Attachment

PCB Emission Calculations
For the 242-A Evaporator

In support of the "*Application for Risk-Based Disposal for Polychlorinated Biphenyls -- Hanford 200 Area Liquid Waste Processing Facilities, Appendix 1*"
DOE/RL-2002-002

February 2002

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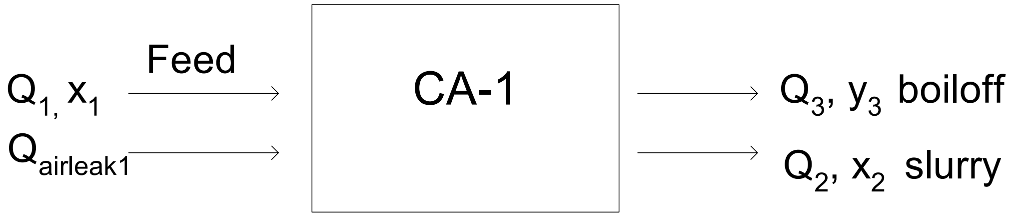
This attachment contains detailed calculations regarding PCB emissions that would be emitted from the Evaporator stack. The initial feed concentration is set at 0.2 mg/L of AroClor 1016. Additional information regarding emission rates is contained in Section A.2.3 of Appendix 1.

Mass Balance/ Operating Data CA-1



$$Q_{airleak1} := 1 \frac{ft^3}{min}$$ (SCFM) (from Safety Analysis Report based on dip tube and leakage)

Converting $Q_{airleak1}$ to mol/min

$$Q_{airleak1molar} := \frac{Q_{airleak1} \cdot \left(28.317 \frac{L}{ft^3}\right)}{22.4 \frac{L}{mol}}$$

$$Q_{airleak1molar} = 1.264 \frac{mol}{min}$$

Converting $Q_{airleak1}$ to kg/min

$$Q_{airleak1mass} := \frac{Q_{airleak1molar} \cdot \left(29 \frac{gm}{mol}\right)}{1000 \frac{gm}{kg}}$$

$$Q_{airleak1mass} = 0.0367 \frac{kg}{min}$$

Feed: Flow is 60 gal/min with SpG = 1.02 (from Campaign 01-01)

$$Q_{1mass} := 60\frac{gal}{min}\cdot\left(3.785\frac{L}{gal}\right)\cdot\left(1.020\frac{kg}{L}\right)$$

$$Q_{1mass} = 231.642\frac{kg}{min}$$

Assume 18gm/mol

$$Q_{1molar} := Q_{1mass}\cdot\frac{\left(1000\frac{gm}{kg}\right)}{18\frac{gm}{mol}}$$

$$Q_{1molar} = 12869\frac{mol}{min}$$

Boiloff: Waste Volume Reduction from Campaign 01-01 boiloff was 81%

$$boiloff_1 := (0.81)\cdot 60\frac{gal}{min}$$

$$boiloff_1 = 48.6\frac{gal}{min}$$

This has a SpG of 1.0

Converting boilofffto kg/min

$$boiloff_2 := \left(boiloff_1\right)\cdot\left(3.785\frac{L}{gal}\right)\cdot\left(1.0\frac{kg}{L}\right)$$

$$boiloff_2 = 183.951\frac{kg}{min}$$

Converting boilofffto mol/min

$$boiloff_3 := \frac{boiloff_2\cdot\left(1000\frac{gm}{kg}\right)}{18\frac{gm}{mol}}$$

$$boiloff_3 = 10220\frac{mol}{min}$$

$Q_3 = \text{boiloff} + Q_{airleak}$

$Q_{3mass} := \text{boiloff}_2 + Q_{airleak1mass}$

$Q_{3mass} = 183.988\frac{kg}{min}$

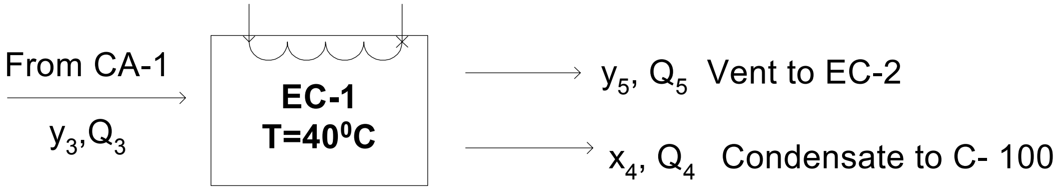
$Q_{3molar} := \text{boiloff}_3 + Q_{airleak1molar}$

$Q_{3molar} = 1.022\times 10^4 \frac{mol}{min}$

$Q_2 := Q_{1molar} - \text{boiloff}_3$

$Q_2 = 2.649\times 10^3 \frac{mol}{min}$

Mass Balance Operating Data EC-1



Q_{3mass} = 184 kg/min, which is 0.0367 kg/min dry air ($Q_{airleak1mass}$)

Q_5 is dry air and moisture; at 40 ^{0}C, there 0.0491 kg H_2O/kg dry air (Perry's 6th Ed., Table 12-1).
The moisture is therefore 0.0367 kg/min(0.0491 kg H_2O/kg dry air) = 1.80x10^{-3} kgH_2O/min

The molar H_2O flow is then (1.80x10^{-3} kgH_2O/min) (1000gm/kg)/(18gm/mol)=0.100 mol H_2O/min

$$Q_5 := Q_{airleak1mass} + 1.80 \cdot 10^{-3} \frac{kg}{min}$$

$$Q_5 = 0.0385 \frac{kg}{min}$$

$$Q_{5molar} := Q_{airleak1molar} + 0.100 \frac{mol}{min}$$

$$Q_{5molar} = 1.364 \frac{mol}{min}$$

$$Q_4 = Q_3 - Q_5$$

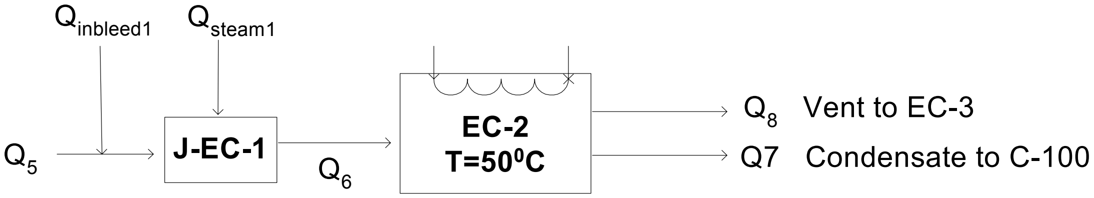
$$Q_{4mass} := Q_{3mass} - Q_5$$

$$Q_{4mass} = 183.949 \frac{kg}{min}$$

$$Q_{4molar} := Q_{3molar} - Q_{5molar}$$

$$Q_{4molar} = 1.022 \times 10^4 \frac{mol}{min}$$

Balance/Operating Data E-C2



$$Q_6 = Q_5 + Q_{inbleed} + Q_{steam}$$

$$Q_{inbleed1} := 25\frac{ft^3}{min} \quad \text{(SCFM)}$$ (From Safety Analysis Report)

$$Q_{steam1} := 1.23\frac{gal}{min}$$ (From Campaign 01-01 totalizer data)

Q_5 = 0.0385 kg/min and consists of 0.0367 kg/min air and 1.80x10 $^{-3}$ kg/min of H_2O
Q_5 = 1.364 mol/min and consists of 1.264 mol/min air and 0.100mol/min of H_2O

Inbleed: Inbleed in mol/min

$$Q_{inbleed1molar} := \frac{Q_{inbleed1}\cdot\left(28.317\frac{L}{ft^3}\right)}{22.4\frac{L}{mol}}$$

$$Q_{inbleed1molar} = 31.604\frac{mol}{min}$$

Inbleed in kg/min

$$Q_{inbleed1mass} := \frac{Q_{inbleed1molar}\cdot\left(29\frac{gm}{mol}\right)}{1000\frac{gm}{kg}}$$

$$Q_{inbleed1mass} = 0.917\frac{kg}{min}$$

Steam: Steam in kg/min

$$Q_{steam1mass} := Q_{steam1}\cdot\left(3.785\frac{L}{gal}\right)\cdot\left(1.0\frac{kg}{L}\right)$$

$$Q_{steam1mass} = 4.656\frac{kg}{min}$$

Convert to mol/min:

$$Q_{steam1molar} := \frac{Q_{steam1mass}\cdot\left(1000\frac{gm}{kg}\right)}{18\frac{gm}{mol}}$$

$$Q_{steam1molar} = 258.642\frac{mol}{min}$$

$$Q_{6mass} := Q_5 + Q_{inbleed1mass} + Q_{steam1mass}$$

$$Q_{6mass} = 5.611\frac{kg}{min}$$

$$Q_{6molar} := Q_{5molar} + Q_{steam1molar} + Q_{inbleed1molar}$$

$$Q_{6molar} = 291.61\frac{mol}{min}$$

Q_8 is the dry air and moisture at 50 °C (assumed), there is 0.0868 kg H_2O/kg dry air (from Perry's 6th Ed., Table 12-1. The total dry air is 0.0367 kg/min + 0.917 kg/min = 0.954 kg/min. The moisture is therefore 0.954kg/min(0.0868)=0.0828 kgH2O/min.

The molar H2O flow is:

$$\mathrm{Molar}_{H2Oflow} := \frac{0.0828\frac{kg}{min}\cdot 1000\frac{gm}{kg}}{18\frac{gm}{mol}}$$

$$\mathrm{Molar}_{H2Oflow} = 4.6\frac{mol}{min}$$

$$Q_8 = \mathrm{dryair} + \mathrm{moisture}$$

$$Q_{8mass} := 0.954\frac{kg}{min} + 0.0828\frac{kg}{min}$$

$$Q_{8mass} = 1.037\frac{kg}{min}$$

$$Q_{8molar} := Q_{airleak1molar} + Q_{inbleed1molar} + \mathrm{Molar}_{H2Oflow}$$

$$Q_{8molar} = 37.468\frac{mol}{min}$$

$$Q_7 = Q_6 - Q_8$$

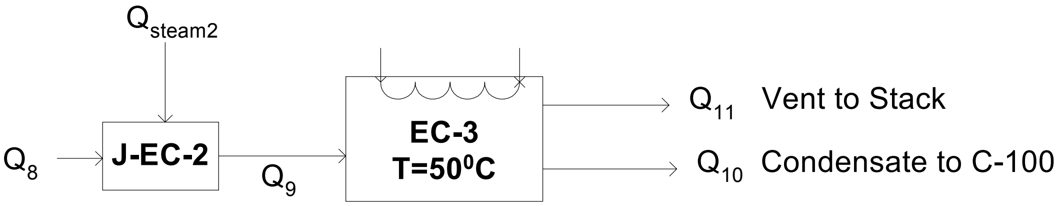
$$Q_{7mass} := Q_{6mass} - Q_{8mass}$$

$$Q_{7mass} = 4.574\frac{kg}{min}$$

$$Q_{7molar} := Q_{6molar} - Q_{8molar}$$

$$Q_{7molar} = 254.142\frac{mol}{min}$$

Mass Balance /Operating Data EC-3



This balance is the same as EC-2 except that there is no air inbleed.

$$Q_{steam2} := 1.23 \cdot \frac{gal}{min}$$

$Q_{8\ (mass)}$ = 1.04 kg/min and is 0.954 kg/min air and 0.083 kg/min H_2O
$Q_{8\ (molar)}$ = 37.5 mol/min and is 32.9 mol/min air and 4.60 mol/minH_2O

$$Q_{steam1mass} = 4.656 \frac{kg}{min}$$

$$Q_{steam1molar} = 258.642 \frac{mol}{min}$$

$$Q_{9mass} := Q_{8mass} + Q_{steam1mass}$$

$$Q_{9mass} = 5.692 \frac{kg}{min}$$

$$Q_{9molar} := Q_{8molar} + Q_{steam1molar}$$

$$Q_{9molar} = 296.11 \frac{mol}{min}$$

Q_{11} is dry air + moisture. Since no additional dry air was added, and the operating temperature is unchanged, the quantity of water is unchanged.

$$Q_{11mass} := Q_{8mass}$$

$$Q_{11mass} = 1.037\frac{kg}{min}$$

$$Q_{11molar} := Q_{8molar}$$

$$Q_{11molar} = 37.468\frac{mol}{min}$$

$$Q_{10} = Q_9 - Q_{11}$$

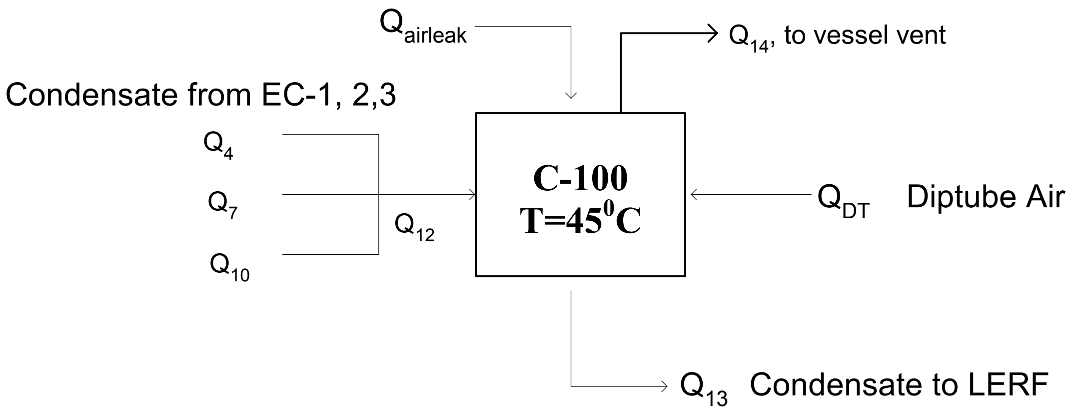
$$Q_{10mass} := Q_{9mass} - Q_{11mass}$$

$$Q_{10mass} = 4.656\frac{kg}{min}$$

$$Q_{10molar} := Q_{9molar} - Q_{11molar}$$

$$Q_{10molar} = 258.642\frac{mol}{min}$$

Mass Balance/Operating Data C-100 Tank



C-100 tank receives condensate from EC-1, EC-2 & EC-3. It also has two air additions. Dip Tube (DT) air sparges through the liquid and is fully saturated. Air inleakage enters the top and is unsaturated.

$$Q_{DT} := 0.10\cdot\frac{ft^3}{min}$$ (SCFM) (from operating data)

$$Q_{airleak3} := 150\frac{ft^3}{min}$$ (SCFM) (from Part B Permit)

$$Q_{DTmolar} := \frac{Q_{DT}\cdot\left(28.317\frac{L}{ft^3}\right)}{\left(\frac{22.4L}{mol}\right)}$$

$$Q_{DTmolar} = 0.126\frac{mol}{min}$$

$$Q_{DTmass} := \frac{Q_{DTmolar}\cdot\left(29\frac{gm}{mol}\right)}{1000\frac{gm}{kg}}$$

$$Q_{DTmass} = 3.666\times 10^{-3}\frac{kg}{min}$$

$$Q_{airleakmol} := \frac{150 \cdot \frac{ft^3}{min} \cdot \left(28.317 \cdot \frac{L}{ft^3}\right)}{22.4 \frac{L}{mol}}$$

$$Q_{airleakmol} = 189.62 \frac{mol}{min}$$

$$Q_{airleakmass} := \frac{189.62 \frac{mol}{min} \cdot \left(29 \cdot \frac{gm}{mol}\right)}{1000 \frac{gm}{kg}}$$

$$Q_{airleakmass} = 5.499 \frac{kg}{min}$$

$$Q_{12mass} := Q_{4mass} + Q_{7mass} + Q_{10mass}$$

$$Q_{12mass} = 193.178 \frac{kg}{min}$$ (approximately 51gpm)

$$Q_{12molar} := Q_{4molar} + Q_{7molar} + Q_{10molar}$$

$$Q_{12molar} = 1.073 \times 10^4 \frac{mol}{min}$$

Q_{14} is the airleakage ($Q_{airleak}$) plus the dip tube air (Q_{DT}) + moisture from diptube air.
At 45°C, there is 0.0654 kg H_2O/kg air (Perry's 6th Ed., Table 12-1).
kgH_2O in diptube air = 0.0654 kg H_2O/kg(3.67×10^{-3} kg/min) = 2.4×10^{-4} kg/min
mol H_2O in diptube air = (2.40×10^{-4} kg/min) (1000 gm/kg)/(18 gm/mol) = 1.33×10^{-2} mol/min

$$Mass_{water} := 2.4 \cdot 10^{-4} \cdot \frac{kg}{min}$$

$$Mol_{water} := \frac{Mass_{water} \cdot \left(1000 \frac{gm}{kg}\right)}{18 \frac{gm}{mol}}$$

$$Mol_{water} = 0.0133 \frac{mol}{min}$$

$$Q_{14mass} := Q_{airleakmass} + Q_{DTmass} + Mass_{water}$$

$$Q_{14mass} = 5.5 \frac{kg}{min}$$

$$Q_{14molar} := Q_{airleakmol} + Q_{DTmolar} + Mol_{water}$$

$$Q_{14molar} = 189.76 \frac{mol}{min}$$

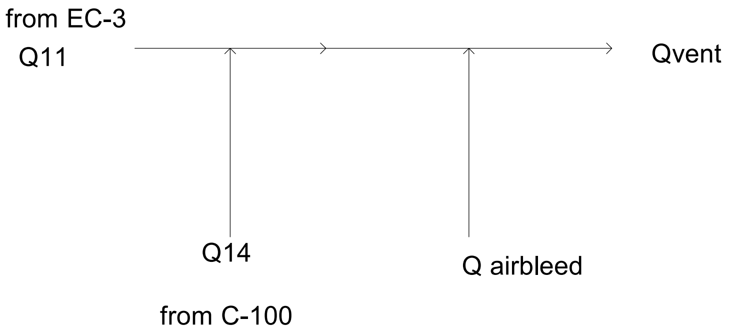
$$Q_{13mass} := Q_{12mass} + Q_{airleakmass} + Q_{DTmass} - Q_{14mass}$$

$$Q_{13mass} = 193.178 \frac{kg}{min}$$

$$Q_{13molar} := Q_{12molar} + Q_{airleakmol} + Q_{DTmolar} - Q_{14molar}$$

$$Q_{13molar} = 10732.17 \frac{mol}{min}$$

Mass Balance/Operating Vessel Vent



$Q_{airbleed}$ is 370 SCFM (based of flow testing performed during HEPA filter efficiency test).

$$Q_{airbleedmol} := \frac{370 \cdot \frac{ft^3}{min} \cdot \left(28.317 \cdot \frac{L}{ft^3}\right)}{22.4 \frac{L}{mol}}$$

$$Q_{airbleedmol} = 467.736 \frac{mol}{min}$$

$$Q_{airbleedmass} := \frac{Q_{airbleedmol} \cdot \left(29 \frac{gm}{mol}\right)}{1000 \frac{gm}{kg}}$$

$$Q_{airbleedmass} = 13.56 \frac{kg}{min}$$

$$Q_{ventmass} := Q_{11mass} + Q_{14mass} + Q_{airbleedmass}$$

$$Q_{ventmass} = 20.104 \frac{kg}{min}$$

$$Q_{ventmol} := Q_{11molar} + Q_{14molar} + Q_{airbleedmol}$$

$$Q_{ventmol} = 694.97 \frac{mol}{min}$$

Volumetric flow at STP

$$\text{Volumetricflow} := \frac{Q_{\text{ventmol}} \cdot \left(22.4 \frac{L}{\text{mol}}\right)}{1000 \frac{L}{m^3}}$$

$$\text{Volumetricflow} = 15.567 \frac{m^3}{\text{min}}$$ (approxim. 550 SCFM)

Henry's Law

This is an example of how the Henry's Law constant is corrected for different operating temperatures. The example is for Aroclor 1016 at 50°C.

Henry's Law constants are given in a variety of units. The U.S. Army Corps of Engineers gives constants in units "atm-m ^{3}/mol", while Sanders gives units of "mol/dm ^{3}-atm", where 1m = 10 dm. The unit used in this PCB analysis is "atm", which is corrected for the molarity of the solution.

The U.S. Army Corps of Engineers gives a Henry's Law constant of $3.3\text{x}10^{-4}$ atm-m^3/mol. To convert this to mol/dm ^{3}-atm (for use with temperature correction factor from Sander):

$$K_H := \frac{1}{3.3 \cdot 10^{-4} \cdot \frac{\text{atm} \cdot \text{m}^3}{\text{mol}}} \qquad K_H = 3030 \frac{\text{mol}}{\text{atm} \cdot \text{m}^3}$$

Convert to dm:

$$\text{dm} := 1\text{m} \cdot 10^{-1}$$

$$K_{H1} := K_H \cdot \left(\frac{1\text{m}}{10\text{dm}} \right)^3$$

$$K_{H1} = 3.03 \frac{\text{mol}}{\text{dm}^3 \cdot \text{atm}}$$

A temperature correction factor is given in Sander:

$$K_{HT} = K_H \cdot e^{\left[\frac{-\Delta\text{solnH}}{R}\cdot\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]}$$

$\frac{-\Delta\text{solnH}}{R}$ is given in Sander. An average of +7400 is used for Aroclor 101

$$K_{50} := K_{H1} \cdot e^{\left[7400\cdot\left[\left(\frac{1}{50+273}\right)-\left(\frac{1}{25+273}\right)\right]\right]}$$

$$K_{50} = 0.443\frac{\text{mol}}{\text{dm}^3\cdot\text{atm}}$$

To convert this to atm, use equation from Sander (which uses the solution molarity, which is the same as water molarity):

$$K_H\left(\frac{\text{mol}}{\text{dm}^3\cdot\text{atm}}\right)\cdot H(\text{atm}) = 55.3$$

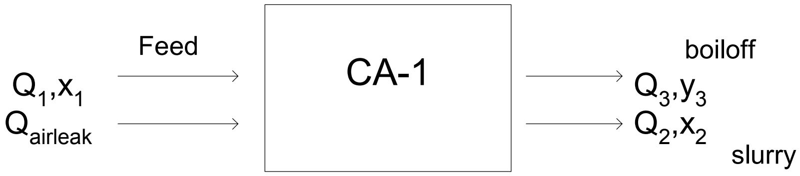
$$H(\text{atm}) = \frac{55.3}{K_H\left(\frac{\text{mol}}{\text{dm}^3\cdot\text{atm}}\right)}$$

$$H(\text{atm}) := 126\cdot\text{atm}$$

Note that the ambient value is :

$$\frac{55.3}{3.03} = 18.251\ \text{atm}$$

242-A EVAP CA-1



x: mol fraction PCB, liquid phase
y: mol fraction PCB, gas phase

$x_1Q_1+y_{airleak1}Q_{airleak1} = y_3Q_3+x_2Q_2$

$y_{airleak1}=0$ (no PCB in air)

Calculate x_1Q_1 (molar feed rate of PCB)

Feed rate = 60 gal/min

Feed PCB conc. = 0.2 μg/L
Feed density = 1.02 kg/L

Feed PCB massflow
$Q_{1(mass)} = 231.6$kg/min
$Q_{1(molar)} = 12869$ mol/min

$$\mu := 1\cdot 10^{-6}$$

$$Feed_{conc} := 0.2\frac{\mu\cdot g}{L}$$

$$Feed_{density} := 1.02\frac{kg}{L}$$

$$PCB_{conc} := \frac{Feed_{conc}}{Feed_{density}}$$

$$PCB_{conc} = 0.196\frac{\mu\cdot g}{kg}$$

$$Q_{1mass} := 231.6 \frac{kg}{min}$$

$$PCB_{rate} := \frac{(PCB_{conc}) \cdot (Q_{1mass})}{\left(1000000 \frac{\mu \cdot g}{gm}\right)}$$

$$PCB_{rate} = 4.541 \times 10^{-5} \frac{gm}{min}$$

Converting to mol/min

(Molecular Weight of PCB = 258 gm/mol)

$$Q_{1molar} := 12869 \frac{mol}{min}$$

$$PCB_{rate2} := \frac{PCB_{rate}}{258 \cdot \frac{gm}{mol}}$$

$$PCB_{rate2} = 1.76 \times 10^{-7} \frac{mol}{min}$$

$$PCB_{rate2} = x_1 Q_1$$

$$x_1 = x_1 Q_1 / Q_1$$

$$x_1 := \frac{PCB_{rate2}}{Q_{1molar}}$$

$$x_1 = 1.368 \times 10^{-11} \quad \text{(unitless)}$$

$P := 60\text{torr}$ (from operating data)

Converting to atmospheres

$$P_{atm} := \frac{60\text{torr}}{760\dfrac{\text{torr}}{\text{atm}}}$$

$P_{atm} = 0.079\text{atm}$

$H_1 := 126\text{atm}$ (at 50°C) (See section on Henry's Law)

$$Q_2 := 2650\frac{\text{mol}}{\text{min}}$$

$$Q_3 := 10221\frac{\text{mol}}{\text{min}}$$

Henry's Law:

$y_3P = x_2H$ or $x_2 = y_3P/H$
$x_1Q_1 = x_2Q_2+y_3Q_3$
$x_1Q_1 = y_3(PQ_2/H + Q_3)$

$$y_3 := \frac{x_1 \cdot Q_{1molar}}{\left(\frac{P_{atm} \cdot Q_2}{H_1} + Q_3\right)}$$

$$y_3 = 1.722 \times 10^{-11}$$

$$PCB_{vent} := y_3 \cdot Q_3$$ (PCB to vent)

$$PCB_{vent} = 1.76 \times 10^{-7} \frac{mol}{min}$$

$$Massrate := PCB_{vent} \cdot \left(258 \frac{gm}{mol}\right)$$

$$\text{Massrate} = 4.54 \times 10^{-5}\,\frac{\text{gm}}{\text{min}}$$

$$x_2 := \frac{y_3 \cdot P_{atm}}{H_1}$$

$$x_2 = 1.08 \times 10^{-14}$$

$$PCB_{slurry} := x_2 \cdot Q_2$$

$$PCB_{slurry} = 2.86 \times 10^{-11}\,\frac{\text{mol}}{\text{min}}$$

$$\text{Slurrymassflow} := PCB_{slurry} \cdot \left(258\,\frac{\text{gm}}{\text{mol}}\right)$$

$$\text{Slurrymassflow} = 7.38 \times 10^{-9}\,\frac{\text{gm}}{\text{min}}$$ (PCB to slurry)

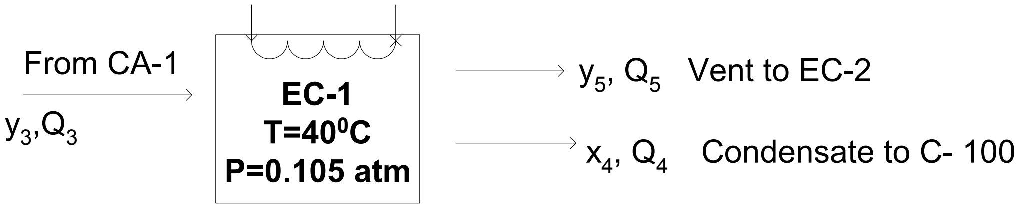
$$DF := \frac{x_1 \cdot Q_{1molar}}{x_2 \cdot Q_2}$$

$$DF = 6156.74$$

$$\%\text{volatized} := \frac{y_3 \cdot Q_3}{x_1 \cdot Q_{1molar}} \cdot 100$$

$$\%\text{volatized} = 99.984\%$$

EC-1 Condenser



Define Temperature Unit

$\text{degC} \equiv 1$

Kelvin to Celsius: $c(k) := (k - 273.15)$ $c(293.15) = 20\,\text{degC}$

Celsius to Kelvin: $k(c) := (c + 273.15)\cdot K$ $k(20) = 293.15K$

Solve similar to CA-1 using mass balance and Henry's Law.

$y_3\cdot Q_3 = x_4\cdot Q_4 + y_5\cdot Q_5$

$y_3 := 1.72\cdot 10^{-11}$

$Q_3 := 10221\cdot\frac{\text{mol}}{\text{min}}$

$y_3\cdot Q_3 = 1.76\times 10^{-7}\,\frac{\text{mol}}{\text{min}}$

$Q_4 := 10219\cdot\frac{\text{mol}}{\text{min}}$

$Q_5 := 1.364\cdot\frac{\text{mol}}{\text{min}}$

$P := 0.105\text{atm}$ Pressure of steam at 47°C.

$T := c(313.15)$ $T = 40\,\text{degC}$

$H := 61\cdot\text{atm}$ At 40°C.

As before:

$$y_5 := \frac{y_3 \cdot Q_3}{\left(\frac{P \cdot Q_4}{H} + Q_5\right)}$$ $$y_5 = 9.28 \times 10^{-9}$$

$$mw := 258 \cdot \frac{gm}{mol}$$ Molecular weight

$$y_5 \cdot Q_5 = 1.27 \times 10^{-8} \frac{mol}{min}$$ PCB mol rate, vent.

$$y_5 \cdot Q_5 \cdot mw = 3.26 \times 10^{-6} \frac{gm}{min}$$ PCB mas rate, vent.

$$x_4 := \frac{y_5 \cdot P}{H}$$ $$x_4 = 1.6 \times 10^{-11}$$

$$x_4 \cdot Q_4 = 1.63 \times 10^{-7} \frac{mol}{min}$$ PCB mol rate, condensate.

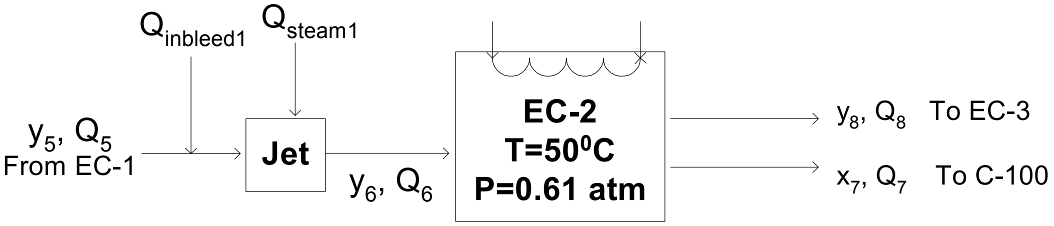
$$x_4 \cdot Q_4 \cdot mw = 4.21 \times 10^{-5} \frac{gm}{min}$$ PCB mass rate, condensate.

$$DF := \frac{y_3 \cdot Q_3 \cdot mw}{x_4 \cdot Q_4 \cdot mw}$$ $$DF = 1.08$$

$$\%volatalized := \frac{y_5 \cdot Q_5 \cdot mw}{y_3 \cdot Q_3 \cdot mw}$$ $$\%volatalized = 7.2\%$$

$$ppm_{vol} := y_5 \cdot 10^6$$ $$ppm_{vol} = 9.28 \times 10^{-3}$$

EC-2 Condenser



Define Temperature Unit

$\text{degC} \equiv 1$

Kelvin to Celsius: $c(k) := (k - 273.15)$ $c(293.15) = 2 \times 10^{1}\ \text{degC}$

Celsius to Kelvin: $k(c) := (c + 273.15)\cdot K$ $k(20) = 2.93 \times 10^{2}\ K$

Solve similar to previous examples.

As before:

$$y_8 = \frac{y_6 \cdot Q_6}{\left(\frac{P \cdot Q_7}{H} + Q_8\right)} \qquad \text{and} \qquad x_7 = \frac{y_8 \cdot P}{H}$$

$P := 0.61\text{atm}$ Assumption that J-EC1-1 pulls 70% of the vacuum. It is the larger jet.

$T := c(323.15)$ $T = 5 \times 10^{1}\ \text{degC}$ Assumption

$H := 126\cdot\text{atm}$ At 50ºC.

$y_5 := 9.28\cdot 10^{-9}$

$Q_5 := 1.364\cdot\frac{\text{mol}}{\text{min}}$

$y_5 \cdot Q_5 = 1.27 \times 10^{-8}\ \frac{\text{mol}}{\text{min}}$

$Q_6 := 292\cdot\frac{\text{mol}}{\text{min}}$

$Q_7 := 254\cdot\frac{\text{mol}}{\text{min}}$

$$Q_8 := 37.5 \cdot \frac{mol}{min}$$

$$y_6 \cdot Q_6 = y_5 \cdot Q_5 + y_{inbleed1} \cdot Q_{inbleed1} + y_{steam1} \cdot Q_{steam1} \qquad y_{inbleed1} := 0 \qquad y_{steam1} := 0$$

$$y_6 := \frac{y_5 \cdot Q_5}{Q_6} \qquad y_6 = 4.33 \times 10^{-11}$$

Note that $y_5 \cdot Q_5 = y_6 \cdot Q_6 = 1.27 \times 10^{-8} \frac{mol}{min}$

$$mw := 258 \cdot \frac{gm}{mol}$$ Molecular weight

$$y_6 \cdot Q_6 \cdot mw = 3.27 \times 10^{-6} \frac{gm}{min}$$ Mass Flow

$$y_8 := \frac{y_6 \cdot Q_6}{\left(\frac{P \cdot Q_7}{H} + Q_8 \right)} \qquad y_8 = 3.27 \times 10^{-10}$$

$$x_7 := \frac{y_8 \cdot P}{H} \qquad x_7 = 1.58 \times 10^{-12}$$

Vent

$$y_8 \cdot Q_8 = 1.23 \times 10^{-8} \frac{mol}{min}$$ Molar Flow

$$y_8 \cdot Q_8 \cdot mw = 3.16 \times 10^{-6} \frac{gm}{min}$$ Mass Flow

Condensate

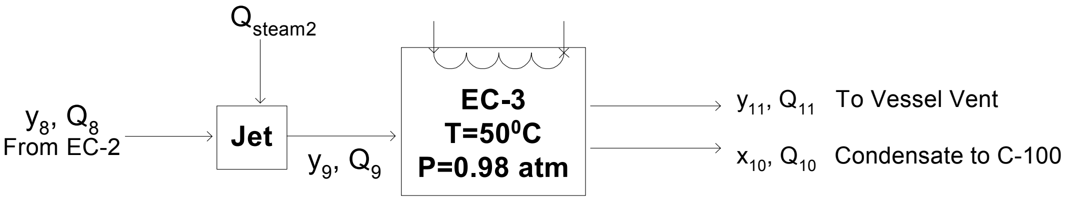
$$x_7 \cdot Q_7 = 4.02 \times 10^{-10} \frac{mol}{min}$$ Molar Flow

$$x_7 \cdot Q_7 \cdot mw = 1.04 \times 10^{-7} \frac{gm}{min}$$ Mass Flow

$$DF := \frac{y_6 \cdot Q_6 \cdot mw}{x_7 \cdot Q_7 \cdot mw} = \frac{\text{Feed}}{\text{Cond}} \qquad DF = 3.15 \times 10^{1}$$

$$\%volatalized := \frac{y_8 \cdot Q_8 \cdot mw}{y_6 \cdot Q_6 \cdot mw} = \frac{\text{Vent}}{\text{Feed}} \qquad \%volatalized = 97\%$$

EC-3 Condenser



Define Temperature Unit

$\mathrm{degC} \equiv 1$

Kelvin to Celsius: $c(k) := (k - 273.15)$ $c(293.15) = 20\,\mathrm{degC}$

Celsius to Kelvin: $k(c) := (c + 273.15)\cdot K$ $k(20) = 293.15K$

Equations are identical to EC-2.

$$y_{11} = \frac{y_9 \cdot Q_9}{\left(\frac{P\cdot Q_{10}}{H} + Q_{11}\right)} \qquad \text{and} \qquad x_{10} = \frac{y_{11}\cdot P}{H}$$

$P := 0.98\,\mathrm{atm}$ From reading, Campaign 2001-01.

$T := c(323.15)$ $T = 50\,\mathrm{degC}$

$H := 126\cdot \mathrm{atm}$ At 50°C.

$y_8 := 3.27\cdot 10^{-10}$

$Q_8 := 37.5\cdot\frac{\mathrm{mol}}{\mathrm{min}}$

$y_8\cdot Q_8 = 1.23\times 10^{-8}\,\frac{\mathrm{mol}}{\mathrm{min}}$

$Q_9 := 293\cdot\frac{\mathrm{mol}}{\mathrm{min}}$

$Q_{10} := 258\cdot\frac{\mathrm{mol}}{\mathrm{min}}$

$Q_{11} := 37.5\cdot\frac{\mathrm{mol}}{\mathrm{min}}$

$y_9 \cdot Q_9 = y_8 \cdot Q_8 + y_{steam2} \cdot Q_{steam2}$ $y_{steam2} := 0$

$y_9 := \frac{y_8 \cdot Q_8}{Q_9}$ $y_9 = 4.19 \times 10^{-11}$

$mw := 258 \cdot \frac{gm}{mol}$ Molecular weight

Note that $y_8 \cdot Q_8 = y_9 \cdot Q_9 = 1.23 \times 10^{-8} \frac{mol}{min}$

$y_{11} := \frac{y_9 \cdot Q_9}{\left(\frac{P \cdot Q_{10}}{H} + Q_{11} \right)}$ $y_{11} = 3.1 \times 10^{-10}$

$x_{10} := \frac{y_{11} \cdot P}{H}$ $x_{10} = 2.41 \times 10^{-12}$

Feed

$y_9 \cdot Q_9 = 1.23 \times 10^{-8} \frac{mol}{min}$ Molar Flow

$y_9 \cdot Q_9 \cdot mw = 3.16 \times 10^{-6} \frac{gm}{min}$ Mass Flow

Vent

$y_{11} \cdot Q_{11} = 1.16 \times 10^{-8} \frac{mol}{min}$ Molar Flow

$y_{11} \cdot Q_{11} \cdot mw = 3 \times 10^{-6} \frac{gm}{min}$ Mass Flow

Condensate

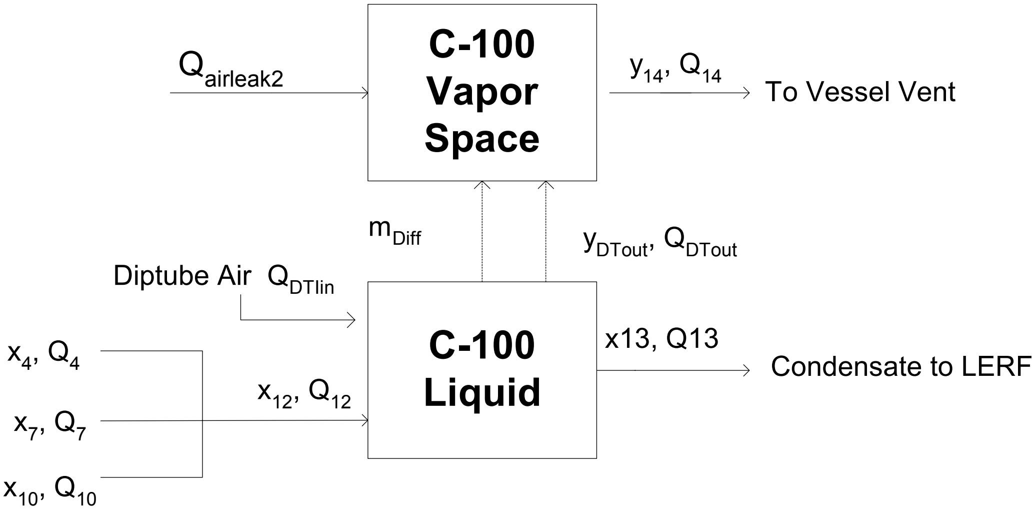
$x_{10} \cdot Q_{10} = 6.23 \times 10^{-10} \frac{mol}{min}$ Molar Flow

$x_{10} \cdot Q_{10} \cdot mw = 1.61 \times 10^{-7} \frac{gm}{min}$ Mass Flow

$DF := \frac{y_9 \cdot Q_9 \cdot mw}{x_{10} \cdot Q_{10} \cdot mw}$ = $\frac{\text{Feed}}{\text{Cond}}$ $DF = 19.7$

$\%volatalized := \frac{y_{11} \cdot Q_{11} \cdot mw}{y_9 \cdot Q_9 \cdot mw}$ = $\frac{\text{Vent}}{\text{Feed}}$ $\%volatalized = 94.9\%$

C-100 Diptubes



Define Temperature Unit

$\text{degC} \equiv 1$

Kelvin to Celsius: $c(k) := (k - 273.15)$ $\quad c(293.15) = 20\,\text{degC}$

Celsius to Kelvin: $k(c) := (c + 273.15)\cdot K$ $\quad k(20) = 293.15K$

The model of C-100 is in two parts: a diffusion emission and a diptube emission. The diptube emision is similar to others using Henry's Law.

$$x_{12}\cdot Q_{12} = x_4\cdot Q_4 + x_7\cdot Q_7 + x_{10}\cdot Q_{10}$$

Molar Flow

$$x4_{Q4} := 1.63\cdot 10^{-7}\cdot\frac{\text{mol}}{\text{min}}$$

$$x7_{Q7} := 4.02\cdot 10^{-10}\cdot\frac{\text{mol}}{\text{min}}$$

$$x10_{Q.10} := 6.23\cdot 10^{-10}\cdot\frac{\text{mol}}{\text{min}}$$

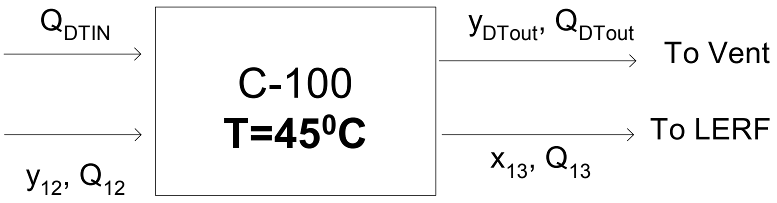
$x12_{Q12} := x4_{Q4} + x7_{Q7} + x10_{Q.10}$ $\quad x12_{Q12} = 1.64\times 10^{-7}\,\frac{\text{mol}}{\text{min}}$

Mass Flow

$mw := 258 \cdot \frac{gm}{mol}$ Molecular weight

$x12_{Q12} \cdot mw = 4.23 \times 10^{-5} \frac{gm}{min}$

Model the Diptubes



$P := 0.98 \cdot atm$ From Campaign 2001-01.

$T := c(318.15)$ $T = 45 \, degC$ From Campaign 2001-01.

$H := 88 \cdot atm$ At 45^{o}C.

$Q_{DTin} := 0.126 \frac{mol}{min}$ Air

$Q_{DTin} \cdot 0.0291 \cdot \frac{kg}{mol} = 3.67 \times 10^{-3} \frac{kg}{min}$ Mass Rate

Calculate the moisture to add to DT_{air}. At 45^{o}C, from Perry's, there is 0.0654 (kg H_2O)/(kg air). Moisture is 3.67×10^{-3} kg/min (0.0654 (kg H_2O)/(kg air) = 2.4×10^{-4} kg H_2O/min.
This converts to (molar):

$$moisture := \frac{2.4 \cdot 10^{-4} \cdot \frac{kg}{min}}{18 \cdot \frac{gm}{mol}} \qquad moisture = 0.0133 \frac{mol}{min}$$

$Q_{DTout} := Q_{DTin} + moisture$ $Q_{DTout} = 0.139 \frac{mol}{min}$

$Q_{13} := 10731 \cdot \frac{mol}{min}$

$$y_{DTout} := \frac{x12Q12}{\left(\frac{P \cdot Q_{13}}{H} + Q_{DTout}\right)}$$ $$y_{DTout} = 1.37 \times 10^{-9}$$

Vent

$$y_{DTout} \cdot Q_{DTout} = 1.91 \times 10^{-10} \frac{mol}{min}$$ Molar Flow

$$y_{DTout} \cdot Q_{DTout} \cdot mw = 4.93 \times 10^{-8} \frac{gm}{min}$$ Mass Flow

$$x_{13} := \frac{y_{DTout} \cdot P}{H}$$ $$x_{13} = 1.53 \times 10^{-11}$$

Condensate to LERF

$$x_{13} \cdot Q_{13} = 1.64 \times 10^{-7} \frac{mol}{min}$$ Molar Flow

$$x_{13} \cdot Q_{13} \cdot mw = 4.23 \times 10^{-5} \frac{gm}{min}$$ Mass Flow

$$DF := \frac{x12Q12}{x_{13} \cdot Q_{13}}$$ = Feed rate / Cond rate $$DF = 1.0012$$

$$\%volatalized := \frac{y_{DTout} \cdot Q_{DTout} \cdot mw}{x12Q12 \cdot mw}$$ = Vent rate / Feed rate $$\%volatalized = 0.12\%$$

C-100 Diffusion

Define Units

$\mathrm{degC} \equiv 1$

Kelvin to Celsius: $c(k) := (k - 273.15)$ $c(293.15) = 20\,\mathrm{degC}$

Celsius to Kelvin: $k(c) := (c + 273.15)\cdot K$ $k(20) = 293.15K$

$\mathrm{scfm} \equiv \dfrac{ft^3}{min}$

$\mu g \equiv \dfrac{gm}{10^6}$

The diffusion rate is given by $m = J\cdot A$

Where: m = mass rate (gm/min)
J = Diffusion flux (gm/cm^2 sec)
A = Surface Area

J is determined by the formula $J = K\cdot\left(c - \dfrac{c_{air}}{H}\right)$

Where: K = overall transfer rate (cm/sec)
c = concentration in liquid (gm/cm^3)
c_{air} = concentration in air (gm/cm^3)
H = Henry's law (dimensionless version)

K is determined by the formula $K = \dfrac{k_g\cdot k_l}{k_g + k_l\cdot H}$

Where: k_g = gas phase diffusion (cm/sec)
k_l = liquid phase diffusion (cm/sec)
H = Henry's law (dimensionless version)

The gas diffusion is the velocity in the vapor space (since airflow is much greater than natural diffusion). The liquid phase is determined by the formula:

$$k_l = \sqrt{\frac{D\cdot\nu}{h}}$$

Where: D = water phase diffusion (cm^2/sec)
ν = liquid velocity (cm/sec)
h = height of liquid in tank

D is determined by the correlation $D = \dfrac{13.26\,10^{-5}}{\mu^{1.14} \cdot v^{0.589}}$

Where: μ = viscosity (cp)
v = specific molar volume, 247.3 cm^3/mol
D = diffusion (cm^2/sec)

The calculation consists of the following steps:

1) Calculate k_g using air velocity in tank
2) Calculate D using assumed viscosity
3) Calculate k_l using a water velocity, D and h
4) Calculate K from k_g and k_l
5) Calculate J from K (assume c_{air} = 0)
6) Calculate m from J and tank surface area (A)

1) For air velocity, use airflow in tank divided by surface area, A.

$d := 4.3 \cdot m$ Tank diameter per RCRA permit.

$A := \frac{\pi}{4} \cdot d^2$ $A = 1.45 \times 10^5\ cm^2$

$airflow := 150 \cdot scfm$ $airflow = 7.08 \times 10^4\ \frac{cm^3}{sec}$ Air inleakage

$k_g := \frac{airflow}{A}$ $k_g = 0.487 \frac{cm}{sec}$ Air velocity

2) $\mu := 0.641\ cP$ At 45°C for H_2O (Literature)

$v := 247.3\ \frac{cm^3}{mol}$

$D := \frac{13.26\,10^{-5}}{\mu^{1.14} \cdot v^{0.589}} \cdot \frac{cm^2}{sec}$ $D = 8.57 \times 10^{-6}\ \frac{cm^2}{sec}$

3) ν : the volumetric flow divided by the surface area; there is no agitation in the tank.

$Q_{12} := 193 \cdot \frac{kg}{min}$ Mass flow into the tank

$\rho := 1.0 \cdot \frac{kg}{L}$ Density of this flow

$volumetric_{flow} := \frac{Q_{12}}{\rho}$ $volumetric_{flow} = 3.22 \times 10^{3} \frac{cm^{3}}{sec}$

$\nu := \frac{volumetric_{flow}}{A}$ $\nu = 0.0222 \frac{cm}{sec}$

$h := 7.5 \cdot ft$ $h = 229 cm$ From operating experience at 50% level.

$k_{l} := \sqrt{\frac{D \cdot \nu}{h}}$ $k_{l} = 2.88 \times 10^{-5} \frac{cm}{sec}$

4) Convert H to dimensionless: [H(dimensionless) = H (mol/dm$^{3}\cdot$atm)$\cdot$ (RT)]

$R := 0.08206 \frac{L \cdot atm}{mol \cdot K}$

$T := 318 \cdot K$ 45^{o}C

$H := 3.0 \cdot \frac{mol}{L \cdot atm} \cdot R \cdot T$ $H = 78$

$K := \frac{k_{l} \cdot k_{g}}{k_{g} + \frac{k_{l}}{H}}$ $K = 2.88 \times 10^{-5} \frac{cm}{sec}$

Note that K is approximately equal to k_{l}. This means liquid phase diffusion is limiting.

5) Assume c_{air}/H << c, so J = Kc.

Determine c (concentration in liquid (gm/cm^{3})

$x12_{Q12} := 1.64 \cdot 10^{-7} \cdot \frac{mol}{min}$ PCB molar flow rate

$mw := 258 \cdot \frac{gm}{mol}$

$x12_{Q12} \cdot mw = 4.23 \times 10^{-5} \frac{gm}{min}$ PCM mass flow rate

$volumetric_{flow} = 3.22\times 10^{3}\,\frac{cm^{3}}{sec}$ Calculated in step 3 above.

$c := \frac{x12_{Q12}\cdot mw}{volumetric_{flow}}$ $c = 2.19\times 10^{-10}\,\frac{gm}{cm^{3}}$

$J := K\cdot c$ $J = 6.32\times 10^{-15}\,\frac{gm}{cm^{2}\cdot sec}$

6) $m := J\cdot A$ $m = 5.51\times 10^{-8}\,\frac{gm}{min}$

Compare this with liquid mass rate of $4.24\text{x}10^{-5}$ gm/min.

$DF := \frac{x12_{Q12}\cdot mw}{x12_{Q12}\cdot mw - m}$ $DF = 1.0013$

$\%volatalized := \frac{m}{\left(x12_{Q12}\cdot mw\right)}$ $\%volatalized = 0.13\%$

Combined Dip Tube and Diffusion

$DipTubevent_{massrate} := 4.94\cdot 10^{-8}\cdot\frac{gm}{min}$

$Combined_{DTDiffusion} := m + DipTubevent_{massrate}$ $Combined_{DTDiffusion} = 1.04\times 10^{-7}\,\frac{gm}{min}$

$LERF_{rate} := \left(x12_{Q12}\cdot mw\right) - Combined_{DTDiffusion}$ $LERF_{rate} = 4.22\times 10^{-5}\,\frac{gm}{min}$

$Liquid_{conc} := \frac{x12_{Q12}\cdot mw}{\frac{Q_{12}}{\rho}}$ $Liquid_{conc} = 2.19\times 10^{-7}\,\frac{gm}{L}$

$Liquid_{conc} = 0.22\,\frac{\mu g}{L}$ to LERF

$C100_{ventconc} := \frac{Combined_{DTDiffusion}}{airflow}$ $C100_{ventconc} = 2.46\times 10^{-14}\,\frac{gm}{cm^{3}}$

C-100 Vent Concentration

$$\mathrm{vent}_{\mathrm{conc}} := \frac{\mathrm{Combined}_{\mathrm{DTDiffusion}}}{\mathrm{airflow}} \qquad \mathrm{vent}_{\mathrm{conc}} = 2.46\times 10^{-14}\,\frac{\mathrm{gm}}{\mathrm{cm}^3}$$

Note: In step 5 assumed $c_{air}/H << c$.

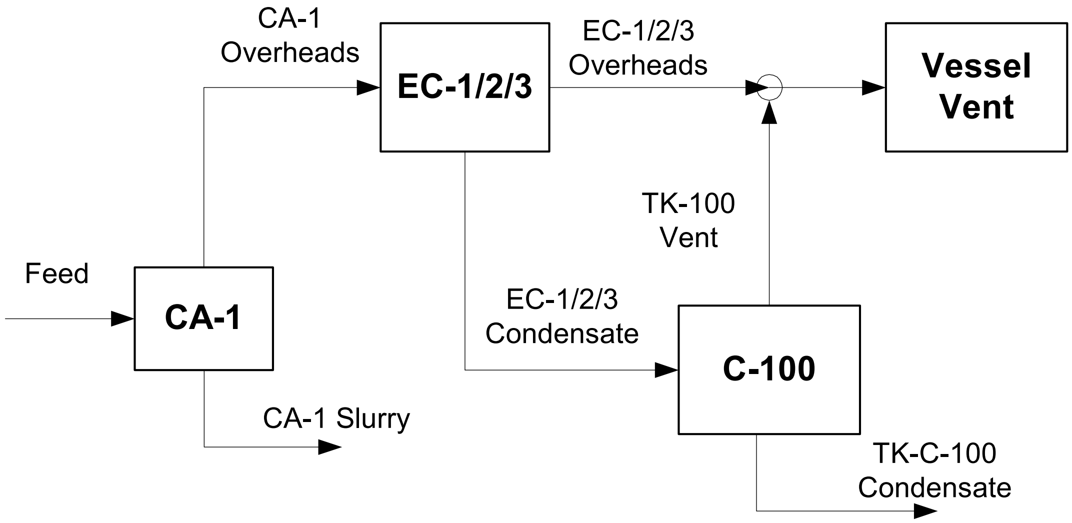
$$c_{air} := 2.46\cdot 10^{-14}$$

$\frac{c_{air}}{H}$ = 3.2x10^{-16} which is << 2.19x10^{-10} gm/cm^3.

$$\mathrm{DF}_{\mathrm{total}} := \frac{\mathrm{x12}_{\mathrm{Q12}}\cdot \mathrm{mw}}{(\mathrm{x12}_{\mathrm{Q12}}\cdot \mathrm{mw}) - \mathrm{Combined}_{\mathrm{DTDiffusion}}} \qquad \mathrm{DF}_{\mathrm{total}} = 1.0025$$

$$\%\mathrm{volatalized} := \frac{\mathrm{Combined}_{\mathrm{DTDiffusion}}}{(\mathrm{x12}_{\mathrm{Q12}}\cdot \mathrm{mw})} \qquad \%\mathrm{volatalized} = 0.25\%$$

Overall Results



Define Units

$$\mu g \equiv \frac{gm}{10^6}$$

PCB rates:

$$CA1_{feedrate} := 4.54\cdot 10^{-5}\cdot\frac{gm}{min}$$

$$CA1_{overheads} := 4.54\cdot 10^{-5}\cdot\frac{gm}{min}$$

$$CA1_{slurry} := 7.39\cdot 10^{-9}\cdot\frac{gm}{min}$$

To Tank Farms

$$\%CA1_{overheads} := \frac{CA1_{overheads}}{CA1_{feedrate}}$$

$$\%CA1_{overheads} = 100\%$$

Note: $\%CA1_{overheads}$ rounds to 100%. Actual number is 99.98%

$$EC123_{feed} := 4.54\cdot 10^{-5}\cdot\frac{gm}{min}$$

$$EC123_{overheads} := 2.98\cdot 10^{-6}\cdot\frac{gm}{min}$$

$$EC123_{condensate} := 4.24\cdot 10^{-5}\cdot\frac{gm}{min}$$

$\%EC123_{overheads} := \frac{EC123_{overheads}}{EC123_{feed}}$ $\%EC123_{overheads} = 7\%$

$C100_{feed} := 4.24 \cdot 10^{-5} \cdot \frac{gm}{min}$

$C100_{vent} := 1.05 \cdot 10^{-7} \cdot \frac{gm}{min}$

$C100_{condesate} := 4.23 \cdot 10^{-5} \cdot \frac{gm}{min}$

$\%C100_{vent} := \frac{C100_{vent}}{C100_{condesate}}$ $\%C100_{vent} = 0.25\%$

To Vessel Vent

$\text{Vessel}_{\text{vent}} := \text{EC123}_{\text{overheads}} + \text{C100}_{\text{vent}}$ $\text{Vessel}_{\text{vent}} = 3.08\times 10^{-6}\,\frac{\text{gm}}{\text{min}}$

Determine % slurry, condesate, vent

$\text{Vessel}_{\text{vent}} = 5.14\times 10^{-8}\,\frac{\text{gm}}{\text{sec}}$

$\text{CA1}_{\text{slurry\%}} := \frac{\text{CA1}_{\text{slurry}}}{\text{CA1}_{\text{feedrate}}}$ $\text{CA1}_{\text{slurry\%}} = 0.016\%$

$\%_{\text{cond}} := \frac{\text{C100}_{\text{condesate}}}{\text{CA1}_{\text{feedrate}}}$ $\%_{\text{cond}} = 93\%$

$\%_{\text{vent}} := \frac{\text{Vessel}_{\text{vent}}}{\text{CA1}_{\text{feedrate}}}$ $\%_{\text{vent}} = 6.8\%$

Calculate slurry, condesate and vent concentrations

$\text{feed}_{\text{flow}} := 60\cdot\frac{\text{gal}}{\text{min}}$

Condensate Flow = boiloff + steam jet flow

Slurry flow = feed - boiloff

Boiloff is 81% (Campaign 01-01)

$\text{Slurry}_{\text{flow}} := \text{feed}_{\text{flow}}\cdot(1 - 0.81)$ $\text{Slurry}_{\text{flow}} = 11.4\,\frac{\text{gal}}{\text{min}}$

$\text{Condensate}_{\text{flow}} := \text{feed}_{\text{flow}}\cdot 0.81 + (1.23 + 1.23)\cdot\frac{\text{gal}}{\text{min}}$ $\text{Condensate}_{\text{flow}} = 51\,\frac{\text{gal}}{\text{min}}$

$\text{Slurry}_{\text{conc}} := \frac{\text{CA1}_{\text{slurry}}}{\text{Slurry}_{\text{flow}}}$ $\text{Slurry}_{\text{conc}} = 1.71\times 10^{-4}\,\frac{\mu\text{g}}{\text{L}}$

$\text{Condensate}_{\text{conc}} := \frac{\text{C100}_{\text{condesate}}}{\text{Condensate}_{\text{flow}}}$ $\text{Condensate}_{\text{conc}} = 0.22\,\frac{\mu\text{g}}{\text{L}}$

Note that the concentration of PCB in the PC is greater than the feed. This is because about 90% of the PCB is in the PC, but only 80% of the volume.

$\text{Vesselvent}_{\text{flow}} := 550\cdot\frac{\text{ft}^3}{\text{min}}$ from annual flow checks

$\text{Vent}_{\text{conc}} := \frac{\text{Vessel}_{\text{vent}}}{\text{Vesselvent}_{\text{flow}}}$ $\text{Vent}_{\text{conc}} = 0.198\,\frac{\mu\text{g}}{\text{m}^3}$