DEN5406: Mass Transfer and Separations Processes I

Week 8: Adsorption, Stripping

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McCabe-Thiele Analysis

Graphical Determination of # of equilibrium stages:

First:

Construct a staircase

Between

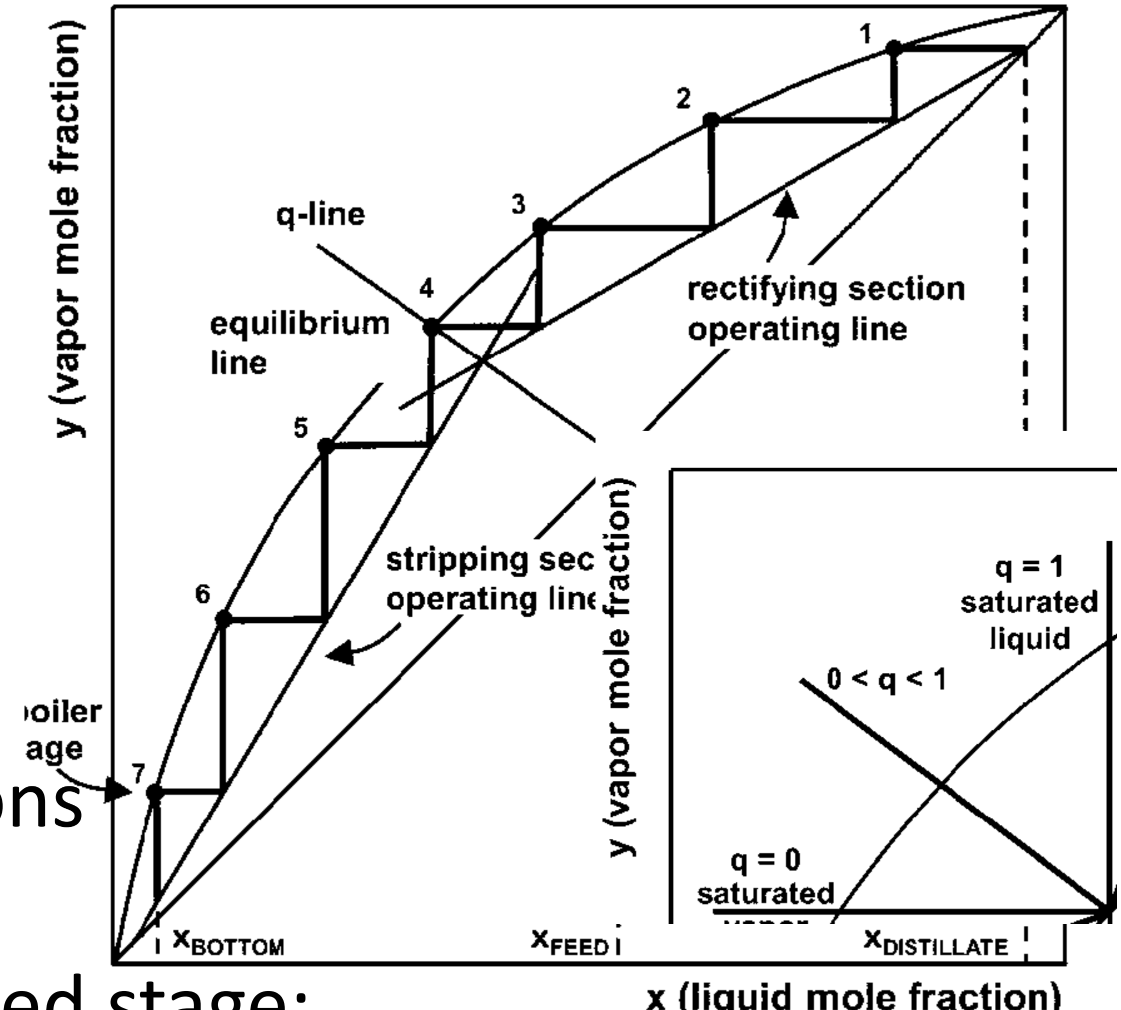
Operating lines and

Equilibrium curve.

Horizontals – equil.

Verticals – compositions

Passing each other

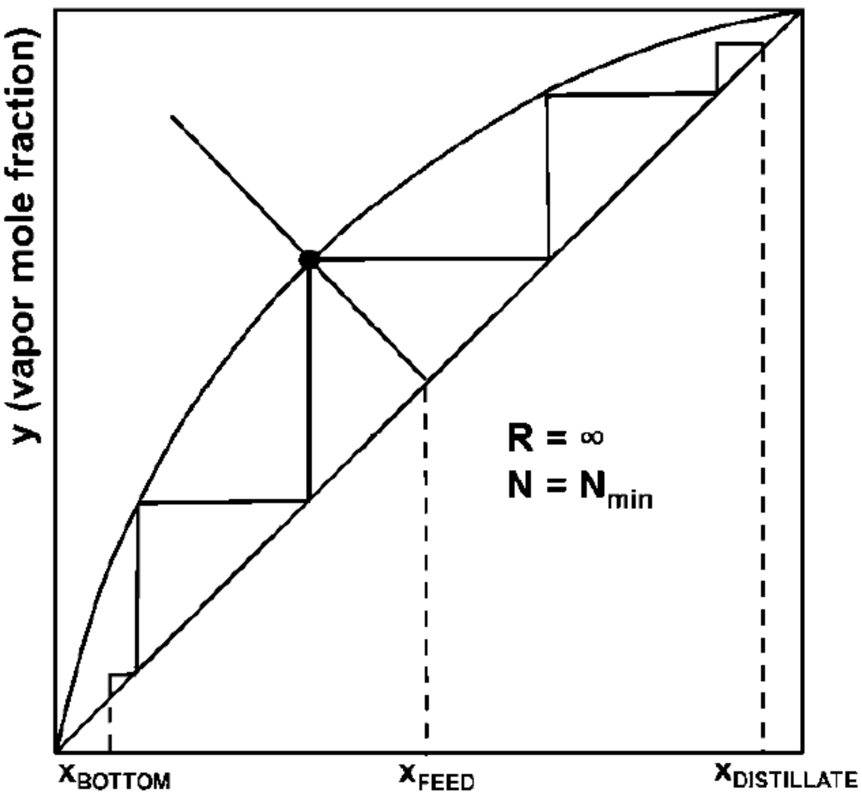


Optimal location of feed stage:

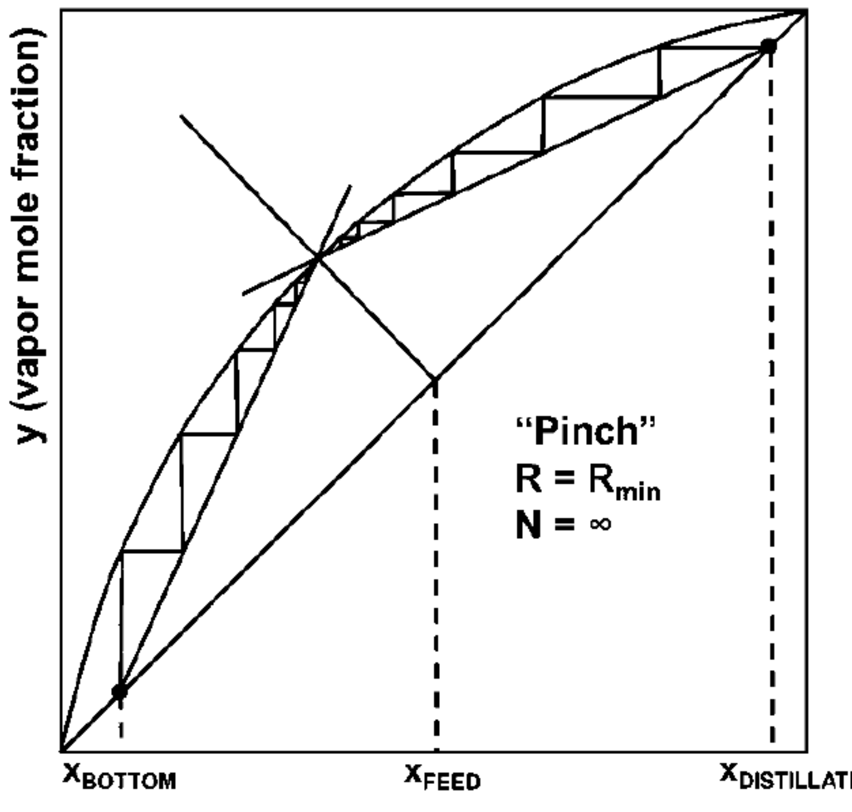
First location after horizontal crosses the q-line.

McCabe-Thiele Analysis

Minimum # stages vs. Minimum reflux ratio

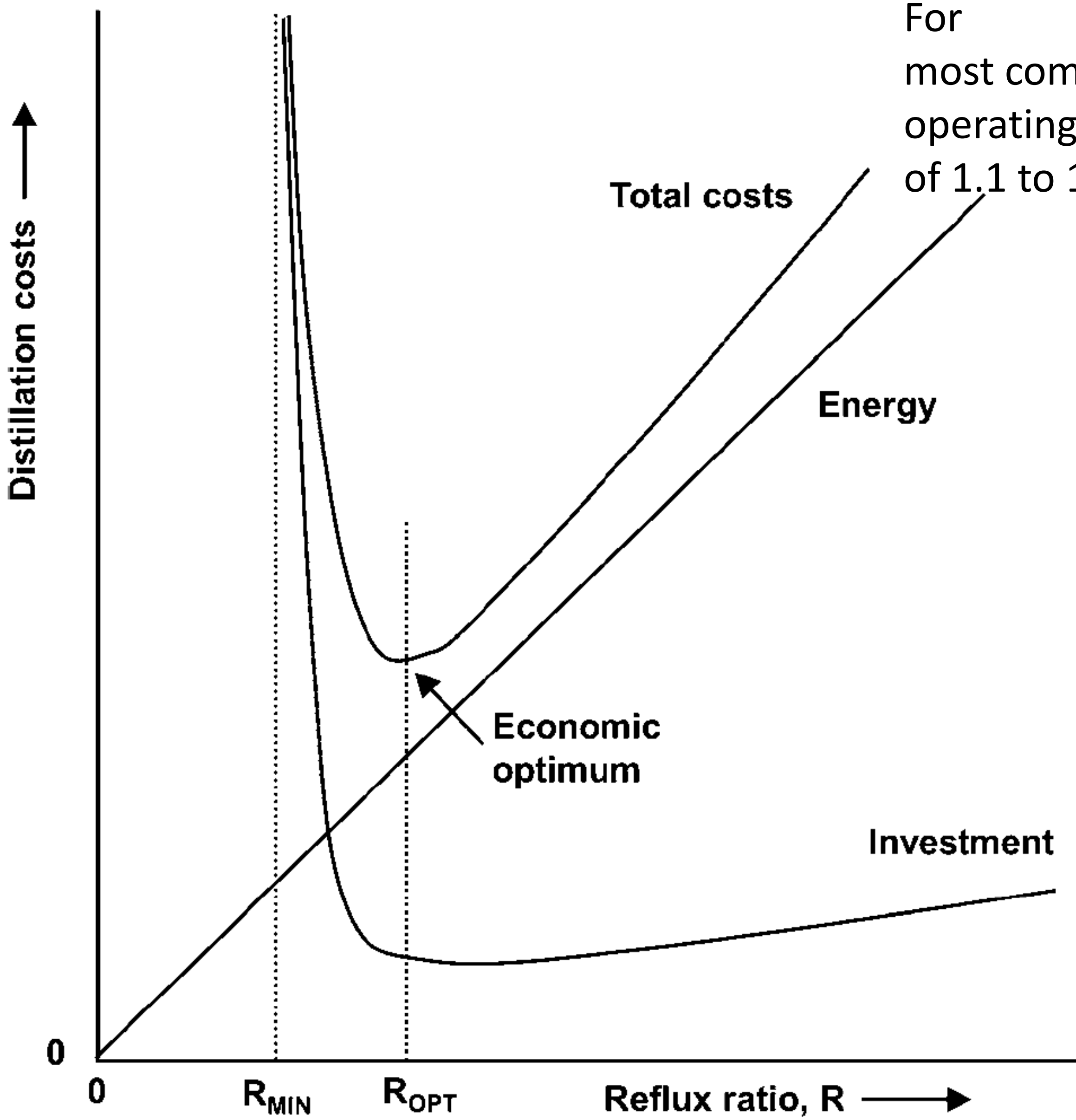


(a)



(b)

McCabe-Thiele Analysis



For
most commercial operations the optimal
operating reflux ratios are in the range
of 1.1 to 1.5 times the minimum reflux ra

Operational cost

McCabe-Thiele Analysis

$$R_{\min} = \left(\frac{L'}{D}\right)_{\min} = \left(\frac{L'}{V' - L'}\right)_{\min} = \frac{\left(\frac{L'}{V'}\right)_{\min}}{1 - \left(\frac{L'}{V'}\right)_{\min}}$$

For most commercial operations the optimal operating reflux ratios are in the range of 1.1 to 1.5 times the minimum reflux ratio.

Operational cost

McCabe-Thiele Analysis

$$y = -\frac{L}{V}x + \left(1 + \frac{L}{V}\right)z$$

Dimensionless Operating Line Equation

R = L/V and graphically:

Distillation Problems

Practice

How was it solving the practical problems?

Separations and Syllabus Goals

Obtain Quantitative Understanding of the following processes:

- ✔ **Filtration - ✔ we started and continue!** **We'll also cover this week:**
- **Aggregation**
- ✔ **Centrifugation**
- **Crystallization (controlled freezing) separation**
- **Adsorption** ✔
- ✔ **Leaching (extracting metals from ores, making coffee, dry cleaning)**
- ✔ **Osmosis**
  - **Forward Osmosis**
  - **Reverse Osmosis**
- **Ion-exchange membranes**

- **Drying**

- ✔ **Distillation (controlled evaporation and condensation)**
  and the many kinds of distillation

Applications: Surviving in Space, on a desert island without fresh water

What we will cover

By the end of this lecture you'll be able to: **Imagine you are Tom Hanks, and you actually have to repair a CO_2 scrubber to survive in space (or underground)**.

Say what are different kinds of **stripping.** Other vocabulary: **countercurrent flow, spray and bubble columns, column with internals, Raschig rings, structured packing, back mixing of gas, regeneration, desorption mechanisms, Lean solvent, pressure reduction, gas purification vs. product recovery, minimum adsorbent flow rate, liquid flooding, downcomer flooding,**

Calculation of the minimum L/V ratio (given initial and final purities)

Determine a realistic operating line

Perform McCabe-Thiele analysis to find the number of stages needed

Efficiency and cost comparisons –
optimum balance of the operating line condition is often 1.5-2* $(L/V)_{min}$

Recommended Reading

Available on Knovel – in the library:
De Haan & Bosch, Industrial Separation Processes, 2013, de Gruyter (Berlin)

Distillation Fundamentals and Principles, Gorak & Sorensen, eds., 2014, Elsevier

Reactive & Membrane-Assisted Separations, Lutze & Gorak, eds., 2016, de Gruyter

Also from
Seader, Henley, & Roper, Separations Process Principles, 2011, Wiley

Will assign pre-class reading -> will have a chance to discuss problems in class

Absorption and stripping:
Ch. 3 in
De Haan & Bosch, Industrial Separation Processes, 2013, de Gruyter (Berlin)

Absorption Applications

Gas purification

Impurity	Process	Absorbent
Ammonia	Indirect Process (Coke Oven Gas)	Water
Carbon Dioxide and Hydrogen Sulfide	Ethanolamine	Mono- or Diethanolamine in Water
	Benfield	Potassium Carbonate and Activator in Water
	Selexol	Polyethylene Glycol Dimethyl Ether
Carbon Monoxide	Copper Ammonium Salt	Cuprous Ammonium Carbonate and Formate in Water
Hydrogen Chloride	Water Wash	Water
Toluene	Toluene Scrubber	Toluene
Cyclohexane	Scrubber	Cyclohexane

vs. Product recovery

Product	Process	Absorbent
Acetylene	Steam Cracking of Hydrocarbons (Naphtha)	Dimethylformamide
Acrylonitrile	Ammoxidation of Propylene	Water
Maleic Anhydride	Butane Oxidation	Water
Melamine	Urea Decomposition	Water
Nitric Acid	Ammonia Oxidation (NO_x Absorption)	Water
Sulfuric Acid	Contact Process (SO_3 Absorption)	Water
Urea	Synthesis (CO_2 and NH_3 Absorption)	Ammonium Carbamate Solution

3 types of absorption

1. Physical solution. In this case, the component being absorbed is more soluble in the liquid absorbent than the other gases with which it is mixed but does not react chemically with the absorbent. As a result, the equilibrium concentration in the liquid phase is primarily a function of partial pressure in the gas phase and temperature. Examples are the drying of natural gas with diethylene glycol or the recovery of ethylene oxide and acrylonitrile with water from the reactor product stream.
2. Reversible reaction. This type of absorption is characterized by the occurrence of a chemical reaction between the gaseous component being absorbed and a component in the liquid phase to form a compound that exerts a significant vapor pressure of the absorbed component. The most important industrial example is the removal of acid gases (CO_2, H_2S) with mono- or diethanolamine solutions.
3. Irreversible reaction. In this case, a reaction occurs between the component being absorbed and a component in the liquid phase, which is essentially irreversible. Sulfuric acid and nitric acid production by SO_3 and NO_2 absorption in water is the most widely used example of this application.

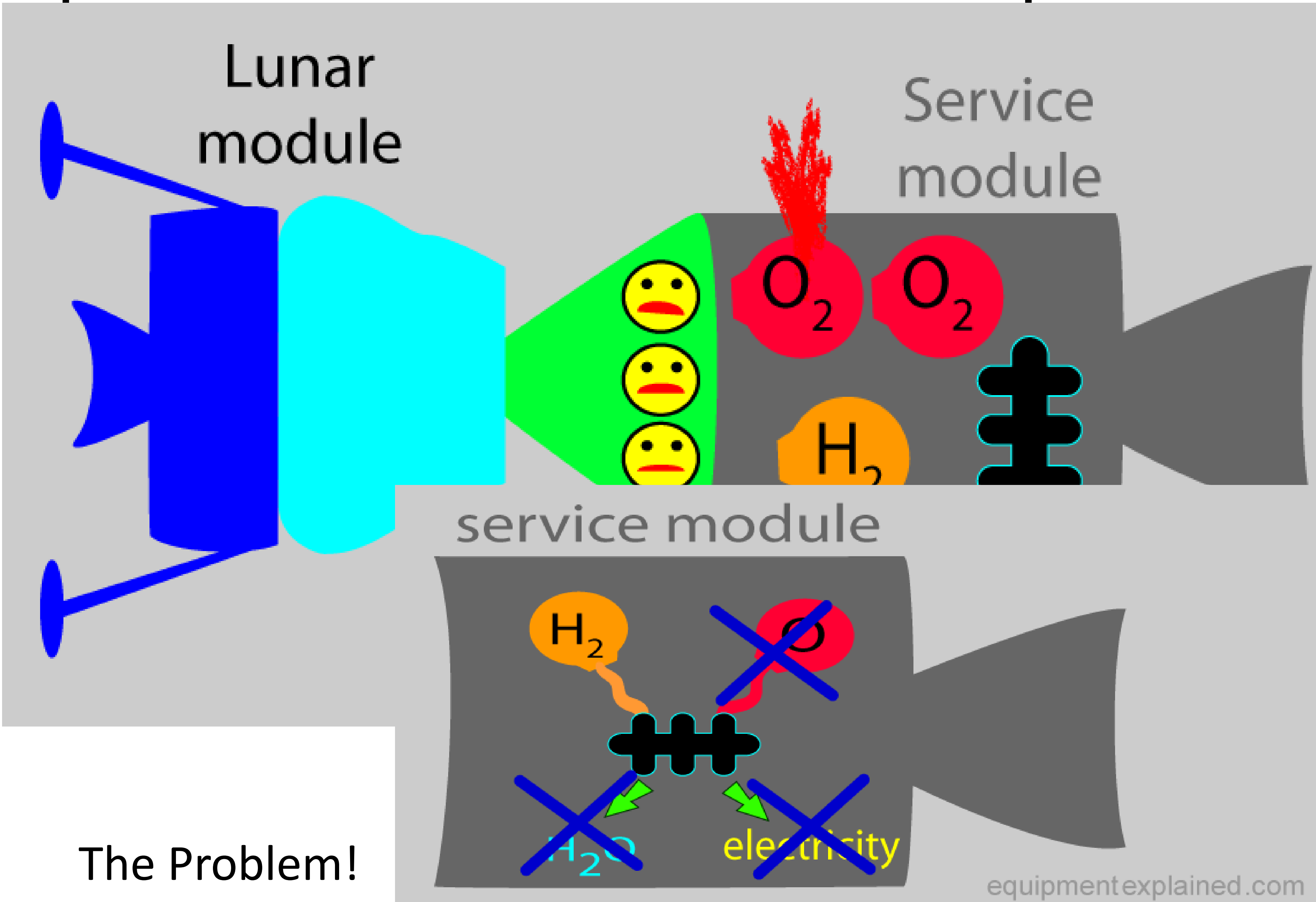
Can we make this more interesting?

Absorption and Stripping

Way to make Chem E impactful and sexy. And true!

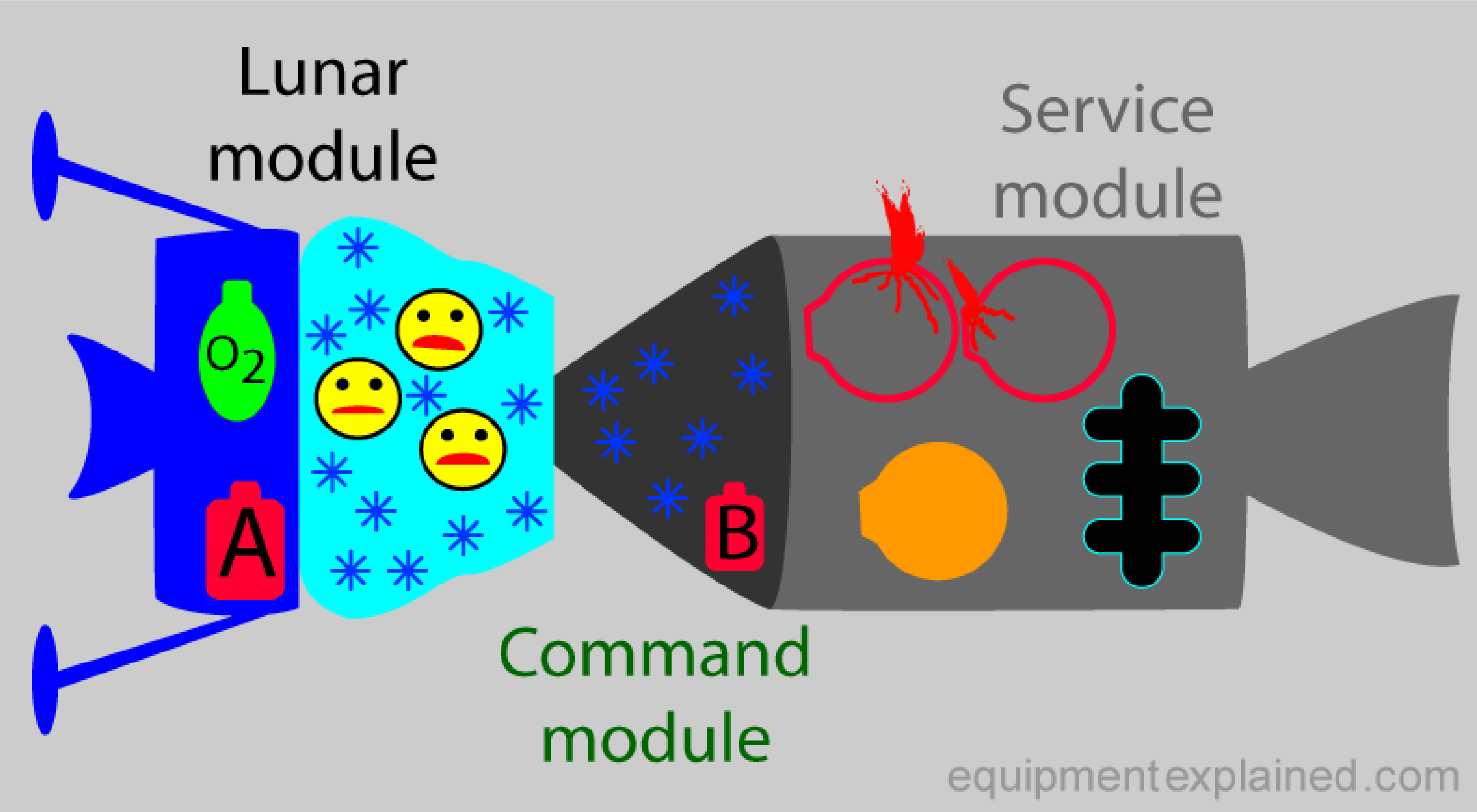
Would you survive?

Apollo13 – Houston we have a problem



The Problem!

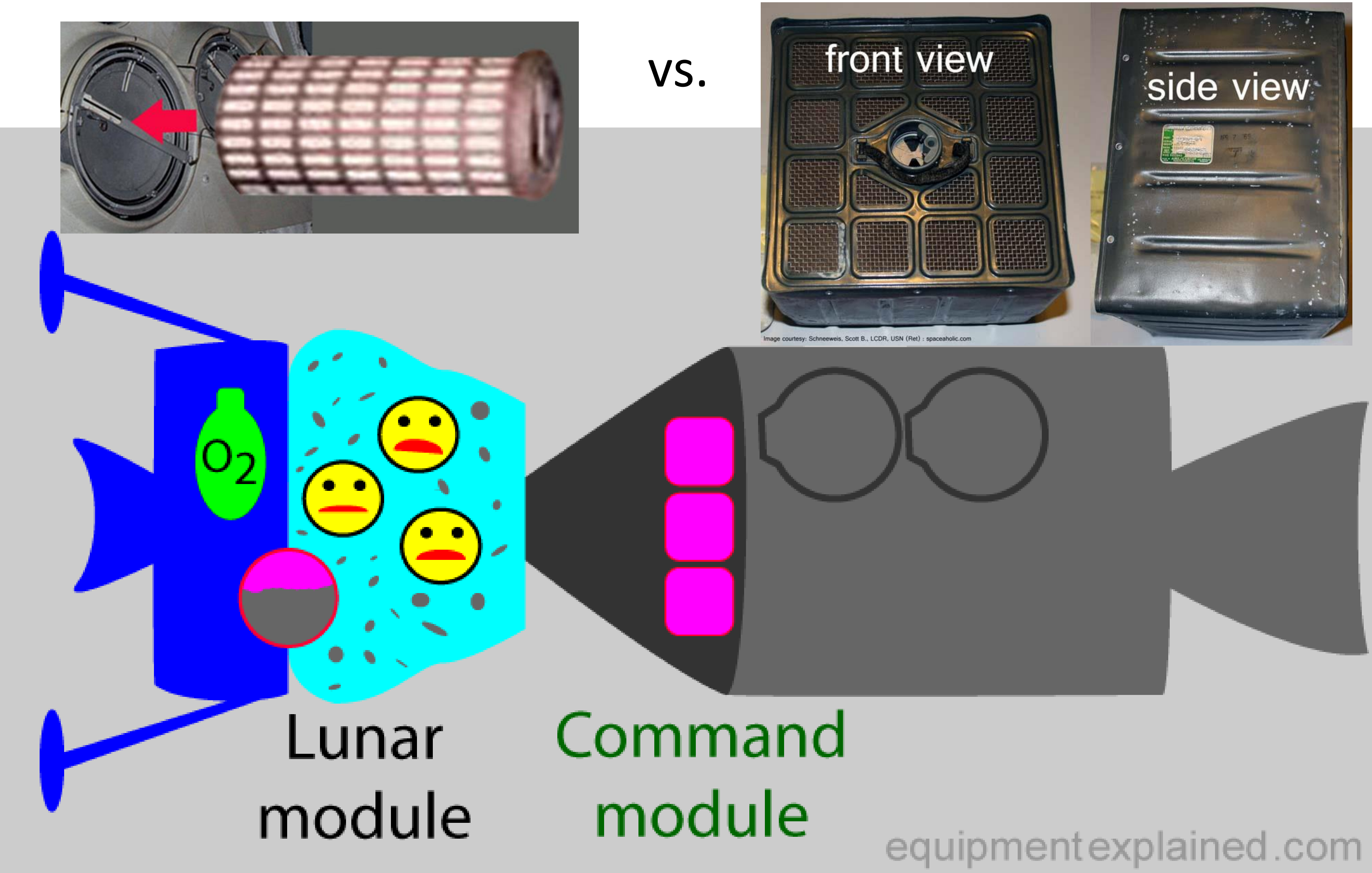
Apollo13 – Houston we have a problem



The Power Problem!

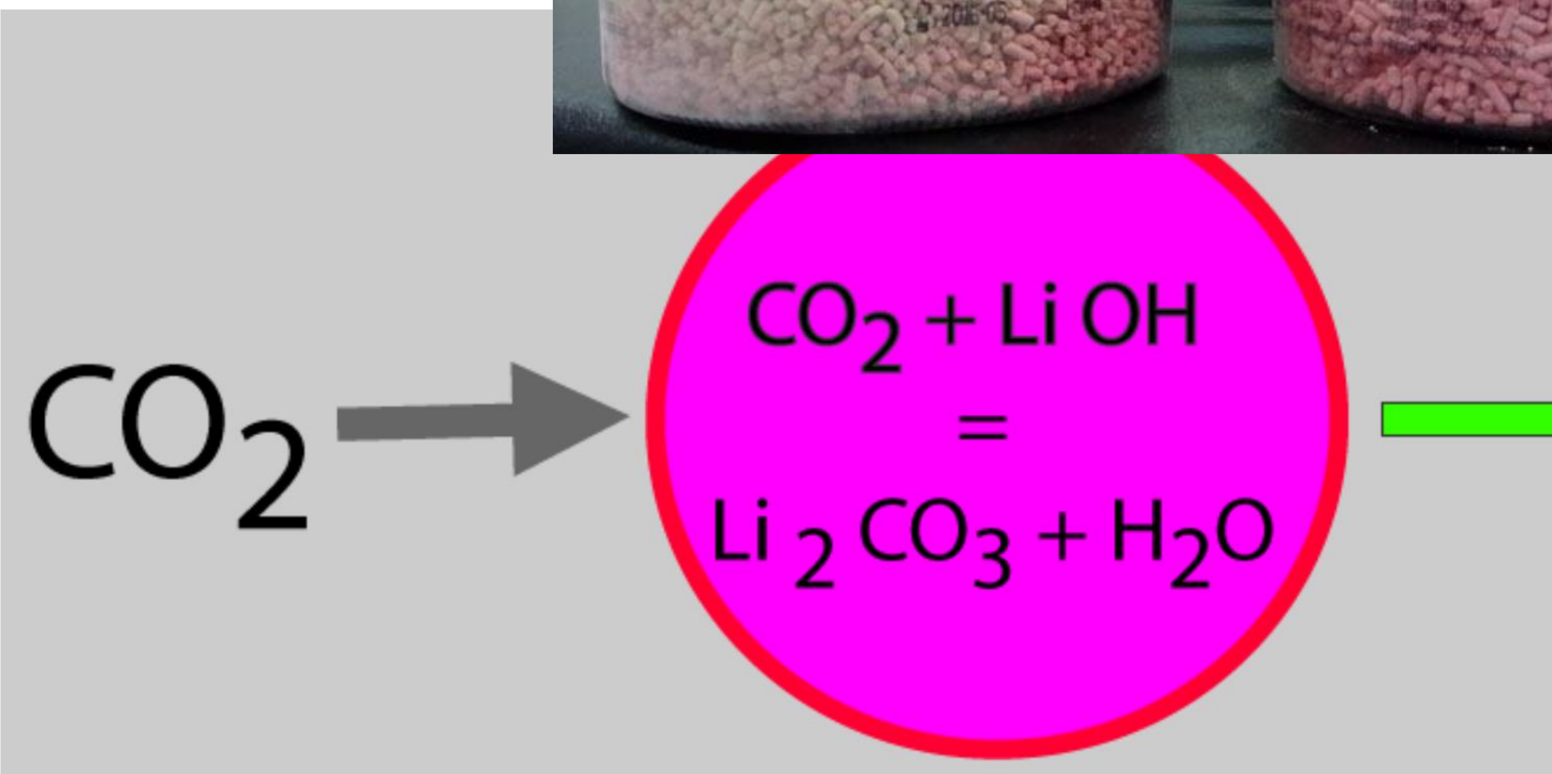
https://www.howequipmentworks.com/apollo_13/

Apollo13 – Houston we have a problem



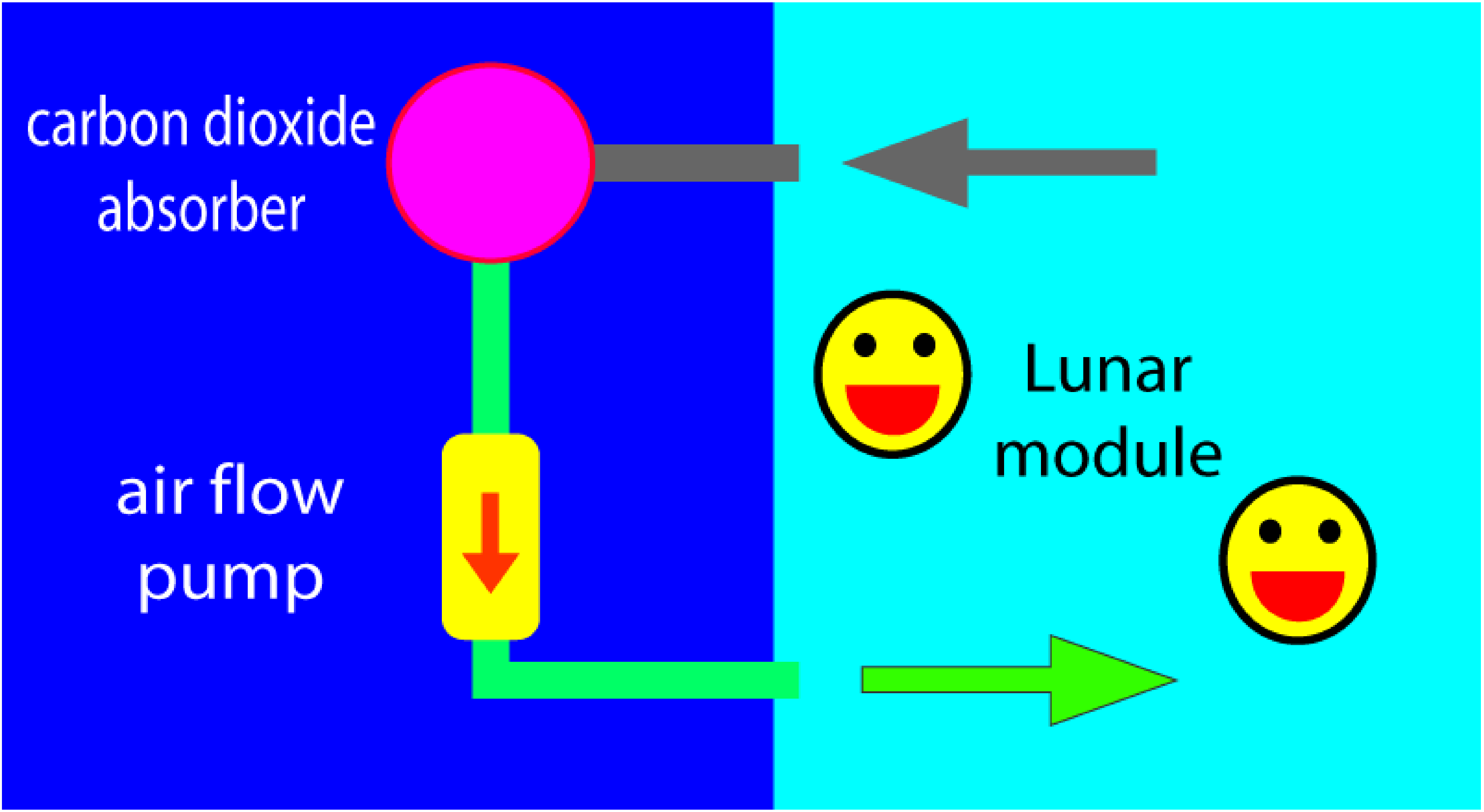
The Scrubber Problem. + Notice Different shapes of scrubbers

Absorption and Stripping



Scrubbing reaction. Problem – after oxygen tank explosion, astronauts exhausted the CO2 scrubbers in the lunar module

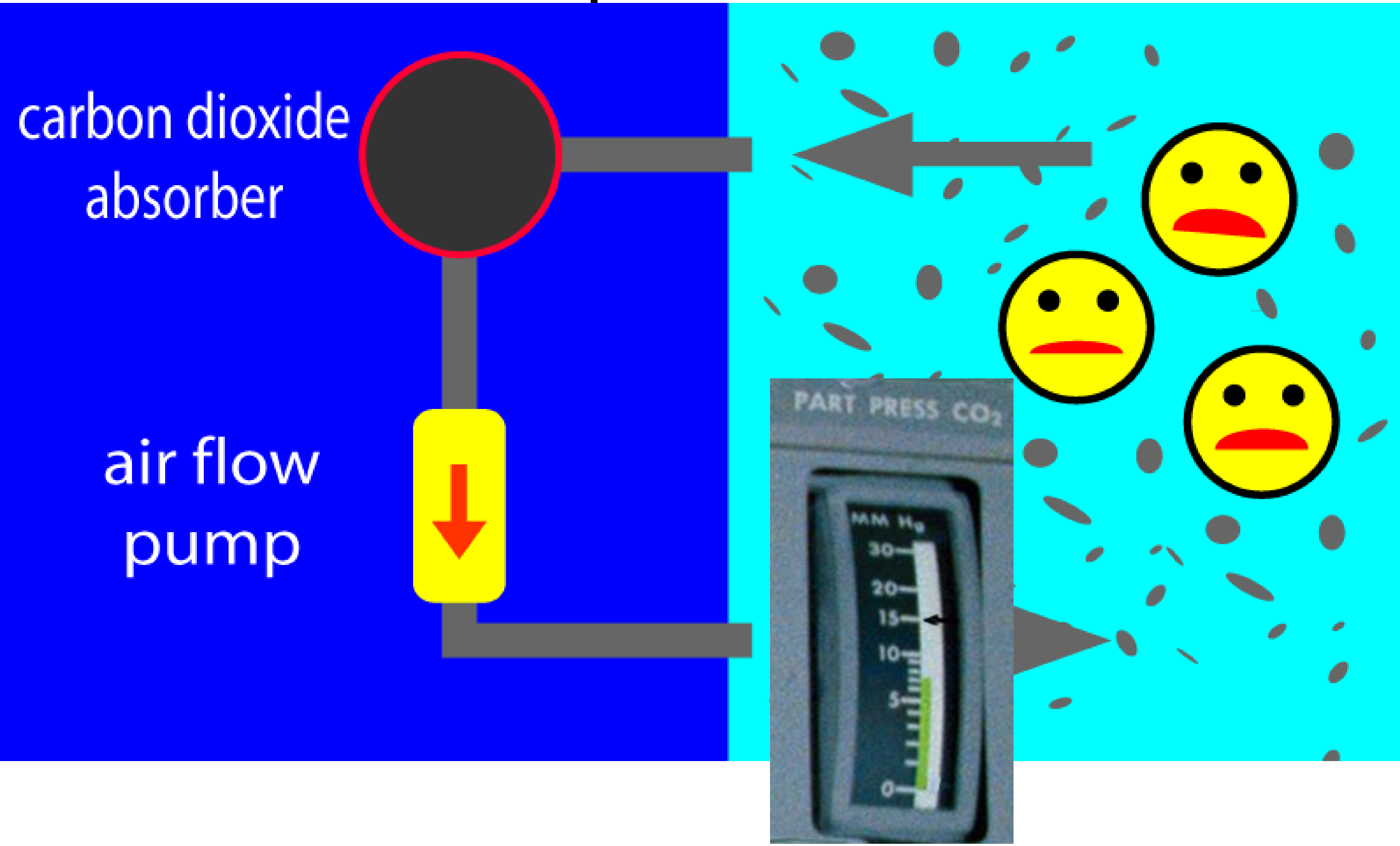
Apollo 13



Initial solution

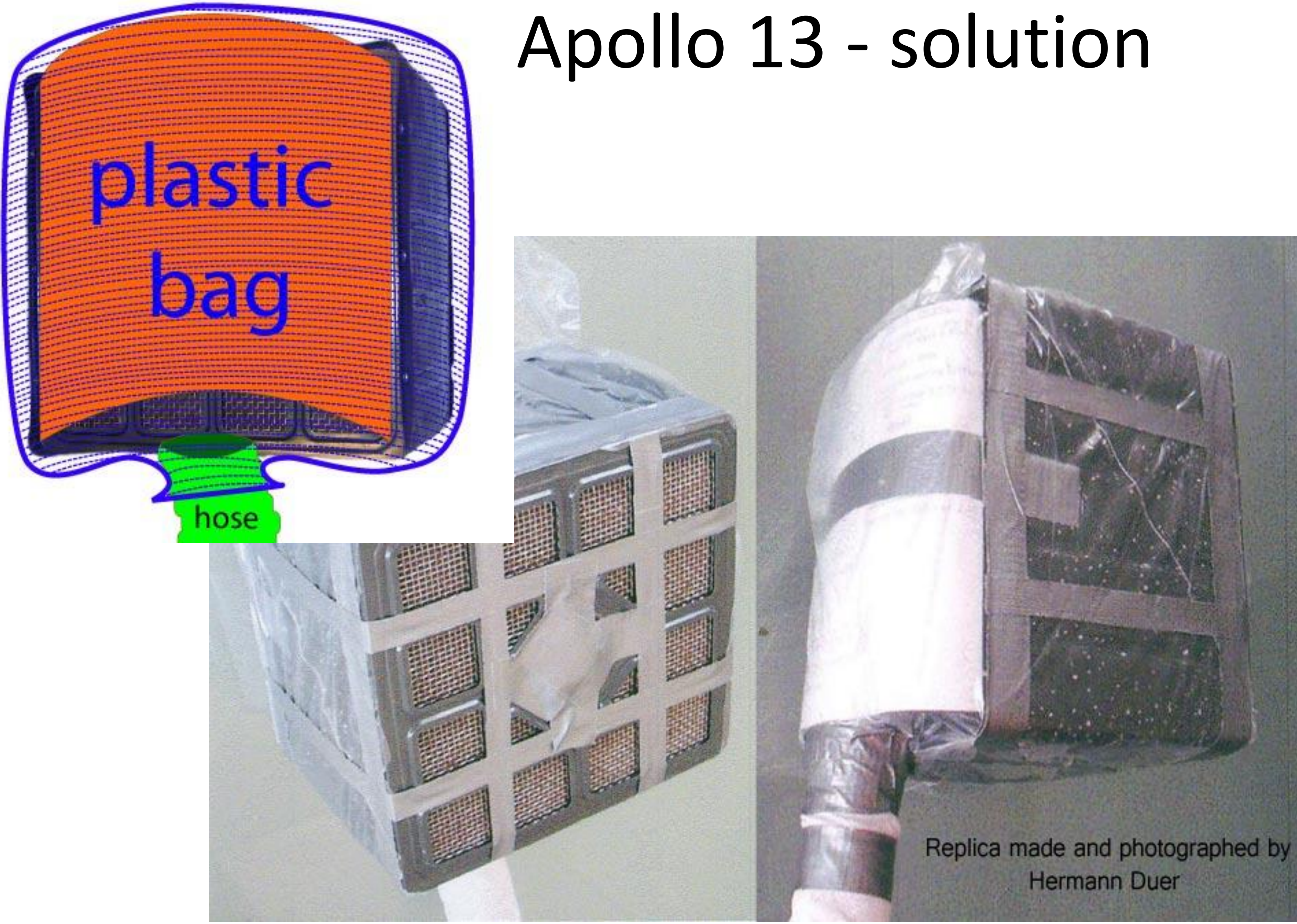
https://www.howequipmentworks.com/apollo_13/

Apollo 13



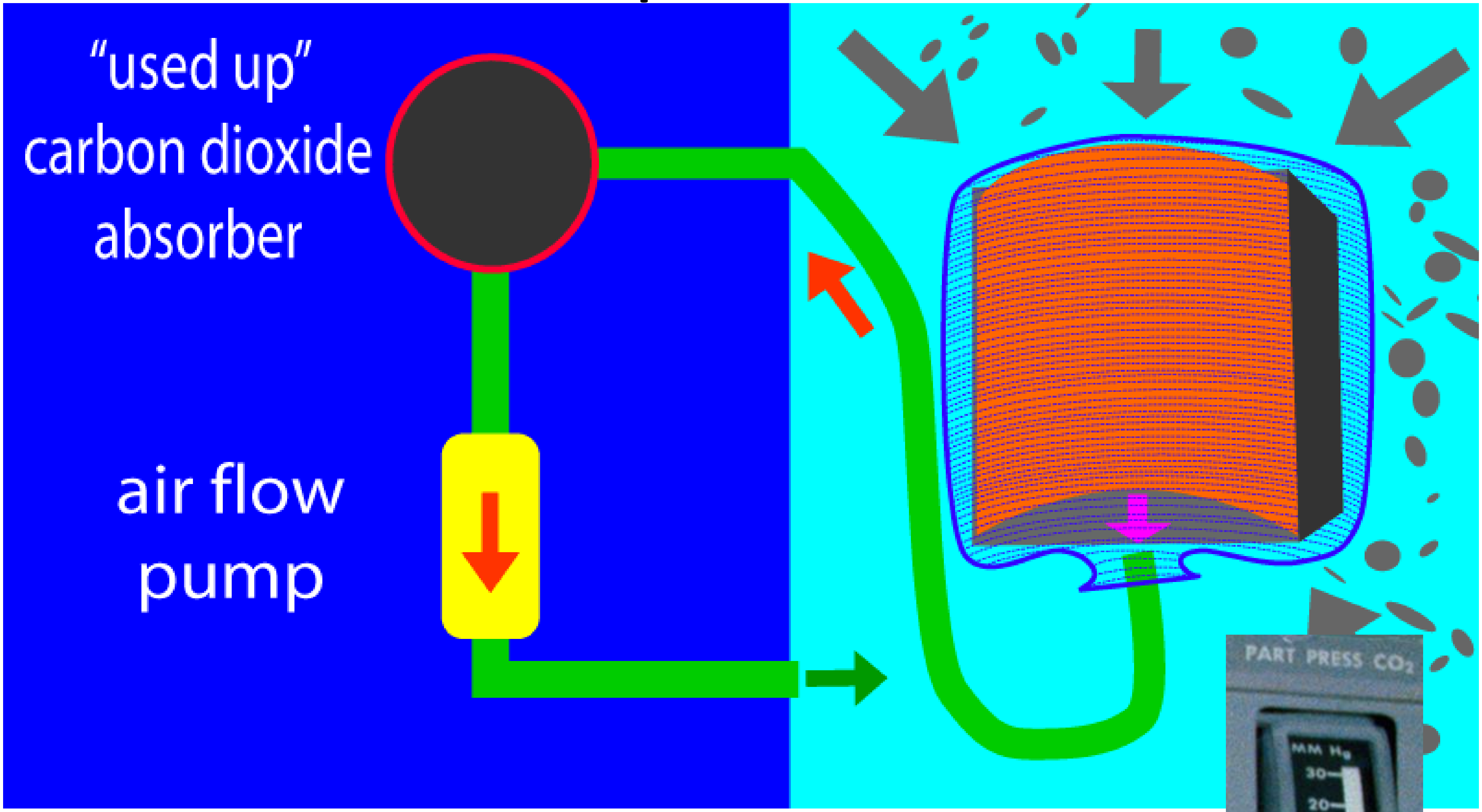
Problem – Few scrubbers needed for more people/ more days

Apollo 13 - solution



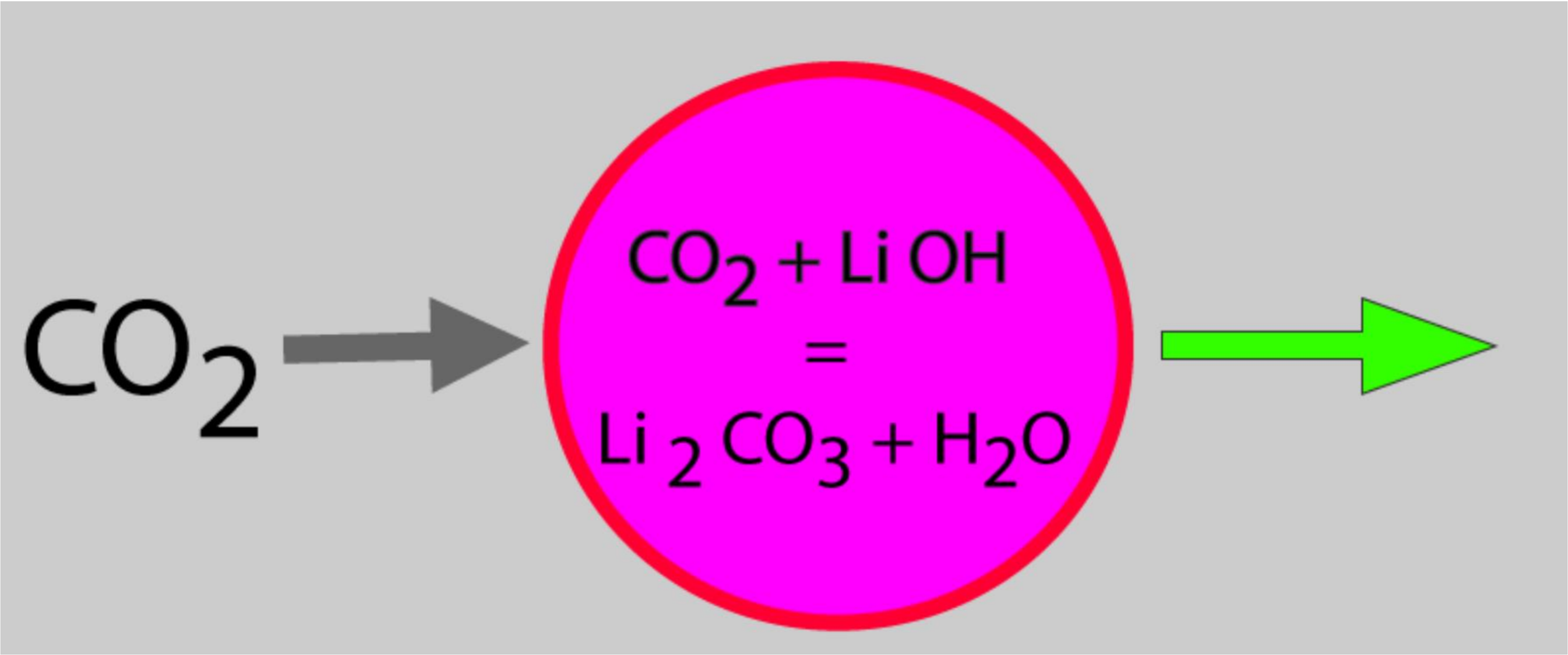
Duck tape! Solves many problems.

Apollo 13 - solution



Did it work?

Absorption and Stripping

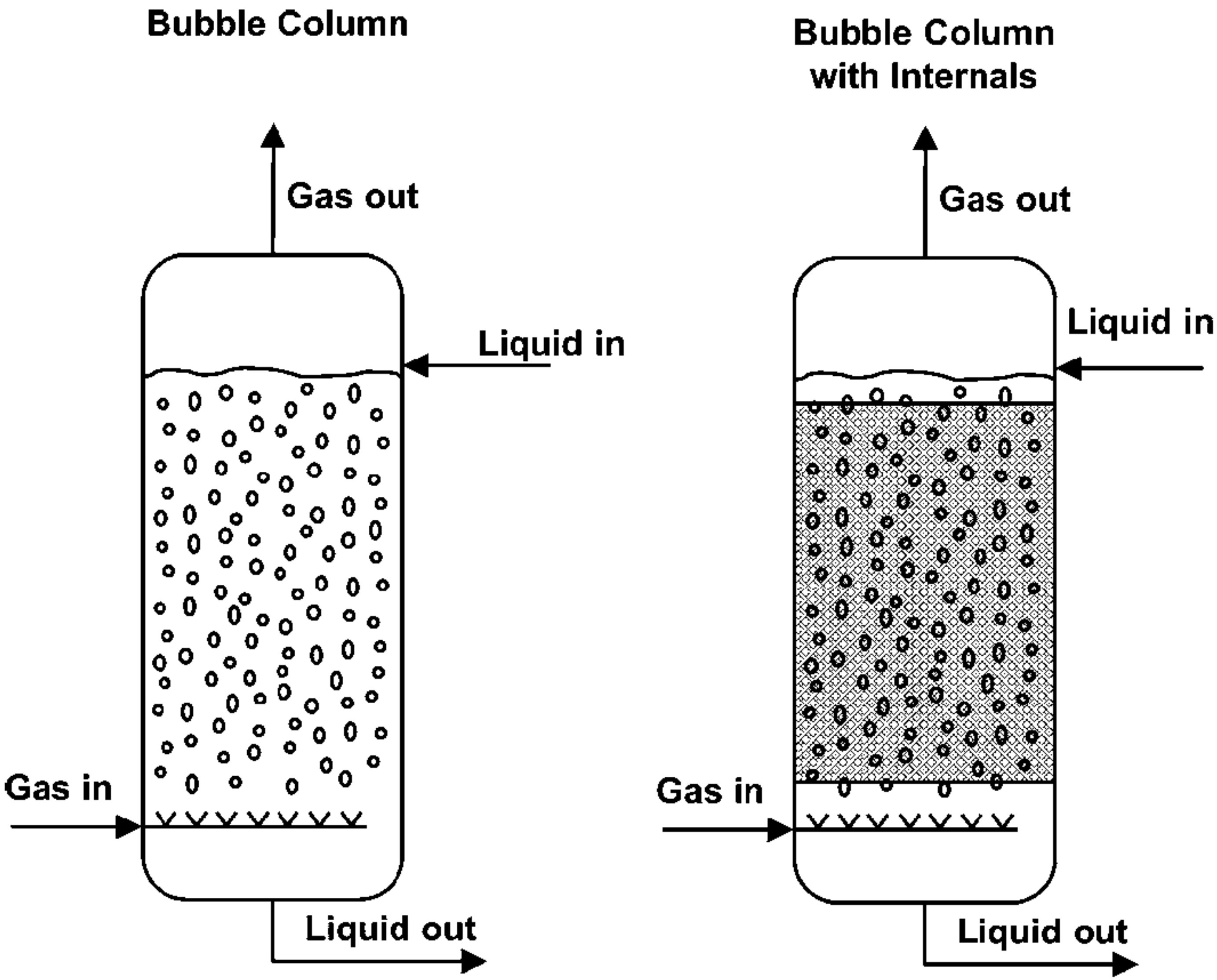


Scrubbing reaction – due to molecular interactions.

Besides saving astronauts, such reactions are crucial for purifying azeotropes, as phase-changes alone are not enough.

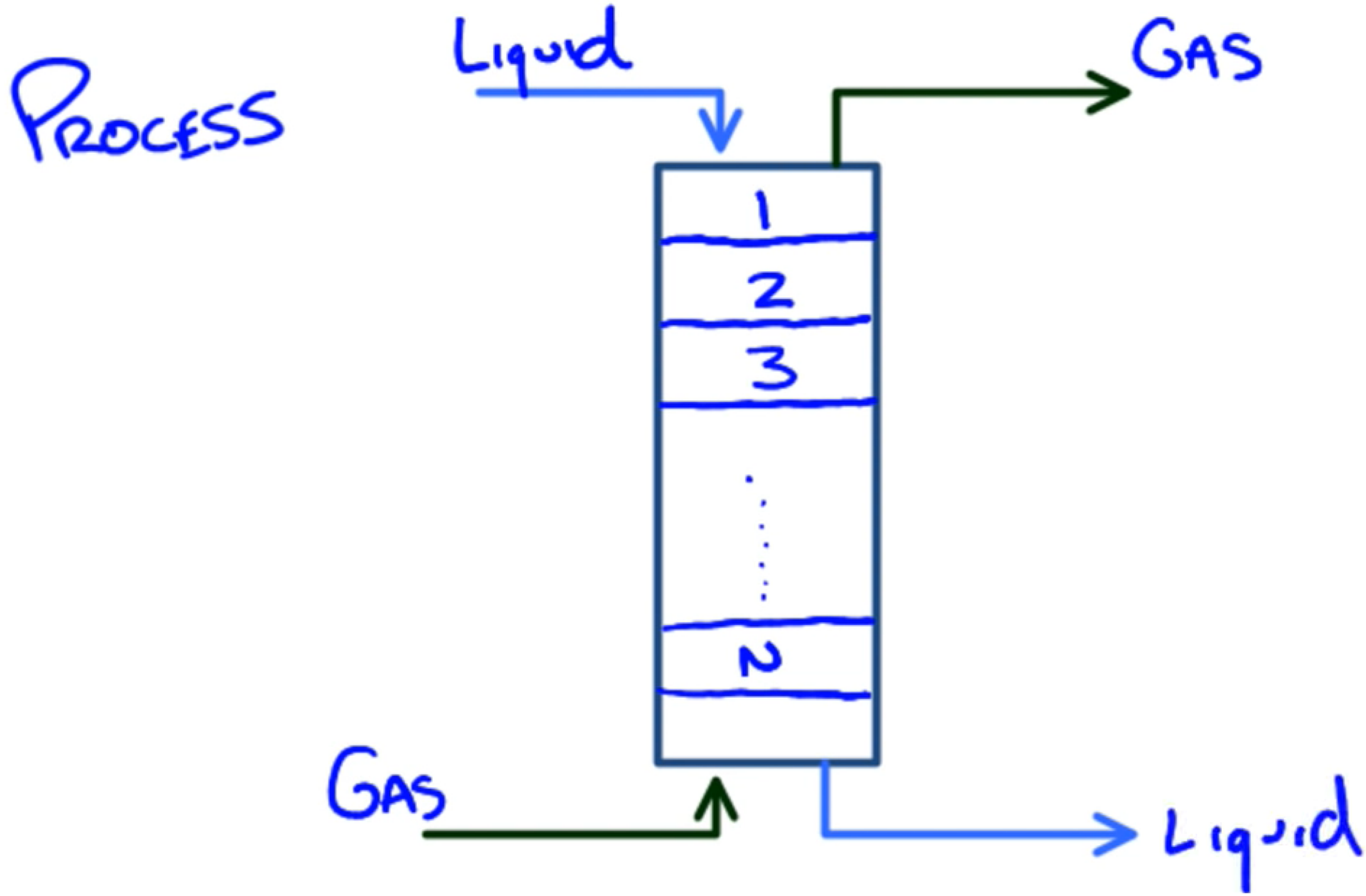
https://www.howequipmentworks.com/apollo_13/

Bubble Columns (continuous process)



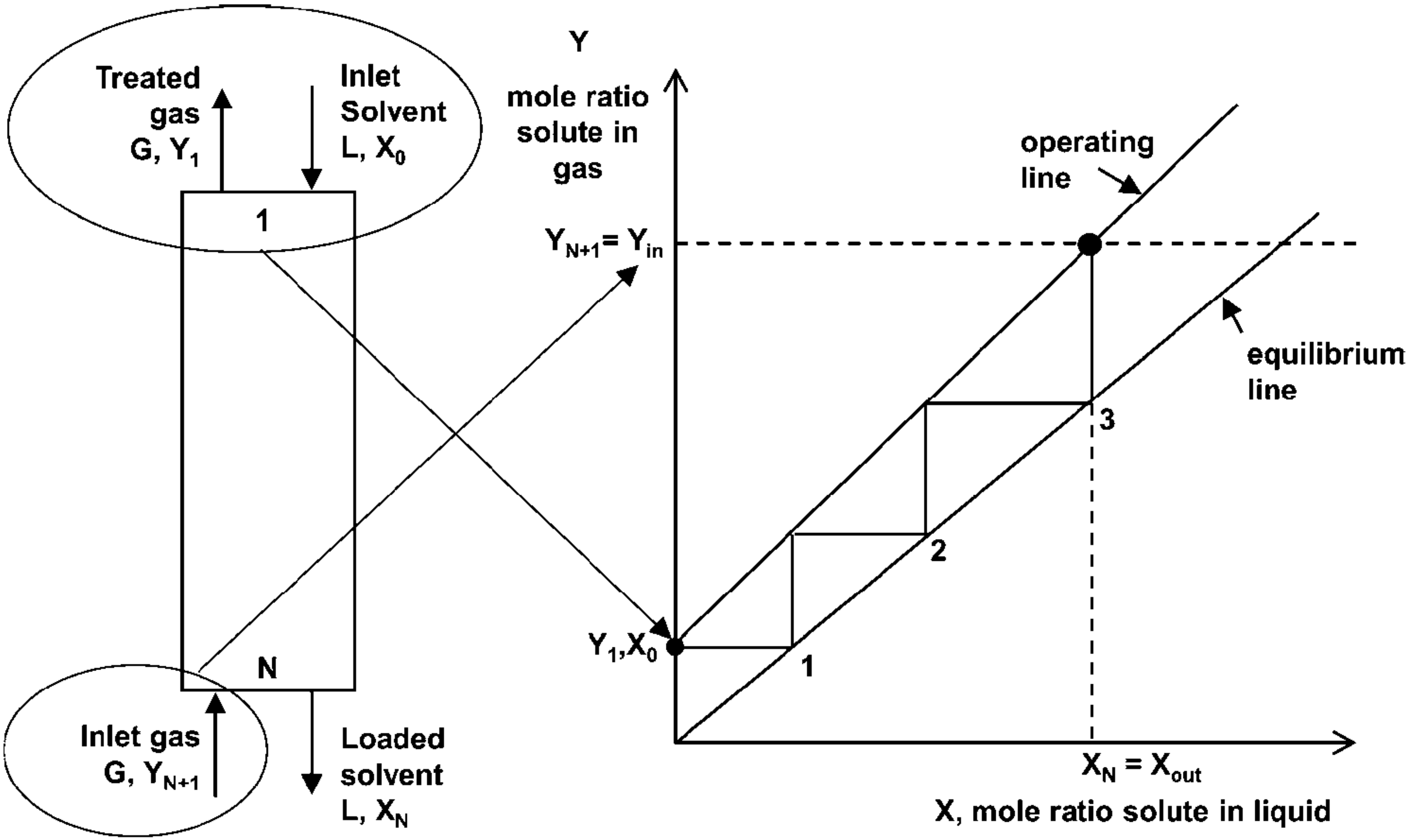
Bubble column absorber, without and with internal packing

Bubble Columns



Gas column absorber schematic – mixed gas in, pure gas out
Conceptual similarity to distillation – but with absorption

Operating Lines for Absorption



McCabe-Thiele diagram for absorption

operating line in absorption is above the equilibrium line

Absorption and Stripping

$$G y_{in} + L x_{in} = G y_{out} + L x_{out}$$ Absorption Balances

G and L are the Gas and Liquid flow rates

$$L_{\min} = G \cdot \frac{y_{in} - y_{out}}{x_{\max} - x_{in}} = G \cdot \frac{y_{in} - y_{out}}{\frac{y_{in}}{K} - x_{in}}$$

Max gas solubility in liquid x_{out} determines minimum Liquid absorbent flow rate L_{min}

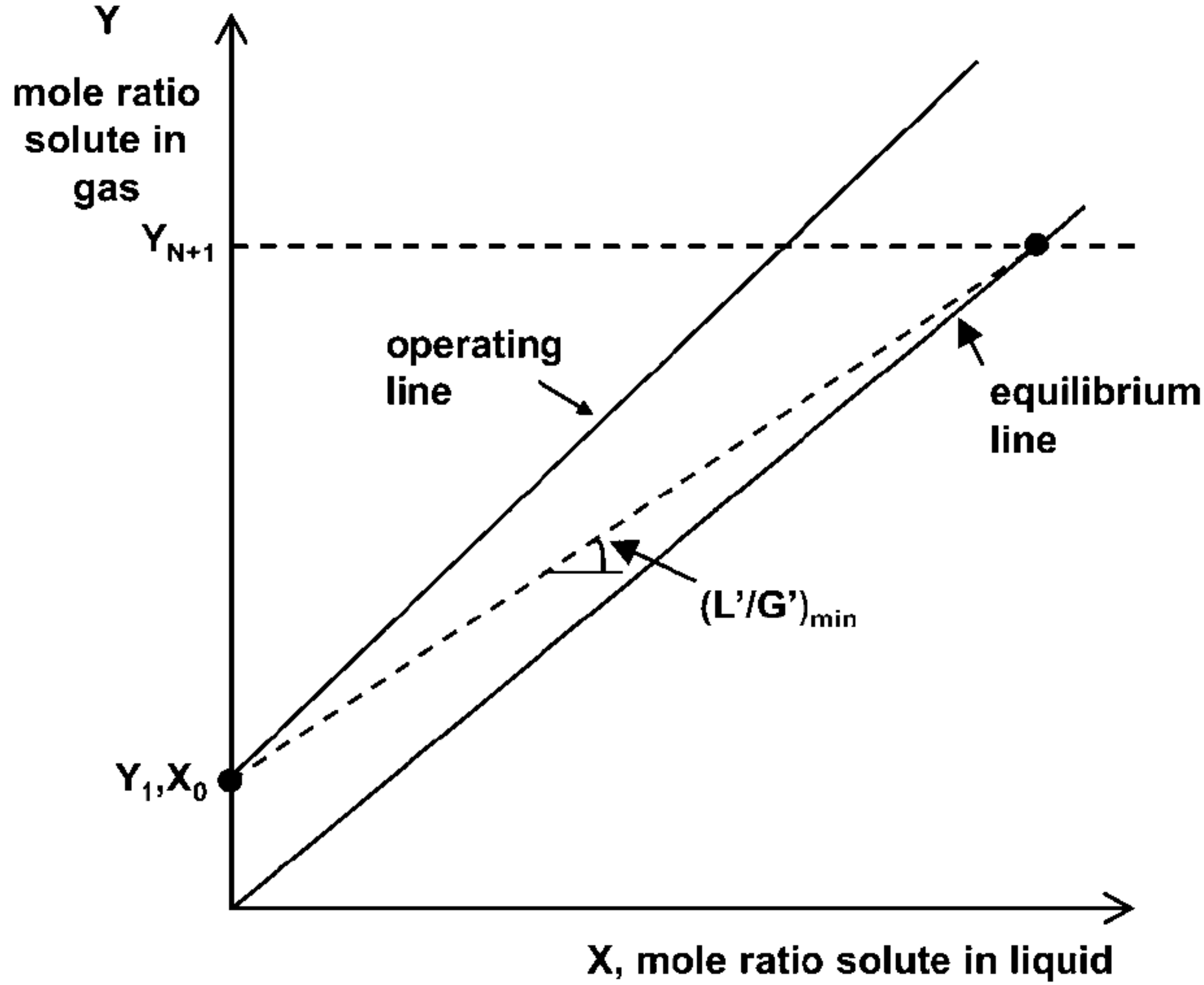
$$G y_{in} + L x_{in} = G y_{out} + L x_{out}$$ Stripping Balances

$$G_{\min} = L \cdot \frac{x_{in} - x_{out}}{y_{\max} - y_{in}} = L \cdot \frac{x_{in} - x_{out}}{K x_{in} - y_{in}}$$

Max y_{out} determines minimum stripping gas flow rate G_{min}

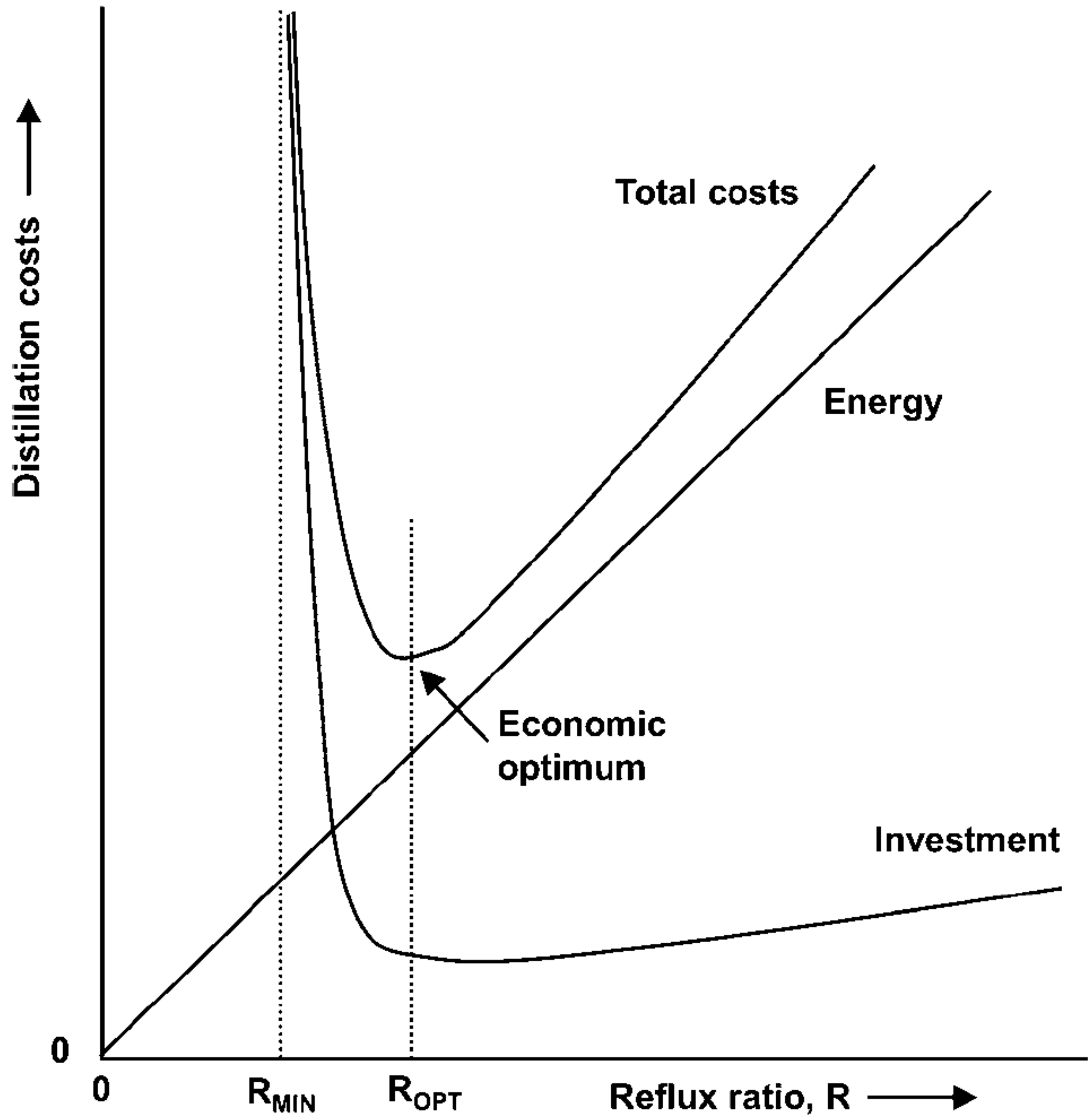
Single component mass balances

Absorption and Stripping



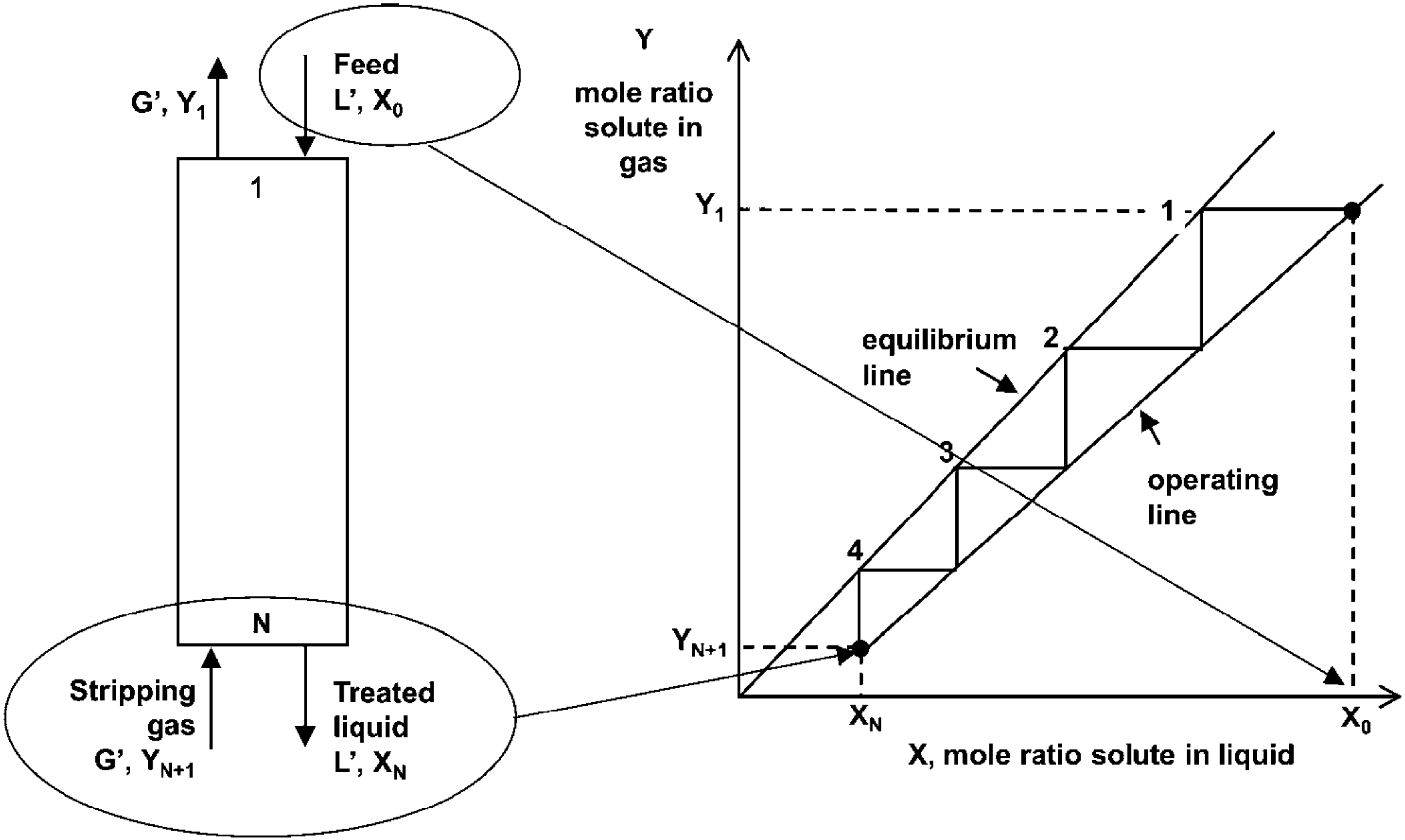
McCabe-Thiele diagram for minimum L/G ratio for absorption

McCabe-Thiele Analysis



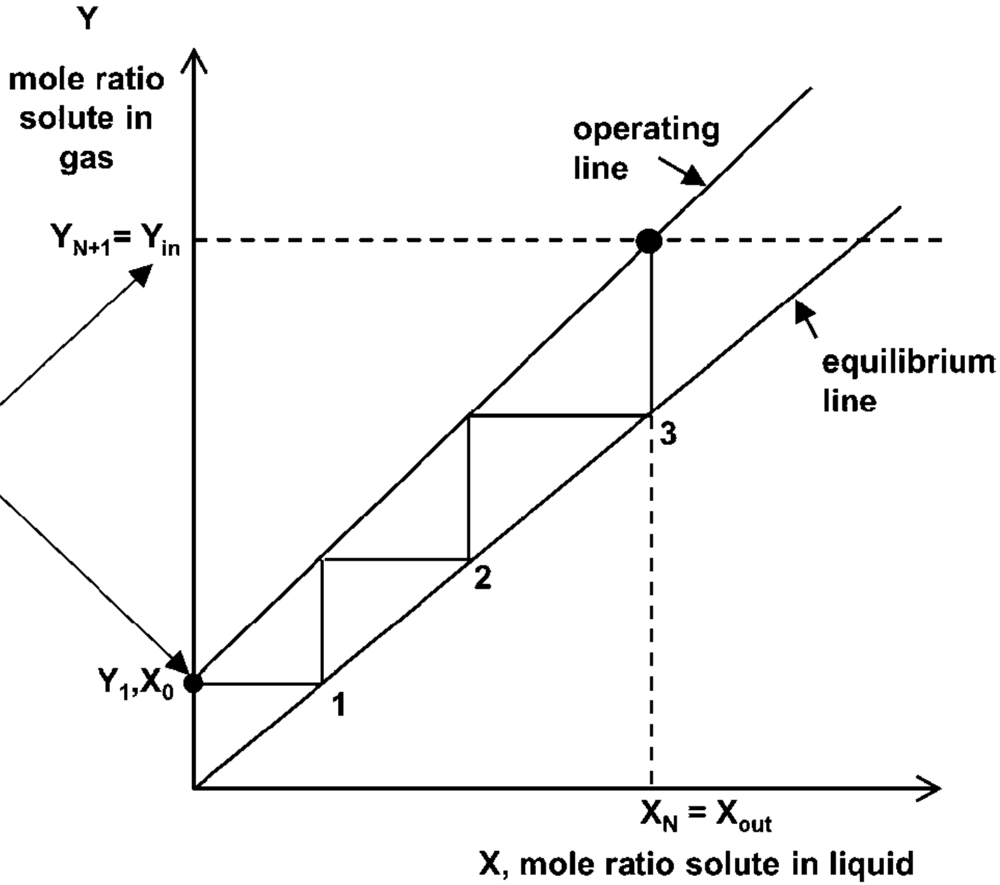
Operational cost – lowest at L/V = 1.5*(L/V)min

Absorption and Stripping



McCabe-Thiele diagram for stripping
operating line is below the equilibrium curve

Operating Lines Examples

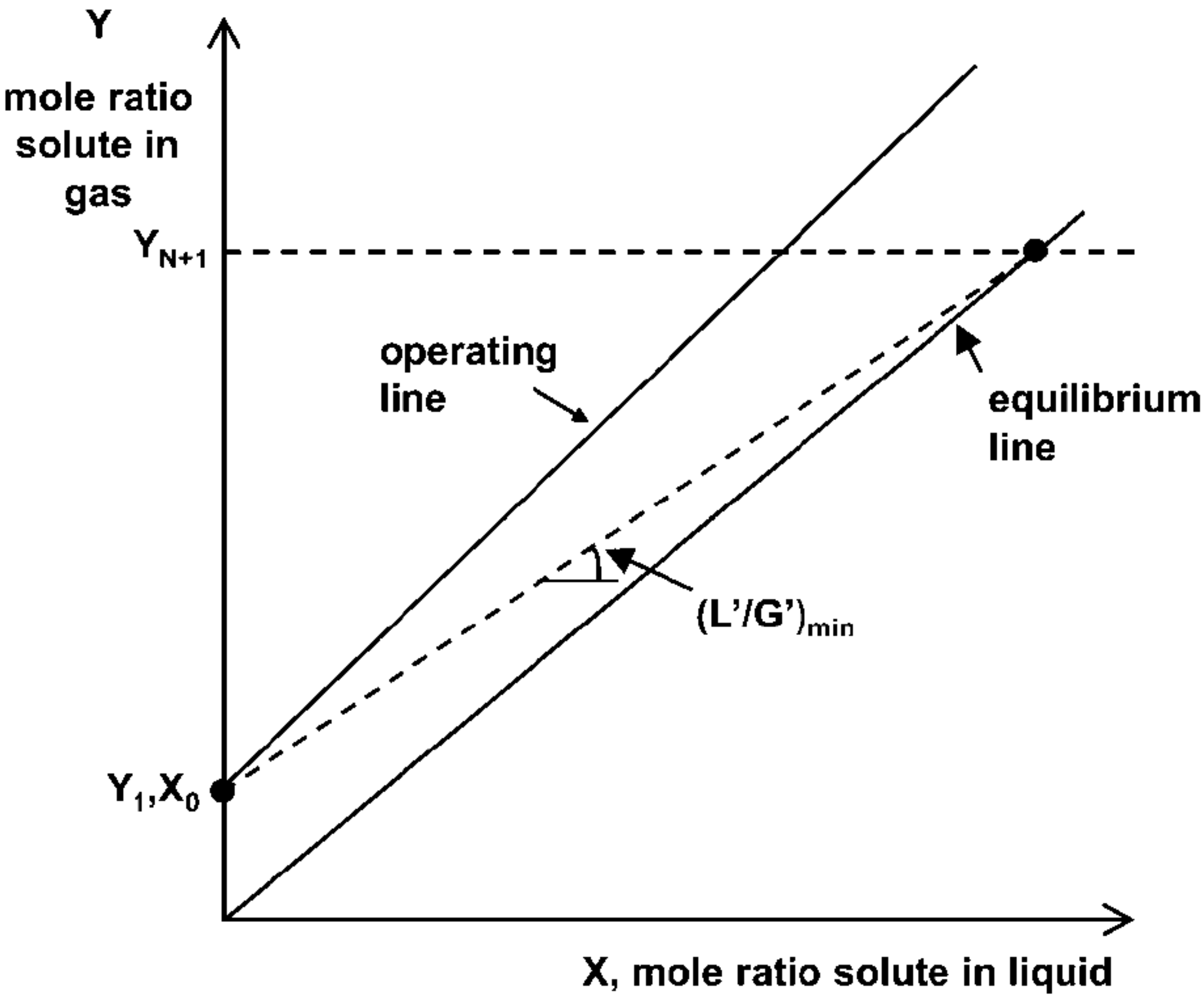


From:
1000 kmol/hr air
With
200 ppm chloroform
T = 25 oC, p = 1.5 atm

So:
V = 1000 kmol/hr air
Y_{N+1}= 200 ppm chloroform
Y_1= 10 ppm chloroform
X_0= 0 ppm water

Example Problem:
Remove Chloroform

Absorption and Stripping



$L/V = 1.4*(L/V)_{min}$

Let's calculate!

McCabe-Thiele diagram for minimum L/G ratio for absorption

Absorption and Stripping

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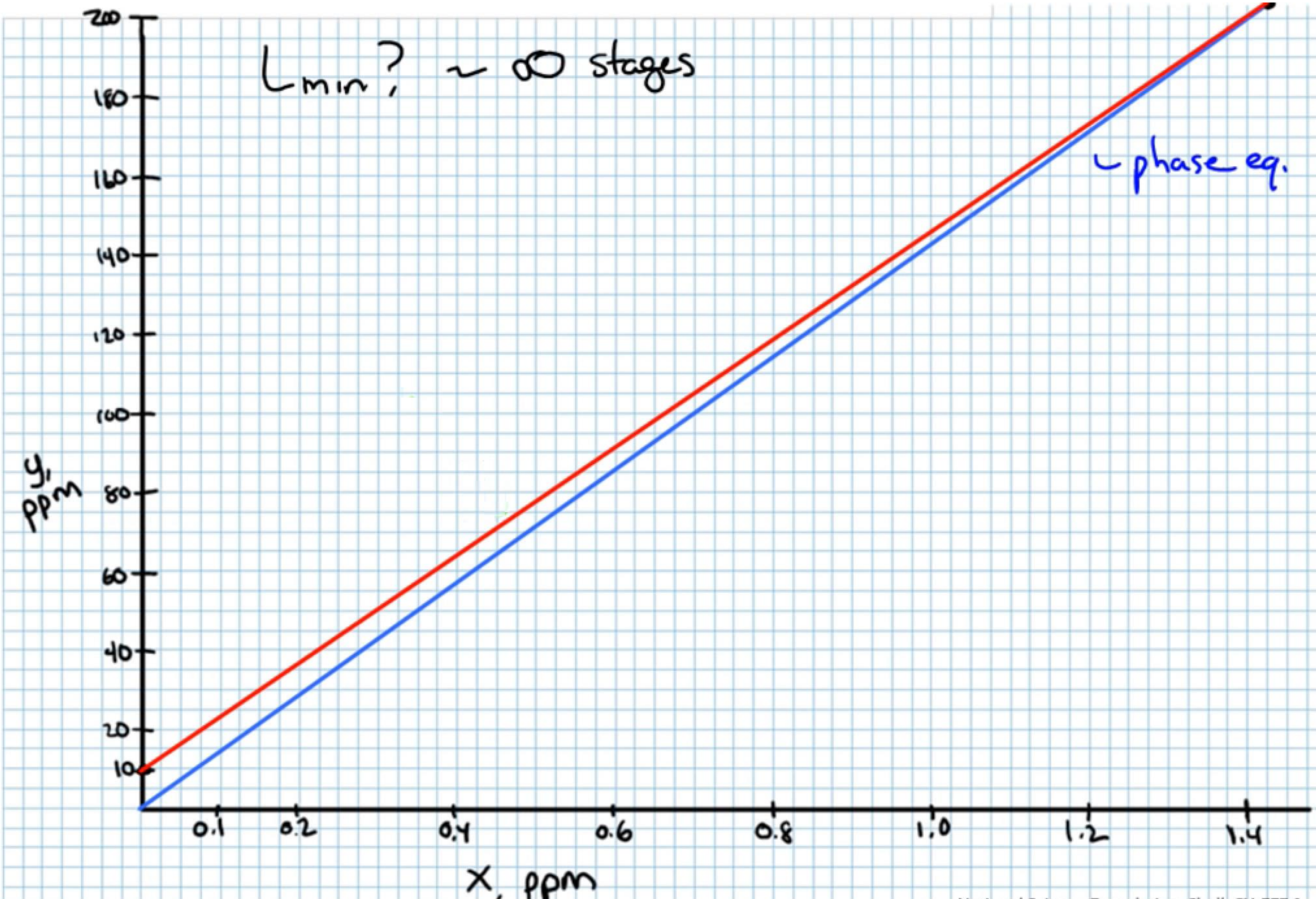
Henry's law – of gas absorption

Absorption and Stripping



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McCabe-Thiele diagram for minimum L/G ratio for absorption

NSF, Shell, and CU Boulder Chem.Eng. https://goo.gl/ZPT1kC

Absorption and Stripping

- Y, X (mole ratios) = y, x (Plot mole fractions, ppm)

LOOK UP:

- HENRY'S LAW CONSTANT: 211.19 atm/mole fraction
  in water (25°C, 1 atm)

PHASE Equilibrium Line:

$$y = \frac{Hx}{P} = \frac{211.19}{1.5} x = \boxed{140.8\, x}$$

y & x in ppm.

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University of Colorado Boulder

McCabe-Thiele diagram for minimum L/G ratio for absorption

Absorption and Stripping

Phase Equilibrium Line:

$$y = \frac{Hx}{P} = \frac{211.19}{1.5}x = 140.8x$$

y & x in ppm.

Operating Line:

$$\frac{200 \text{ ppm}}{140.8} = x = 1.42 \text{ ppm}$$

(top of phase equilibrium line for operating conditions)

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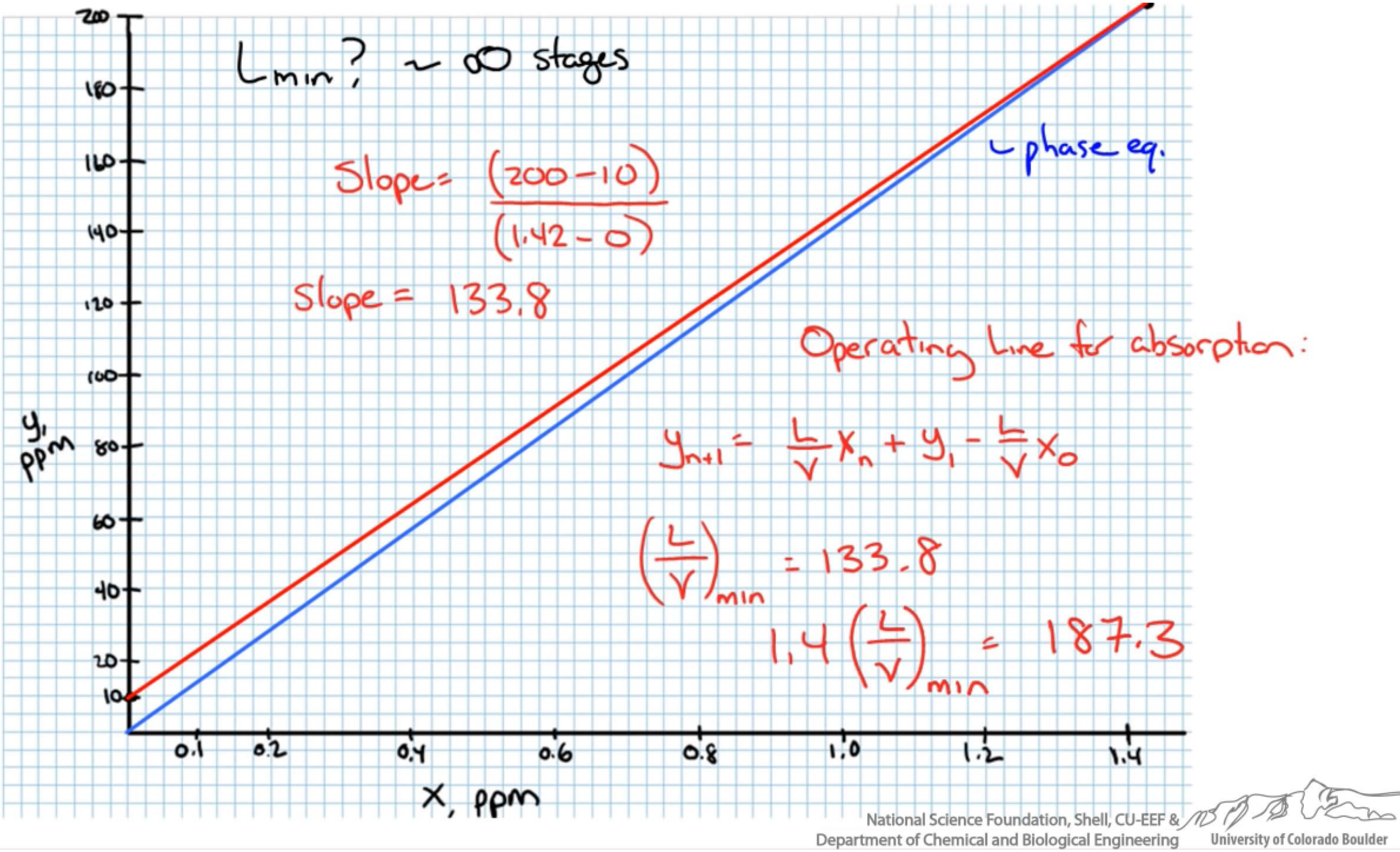
University of Colorado Boulder

McCabe-Thiele diagram for minimum L/G ratio for absorption

Absorption and Stripping



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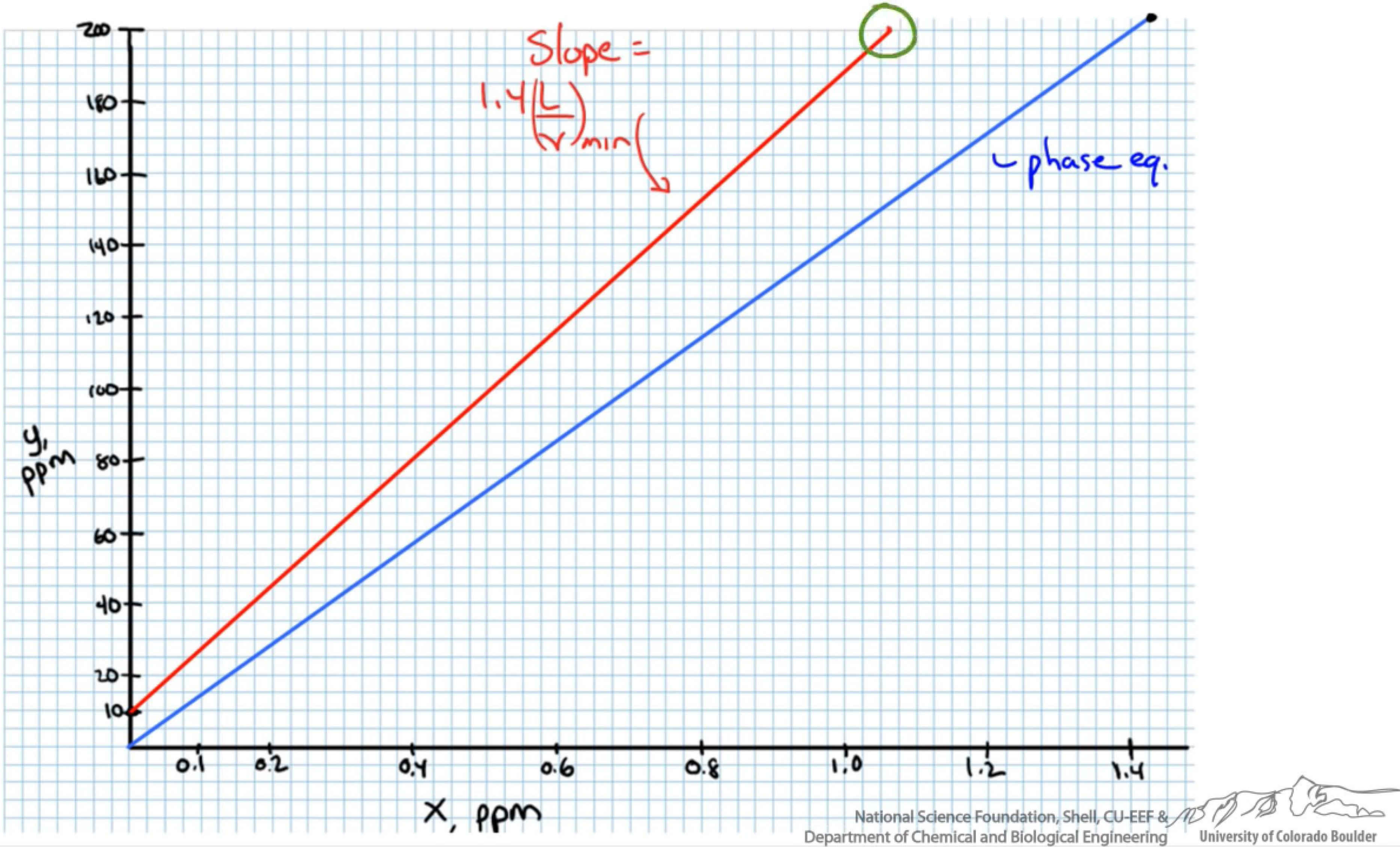
Absorption and Stripping



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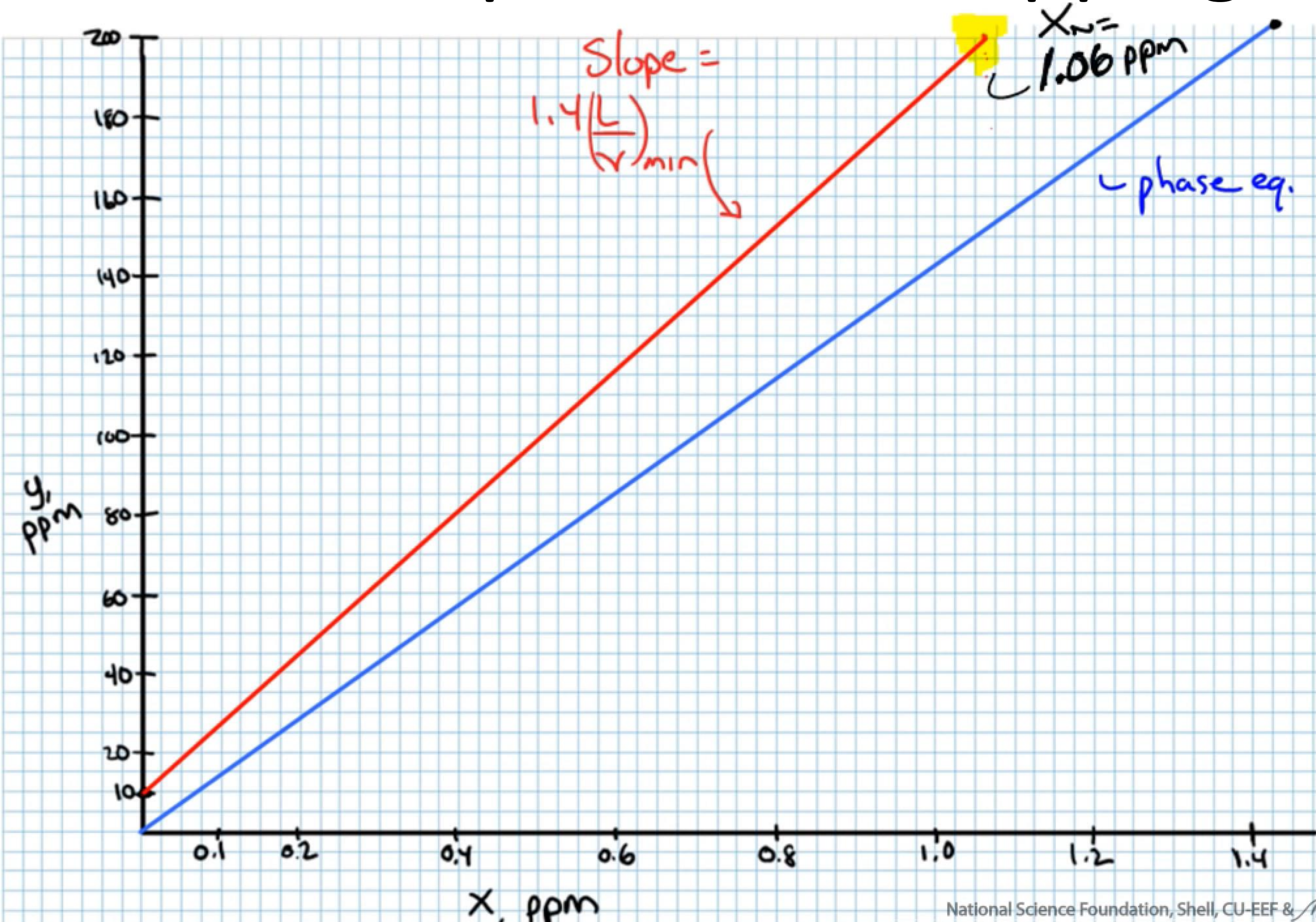
Absorption and Stripping



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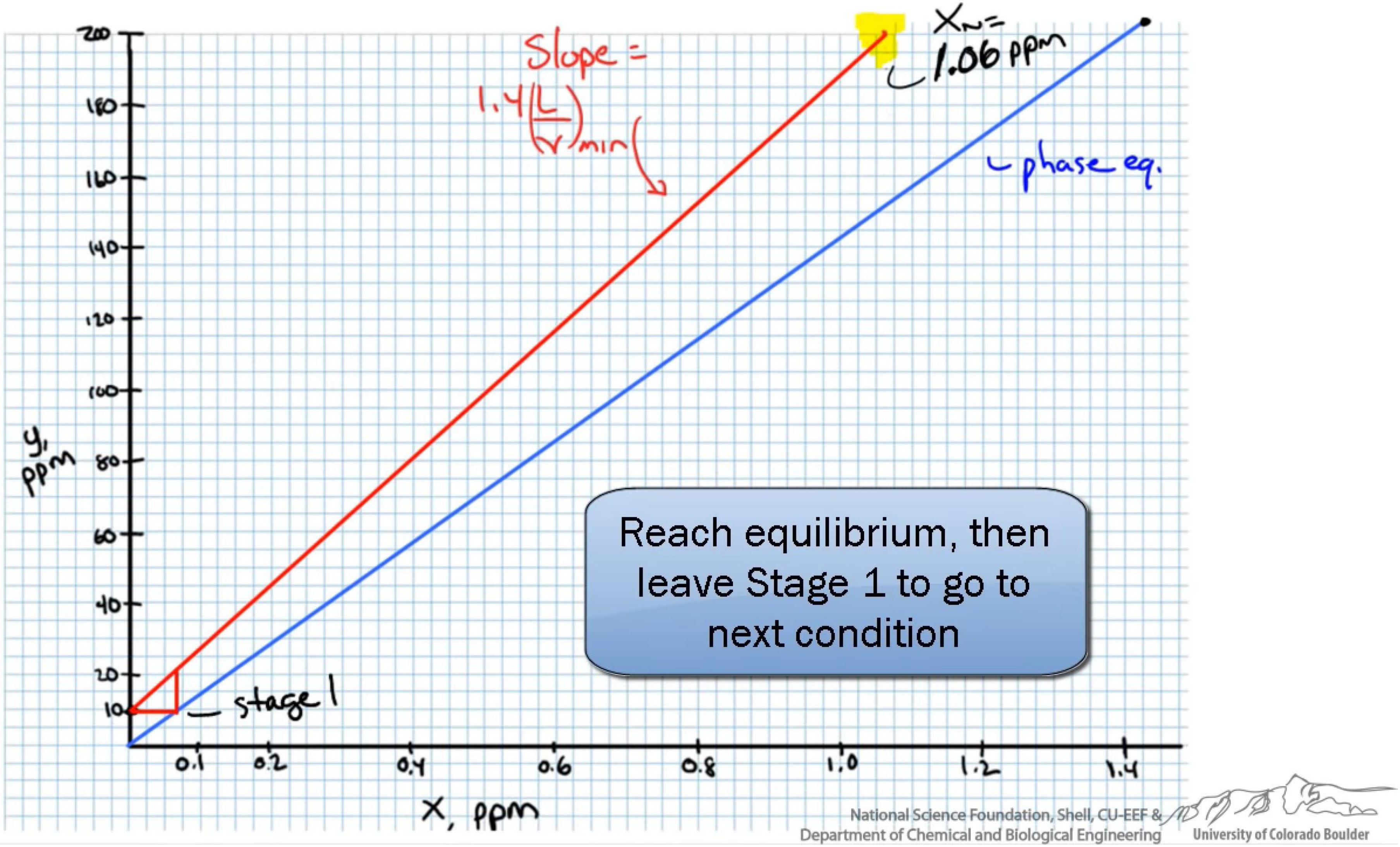
McCabe-Thiele diagram for minimum L/G ratio for absorption

Absorption and Stripping



McCabe-Thiele diagram for minimum L/G ratio for absorption

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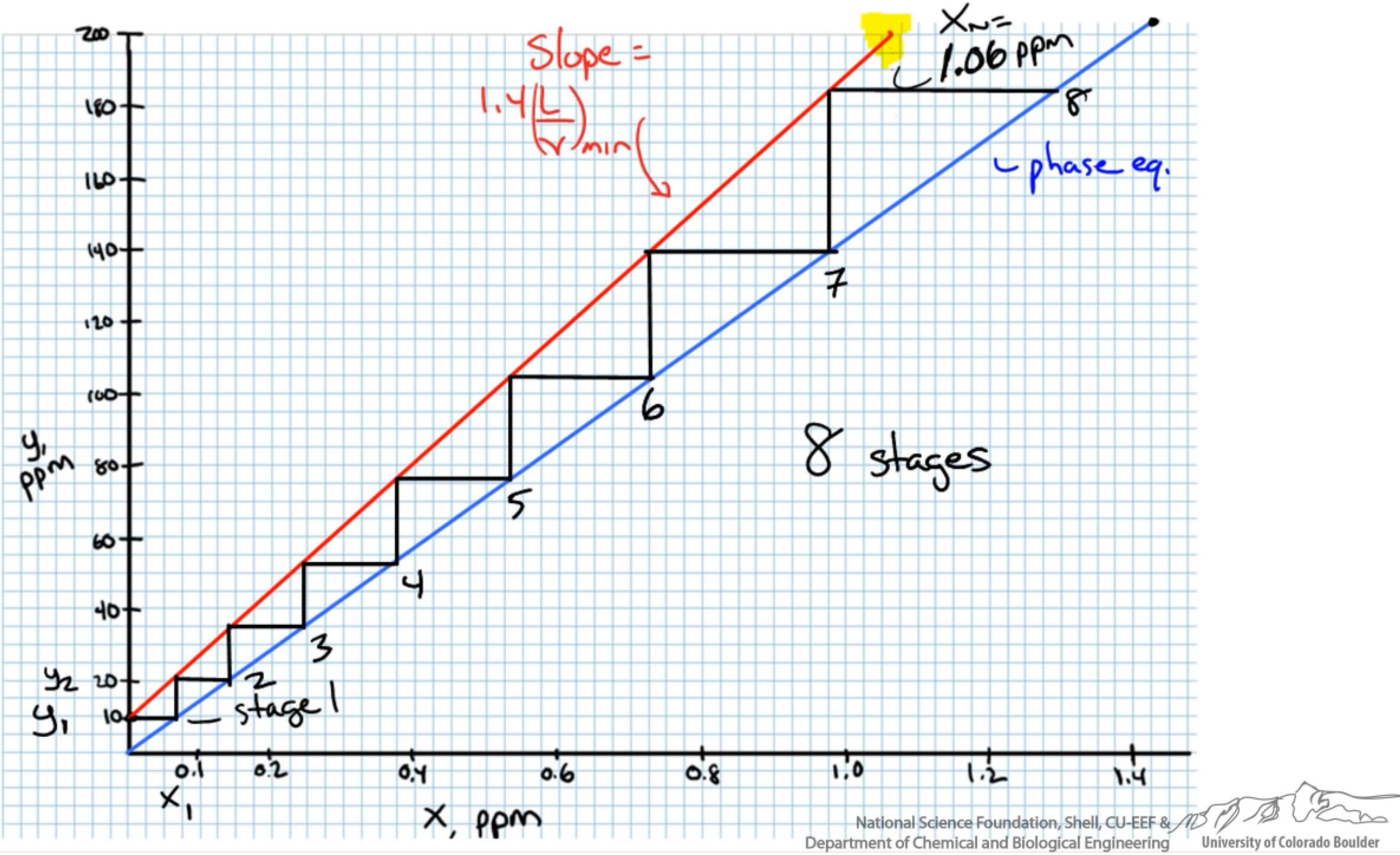
Absorption and Stripping



McCabe-Thiele diagram for minimum L/G ratio for absorption

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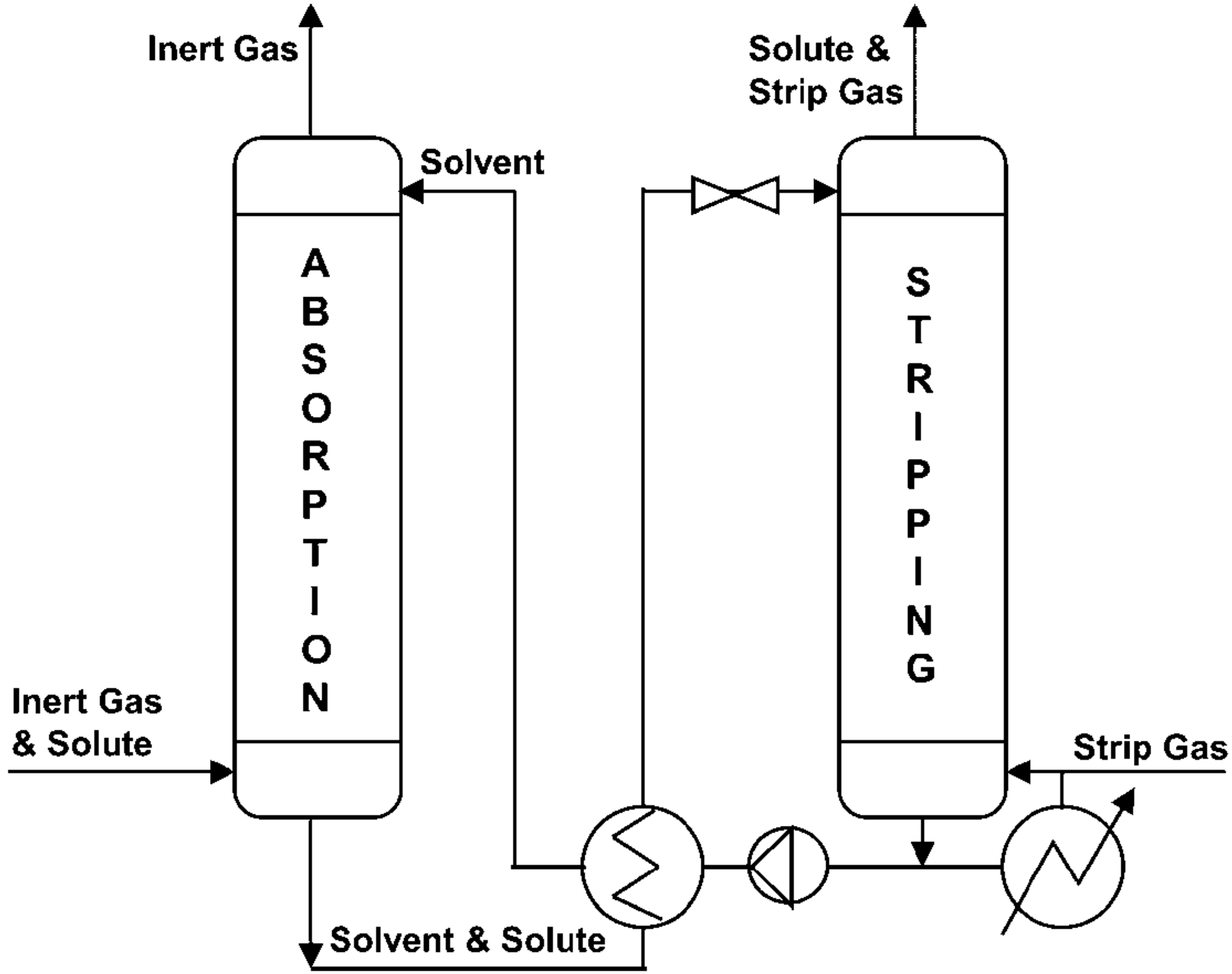
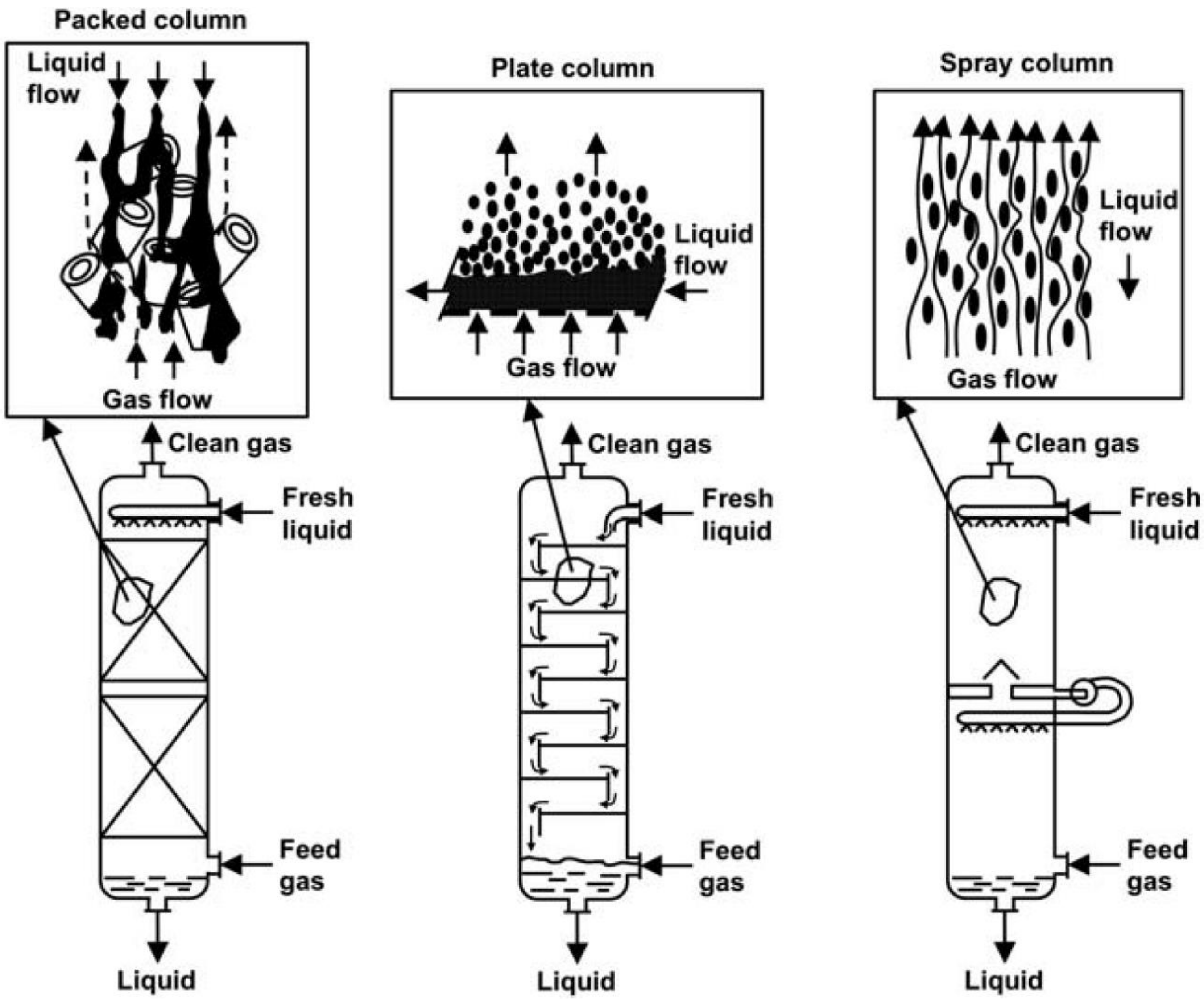
Preview for next week: Vertical Countercurrent Columns



Absorption installation with stripping for regeneration

Columns with Countercurrent Flow



Operating principles of packed, tray and spray towers