and the geometry of the particles of the adsorbent. The table below shows the properties of the commonly used activated carbon.



Properties of Activated Carbon

Property	Activated Carbon			
	Filtrasorb 100	Filtrasorb 200	Filtrasorb 300	Filtrasorb 400
Surface area, BET (m^2/g)	800-900	800-900	950-1050	1000-1200
Apparent density (g/mL)	no data	≥0.48	≥0.48	≥0.44
Wetted density (g/mL)	1.4-1.5	1.4-1.5	1.3-1.4	1.3-1.4
Effective size (mm)	0.8-1.0	0.55-0.75	0.8-1.0	0.55-0.75
Uniformity coefficient	2.1	1.9	2.1	1.9
Abrasion number	75	75	78	75

Table 4. Properties of Activated Carbon

Process description

At equilibrium, the rate of adsorption on the surface of the adsorbent is equal to the rate at which desorption occurs. When this occurs, an increase in the residence time of the adsorbate in the column of adsorbate has no effect. The adsorption process can be described as in the usual chemical reaction as shown below:

$$C + X \leftrightarrow C \cdot X \qquad \text{Equation 10}$$

where:

C = adsorbent concentration (kg/m^3)

$C \cdot X$ = concentration of the sites occupied by adsorbate molecules (kg adsorbate adsorbed/kg adsorbent/m^3 solution)

X = adsorbate sites not occupied per unit adsorbent in a unit volume (kg unoccupied adsorbate/kg adsorbent/m^3 solution)

At equilibrium, the rate of adsorption and desorption are equal. The equilibrium constant can be then introduced as below.

$$K_{eq} = K = \frac{[C \cdot X]}{[C]^*[X]^*} \qquad \text{Equation 11}$$

where: K_{eq} = K = adsorption equilibrium constant

[C]* = adsorbate concentrate, C, at equilibrium

(kg adsorbent/m^3 solution)

Langmuir Isotherm

Adsorption isotherm relates the amount of substance attached to the surface of the adsorbent to the amount in the solution at a defined temperature. The Langmuir isotherm which is used for the process assumes that the surface of the activated carbon is homogeneous and as mentioned previously adsorption occurs in a single layer.

$$\overline{X} = \frac{X_{\max} KC}{KC} \qquad \text{Equation 12}$$

where: K = Langmuir equilibrium constant = K_{eq}

X_{max} = maximum amount of adsorbate in solid phase per adsorbent (kg adsorbate/kg adsorbent)

C = concentration in solution at equilibrium (kg adsorbate/m^3 solution)

It is assumed that the internal (pore) diffusion is rate controlling in the adsorption process. It is also assumed that the geometry of the activated carbon particle is spherical and all the assumptions made for the Langmuir isotherm is also used. Finally, the bed is assumed to be a batch process in a tank of volume, V.

Mathematical model

To design the activated carbon adsorption process, the fixed bed was chosen rather than the slurry adsorption. This is due to the fact that the fixed bed is more efficient and the bed can be regenerated not disposed as in the case of slurry adsorption.

Assuming the process is a plug flow of the wastewater through the bed is at a constant interstitial velocity, there is no axial dispersion and the temperature is constant throughout the process (isothermal); the mass balance on the solute flowing through a bed length z at differential length Δz is given by the equation:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial z} + \frac{(1-\varepsilon)}{\varepsilon}\cdot\frac{\partial q}{\partial t} = 0 \qquad \text{Equation 13}$$

However, when the axial dispersion and transfer of mass from the solute to the activated carbon is not neglected as initially assumed, the equation above is modified to a partial differential which is given below:

$$-D_L\frac{\partial^2 C_b}{\partial z^2} + V\frac{\partial C_b}{\partial z} + C_b\frac{\partial V}{\partial z} + \frac{\partial C_b}{\partial t} + \rho_p\left[\frac{1-\varepsilon}{\varepsilon}\right]\cdot\frac{\partial q_p}{\partial t} = 0 \qquad \text{Equation 14}$$

In the above equation, the D_L is known as the term which accounts for the axial dispersion with diffusion to the activated carbon bed, the second term is related to the change in velocity of flow axially. This equation has to be solved numerically, but an analytical solution can be found when the equation is made simple. Klinkenberg approximation was used to determine the solution with certain assumptions which include that the axial dispersion can be ignored, the fluid velocity is constant and the mass transfer model is linear. The Klinkenberg approximation is as below:

$$\frac{C}{C_F} \approx \frac{1}{2}\left[1 + erf\left(\sqrt{\tau} - \sqrt{\varepsilon} + \frac{1}{8\sqrt{\tau}} + \frac{1}{8\sqrt{\varepsilon}}\right)\right] \qquad \text{Equation 15}$$

where: $\varepsilon = \frac{kKz}{u}\left[\frac{1-s}{s}\right]$ Dimensionless distance coordinates

$\tau = k\left[t - \frac{z}{u}\right]$ Dimensionless time coordinate corrected for displacement

Using this formula, the effluent concentration was estimated to be approximately zero based on the residence time in the column.

Chevron waste water treatment

Chevron waste water treatment (WWT) strips hydrogen sulfide and ammonia from sour water generated in petroleum refineries[xvi]. The two-stage stripping process produces separate purified ammonia and hydrogen sulfide streams, wherein the hydrogen sulfide can be sent to sulfur recovery units, the ammonia can be sold commercially or used again in Selective Catalytic or Selective Non-catalytic Reduction units in the refinery, and the purified wastewater can either be sent to end-of-pipe treatments or reused. A process-flow diagram for a Chevron water treatment plant is shown below.

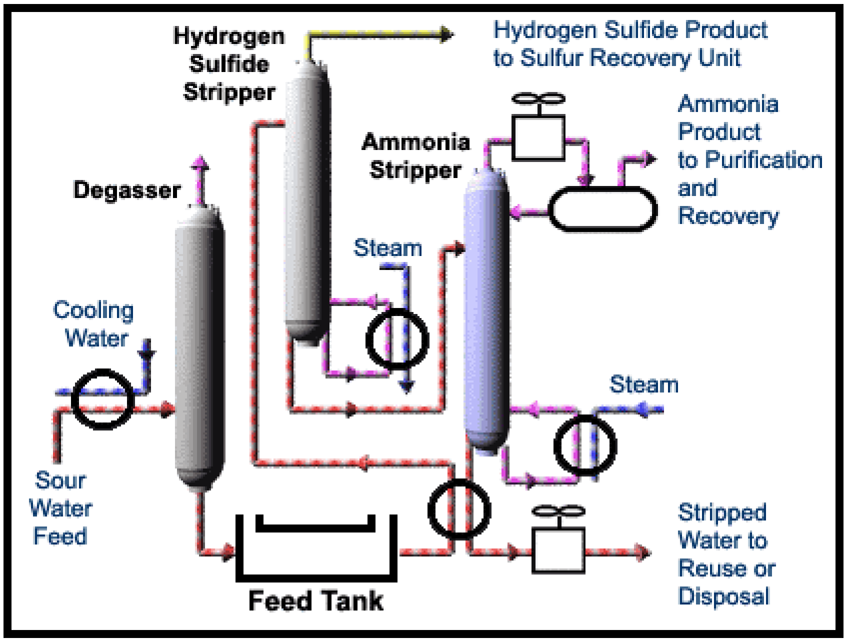


Figure 10. Chevron Wastewater Treatment Plant[xvii]

Biological treatment

Biological treatment operates on the idea that microorganisms present in wastewater will feed on the carbonaceous organic matter in the wastewater and repopulate in an aquatic aerobic environment. With a sufficient oxygen supply and an organic material food supply, the bugs (bacteria) will consume and metabolize the organic waste and transform it into cell mass, which settles in the bottom of a settling tank.

Most biological treatment plants have two forms of operation: primary and secondary. Primary treatment involves the physical removal of solids and secondary treatment involves the biological removal of dissolved solids[xviii]. Secondary treatment mainly uses biological treatment processes, whereby the introduction of microorganisms to the system creates solids which precipitate out and are collected in the settling tank. Three common options for secondary treatment include:

I. Activated sludge
II. Trickling filters
III. Lagoons

The treatment that will be modeled in this project is the activated sludge system. The wastewater influent is sent through an aeration tank where air is pumped through the bottom of the tank and rises through the water in the form of bubbles. The purpose for this is two-fold: air provides oxygen to the water and creates turbulent conditions ideal for organic material consumption[xix]. The wastewater is then sent through what is called a secondary clarifier. The clarifier is a settling tank that separates the used cellular material from the treated wastewater. The cellular material sinks to the bottom of the basin whereby it is either sent back to aeration tank to assist in producing new bacteria or sent as sludge for anaerobic treatment. A schematic of the process is shown on the next page in Figure 11.

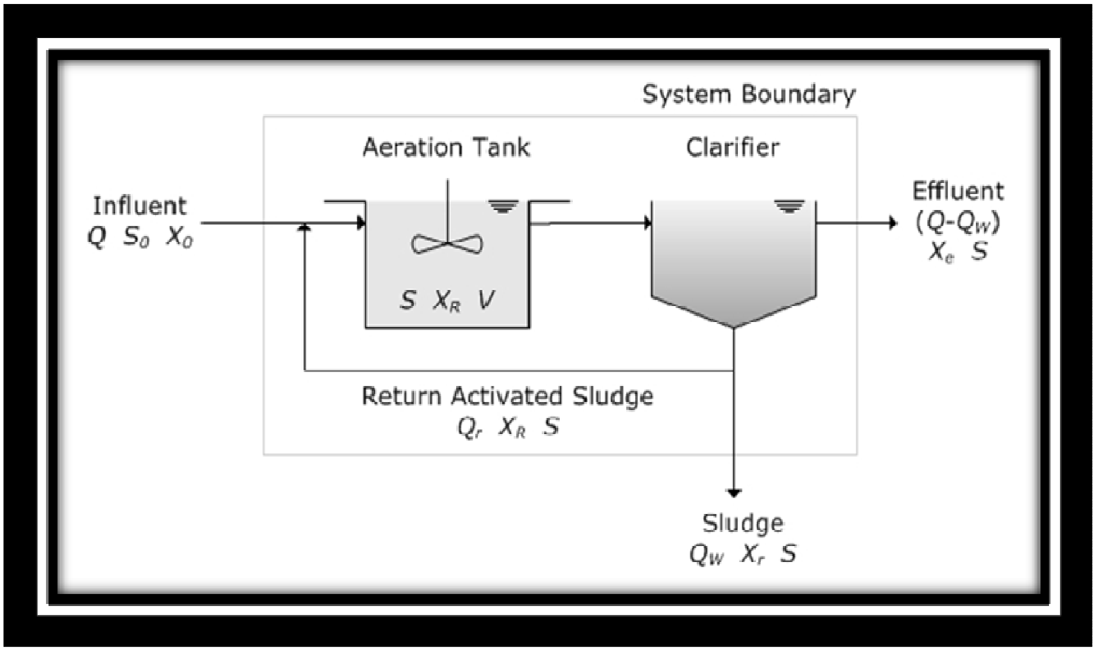


Figure 11. Activated sludge system[xx]

where:

Q = flowrate of influent $[m^3/d]$

Q_W = waste sludge $[m^3/d]$

Q_r = flowrate in return line from clarifier $[m^3/d]$

V = volume of aeration tank $[m^3]$

S_0 = influent soluble substrate concentration (bsCOD) $[m^3/d]$

S = effluent soluble substrate concentration (bsCOD) [BOD g/m^3] or [bsCOD g/m^3]

X_0 = concentration of biomass in influent [g VSS/m^3]

X_R = concentration of biomass in return line from clarifier [g VSS/m^3]

X_r = concentration of biomass in sludge drain [g VSS/m^3]

X_e = concentration of biomass in effluent [g VSS/m^3]

Simulation Methods

Several different methods were used in this study to simulate real-life water-using and water treating process units. PRO/II, *Steady*, Mathcad, and Excel were used to generate points by varying inlet system parameters, like temperature, pressure, flowrate, etc. These points were then analyzed to find the nature of correlations between components varied and outlet concentration. The Casestudy function in PRO/II has the capability of varying more than one inlet parameter at once (maximum used in this study was six) and this eased the workload. The Excel files made by the researchers were used mostly for cost analyses purposes.

PRO/II

The primary simulation program used in this study was PRO/II. Its proven accuracy in predicting results from specifications of inlet parameters and its applicability to the processes currently being modeled were the reasons for its use. The H_2S stripper, NH_3 stripper, amine sweetening, and atmospheric columns were modeled in PRO/II as distillation columns. The H_2S differed slightly from the other distillation columns in that it contained only a partial reboiler and not a partial condenser. A snapshot of the crude oil distillation unit is shown in Figure 12.

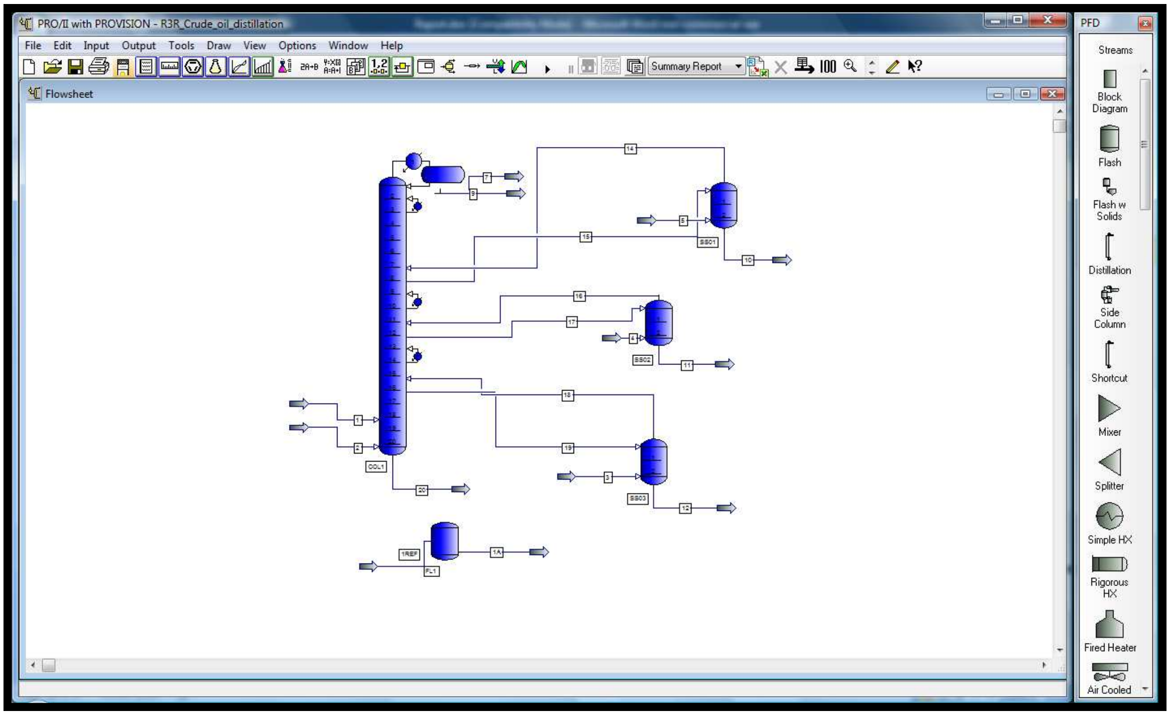
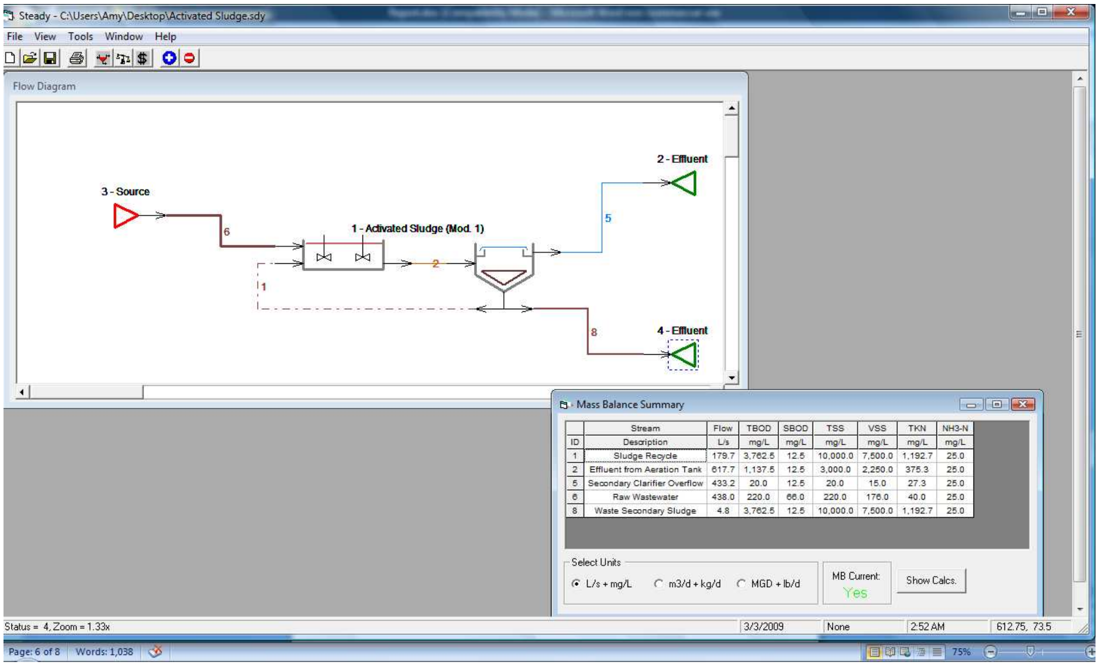


Figure 12. Snapshot of Pro/II crude oil distillation unit

Steady

The simulation program used to model the activated sludge system was a computer program called *Steady*^{xxi}. *Steady* is a steady-state wastewater treatment plant modeling program developed by researchers at the University of Texas that characterizes wastewater in terms of water quality assessment procedures, like BOD_5, TSS, VSS, TKN, and NH_3-N. The model assumes steady-state conditions for influent contaminants to a plant and calculates a plant-wide mass balance and general dimensions of the unit processes involved. *Steady* has the capability of modeling a full activated sludge system, complete with a source stream, aeration tank, clarifier tank with recycle, sludge stream, and a wastewater effluent stream. A snapshot of the file made in this study is shown below.



	Stream	Flow	TBOD	SBOD	TSS	VSS	TKN	NH3-N
ID	Description	L/s	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1	Sludge Recycle	179.7	3,762.5	12.5	10,000.0	7,500.0	1,192.7	25.0
2	Effluent from Aeration Tank	617.7	1,137.5	12.5	3,000.0	2,250.0	375.3	25.0
5	Secondary Clarifier Overflow	433.2	20.0	12.5	20.0	15.0	27.3	25.0
6	Raw Wastewater	438.0	220.0	66.0	220.0	176.0	40.0	25.0
8	Waste Secondary Sludge	4.8	3,762.5	12.5	10,000.0	7,500.0	1,192.7	25.0

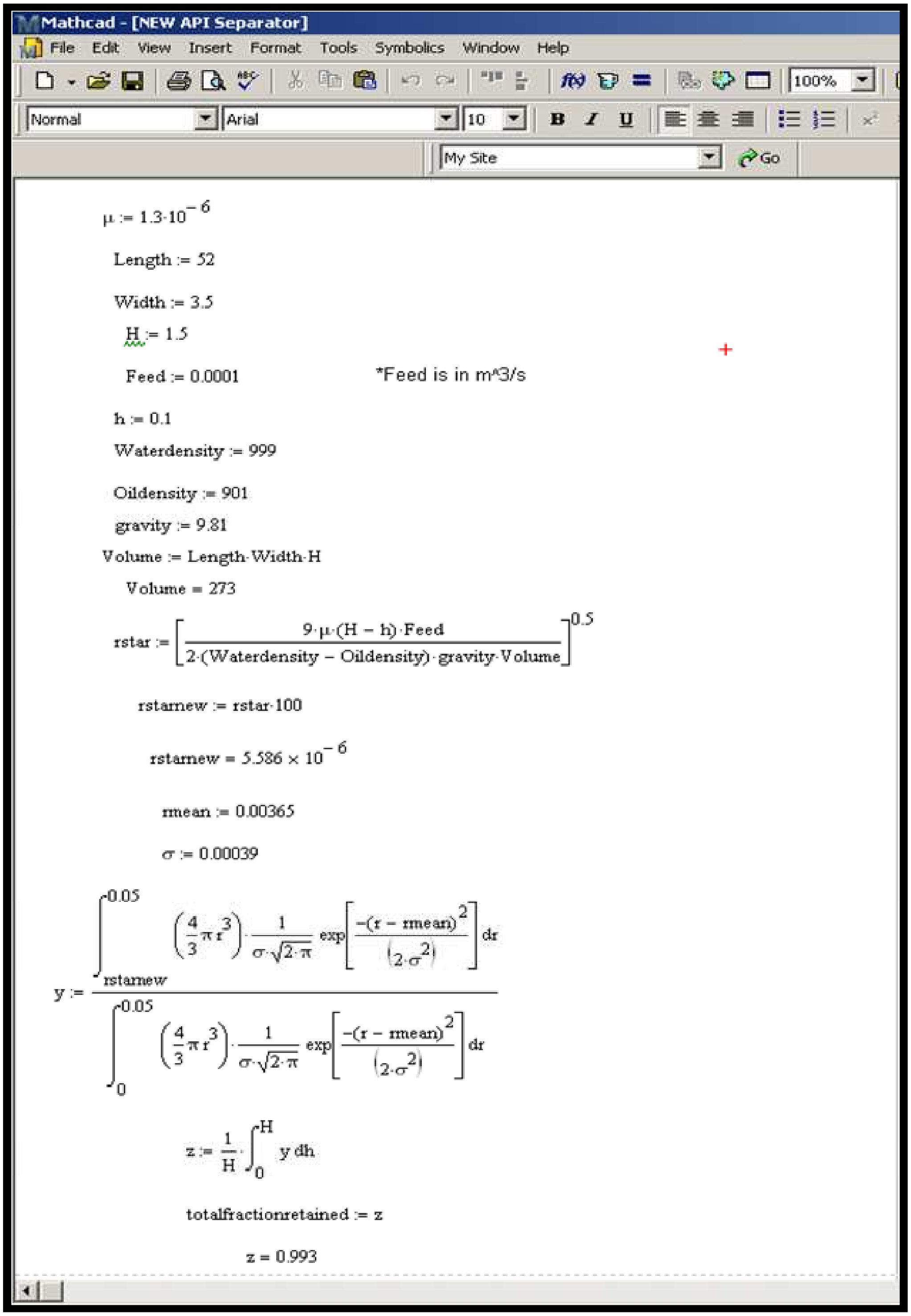
Select Units
● L/s + mg/L ○ m3/d + kg/d ○ MGD + lb/d

MB Current: Yes

Figure 13. Snapshot of *Steady* file with activated sludge model and mass balance summary

Mathcad

Mathcad was used to generate points for the API separator and the reverse osmosis system. System parameters and inlet stream variables were varied and points were generated to be input to GAMS as tables. A screenshot of the Mathcad file simulating the API separator is shown in Figure 14.



$\mu := 1.3 \cdot 10^{-6}$

$Length := 52$

$Width := 3.5$

$H := 1.5$

$Feed := 0.0001$ *Feed is in m^3/s

$h := 0.1$

$Waterdensity := 999$

$Oildensity := 901$

$gravity := 9.81$

$Volume := Length \cdot Width \cdot H$

$Volume = 273$

$$rstar := \left[\frac{9 \cdot \mu \cdot (H - h) \cdot Feed}{2 \cdot (Waterdensity - Oildensity) \cdot gravity \cdot Volume}\right]^{0.5}$$

$rstarnew := rstar \cdot 100$

$rstarnew = 5.586 \times 10^{-6}$

$rmean := 0.00365$

$\sigma := 0.00039$

$$y := \frac{\int_{rstarnew}^{0.05} \left(\frac{4}{3}\pi r^3\right) \cdot \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \exp\left[\frac{-(r - rmean)^2}{(2 \cdot \sigma^2)}\right] dr}{\int_{0}^{0.05} \left(\frac{4}{3}\pi r^3\right) \cdot \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \exp\left[\frac{-(r - rmean)^2}{(2 \cdot \sigma^2)}\right] dr}$$

$$z := \frac{1}{H} \cdot \int_{0}^{H} y \, dh$$

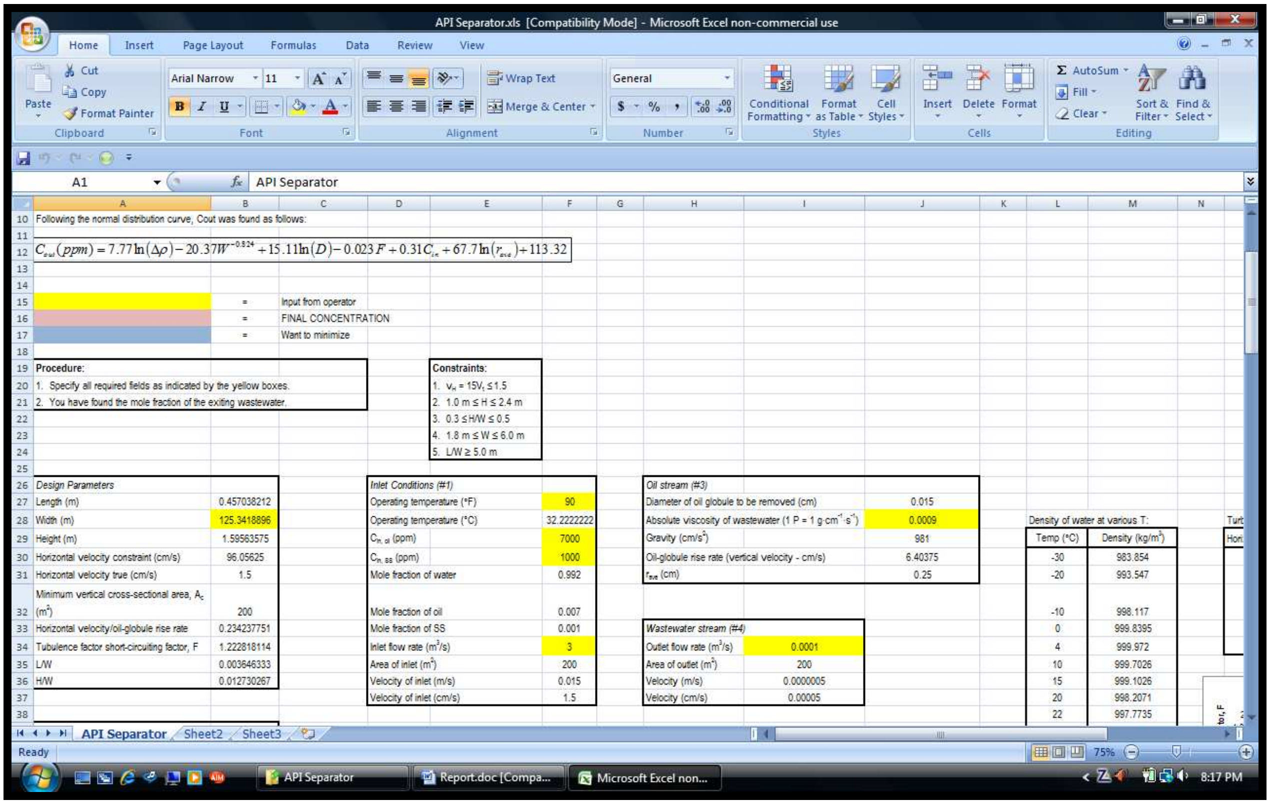
$totalfractionretained := z$

$z = 0.993$

Figure 14. Snapshot of Mathcad file for API separator

Excel

Excel files were made for the API separator and the Chevron Wastewater Treatment plant to model the processes and the cost of the treatment unit. A snapshot is shown in Figure 15.



Following the normal distribution curve, Cout was found as follows:

$$C_{out}(ppm) = 7.77\ln(\Delta\rho) - 20.37W^{-0.824} + 15.11\ln(D) - 0.023F + 0.31C_{in} + 67.7\ln(r_{ave}) + 113.32$$

🟨 = Input from operator
🟥 = FINAL CONCENTRATION
🟦 = Want to minimize

Procedure:
1. Specify all required fields as indicated by the yellow boxes.
2. You have found the mole fraction of the exiting wastewater.

Constraints:
1. $v_H = 15V_t \le 1.5$
2. $1.0\ m \le H \le 2.4\ m$
3. $0.3 \le H/W \le 0.5$
4. $1.8\ m \le W \le 6.0\ m$
5. $L/W \ge 5.0\ m$

Design Parameters	
Length (m)	0.457038212
Width (m)	125.3418896
Height (m)	1.59563575
Horizontal velocity constraint (cm/s)	96.05625
Horizontal velocity true (cm/s)	1.5
Minimum vertical cross-sectional area, A_c (m^2)	200
Horizontal velocity/oil-globule rise rate	0.234237751
Tubulence factor short-circuiting factor, F	1.222818114
L/W	0.003646333
H/W	0.012730267

Inlet Conditions (#1)	
Operating temperature (°F)	90
Operating temperature (°C)	32.2222222
$C_{in,\ oil}$ (ppm)	7000
$C_{in,\ ss}$ (ppm)	1000
Mole fraction of water	0.992
Mole fraction of oil	0.007
Mole fraction of SS	0.001
Inlet flow rate (m^3/s)	3
Area of inlet (m^2)	200
Velocity of inlet (m/s)	0.015
Velocity of inlet (cm/s)	1.5

Oil stream (#3)	
Diameter of oil globule to be removed (cm)	0.015
Absolute viscosity of wastewater ($1\ P = 1\ g\cdot cm^{-1}\cdot s^{-1}$)	0.0009
Gravity (cm/s^2)	981
Oil-globule rise rate (vertical velocity - cm/s)	6.40375
r_{ave} (cm)	0.25

Wastewater stream (#4)	
Outlet flow rate (m^3/s)	0.0001
Area of outlet (m^2)	200
Velocity (m/s)	0.0000005
Velocity (cm/s)	0.00005

Density of water at various T:

Temp (°C)	Density (kg/m^3)
-30	983.854
-20	993.547
-10	998.117
0	999.8395
4	999.972
10	999.7026
15	999.1026
20	998.2071
22	997.7735

Figure 15. Snapshot of API separator Excel file

Simulations were run in PRO/II, *Steady*, Mathcad, and Excel, varying any and all parameters that could be varied. Inlet parameters in PRO/II were varied based on the model being used and they include, but are not limited to, column efficiency, number of trays, inlet temperature, inlet concentration, pressure, reboil and/or reflux ratio, and feed flowrate. A case study was performed for each simulation in PRO/II and results were exported to Microsoft Excel. Graphs plotting outlet concentration (dependent variable) vs. each inlet parameter (independent variable) were then generated to find the relationship between the two variables. Whatever shape the points in the graph appeared to take was the basis of determination of which type of regression (linear or non-linear) would be performed. So, for instance, if the graph appeared to follow a straight line, a linear regression was performed. If the graph had some curvature to it, a non-linear regression (including exponential fit, power law, or logarithmic) was performed. The regression which produced the highest coefficient of determination, R^2, was kept and regarded as the best fitting line. The graph with the highest coefficient of determination was kept because it represented the smallest different between the actual and predicted values for that curve. All R^2 and regressions were performed in and by Excel algorithms.

After graphs were generated in Excel, a model was guessed that represented an outlet contaminant concentration as a function of all of the aforementioned inlet variables. This model was essentially based on adding together all of the best fit equations of the component curves that were found to have an effect on effluent concentration. For instance, if C_{out} were found to depend on pressure in the form $C_{out} = a*\ln(P)^b$ as determined by non-linear regression in Excel and temperature in the form $C_{out} = c*T + d$ as determined by linear regression in Excel, then the resulting model would be $C_{out} = a*\ln(P)^b + (c*T + d)$. Parameters a-d were guessed to have the same values as each component curve did in Excel. All data points and the guessed model were entered into Polymath and Polymath was left to perform a final non-linear regression.

It's worth mentioning that although it's probable that these parameter effects are not additive and probably have some co-dependence on each other, it will not matter in obtaining an end result. There is not one right answer in the final model. For any equation guessed as a model, Polymath takes the non-linearities into account if one uses non-linear data point regression. As long as the numbers converge and the simulation program used to generate the data points is accurate, the predicted model will be accurate as well. All results obtained in this study converged under the maximum number of iterations.

Results

Two types of models were generated in this study: outlet concentration models and equipment cost models. The outlet concentration models describe the outlet contaminant concentration being investigated in units of parts per million (ppm) as a function of inlet parameters such as feedrate (ton/hr), pressure (psia), temperature (°F), number of trays (N), tray efficiency (η), etc. These types of models were made for the API separator, H_2S stripper, NH_3 stripper, biological treatment (activated sludge), activated carbon adsorption treatment, reverse osmosis, and the atmospheric distillation column. The equipment cost models were made for the API separator, Chevron Wastewater Treatment plant, activated sludge, and the reverse osmosis units. They describe process machinery cost in terms of dimensional parameters (length, width, height), number of trays, reboil ratio, etc. Results are shown in the proceeding sections.

Outlet Concentration models

I. API separator

The API separator was modeled under the assumption that all of the particles coming into the separator follow a normal distribution, also called a Gaussian distribution. All particles ranged in size from miniscule to some maximum measured size and the majority of particles lay somewhere near the average mean particle size. Outliers exist (i.e. particles very large or very small), but they are present in small quantities and of course, no particles are seen beneath the z = 0 line on the Gaussian curve. Particles cannot have a negative radius. As the contaminant particle enters the separator, it has a horizontal velocity v_x as well as a vertical settling velocity v_y. The time for a particle to reach the other end of the API Separator (t_L), that is to travel its length L is determined by:

$$t_L = \frac{L}{v_x} \qquad \text{Equation 16}$$

But v_x is given by the flowrate F divided by the cross sectional area A given by the product of width and height, that is $A = W*H$. Therefore

$$t_L(s) = \frac{L}{F/\{H \cdot W\}} = \frac{L \cdot H \cdot W}{F} = \frac{V}{F} \qquad \text{Equation 17}$$

where V is the volume of the API separator. At the same time, the time that a particle that is at height h at the beginning of the separator will reach the top is:

$$t_h(s) = \frac{(H-h)}{v_y} \qquad \text{Equation 18}$$

The settling velocity of a particle with radius r is given by Stokes Law seen previously in Equation 1:

$$v_y = \frac{2}{9\mu}(\rho_W - \rho_O) g r^2 \qquad \text{Equation 19}$$

Thus:

$$t_h = \frac{9\mu(H-h)}{2\left(\rho_W - \rho_O\right)gr^2}$$

Equation 20

If we now equate $t_h = t_L$, we will obtain the radius of the particle that will exactly reach the top, if started at height *h*.

$$t_h = \frac{9\mu(H-h)}{2\left(\rho_W - \rho_O\right)gr^2} = \frac{V}{F} = t_L$$

Equation 21

The radius is then given by:

$$\hat{r} = \sqrt{\frac{9\mu(H-h)F}{2\left(\rho_W - \rho_O\right)gV}}$$

Equation 22

This equation for $\hat{r}$ was assigned as the critical radius, above which, all particles separate and will be removed from the wastewater (and stay in the API separator). Below which, particles are carried with the wastewater effluent stream (particles smaller that $\hat{r}$ will stay in the exiting water). Finally, assuming a Gaussian distribution of particle sizes, we find that the fraction of particles y_h that started at height *h* that are retained is:

$$y_h = \frac{\int_{\hat{r}}^{\infty} \left(\frac{4}{3}\pi r^3\right) e^{\frac{-(r-r_s)^2}{\sigma^r}} dr}{\int_{0}^{\infty} \left(\frac{4}{3}\pi r^3\right) e^{\frac{-(r-r_s)^2}{\sigma^r}} dr}$$

Equation 23

Being a normal density function, finding the mass of contaminant at any given time involves a simple multiplication of the density (g/cm^3) and the volume (cm^3). Now, the particles are uniformly distributed in height. Then, the total fraction of contaminants removed is:

$$z = \int_0^H y_h \cdot \frac{1}{H} dh$$

Equation 24

Therefore,

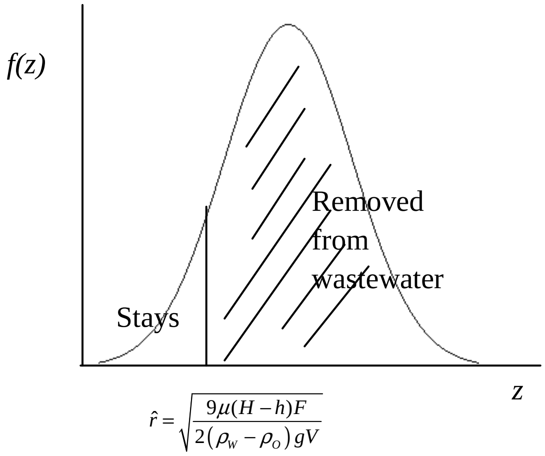
$$z = \frac{1}{H}\int_0^H \left\{ \frac{\int_{\sqrt{\frac{9\mu(H-h)F}{2(\rho_W-\rho_O)gV}}}^{\infty} \left(\frac{4}{3}\pi r^3\right) e^{\frac{-(r-r_s)^2}{\sigma^r}} dr}{\int_{0}^{\infty} \left(\frac{4}{3}\pi r^3\right) e^{\frac{-(r-r_s)^2}{\sigma^r}} dr} \right\} dh$$

Equation 25

The outlet concentration of organics is then given by:

$$c_{out}^{Org} = (1 - z)c_{in}^{Org} \qquad \text{Equation 26}$$

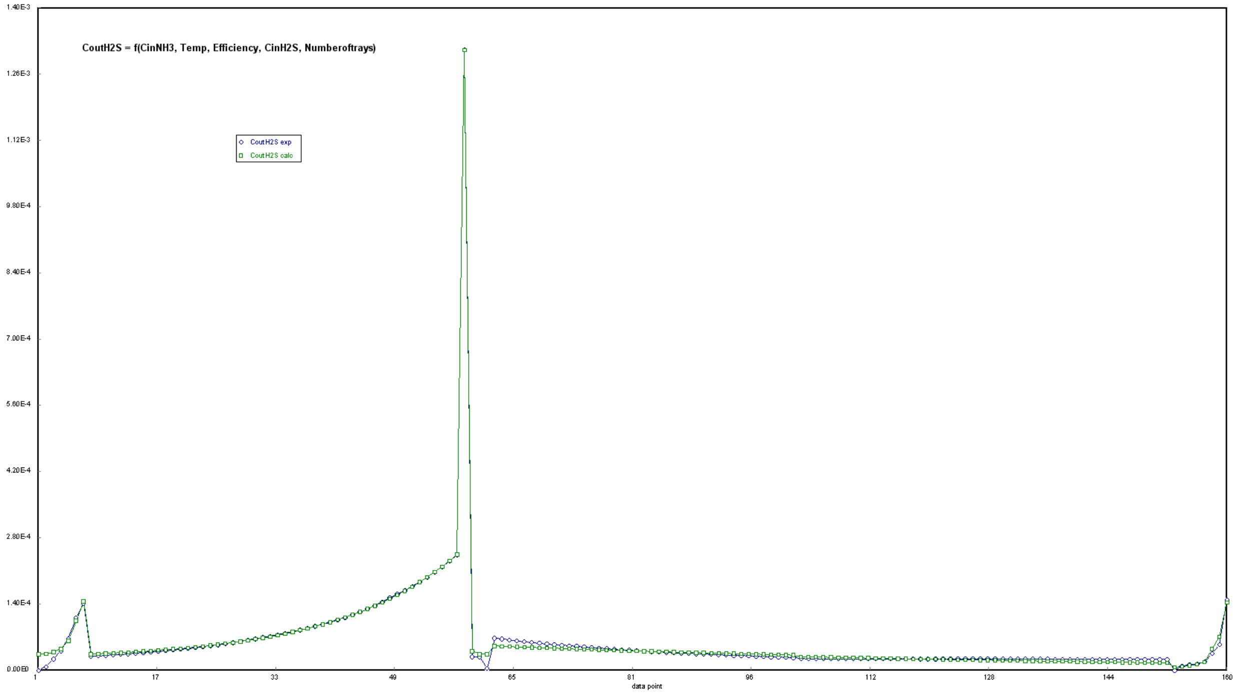
We conclude that $c_{out}^{Org} = c_{out}^{Org}(c_{in}^{Org}, V, H)$. In doing this we are assuming that the distribution of particles is known (it is Gaussian with known mean and std. dev). In addition, an underlying assumption exists that temperature does not significantly affect the densities of water and the organic phase. A pictorial representation of the normal density function is seen below.



The area that is shaded is the percentage of the contaminants (oil or suspended solids) removed from the influent wastewater. All particle sizes are represented in the normal distribution, thus the area under the Gaussian curve is 1, where 1 represents the entire range of contaminants sizes from 0 to r_{max}. The table generated from simulating the numerical integration in Mathcad is seen in Appendix I.

II. Chevron Wastewater Treatment

As stated before, the Chevron Wastewater Treatment consists of a hydrogen sulfide stripper followed by an ammonia stripper. The H_2S, with a partial reboiler, strips H_2S from the influent wastewater leaving mostly H_2S and a negligible amount of ammonia in the vapor stream. The wastewater then enters into an ammonia stripper, containing a partial reboiler and a partial condenser, where ammonia is stripped from the wastewater. The curve for the hydrogen sulfide stripper is shown below.



From points 1-11, the mole fraction of hydrogen sulfide coming into the stripper was varied. From points 12-21, the number of trays was varied. From points 22-55, tray efficiency was varied from 0.56 through 0.89. From points 56-177, the case study function was used in Pro/II where the feedrate was varied by increments of 1 kg/hr and the result was the outlet concentration of H_2S. From points 178 on, the inlet temperature was varied. It's important to mention that reboiler duty and inlet pressure were run as parameters in the case study in Pro/II, but the outlet concentration of H_2S was found to not be affected by it. A model was guessed and the result of non-linear regression in Polymath is as follows:

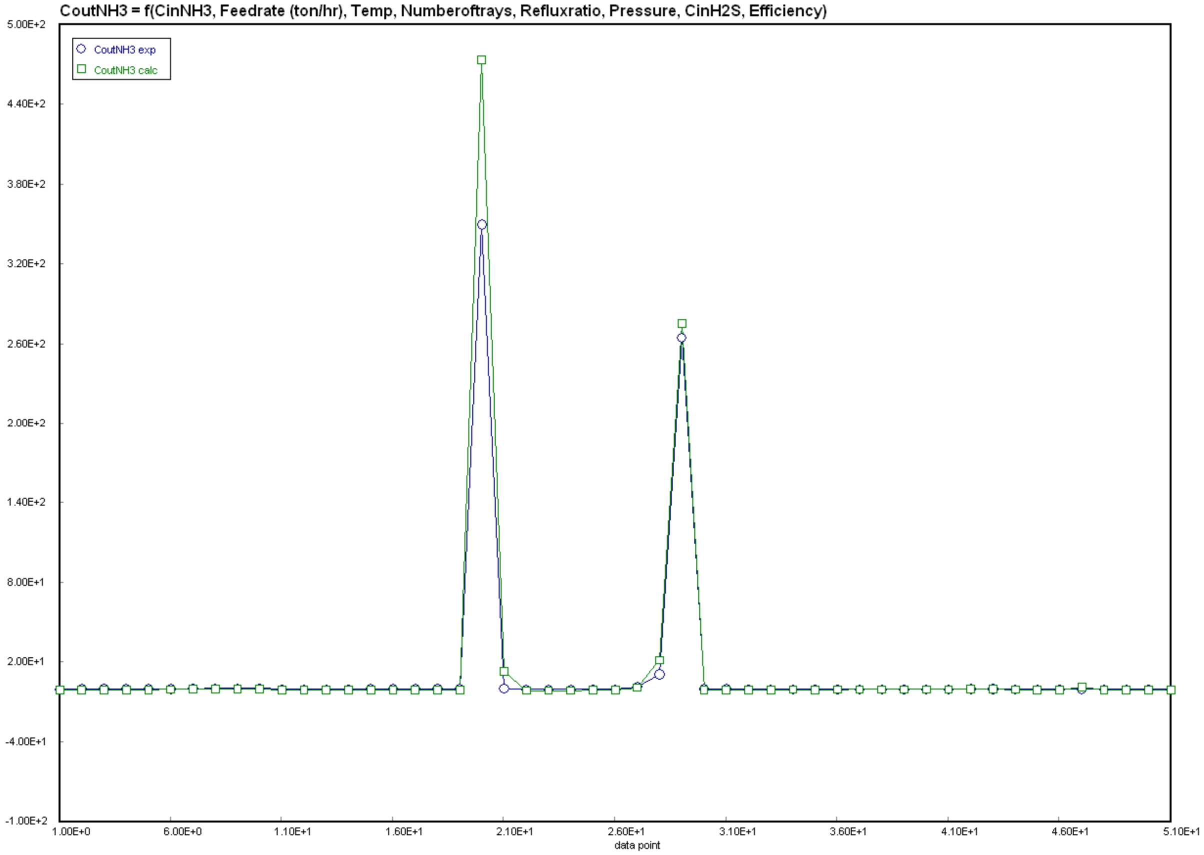
$$C_{out,H_2S}(ppm) = 0.0024e^{0.079C_{in,NH_3}} - e^{-0.039T} - 0.014\eta^{-0.138} + \left(1.011x10^{-4}\right)\cdot C_{in,H_2S}{}^{2} - 0.0012\cdot C_{in,H_2S} \\ + 21{,}700(Numberoftrays)^{-7.077} + 0.0158$$

Equation 27

The Polymath report for H_2S is seen in Appendix I.

From Figure 10 on page 19, it is clear that the liquid stream that exits from the bottom of the hydrogen sulfide stripper is the entering stream ammonia str9pper. Thus, the outlet concentration of the H_2S stripper is the inlet concentration of the NH_3 stripper. The component

H_2S was the contaminant that was modeled in this study. The non-linear regression graph is shown below.



In this case, case study function was used rather than single-handedly generating points, which is tedious. A step size of 100 variations was specified and run in PRO/II. Inlet parameters were specified to be overall column tray efficiency, feedrate (ton/hr), inlet pressure (psia), reflux ratio (by changes of 0.5), and inlet temperature (degrees Fahrenheit) was varied. The result was outlet concentration of H_2S and given in units of ppmw.

$$C_{out,NH_3}\left(ppm\right) = 0.00068F^{2} - 0.0065F - 0.057C_{in,NH_3} + 1546e^{-0.697N} + 0.00008069e^{0.025T} + 0.0613RFR - 4436000P^{-2.941} - 0.527\eta^{2} - 0.752\eta + 7.105{C_{in,H_2S}}^{0.47} + 0.238$$

Equation 28

An inequality exists that must be able to find optimal column diameter based on flowrate. From Seader and Henley's *Separation Process Principles*[xxii]:

$$D_T = \left[\frac{4VM_V}{fU_f \pi (1 - A_d / A) \rho_V} \right] \qquad \text{Equation 29}$$

where: V = molar vapor flow rate

M_V = molecular weight of the vapor

f = the fraction of flooding, typically taken as 0.80

U_f = flooding velocity = $\left(\frac{4d_p g}{3C_D} \right)^{1/2} \cdot \left(\frac{\rho_L - \rho_V}{\rho_V} \right)^{1/2}$

ρ_V = density of the vapor, ρ_L = density of the liquid

d_p = particle diameter, g = gravity, C_D = drag coefficient

$$\frac{A_d}{A} = \begin{cases} 0.1, & F_{LV} \le 0.1 \\ 0.1 + \frac{(F_{LV} - 0.1)}{9} & 0.1 \le F_{LV} \le 1.0 \\ 0.2, & F_{LV} \ge 1.0 \end{cases}$$

$$F_{LV} = \left(\frac{LM_L}{VM_V} \right) \left(\frac{\rho_V}{\rho_L} \right)^{0.5} \qquad \text{Equation 30}$$

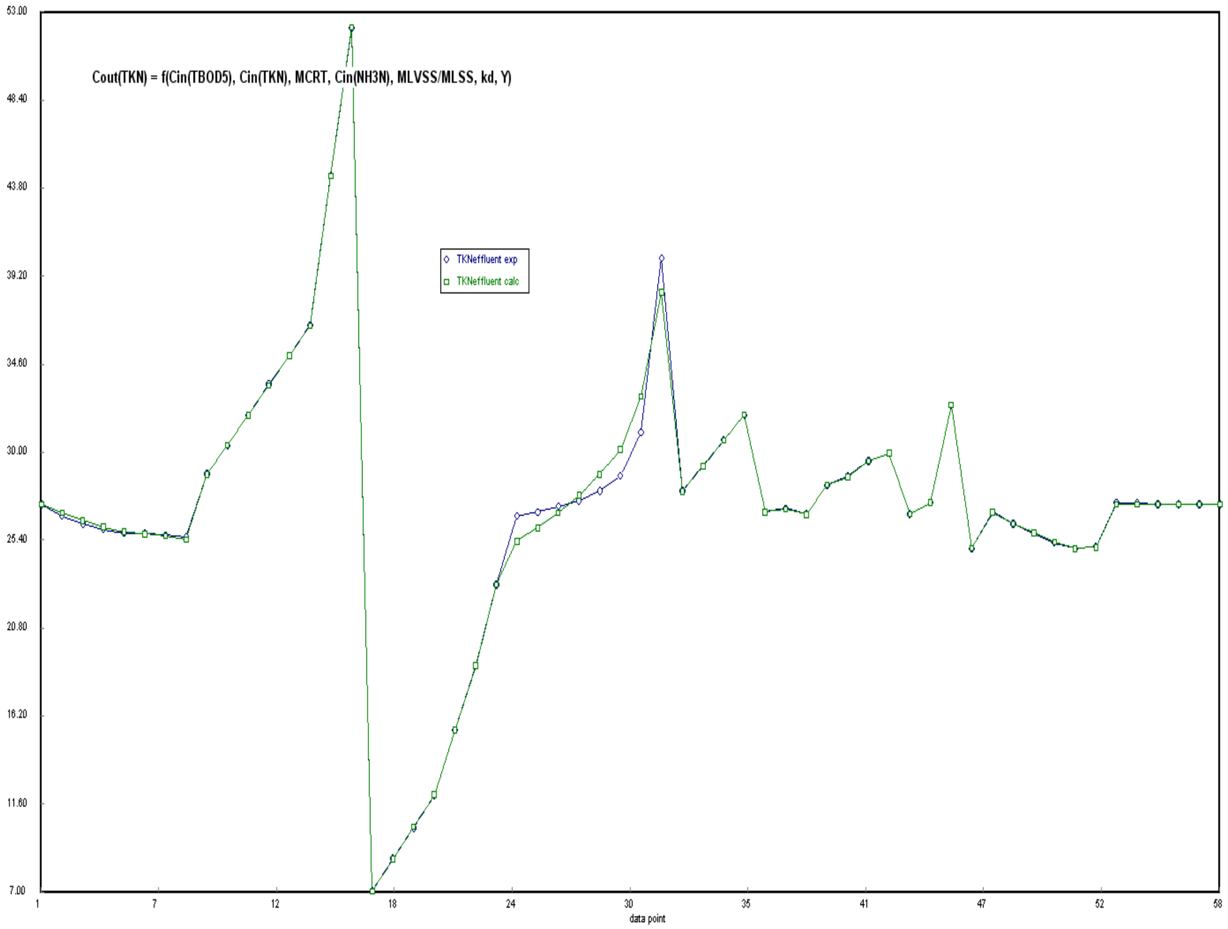
So, the procedure for determining this inequality is to first calculate F_{LV} (abscissa ratio) and then choose one of three options:

Case	Inequality that must be satisfied	Result
1	$F_{LV} = \left(\frac{LM_L}{VM_V} \right) \left(\frac{\rho_V}{\rho_L} \right)^{0.5} \le 0.1$	$D_T = \left[\frac{4VM_V}{0.80 \cdot [4d_p g/(3C_D)]^{1/2} \cdot [(\rho_L - \rho_V)/\rho_V]^{1/2} \cdot \pi \cdot 0.90 \cdot \rho_V} \right]$
2	$0.1 \le F_{LV} = \left(\frac{LM_L}{VM_V} \right) \left(\frac{\rho_V}{\rho_L} \right)^{0.5} \le 1.0$	$D_T = \left[\frac{4VM_V}{0.80 \cdot [4d_p g/(3C_D)]^{1/2} \cdot [(\rho_L - \rho_V)/\rho_V]^{1/2} \cdot \pi \cdot \left[8 - \left(\frac{LM_L}{VM_V} \right) \left(\frac{\rho_V}{\rho_L} \right)^{0.5} \right] / 9 \cdot \rho_V} \right]$
3	$F_{LV} = \left(\frac{LM_L}{VM_V} \right) \left(\frac{\rho_V}{\rho_L} \right)^{0.5} \ge 1.0$	$D_T = \left[\frac{4VM_V}{0.80 \cdot [4d_p g/(3C_D)]^{1/2} \cdot [(\rho_L - \rho_V)/\rho_V]^{1/2} \cdot \pi \cdot 0.80 \cdot \rho_V} \right]$

Table 5. Total column diameter as a function of liquid and vapor flowrates

III. Biological Treatment (Activated Sludge)

The most commonly used biological treatment is the activated sludge process[xxiii], where microorganisms present in wastewater feed on the organic constituents thereby purifying the water. Since activated sludge is the most common process, it was the one modeled. As mentioned before, the program *Steady* developed by professors at the University of Texas was used to simulate an activated sludge process. The activated sludge simulation required outlet concentrations of $TBOD_5$ (mg/L) and SBOD (mg/L) to be specified, and since no nitrification was occurring in the process, the only outlet concentration that varied was the outlet concentration of the TKN (mg/L). This was the contaminant that was modeled. Results from the non-linear regression are shown below.



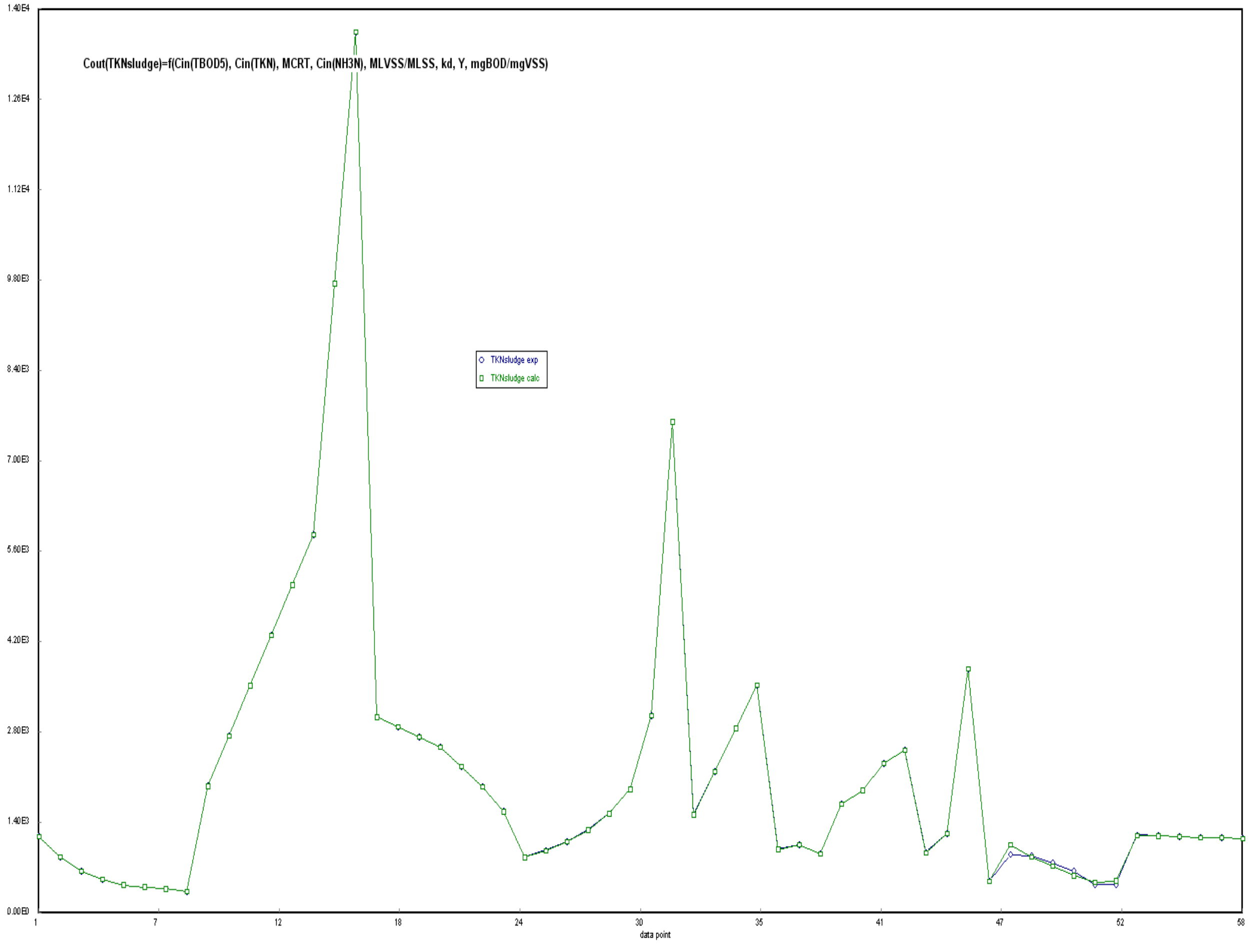
From points 1-8, inlet concentration of $TBOD_5$ (mg/L) was varied. From points 9-16, inlet concentration of TKN (mg/L) was varied. From points 17-23, inlet concentration of NH_3—N (mg/L) was varied. From points 24-31, the Y value, which is the biomass yield, was varied.

Biomass yield is the grams of biomass produced per gram of substrate utilized [g VSS/g COD used]. From points 32-38, k_d was varied and k_d is the endogenous decay coefficient [g VSS/g VSS·d]. From points 39-45, the mean cell residence time (MCRT), the amount of time a contaminant stays in the process, was varied. From points 46-52, the ratio of mixed liquor volatile suspended solids to mixed liquor suspended solids was varied. The final result is given below:

$$C_{TKN,\ effluent}\left(ppmw\right) = -135C^{0.01}_{in,\ TBOD_5} + 0.16C_{in,\ TKN} + 0.84C_{in,\ NH_3-N} - 2287Y^{0.0026} + 13.4k_d + 0.08MCRT - 12.25e^{-0.27\left(\frac{MLVSS}{MLSS}\right)} + 2436$$

Equation 31

The sludge that exits from the secondary clarifier is rich in the microorganisms used to eat the contaminants. This stream was also modeled to aid the pre-treatment process for this stream. Regression graph results are shown below:



Parameters were varied in the same manner as for the effluent wastewater stream, however, an extra parameter was found to make a difference in outlet TKN concentration; [mgBOD/mg VSS]. The outlet TKN concentration in the exiting sludge is:

$$C_{TKN,\ sludge}(ppmw) = 3.436x10^{5} C_{in,\ TBOD_5}^{-1.057} + 77.9C_{in,\ TKN} - 77C_{in,\ NH_3-N} + 762.5Y^{-0.998} + 6684.5k_d + 41.8MCRT - 99.8e^{1021.6\left(\frac{MLVSS}{MLSS}\right)} - 75.9\frac{mgBOD}{mgVSS} - 3663.7$$

Equation 32

The Polymath report can be seen in Appendix I for the activated sludge process.

IV. Desalter

Finding the outlet H_2S concentration in water was the first task in modeling the desalter. In order to accomplish this, a contaminant mass balance was performed for H_2S:

$$F_{oil} x_{H_2S,in}^{Oil} + F_{Water} x_{H_2S,in}^{Water} = F_{oil} x_{H_2S,out}^{Oil} + F_{Water} x_{H_2S,out}^{Water}$$

Equation 33

A partition coefficient was then applied because water and crude oil are vigorously mixed prior to entering the desalter and so a two-phase mixture exists of water (aqueous) and oil (organic). H_2S partitions between these two phases and exits with the water. The partition coefficient is a function *solely* of temperature and is defined as the differential solubility of H_2S in water and oil:

$$K(T) = \frac{x_{H_2S}^{Water}}{x_{H_2S}^{Oil}}$$

Equation 34

A schematic is shown below for process flow of a desalter. However, PRO/II was NOT used in the derivation of the desalter equation. The diagram in Figure 16 is used for aesthetic and description purposes only.

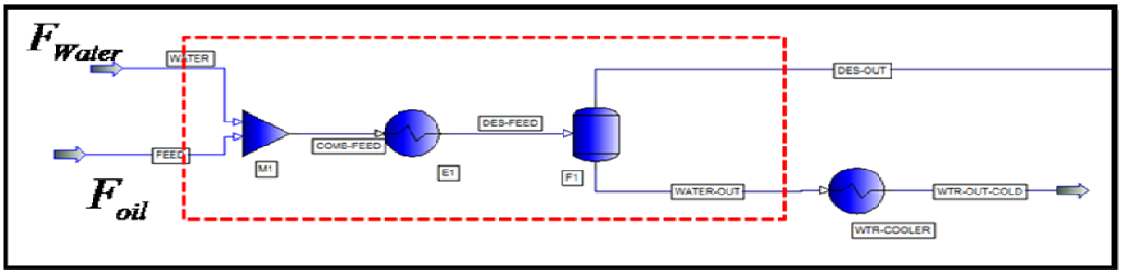


Figure 16. PRO/II file for desalter

Rearranging Equation 16 to solve for $x_{H2S,\ out}$ and combining with Equation 17:

$$x_{H_2S,out} = \frac{F_{Oil} x^{Oil}_{H_2S,in} + F_{Water} x^{Water}_{H_2S,in}}{F_{Water} + \frac{F_{Oil}}{K(T)}} \qquad \text{Equation 35}$$

From http://www.atsdr.cdc.gov/toxprofiles/tp114-c4.pdf, the solubility of H2S in water at various temperatures is:

at	10	°C	5.3	g/L
at	20	°C	4.1	g/L
at	30	°C	3.2	g/L

Also, the solubility of H2S in oil at various temperatures is:

at	20	°C	6	g/L
at	100	°C	3	g/L

Plots of these solubilities as a function of temperature is seen as:

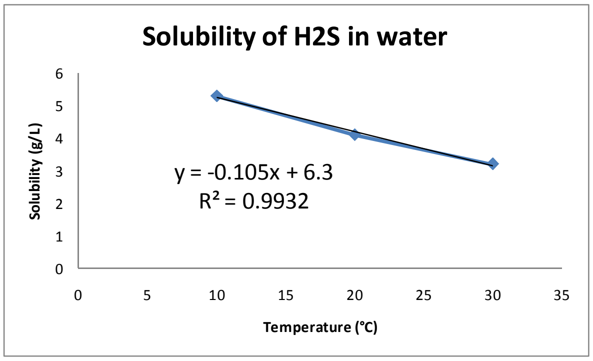


Figure 17. Solubility of H_2S in water

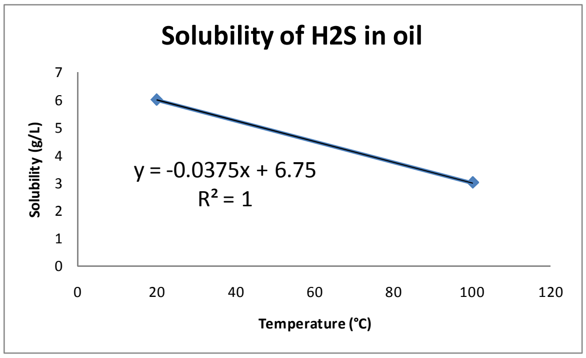


Figure 18. Solubility of H_2S in oil

The solubilities of H_2S in water and oil are then:

$$K(T) = \frac{x^{Water}_{H_2S}}{x^{Oil}_{H_2S}} = \frac{-0.105T + 6.3}{-0.0375T + 6.75} \qquad \text{Equation 36}$$

Finally,

$$x_{H_2S,out} = \frac{F_{Oil} x^{Oil}_{H_2S,in} + F_{Water} x^{Water}_{H_2S,in}}{F_{Water} + F_{Oil}\left(\frac{-0.0375T + 6.75}{-0.105T + 6.3}\right)} \qquad \text{Equation 37}$$

Finding the outlet salt concentration in water from the desalter was the second task in modeling the desalter. A paper written by Gary W. Sams and Kenneth W. Warren titled *New Methods of Application of Electrostatic Fields* prepared for presentation at AICHE Spring National Meeting was referenced. In a desalter, a suspended water droplet between a pair of electrodes is acted on by five forces:

1. Gravity
2. Drag
3. Electrophoretic
4. Di-electrophoretic
5. Dipole

The following diagram shows the five forces at work in a desalter:

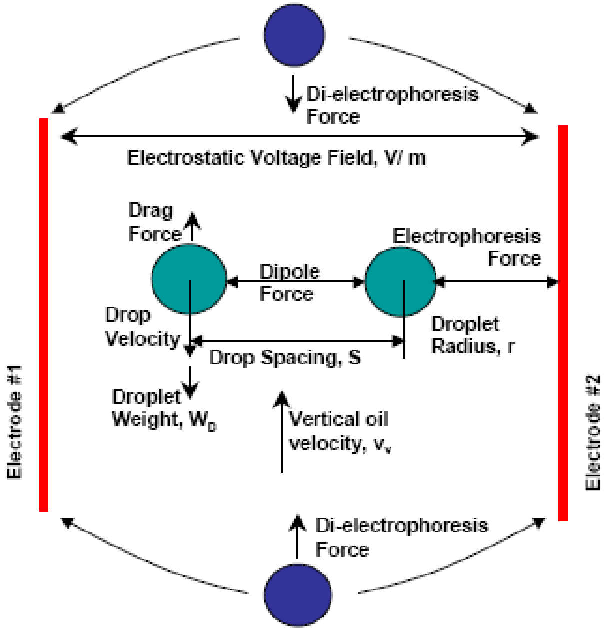


Figure 19. Forces acting on a water droplet inside of a desalter

Gravity and drag forces are taken into account when using Stokes Law (see Equation 1) and in order to maximize desalting process performance, electrostatic forces must enhance coalescence to droplet sizes larger than Stokes diameter.

Dipole forces are established due to the alignment of polar water molecules in the droplet and are given by the equation:

$$F_{dipole} = \frac{6KE^2r^6}{s^4}$$

Equation 38

Electrophoretic forces are attractive and repulsive forces between charged droplets and electrodes and are given by the equation:

$$F_e = C\pi^3\mu\varepsilon_C r^2E^2e^{\left(\frac{-\sigma_C t}{\varepsilon_C}\right)}$$

Equation 39

Finally, di-electrophoretic forces are attractive forces established in a non-uniform field (all particles exhibit di-electrophoretic activity in the presence of electric fields).

$$F_{diel} = 2\pi r^3\varepsilon_C\left(\frac{\varepsilon_D^* - \varepsilon_C^*}{\varepsilon_D^* + 2\varepsilon_C^*}\right)\nabla E^2$$

Equation 40

In order to find the minimum particle size, a force balance was performed for the x and y components of the force acting on a suspended particle in the desalter. Because each particle would be falling at a constant velocity, the sum of the forces were set equal to 0 as acceleration would be 0.

$$\sum F_x = F_{dipole} + F_e + F_{diel} = \frac{6KE^2r^6}{s^4} + C\pi^3\mu\varepsilon_C r^2E^2e^{\left(\frac{-\sigma_C t}{\varepsilon_C}\right)} + 2\pi r^3\varepsilon_C\left(\frac{\varepsilon_D^* - \varepsilon_C^*}{\varepsilon_D^* + 2\varepsilon_C^*}\right)\nabla E^2 = 0$$

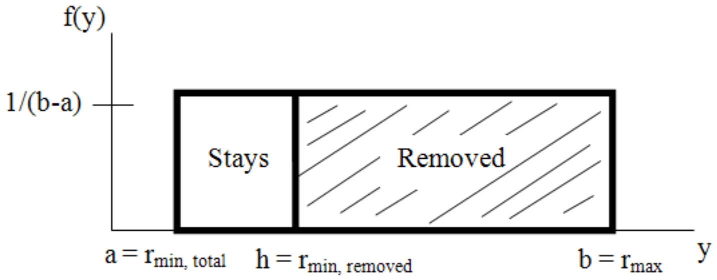
Equation 41

where the minimum particle size removed in the desalter is represented in the rearrangement of Stokes Law as seen in Equation 13:

$$\hat{r} = \sqrt{\frac{9\mu(H-h)F}{2(\rho_W - \rho_O)gV}}$$

Equation 42

The water particles entering the desalter were assumed to be uniformly distributed throughout the crude oil. Thus, the particles follow a uniform probability distribution:

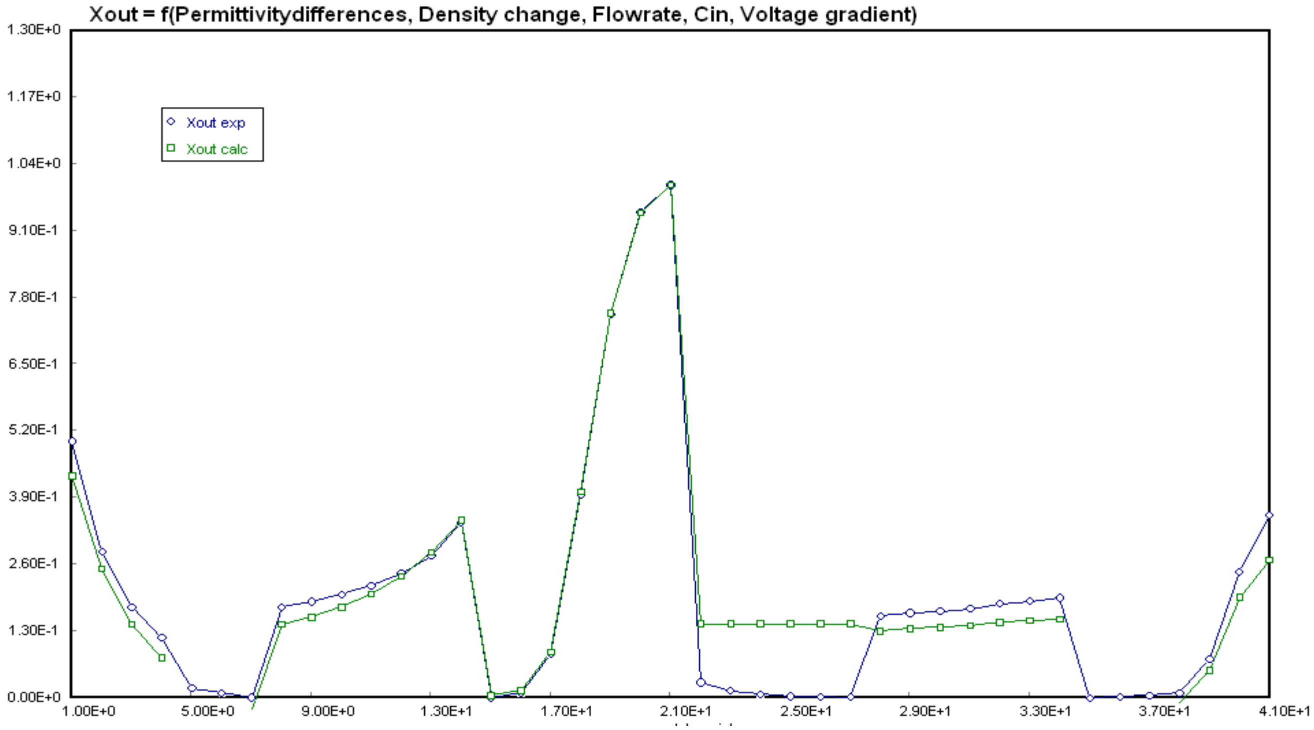


Thus, the mass fraction of contaminants removed from the wastewater is:

$$y = \frac{\displaystyle\int_{\sqrt{\frac{9\mu(H-h)F}{2(\rho_W-\rho_O)gV}}}^{\infty}\left[\left(\frac{4}{3}\pi r^{3}\right)\cdot\frac{1}{H}\right]dr}{\displaystyle\int_{0}^{\infty}\left[\left(\frac{4}{3}\pi r^{3}\right)\cdot\frac{1}{H}\right]dr}$$

Equation 43

System properties such as voltage, electric field gradient, C_{in}, density change, flowrate, etc. were varied and the mass fraction of contaminants remaining in the desalter was measured. The results from a non-linear regression are shown below:



From points 1-7, permittivity differences in the group of $\varepsilon_C\left(\frac{\varepsilon_D^* - \varepsilon_C^*}{\varepsilon_D^* + 2\varepsilon_C^*}\right)$ (Farad/meter) were varied. From points 8-14, the $\frac{\Delta\rho}{F}$ (g·hr/cm^3·ton) was varied. From points 15-21, inlet concentration of organics (C_{in}) (mg/L) was varied. From points 22-27, voltage (V) was varied. From points 28-34, the exponential of conductivity divided by continuous phase permittivity $e^{\left(\frac{-\sigma_C t}{\varepsilon_C}\right)}$ was varied. From points 35-41, the voltage field gradient, ΔE, in Volts, was varied. The final resulting equation is shown below:

$$X_{out} = 0.035e^{\left(5.40x10^{-6}\right)\varepsilon_C\left(\frac{\varepsilon_D^* - \varepsilon_C^*}{\varepsilon_D^* + 2\varepsilon_C^*}\right)} + \left(5.77x10^{-5}\right)e^{4.77\cdot\frac{\Delta\rho}{F}} + \left(1.85x10^{-23}\right)C_{in}^{1.03x10^{-4}} + 2.99V^{0.0013} + \left(3.69x10^{-4}\right)e^{\left(\frac{-\sigma_C t}{\varepsilon_C}\right)}$$
$$+ \left(5.04x10^{8}\right)\Delta E^{8.26x10^{-4}} + 0.00023$$

Equation 44

V. Crude oil distillation column

The crude oil distillation column modeling was completed using a Casestudy, built-in distillation column made from the creators of PRO/II as seen in Figure 20 below. The stream circled in red is the wastewater stream. Inlet stream variables and system properties were varied. The different types and amount of organics present in the wastewater stream were various (i.e. ethane, pentane, propane, n-butane, etc.), thus the total amount of organics leaving in the wastewater was found by subtracting sum of all organics from unity.

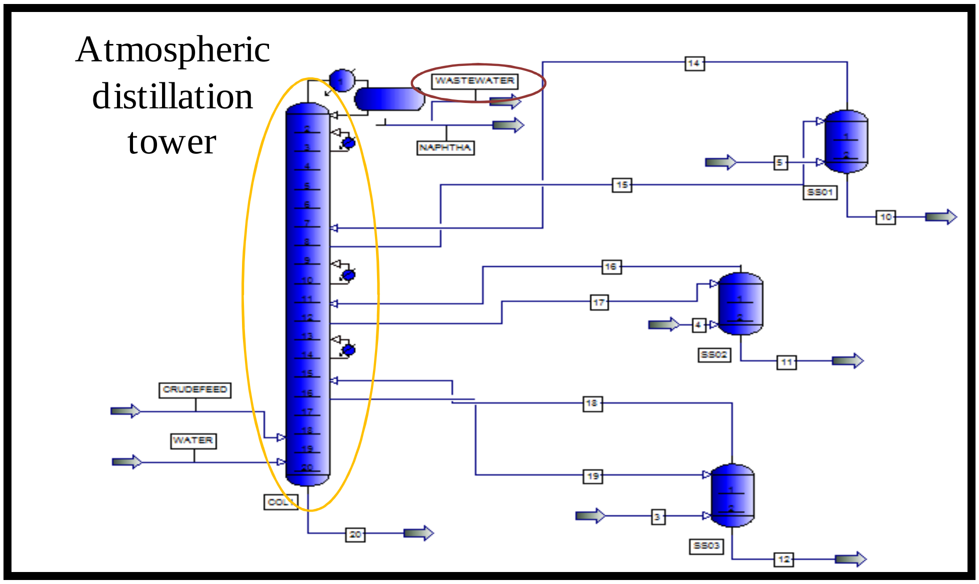
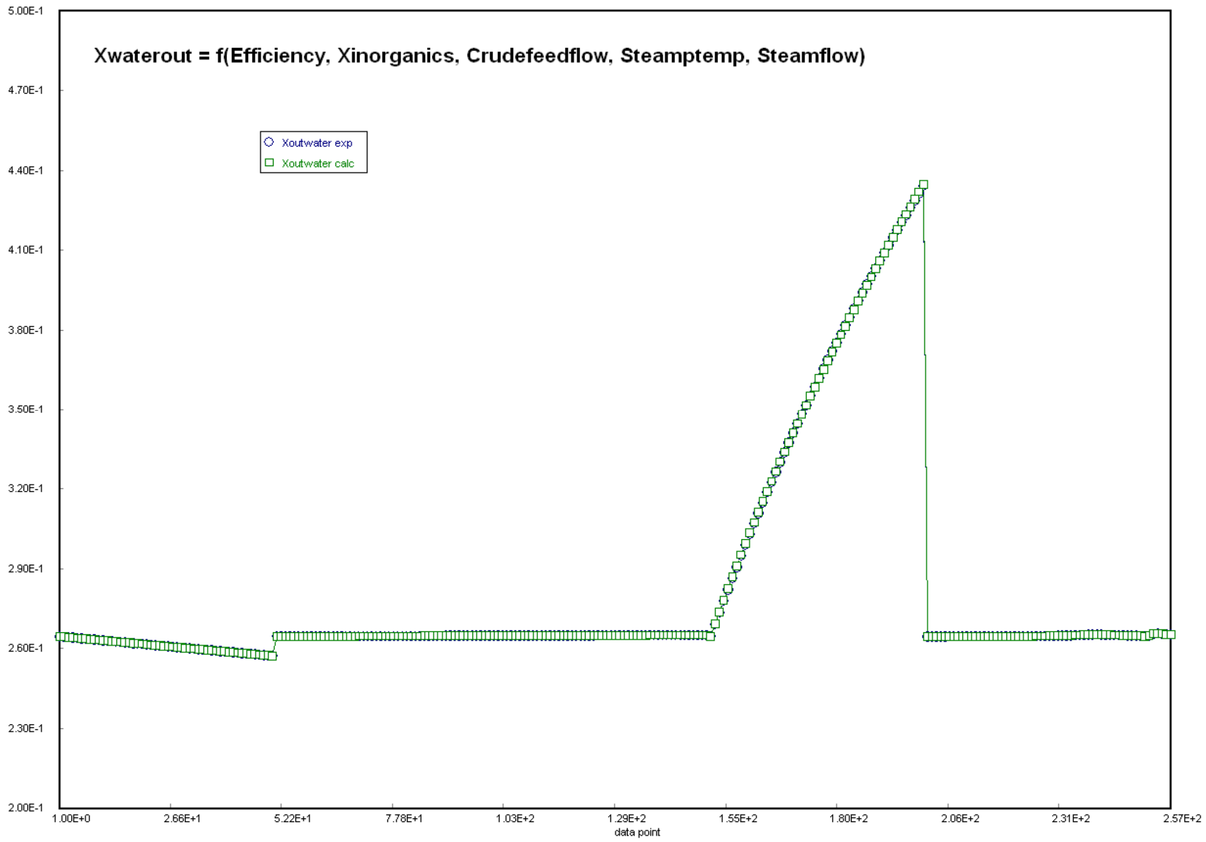


Figure 20. Crude oil distillation column

The non-linear regression is shown below:



From points 1-50, crude feedrate, F_{crude} (ton/hr), was varied. From points 51-150, steam temperature, T (°F), was varied. From points 151-200, steam flowrate, F_{steam} (ton/hr), was varied. From points 201-250, efficiency (η) was varied. From points 251-257, the mass fraction of organics in ($X_{in,\ organics}$) was varied. The resulting equation is shown below:

$$
\begin{aligned}
x_{out,old} &= 0.113\cdot\eta^{6} - 0.606\cdot\eta^{5} + 1.298\cdot\eta^{4} - 1.419\cdot\eta^{3} + 0.834\cdot\eta^{2} - 0.250\cdot\eta - \left(3x10^{-5}\right)F_{crude} \\
&+ \left(2.202x10^{-7}\right)T + \left(1.88x10^{-4}\right)F_{steam}{}^{0.557} + 0.014\cdot x_{in}{}^{4} - 0.135\cdot x_{in}{}^{3} + 0.472\cdot x_{in}{}^{2} - 0.719\cdot x_{in} + 0.686
\end{aligned}
$$

Equation 45

Comparison of concentration models with simulation results

As is obvious from descriptions of how the equations were developed, the models are linear in the sense that they were made by varying only one parameter at a time (for instance, pressure was varied for 10 points, temperature for 10 poitns, flowrate for 10 points, etc.) Effects between parameters were not considered (like how temperature would realistically change with pressure) and this was hypothesized to introduce differences between real, simulated results and those predicted from the theoretical, developed equations. To check for differences, inlet stream parameters and system properties were randomly varied and 15 points were generated using the simulation program and these results were compared to those predicted from the theoretical equations. A correction equation was then applied to any model with a percent error of greater than 5%, as this would be a difference of ~1-2 ppm (an acceptable difference).

$$\%\ error = \frac{\left| Actual\ result - theoretical\ result \right|}{Theoretical\ result} \times 100\% \qquad \text{Equation 46}$$

An example of a table generated is shown in Tables 6-7 below for the activated sludge system. The % error was found to be at most ~3%.

From Simulation (*Steady*)								
	Cin,TBOD$_5$ (mg/L)	Cin,TKN (mg/L)	Cin, NH3-N (mg/L)	Y (mg VSS/mg SBOD$_5$)	k_D (d^{-1})	MCRT (d)	MLVSS/MLSS	Cout, TKN (ppm)
Run 1	220	40	25	0.65	0.05	8	0.75	27.3
Run 2	220	85	50	0.65	0.05	8	0.75	55.4
Run 3	400	70	40	0.65	0.05	8	0.75	43
Run 4	200	70	40	0.4	0.1	5	0.75	49
Run 5	300	65	30	0.6	0.2	7	0.6	36.8
Run 6	110	30	12	0.3	0.09	3	0.55	20.8
Run 7	275	50	45	0.8	0.3	4	0.55	45.6
Run 8	275	50	25	0.65	0.15	8	0.4	29.2
Run 9	220	45	35	0.7	0.15	8	0.7	37.1
Run 10	200	70	50	0.65	0.3	10	0.3	54
Run 11	350	85	30	0.5	0.05	5	0.75	39.1
Run 12	325	85	25	0.8	0.25	8	0.8	36.5
Run 13	220	100	25	0.55	0.08	6	0.5	37.8
Run 14	300	35	30	0.65	0.05	7	0.5	30.4
Run 15	285	55	20	0.6	0.07	5	0.75	25.9

Table 6. Simulated results from *Steady* by randomly varying variables that affect outlet concentration

From Equation								
	Cin,TBOD$_5$ (mg/L)	Cin,TKN (mg/L)	Cin, NH3-N (mg/L)	Y (mg VSS/mg SBOD$_5$)	k_D (d^{-1})	MCRT (d)	MLVSS/MLSS	Cout, TKN (ppm)
Run 1	220	40	25	0.65	0.05	8	0.75	27.78433656
Run 2	220	85	50	0.65	0.05	8	0.75	55.98433656
Run 3	400	70	40	0.65	0.05	8	0.75	44.32997909
Run 4	200	70	40	0.4	0.1	5	0.75	48.6319467
Run 5	300	65	30	0.6	0.2	7	0.6	37.53360999
Run 6	110	30	12	0.3	0.09	3	0.55	20.41721864
Run 7	275	50	45	0.8	0.3	4	0.55	47.10733691
Run 8	275	50	25	0.65	0.15	8	0.4	29.41451499
Run 9	220	45	35	0.7	0.15	8	0.7	37.74815131
Run 10	200	70	50	0.65	0.3	10	0.3	55.93760778
Run 11	350	85	30	0.5	0.05	5	0.75	39.83904217
Run 12	325	85	25	0.8	0.25	8	0.8	36.00782756
Run 13	220	100	25	0.55	0.08	6	0.5	37.91973565
Run 14	300	35	30	0.65	0.05	7	0.5	29.96312713
Run 15	285	55	20	0.6	0.07	5	0.75	26.11839694

Table 7. Predicted results from *Steady* by randomly varying variables that affect outlet concentration

The corresponding % error between each simulated and theoretical result is shown in Table 8. The greatest % error is highlighted in yellow.

Cout, TKN (ppm) SIMULATION	Cout, TKN (ppm) THEORETICAL	% Error
27.3	27.78433656	1.774126584
55.4	55.98433656	1.054759129
43	44.32997909	3.092974631
49	48.6319467	0.75112918
36.8	37.53360999	1.99350542
20.8	20.41721864	1.840294983
45.6	47.10733691	3.30556339
29.2	29.41451499	0.734640393
37.1	37.74815131	1.747038569
54	55.93760778	3.58816255
39.1	39.83904217	1.890133416
36.5	36.00782756	1.348417653
37.8	37.91973565	0.316760976
30.4	29.96312713	1.437081801
25.9	26.11839694	0.843231418

Table 8. % error between simulation and theoretical results

The maximum % error was 3.59 %. As this is under 5%, the equation was regarded as acceptable in predicting outlet concentrations. This same procedure was followed for the other equations developed through a simulation program (Mathcad, PRO/II). The results are shown below:

Water-using unit	Error
H_2S Stripper	± 38%
NH_3 Stripper	± 31%
Crude oil distillation	± 5%
Biological Treatment	± 3%

Table 9. % Error for water-using units between simulated and theoretical equations

The crude oil distillation and biological treatment produced acceptable ranges for error, while the H_2S stripper and the NH_3 stripper produced errors on the magnitude of ~30-40%. Thus, a correction equation was developed to account for these differences and to try to equate the equation result with the simulated result. As the H_2S stripper always produced concentrations less than the maximum outlet concentration of the Chevron Wastewater Treatment plant (5 ppm), no correction equation was made. The ammonia stripper results are shown in Figure 21. The correction equation is found to be y = 0.9392x+ 4.1579, where "x" is the result predicted from the equation and "y" is the result found from the simulation program. The coefficient of determination was found to be $R^2 = 0.6289$. It's clear that an applied linear regression did not provide the best fit between simulated and predicted results. If any differences exist between actual data from a refinery and predicted results, neglecting effects between stream variables whilst developing models for the regeneration processes could be the source of error.

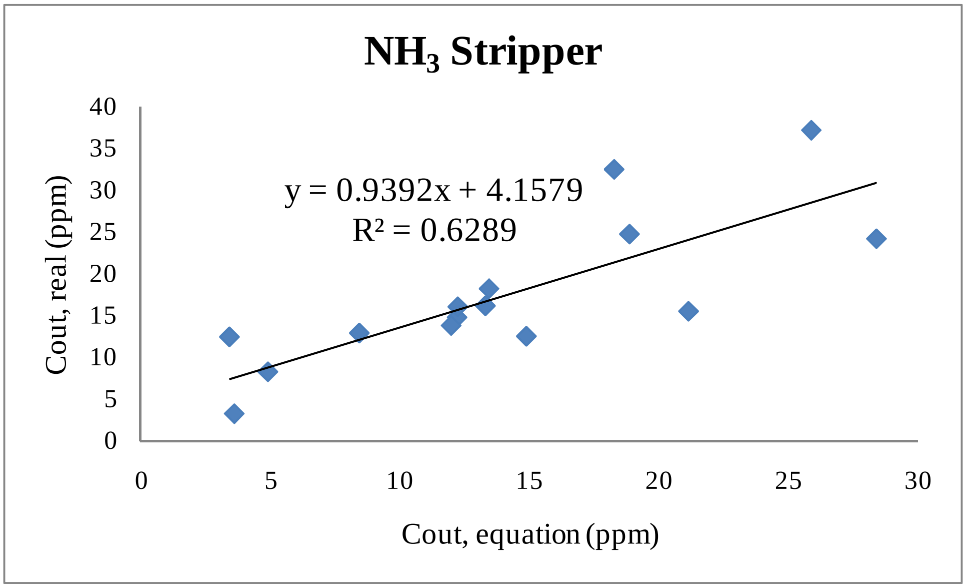


Figure 21. Correction equation for NH_3 Stripper

Equipment Cost models

I. API separator

The majority of the costs that go into purchasing an API separator are the costs of the material being used. Therefore, equipment cost will be a function primarily of the separator volume. All that needs to be done are simple multiplications involving properties of the material chosen to build the reactor. Stainless steel will be chosen as the API separator material because it is durable and resistant to corrosion[xxiv]. The final equation is based off of density, volume, and price of steel. A full derivation is shown in Appendix II.

$$Cost = 6539.05 \cdot V\left(m^3\right) \qquad \text{Equation 47}$$

II. Chevron Wastewater Treatment

Equipment costs for a Chevron Wastewater Treatment (CWWT) plant are dependent on the number of trays, feedrate, vertical height of the columns, reboil ratio, materials cost, and density difference between the passing streams. Since the CWWT plant consists of two stripping columns, the equipment cost for one will be dependent on the same parameters as the other. Basically, the diameter of the column was first solved for in terms of feedrate and the Souders and Brown factor, which is a function of the density difference between passing streams. Standard tray spacing for large-diameter columns are generally either 0.46 or 0.61 m[xxv]. 0.61 meter tray spacing was chosen in this study. The final result of equipment cost for a CWWT is shown in Equation 27. A full derivation of the CWWT plant equipment costs is shown in Appendix II.

$$Equipment\ Cost = 7423H + \left(674.4N\right) \cdot e^{\frac{1.12\sqrt{F}}{-0.071\Delta\rho^{1/4}\ln\left(RBR\cdot\Delta\rho^{1/2}\right)+0.195\Delta\rho^{1/4}}} + 42193$$

Equation 48

III. Biological Treatment (Activated Sludge)

As mentioned before, an activated sludge system is the most common biological treatment type. The system consists of an aeration tank where air is bubbled through the tank wastewater followed by a settling tank where cellular material is removed by gravitational settling. The aeration tank was modeled as an ideal CSTR. The turbulent conditions created by the high flow rate air stream establish a perfect mixing environment. Equipment cost for the secondary clarifier (settling tank) was found to be dependent on reactor size (m^3), inlet flow rate (ton/hr), and inlet concentration (ppm). A full derivation is shown in Appendix II.

$$\text{Equipment Cost}(\$) = 183 \cdot V(m^3) = \frac{646.48 \cdot F \cdot (100 - Cin,org)}{[0.1 \cdot (Cin,org - 100) + 0.001]} + 866{,}019 \cdot F$$

Equation 49

$$\text{where} \quad V \geq \frac{70.65 \cdot F \cdot (100 - Cin,org)}{(Cin,org - 100) + 0.01} + 9464 \cdot F$$

Equation 50

IV. Reverse Osmosis

The cost of the reverse osmosis was computed based on the most significant equipment costs associated with the plant in the industry. These are the cost of the membrane replacement, which has to be done frequently to avoid fouling and reduce efficiency and the pump cost. The equation governing this cost was found to be:

$$\text{Equipment Cost}\left(\frac{\$}{yr}\right) = 180 \cdot A \cdot N + 8053.25 \cdot \left(\frac{\Delta P \cdot F}{\eta}\right)$$

Equation 51

where A: area per membrane

N: number of membrane used

F: flow rate to the process

V. Activated Carbon Adsorption

As a result of the adsorption being a fixed bed, the basic cost of the process was the cost of regeneration of the bed after saturation. This cost of the fixed bed adsorber depends on the capacity of the bed based on the feed concentration of the wastewater and given the equation:

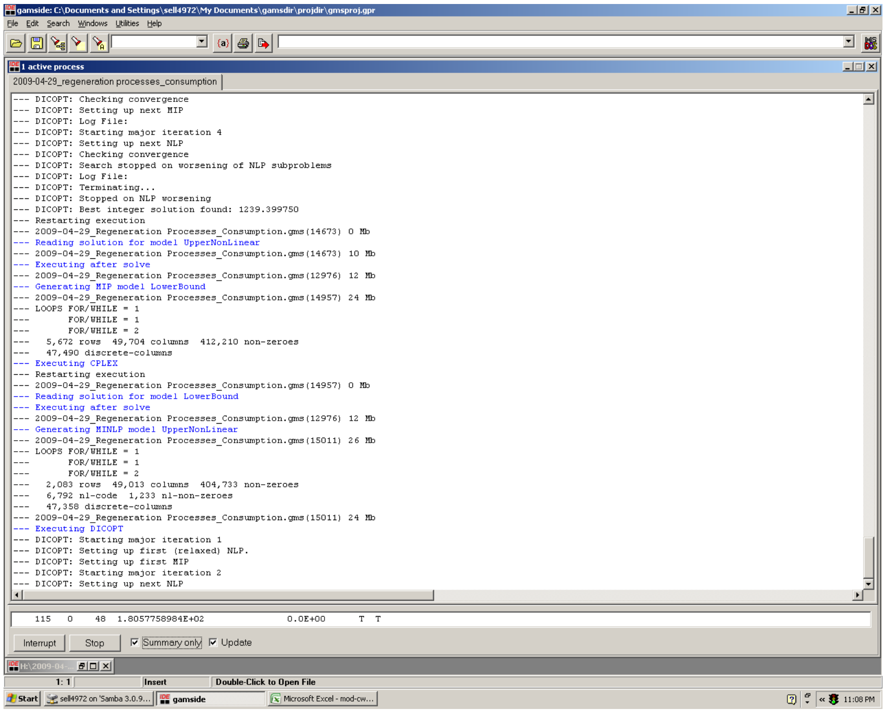
$$Equipment\cos t(\$) = \$7200 C_F Q$$

Equation 52

Mathematical Programming Results

General Algebraic Modeling System (GAMS)

The GAMS mathematical modeling program was used to optimize the placement and size of the water streams in an oil refinery setting. Using the mixed integer program (MIP) and the relaxed mixed integer program (rMIP) to solve the linear portions of the model as well as the mixed integer non-linear program (MINLP) to solve the non-linear portions, we were able to employ the CPLEX and DICOPT solvers to optimize the water regeneration system.



```
--- DICOPT: Checking convergence
--- DICOPT: Setting up next MIP
--- DICOPT: Log File:
--- DICOPT: Starting major iteration 4
--- DICOPT: Setting up next NLP
--- DICOPT: Checking convergence
--- DICOPT: Search stopped on worsening of NLP subproblems
--- DICOPT: Log File:
--- DICOPT: Terminating...
--- DICOPT: Stopped on NLP worsening
--- DICOPT: Best integer solution found: 1239.399750
--- Restarting execution
--- 2009-04-29_Regeneration Processes_Consumption.gms(14673) 0 Mb
--- Reading solution for model UpperNonLinear
--- 2009-04-29_Regeneration Processes_Consumption.gms(14673) 10 Mb
--- Executing after solve
--- 2009-04-29_Regeneration Processes_Consumption.gms(12976) 12 Mb
--- Generating MIP model LowerBound
--- 2009-04-29_Regeneration Processes_Consumption.gms(14957) 24 Mb
--- LOOPS FOR/WHILE = 1
---       FOR/WHILE = 1
---       FOR/WHILE = 2
---   5,672 rows  49,704 columns  412,210 non-zeroes
---   47,490 discrete-columns
--- Executing CPLEX
--- Restarting execution
--- 2009-04-29_Regeneration Processes_Consumption.gms(14957) 0 Mb
--- Reading solution for model LowerBound
--- Executing after solve
--- 2009-04-29_Regeneration Processes_Consumption.gms(12976) 12 Mb
--- Generating MINLP model UpperNonLinear
--- 2009-04-29_Regeneration Processes_Consumption.gms(15011) 26 Mb
--- LOOPS FOR/WHILE = 1
---       FOR/WHILE = 1
---       FOR/WHILE = 2
---   2,083 rows  49,013 columns  404,733 non-zeroes
---   6,792 nl-code  1,233 nl-non-zeroes
---   47,358 discrete-columns
--- 2009-04-29_Regeneration Processes_Consumption.gms(15011) 24 Mb
--- Executing DICOPT
--- DICOPT: Starting major iteration 1
--- DICOPT: Setting up first (relaxed) NLP.
--- DICOPT: Setting up first MIP
--- DICOPT: Starting major iteration 2
--- DICOPT: Setting up next NLP
```

```
    115   0    48  1.8057758984E+02              0.0E+00       T  T
```

Figure 22. GAMS Program Screenshot

We optimized the system of equations based on two different objective functions, cost and consumption:

- *Cost = Annual Operation Cost + Annual Fixed Cost*
- *Consumption = Freshwater to water-using units + Freshwater to regeneration units*

With these two objective functions, we set the output to give the lowest total annualized cost or the lowest annual amount of freshwater consumed.

Past models of water regeneration processes made assumptions for the outlet concentrations coming out of the water-using units and the regeneration processes. Assumptions such as a fixed outlet concentration or a fixed unit efficiency caused previous models to provide less than ideal results. With the modeled outlet concentrations mentioned in the first part of this report, we are able to find more realistic results spanning a wider range of operating conditions. With these more realistic results, a more confident conclusion can be reached on the economic and environmental impact of utilizing the regeneration process model.

Results

The GAMS model that was created provided over 400,000 non-zero terms with over 1,200 non-linear, non-zero terms. The model took anywhere from one to five hours to run for each simulation and read and processed over 17,000 lines of code. The output of the model provided stream by stream data linking the freshwater source, water-using units, regeneration processes, and water disposal sites all together. An example of the output data is shown in the appendix. The program was run with only the regeneration processes containing outlet concentration models. The water-using units will be added to the program at a later date. With the model standing as it is now though, the process flow diagram of the refinery's water using units changed from a traditional flow like this:

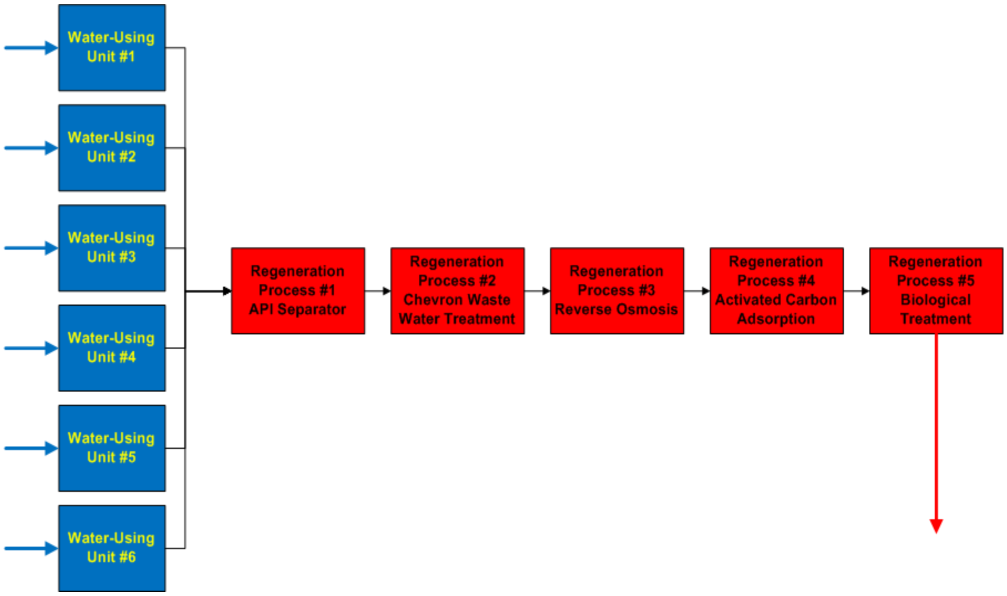


Figure 23. Traditional Water Regeneration

to a new output where streams can flow back and forth from regeneration processes to water-using units and back in the most efficient manner. An example of this new output is shown below:

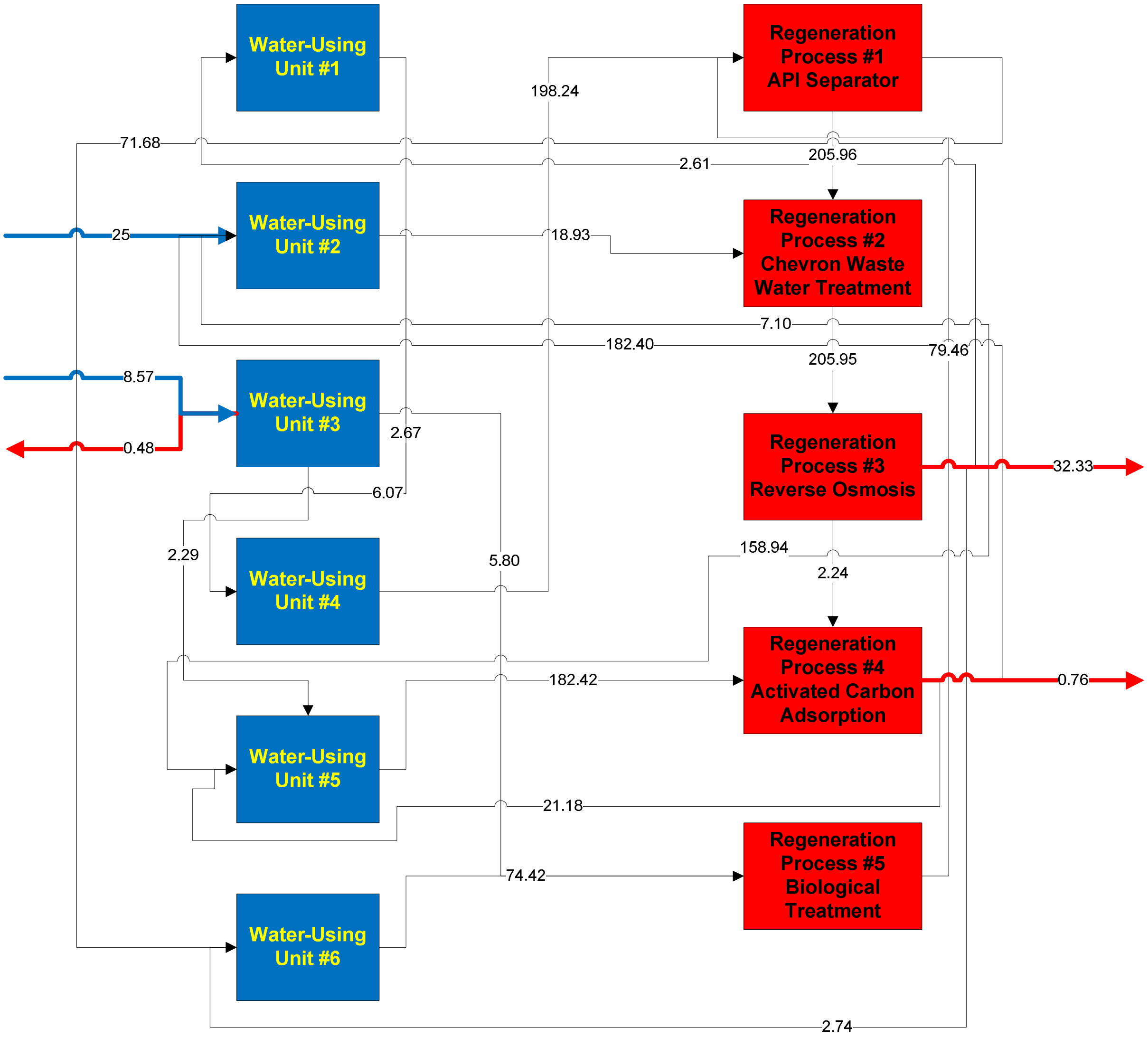


Figure 24. Optimized Water Regeneration

with this schematic, the following contaminant concentrations were cleaned using the regeneration processes:

Contaminant Stream Concentration Reduction (ppm)			
Salts	Organics	H_2S	Ammonia
621.18	7153.77	27.23	18.61

By including the modeled outlet concentrations of the regeneration processes into our mathematical model, we provided more realistic results to conclude an expected cost of $950,000 (instead of $1,220,000 as seen with the fixed outlet concentration model) and a water consumption of 31 tons/hour (instead of 33 tons/hour). We obtained these results by setting constraints of 250 tons/hour as the maximum stream flow rate and a contaminant outlet limit of 20, 50, 5, and 30 ppm for salts, organics, H_2S, and ammonia respectively. These model results might differ minimally between fixed outlet concentrations and modeled outlet concentrations, but the improved reliability and confidence provides a more usable program for any user who might find it useful. Further tables indicating water stream placement (i.e. flow rate to and from water-using and regeneration processes in ton/hr) are seen in Appendix III.

Conclusions

This study focused on deriving original correlations for predicting wastewater contaminant levels from water treatment and a few water-using units in petroleum refineries. While there is no exact model that exists to find contaminant levels, non-linear regression can be used to approximate a highly accurate answer (with determination coefficients in the range of ~0.99). However, since developed models were found by varying one parameter at a time, non-linear models (i.e. accounting for how pressure might be related to temperature simultaneously) of the outlet concentration of contaminants provide a more accurate model to represent refinery waste water generation. Of course, all of the procedures aforementioned are performed based on the assumption that the simulation method used is highly accurate. For the sake of this study, which uses programs like PRO/II and Mathcad to generate points for a guessed model, it will be assumed that errors are at a minimum within the system. Other simulation programs like Aspen’s HYSYS could be used to check the accuracy of PRO/II runs, if made available to the student. Also, comparing actual data from a petroleum refinery with theoretical model results would ensure that the guessed models in this study are at least close to predicted values, if not entirely incorrect. Once again though, availability is the dilemma at hand, as the information needed to compare could be closely guarded and perhaps laden with legal consequences. As government regulations are becoming increasingly strict in laws regarding treated wastewater, it is, in effect, becoming important to develop more accurate models. Accurate predictions of treated water streams and obeying the government standards set for these contaminant levels not only guarantees a trouble-free work environment, but also promotes a safe and healthy living environment. A final conclusion is that equipment costs of the water regeneration processes are a function of inlet concentrations and flow rates, as well as design parameters.

Recommendations

The crux of wastewater management lies in the optimization of wastewater and freshwater streams. Thus, as optimization models increase in accuracy, the accuracy of corresponding stream placement and flowrates increase. Recommendations for future work in the continuing water management problem include:

- Modeling of the vacuum distillation column, hydrotreatment unit, and Merox I sweetening unit
- More accurate modeling of operating costs for the regeneration processes
- Implement all newly-found models in GAMS file (mathematical model)
- Expand the scope of the project to include other industrial cases where water is used to treat contaminants, e.g. a tricresyl phosphate process or a paper mill process
- Derive an economic plan for refinery wastewater system (including costs of piping, costs of process units, location and prices of pumps, salaries, etc.)
- Investigate water treatment and water-using units for countries other than the U.S., like Canada or Mexico
    - Find out if the water treatment and water-using units are similar to those used in the U.S.
    - What are the permitted drinking water contaminant levels in that country? Are they similar to the U.S.? If so, are large oil companies abiding by these laws?
    - Are industries really following government guidelines? Is the government even setting a guideline? If not, could this be the reason why so many oil companies are willing to export their business to countries outside of the U.S. so they don't have to adhere to strict water laws? What kind of money could be saved if water treatment processes were used at a bare minimum?

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Appendix I

API Separator table:

			Mole fraction retained								
	L (m)		20	24	28	32	36	40	44	48	52
	W (m)		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	H (m)		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	V (m^3)		105	126	147	168	189	210	231	252	273
Height at which particle enters	Flow (m^3/s)	Flow (ton/hr)									
0.01	0.0010	3.961270121	0.962	0.965	0.968	0.970	0.971	0.973	0.974	0.975	0.976
0.01	0.0051	20.20247762	0.911	0.919	0.925	0.930	0.934	0.938	0.941	0.943	0.946
0.01	0.0101	40.00882822	0.874	0.885	0.894	0.901	0.907	0.912	0.916	0.920	0.923
0.01	0.0151	59.81517883	0.845	0.859	0.870	0.878	0.885	0.891	0.897	0.901	0.905
0.01	0.0201	79.62152944	0.821	0.837	0.849	0.859	0.867	0.874	0.880	0.886	0.890
0.01	0.0251	99.42788004	0.801	0.818	0.831	0.842	0.851	0.859	0.866	0.872	0.877
0.01	0.0301	119.2342307	0.782	0.801	0.815	0.827	0.837	0.846	0.853	0.859	0.865
0.01	0.0351	139.0405813	0.765	0.785	0.801	0.813	0.824	0.833	0.841	0.848	0.854
0.01	0.0401	158.8469319	0.750	0.771	0.787	0.801	0.812	0.822	0.830	0.837	0.844
0.01	0.0451	178.6532825	0.736	0.758	0.775	0.789	0.801	0.811	0.820	0.827	0.834
0.01	0.0501	198.4596331	0.723	0.745	0.763	0.778	0.790	0.801	0.810	0.818	0.825
0.01	0.0551	218.2659837	0.711	0.734	0.752	0.767	0.780	0.791	0.801	0.809	0.817
0.3	0.0010	3.961270121	0.966	0.969	0.971	0.973	0.974	0.976	0.977	0.978	0.979
0.3	0.0051	20.20247762	0.921	0.928	0.933	0.938	0.941	0.944	0.947	0.949	0.951
0.3	0.0101	40.00882822	0.887	0.897	0.905	0.911	0.917	0.921	0.925	0.928	0.931
0.3	0.0151	59.81517883	0.861	0.874	0.883	0.891	0.897	0.903	0.908	0.912	0.915
0.3	0.0201	79.62152944	0.840	0.854	0.865	0.874	0.881	0.888	0.893	0.898	0.902
0.3	0.0251	99.42788004	0.821	0.837	0.849	0.859	0.867	0.874	0.880	0.885	0.890
0.3	0.0301	119.2342307	0.804	0.821	0.834	0.845	0.854	0.862	0.868	0.874	0.879
0.3	0.0351	139.0405813	0.789	0.807	0.821	0.833	0.842	0.850	0.857	0.864	0.869
0.3	0.0401	158.8469319	0.774	0.794	0.809	0.821	0.831	0.840	0.848	0.854	0.860
0.3	0.0451	178.6532825	0.761	0.781	0.797	0.810	0.821	0.830	0.838	0.845	0.851
0.3	0.0501	198.4596331	0.749	0.770	0.787	0.800	0.811	0.821	0.829	0.837	0.843
0.3	0.0551	218.2659837	0.738	0.759	0.776	0.791	0.802	0.812	0.821	0.829	0.835
0.5	0.0010	3.961270121	0.969	0.971	0.974	0.975	0.977	0.978	0.979	0.980	0.981
0.5	0.0051	20.20247762	0.928	0.934	0.939	0.943	0.947	0.949	0.952	0.954	0.956
0.5	0.0101	40.00882822	0.897	0.906	0.914	0.919	0.924	0.928	0.932	0.935	0.937
0.5	0.0151	59.81517883	0.874	0.885	0.894	0.901	0.907	0.912	0.916	0.920	0.923
0.5	0.0201	79.62152944	0.854	0.867	0.877	0.885	0.892	0.898	0.902	0.907	0.911
0.5	0.0251	99.42788004	0.837	0.851	0.862	0.871	0.879	0.885	0.891	0.895	0.900
0.5	0.0301	119.2342307	0.821	0.837	0.849	0.859	0.867	0.874	0.880	0.885	0.890
0.5	0.0351	139.0405813	0.807	0.823	0.837	0.847	0.856	0.864	0.870	0.876	0.881
0.5	0.0401	158.8469319	0.794	0.811	0.825	0.837	0.846	0.854	0.861	0.867	0.872
0.5	0.0451	178.6532825	0.781	0.800	0.815	0.827	0.837	0.845	0.852	0.859	0.864
0.5	0.0501	198.4596331	0.770	0.789	0.805	0.817	0.828	0.837	0.844	0.851	0.857
0.5	0.0551	218.2659837	0.759	0.780	0.795	0.808	0.819	0.829	0.837	0.844	0.850
0.75	0.0010	3.961270121	0.973	0.975	0.977	0.979	0.980	0.981	0.982	0.983	0.983
0.75	0.0051	20.20247762	0.938	0.943	0.948	0.951	0.954	0.956	0.958	0.960	0.962
0.75	0.0101	40.00882822	0.911	0.919	0.926	0.930	0.935	0.938	0.941	0.944	0.946
0.75	0.0151	59.81517883	0.891	0.901	0.908	0.914	0.920	0.924	0.927	0.931	0.933
0.75	0.0201	79.62152944	0.874	0.885	0.894	0.901	0.907	0.912	0.916	0.920	0.923
0.75	0.0251	99.42788004	0.859	0.871	0.881	0.889	0.895	0.901	0.906	0.910	0.913
0.75	0.0301	119.2342307	0.845	0.859	0.869	0.878	0.885	0.891	0.896	0.901	0.905
0.75	0.0351	139.0405813	0.833	0.847	0.859	0.868	0.876	0.882	0.888	0.893	0.897
0.75	0.0401	158.8469319	0.821	0.837	0.849	0.859	0.867	0.874	0.880	0.885	0.890
0.75	0.0451	178.6532825	0.810	0.827	0.840	0.850	0.859	0.866	0.873	0.878	0.883
0.75	0.0501	198.4596331	0.800	0.817	0.831	0.842	0.851	0.859	0.866	0.871	0.877
0.75	0.0551	218.2659837	0.791	0.808	0.823	0.834	0.844	0.852	0.859	0.865	0.870
1	0.0010	3.961270121	0.978	0.980	0.981	0.983	0.984	0.984	0.985	0.986	0.986
1	0.0051	20.20247762	0.949	0.954	0.957	0.960	0.963	0.964	0.966	0.968	0.969
1	0.0101	40.00882822	0.928	0.935	0.940	0.944	0.947	0.950	0.952	0.954	0.956
1	0.0151	59.81517883	0.912	0.920	0.926	0.931	0.935	0.938	0.941	0.944	0.946
1	0.0201	79.62152944	0.898	0.907	0.914	0.920	0.924	0.928	0.932	0.935	0.937
1	0.0251	99.42788004	0.885	0.895	0.903	0.910	0.915	0.920	0.923	0.927	0.930
1	0.0301	119.2342307	0.874	0.885	0.894	0.901	0.907	0.912	0.916	0.920	0.923
1	0.0351	139.0405813	0.864	0.876	0.885	0.893	0.899	0.904	0.909	0.913	0.917
1	0.0401	158.8469319	0.854	0.867	0.877	0.885	0.892	0.898	0.903	0.907	0.911
1	0.0451	178.6532825	0.845	0.859	0.870	0.878	0.885	0.891	0.897	0.901	0.905
1	0.0501	198.4596331	0.837	0.851	0.862	0.871	0.879	0.885	0.891	0.896	0.900
1	0.0551	218.2659837	0.829	0.844	0.855	0.865	0.873	0.880	0.885	0.890	0.895
1.25	0.0010	3.961270121	0.984	0.986	0.987	0.988	0.988	0.989	0.990	0.990	0.990
1.25	0.0051	20.20247762	0.964	0.968	0.970	0.972	0.974	0.975	0.976	0.977	0.978
1.25	0.0101	40.00882822	0.950	0.954	0.958	0.960	0.963	0.965	0.966	0.968	0.969
1.25	0.0151	59.81517883	0.938	0.944	0.948	0.951	0.954	0.957	0.959	0.960	0.962
1.25	0.0201	79.62152944	0.928	0.935	0.940	0.944	0.947	0.950	0.952	0.954	0.956
1.25	0.0251	99.42788004	0.920	0.927	0.932	0.937	0.941	0.944	0.946	0.949	0.951
1.25	0.0301	119.2342307	0.912	0.920	0.926	0.931	0.935	0.938	0.941	0.944	0.946
1.25	0.0351	139.0405813	0.904	0.913	0.920	0.925	0.929	0.933	0.936	0.939	0.942
1.25	0.0401	158.8469319	0.898	0.907	0.914	0.920	0.924	0.928	0.932	0.935	0.937
1.25	0.0451	178.6532825	0.891	0.901	0.909	0.915	0.920	0.924	0.928	0.931	0.934
1.25	0.0501	198.4596331	0.885	0.896	0.904	0.910	0.915	0.920	0.924	0.927	0.930
1.25	0.0551	218.2659837	0.880	0.890	0.899	0.905	0.911	0.916	0.920	0.923	0.926
1.49	0.0010	3.961270121	0.997	0.997	0.997	0.998	0.998	0.998	0.998	0.998	0.998
1.49	0.0051	20.20247762	0.993	0.994	0.994	0.994	0.995	0.995	0.995	0.996	0.996
1.49	0.0101	40.00882822	0.990	0.991	0.992	0.992	0.993	0.993	0.993	0.994	0.994
1.49	0.0151	59.81517883	0.988	0.989	0.990	0.990	0.991	0.991	0.992	0.992	0.993
1.49	0.0201	79.62152944	0.986	0.987	0.988	0.989	0.990	0.990	0.991	0.991	0.991
1.49	0.0251	99.42788004	0.984	0.986	0.987	0.988	0.988	0.989	0.990	0.990	0.990
1.49	0.0301	119.2342307	0.983	0.984	0.986	0.987	0.987	0.988	0.989	0.989	0.989
1.49	0.0351	139.0405813	0.982	0.983	0.984	0.985	0.986	0.987	0.988	0.988	0.989
1.49	0.0401	158.8469319	0.980	0.982	0.983	0.984	0.985	0.986	0.987	0.987	0.988
1.49	0.0451	178.6532825	0.979	0.981	0.982	0.983	0.984	0.985	0.986	0.987	0.987
1.49	0.0501	198.4596331	0.978	0.980	0.981	0.983	0.984	0.984	0.985	0.986	0.986
1.49	0.0551	218.2659837	0.977	0.979	0.980	0.982	0.983	0.984	0.984	0.985	0.986

Polymath results for activated sludge:

POLYMATH Results

No Title 03-02-2009

Nonlinear regression (L-M)

Model: TKNeffluent = a*(TBOD5^b)+c*TKN+e*NH3N+g*(Y^i)+j*kd+m*MCRT+(o*MLVSStoMLSS*MLVSStoMLSS)+(p*MLVSStoMLSS)+d

```
Variable     Ini guess      Value      95% confidence
a             35          20.033392     0.2483401
b            -0.04        -0.1381159    0.0022601
c             0.16         0.0055365    0.0021003
e             0.843        0.4414261    0.0049
g             26          15.213166     0.1693005
i            -0.11         0.8397723    0.0251757
j             13.4       -69.166537     1.3530784
m             0.083       -0.4107851    0.0080561
o             25           7.3439867    0.2195136
p             0.123      -13.176989     0.1637615
d             1300       1290.1729      0.1163555
```

Nonlinear regression settings

Max # iterations = 300

Precision

```
R^2       = -3.233E+04
R^2adj    = -3.921E+04
Rmsd      =  167.96354
Variance  =  2.019E+06
```

General

```
Sample size   = 58
# Model vars  = 11
# Indep vars  = 7
# Iterations  = 22
```

Polymath report for sludge in activated sludge:

POLYMATH Results

No Title 02-25-2009

Nonlinear regression (L-M)

Model: TKNsludge = a*(TBOD5^b)+c*TKN+e*NH3N+g*(Y^i)+j*kd+m*MCRT+(o*MLVSStoMLSS*MLVSStoMLSS)+(p*MLVSStoMLSS)+(q*mgBODtomgVSS)+d

```
Variable      Ini guess    Value        95% confidence
a              2.447E+05   3.436E+05    6.195E+05
b             -0.989      -1.0566498    0.3699678
c              77.9        77.885427    0.2837419
e             -77         -77.035544    1.3641259
g              780         762.48543    74.635933
i             -0.99       -0.998504     0.03776
j              6673        6684.5207    127.00663
m              42          41.789081    0.7679007
o             -1798       -99.853572    307.24985
p              1829        1021.5736    253.5563
q             -83.4       -75.891695    97.216543
d              4598       -3663.6664    255.4147
```

Nonlinear regression settings

Max # iterations = 300

Precision

```
R^2       = 0.9998816
R^2adj    = 0.9998533
Rmsd      = 3.3082243
Variance  = 800.36492
```

General

```
Sample size   = 58
# Model vars  = 12
# Indep vars  = 8
# Iterations  = 27
```

Polymath report for Amine Sweetening

POLYMATH Results

03-08-2009

Nonlinear regression (L-M)

Model: steam = (a*(Regcondenpress^(-1)))+((b*Feedtemp)+c)

```
Variable      Ini guess      Value     95% confidence
a             1.705        0.0232341     8.851E-04
b             1.0E-08     -2.967E-05     7.559E-06
c             0.125        0.006946      0.0040712
```

Nonlinear regression settings

Max # iterations = 64

Precision

```
R^2       = 0.9887651
R^2adj    = 0.9885335
Rmsd      = 3.421E-04
Variance  = 1.206E-05
```

General

```
Sample size   = 100
# Model vars  = 3
# Indep vars  = 2
# Iterations  = 5
```

Polymath results for H_2S Stripper:

POLYMATH Results

No Title 04-20-2009

Nonlinear regression (L-M)

Model: CoutH2S = a*exp(b*CinNH3)+c*exp(d*Temp)+e*(Efficiency^f)+g*(CinH2S^2)+(h*CinH2S)+i*(Numberoftrays^j)+k

```
Variable      Ini guess      Value     95% confidence
a             2.0E-06      0.0023514     6.18E-04
b             0.7648       0.0792118     0.0565716
c             3.0E-06     -1.0002578     0.3104719
d             0.0142      -0.0385425     0.0020614
e             3.0E-05     -0.0143649     7.966E-04
f            -0.908       -0.137697      0.1722801
g             1.0E-06      0.0112059     2.959E-05
h            -2.0E-06      0.0012207     1.618E-04
i             5244         2.17E+04      24.371227
j            -7.377       -7.0772926     0.0010207
k             9.0E-06      0.015824    8.152E-05
```

Nonlinear regression settings

Max # iterations = 300

Precision

```
R^2       = 0.9994561
R^2adj    = 0.9994201
Rmsd      = 0.0013088
Variance  = 2.977E-04
```

General

```
Sample size   = 162
# Model vars  = 11
# Indep vars  = 5
# Iterations  = 71
```

Polymath results for NH_3 Stripper:

POLYMATH Report	No Title
Nonlinear Regression (L-M)	28-Apr-2009

Model: CoutNH3 = a*(Feedrate^2)+b*Feedrate+c*CinNH3+d*exp(Numberoftrays*e)+f*exp(g*Temp)+h*RFR+i*(Pressure^j)+k*(Efficiency^2)+l*Efficiency+m*(CinH2S^n)+o

Variable	Initial guess	Value	95% confidence
a	0.0006	0.0006762	3.554E-06
b	0.0106	-0.0064736	9.96E-05
c	0.0306	-0.056633	0.0006159
d	9106.6	1.546E+04	0.4341984
e	-0.824	-0.6966562	5.606E-06
f	7.0E-05	8.069E-05	3.885E-09
g	0.0247	0.0250764	8.003E-08
h	0.0069	0.0612676	0.0005577
i	4.481E+04	-4.436E+06	2.257E+04
j	-2.572	-2.940971	0.0009171
k	0.1883	-0.5269187	0.0029861
l	-0.3277	-0.7517399	0.0023763
m	0.041	7.1049645	7.0639645
n	-0.065	0.470095	0.535095
o	0.322	0.237672	0.0018679

Nonlinear regression settings

Max # iterations = 300

Precision

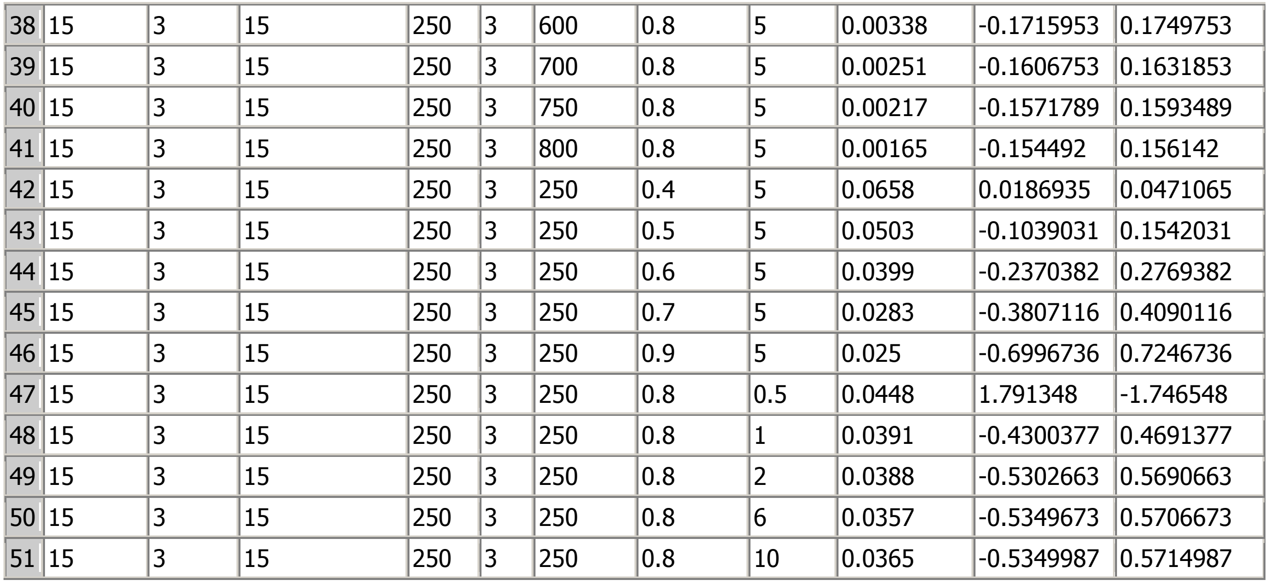
R^2	0.9148893
R^2adj	0.8817907
Rmsd	2.460408
Variance	437.3733

General

Sample size	51
Model vars	15
Indep vars	8
Iterations	18

Source data points and calculated data points

	Feedrate	CinNH3	Numberoftrays	Temp	RFR	Pressure	Efficiency	CinH2S	CoutNH3	CoutNH3 calc	Delta CoutNH3
1	5	3	15	250	3	250	0.8	5	0.00642	-0.6054326	0.6118526
2	10	3	15	250	3	250	0.8	5	0.0752	-0.5870836	0.6622836
3	15	3	15	250	3	250	0.8	5	0.0924	-0.5349234	0.6273234
4	20	3	15	250	3	250	0.8	5	0.124	-0.448952	0.572952
5	25	3	15	250	3	250	0.8	5	0.187	-0.3291694	0.5161694
6	30	3	15	250	3	250	0.8	5	0.277	-0.1755756	0.4525756
7	35	3	15	250	3	250	0.8	5	0.406	0.0118294	0.3941706
8	40	3	15	250	3	250	0.8	5	0.597	0.2330456	0.3639544
9	42	3	15	250	3	250	0.8	5	0.697	0.3309992	0.3660008
10	43	3	15	250	3	250	0.8	5	0.755	0.3820047	0.3729953
11	15	0.3	15	250	3	250	0.8	5	0.00541	-0.3820144	0.3874244
12	15	0.75	15	250	3	250	0.8	5	0.0153	-0.4074992	0.4227992
13	15	1	15	250	3	250	0.8	5	0.0219	-0.4216575	0.4435575
14	15	1.5	15	250	3	250	0.8	5	0.0334	-0.449974	0.483374
15	15	2	15	250	3	250	0.8	5	0.0461	-0.4782904	0.5243904
16	15	2.5	15	250	3	250	0.8	5	0.061	-0.5066069	0.5676069
17	15	4	15	250	3	250	0.8	5	0.108	-0.5915564	0.6995564
18	15	5	15	250	3	250	0.8	5	0.143	-0.6481894	0.7911894
19	15	6	15	250	3	250	0.8	5	0.18	-0.7048223	0.8848223
20	15	3	5	250	3	250	0.8	5	350	473.8129	-123.8129
21	15	3	10	250	3	250	0.8	5	0.424	13.5967	-13.1727
22	15	3	20	250	3	250	0.8	5	0.00483	-0.9688562	0.9736862
23	15	3	25	250	3	250	0.8	5	0.00000242	-0.9821808	0.9821832
24	15	3	30	250	3	250	0.8	5	0.00000022	-0.9825899	0.9825901
25	15	3	15	200	3	250	0.8	5	0.0236	-0.5653663	0.5889663
26	15	3	15	300	3	250	0.8	5	0.0273	-0.4282608	0.4555608
27	15	3	15	400	3	250	0.8	5	1.8	1.254832	0.5451683
28	15	3	15	500	3	250	0.8	5	11.2	21.9163	-10.7163
29	15	3	15	600	3	250	0.8	5	265	275.5544	-10.55436
30	15	3	15	250	2	250	0.8	5	0.0658	-0.596191	0.661991
31	15	3	15	250	4	250	0.8	5	0.0503	-0.4736559	0.5239559
32	15	3	15	250	5	250	0.8	5	0.0399	-0.4123883	0.4522883
33	15	3	15	250	7	250	0.8	5	0.0283	-0.2898532	0.3181532
34	15	3	15	250	8	250	0.8	5	0.025	-0.2285856	0.2535856
35	15	3	15	250	3	300	0.8	5	0.0354	-0.3716959	0.4070959
36	15	3	15	250	3	400	0.8	5	0.00475	-0.2403553	0.2451053
37	15	3	15	250	3	500	0.8	5	0.00332	-0.1928509	0.1961709



38	15	3	15	250	3	600	0.8	5	0.00338	-0.1715953	0.1749753
39	15	3	15	250	3	700	0.8	5	0.00251	-0.1606753	0.1631853
40	15	3	15	250	3	750	0.8	5	0.00217	-0.1571789	0.1593489
41	15	3	15	250	3	800	0.8	5	0.00165	-0.154492	0.156142
42	15	3	15	250	3	250	0.4	5	0.0658	0.0186935	0.0471065
43	15	3	15	250	3	250	0.5	5	0.0503	-0.1039031	0.1542031
44	15	3	15	250	3	250	0.6	5	0.0399	-0.2370382	0.2769382
45	15	3	15	250	3	250	0.7	5	0.0283	-0.3807116	0.4090116
46	15	3	15	250	3	250	0.9	5	0.025	-0.6996736	0.7246736
47	15	3	15	250	3	250	0.8	0.5	0.0448	1.791348	-1.746548
48	15	3	15	250	3	250	0.8	1	0.0391	-0.4300377	0.4691377
49	15	3	15	250	3	250	0.8	2	0.0388	-0.5302663	0.5690663
50	15	3	15	250	3	250	0.8	6	0.0357	-0.5349673	0.5706673
51	15	3	15	250	3	250	0.8	10	0.0365	-0.5349987	0.5714987

Polymath results for crude oil distillation column:

POLYMATH Report
Nonlinear Regression (L-M)
No Title
20-Apr-2009

Model: Xoutwater = a*Efficiency^6-b*Efficiency^5+c*Efficiency^4-d*Efficiency^3+e*Efficiency^2-f*Efficiency-g*Crudefeed+h*Steamtemp+i*Steamflow^j+k+l*(Xinorganics^4)+m*(Xinorganics^3)+n*(Xinorganics^2)+o*Xinorganics

Variable	Initial guess	Value	95% confidence
a	0.1236	0.1129874	0.1295418
b	0.6655	0.6058456	0.684952
c	1.4344	1.297872	1.466419
d	1.5817	1.418556	1.622575
e	0.9411	0.8338002	0.9757995
f	0.2865	0.2497371	0.3015229
g	3.0E-05	2.992E-05	4.024E-07
h	1.0E-07	2.202E-07	3.411E-08
i	0.0174	0.0055334	0.0001881
j	0.4295	0.5565462	0.003919
k	1.7	0.7096117	0.3139925
l	0.0149	0.0143246	0.0101507
m	-0.1402	-0.1353119	0.0970516
n	0.488	0.4716159	0.3442684
o	-0.7433	-0.7189798	0.5370286

Nonlinear regression settings
Max # iterations = 300

Precision

R^2	0.999988
R^2adj	0.9999873
Rmsd	9.227E-06
Variance	2.324E-08

General

Sample size	257
Model vars	15
Indep vars	5
Iterations	26

Source data points and calculated data points

	Efficiency	Crudefeed	Steamtemp	Steamflow	Xinorganics	Xoutwater	Xoutwater calc	Delta Xoutwater
1	0.4	6548.3	600	555	3	0.26486	0.2648542	5.751E-06
2	0.4	6553.3	600	555	3	0.26471	0.2647047	5.346E-06
3	0.4	6558.3	600	555	3	0.26456	0.2645551	4.942E-06
4	0.4	6563.3	600	555	3	0.26441	0.2644055	4.537E-06
5	0.4	6568.3	600	555	3	0.26425	0.2642559	-5.868E-06
6	0.4	6573.3	600	555	3	0.2641	0.2641063	-6.273E-06
7	0.4	6578.3	600	555	3	0.26395	0.2639567	-6.678E-06
8	0.4	6583.3	600	555	3	0.2638	0.2638071	-7.083E-06
9	0.4	6588.3	600	555	3	0.26365	0.2636575	-7.487E-06
10	0.4	6593.3	600	555	3	0.26349	0.2635079	-1.789E-05
11	0.4	6598.3	600	555	3	0.26334	0.2633583	-1.83E-05
12	0.4	6603.3	600	555	3	0.26319	0.2632087	-1.87E-05
13	0.4	6608.3	600	555	3	0.26304	0.2630591	-1.911E-05
14	0.4	6613.3	600	555	3	0.26289	0.2629095	-1.951E-05
15	0.4	6618.3	600	555	3	0.26274	0.2627599	-1.992E-05
16	0.4	6623.3	600	555	3	0.26259	0.2626103	-2.032E-05
17	0.4	6628.3	600	555	3	0.26244	0.2624607	-2.073E-05
18	0.4	6633.3	600	555	3	0.26229	0.2623111	-2.113E-05
19	0.4	6638.3	600	555	3	0.26214	0.2621615	-2.154E-05
20	0.4	6643.3	600	555	3	0.26199	0.2620119	-2.194E-05
21	0.4	6648.3	600	555	3	0.26184	0.2618623	-2.235E-05
22	0.4	6653.3	600	555	3	0.26169	0.2617128	-2.275E-05
23	0.4	6658.3	600	555	3	0.26154	0.2615632	-2.316E-05
24	0.4	6663.3	600	555	3	0.26139	0.2614136	-2.356E-05
25	0.4	6668.3	600	555	3	0.26124	0.261264	-2.396E-05
26	0.4	6673.3	600	555	3	0.26109	0.2611144	-2.437E-05
27	0.4	6678.3	600	555	3	0.26094	0.2609648	-2.477E-05
28	0.4	6683.3	600	555	3	0.26079	0.2608152	-2.518E-05
29	0.4	6688.3	600	555	3	0.26065	0.2606656	-1.558E-05
30	0.4	6693.3	600	555	3	0.2605	0.260516	-1.599E-05
31	0.4	6698.3	600	555	3	0.26035	0.2603664	-1.639E-05
32	0.4	6703.3	600	555	3	0.2602	0.2602168	-1.68E-05

33	0.4	6708.3	600	555	3	0.26005	0.2600672	-1.72E-05
34	0.4	6713.3	600	555	3	0.25991	0.2599176	-7.608E-06
35	0.4	6718.3	600	555	3	0.25976	0.259768	-8.013E-06
36	0.4	6723.3	600	555	3	0.25961	0.2596184	-8.418E-06
37	0.4	6728.3	600	555	3	0.25946	0.2594688	-8.823E-06
38	0.4	6733.3	600	555	3	0.25932	0.2593192	7.725E-07
39	0.4	6738.3	600	555	3	0.25917	0.2591696	3.677E-07
40	0.4	6743.3	600	555	3	0.25902	0.25902	-3.716E-08
41	0.4	6748.3	600	555	3	0.25888	0.2588704	9.558E-06
42	0.4	6753.3	600	555	3	0.25873	0.2587208	9.153E-06
43	0.4	6758.3	600	555	3	0.25859	0.2585713	1.875E-05
44	0.4	6763.3	600	555	3	0.25844	0.2584217	1.834E-05
45	0.4	6768.3	600	555	3	0.25829	0.2582721	1.794E-05
46	0.4	6773.3	600	555	3	0.25815	0.2581225	2.753E-05
47	0.4	6778.3	600	555	3	0.258	0.2579729	2.713E-05
48	0.4	6783.3	600	555	3	0.25786	0.2578233	3.672E-05
49	0.4	6788.3	600	555	3	0.25771	0.2576737	3.632E-05
50	0.4	6793.3	600	555	3	0.25757	0.2575241	4.591E-05
51	0.4	6548.3	600	555	3	0.26498	0.2648542	0.0001258
52	0.4	6548.3	625	555	3	0.26498	0.2648598	0.0001202
53	0.4	6548.3	650	555	3	0.26498	0.2648653	0.0001147
54	0.4	6548.3	675	555	3	0.26499	0.2648708	0.0001192
55	0.4	6548.3	700	555	3	0.26499	0.2648763	0.0001137
56	0.4	6548.3	725	555	3	0.26499	0.2648818	0.0001082
57	0.4	6548.3	750	555	3	0.265	0.2648873	0.0001127
58	0.4	6548.3	775	555	3	0.265	0.2648928	0.0001072
59	0.4	6548.3	800	555	3	0.265	0.2648983	0.0001017
60	0.4	6548.3	825	555	3	0.26501	0.2649038	0.0001062
61	0.4	6548.3	850	555	3	0.26501	0.2649093	0.0001007
62	0.4	6548.3	875	555	3	0.26501	0.2649148	9.519E-05
63	0.4	6548.3	900	555	3	0.26502	0.2649203	9.968E-05
64	0.4	6548.3	925	555	3	0.26502	0.2649258	9.418E-05
65	0.4	6548.3	950	555	3	0.26503	0.2649313	9.867E-05
66	0.4	6548.3	975	555	3	0.26503	0.2649368	9.316E-05
67	0.4	6548.3	1000	555	3	0.26503	0.2649423	8.766E-05

68	0.4	6548.3	1025	555	3	0.26504	0.2649478	9.215E-05
69	0.4	6548.3	1050	555	3	0.26504	0.2649534	8.665E-05
70	0.4	6548.3	1075	555	3	0.26504	0.2649589	8.114E-05
71	0.4	6548.3	1100	555	3	0.26505	0.2649644	8.564E-05
72	0.4	6548.3	1125	555	3	0.26505	0.2649699	8.013E-05
73	0.4	6548.3	1150	555	3	0.26505	0.2649754	7.462E-05
74	0.4	6548.3	1175	555	3	0.26506	0.2649809	7.912E-05
75	0.4	6548.3	1200	555	3	0.26506	0.2649864	7.361E-05
76	0.4	6548.3	1225	555	3	0.26506	0.2649919	6.811E-05
77	0.4	6548.3	1250	555	3	0.26507	0.2649974	7.26E-05
78	0.4	6548.3	1275	555	3	0.26507	0.2650029	6.71E-05
79	0.4	6548.3	1300	555	3	0.26508	0.2650084	7.159E-05
80	0.4	6548.3	1325	555	3	0.26508	0.2650139	6.608E-05
81	0.4	6548.3	1350	555	3	0.26508	0.2650194	6.058E-05
82	0.4	6548.3	1375	555	3	0.26509	0.2650249	6.507E-05
83	0.4	6548.3	1400	555	3	0.26509	0.2650304	5.957E-05
84	0.4	6548.3	1425	555	3	0.26509	0.2650359	5.406E-05
85	0.4	6548.3	1450	555	3	0.2651	0.2650414	5.856E-05
86	0.4	6548.3	1475	555	3	0.2651	0.265047	5.305E-05
87	0.4	6548.3	1500	555	3	0.26511	0.2650525	5.754E-05
88	0.4	6548.3	1525	555	3	0.26511	0.265058	5.204E-05
89	0.4	6548.3	1550	555	3	0.26511	0.2650635	4.653E-05
90	0.4	6548.3	1575	555	3	0.26512	0.265069	5.103E-05
91	0.4	6548.3	1600	555	3	0.26512	0.2650745	4.552E-05
92	0.4	6548.3	1625	555	3	0.26512	0.26508	4.001E-05
93	0.4	6548.3	1650	555	3	0.26513	0.2650855	4.451E-05
94	0.4	6548.3	1675	555	3	0.26513	0.265091	3.9E-05
95	0.4	6548.3	1700	555	3	0.26513	0.2650965	3.35E-05
96	0.4	6548.3	1725	555	3	0.26514	0.265102	3.799E-05
97	0.4	6548.3	1750	555	3	0.26514	0.2651075	3.249E-05
98	0.4	6548.3	1775	555	3	0.26514	0.265113	2.698E-05
99	0.4	6548.3	1800	555	3	0.26515	0.2651185	3.147E-05
100	0.4	6548.3	1825	555	3	0.26515	0.265124	2.597E-05
101	0.4	6548.3	1850	555	3	0.26516	0.2651295	3.046E-05
102	0.4	6548.3	1875	555	3	0.26516	0.265135	2.496E-05

103	0.4	6548.3	1900	555	3	0.26516	0.2651405	1.945E-05
104	0.4	6548.3	1925	555	3	0.26517	0.2651461	2.395E-05
105	0.4	6548.3	1950	555	3	0.26517	0.2651516	1.844E-05
106	0.4	6548.3	1975	555	3	0.26517	0.2651571	1.293E-05
107	0.4	6548.3	2000	555	3	0.26518	0.2651626	1.743E-05
108	0.4	6548.3	2025	555	3	0.26518	0.2651681	1.192E-05
109	0.4	6548.3	2050	555	3	0.26519	0.2651736	1.642E-05
110	0.4	6548.3	2075	555	3	0.26519	0.2651791	1.091E-05
111	0.4	6548.3	2100	555	3	0.26519	0.2651846	5.405E-06
112	0.4	6548.3	2125	555	3	0.2652	0.2651901	9.899E-06
113	0.4	6548.3	2150	555	3	0.2652	0.2651956	4.394E-06
114	0.4	6548.3	2175	555	3	0.26521	0.2652011	8.888E-06
115	0.4	6548.3	2200	555	3	0.26521	0.2652066	3.382E-06
116	0.4	6548.3	2225	555	3	0.26521	0.2652121	-2.124E-06
117	0.4	6548.3	2250	555	3	0.26522	0.2652176	2.371E-06
118	0.4	6548.3	2275	555	3	0.26522	0.2652231	-3.135E-06
119	0.4	6548.3	2300	555	3	0.26523	0.2652286	1.359E-06
120	0.4	6548.3	2325	555	3	0.26523	0.2652341	-4.147E-06
121	0.4	6548.3	2350	555	3	0.26523	0.2652397	-9.652E-06
122	0.4	6548.3	2375	555	3	0.26524	0.2652452	-5.158E-06
123	0.4	6548.3	2400	555	3	0.26524	0.2652507	-1.066E-05
124	0.4	6548.3	2425	555	3	0.26524	0.2652562	-1.617E-05
125	0.4	6548.3	2450	555	3	0.26525	0.2652617	-1.168E-05
126	0.4	6548.3	2475	555	3	0.26525	0.2652672	-1.718E-05
127	0.4	6548.3	2500	555	3	0.26526	0.2652727	-1.269E-05
128	0.4	6548.3	2525	555	3	0.26526	0.2652782	-1.819E-05
129	0.4	6548.3	2550	555	3	0.26526	0.2652837	-2.37E-05
130	0.4	6548.3	2575	555	3	0.26527	0.2652892	-1.92E-05
131	0.4	6548.3	2600	555	3	0.26527	0.2652947	-2.471E-05
132	0.4	6548.3	2625	555	3	0.26527	0.2653002	-3.022E-05
133	0.4	6548.3	2650	555	3	0.26528	0.2653057	-2.572E-05
134	0.4	6548.3	2675	555	3	0.26528	0.2653112	-3.123E-05
135	0.4	6548.3	2700	555	3	0.26529	0.2653167	-2.673E-05
136	0.4	6548.3	2725	555	3	0.26529	0.2653222	-3.224E-05
137	0.4	6548.3	2750	555	3	0.26529	0.2653277	-3.774E-05

138	0.4	6548.3	2775	555	3	0.2653	0.2653333	-3.325E-05
139	0.4	6548.3	2800	555	3	0.2653	0.2653388	-3.876E-05
140	0.4	6548.3	2825	555	3	0.26531	0.2653443	-3.426E-05
141	0.4	6548.3	2850	555	3	0.26531	0.2653498	-3.977E-05
142	0.4	6548.3	2875	555	3	0.26531	0.2653553	-4.527E-05
143	0.4	6548.3	2900	555	3	0.26532	0.2653608	-4.078E-05
144	0.4	6548.3	2925	555	3	0.26532	0.2653663	-4.629E-05
145	0.4	6548.3	2950	555	3	0.26533	0.2653718	-4.179E-05
146	0.4	6548.3	2975	555	3	0.26533	0.2653773	-4.73E-05
147	0.4	6548.3	3000	555	3	0.26533	0.2653828	-5.28E-05
148	0.4	6548.3	3025	555	3	0.26534	0.2653883	-4.831E-05
149	0.4	6548.3	3050	555	3	0.26534	0.2653938	-5.381E-05
150	0.4	6548.3	3075	555	3	0.26534	0.2653993	-5.932E-05
151	0.4	6548.3	600	555.09	3	0.26498	0.2648711	0.0001089
152	0.4	6548.3	600	580.09	3	0.26943	0.2694967	-6.668E-05
153	0.4	6548.3	600	605.09	3	0.27384	0.2740347	-0.0001947
154	0.4	6548.3	600	630.09	3	0.27819	0.2784903	-0.0003003
155	0.4	6548.3	600	655.09	3	0.28249	0.2828682	-0.0003782
156	0.4	6548.3	600	680.09	3	0.28674	0.2871725	-0.0004325
157	0.4	6548.3	600	705.09	3	0.29094	0.2914073	-0.0004673
158	0.4	6548.3	600	730.09	3	0.29509	0.295576	-0.000486
159	0.4	6548.3	600	755.09	3	0.2992	0.2996818	-0.0004818
160	0.4	6548.3	600	780.09	3	0.30325	0.3037278	-0.0004778
161	0.4	6548.3	600	805.09	3	0.30726	0.3077167	-0.0004567
162	0.4	6548.3	600	830.09	3	0.31123	0.311651	-0.000421
163	0.4	6548.3	600	855.09	3	0.31515	0.3155331	-0.0003831
164	0.4	6548.3	600	880.09	3	0.31902	0.3193652	-0.0003452
165	0.4	6548.3	600	905.09	3	0.32285	0.3231494	-0.0002994
166	0.4	6548.3	600	930.09	3	0.32664	0.3268874	-0.0002474
167	0.4	6548.3	600	955.09	3	0.33039	0.3305812	-0.0001912
168	0.4	6548.3	600	980.09	3	0.33409	0.3342323	-0.0001423
169	0.4	6548.3	600	1005.1	3	0.33776	0.3378437	-8.375E-05
170	0.4	6548.3	600	1030.1	3	0.34138	0.3414142	-3.417E-05
171	0.4	6548.3	600	1055.1	3	0.34497	0.3449464	2.364E-05
172	0.4	6548.3	600	1080.1	3	0.34851	0.3484416	6.836E-05

173	0.4	6548.3	600	1105.1	3	0.35202	0.3519012	0.0001188
174	0.4	6548.3	600	1130.1	3	0.35549	0.3553263	0.0001637
175	0.4	6548.3	600	1155.1	3	0.35893	0.3587179	0.0002121
176	0.4	6548.3	600	1180.1	3	0.36232	0.3620771	0.0002429
177	0.4	6548.3	600	1205.1	3	0.36569	0.3654048	0.0002852
178	0.4	6548.3	600	1230.1	3	0.36901	0.3687022	0.0003078
179	0.4	6548.3	600	1255.1	3	0.3723	0.3719699	0.0003301
180	0.4	6548.3	600	1280.1	3	0.37556	0.3752089	0.0003511
181	0.4	6548.3	600	1305.1	3	0.37878	0.3784199	0.0003601
182	0.4	6548.3	600	1330.1	3	0.38198	0.3816038	0.0003762
183	0.4	6548.3	600	1355.1	3	0.38513	0.3847613	0.0003687
184	0.4	6548.3	600	1380.1	3	0.38826	0.387893	0.000367
185	0.4	6548.3	600	1405.1	3	0.39136	0.3909997	0.0003603
186	0.4	6548.3	600	1430.1	3	0.39442	0.3940819	0.0003381
187	0.4	6548.3	600	1455.1	3	0.39745	0.3971404	0.0003096
188	0.4	6548.3	600	1480.1	3	0.40045	0.4001756	0.0002744
189	0.4	6548.3	600	1505.1	3	0.40343	0.4031882	0.0002418
190	0.4	6548.3	600	1530.1	3	0.40637	0.4061787	0.0001913
191	0.4	6548.3	600	1555.1	3	0.40928	0.4091476	0.0001324
192	0.4	6548.3	600	1580.1	3	0.41217	0.4120954	7.461E-05
193	0.4	6548.3	600	1605.1	3	0.41503	0.4150226	7.423E-06
194	0.4	6548.3	600	1630.1	3	0.41786	0.4179296	-6.961E-05
195	0.4	6548.3	600	1655.1	3	0.42066	0.4208169	-0.0001569
196	0.4	6548.3	600	1680.1	3	0.42344	0.423685	-0.000245
197	0.4	6548.3	600	1705.1	3	0.42619	0.4265342	-0.0003442
198	0.4	6548.3	600	1730.1	3	0.42891	0.4293649	-0.0004549
199	0.4	6548.3	600	1755.1	3	0.43161	0.4321776	-0.0005676
200	0.4	6548.3	600	1780.1	3	0.43428	0.4349725	-0.0006925
201	0.4	6548.3	600	555	3	0.26486	0.2648542	5.751E-06
202	0.42	6548.3	600	555	3	0.26487	0.2648271	4.287E-05
203	0.44	6548.3	600	555	3	0.26487	0.2648193	5.072E-05
204	0.46	6548.3	600	555	3	0.26487	0.2648246	4.538E-05
205	0.48	6548.3	600	555	3	0.26487	0.2648382	3.185E-05
206	0.5	6548.3	600	555	3	0.26488	0.2648559	2.407E-05
207	0.52	6548.3	600	555	3	0.26488	0.2648749	5.108E-06

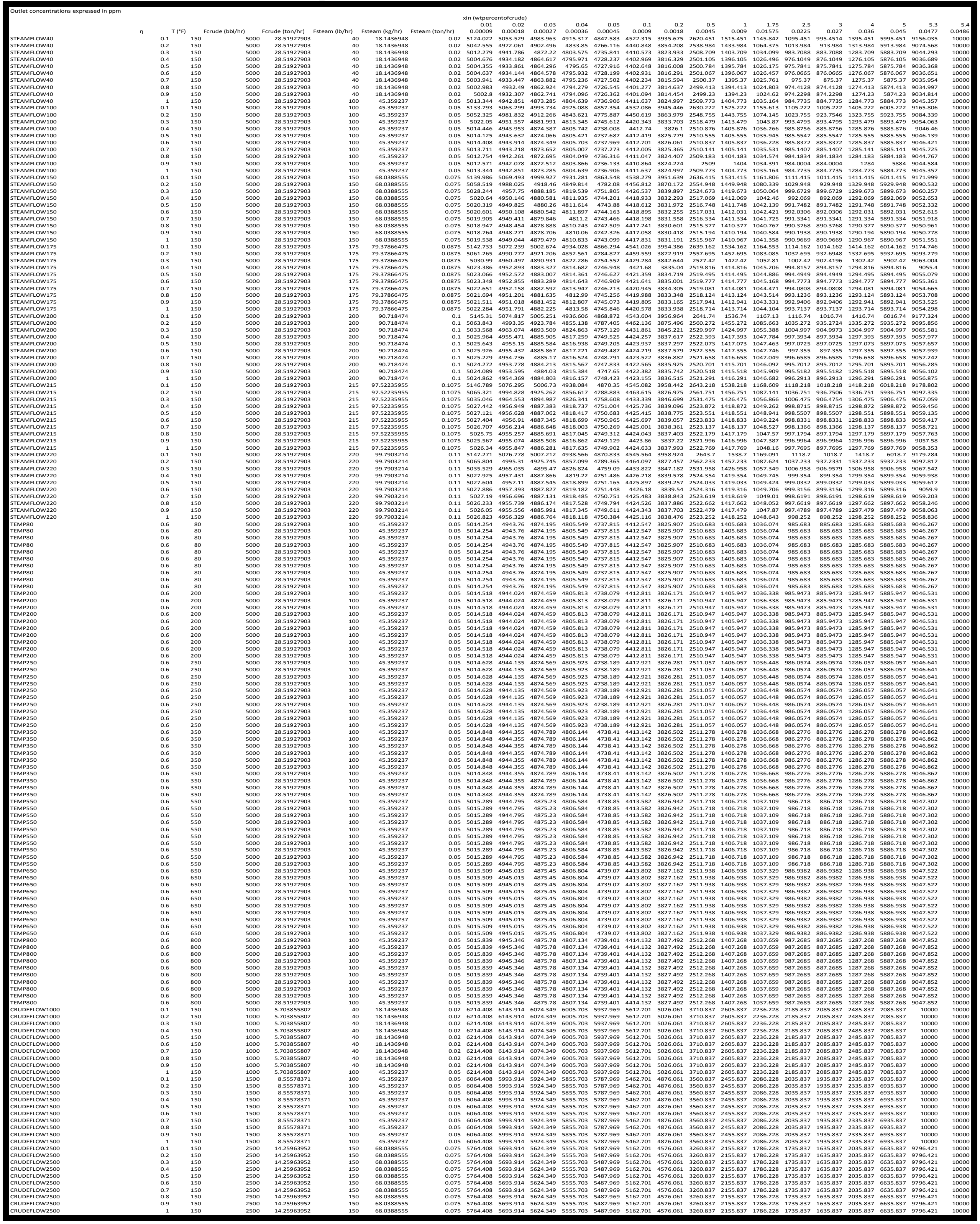
208	0.54	6548.3	600	555	3	0.26488	0.2648928	-1.277E-05
209	0.56	6548.3	600	555	3	0.26488	0.264908	-2.799E-05
210	0.58	6548.3	600	555	3	0.26488	0.2649196	-3.958E-05
211	0.6	6548.3	600	555	3	0.26489	0.2649271	-3.71E-05
212	0.62	6548.3	600	555	3	0.26489	0.2649305	-4.05E-05
213	0.64	6548.3	600	555	3	0.26489	0.2649301	-4.011E-05
214	0.66	6548.3	600	555	3	0.26489	0.2649265	-3.651E-05
215	0.68	6548.3	600	555	3	0.26489	0.2649205	-3.052E-05
216	0.7	6548.3	600	555	3	0.26489	0.2649131	-2.306E-05
217	0.72	6548.3	600	555	3	0.2649	0.2649052	-5.167E-06
218	0.74	6548.3	600	555	3	0.26491	0.2648979	1.211E-05
219	0.76	6548.3	600	555	3	0.26492	0.2648923	2.773E-05
220	0.78	6548.3	600	555	3	0.26493	0.2648893	4.071E-05
221	0.8	6548.3	600	555	3	0.26493	0.2648898	4.017E-05
222	0.82	6548.3	600	555	3	0.26494	0.2648946	4.535E-05
223	0.84	6548.3	600	555	3	0.26495	0.2649043	4.567E-05
224	0.86	6548.3	600	555	3	0.26495	0.2649193	3.068E-05
225	0.88	6548.3	600	555	3	0.26496	0.2649398	2.018E-05
226	0.9	6548.3	600	555	3	0.26496	0.2649659	-5.857E-06
227	0.92	6548.3	600	555	3	0.26497	0.2649972	-2.725E-05
228	0.94	6548.3	600	555	3	0.26501	0.2650336	-2.358E-05
229	0.96	6548.3	600	555	3	0.26506	0.2650742	-1.425E-05
230	0.98	6548.3	600	555	3	0.2651	0.2651184	-1.844E-05
231	1	6548.3	600	555	3	0.26513	0.2651651	-3.515E-05
232	1.02	6548.3	600	555	3	0.26516	0.2652132	-5.322E-05
233	1.04	6548.3	600	555	3	0.26519	0.2652614	-7.136E-05
234	1.06	6548.3	600	555	3	0.26522	0.2653082	-8.816E-05
235	1.08	6548.3	600	555	3	0.26529	0.2653521	-6.212E-05
236	1.1	6548.3	600	555	3	0.26538	0.2653917	-1.175E-05
237	1.12	6548.3	600	555	3	0.26546	0.2654255	3.448E-05
238	1.14	6548.3	600	555	3	0.26552	0.265452	6.799E-05
239	1.16	6548.3	600	555	3	0.26558	0.2654699	0.0001101
240	1.18	6548.3	600	555	3	0.26563	0.265478	0.000152
241	1.2	6548.3	600	555	3	0.26556	0.2654755	8.446E-05
242	1.22	6548.3	600	555	3	0.26546	0.2654619	-1.857E-06

243	1.24	6548.3	600	555	3	0.26539	0.2654368	-4.68E-05
244	1.26	6548.3	600	555	3	0.26534	0.2654007	-6.069E-05
245	1.28	6548.3	600	555	3	0.2653	0.2653544	-5.439E-05
246	1.3	6548.3	600	555	3	0.26525	0.2652995	-4.945E-05
247	1.32	6548.3	600	555	3	0.2652	0.2652382	-3.817E-05
248	1.34	6548.3	600	555	3	0.26516	0.2651737	-1.369E-05
249	1.36	6548.3	600	555	3	0.26513	0.2651101	1.985E-05
250	1.38	6548.3	600	555	3	0.2651	0.2650528	4.724E-05
251	0.7	6548.3	600	555	3	0.265	0.2649131	8.694E-05
252	0.7	6548.3	600	555	2.73	0.2651	0.2650876	1.241E-05
253	0.7	6548.3	600	555	2.54	0.2657	0.2657772	-7.72E-05
254	0.7	6548.3	600	555	2.45	0.2661	0.2660144	8.563E-05
255	0.7	6548.3	600	555	2.1	0.2658	0.2658702	-7.024E-05
256	0.7	6548.3	600	555	2	0.2657	0.2656414	5.861E-05
257	0.7	6548.3	600	555	1.82	0.2655	0.2655088	-8.754E-06

CWWT table example:

						Inlet NH3							
					Inlet NH3 (mass %)	0.005	0.05	0.1	0.15	0.2	0.25	0.3	0.345
Flowrates	Efficiencies	Reflux Ratio	Number of Trays	Inlet H2S	Inlet H2S (mass %)	50	500	1000	1500	2000	2500	3000	3450
10	30	1	5	100	0.01	49.11209	49.10954	49.1067	49.10386	49.10102	49.09818	49.09534	49.09279
10	30	1	5	500	0.05	50.03104	50.02848	50.02564	50.0228	50.01996	50.01713	50.01429	50.01173
10	30	1	5	1000	0.1	50.69793	50.69537	50.69253	50.68969	50.68685	50.68402	50.68118	50.67862
10	30	1	5	3000	0.3	52.31912	52.31656	52.31372	52.31088	52.30804	52.30521	52.30237	52.29981
10	30	1	5	5000	0.5	53.40993	53.40737	53.40453	53.40169	53.39885	53.39601	53.39318	53.39062
10	30	1	5	7000	0.7	54.28554	54.28298	54.28014	54.2773	54.27446	54.27162	54.26878	54.26623
10	30	1	5	9000	0.9	55.03606	55.03351	55.03067	55.02783	55.02499	55.02215	55.01931	55.01676
10	30	1	5	10900	1.09	55.67066	55.6681	55.66526	55.66242	55.65958	55.65675	55.65391	55.65135
10	30	1	10	100	0.01	3.344057	3.341502	3.338662	3.335823	3.332983	3.330144	3.327304	3.324749
10	30	1	10	500	0.05	4.263002	4.260447	4.257607	4.254768	4.251928	4.249089	4.246249	4.243694
10	30	1	10	1000	0.1	4.929892	4.927337	4.924497	4.921658	4.918818	4.915979	4.91314	4.910584
10	30	1	10	3000	0.3	6.551082	6.548527	6.545687	6.542848	6.540008	6.537169	6.53433	6.531774
10	30	1	10	5000	0.5	7.641891	7.639336	7.636496	7.633657	7.630818	7.627978	7.625139	7.622583
10	30	1	10	7000	0.7	8.517499	8.514944	8.512105	8.509265	8.506426	8.503586	8.500747	8.498191
10	30	1	10	9000	0.9	9.268028	9.265472	9.262633	9.259793	9.256954	9.254114	9.251275	9.248719
10	30	1	10	10900	1.09	9.902622	9.900067	9.897227	9.894388	9.891548	9.888709	9.885869	9.883314
10	30	1	15	100	0.01	1.941095	1.938539	1.9357	1.93286	1.930021	1.927181	1.924342	1.921787
10	30	1	15	500	0.05	2.86004	2.857484	2.854645	2.851805	2.848966	2.846127	2.843287	2.840732
10	30	1	15	1000	0.1	3.52693	3.524375	3.521535	3.518696	3.515856	3.513017	3.510177	3.507622
10	30	1	15	3000	0.3	5.14812	5.145564	5.142725	5.139886	5.137046	5.134207	5.131367	5.128812
10	30	1	15	5000	0.5	6.238929	6.236374	6.233534	6.230695	6.227855	6.225016	6.222176	6.219621
10	30	1	15	7000	0.7	7.114537	7.111982	7.109142	7.106303	7.103463	7.100624	7.097784	7.095229
10	30	1	15	9000	0.9	7.865065	7.86251	7.85967	7.856831	7.853991	7.851152	7.848312	7.845757
10	30	1	15	10900	1.09	8.49966	8.497104	8.494265	8.491425	8.488586	8.485747	8.482907	8.480352
10	30	1	20	100	0.01	1.898089	1.895533	1.892694	1.889854	1.887015	1.884175	1.881336	1.87878
10	30	1	20	500	0.05	2.817034	2.814478	2.811639	2.808799	2.80596	2.80312	2.800281	2.797725
10	30	1	20	1000	0.1	3.483924	3.481368	3.478529	3.47569	3.47285	3.470011	3.467171	3.464616
10	30	1	20	3000	0.3	5.105114	5.102558	5.099719	5.096879	5.09404	5.091201	5.088361	5.085806
10	30	1	20	5000	0.5	6.195923	6.193368	6.190528	6.187689	6.184849	6.18201	6.17917	6.176615
10	30	1	20	7000	0.7	7.071531	7.068976	7.066136	7.063297	7.060457	7.057618	7.054778	7.052223
10	30	1	20	9000	0.9	7.822059	7.819504	7.816664	7.813825	7.810985	7.808146	7.805306	7.802751
10	30	1	20	10900	1.09	8.456654	8.454098	8.451259	8.448419	8.44558	8.44274	8.439901	8.437345
10	30	1	25	100	0.01	1.89677	1.894215	1.891375	1.888536	1.885697	1.882857	1.880018	1.877462
10	30	1	25	500	0.05	2.815715	2.81316	2.810321	2.807481	2.804642	2.801802	2.798963	2.796407
10	30	1	25	1000	0.1	3.482606	3.48005	3.477211	3.474371	3.471532	3.468692	3.465853	3.463297
10	30	1	25	3000	0.3	5.103796	5.10124	5.098401	5.095561	5.092722	5.089882	5.087043	5.084487
10	30	1	25	5000	0.5	6.194605	6.192049	6.18921	6.18637	6.183531	6.180691	6.177852	6.175296
10	30	1	25	7000	0.7	7.070213	7.067657	7.064818	7.061978	7.059139	7.056299	7.05346	7.050904
10	30	1	25	9000	0.9	7.820741	7.818185	7.815346	7.812506	7.809667	7.806828	7.803988	7.801433
10	30	1	25	10900	1.09	8.455335	8.45278	8.449941	8.447101	8.444262	8.441422	8.438583	8.436027
10	30	3	5	100	0.01	49.23424	49.23168	49.22885	49.22601	49.22317	49.22033	49.21749	49.21493
10	30	3	5	500	0.05	50.15319	50.15063	50.14779	50.14495	50.14211	50.13927	50.13643	50.13388
10	30	3	5	1000	0.1	50.82008	50.81752	50.81468	50.81184	50.809	50.80616	50.80332	50.80077
10	30	3	5	3000	0.3	52.44127	52.43871	52.43587	52.43303	52.43019	52.42735	52.42451	52.42196
10	30	3	5	5000	0.5	53.53207	53.52952	53.52668	53.52384	53.521	53.51816	53.51532	53.51277
10	30	3	5	7000	0.7	54.40768	54.40513	54.40229	54.39945	54.39661	54.39377	54.39093	54.38837
10	30	3	5	9000	0.9	55.15821	55.15565	55.15282	55.14998	55.14714	55.1443	55.14146	55.1389
10	30	3	5	10900	1.09	55.79281	55.79025	55.78741	55.78457	55.78173	55.77889	55.77605	55.7735
10	30	3	10	100	0.01	3.466204	3.463648	3.460809	3.457969	3.45513	3.45229	3.449451	3.446895
10	30	3	10	500	0.05	4.385149	4.382593	4.379754	4.376914	4.374075	4.371235	4.368396	4.36584
10	30	3	10	1000	0.1	5.052039	5.049483	5.046644	5.043804	5.040965	5.038125	5.035286	5.03273
10	30	3	10	3000	0.3	6.673229	6.670673	6.667834	6.664994	6.662155	6.659315	6.656476	6.65392
10	30	3	10	5000	0.5	7.764038	7.761482	7.758643	7.755803	7.752964	7.750124	7.747285	7.74473
10	30	3	10	7000	0.7	8.639646	8.63709	8.634251	8.631411	8.628572	8.625733	8.622893	8.620338
10	30	3	10	9000	0.9	9.390174	9.387618	9.384779	9.38194	9.3791	9.376261	9.373421	9.370866
10	30	3	10	10900	1.09	10.02477	10.02221	10.01937	10.01653	10.01369	10.01086	10.00802	10.00546
10	30	3	15	100	0.01	2.063241	2.060686	2.057846	2.055007	2.052167	2.049328	2.046488	2.043933
10	30	3	15	500	0.05	2.982186	2.979631	2.976791	2.973952	2.971112	2.968273	2.965433	2.962878
10	30	3	15	1000	0.1	3.649076	3.646521	3.643681	3.640842	3.638003	3.635163	3.632324	3.629768
10	30	3	15	3000	0.3	5.270266	5.267711	5.264871	5.262032	5.259192	5.256353	5.253514	5.250958
10	30	3	15	5000	0.5	6.361075	6.35852	6.355681	6.352841	6.350002	6.347162	6.344323	6.341767
10	30	3	15	7000	0.7	7.236684	7.234128	7.231289	7.228449	7.22561	7.22277	7.219931	7.217375
10	30	3	15	9000	0.9	7.987212	7.984656	7.981817	7.978977	7.976138	7.973298	7.970459	7.967903
10	30	3	15	10900	1.09	8.621806	8.619251	8.616411	8.613572	8.610732	8.607893	8.605053	8.602498
10	30	3	20	100	0.01	2.020235	2.01768	2.01484	2.012001	2.009161	2.006322	2.003482	2.000927
10	30	3	20	500	0.05	2.93918	2.936625	2.933785	2.930946	2.928106	2.925267	2.922427	2.919872
10	30	3	20	1000	0.1	3.60607	3.603515	3.600675	3.597836	3.594996	3.592157	3.589318	3.586762
10	30	3	20	3000	0.3	5.22726	5.224705	5.221865	5.219026	5.216186	5.213347	5.210507	5.207952
10	30	3	20	5000	0.5	6.318069	6.315514	6.312674	6.309835	6.306996	6.304156	6.301317	6.298761
10	30	3	20	7000	0.7	7.193677	7.191122	7.188283	7.185443	7.182604	7.179764	7.176925	7.174369
10	30	3	20	9000	0.9	7.944206	7.94165	7.938811	7.935971	7.933132	7.930292	7.927453	7.924897
10	30	3	20	10900	1.09	8.5788	8.576245	8.573405	8.570566	8.567726	8.564887	8.562047	8.559492
10	30	3	25	100	0.01	2.018917	2.016361	2.013522	2.010682	2.007843	2.005003	2.002164	1.999609
10	30	3	25	500	0.05	2.937862	2.935306	2.932467	2.929627	2.926788	2.923949	2.921109	2.918554
10	30	3	25	1000	0.1	3.604752	3.602197	3.599357	3.596518	3.593678	3.590839	3.587999	3.585444
10	30	3	25	3000	0.3	5.225942	5.223386	5.220547	5.217708	5.214868	5.212029	5.209189	5.206634
10	30	3	25	5000	0.5	6.316751	6.314196	6.311356	6.308517	6.305677	6.302838	6.299998	6.297443
10	30	3	25	7000	0.7	7.192359	7.189804	7.186964	7.184125	7.181285	7.178446	7.175606	7.173051
10	30	3	25	9000	0.9	7.942887	7.940332	7.937492	7.934653	7.931813	7.928974	7.926134	7.923579
10	30	3	25	10900	1.09	8.577482	8.574926	8.572087	8.569247	8.566408	8.563569	8.560729	8.558174
10	30	5	5	100	0.01	49.35639	49.35383	49.35099	49.34815	49.34531	49.34247	49.33963	49.33708
10	30	5	5	500	0.05	50.27533	50.27278	50.26994	50.2671	50.26426	50.26142	50.25858	50.25602
10	30	5	5	1000	0.1	50.94222	50.93967	50.93683	50.93399	50.93115	50.92831	50.92547	50.92291
10	30	5	5	3000	0.3	52.56341	52.56086	52.55802	52.55518	52.55234	52.5495	52.54666	52.5441
10	30	5	5	5000	0.5	53.65422	53.65167	53.64883	53.64599	53.64315	53.64031	53.63747	53.63491
10	30	5	5	7000	0.7	54.52983	54.52727	54.52443	54.52159	54.51875	54.51592	54.51308	54.51052
10	30	5	5	9000	0.9	55.28036	55.2778	55.27496	55.27212	55.26928	55.26644	55.2636	55.26105
10	30	5	5	10900	1.09	55.91495	55.9124	55.90956	55.90672	55.90388	55.90104	55.8982	55.89564
10	30	5	10	100	0.01	3.58835	3.585794	3.582955	3.580115	3.577276	3.574437	3.571597	3.569042
10	30	5	10	500	0.05	4.507295	4.504739	4.5019	4.499061	4.496221	4.493382	4.490542	4.487987
10	30	5	10	1000	0.1	5.174185	5.17163	5.16879	5.165951	5.163111	5.160272	5.157432	5.154877
10	30	5	10	3000	0.3	6.795375	6.79282	6.78998	6.787141	6.784301	6.781462	6.778622	6.776067
10	30	5	10	5000	0.5	7.886184	7.883629	7.880789	7.87795	7.87511	7.872271	7.869431	7.866876
10	30	5	10	7000	0.7	8.761792	8.759237	8.756397	8.753558	8.750718	8.747879	8.745039	8.742484
10	30	5	10	9000	0.9	9.51232	9.509765	9.506925	9.504086	9.501246	9.498407	9.495568	9.493012
10	30	5	10	10900	1.09	10.14691	10.14436	10.14152	10.13868	10.13584	10.133	10.13016	10.12761
10	30	5	15	100	0.01	2.185388	2.182832	2.179993	2.177153	2.174314	2.171474	2.168635	2.166079
10	30	5	15	500	0.05	3.104333	3.101777	3.098938	3.096098	3.093259	3.090419	3.08758	3.085024
10	30	5	15	1000	0.1	3.771223	3.768667	3.765828	3.762988	3.760149	3.757309	3.75447	3.751914
10	30	5	15	3000	0.3	5.392413	5.389857	5.387018	5.384178	5.381339	5.378499	5.37566	5.373104
10	30	5	15	5000	0.5	6.483222	6.480666	6.477827	6.474987	6.472148	6.469309	6.466469	6.463914
10	30	5	15	7000	0.7	7.35883	7.356274	7.353435	7.350595	7.347756	7.344917	7.342077	7.339522
10	30	5	15	9000	0.9	8.109358	8.106803	8.103963	8.101124	8.098284	8.095445	8.092605	8.09005
10	30	5	15	10900	1.09	8.743953	8.741397	8.738558	8.735718	8.732879	8.730039	8.7272	8.724644
10	30	5	20	100	0.01	2.142382	2.139826	2.136987	2.134147	2.131308	2.128468	2.125629	2.123073
10	30	5	20	500	0.05	3.061327	3.058771	3.055932	3.053092	3.050253	3.047413	3.044574	3.042018
10	30	5	20	1000	0.1	3.728217	3.725661	3.722822	3.719982	3.717143	3.714303	3.711464	3.708908
10	30	5	20	3000	0.3	5.349407	5.346851	5.344012	5.341172	5.338333	5.335493	5.332654	5.330098
10	30	5	20	5000	0.5	6.440216	6.43766	6.434821	6.431981	6.429142	6.426302	6.423463	6.420907
10	30	5	20	7000	0.7	7.315824	7.313268	7.310429	7.307589	7.30475	7.301911	7.299071	7.296516
10	30	5	20	9000	0.9	8.066352	8.063796	8.060957	8.058118	8.055278	8.052439	8.049599	8.047044
10	30	5	20	10900	1.09	8.700947	8.698391	8.695552	8.692712	8.689873	8.687033	8.684194	8.681638
10	30	5	25	100	0.01	2.141063	2.138508	2.135668	2.132829	2.129989	2.12715	2.12431	2.121755
10	30	5	25	500	0.05	3.060008	3.057453	3.054613	3.051774	3.048934	3.046095	3.043255	3.0407
10	30	5	25	1000	0.1	3.726898	3.724343	3.721503	3.718664	3.715825	3.712985	3.710146	3.70759
10	30	5	25	3000	0.3	5.348088	5.345533	5.342693	5.339854	5.337014	5.334175	5.331336	5.32878
10	30	5	25	5000	0.5	6.438897	6.436342	6.433503	6.430663	6.427824	6.424984	6.422145	6.419589
10	30	5	25	7000	0.7	7.314506	7.31195	7.309111	7.306271	7.303432	7.300592	7.297753	7.295197
10	30	5	25	9000	0.9	8.065034	8.062478	8.059639	8.056799	8.05396	8.05112	8.048281	8.045725
10	30	5	25	10900	1.09	8.699628	8.697073	8.694233	8.691394	8.688554	8.685715	8.682875	8.68032
10	30	7	5	100	0.01	49.47853	49.47598	49.47314	49.4703	49.46746	49.46462	49.46178	49.45922
10	30	7	5	500	0.05	50.39748	50.39492	50.39208	50.38924	50.3864	50.38356	50.38073	50.37817
10	30	7	5	1000	0.1	51.06437	51.06181	51.05897	51.05613	51.05329	51.05045	51.04762	51.04506
10	30	7	5	3000	0.3	52.68556	52.683	52.68016	52.67732	52.67448	52.67164	52.66881	52.66625
10	30	7	5	5000	0.5	53.77637	53.77381	53.77097	53.76813	53.76529	53.76245	53.75961	53.75706
10	30	7	5	7000	0.7	54.65198	54.64942	54.64658	54.64374	54.6409	54.63806	54.63522	54.63267
10	30	7	5	9000	0.9	55.4025	55.39995	55.39711	55.39427	55.39143	55.38859	55.38575	55.38319
10	30	7	5	10900	1.09	56.0371	56.03454	56.0317	56.02886	56.02602	56.02318	56.02035	56.01779
10	30	7	10	100	0.01	3.710496	3.707941	3.705101	3.702262	3.699422	3.696583	3.693744	3.691188
10	30	7	10	500	0.05	4.629441	4.626886	4.624046	4.621207	4.618367	4.615528	4.612689	4.610133
10	30	7	10	1000	0.1	5.296331	5.293776	5.290937	5.288097	5.285258	5.282418	5.279579	5.277023
10	30	7	10	3000	0.3	6.917521	6.914966	6.912126	6.909287	6.906448	6.903608	6.900769	6.898213
10	30	7	10	5000	0.5	8.008331	8.005775	8.002936	8.000096	7.997257	7.994417	7.991578	7.989022
10	30	7	10	7000	0.7	8.883939	8.881383	8.878544	8.875704	8.872865	8.870025	8.867186	8.86463
10	30	7	10	9000	0.9	9.634467	9.631911	9.629072	9.626232	9.623393	9.620553	9.617714	9.615158
10	30	7	10	10900	1.09	10.26906	10.26651	10.26367	10.26083	10.25799	10.25515	10.25231	10.24975
10	30	7	15	100	0.01	2.307534	2.304978	2.302139	2.2993	2.29646	2.293621	2.290781	2.288226
10	30	7	15	500	0.05	3.226479	3.223923	3.221084	3.218245	3.215405	3.212566	3.209726	3.207171
10	30	7	15	1000	0.1	3.893369	3.890814	3.887974	3.885135	3.882295	3.879456	3.876616	3.874061
10	30	7	15	3000	0.3	5.514559	5.512004	5.509164	5.506325	5.503485	5.500646	5.497806	5.495251
10	30	7	15	5000	0.5	6.605368	6.602813	6.599973	6.597134	6.594294	6.591455	6.588615	6.58606
10	30	7	15	7000	0.7	7.480976	7.478421	7.475581	7.472742	7.469902	7.467063	7.464224	7.461668
10	30	7	15	9000	0.9	8.231504	8.228949	8.226109	8.22327	8.220431	8.217591	8.214752	8.212196
10	30	7	15	10900	1.09	8.866099	8.863543	8.860704	8.857865	8.855025	8.852186	8.849346	8.846791

Crude oil distillation table example:



Outlet concentrations expressed in ppm

								xin (wtpercentofcrude)															
								0.01	0.02	0.03	0.04	0.05	0.1	0.2	0.5	1	1.75	2.5	3	4	5	5.3	5.4
	η	T (°F)	Fcrude (bbl/hr)	Fcrude (ton/hr)	Fsteam (lb/hr)	Fsteam (kg/hr)	Fsteam (ton/hr)	0.00009	0.00018	0.00027	0.00036	0.00045	0.0009	0.0018	0.0045	0.009	0.01575	0.0225	0.027	0.036	0.045	0.0477	0.0486
STEAMFLOW40	0.1	150	5000	28.51927903	40	18.1436948	0.02	5124.022	5053.529	4983.963	4915.317	4847.583	4522.315	3935.675	2620.451	1515.451	1145.842	1095.451	995.4514	1395.451	5995.451	9156.035	10000
STEAMFLOW40	0.2	150	5000	28.51927903	40	18.1436948	0.02	5042.555	4972.061	4902.496	4833.85	4766.116	4440.848	3854.208	2538.984	1433.984	1064.375	1013.984	913.984	1313.984	5913.984	9074.568	10000
STEAMFLOW40	0.3	150	5000	28.51927903	40	18.1436948	0.02	5012.279	4941.786	4872.22	4803.575	4735.841	4410.573	3823.933	2508.709	1403.709	1034.099	983.7088	883.7088	1283.709	5883.709	9044.293	10000
STEAMFLOW40	0.4	150	5000	28.51927903	40	18.1436948	0.02	5004.676	4934.182	4864.617	4795.971	4728.237	4402.969	3816.329	2501.105	1396.105	1026.496	976.1049	876.1049	1276.105	5876.105	9036.689	10000
STEAMFLOW40	0.5	150	5000	28.51927903	40	18.1436948	0.02	5004.355	4933.861	4864.296	4795.65	4727.916	4402.648	3816.008	2500.784	1395.784	1026.175	975.7841	875.7841	1275.784	5875.784	9036.368	10000
STEAMFLOW40	0.6	150	5000	28.51927903	40	18.1436948	0.02	5004.637	4934.144	4864.578	4795.932	4728.199	4402.931	3816.291	2501.067	1396.067	1026.457	976.0665	876.0665	1276.067	5876.067	9036.651	10000
STEAMFLOW40	0.7	150	5000	28.51927903	40	18.1436948	0.02	5003.941	4933.447	4863.882	4795.236	4727.502	4402.234	3815.594	2500.37	1395.37	1025.761	975.37	875.37	1275.37	5875.37	9035.954	10000
STEAMFLOW40	0.8	150	5000	28.51927903	40	18.1436948	0.02	5002.983	4932.49	4862.924	4794.279	4726.545	4401.277	3814.637	2499.413	1394.413	1024.803	974.4128	874.4128	1274.413	5874.413	9034.997	10000
STEAMFLOW40	0.9	150	5000	28.51927903	40	18.1436948	0.02	5002.8	4932.307	4862.741	4794.096	4726.362	4401.094	3814.454	2499.23	1394.23	1024.62	974.2298	874.2298	1274.23	5874.23	9034.814	10000
STEAMFLOW40	1	150	5000	28.51927903	100	45.359237	0.05	5013.344	4942.851	4873.285	4804.639	4736.906	4411.637	3824.997	2509.773	1404.773	1035.164	984.7735	884.7735	1284.773	5884.773	9045.357	10000
STEAMFLOW100	0.1	150	5000	28.51927903	100	45.359237	0.05	5133.793	5063.299	4993.734	4925.088	4857.354	4532.086	3945.446	2630.222	1525.222	1155.613	1105.222	1005.222	1405.222	6005.222	9165.806	10000
STEAMFLOW100	0.2	150	5000	28.51927903	100	45.359237	0.05	5052.325	4981.832	4912.266	4843.621	4775.887	4450.619	3863.979	2548.755	1443.755	1074.145	1023.755	923.7546	1323.755	5923.755	9084.339	10000
STEAMFLOW100	0.3	150	5000	28.51927903	100	45.359237	0.05	5022.05	4951.557	4881.991	4813.345	4745.612	4420.343	3833.703	2518.479	1413.479	1043.87	993.4795	893.4795	1293.479	5893.479	9054.063	10000
STEAMFLOW100	0.4	150	5000	28.51927903	100	45.359237	0.05	5014.446	4943.953	4874.387	4805.742	4738.008	4412.74	3826.1	2510.876	1405.876	1036.266	985.8756	885.8756	1285.876	5885.876	9046.46	10000
STEAMFLOW100	0.5	150	5000	28.51927903	100	45.359237	0.05	5014.125	4943.632	4874.066	4805.421	4737.687	4412.419	3825.779	2510.555	1405.555	1035.945	985.5547	885.5547	1285.555	5885.555	9046.139	10000
STEAMFLOW100	0.6	150	5000	28.51927903	100	45.359237	0.05	5014.408	4943.914	4874.349	4805.703	4737.969	4412.701	3826.061	2510.837	1405.837	1036.228	985.8372	885.8372	1285.837	5885.837	9046.421	10000
STEAMFLOW100	0.7	150	5000	28.51927903	100	45.359237	0.05	5013.711	4943.218	4873.652	4805.007	4737.273	4412.005	3825.365	2510.141	1405.141	1035.531	985.1407	885.1407	1285.141	5885.141	9045.725	10000
STEAMFLOW100	0.8	150	5000	28.51927903	100	45.359237	0.05	5012.754	4942.261	4872.695	4804.049	4736.316	4411.047	3824.407	2509.183	1404.183	1034.574	984.1834	884.1834	1284.183	5884.183	9044.767	10000
STEAMFLOW100	0.9	150	5000	28.51927903	100	45.359237	0.05	5012.571	4942.078	4872.512	4803.866	4736.133	4410.864	3824.224	2509	1404	1034.391	984.0004	884.0004	1284	5884	9044.584	10000
STEAMFLOW100	1	150	5000	28.51927903	100	45.359237	0.05	5013.344	4942.851	4873.285	4804.639	4736.906	4411.637	3824.997	2509.773	1404.773	1035.164	984.7735	884.7735	1284.773	5884.773	9045.357	10000
STEAMFLOW150	0.1	150	5000	28.51927903	150	68.0388555	0.075	5139.986	5069.493	4999.927	4931.281	4863.548	4538.279	3951.639	2636.415	1531.415	1161.806	1111.415	1011.415	1411.415	6011.415	9171.999	10000
STEAMFLOW150	0.2	150	5000	28.51927903	150	68.0388555	0.075	5058.519	4988.025	4918.46	4849.814	4782.08	4456.812	3870.172	2554.948	1449.948	1080.339	1029.948	929.948	1329.948	5929.948	9090.532	10000
STEAMFLOW150	0.3	150	5000	28.51927903	150	68.0388555	0.075	5028.244	4957.75	4888.185	4819.539	4751.805	4426.537	3839.897	2524.673	1419.673	1050.064	999.6729	899.6729	1299.673	5899.673	9060.257	10000
STEAMFLOW150	0.4	150	5000	28.51927903	150	68.0388555	0.075	5020.64	4950.146	4880.581	4811.935	4744.201	4418.933	3832.293	2517.069	1412.069	1042.46	992.069	892.069	1292.069	5892.069	9052.653	10000
STEAMFLOW150	0.5	150	5000	28.51927903	150	68.0388555	0.075	5020.319	4949.825	4880.26	4811.614	4743.88	4418.612	3831.972	2516.748	1411.748	1042.139	991.7482	891.7482	1291.748	5891.748	9052.332	10000
STEAMFLOW150	0.6	150	5000	28.51927903	150	68.0388555	0.075	5020.601	4950.108	4880.542	4811.897	4744.163	4418.895	3832.255	2517.031	1412.031	1042.421	992.0306	892.0306	1292.031	5892.031	9052.615	10000
STEAMFLOW150	0.7	150	5000	28.51927903	150	68.0388555	0.075	5019.905	4949.411	4879.846	4811.2	4743.466	4418.198	3831.558	2516.334	1411.334	1041.725	991.3341	891.3341	1291.334	5891.334	9051.918	10000
STEAMFLOW150	0.8	150	5000	28.51927903	150	68.0388555	0.075	5018.947	4948.454	4878.888	4810.243	4742.509	4417.241	3830.601	2515.377	1410.377	1040.767	990.3768	890.3768	1290.377	5890.377	9050.961	10000
STEAMFLOW150	0.9	150	5000	28.51927903	150	68.0388555	0.075	5018.764	4948.271	4878.706	4810.06	4742.326	4417.058	3830.418	2515.194	1410.194	1040.584	990.1938	890.1938	1290.194	5890.194	9050.778	10000
STEAMFLOW150	1	150	5000	28.51927903	150	68.0388555	0.075	5019.538	4949.044	4879.479	4810.833	4743.099	4417.831	3831.191	2515.967	1410.967	1041.358	990.9669	890.9669	1290.967	5890.967	9051.551	10000
STEAMFLOW175	0.1	150	5000	28.51927903	175	79.37866475	0.0875	5142.733	5072.239	5002.674	4934.028	4866.294	4541.026	3954.386	2639.162	1534.162	1164.553	1114.162	1014.162	1414.162	6014.162	9174.746	10000
STEAMFLOW175	0.2	150	5000	28.51927903	175	79.37866475	0.0875	5061.265	4990.772	4921.206	4852.561	4784.827	4459.559	3872.919	2557.695	1452.695	1083.085	1032.695	932.6948	1332.695	5932.695	9093.279	10000
STEAMFLOW175	0.3	150	5000	28.51927903	175	79.37866475	0.0875	5030.99	4960.497	4890.931	4822.286	4754.552	4429.284	3842.644	2527.42	1422.42	1052.81	1002.42	902.4196	1302.42	5902.42	9063.004	10000
STEAMFLOW175	0.4	150	5000	28.51927903	175	79.37866475	0.0875	5023.386	4952.893	4883.327	4814.682	4746.948	4421.68	3835.04	2519.816	1414.816	1045.206	994.8157	894.8157	1294.816	5894.816	9055.4	10000
STEAMFLOW175	0.5	150	5000	28.51927903	175	79.37866475	0.0875	5023.066	4952.572	4883.007	4814.361	4746.627	4421.359	3834.719	2519.495	1414.495	1044.886	994.4949	894.4949	1294.495	5894.495	9055.079	10000
STEAMFLOW175	0.6	150	5000	28.51927903	175	79.37866475	0.0875	5023.348	4952.855	4883.289	4814.643	4746.909	4421.641	3835.001	2519.777	1414.777	1045.168	994.7773	894.7773	1294.777	5894.777	9055.361	10000
STEAMFLOW175	0.7	150	5000	28.51927903	175	79.37866475	0.0875	5022.651	4952.158	4882.592	4813.947	4746.213	4420.945	3834.305	2519.081	1414.081	1044.471	994.0808	894.0808	1294.081	5894.081	9054.665	10000
STEAMFLOW175	0.8	150	5000	28.51927903	175	79.37866475	0.0875	5021.694	4951.201	4881.635	4812.99	4745.256	4419.988	3833.348	2518.124	1413.124	1043.514	993.1236	893.1236	1293.124	5893.124	9053.708	10000
STEAMFLOW175	0.9	150	5000	28.51927903	175	79.37866475	0.0875	5021.511	4951.018	4881.452	4812.807	4745.073	4419.805	3833.165	2517.941	1412.941	1043.331	992.9406	892.9406	1292.941	5892.941	9053.525	10000
STEAMFLOW175	1	150	5000	28.51927903	175	79.37866475	0.0875	5022.284	4951.791	4882.225	4813.58	4745.846	4420.578	3833.938	2518.714	1413.714	1044.104	993.7137	893.7137	1293.714	5893.714	9054.298	10000
STEAMFLOW200	0.1	150	5000	28.51927903	200	90.718474	0.1	5145.31	5074.817	5005.251	4936.606	4868.872	4543.604	3956.964	2641.74	1536.74	1167.13	1116.74	1016.74	1416.74	6016.74	9177.324	10000
STEAMFLOW200	0.2	150	5000	28.51927903	200	90.718474	0.1	5063.843	4993.35	4923.784	4855.138	4787.405	4462.136	3875.496	2560.272	1455.272	1085.663	1035.272	935.2724	1335.272	5935.272	9095.856	10000
STEAMFLOW200	0.3	150	5000	28.51927903	200	90.718474	0.1	5033.568	4963.074	4893.509	4824.863	4757.129	4431.861	3845.221	2529.997	1424.997	1055.388	1004.997	904.9973	1304.997	5904.997	9065.581	10000
STEAMFLOW200	0.4	150	5000	28.51927903	200	90.718474	0.1	5025.964	4955.471	4885.905	4817.259	4749.525	4424.257	3837.617	2522.393	1417.393	1047.784	997.3934	897.3934	1297.393	5897.393	9057.977	10000
STEAMFLOW200	0.5	150	5000	28.51927903	200	90.718474	0.1	5025.643	4955.15	4885.584	4816.938	4749.205	4423.937	3837.297	2522.073	1417.073	1047.463	997.0725	897.0725	1297.073	5897.073	9057.657	10000
STEAMFLOW200	0.6	150	5000	28.51927903	200	90.718474	0.1	5025.926	4955.432	4885.867	4817.221	4749.487	4424.219	3837.579	2522.355	1417.355	1047.746	997.355	897.355	1297.355	5897.355	9057.939	10000
STEAMFLOW200	0.7	150	5000	28.51927903	200	90.718474	0.1	5025.229	4954.736	4885.17	4816.524	4748.791	4423.522	3836.882	2521.658	1416.658	1047.049	996.6585	896.6585	1296.658	5896.658	9057.242	10000
STEAMFLOW200	0.8	150	5000	28.51927903	200	90.718474	0.1	5024.272	4953.778	4884.213	4815.567	4747.833	4422.565	3835.925	2520.701	1415.701	1046.092	995.7012	895.7012	1295.701	5895.701	9056.285	10000
STEAMFLOW200	0.9	150	5000	28.51927903	200	90.718474	0.1	5024.089	4953.595	4884.03	4815.384	4747.65	4422.382	3835.742	2520.518	1415.518	1045.909	995.5182	895.5182	1295.518	5895.518	9056.102	10000
STEAMFLOW200	1	150	5000	28.51927903	200	90.718474	0.1	5024.862	4954.369	4884.803	4816.157	4748.423	4423.155	3836.515	2521.291	1416.291	1046.682	996.2913	896.2913	1296.291	5896.291	9056.875	10000
STEAMFLOW215	0.1	150	5000	28.51927903	215	97.52235955	0.1075	5146.789	5076.295	5006.73	4938.084	4870.35	4545.082	3958.442	2643.218	1538.218	1168.609	1118.218	1018.218	1418.218	6018.218	9178.802	10000
STEAMFLOW215	0.2	150	5000	28.51927903	215	97.52235955	0.1075	5065.321	4994.828	4925.262	4856.617	4788.883	4463.615	3876.975	2561.751	1456.751	1087.141	1036.751	936.7506	1336.751	5936.751	9097.335	10000
STEAMFLOW215	0.3	150	5000	28.51927903	215	97.52235955	0.1075	5035.046	4964.553	4894.987	4826.341	4758.608	4433.339	3846.699	2531.475	1426.475	1056.866	1006.475	906.4754	1306.475	5906.475	9067.059	10000
STEAMFLOW215	0.4	150	5000	28.51927903	215	97.52235955	0.1075	5027.442	4956.949	4887.383	4818.737	4751.004	4425.736	3839.096	2523.872	1418.872	1049.262	998.8715	898.8715	1298.872	5898.872	9059.456	10000
STEAMFLOW215	0.5	150	5000	28.51927903	215	97.52235955	0.1075	5027.121	4956.628	4887.062	4818.417	4750.683	4425.415	3838.775	2523.551	1418.551	1048.941	998.5507	898.5507	1298.551	5898.551	9059.135	10000
STEAMFLOW215	0.6	150	5000	28.51927903	215	97.52235955	0.1075	5027.404	4956.91	4887.345	4818.699	4750.965	4425.697	3839.057	2523.833	1418.833	1049.224	998.8331	898.8331	1298.833	5898.833	9059.417	10000
STEAMFLOW215	0.7	150	5000	28.51927903	215	97.52235955	0.1075	5026.707	4956.214	4886.648	4818.003	4750.269	4425.001	3838.361	2523.137	1418.137	1048.527	998.1366	898.1366	1298.137	5898.137	9058.721	10000
STEAMFLOW215	0.8	150	5000	28.51927903	215	97.52235955	0.1075	5025.75	4955.257	4885.691	4817.045	4749.312	4424.043	3837.403	2522.179	1417.179	1047.57	997.1794	897.1794	1297.179	5897.179	9057.763	10000
STEAMFLOW215	0.9	150	5000	28.51927903	215	97.52235955	0.1075	5025.567	4955.074	4885.508	4816.862	4749.129	4423.86	3837.22	2521.996	1416.996	1047.387	996.9964	896.9964	1296.996	5896.996	9057.58	10000
STEAMFLOW215	1	150	5000	28.51927903	215	97.52235955	0.1075	5026.34	4955.847	4886.281	4817.635	4749.902	4424.633	3837.993	2522.769	1417.769	1048.16	997.7695	897.7695	1297.769	5897.769	9058.353	10000
STEAMFLOW220	0.1	150	5000	28.51927903	220	99.7903214	0.11	5147.271	5076.778	5007.212	4938.566	4870.833	4545.564	3958.924	2643.7	1538.7	1169.091	1118.7	1018.7	1418.7	6018.7	9179.284	10000
STEAMFLOW220	0.2	150	5000	28.51927903	220	99.7903214	0.11	5065.804	4995.31	4925.745	4857.099	4789.365	4464.097	3877.457	2562.233	1457.233	1087.624	1037.233	937.2331	1337.233	5937.233	9097.817	10000
STEAMFLOW220	0.3	150	5000	28.51927903	220	99.7903214	0.11	5035.529	4965.035	4895.47	4826.824	4759.09	4433.822	3847.182	2531.958	1426.958	1057.349	1006.958	906.9579	1306.958	5906.958	9067.542	10000
STEAMFLOW220	0.4	150	5000	28.51927903	220	99.7903214	0.11	5027.925	4957.431	4887.866	4819.22	4751.486	4426.218	3839.578	2524.354	1419.354	1049.745	999.354	899.354	1299.354	5899.354	9059.938	10000
STEAMFLOW220	0.5	150	5000	28.51927903	220	99.7903214	0.11	5027.604	4957.11	4887.545	4818.899	4751.165	4425.897	3839.257	2524.033	1419.033	1049.424	999.0332	899.0332	1299.033	5899.033	9059.617	10000
STEAMFLOW220	0.6	150	5000	28.51927903	220	99.7903214	0.11	5027.886	4957.393	4887.827	4819.182	4751.448	4426.18	3839.54	2524.316	1419.316	1049.706	999.3156	899.3156	1299.316	5899.316	9059.9	10000
STEAMFLOW220	0.7	150	5000	28.51927903	220	99.7903214	0.11	5027.19	4956.696	4887.131	4818.485	4750.751	4425.483	3838.843	2523.619	1418.619	1049.01	998.6191	898.6191	1298.619	5898.619	9059.203	10000
STEAMFLOW220	0.8	150	5000	28.51927903	220	99.7903214	0.11	5026.233	4955.739	4886.174	4817.528	4749.794	4424.526	3837.886	2522.662	1417.662	1048.052	997.6619	897.6619	1297.662	5897.662	9058.246	10000
STEAMFLOW220	0.9	150	5000	28.51927903	220	99.7903214	0.11	5026.05	4955.556	4885.991	4817.345	4749.611	4424.343	3837.703	2522.479	1417.479	1047.87	997.4789	897.4789	1297.479	5897.479	9058.063	10000
STEAMFLOW220	1	150	5000	28.51927903	220	99.7903214	0.11	5026.823	4956.329	4886.764	4818.118	4750.384	4425.116	3838.476	2523.252	1418.252	1048.643	998.252	898.252	1298.252	5898.252	9058.836	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP80	0.6	80	5000	28.51927903	100	45.359237	0.05	5014.254	4943.76	4874.195	4805.549	4737.815	4412.547	3825.907	2510.683	1405.683	1036.074	985.683	885.683	1285.683	5885.683	9046.267	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP200	0.6	200	5000	28.51927903	100	45.359237	0.05	5014.518	4944.024	4874.459	4805.813	4738.079	4412.811	3826.171	2510.947	1405.947	1036.338	985.9473	885.9473	1285.947	5885.947	9046.531	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP250	0.6	250	5000	28.51927903	100	45.359237	0.05	5014.628	4944.135	4874.569	4805.923	4738.189	4412.921	3826.281	2511.057	1406.057	1036.448	986.0574	886.0574	1286.057	5886.057	9046.641	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP350	0.6	350	5000	28.51927903	100	45.359237	0.05	5014.848	4944.355	4874.789	4806.144	4738.41	4413.142	3826.502	2511.278	1406.278	1036.668	986.2776	886.2776	1286.278	5886.278	9046.862	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP550	0.6	550	5000	28.51927903	100	45.359237	0.05	5015.289	4944.795	4875.23	4806.584	4738.85	4413.582	3826.942	2511.718	1406.718	1037.109	986.718	886.718	1286.718	5886.718	9047.302	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP650	0.6	650	5000	28.51927903	100	45.359237	0.05	5015.509	4945.015	4875.45	4806.804	4739.07	4413.802	3827.162	2511.938	1406.938	1037.329	986.9382	886.9382	1286.938	5886.938	9047.522	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
TEMP800	0.6	800	5000	28.51927903	100	45.359237	0.05	5015.839	4945.346	4875.78	4807.134	4739.401	4414.132	3827.492	2512.268	1407.268	1037.659	987.2685	887.2685	1287.268	5887.268	9047.852	10000
CRUDEFLOW1000	0.1	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.2	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.3	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.4	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.5	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.6	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.7	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.8	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	0.9	150	1000	5.703855807	40	18.1436948	0.02	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1000	1	150	1000	5.703855807	100	45.359237	0.05	6214.408	6143.914	6074.349	6005.703	5937.969	5612.701	5026.061	3710.837	2605.837	2236.228	2185.837	2085.837	2485.837	7085.837	10000	10000
CRUDEFLOW1500	0.1	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.2	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.3	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.4	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.5	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.6	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.7	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.8	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	0.9	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW1500	1	150	1500	8.55578371	100	45.359237	0.05	6064.408	5993.914	5924.349	5855.703	5787.969	5462.701	4876.061	3560.837	2455.837	2086.228	2035.837	1935.837	2335.837	6935.837	10000	10000
CRUDEFLOW2500	0.1	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.2	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.3	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.4	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.5	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.6	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.7	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.8	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	0.9	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000
CRUDEFLOW2500	1	150	2500	14.25963952	150	68.0388555	0.075	5764.408	5693.914	5624.349	5555.703	5487.969	5162.701	4576.061	3260.837	2155.837	1786.228	1735.837	1635.837	2035.837	6635.837	9796.421	10000

Appendix II

Derivation of API separator equipment cost

$$Cost = f(Volume)$$

$$Cost = Weight(tons)\cdot Cost\ of\ steel\left(\frac{\$}{ton}\right) = Mass(kg)\cdot\frac{0.001\,ton}{1\,kg}\cdot Cost\ of\ steel\left(\frac{\$}{ton}\right)$$

$$Cost = Density\left(\frac{kg}{m^3}\right)\cdot V(m^3)\cdot\frac{0.001\,ton}{1\,kg}\cdot Cost\ of\ steel\left(\frac{\$}{ton}\right)$$

$$Cost = 7850\frac{kg}{m^3}\cdot V(m^3)\cdot\frac{0.001\,ton}{1\,kg}\cdot\frac{\$833}{ton}$$

$$Cost = 6539.05\cdot V$$

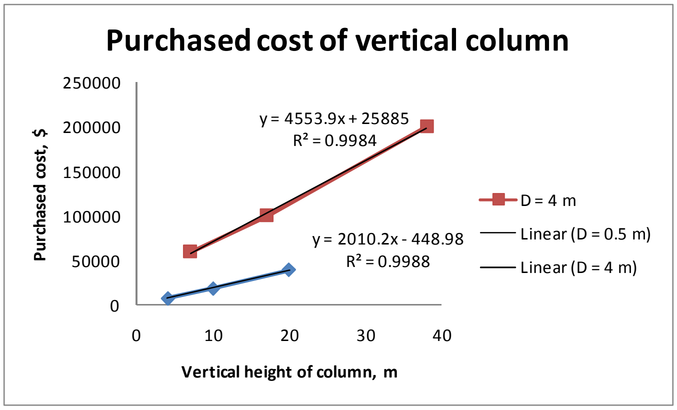
Derivation of Chevron Wastewater Treatment plant cost:

$$D = \left(\frac{4A_c}{\pi}\right)^{1/2} = \left(\frac{4A_n}{0.85\pi}\right)^{1/2} = \left(\frac{4F}{0.85\pi V_n}\right)^{1/2} = \left(\frac{4F}{0.85\pi 0.8V_{nf}}\right)^{1/2} = \left(\frac{1.87F}{V_{nf}}\right)^{1/2} = \left(\frac{(20)^{0.2}(1.87)F}{C_{sb}(\sigma)^{0.2}(\Delta\rho)^{1/2}}\right)^{1/2}$$

Assume the downcomer occupies 15 percent of the cross-sectional area of the column (A_n = $0.85A_C$) and A_n = (F/V_n). Assume 80 percent flooding ($V_n = 0.8V_{nf}$).

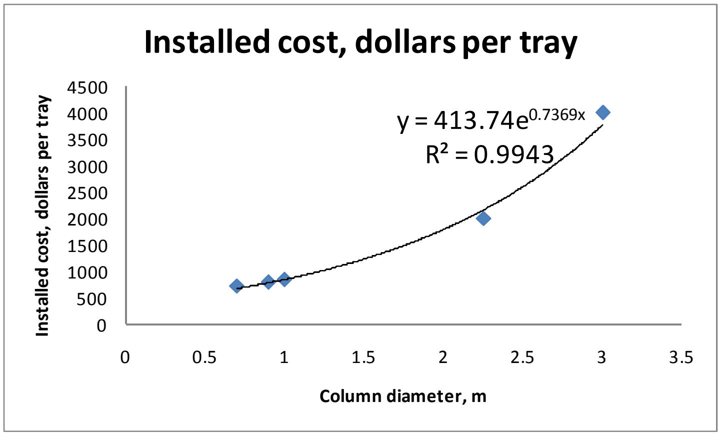
$$D = \left(\frac{3.40F}{C_{sb}(\sigma)^{0.2}(\Delta\rho)^{1/2}}\right)^{1/2}$$

Standard tray spacings for large-diameter columns are generally either 0.46 or 0.61 m.



Points taken from Figure 15-11 on page 783 in PT&W *Plant Design and Economics for Chemical Engineers*. Thus, equation is of the form:

$$\text{Purchased cost (\$)} = a * \text{Vertical Height of column (meters)} + b$$



Points taken from Figure 15-13 on page 794 in PT&W *Plant Design and Economics for Chemical Engineers*. This equation is valid for a sieve tray made of stainless steel. The non-linear regression equation is of the form:

$$\text{Installed cost (\$/tray)} = a*\exp[b*\text{Column Diameter (meters)}]$$

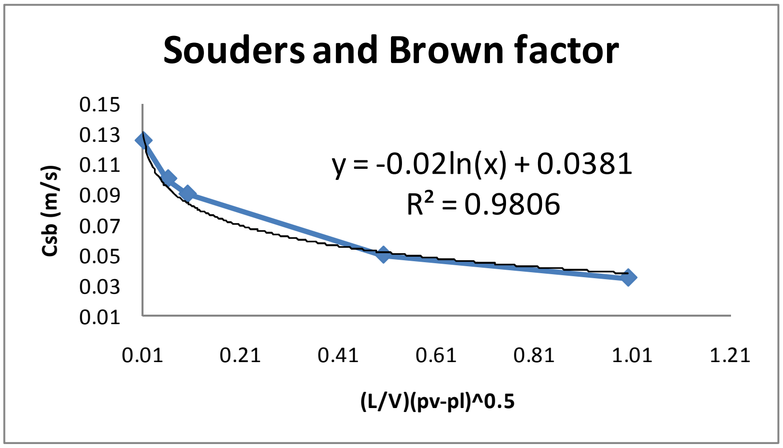
Thus,

$$\text{Total cost} = \text{Purchased cost (\$)} + \text{Installed cost (\$/tray)} * \text{Number of trays (tray)}$$

$$\text{Total cost} = 1.63 \cdot (4553.9H + 25885) + 1.63 \cdot (\text{Installed cost} \cdot \text{N})$$

$$\text{Total cost} = 1.63 \cdot (4553.9H + 25885) + 1.63 \cdot N \cdot \left(413.74e^{0.7639D}\right)$$

Now, it's necessary to find D in terms of feedrate and other parameters. Using Figure 15-5 on page 778 of PT&W *Plant Design and Economics for Chemical Engineers*:



This figure was used for a standard tray spacing of 0.61 meters. The non-linear regression equation is of the form:

Souders and Brown factor = a * ln[RBR*$(\Delta\rho)^{0.5}$] + b

Thus,

$$D = \left(\frac{3.40F}{10^{0.2}\left(-0.02\ln\left(RBR\cdot(\Delta\rho)^{0.5}\right)+0.0381\right)\cdot(\Delta\rho)^{1/2}} \right)$$

Note that a surface tension of 10 was used; H_2S surface tension values range from 11.3 to 8.7 dyne/cm. Check reference folder for details.

Rearranging terms:

$$D = 1.46\left(\frac{F}{\left(-0.02\ln\left(RBR\cdot(\Delta\rho)^{0.5}\right)+0.0381\right)\cdot(\Delta\rho)^{1/2}} \right)$$

$$\text{Total cost} = 7423\text{H} + 42193 + 674.4N\left[e^{1.12\left(\frac{F}{\left(-0.02\cdot\ln\left(RBR\sqrt{\Delta\rho}\right)+0.0381\right)\left(\sqrt{\Delta\rho}\right)}\right)^{1/2}} \right]$$

$$\text{Total cost} = 7423\text{H} + 674.4N\left[e^{\frac{1.12F^{1/2}}{\left(-0.02\cdot\ln\left(RBR\sqrt{\Delta\rho}\right)\left(\sqrt{\Delta\rho}\right)+0.0381\left(\sqrt{\Delta\rho}\right)\right)^{1/2}}} \right] + 42193$$

$$\text{Total cost} = 7423\text{H} + 674.4N\left[e^{\frac{1.12F^{1/2}}{-0.14\cdot\Delta\rho^{1/4}\cdot\frac{1}{2}\cdot\ln\left(RBR\sqrt{\Delta\rho}\right)+0.195\cdot\Delta\rho^{1/4}}} \right] + 42193$$

Final equation:

$$\text{Total equipment cost} = 7423\text{H} + 674.4N\left[e^{\frac{1.12\sqrt{F}}{-0.071\cdot\Delta\rho^{1/4}\cdot\ln\left(RBR\sqrt{\Delta\rho}\right)+0.195\cdot\Delta\rho^{1/4}}} \right] + 42193$$

Derivation of Activated Sludge process:

From Wikipedia.com: Atmospheric air or pure oxygen is bubbled through primary treated sewage (or industrial wastewater) combined with organisms to develop a biological floc which reduces the organic content of the sewage. Thus, we're measuring outlet organic content.

What's going on inside of an activated sludge system is the wastewater flows first through an aeration tank where oxygen is bubbled through to create turbulent conditions. Then, the wastewater is sent to a secondary clarifier where particles settle naturally to the bottom (bacteria consume carbonaceous matter in the aeration tank and then settle by weight in the calm conditions of the secondary clarifier). Assume ideal CSTR for the aeration tank. Why? Perfect mixing because oxygen is being pumped through the aeration tank at very high speeds. It's like a stirrer stirring the mixture.

$$V = \frac{F_{AO} X}{-r_{A,exit}} \quad \text{where A is organics}$$

$$Cost(\$) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\, m^3} \cdot V(m^3) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\, m^3} \cdot \frac{F_{AO}\left(\frac{Cout,org - Cin,org}{Cin,org}\right)}{-r_{A,exit}}$$

$70/yd is the price of concrete. A former wastewater plant operator told me that concrete was widely used to build activated sludge systems.

$$Cost(\$) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\, m^3} \cdot \frac{F_{AO}\left(\frac{Cout,org - Cin,org}{Cin,org}\right)}{-r_{A,exit}} = \frac{91.5 \cdot (C_{\cancel{AO}} \cdot v_O)\left(\frac{Cout,org - Cin,org}{Cin,o\cancel{r}g}\right)}{-r_{A,exit}}$$

Using the Monod equation for biological reactions:

$$-r_A = \frac{kC_S C_C}{K_M + C_S}$$

where k is the maximum utilization rate for the substrate per unit mass of bacteria

K_M is the half velocity coefficient for the substrate

C_S is the $C_{in,\ organics}$

$C_C = 0.1(C_{S0} - C_S) + 0.001$

Look on page 75 of the Kinetics reaction book for reference.

Thus,

$$Cost(\$) = \frac{91.5 \cdot (v_O)(Cout,org - Cin,org)}{\dfrac{k \cdot Cout,org\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]}{K_M + Cout,org}} = \frac{91.5 \cdot \left(\dfrac{F\left(\dfrac{ton}{hr}\right) \cdot \dfrac{907\ kg}{ton}}{1\dfrac{kg}{m^3}}\right)(Cout,org - Cin,org)}{\dfrac{k \cdot Cout,org\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]}{K_M + Cout,org}}$$

because volumetric flowrate is flowrate divided by density.

I found a paper online that gave a "k" and "K_M" value for phenol. Phenol is an organic. Source is down below. k = 0.19/hr, K_M = 48 ppm (mg/L).

From the book: *Design and Operation of Activated Sludge Processes Using Respirometry* by Alan F. Rozich, Anthony F. Gaudy; CRC Press, 1992, page 46.

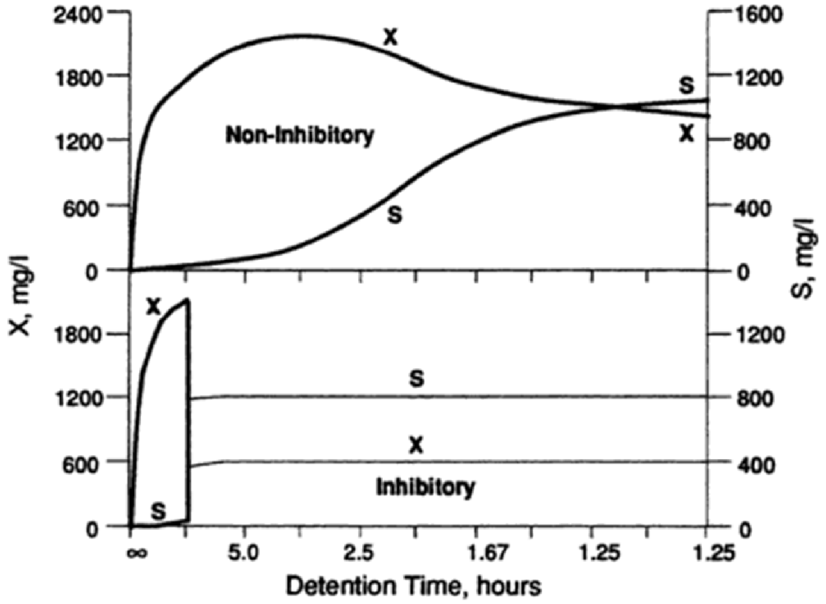


Figure 3.2. **Comparison of predictive curves for effluent quality calculated from the Monod and Haldane equations for a constant X_R activated sludge process treating phenol at an S_i of 1500 mg/L. Values of parameters and biokinetic constants are: X_R = 6,000 mg/L, α = 0.25, μ_{max} = 0.19 hr^{-1}, K_s = 48 mg/L, K_i = 62 mg/L, Y_t = 1.02, and k_d = 0.47 $days^{-1}$.**

Finally:

$$Cost(\$) = \frac{91.5 \cdot \left(907 \cdot F\, \frac{m^3}{hr}\right)(Cout,org - Cin,org) \cdot (48 + Cout,org)}{0.19 \cdot Cout,org\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right] \cdot \frac{1000\ mg}{g}}$$

$$Cost(\$) = \frac{436.81 \cdot F \cdot (Cout,org - Cin,org) \cdot (48 + Cout,org)}{Cout,org\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]}$$

where F is in ton/hr and Cout, org and Cin, org are in ppm.

That was the cost of the first part of the biological treatment (the aeration tank). There is a second part: the secondary clarifier. Particles settle naturally (by gravity). Conditions are calm and no reaction is occurring so neither a CSTR or a batch reactor can be used.

Reactor tank is emptied once a day. Source: wastewater plant operator. Assume 24 hr time period.

$$Volume\ needed\left(m^3\right) = Efficiency \cdot F\left(\frac{ton}{hr}\right) \cdot \frac{907\ kg}{ton} \cdot 24\ hr \cdot \frac{m^3}{kg} = \frac{Cin,org}{Cout,org} \cdot F\left(\frac{ton}{hr}\right) \cdot \frac{907\ kg}{ton} \cdot 24\ hr \cdot \frac{m^3}{kg}$$

But, Cinorg = Coutorg, aeration tank. Cout,max = 230 ppm from the slide show (I have a reference). Let’s specify a maximum outlet concentration to give a maximum amount of volume that we need.

We’ll use concrete as a tank material.

$$Cost(\$) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\ m^3} \cdot V\left(m^3\right) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\ m^3} \cdot \frac{Cin,org}{230\ \ ppm} \cdot F\left(\frac{ton}{hr}\right) \cdot \frac{907\ kg}{ton} \cdot 24\ hr \cdot \frac{m^3}{kg}$$

Even though there is a recycle that enters into the clarifier, we’ll assume it is zero for now.

Finally,

$$Cost(\$) = \frac{\$70}{yd^3} \cdot \frac{yd^3}{0.765\ m^3} \cdot \frac{Cin,org}{230\ \ ppm} \cdot F\left(\frac{ton}{hr}\right) \cdot \frac{907\ kg}{ton} \cdot 24\ hr \cdot \frac{m^3}{kg}$$

$$Cost(\$) = 8660.19 \cdot Cin,org \cdot F\left(\frac{ton}{hr}\right)$$

$$Cin,org = \frac{Cost(\$)}{8660.19 \cdot F\left(\frac{ton}{hr}\right)}$$

$$Total\ Cost(\$) = Cost1 + Cost2 = \frac{436.81 \cdot F \cdot (Cout,org,Aera - Cin,org) \cdot (48 + Cout,org,Aera)}{Cout,org,Aera[0.1 \cdot (Cin,org - Cout,org,Aera) + 0.001]} + 8660.19 \cdot Cin,org,Clarifier \cdot F\left(\frac{ton}{hr}\right)$$

Assume Cout,org, Aera = Cin,org, Clar = 100 ppm.

$$Total\ Cost(\$) = Cost1 + Cost2 = \frac{436.81 \cdot F \cdot (100 - Cin,org) \cdot (48 + 100)}{100[0.1 \cdot (Cin,org - 100) + 0.001]} + 8660.19 \cdot 100 \cdot F\left(\frac{ton}{hr}\right)$$

Finally,

$$\boxed{Total\ Cost(\$) = 183 \cdot V(m^3) = \frac{646.48 \cdot F \cdot (100 - Cin,org)}{[0.1 \cdot (Cin,org - 100) + 0.001]} + 866{,}019 \cdot F}$$

To find constraint for volume needed for the activated sludge, it is clear that any volume predicted by the equation given below is the minimum volume needed for removing specified contaminant level. Any volume larger is acceptable and is capable of removing more organics:

$$V_{\text{aeration tank}} \geq \frac{F_{AO} X}{-r_{A,exit}} \quad \text{where A is organics}$$

$$V_{\text{secondary clarifier}} \geq \frac{Cin,org}{230\ ppm} \cdot F\left(\frac{ton}{hr}\right) \cdot \frac{907\ kg}{ton} \cdot 24\ hr \cdot \frac{m^3}{kg} \geq 94.64 \cdot Cin,org \cdot F$$

Of course, the volume needed is the addition of $V_{\text{aeration tank}} + V_{\text{secondary clarifier}}$.

$$Total\ volume = V_{\text{aeration tank}} + V_{\text{secondary clarifier}} \geq \frac{F_{AO} X}{-r_{A,exit}} + 94.64 \cdot Cin,org \cdot F$$

$$Total\ volume \geq \frac{\left(907 \cdot F \frac{m^3}{hr}\right)(Cout,org - Cin,org) \cdot (48 + Cout,org)}{0.19 \cdot Cout,org[0.1 \cdot (Cin,org - Cout,org) + 0.001] \cdot \frac{1000\ mg}{g}} + 94.64 \cdot Cin,org \cdot F$$

$$Total\ volume \geq \frac{\left(4.77 \cdot F\,\frac{m^3}{hr}\right)(Cout,org - Cin,org) \cdot (48 + Cout,org)}{Cout,org\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]} + 94.64 \cdot Cin,org \cdot F$$

Assume Cout,org, Aera = Cin,org, Clar = 100 ppm.

$$Total\ volume \geq \frac{\left(4.77 \cdot F\,\frac{m^3}{hr}\right)(100 - Cin,org) \cdot (48 + 100)}{100\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]} + 94.64 \cdot 100 \cdot F$$

$$Total\ volume \geq \frac{\left(7.065 \cdot F\,\frac{m^3}{hr}\right)(100 - Cin,org)}{\left[0.1 \cdot (Cin,org - Cout,org) + 0.001\right]} + 9464 \cdot F$$

Finally,

$$\boxed{V \geq \frac{70.65 \cdot F \cdot (100 - Cin,org)}{(Cin,org - 100) + 0.01} + 9464 \cdot F}$$

Appendix III

Tabulated data for water stream placement:

Freshwater to Units

	2	3
FW	25.00	8.57

Units to Units

	4	5
1	2.67	0.00
2	6.07	0.00
3	0.00	2.29

Units to Sink

	1
3	0.48

Units to Regeneration

	API	ACA	AS
2	0.00	18.93	0.00
3	0.00	0.00	5.80
4	198.24	0.00	0.00
5	0.00	182.42	0.00
6	0.00	0.00	74.42

Regeneration to Units

	1	2	5	6
API	0.06	0.00	0.00	71.68
RO	2.61	7.10	158.94	2.74
ACA	0.00	182.40	21.18	0.00

Regeneration to Regeneration

	API	CWW	RO	ACA
API	0.00	205.96	0.00	0.00
CWW	0.00	0.00	205.95	0.00
RO	0.00	0.00	0.00	2.24
AS	79.46	0.00	0.00	0.00

Regeneration to Sink

	1
RO	32.33
AS	0.76

Contaminant Concentration Out of Units				
	Salts	Organics	H2S	Ammonia
1	101.09	500.00	286.85	67.91
2	144.40	4000.00	10.00	32.00
3	70.00	3500.00	175.00	116.67
4	66.64	502.67	20.97	46.90
5	45.48	342.84	14.17	43.47
6	2230.79	6500.00	51.38	47.93

Contaminant Concentration Into Regeneration				
	Salts	Organics	H2S	Ammonia
API	641.18	376.01	32.23	48.61
CWW	641.18	50.00	32.23	48.61
RO	641.18	50.00	5.00	30.00
ACA	54.40	679.69	13.68	42.26
AS	2074.55	6283.08	60.32	52.90

Contaminant Concentration Out of Regeneration				
	Salts	Organics	H2S	Ammonia
API	641.18	50.00	32.23	48.61
CWW	641.18	50.00	5.00	30.00
RO	20.00	50.00	5.00	30.00
ACA	54.40	75.00	13.68	42.26
AS	2074.55	60.00	60.32	52.90

Endnotes

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