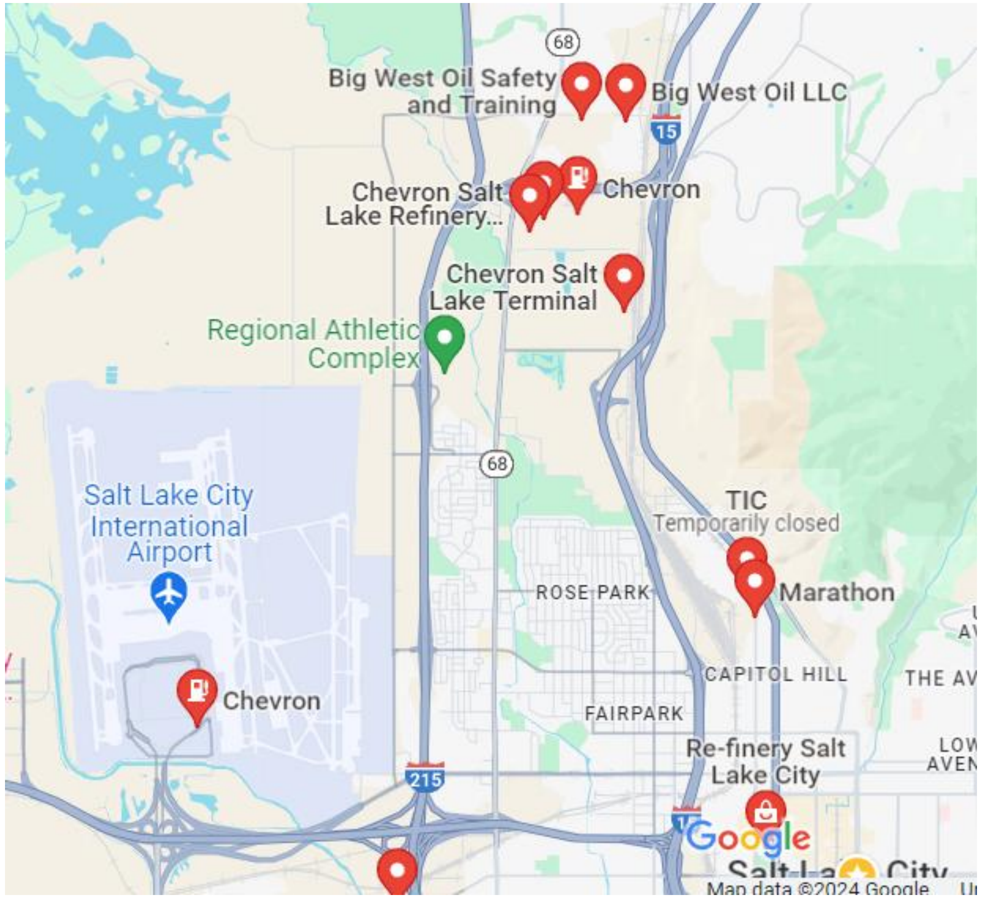
ANEK SUWANNAPHOOM

Refineries use huge amounts of thermal energy to process crude oil.


68
Big West Oil Safety and Training
Big West Oil LLC
15
Chevron Salt Lake Refinery...
Chevron
Chevron Salt Lake Terminal
Regional Athletic Complex
68
Salt Lake City International Airport
TIC
Temporarily closed
ROSE PARK
Marathon
CAPITOL HILL
THE AV
Chevron
FAIRPARK
Re-finery Salt Lake City
215
15
Google
Salt La City
Map data ©2024 Google

- A **refinery** is a production facility composed of a group of chemical engineering unit processes and unit operations refining certain materials or converting raw material into products of value.

Introduction

SHR Chapter 1

Content

- Basic concepts (SHR 1.0-1.1)
- Types of separation techniques (SHR 1.2-1.6)
- Example: distillation (SHR 1.7-1.8)
- Selection of separation process (SHR 1.10)

Basic concepts

- Operations in a chemical plant
  - Key operation: chemical reactions, separation of chemical mixtures
  - Auxiliary operation: phase separation, heat exchange, shaft work (pump, compressor), mixing or dividing, solids agglomeration, size reduction

- Separation
  - Batch-wise
  - Continuous
  - Semi-continuous

Examples: product as a single component vs a mixture

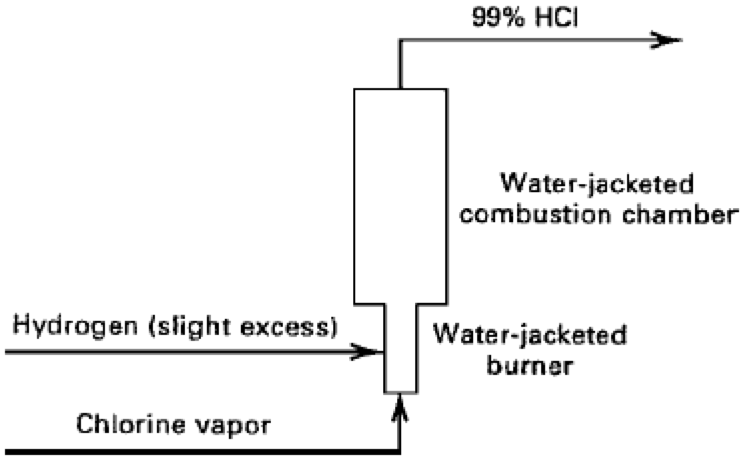


Figure 1.2 Process for anhydrous HCl production.

$$C_2H_4 + H_2O \underset{r_2}{\overset{r_1}{\rightleftarrows}} C_2H_5OH$$

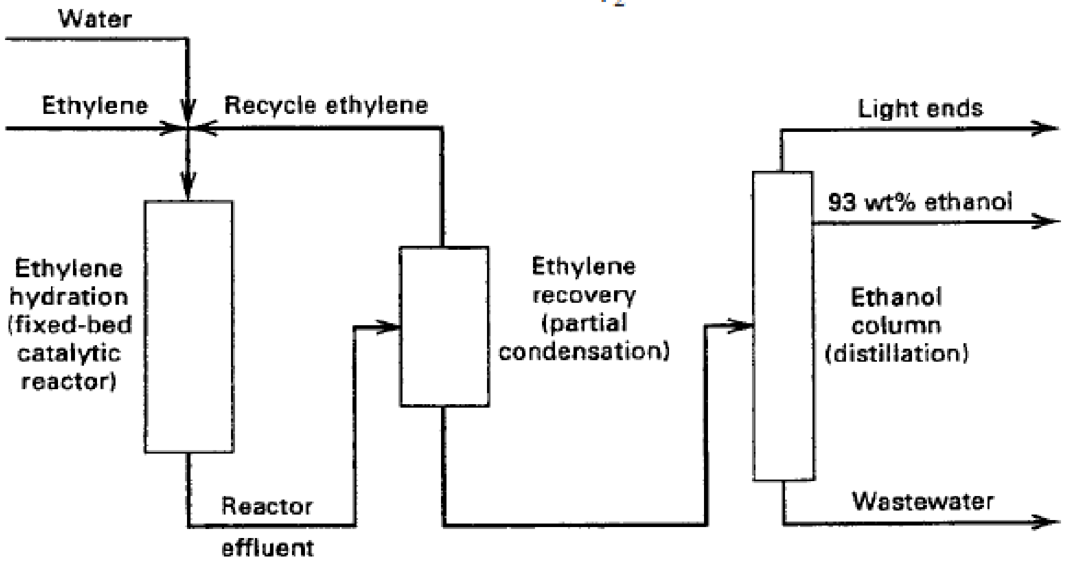
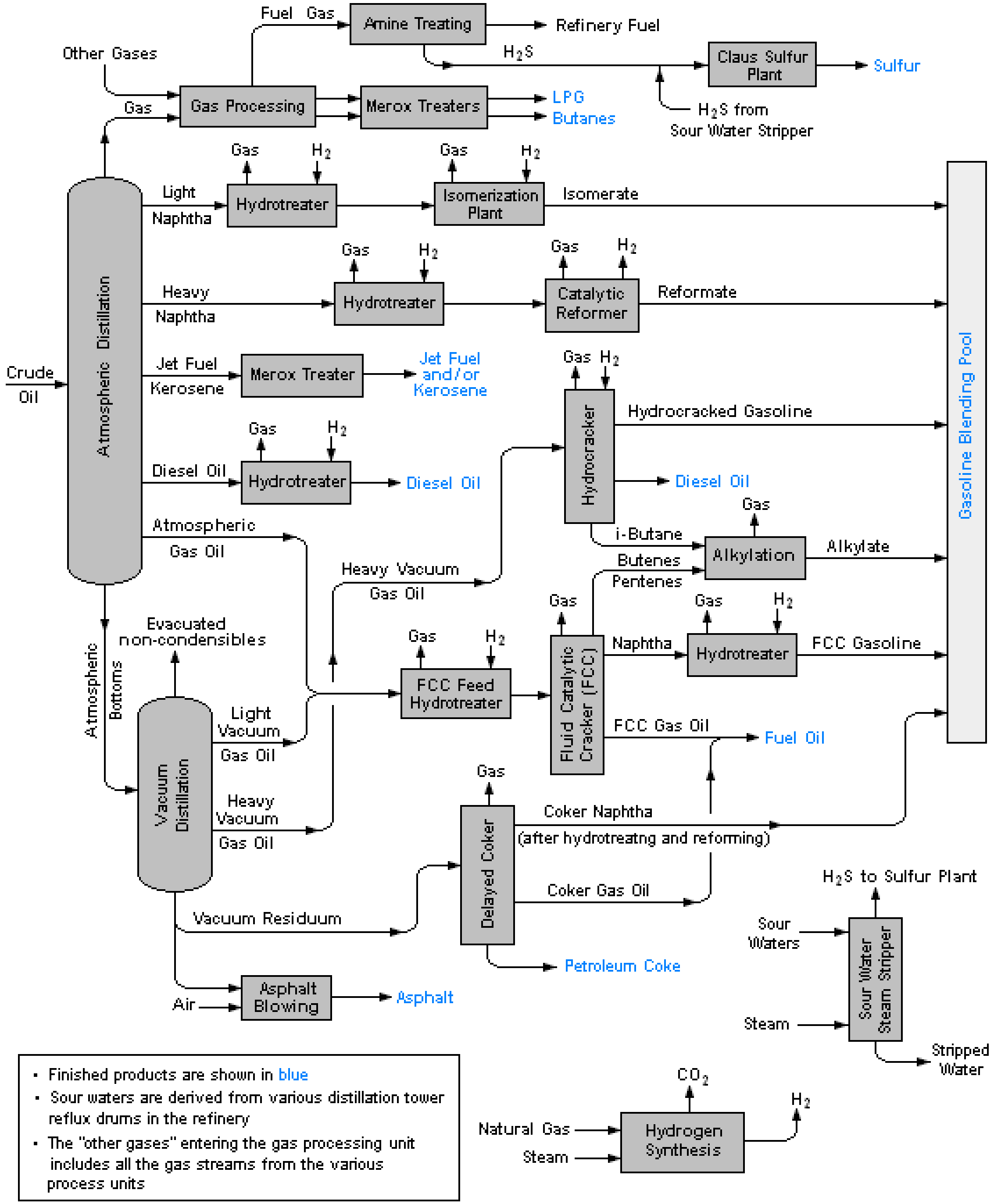


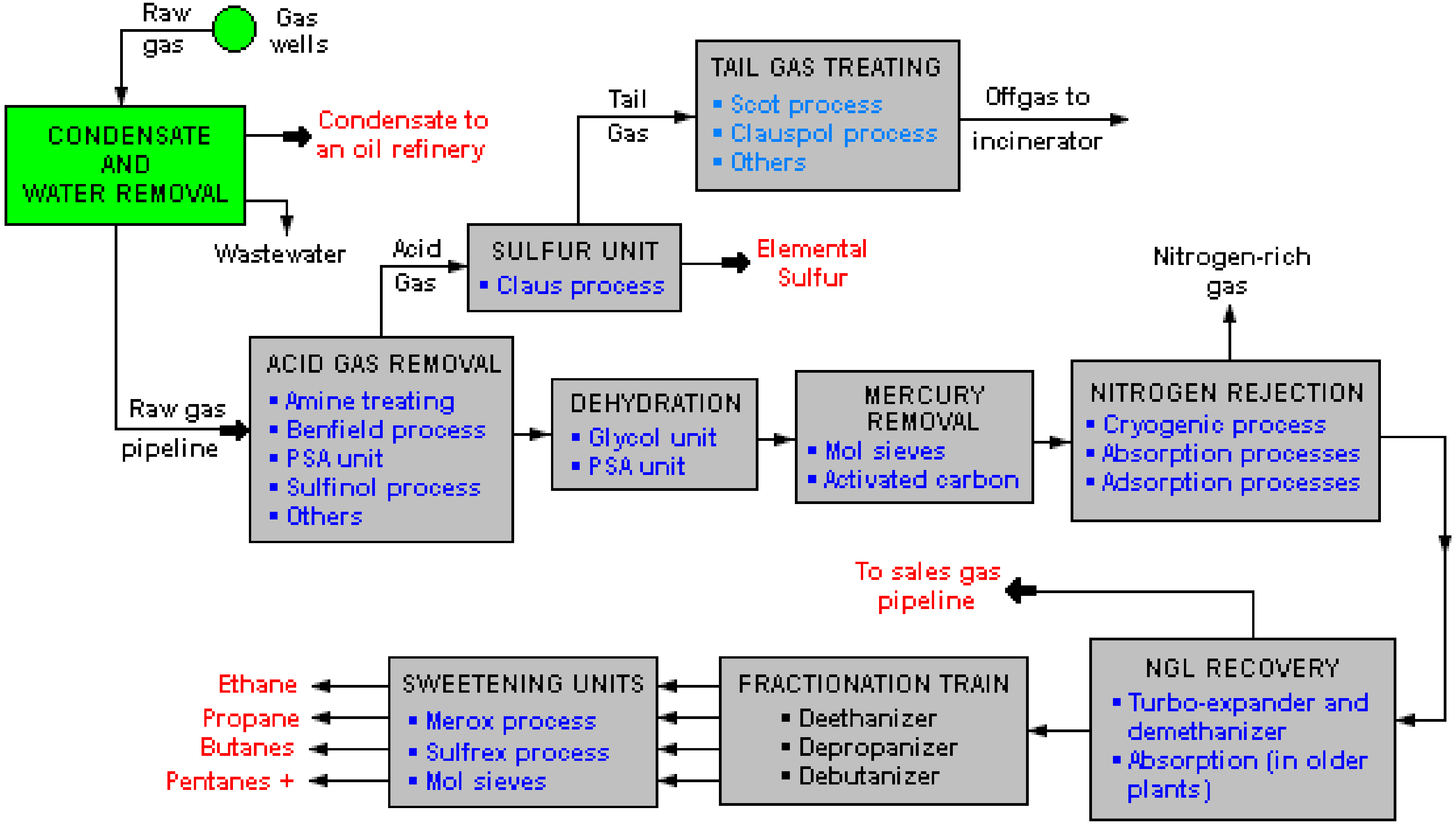
Figure 1.3 Hypothetical process for hydration of ethylene to ethanol.

- Simple processes that do not require separation operations are very rare
- Most chemical and biochemical processes are dominated by separation equipment
- More than 95% of industrial chemical separation operations involve feed mixtures of organic chemicals



- Finished products are shown in blue
- Sour waters are derived from various distillation tower reflux drums in the refinery
- The "other gases" entering the gas processing unit includes all the gas streams from the various process units

Schematic flow diagram of a typical oil refinery



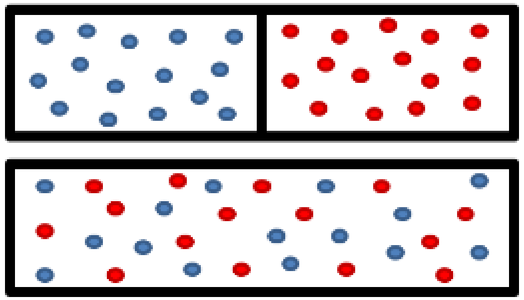
LEGEND:

- 🟩 Located at gas wells ▨ Located in gas processing plant
  Red Indicates final sales products Blue Indicates optional unit processes available
- Condensate is also called natural gasoline or casinghead gasoline
- Pentanes + are pentanes plus heavier hydrocarbons and also called natural gasoline
- Acid gases are hydrogen sulfide and carbon dioxide
- Sweetening processes remove mercaptans from the NGL products
- PSA is Pressure Swing Adsorption
- NGL is Natural Gas Liquids

Schematic flow diagram of a typical natural gas processing plant

Energy is required for separation

- The creation of a chemical mixture is spontaneous
    - If the mixing occurs (ΔGmix<0) instead of phase segregation
- Separation of a chemical mixture into pure components, is not spontaneous and thus requires energy.
    - A mixture to be separated may be single or multiphase.
    - If it is multiphase, it is usually advantageous to first separate the phases.



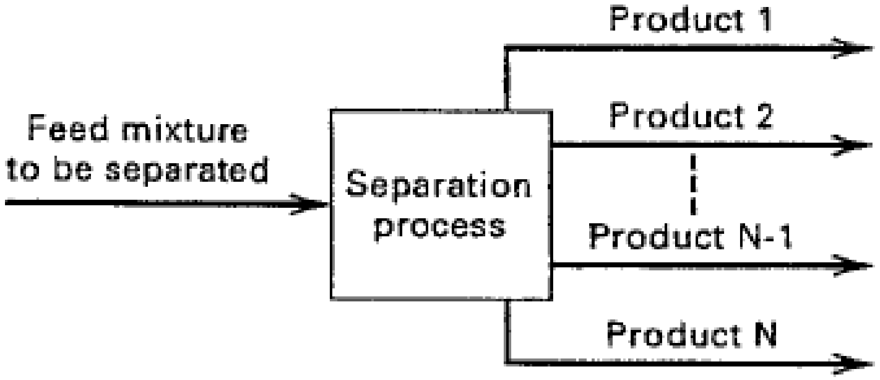
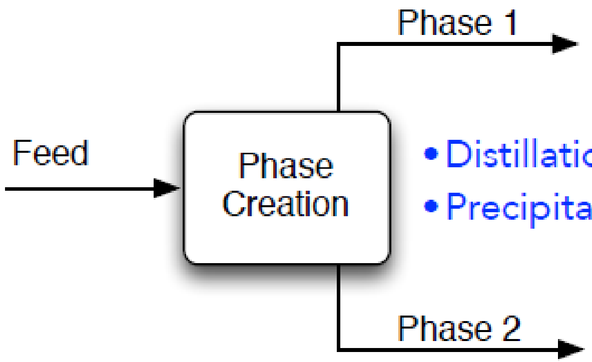


Figure 1.5 General separation process.

Content

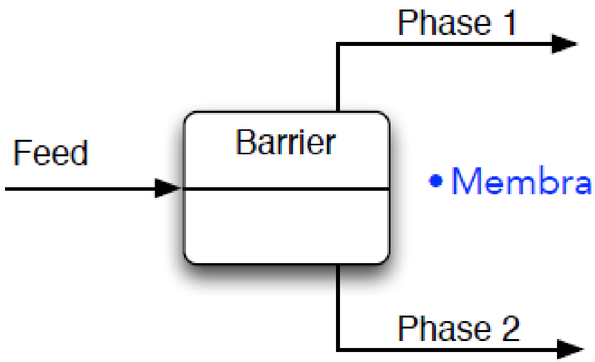
- Basic concepts (SHR 1.0-1.1)
- Types of separation techniques (SHR 1.2-1.6)
- Example: distillation (SHR 1.7-1.8)
- Selection of separation process (SHR 1.10)

Types of separation techniques

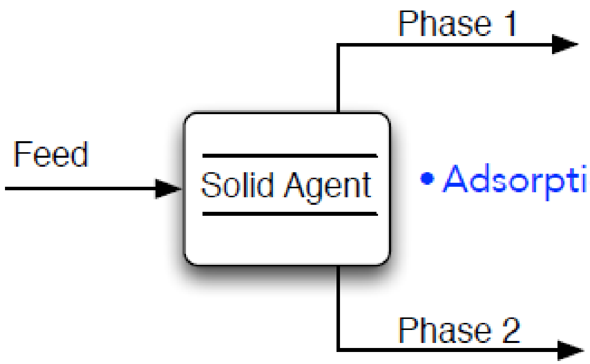


- Distillation
- Precipitation

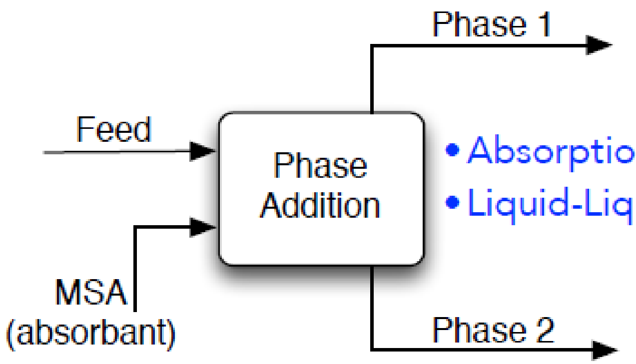
Note:
These show **mass** flow. Most separation processes also involve significant **energy** input to the system!



- Membranes



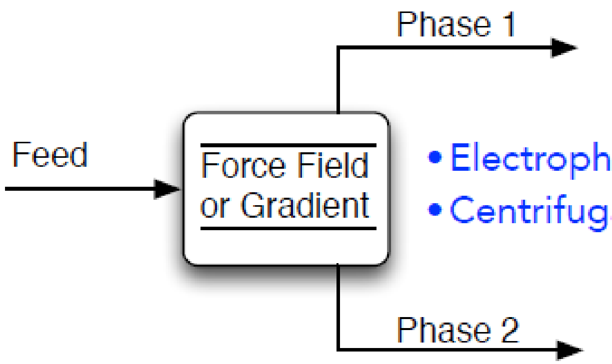
- Adsorption



- Absorption/Stripping
- Liquid-Liquid Extraction

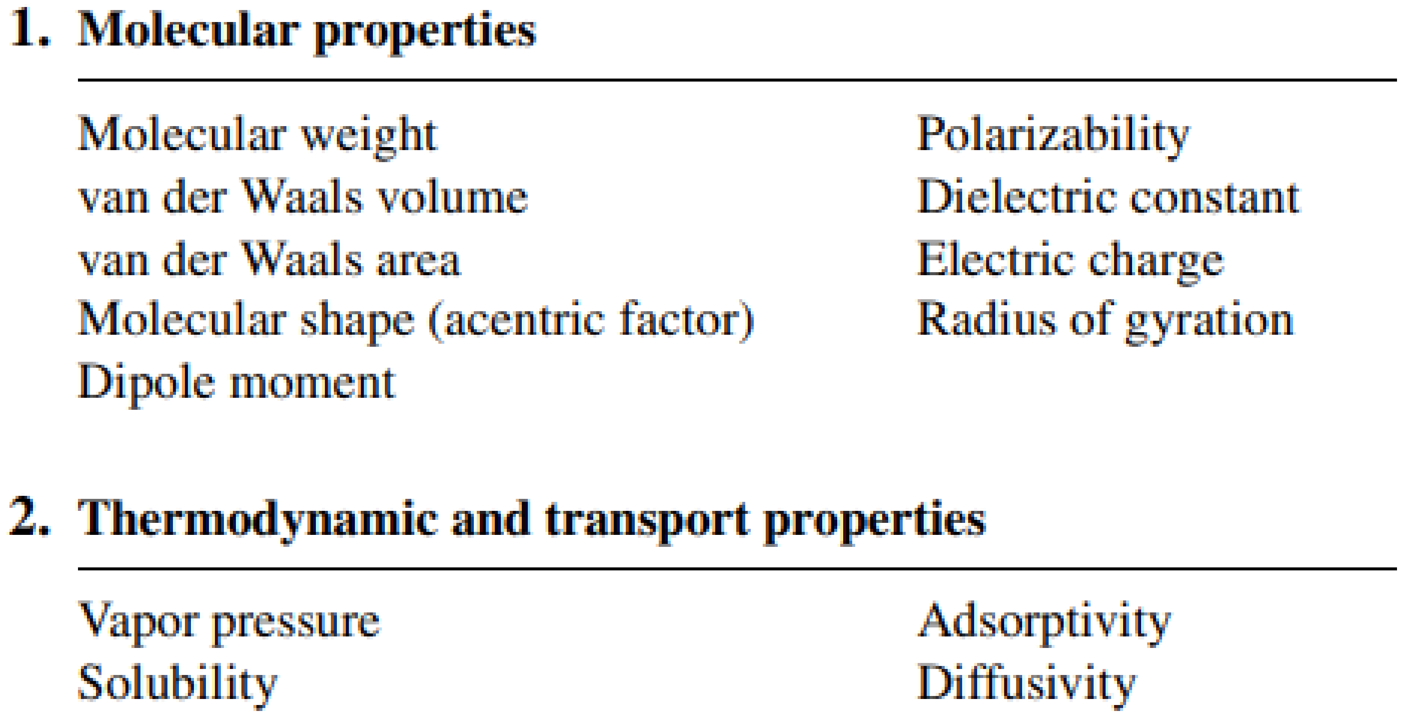
Terminology

- **adsorption** - adhesion of molecules to a surface
- **absorption** - molecules enter a phase volume



- Electrophoresis
- Centrifugation

- The extent of separation depends on differences among components to be separated



1. Molecular properties

Molecular weight
van der Waals volume
van der Waals area
Molecular shape (acentric factor)
Dipole moment
Polarizability
Dielectric constant
Electric charge
Radius of gyration

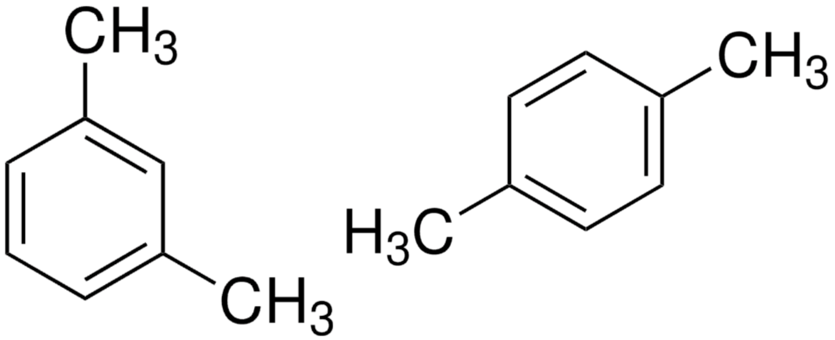
2. Thermodynamic and transport properties

Vapor pressure
Solubility
Adsorptivity
Diffusivity

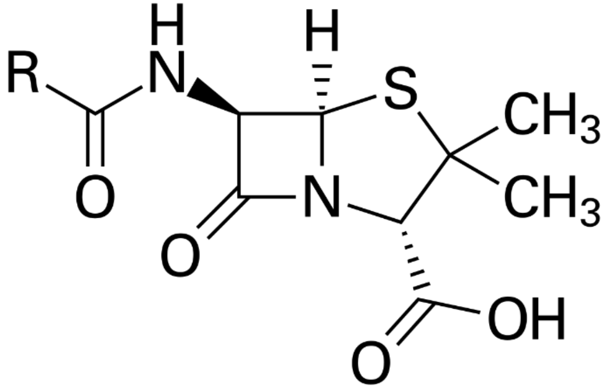
Examples: choosing separation based on molecular difference

A. Separation of air into oxygen-rich and nitrogen-rich products
   - Boiling points: O_2 (-183 °C) and N_2 (-195.8 °C)

B. Separation of m-xylene from p-xylene
   - Boiling points: m-xylene (139.3 ° C) and p-xylene (138.5 ° C),
   - Melting points: 47.4 ° C for m-xylene and 13.2 ° C for p-xylene



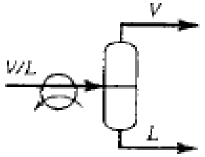
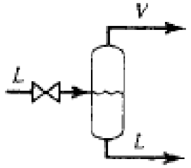
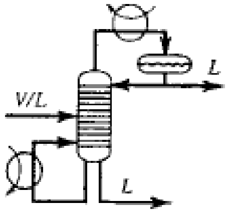
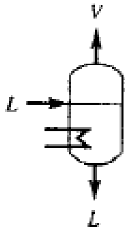
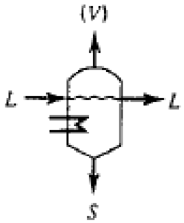
C. Separation of penicillin from water
   - Penicillin has a melting point of 97 ° C
   - Water has a boiling point of 100 ° C



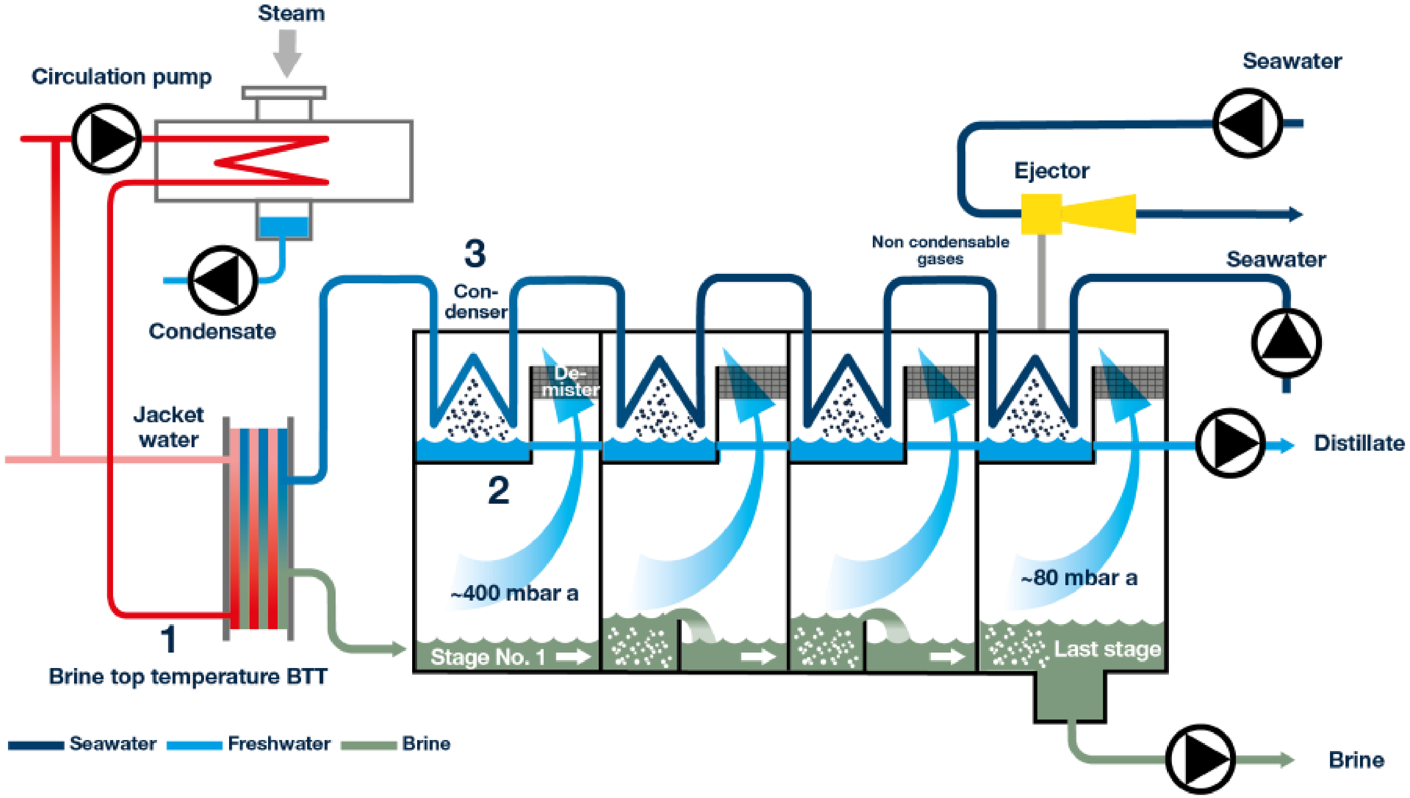
Examples: choosing separation based on molecular difference

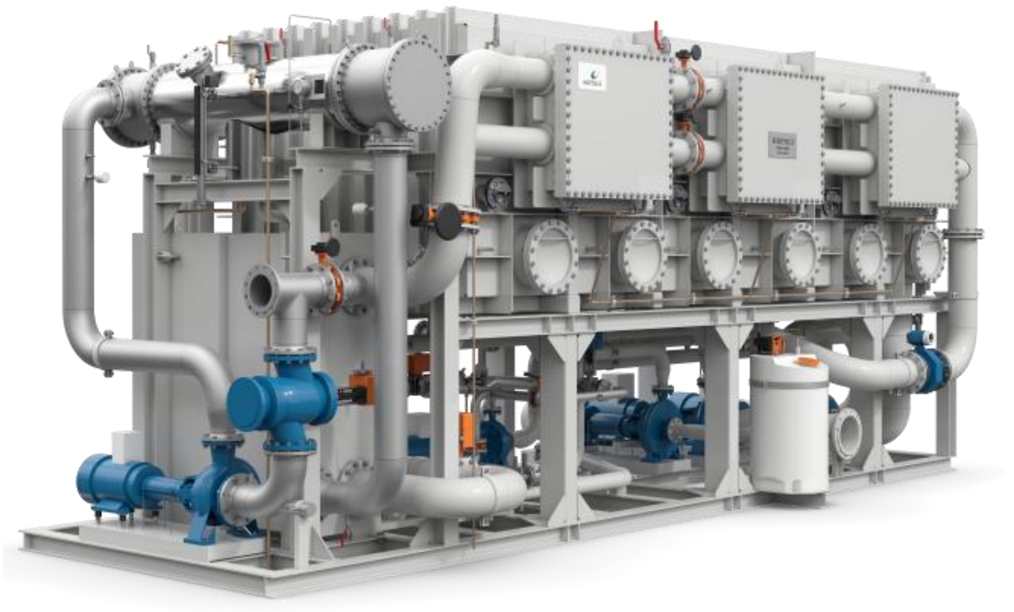
A. Distillation at higher pressure or low temperature
B. Crystallization
C. Liquid-liquid extraction of the penicillin with n-butyl acetate or n-amyl acetate.
    - penicillin decomposes before reaching the normal boiling point of water.

Separation Operations Based on Phase Creation

Separation Operation	Symbol^a	Initial or Feed Phase	Created or Added Phase	Separating Agent(s)	Industrial Example^b
Partial condensation or vaporization* (1)		Vapor and/or liquid	Liquid or vapor	Heat transfer (ESA)	Recovery of H_2 and N_2 from ammonia by partial condensation and high-pressure phase separation
Flash vaporization* (2)		Liquid	Vapor	Pressure reduction	Recovery of water from sea water
Distillation* (3)		Vapor and/or liquid	Vapor and liquid	Heat transfer (ESA) and sometimes work transfer	Purification of styrene
Evaporation (14)		Liquid	Vapor	Heat transfer (ESA)	Evaporation of water from a solution of urea and water
Crystallization (15)		Liquid	Solid (and vapor)	Heat transfer (ESA)	Recovery of a protease inhibitor from an organic solvent. Crystallization of *p*-xylene from a mixture with *m*-xylene

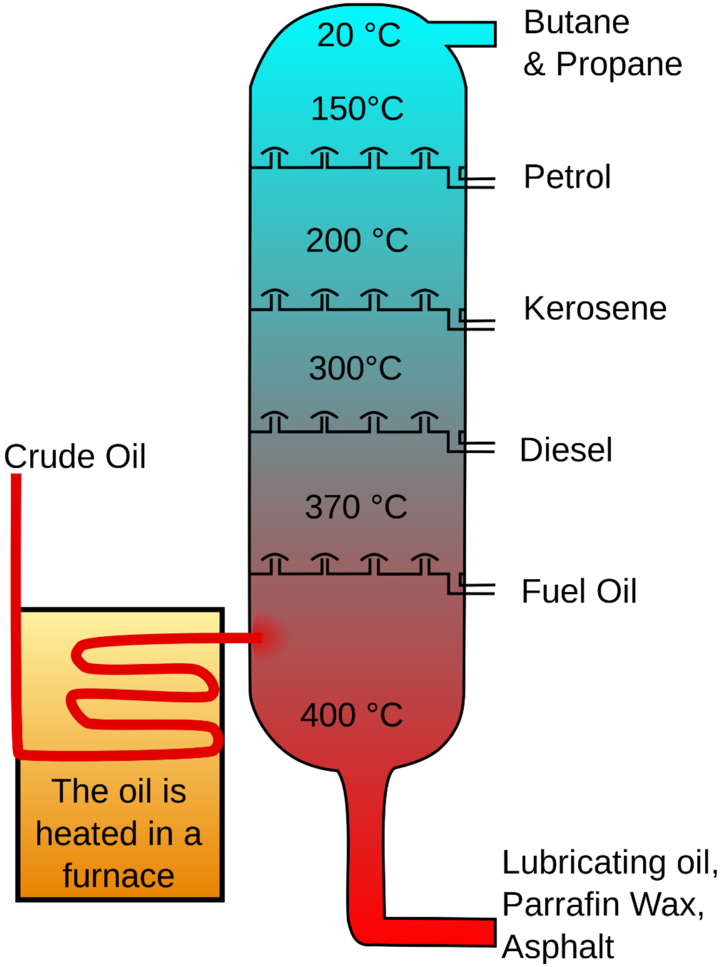
Flash vaporization





Multi-stage flash vaporization plants produce about 26% of all desalinated water in the world, but almost all of new desalination plants currently use reverse osmosis due to much lower energy consumption

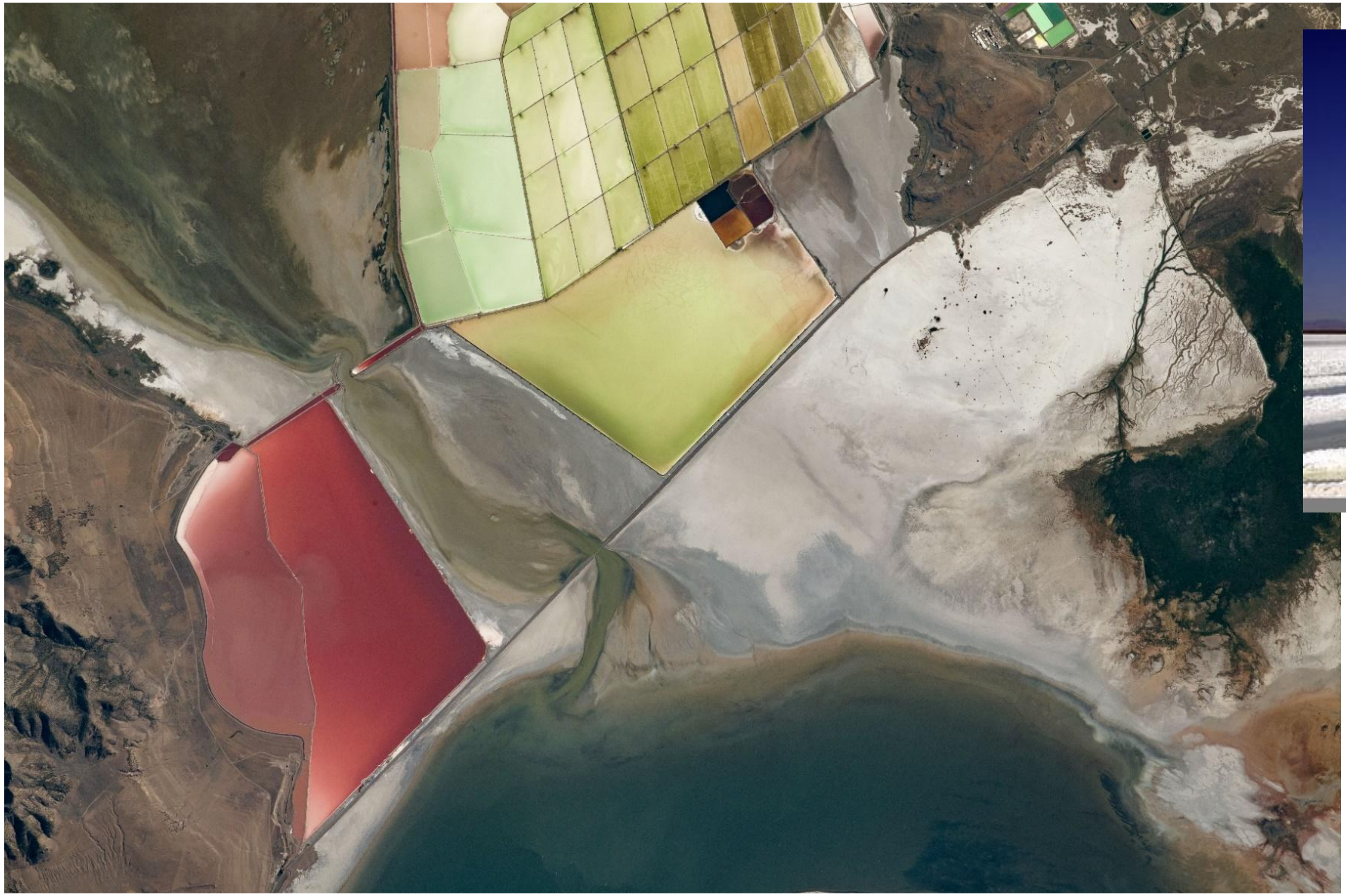
Distillation



- Multistage distillation is the most widely used industrial method for separating chemical mixtures.
  - petroleum refineries
  - biochemical industry to separate small molecules

Evaporation

Solar evaporation

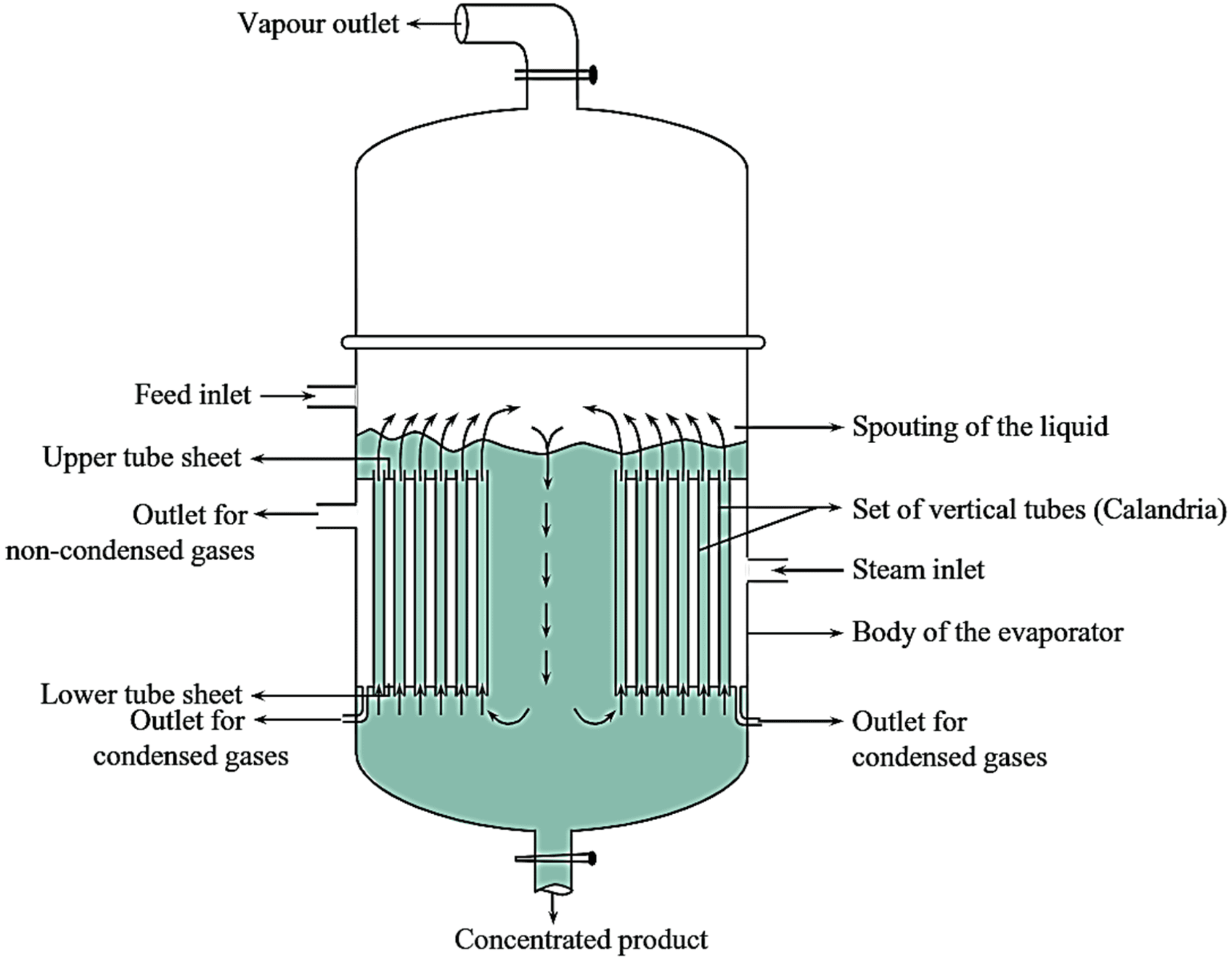


GSL evaporation pond

- Sea salt
- Metals, such as Mg
- Fertilizer, such as potash

- Sea salt
- Metals, such as Mg
- Fertilizer, such as potash

Evaporator

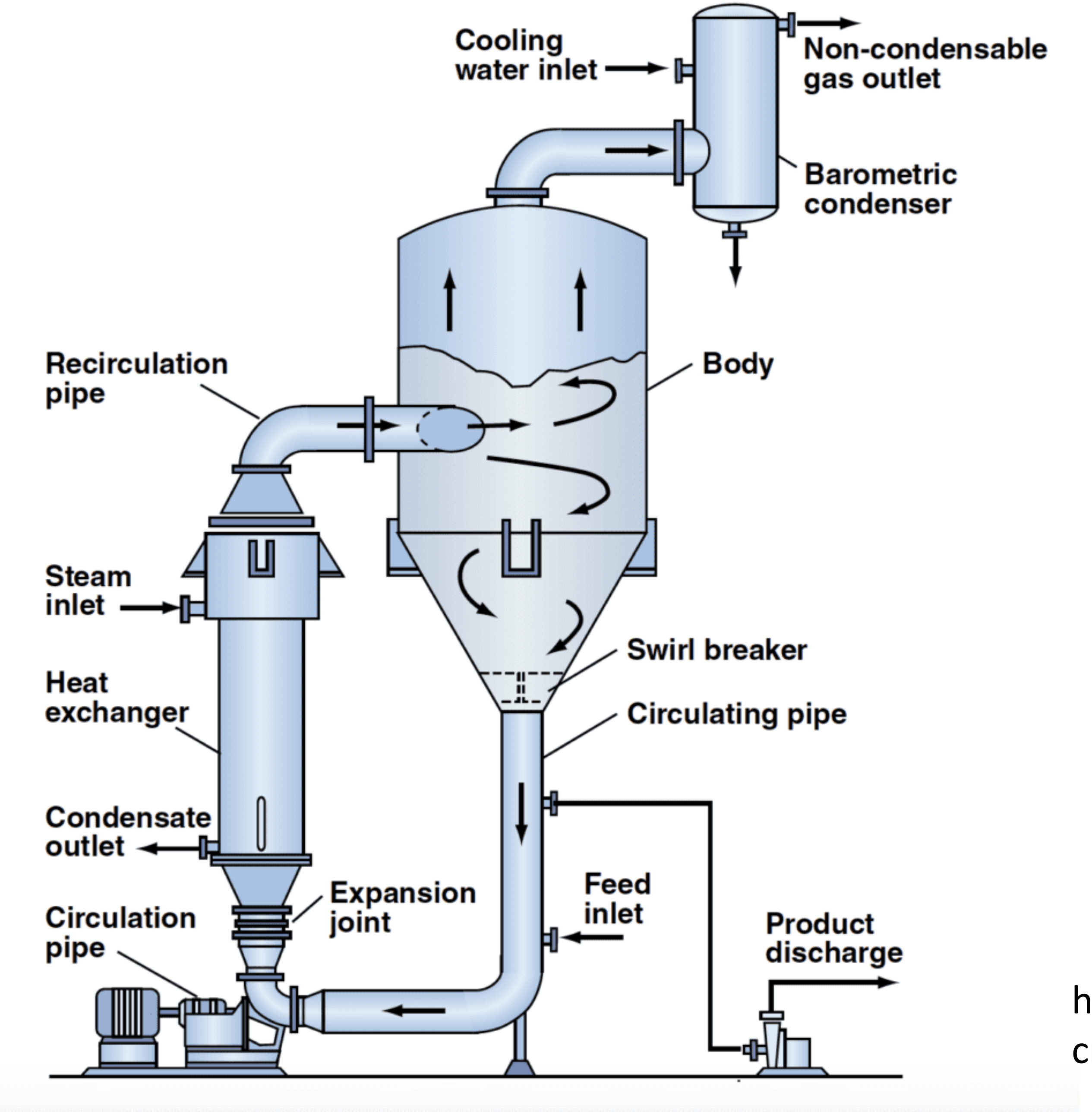

Vapour outlet
Feed inlet
Upper tube sheet
Outlet for non-condensed gases
Lower tube sheet
Outlet for condensed gases
Spouting of the liquid
Set of vertical tubes (Calandria)
Steam inlet
Body of the evaporator
Outlet for condensed gases
Concentrated product

Crystallization

https://youtu.be/lo0cp2uhxb0?si=h9nCvbfR5TTKRgTG

Vertical cooling crystallizer in a beet sugar factory

- Crystallization is a key unit operation used in the separation and purification of intermediate compounds and Active Pharmaceutical Ingredients (APIs). Over 80% of drug products involving at least one crystallization step.

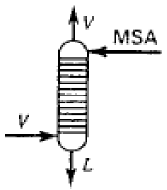
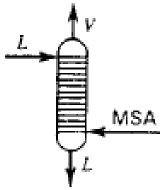
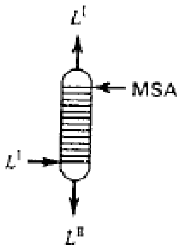


https://www.chemengonline.com/a-clearer-view-of-crystallizers/

Compass Minerals Planned Lithium Production Process – Phase One

	Commonly Used Today			Commonly Used in Li and Other Chemical Process Today					
	Step 1: Evaporation Ponds	**Step 2:** Pre-Filtration	**Step 3:** ILiAD^{TM} DLE	**Step 4: Softening**	**Step 5:** Ion Exchange & Reverse Osmosis	**Step 6:** Evaporation	**Step 7:** Crystallization	**Step 8:** Drying	Step 9: Packaging and Storage
Inputs	North Arm Lake Brine	$MgCl_2$ Brine or Interstitial Brine	Pre-filtered Brine and Water	Concentrated LiCl brine from DLE and NaOH	Softened LiCl Brine and $Mg(OH)_2$	Purified LiCl	Concentrated LiCl and Soda Ash	Crystalized Li_2CO_3	Final Product Li_2CO_3
Outputs and Co-products	Sodium, Potassium and Magnesium based products	Pre-filtered Brine for DLE	Concentrated LiCl brine and spent brine	Softened LiCl Brine and $Mg(OH)_2$	Purified LiCl	Concentrated LiCl	Crystalized Li_2CO_3	Final Product Li_2CO_3	Packaged finished battery grade product
Output and/or Co-product Fate	Sales to other industries		Spent brine **recycled** to Mg product stream or pond system	$Mg(OH)_2$ utilized in other industries or landfill	Permeate **recycled** back to DLE	Water **recycled** back to process	Residual liquids **recycled** back to process or to ponds	Water **recycled** back to process	Option to continue conversion process to $LiOH{\cdot}H_2O$
	Co-product		Recycle		Recycle	Recycle	Recycle	Recycle	Final product

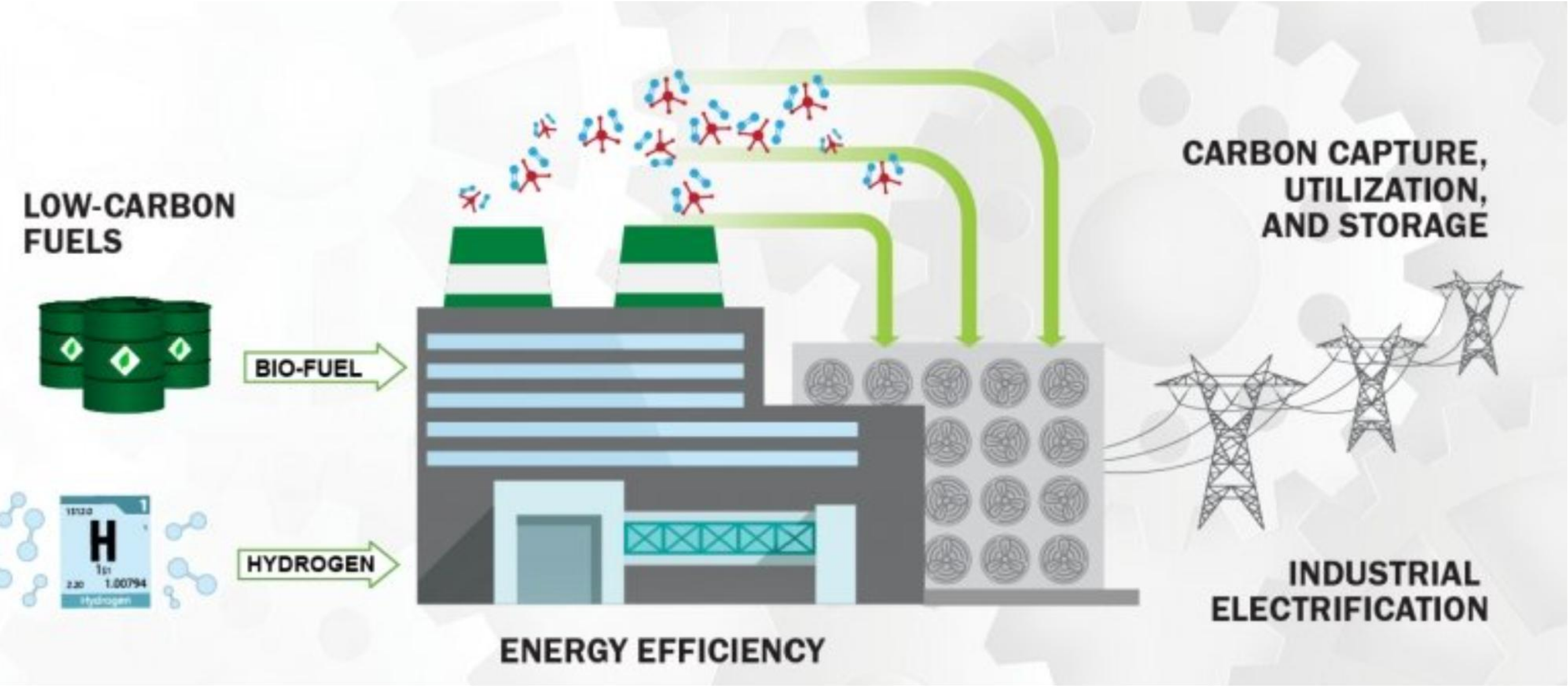
Separation Operations Based on Phase Addition

Separation Operation	Symbol[a]	Initial or Feed Phase	Created or Added Phase	Separating Agent(s)	Industrial Example[b]
Absorption* (6)		Vapor	Liquid	Liquid absorbent (MSA)	Separation of carbon dioxide from combustion products by absorption with aqueous solutions of an ethanolamine
Stripping* (7)		Liquid	Vapor	Stripping vapor (MSA)	Stream stripping of naphtha, kerosene, and gas oil side cuts from crude distillation unit to remove light ends
Liquid–liquid extraction* (11)		Liquid	Liquid	Liquid solvent (MSA)	Recovery of penicillin from aqueous fermentation medium by methyl isobutyl ketone. Recovery of aromatics

Industry decarbonization

U.S. DEPARTMENT OF
ENERGY

Industrial Decarbonization Roadmap

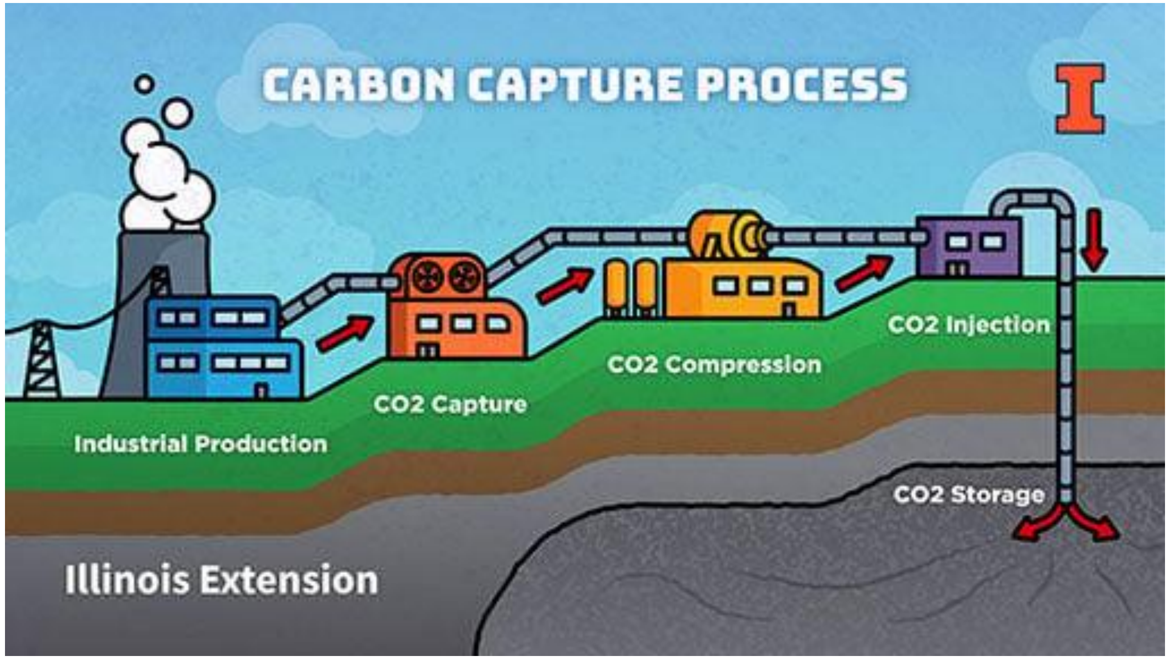


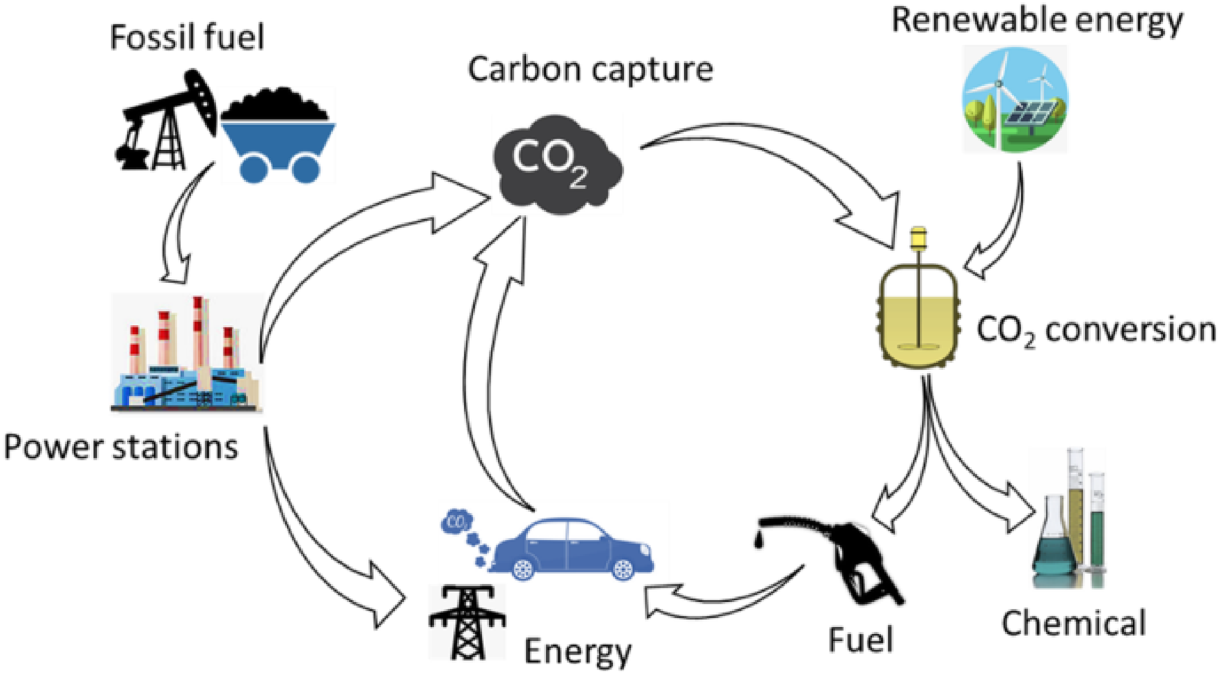
Reading: https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap

Interested in the electrification of chemical production?

CH EN 5308/6308: Electrochemical system/Battery Technology (offered every Fall)

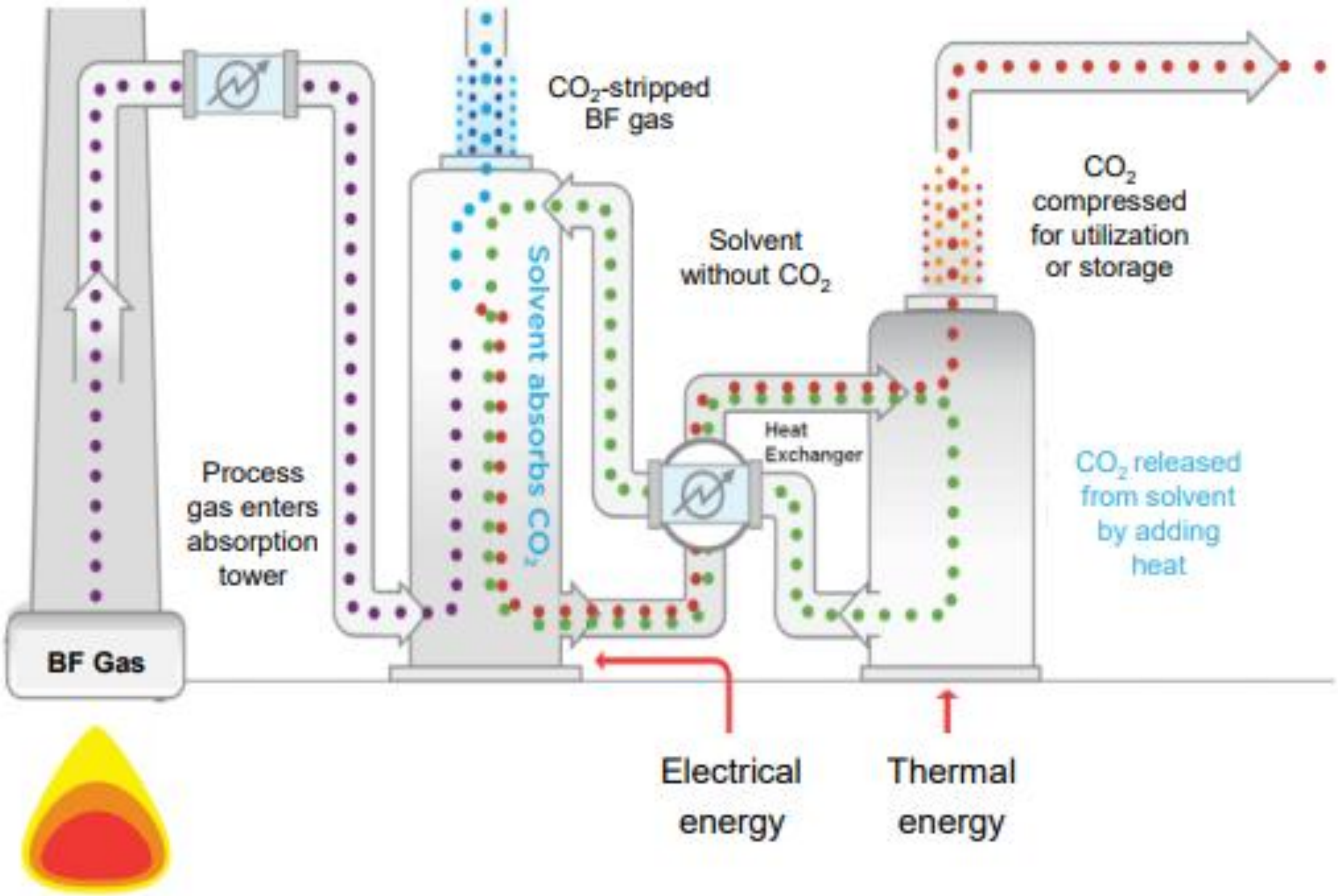
Carbon capture, utilization, and storage (CCUS)



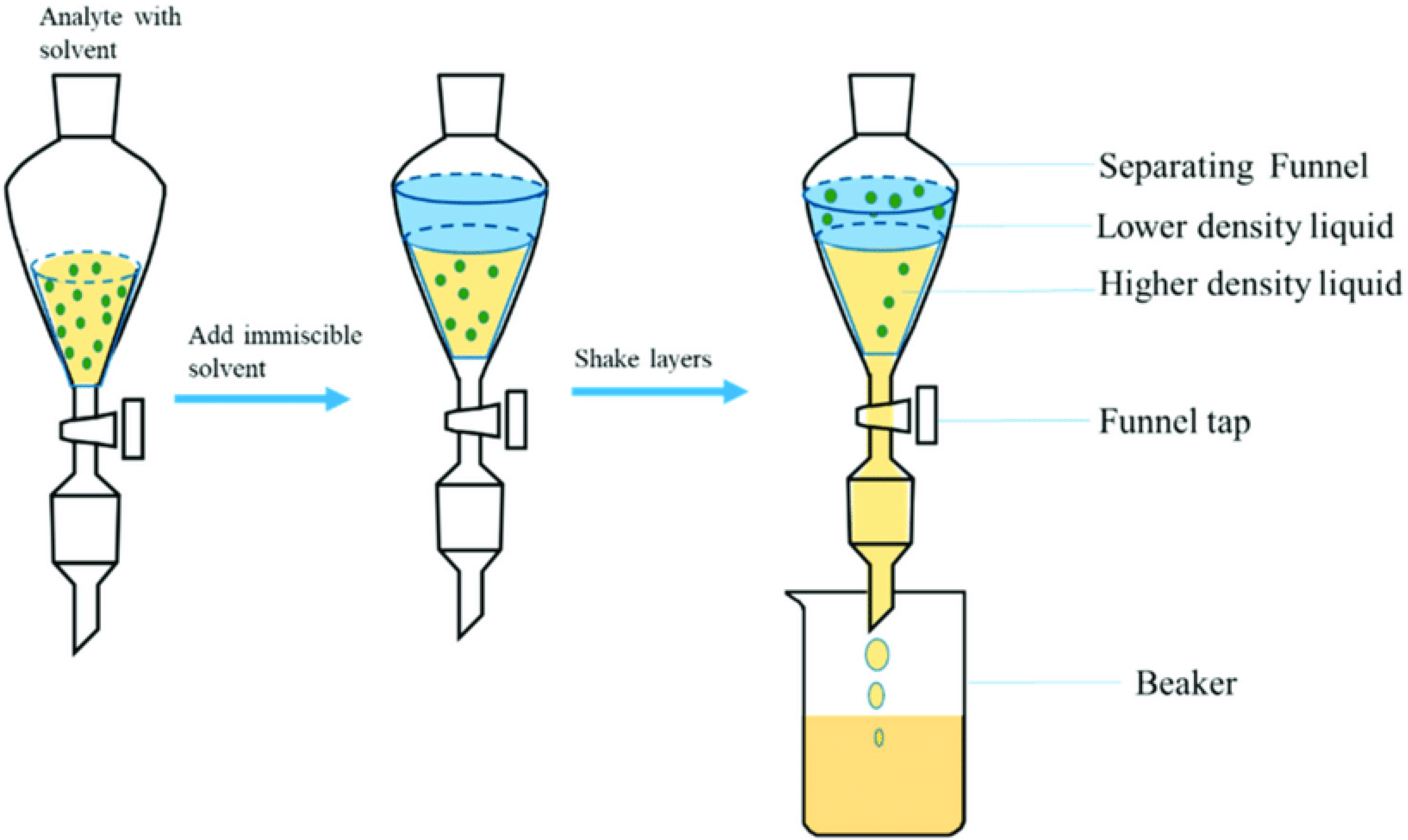


Interested in the electrification of chemical production?
CH EN 5308/6308: Electrochemical system/Battery Technology (offered every Fall)

Absorption


CO$_2$-stripped BF gas
CO$_2$ compressed for utilization or storage
Solvent without CO$_2$
Solvent absorbs CO$_2$
Heat Exchanger
Process gas enters absorption tower
CO$_2$ released from solvent by adding heat
BF Gas
Electrical energy
Thermal energy

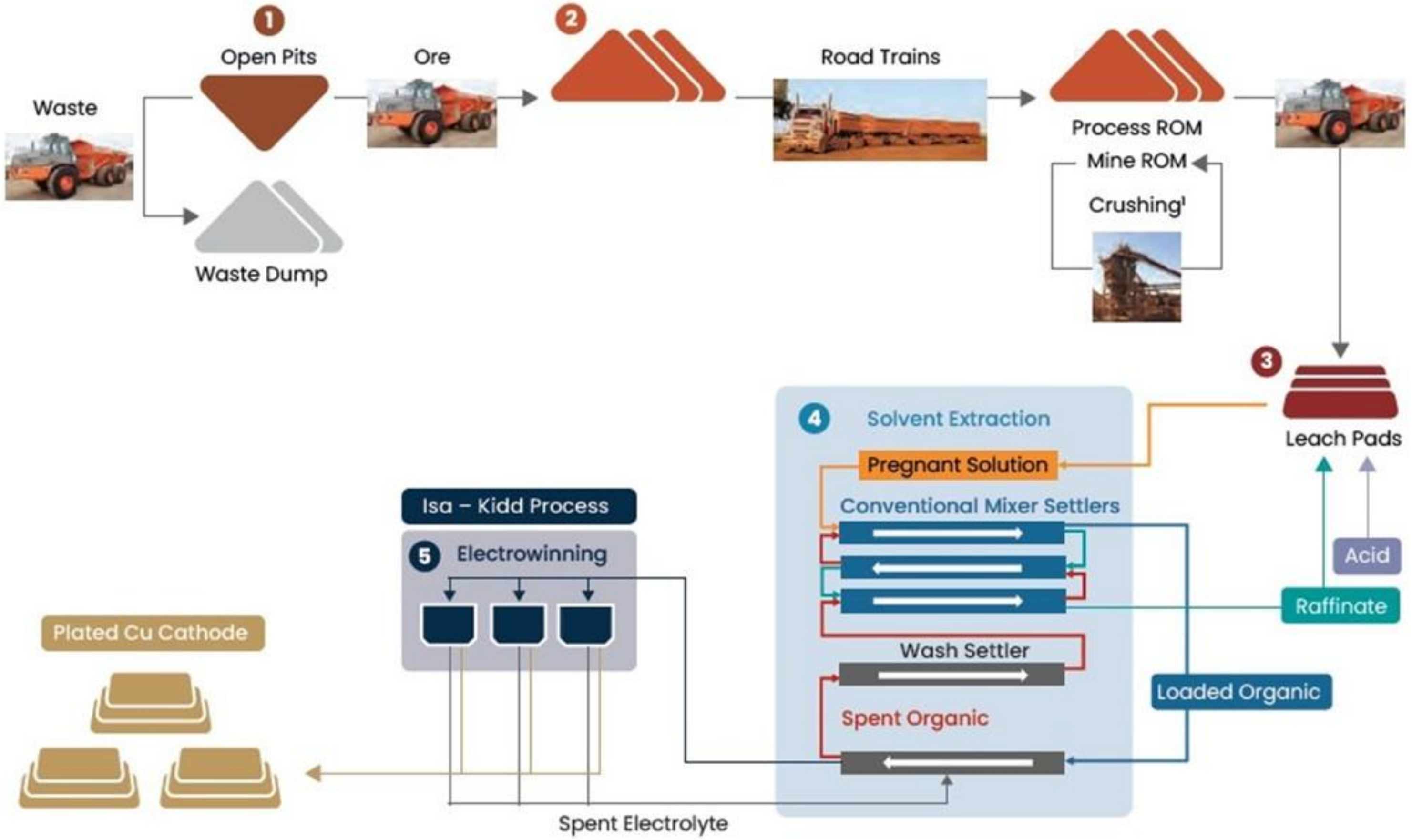
Liquid-liquid extraction (solvent extraction)



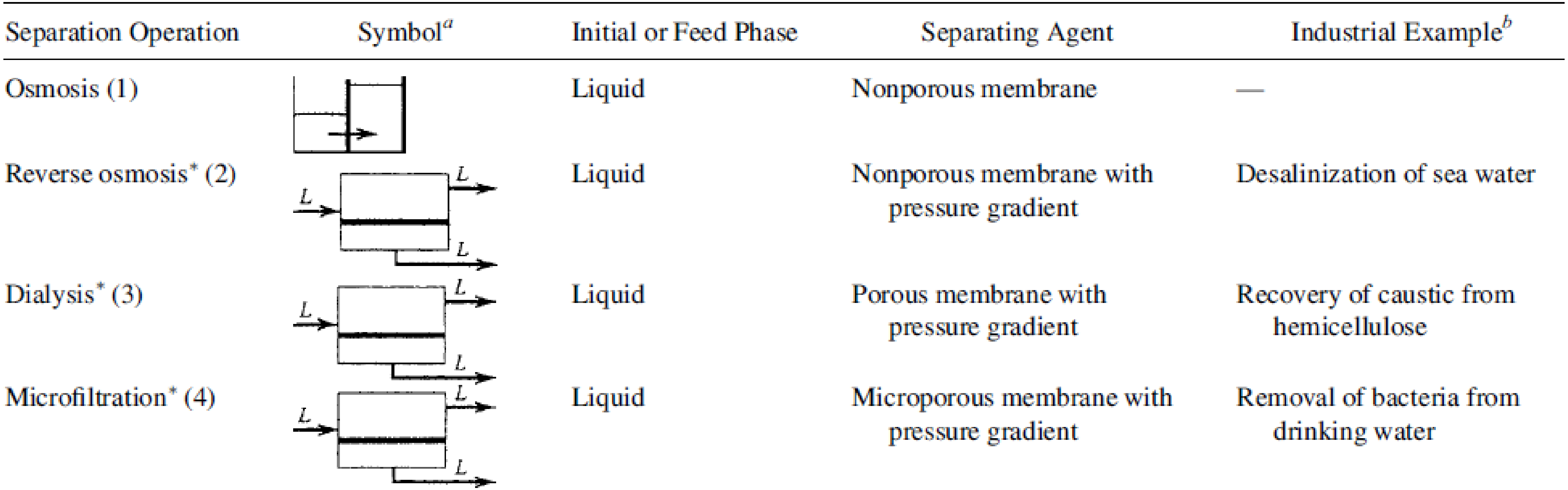
Industry application

- Copper production
- Rare earth metal production

1 Mining	2 Crushing & Agglomeration[1]	3 Heap Leach	4 Solvent Extraction	5 Electrowinning
Ore is mined and transported to the ROM Pad.	Crushed ore is agglomerated with water and acid; allowing the smaller particles to bind to crushed ore. This binding process allows the acid in the heap to percolate evenly and leach the copper at a faster rate.	The agglomerated ore is stacked on the heap leach pad via conveyors. Raffinate is sprinkled continuously over the stacked ore and reacts with the malachite to form the PLS[2], which forms the gravity feed that drains into the ponds.	Within Solvent Extraction (SX) tanks, copper is transferred from the PLS to the electrolyte using an organic solution. The raffinate is recycled to the heap for further leaching. The electrolyte is pumped to the EW cells.	Within the Electrowinning (EW) galvanic cells, copper cathode is plated via an electrical current. The spent electrolyte is returned to the SX. The copper is stripped from the cathode plates and packed for sales.



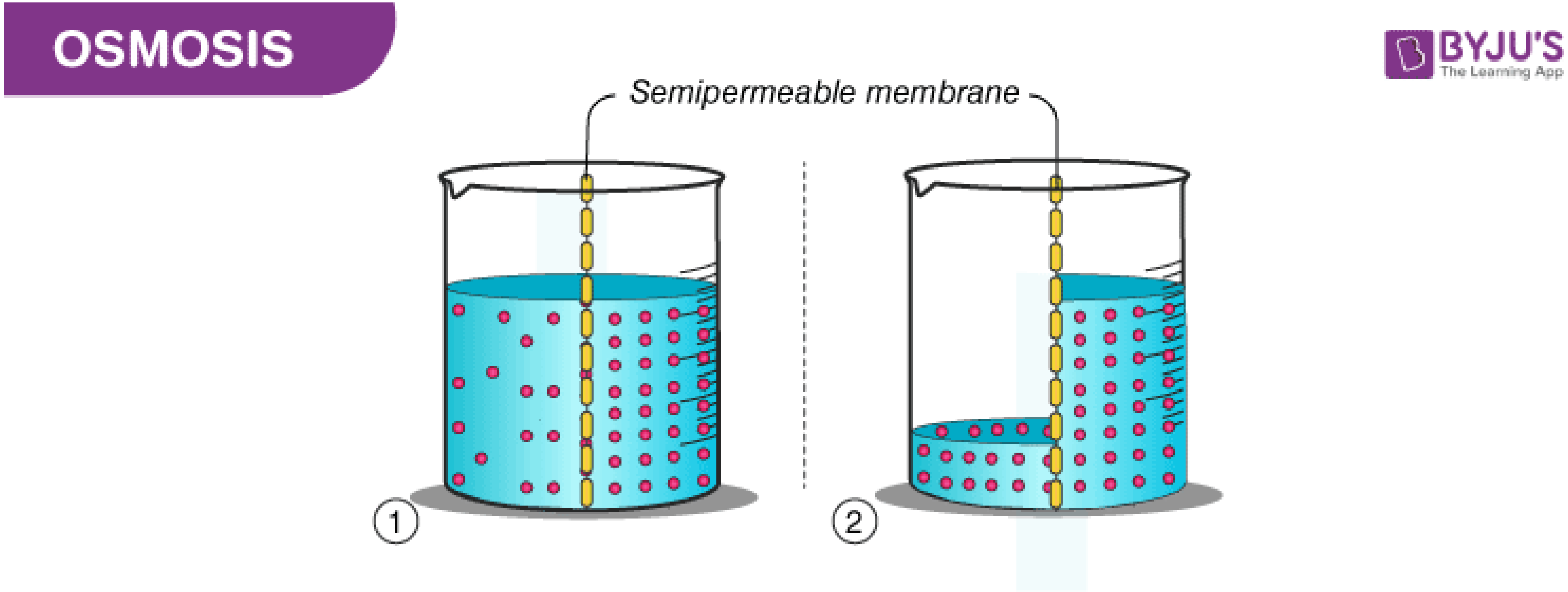
Separation Operations Based on a Barrier



Separation Operation	Symbol[a]	Initial or Feed Phase	Separating Agent	Industrial Example[b]
Osmosis (1)		Liquid	Nonporous membrane	—
Reverse osmosis* (2)		Liquid	Nonporous membrane with pressure gradient	Desalinization of sea water
Dialysis* (3)		Liquid	Porous membrane with pressure gradient	Recovery of caustic from hemicellulose
Microfiltration* (4)		Liquid	Microporous membrane with pressure gradient	Removal of bacteria from drinking water

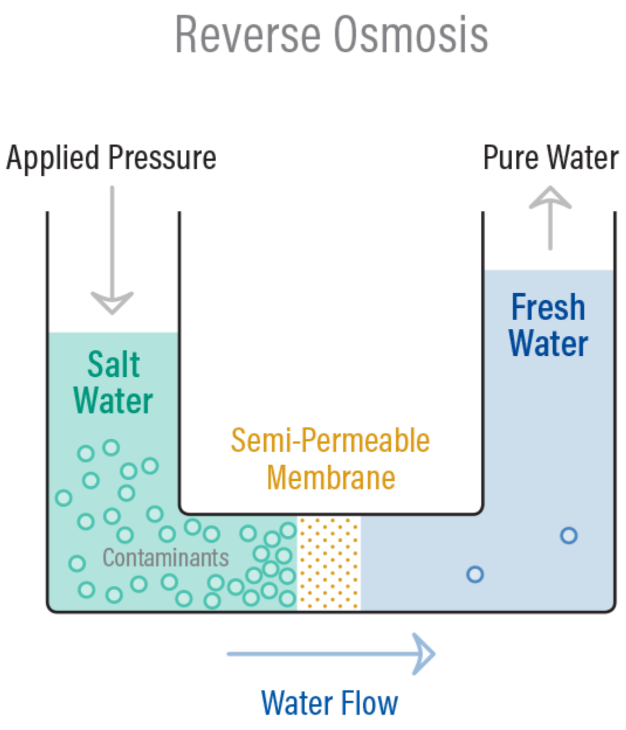
- For microporous membranes, separation is affected by rate of species diffusion through the pores
- For nonporous membranes, separation is controlled by differences in solubility in the membrane and rate of species diffusion

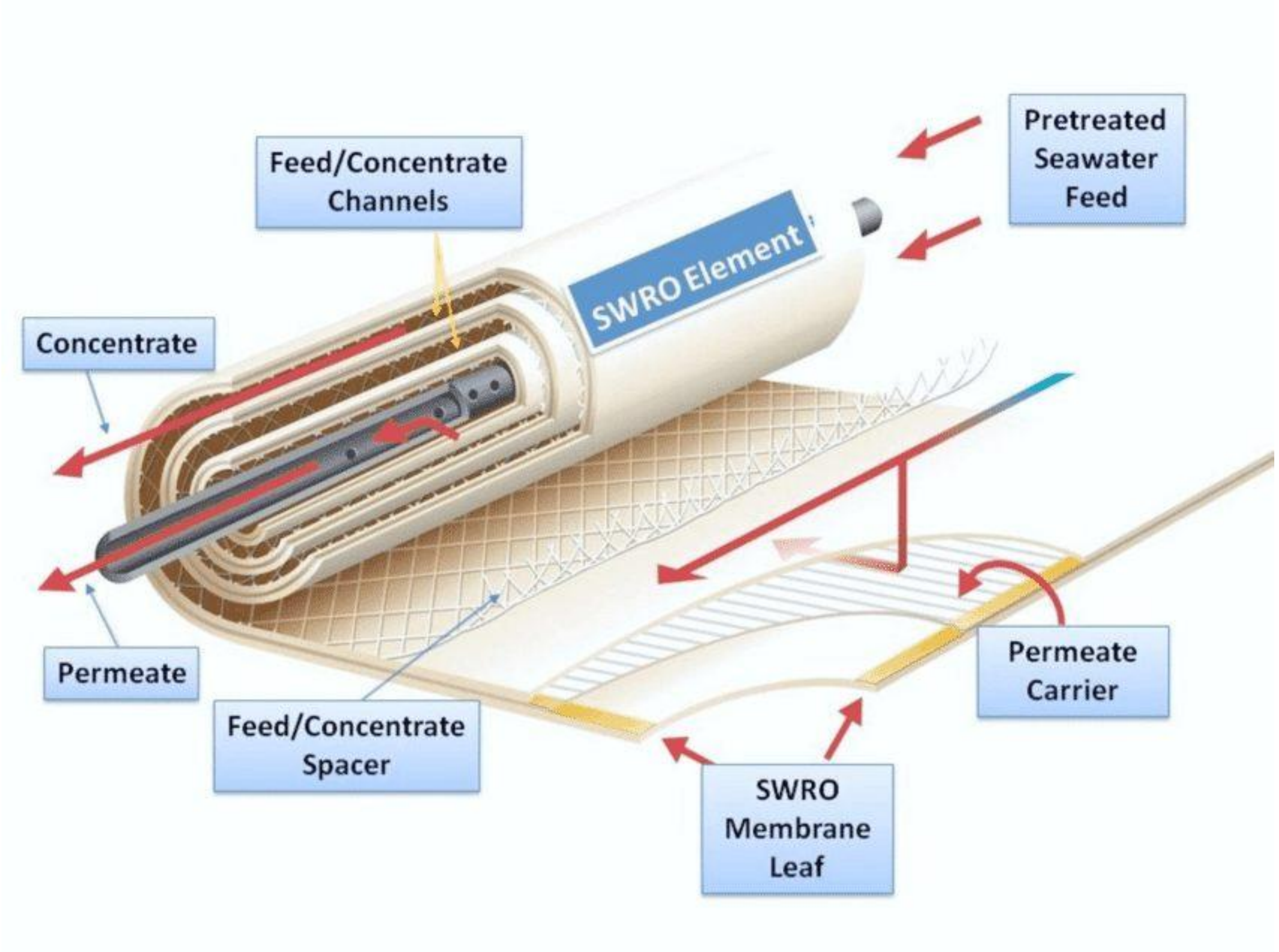
Osmosis



https://byjus.com/biology/osmosis/

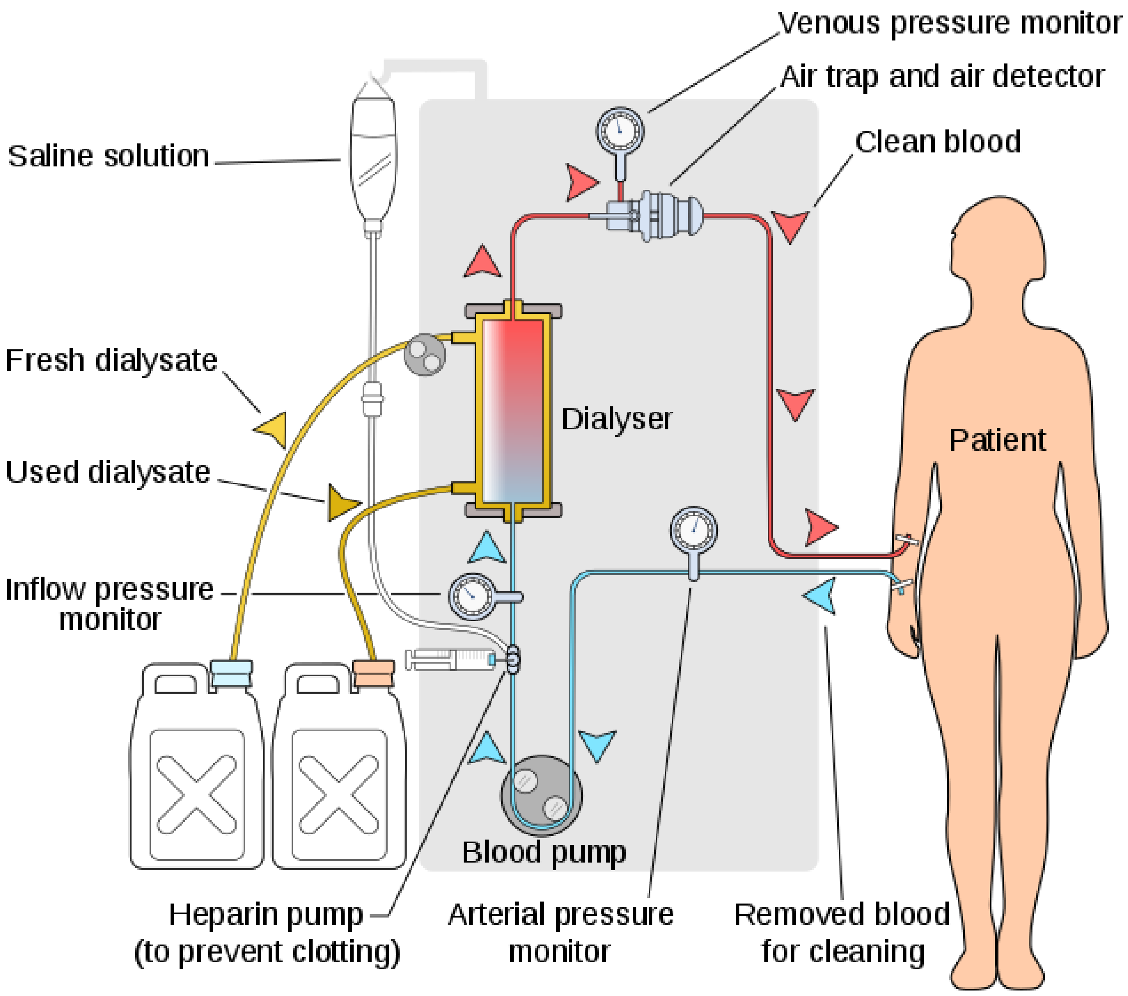
Reverse Osmosis

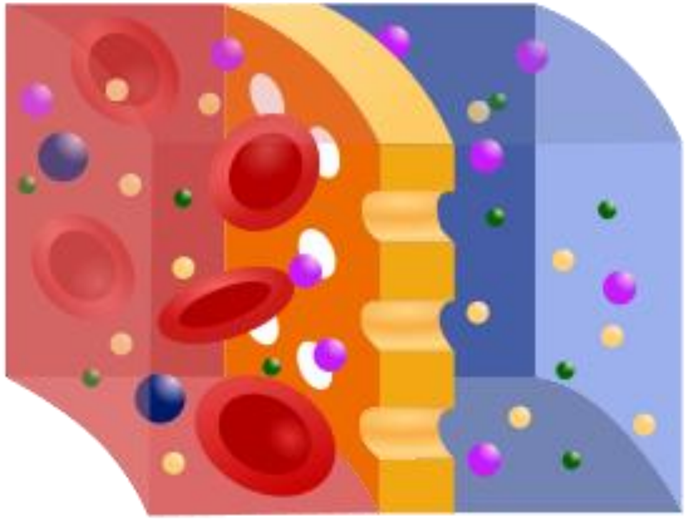




According to the International Desalination Association, for 2011, RO was used in 66% of installed desalination capacity (0.0445 of 0.0674 km³/day), and nearly all new plants

Dialysis

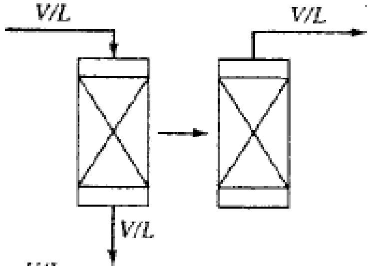
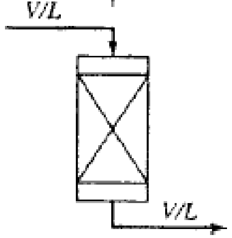
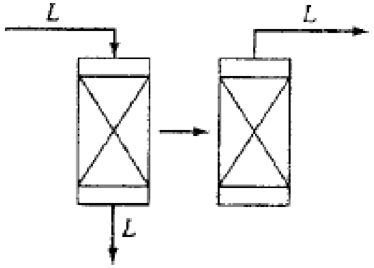




Dialysis is used for removing excess water, solutes, and toxins from the blood in people whose kidneys can no longer perform these functions naturally

Dialysis is used as a temporary measure in either acute kidney injury or in those awaiting kidney transplant and as a permanent measure in those for whom a transplant is not indicated or not possible

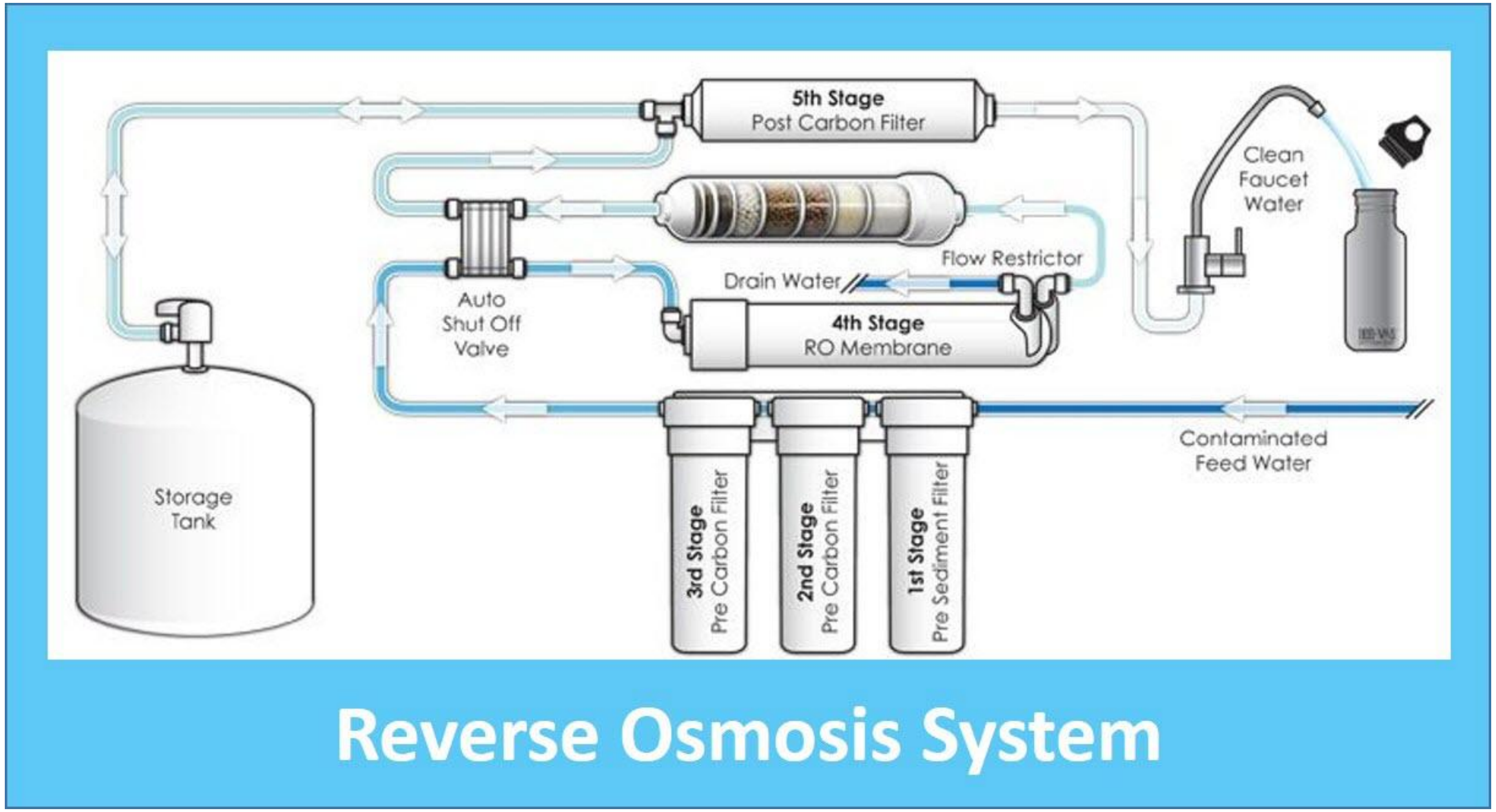
Separation Operations Based on a Solid Agent

Separation Operation	Symbol[a]	Initial or Feed Phase	Separating Agent	Industrial Example[b]
Adsorption* (1)		Vapor or liquid	Solid adsorbent	Purification of *p*-xylene
Chromatography* (2)		Vapor or liquid	Solid adsorbent or liquid adsorbent on a solid support	Separation and purification of proteins from complex mixtures. Separation of xylene isomers and ethylbenzene
Ion exchange* (3)		Liquid	Resin with ion-active sites	Demineralization of water

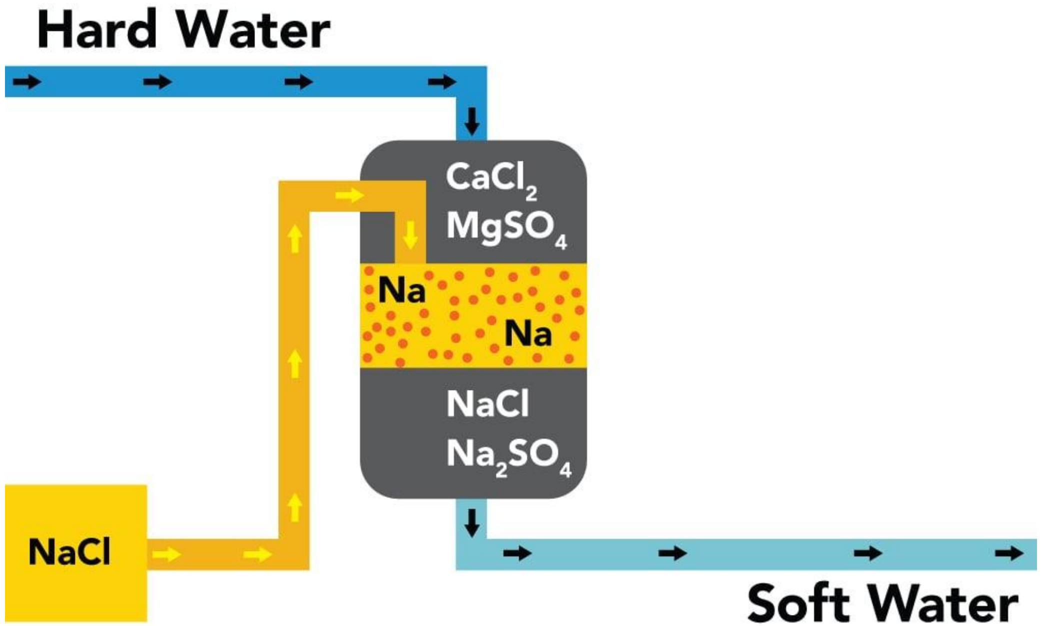
- Adsorption is confined to the surface of the solid adsorbent, unlike absorption, which occurs throughout the absorbent.
- The active separating agent eventually becomes saturated with solute and must be regenerated or replaced.
- Such separations are often conducted batchwise or semi-continuously.

Adsorption

In-house water treatment system



Ion-exchange



Hard Water

$CaCl_2$

$MgSO_4$

Na

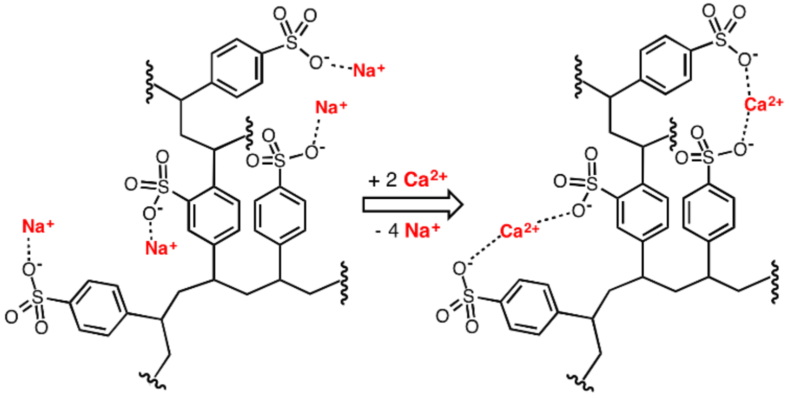
Na

$NaCl$

Na_2SO_4

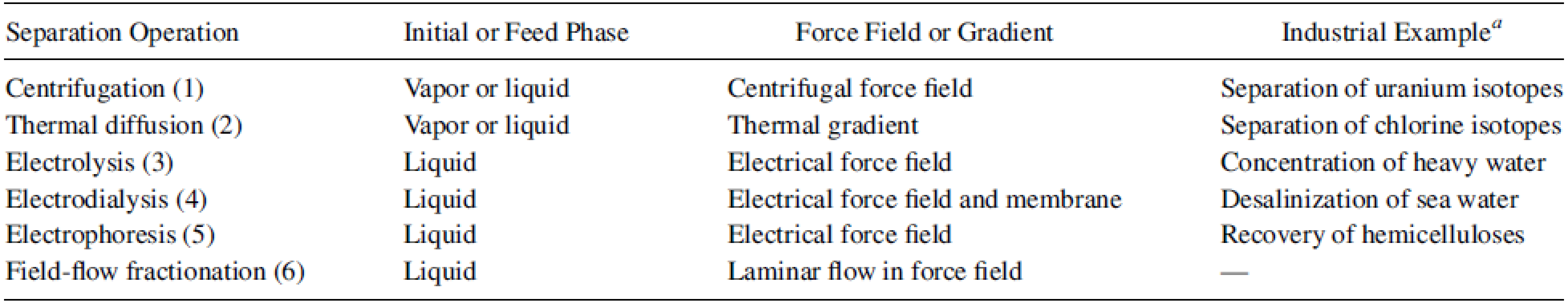
NaCl

Soft Water



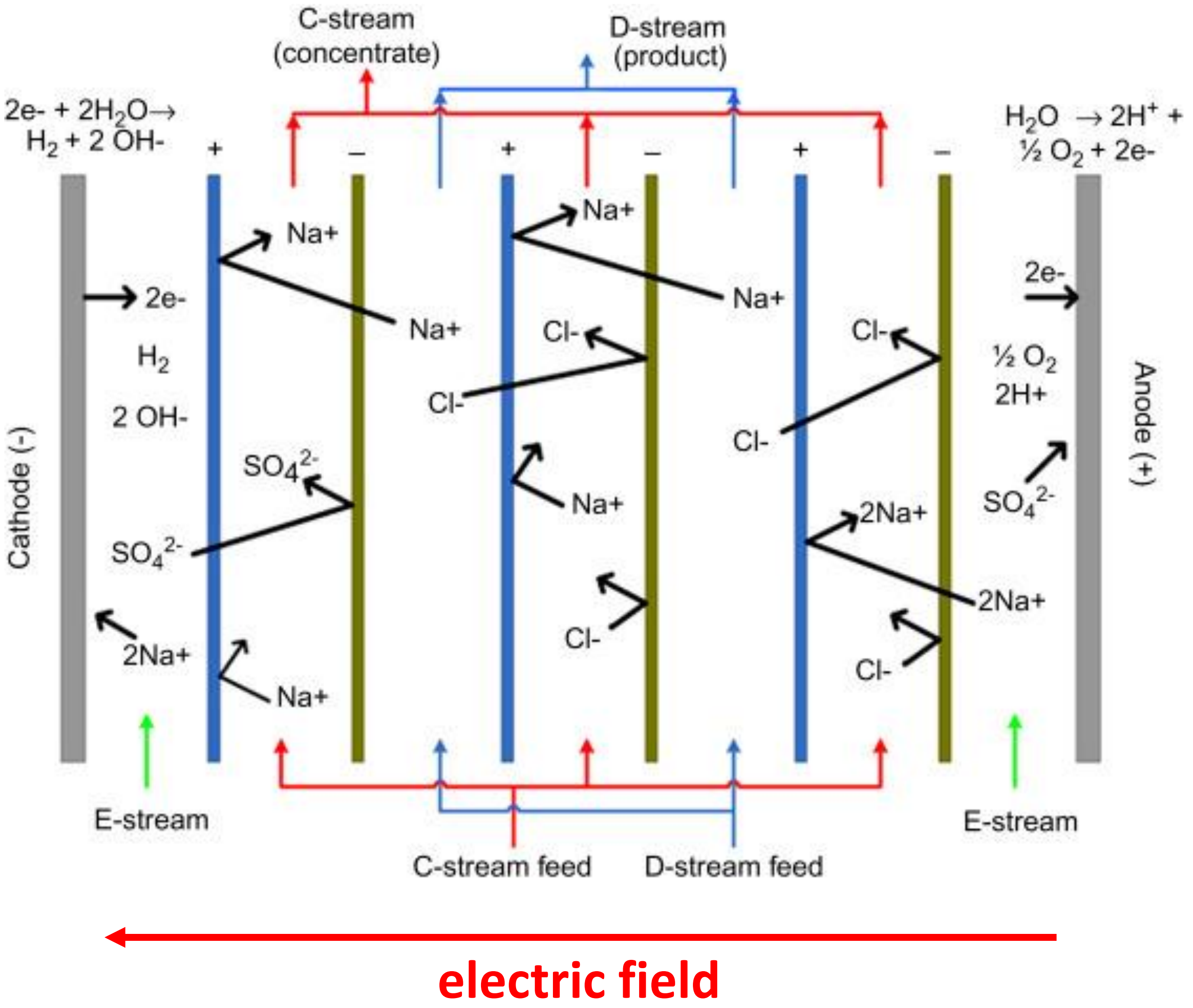
Water softening is the removal of calcium, magnesium, and certain other metal cations in hard water. Soft water also extends the lifetime of plumbing by reducing or eliminating scale build-up in pipes and fittings.

Separation Operations by Applied Field or Gradient



Separation Operation	Initial or Feed Phase	Force Field or Gradient	Industrial Example[a]
Centrifugation (1)	Vapor or liquid	Centrifugal force field	Separation of uranium isotopes
Thermal diffusion (2)	Vapor or liquid	Thermal gradient	Separation of chlorine isotopes
Electrolysis (3)	Liquid	Electrical force field	Concentration of heavy water
Electrodialysis (4)	Liquid	Electrical force field and membrane	Desalinization of sea water
Electrophoresis (5)	Liquid	Electrical force field	Recovery of hemicelluloses
Field-flow fractionation (6)	Liquid	Laminar flow in force field	—

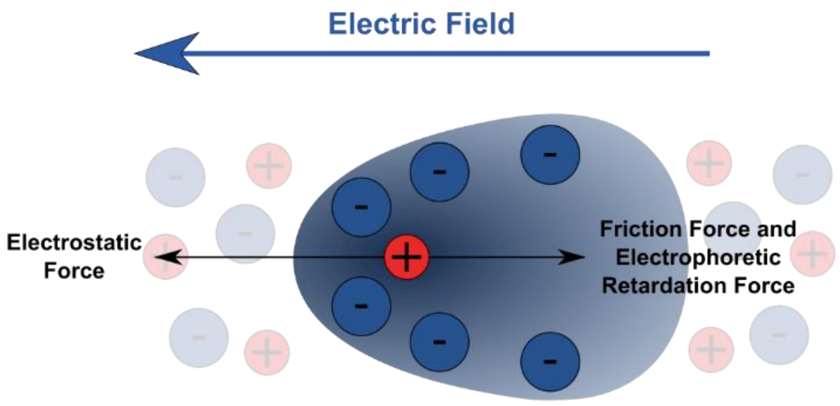
Electrodialysis

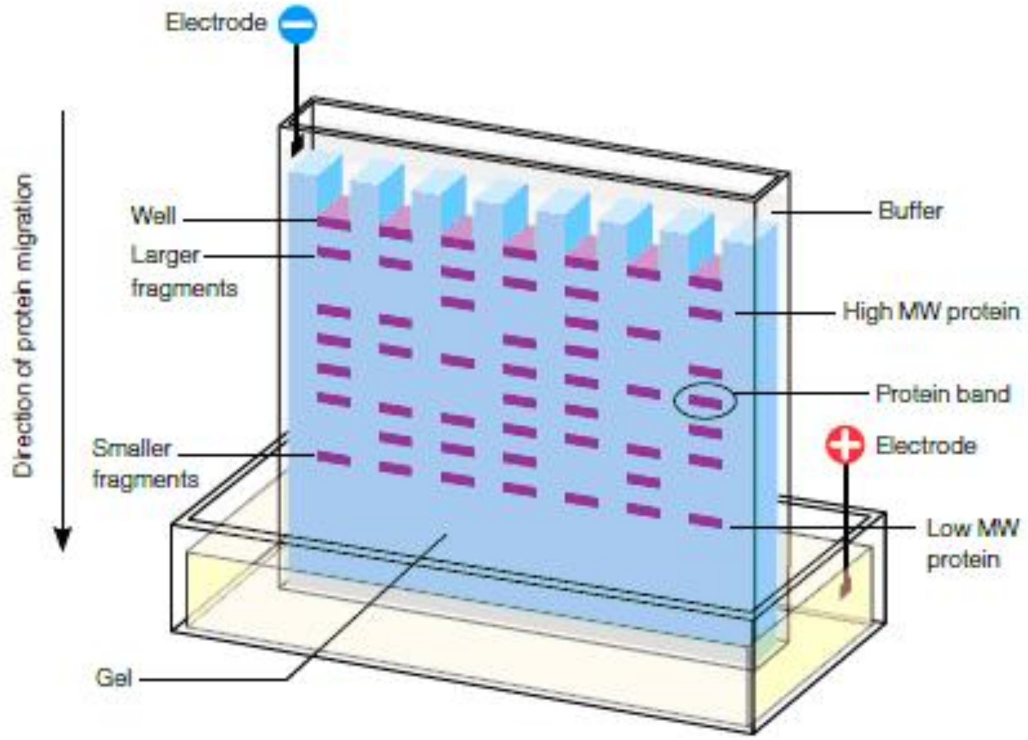


- Desalination and salt production.
- Small and medium scale drinking water production
- Water reuse
- Pre-demineralization (e.g., boiler makeup & pretreatment,)
- Food processing
- ..


STACK 1
STACK 2
DOSATRON
D 500
NetSol Water

Electrophoresis





Electrophoresis is used in laboratories to separate [macromolecules] based on charge. The [technique normally applies a negative charge so proteins move towards a positive charge]. It is used extensively in [DNA], [RNA] and [protein] analysis

Quiz

- To produce potable water from seawater, what separation process can be used?
  1. Flash vaporization
  2. Distillation
  3. Reverse osmosis
  4. Electrodialysis
  5. Adsorption
  6. Ion-exchange

ABCD

E is used to remove trace contaminations in water, such as lead, chlorine and organic matter

F is used to soften water

- What type do the following separation techniques belong to?
  - A. Flash evaporation
  - B. Absorption
  - C. Dialysis
  - D. Electrophoresis

A is phase creation

B is phase addition

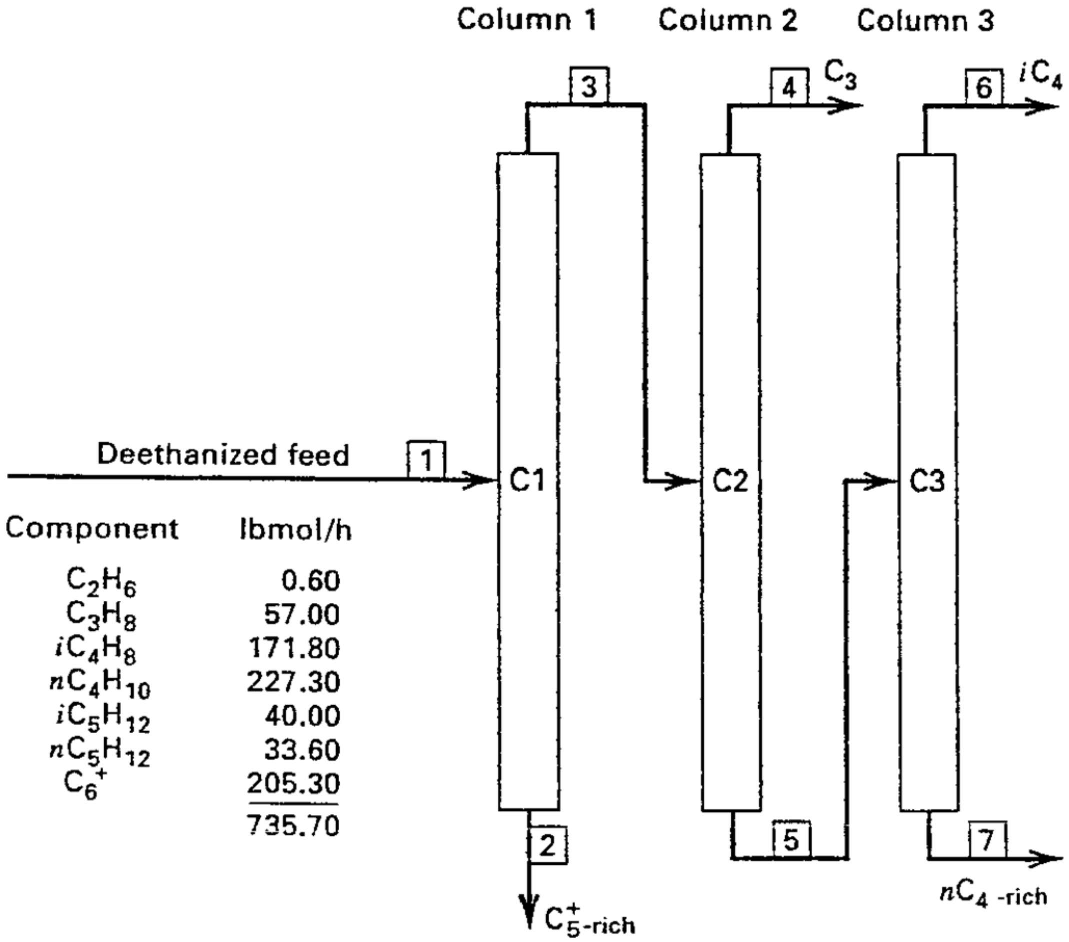
C is solid barrier based

D is electric field based

Content

- Basic concepts (SHR 1.0-1.1)
- Types of separation techniques (SHR 1.2-1.6)
- Example: distillation (SHR 1.7-1.8)
    - Mass balance
    - Split fraction and ratio
    - Recovery and purity
    - Separation sequences
    - Separation factor
- Selection of separation process (SHR 1.10)

Example: distillation



Component	lbmol/h
C_2H_6	0.60
C_3H_8	57.00
iC_4H_8	171.80
nC_4H_{10}	227.30
iC_5H_{12}	40.00
nC_5H_{12}	33.60
C_6^+	205.30
	735.70

Figure 1.8 Hydrocarbon recovery process.

For each column, feed components are partitioned between the overhead and the bottoms

How do we measure the efficacy of the separation?

- Split fraction and ratio
- Purity and recovery
- Separation factor/power

Mass balance

- For a C component, N phase mixture
- The molar flow rate in the feed equals to that in the product

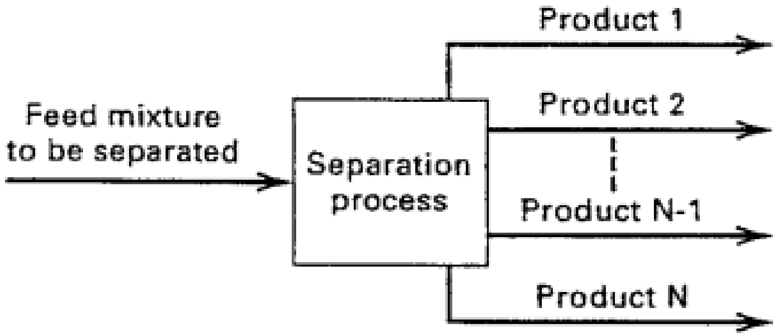


Figure 1.5 General separation process.

$$n_i^{(F)} = \sum_{p=1}^{N} n_i^{(p)} = n_i^{(1)} + n_i^{(2)} + \cdots + n_i^{(N-1)} + n_i^{(N)}$$

$$n_i^{(F)} = \sum_{p=1}^{N} n_i^{(p)} = n_i^{(1)} + n_i^{(2)} + \cdots + n_i^{(N-1)} + n_i^{(N)}$$

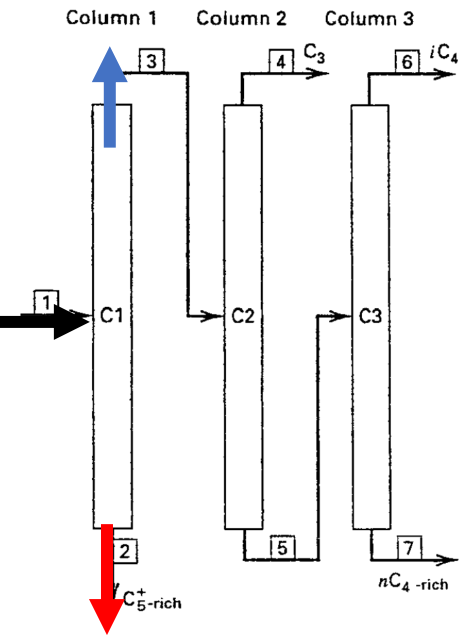


Table 1.5 Operating Material Balance for Hydrocarbon Recovery Process

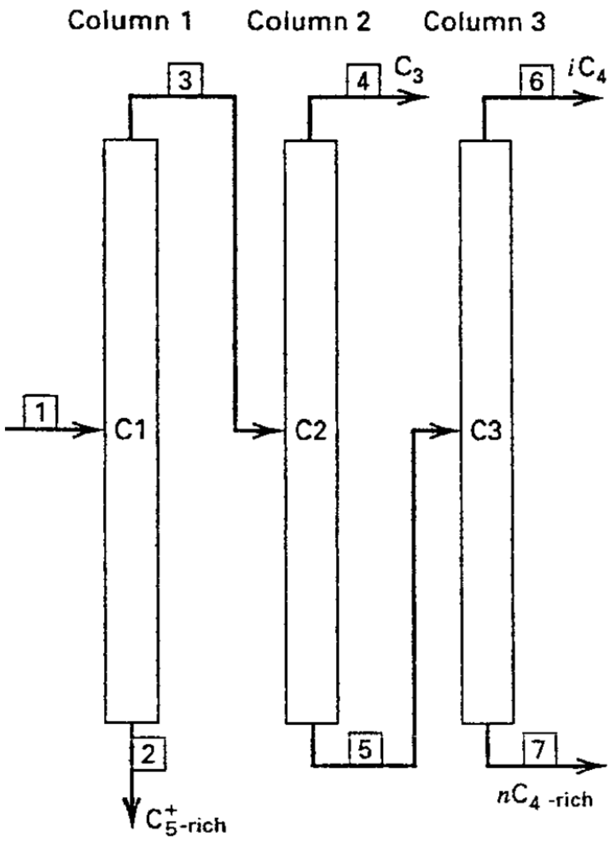
	lbmol/h in Stream						
Component	1 Feed to C1	2 C_5^+-rich	3 Feed to C2	4 C_3	5 Feed to C3	6 iC_4	7 nC_4-rich
C_2H_6	0.60	0.00		0.60	0.00	0.00	0.00
C_3H_8	57.00	0.00		54.80	2.20	2.20	0.00
iC_4H_{10}	171.80	0.10		0.60	171.10	162.50	8.60
nC_4H_{10}	227.30	0.70		0.00	226.60	10.80	215.80
iC_5H_{12}	40.00	11.90		0.00	28.10	0.00	28.10
nC_5H_{12}	33.60	16.10		0.00	17.50	0.00	17.50
C_6^+	205.30	205.30		0.00	0.00	0.00	0.00
Total	735.60	234.10		56.00	445.50	175.50	270.00

Overhead from C1

Feed to C1

Bottom from C1

Split fraction and ratio



- Split fraction (SF), the fraction of one component found in the first product

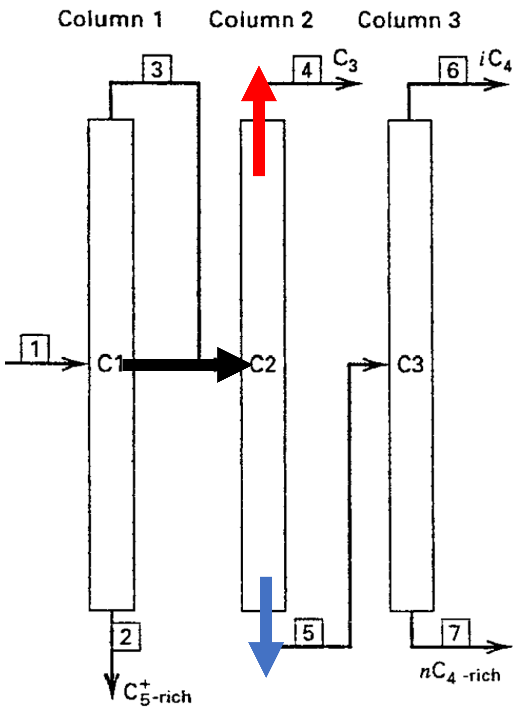
$$\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}$$

- **i: component**, **k: separator**
- Depends on
  - the component thermodynamic properties
  - the component transport properties
  - the number of stages
  - the vapor and liquid flows through the column

- A split ratio between two products

$$\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{\left(1 - \mathrm{SF}_{i,k}\right)}$$

- A sharp split is desired in separation
  - SF close to 1 or 0
  - SR>>1 or <<1



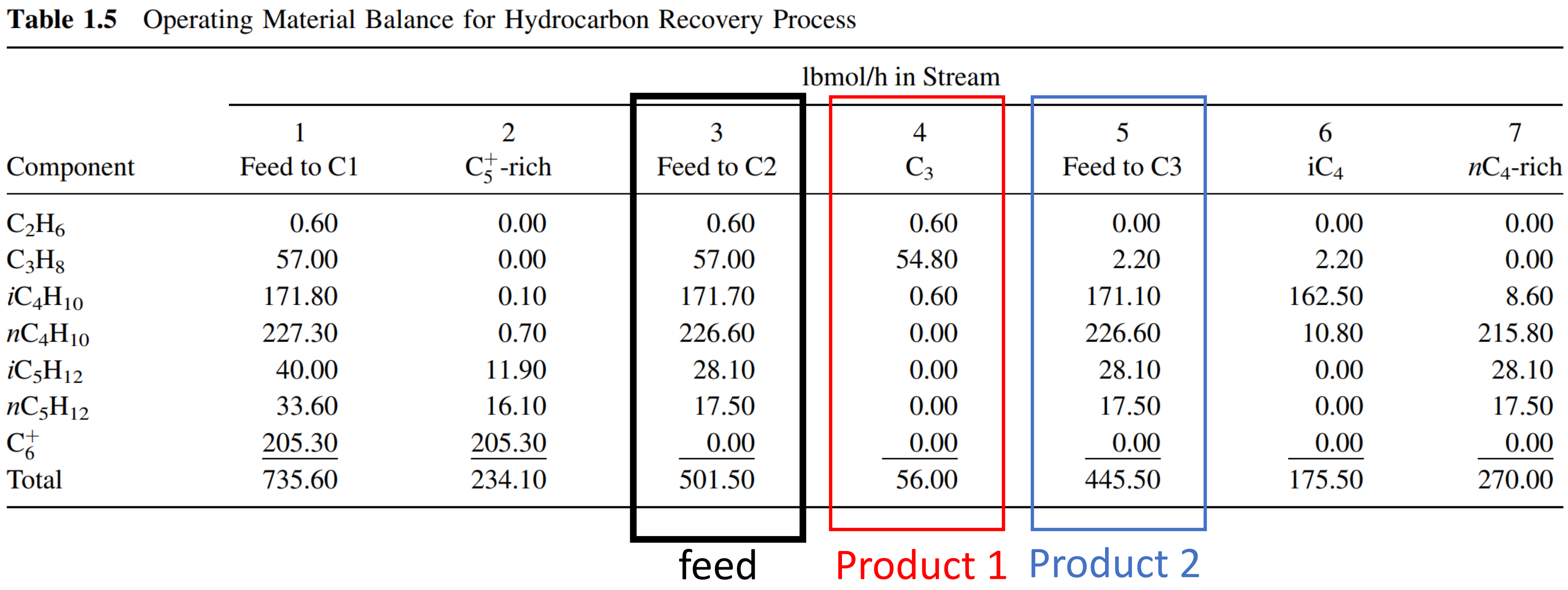


Table 1.5 Operating Material Balance for Hydrocarbon Recovery Process

	lbmol/h in Stream						
Component	1 Feed to C1	2 C_5^+-rich	3 Feed to C2	4 C_3	5 Feed to C3	6 iC_4	7 nC_4-rich
C_2H_6	0.60	0.00	0.60	0.60	0.00	0.00	0.00
C_3H_8	57.00	0.00	57.00	54.80	2.20	2.20	0.00
iC_4H_{10}	171.80	0.10	171.70	0.60	171.10	162.50	8.60
nC_4H_{10}	227.30	0.70	226.60	0.00	226.60	10.80	215.80
iC_5H_{12}	40.00	11.90	28.10	0.00	28.10	0.00	28.10
nC_5H_{12}	33.60	16.10	17.50	0.00	17.50	0.00	17.50
C_6^+	205.30	205.30	0.00	0.00	0.00	0.00	0.00
Total	735.60	234.10	501.50	56.00	445.50	175.50	270.00

feed

Product 1

Product 2

$$\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}$$

$$\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{(1 - \mathrm{SF}_{i,k})}$$

taking column 2 as an example, stream 3 is the feed, stream 4 is product 1.

Split fraction

- C2: 0.6/0.6=1
- C3: 54.8/57.0=0.9614
- iC4: 0.6/171.7=0.0035
- nC4:0
- iC5:0
- nC6:0

Split ratio

- C2: 1/(1-0)=infinite
- C3: 0.9614/(1-0.9614)=24.91
- iC4: 0.0035/(1-0.0035)=0.0035
- nC4:0
- iC5:0
- nC6:0

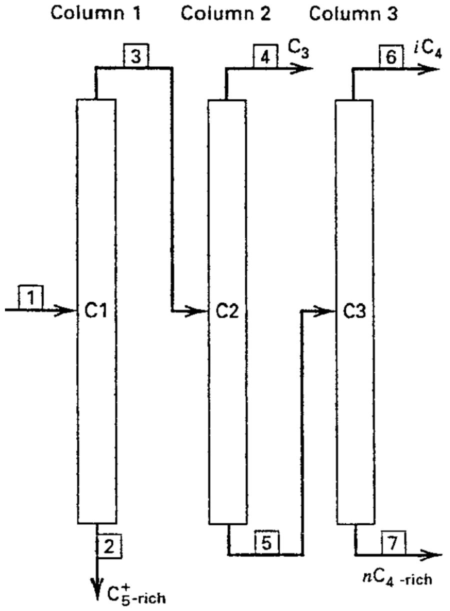


Table 1.6 Computed Split Fractions (SF) and Split Ratios (SR) for Hydrocarbon Recovery Process

	Column 1		Column 2		Column 3		
Component	SF	SR	SF	SR	SF	SR	Overall Percent Recovery
C_2H_6	1.00	Large	1.00	Large	—	—	100
C_3H_8	1.00	Large	0.9614	24.91	1.00	Large	96.14
iC_4H_{10}	0.9994	1,717	0.0035	0.0035	0.9497	18.90	94.59
nC_4H_{10}	0.9969	323.7	0.00	0.00	0.0477	0.0501	94.94
iC_5H_{12}	0.7025	2.361	0.00	0.00	0.00	0.00	29.75
nC_5H_{12}	0.5208	1.087	0.00	0.00	0.00	0.00	47.92
C_6^+	0.00	Small	—	—	—	—	100

$$\boxed{\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}}$$

$$\boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{(1 - \mathrm{SF}_{i,k})}}$$

- A sharp split is desired in separation
  - SF close to 1 or 0
  - SR>>1 or <<1

- Each column is designed to make a split between two adjacent key components in the feed
- splits are sharp (SF > 0.95 for the light key and SF < 0.05 for the heavy key), except for Column C1

Purity and recovery

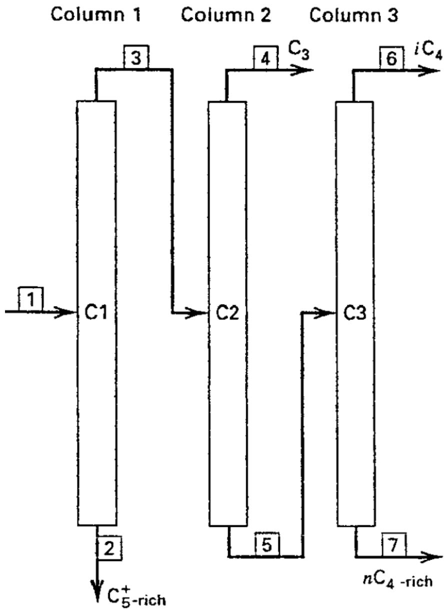


Table 1.5 Operating Material Balance for Hydrocarbon Recovery Process

	lbmol/h in Stream						
Component	1 Feed to C1	2 C_5^+-rich	3 Feed to C2	4 C_3	5 Feed to C3	6 iC_4	7 nC_4-rich
C_2H_6	0.60	0.00	0.60	0.60	0.00	0.00	0.00
C_3H_8	57.00	0.00	57.00	54.80	2.20	2.20	0.00
iC_4H_{10}	171.80	0.10	171.70	0.60	171.10	162.50	8.60
nC_4H_{10}	227.30	0.70	226.60	0.00	226.60	10.80	215.80
iC_5H_{12}	40.00	11.90	28.10	0.00	28.10	0.00	28.10
nC_5H_{12}	33.60	16.10	17.50	0.00	17.50	0.00	17.50
C_6^+	205.30	205.30	0.00	0.00	0.00	0.00	0.00
Total	735.60	234.10	501.50	56.00	445.50	175.50	270.00
		Product		Product		Product	Product

Purity: flow rate of the major component/total flow rate in a certain product stream

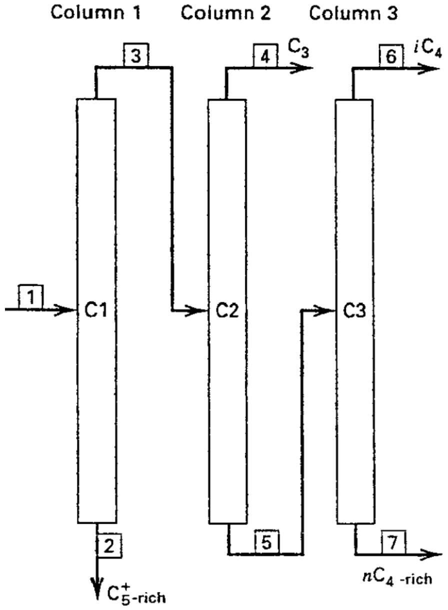
- Purity of C3 in stream 4: flow rate of C3 /total flow rate of stream 4=54.8/56.0=97.86%
- Purity of iC4 in stream 6: flow rate of iC4 /total flow rate of stream 6= 162.50/175.50=92.59%

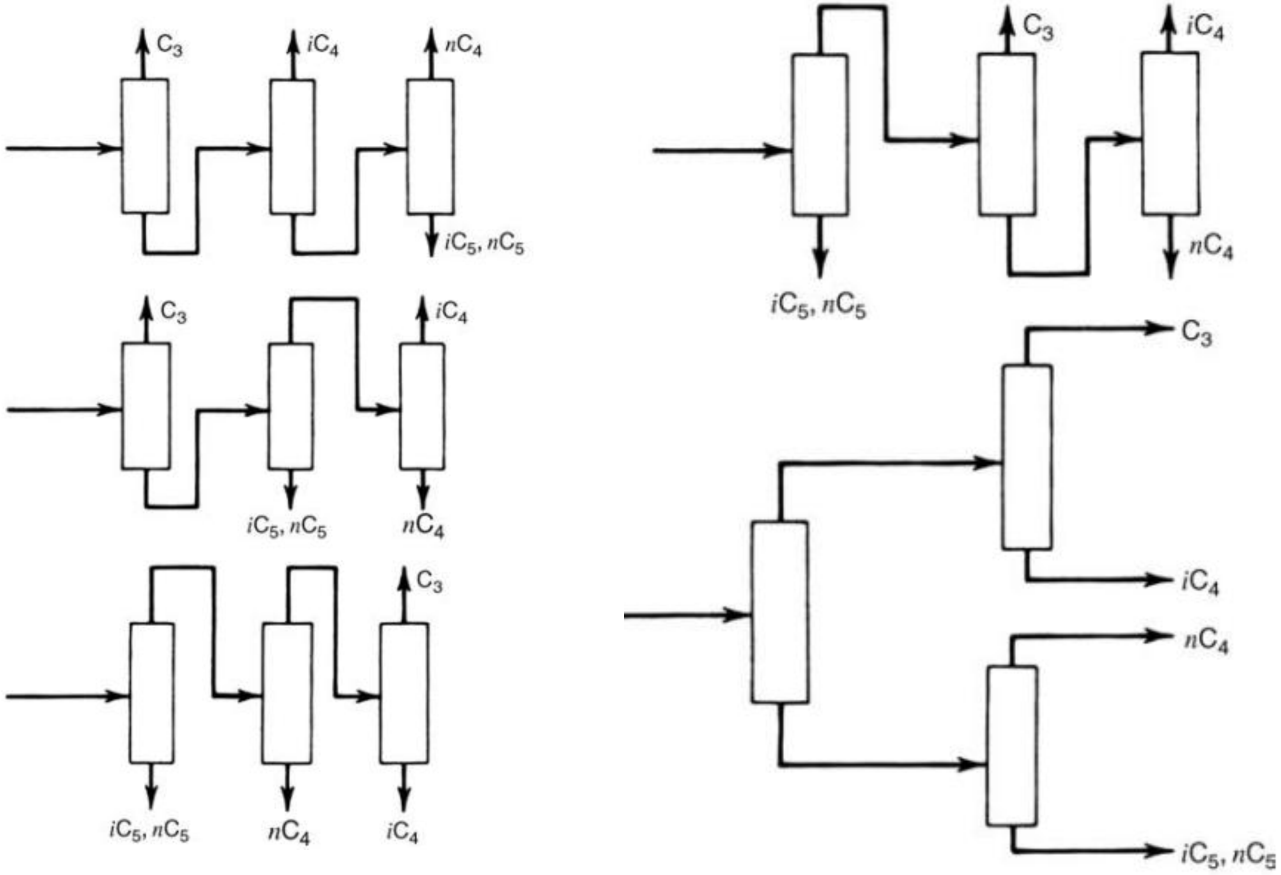
Recovery: flow rate of the major component/total flow rate of the component in the initial feed

- Recovery of C3: flow rate of C3 in stream 4/total flow rate of C3 in the feed=54.8/57.0=96.14%
- Recovery of iC4:flow rate of iC4 in stream 6/total flow rate of iC4 in the feed = 162.50/171.8=94.59%

Separation sequence

- The three-column recovery process has other alternative sequences that can separate the feed into the four products
  - Each column has a single feed and produces an overhead product and a bottom product.
  - If only two products are desired, only a single column is required.





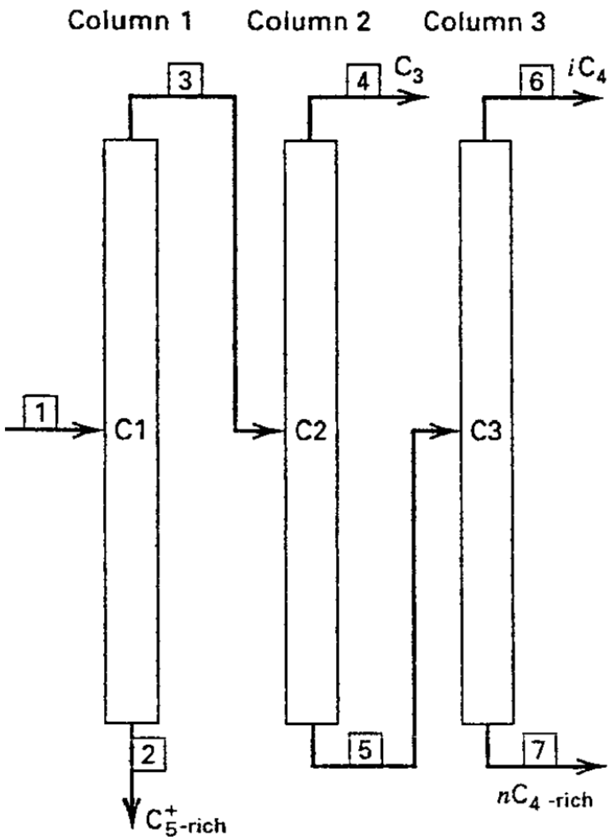
Separation factor/power

- Some separation operations are incapable of making a sharp split between key components.
- The split fraction (SF), split ratio (SR), recovery, or purity depends on
  - the relative molar amounts of the two phases leaving the separator
  - thermodynamic, mass transport, and other component properties
  - Number of stages and configurations
- A measure of **the relative degree of separation** between **two key components**, i and j, is the separation factor or power, SP

$$\boxed{\mathrm{SP}_{i,j} = \frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}} \qquad \boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{(1-\mathrm{SF}_{i,k})}} \qquad \mathrm{SP}_{i,j} = \frac{\mathrm{SR}_i}{\mathrm{SR}_j} \quad \mathrm{SP}_{i,j} = \frac{\mathrm{SF}_i/\mathrm{SF}_j}{(1-\mathrm{SF}_i)/(1-\mathrm{SF}_j)}$$

  - C: composition of the product, usually described by the molar flow rate n, unit: mol/s or kmol/h
  - Physical meaning: the ratio of relative composition of i to j in two product streams
  - a large value corresponds to a relatively high degree of separation
  - a small value close to 1.0 corresponds to a low degree of separation factor

Split fraction and ratio: review



- **Split fraction** (SF) of component ***i*** in the *k*th separator: the fraction of one component found in the first product

$$\boxed{\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}}$$

  - **i: component, k: separator**
  - First and second products need to be defined

- A **split ratio** between two products

$$\boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{\left(1 - \mathrm{SF}_{i,k}\right)}}$$

- A **sharp split** is desired in separation
  - SF close to 1 or 0
  - SR>>1 or <<1

Separation factor/power: review

- A measure of **the relative degree of separation** between **two key components, *i*** and ***j***, is the **separation factor** or **power, SP**

Superscript refers to product #

$$\boxed{\mathrm{SP}_{i,j} = \frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}} \qquad \boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{(1-\mathrm{SF}_{i,k})}} \qquad \mathrm{SP}_{i,j} = \frac{\mathrm{SR}_i}{\mathrm{SR}_j} \quad \mathrm{SP}_{i,j} = \frac{\mathrm{SF}_i/\mathrm{SF}_j}{(1-\mathrm{SF}_i)/(1-\mathrm{SF}_j)}$$

subscript refers to component #

Separation factor: relative composition of i vs j

- C: composition of the product, usually described by the molar flow rate n, unit: mol/s or kmol/h
- Physical meaning: the ratio of relative composition of i to j in two product streams
- a large value corresponds to a relatively high degree of separation
- a small value close to 1.0 corresponds to a low degree of separation factor

Notes

- Split fraction (SF), split ratio (SR), and separation power (SP) are all dimensionless
- Split fraction (SF), split ratio (SR)
    - Measures how well one component is split into two different products by the separator
    - Best separation: SF=0 or 1, SR: very large or very small
- Separation power (SP)
    - Measures how well two components are separated
    - Best separation: SP: very large
- Recovery and purity are also dimensionless, usually presented as percentage
    - Range: 0% to 100%
    - Recovery: measures how much a product recovers a component from **the feed**
    - Purity: measures how pure a product is

$$\boxed{\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}}$$

$$\boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{(1 - \mathrm{SF}_{i,k})}}$$

$$\boxed{\mathrm{SP}_{i,j} = \frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}}$$

$$\mathrm{SP}_{i,j} = \frac{\mathrm{SF}_i/\mathrm{SF}_j}{(1 - \mathrm{SF}_i)/(1 - \mathrm{SF}_j)}$$

Separation power: examples

$$\mathrm{SP}_{i,j} = \frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}$$

Table 1.9 Key Component Separation Factors for Hydrocarbon Recovery Process

Key-Component Split	Column	Separation Factor, SP
nC_4H_{10}/iC_5H_{12}	C1	137.1
C_3H_{10}/iC_4H_{10}	C2	7103
iC_4H_{10}/nC_4H_{10}	C3	377.6

= (226.6/0.7)/(28.1/11.9)=137.1

or= (226.6/28.1)/(0.7/11.9)=8.06/0.0588=137.1

= (2.2/171.1)/(54.8/0.6)=0.00014, different from the text, why?

Take its reciprocal, get ~7100

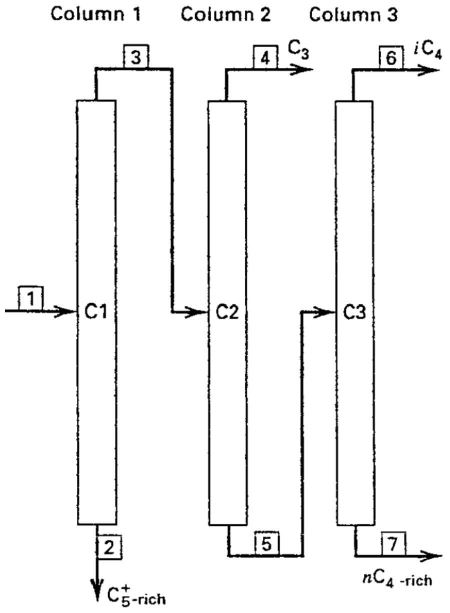
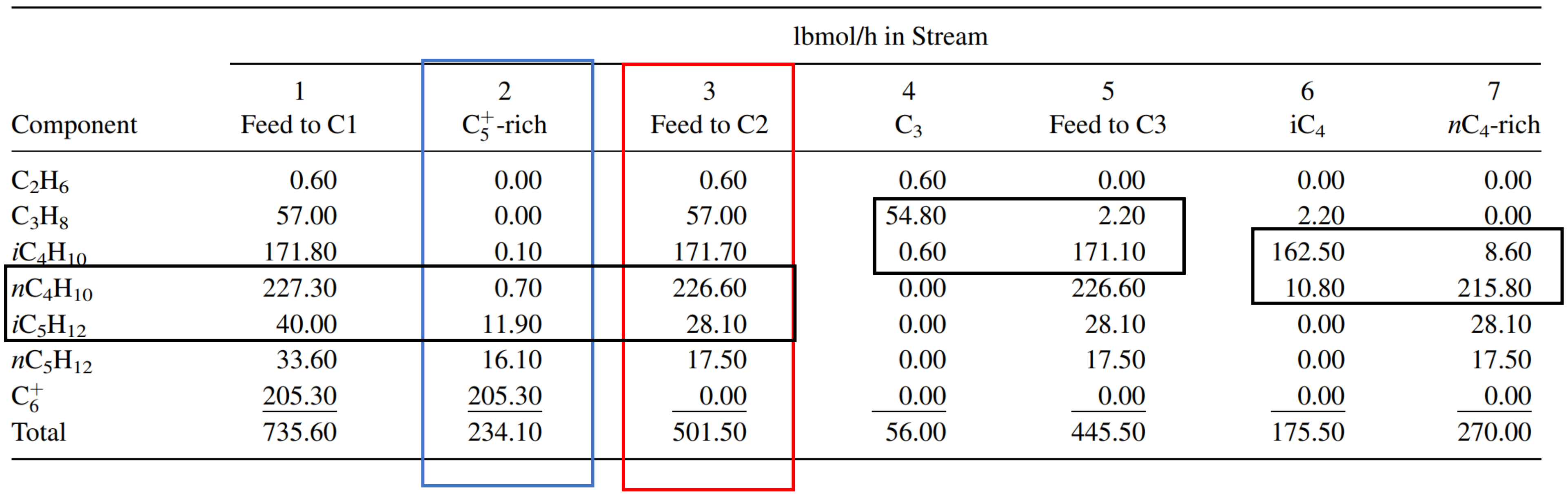


Table 1.5 Operating Material Balance for Hydrocarbon Recovery Process

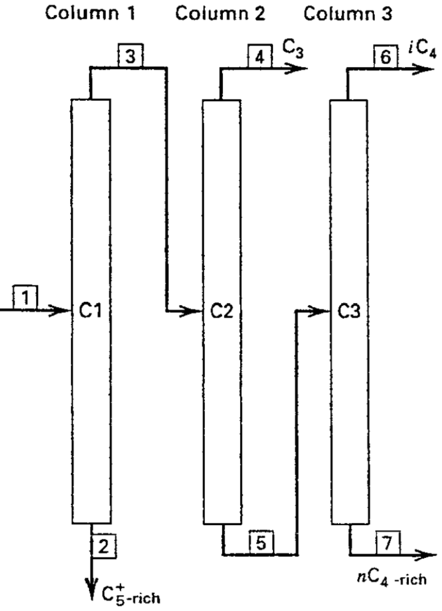


	lbmol/h in Stream						
Component	1 Feed to C1	2 C_5^+-rich	3 Feed to C2	4 C_3	5 Feed to C3	6 iC_4	7 nC_4-rich
C_2H_6	0.60	0.00	0.60	0.60	0.00	0.00	0.00
C_3H_8	57.00	0.00	57.00	54.80	2.20	2.20	0.00
iC_4H_{10}	171.80	0.10	171.70	0.60	171.10	162.50	8.60
nC_4H_{10}	227.30	0.70	226.60	0.00	226.60	10.80	215.80
iC_5H_{12}	40.00	11.90	28.10	0.00	28.10	0.00	28.10
nC_5H_{12}	33.60	16.10	17.50	0.00	17.50	0.00	17.50
C_6^+	205.30	205.30	0.00	0.00	0.00	0.00	0.00
Total	735.60	234.10	501.50	56.00	445.50	175.50	270.00

Product 2 Product 1

In general, when reporting SP of i and j, the order of i and j is arbitrary, we choose them so the $\mathrm{SP}_{i,j}$ > 1.0. In another words, SP is always > 1 by definition

Quiz: 5 minutes



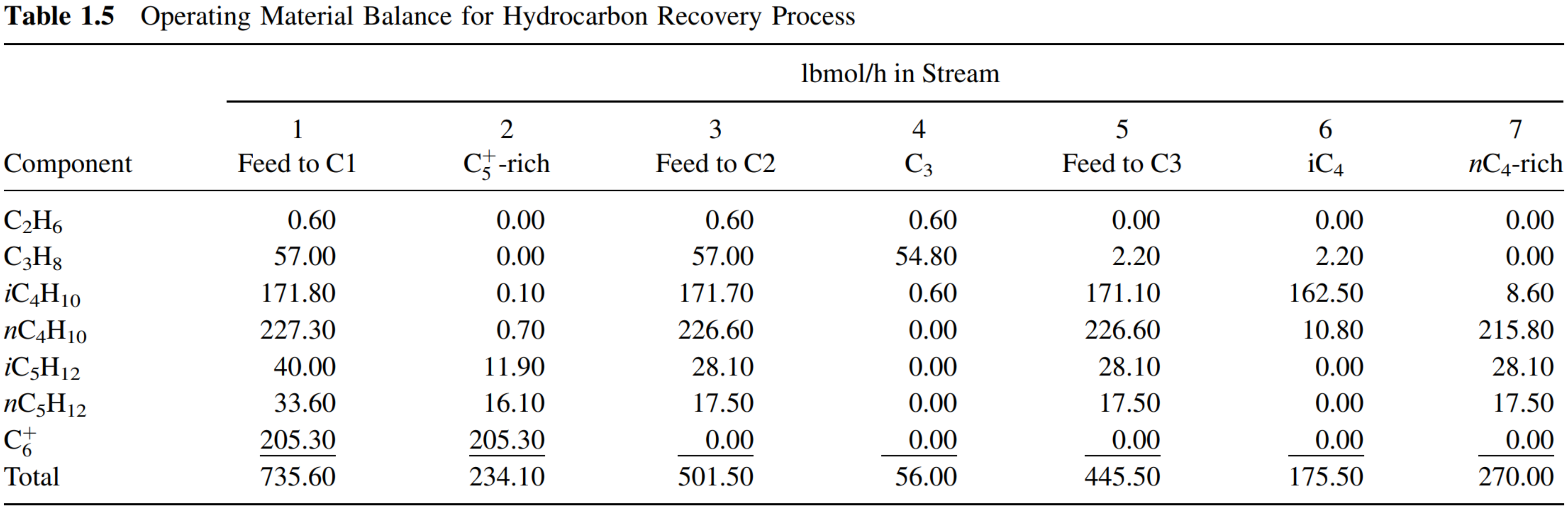


Table 1.5 Operating Material Balance for Hydrocarbon Recovery Process

	lbmol/h in Stream						
Component	1 Feed to C1	2 C_5^+-rich	3 Feed to C2	4 C_3	5 Feed to C3	6 iC_4	7 nC_4-rich
C_2H_6	0.60	0.00	0.60	0.60	0.00	0.00	0.00
C_3H_8	57.00	0.00	57.00	54.80	2.20	2.20	0.00
iC_4H_{10}	171.80	0.10	171.70	0.60	171.10	162.50	8.60
nC_4H_{10}	227.30	0.70	226.60	0.00	226.60	10.80	215.80
iC_5H_{12}	40.00	11.90	28.10	0.00	28.10	0.00	28.10
nC_5H_{12}	33.60	16.10	17.50	0.00	17.50	0.00	17.50
C_6^+	205.30	205.30	0.00	0.00	0.00	0.00	0.00
Total	735.60	234.10	501.50	56.00	445.50	175.50	270.00

1. What is the split fraction of iC4 in the overhead of column 3 (stream 6)?
2. What is its purity and recovery?
3. What is the separation power of iC4/nC4 in column 3?

1. What is the split fraction of iC4 in the overhead of column 3 (stream 6)?
    - How much iC4 from the feed ends up in the referred product
    - 162.5/171.1=0.9497
2. What is its purity and recovery?
    - Purity, how much iC4 is in the referred product, 162.5/175.5=0.9259=92.59%
    - Recovery, how much iC4 is recovered from the initial feed, 162.5/171.8=0.9459=94.59%
3. What is the separation factor of iC4/nC4?
    - How well iC4 is separated from nC4
    - Relative concentration in the overhead: 162.5/10.8=15.04
    - Relative concentration in the bottom: 8.6/215.8=0.03985
    - Separation factor/power: 15.04/0.03985=377.6

Quiz

1. What does a split ratio of 1 mean?

$$\mathrm{SR}_{i,k}=\frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}}=\frac{\mathrm{SF}_{i,k}}{\left(1-\mathrm{SF}_{i,k}\right)}$$

2. What does a split fraction of 1 suggest?

$$\mathrm{SF}_{i,k}=\frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}$$

3. What does a separation factor of 1 suggest?

$$\mathrm{SP}_{i,j}=\frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}$$

Quiz

1. What does a split ratio of 1 mean?

   The component to be separated is equally distributed in two product streams, no separation at all

2. What does a split fraction of 1 suggest?

   The component to be separated all ends up in one product stream, best separation possible

3. What does a separation factor of 1 suggest?

   The relative composition of component i to j is the same in two product streams, no separation at all

Quiz

- A sharp split between two species occurs when

  A. The split fraction is close to 1 or 0
  B. The split ratio is close to 1 or 0
  C. The separation factor is far larger than 1
  D. The separation factor is close to 1
  E. The recovery is close to 100%
  F. The purity is close to 100%

$$\boxed{\mathrm{SR}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(2)}} = \frac{\mathrm{SF}_{i,k}}{\left(1 - \mathrm{SF}_{i,k}\right)}}$$

$$\boxed{\mathrm{SF}_{i,k} = \frac{n_{i,k}^{(1)}}{n_{i,k}^{(F)}}}$$

$$\boxed{\mathrm{SP}_{i,j} = \frac{C_i^{(1)}/C_i^{(2)}}{C_j^{(1)}/C_j^{(2)}}}$$

Quiz

- A sharp split between two species occurs when
  A. The split fraction is close to 1 or 0
  B. The split ratio is close to 1 or 0
  C. The separation factor is far larger than 1
  D. The separation factor is close to 1
  E. The recovery is close to 100%
  F. The purity is close to 100%

ACF
B: sharp split occurs if the split ratio is close to 0, but no separation effect if the split ratio is 1
E: necessary conditions to achieve good separation
F: close to 100% purity means in the product stream there is very little impurity. It usually indicates a sharp split

Content

- Basic concepts (SHR 1.0-1.1)
- Types of separation techniques (SHR 1.2-1.6)
- Example: distillation (SHR 1.7-1.8)
- Selection of separation process (SHR 1.10)

Selection of Separation process

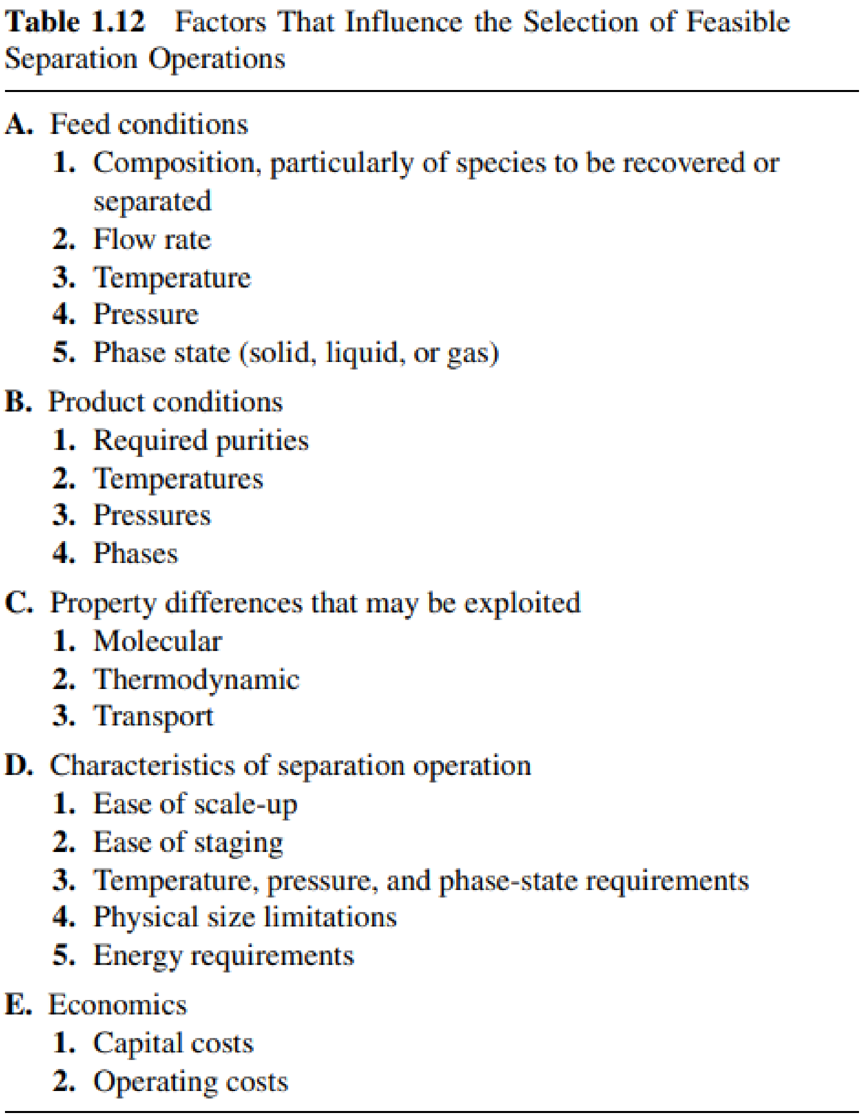


Table 1.12 Factors That Influence the Selection of Feasible Separation Operations

A. Feed conditions
  1. Composition, particularly of species to be recovered or separated
  2. Flow rate
  3. Temperature
  4. Pressure
  5. Phase state (solid, liquid, or gas)

B. Product conditions
  1. Required purities
  2. Temperatures
  3. Pressures
  4. Phases

C. Property differences that may be exploited
  1. Molecular
  2. Thermodynamic
  3. Transport

D. Characteristics of separation operation
  1. Ease of scale-up
  2. Ease of staging
  3. Temperature, pressure, and phase-state requirements
  4. Physical size limitations
  5. Energy requirements

E. Economics
  1. Capital costs
  2. Operating costs

- Most important feed conditions
  - Composition and flow rate
  - The cost depends strongly on the concentration in the feed.
- Other conditions (temperature, pressure, and phase) can be altered
  - But can be energetic costly
  - vaporization, condensation, compression
- Some separations perform best on dilute feeds
  - use of barriers or solid agents

Separation cost

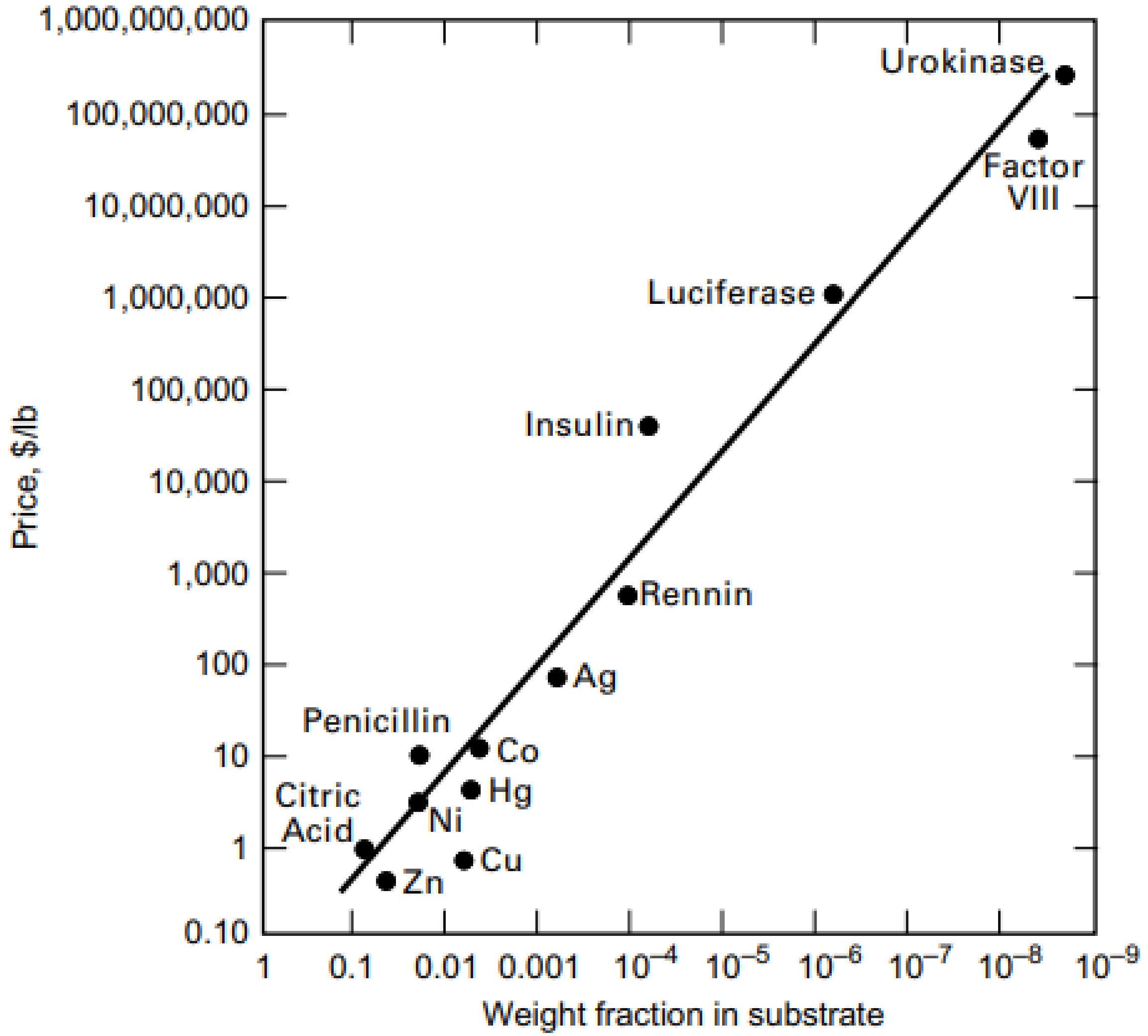
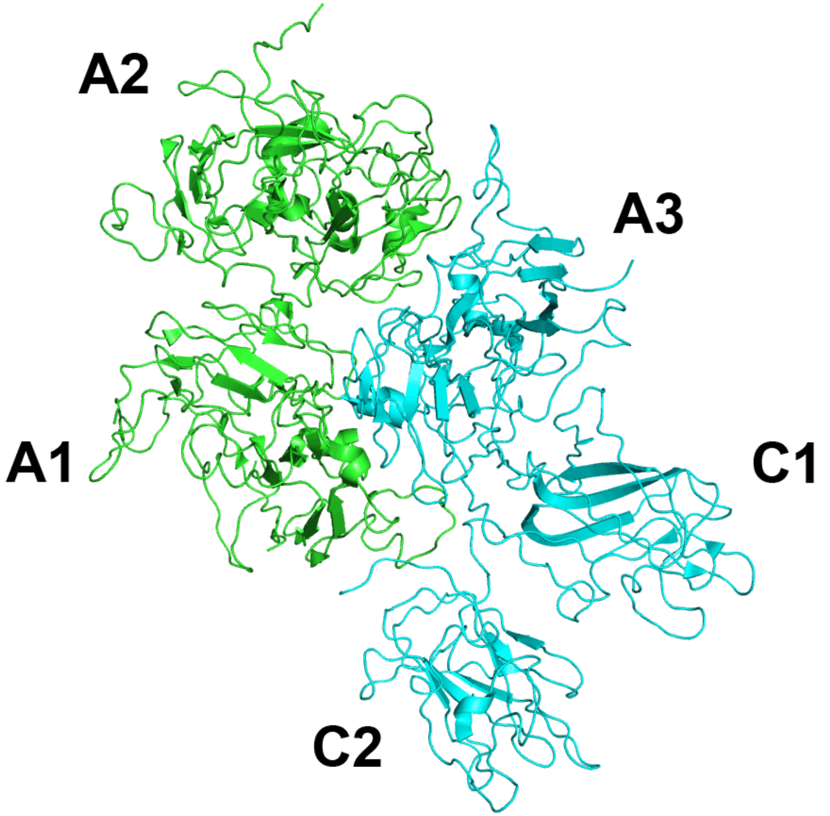


Figure 1.14 Effect of concentration of product in feed material on price [13].

Entropy barrier

$$\Delta G_{\text{separation}} \geq RT \ln\left(\frac{1}{x}\right)$$



Factor VIII

Maturity of different separation technologies

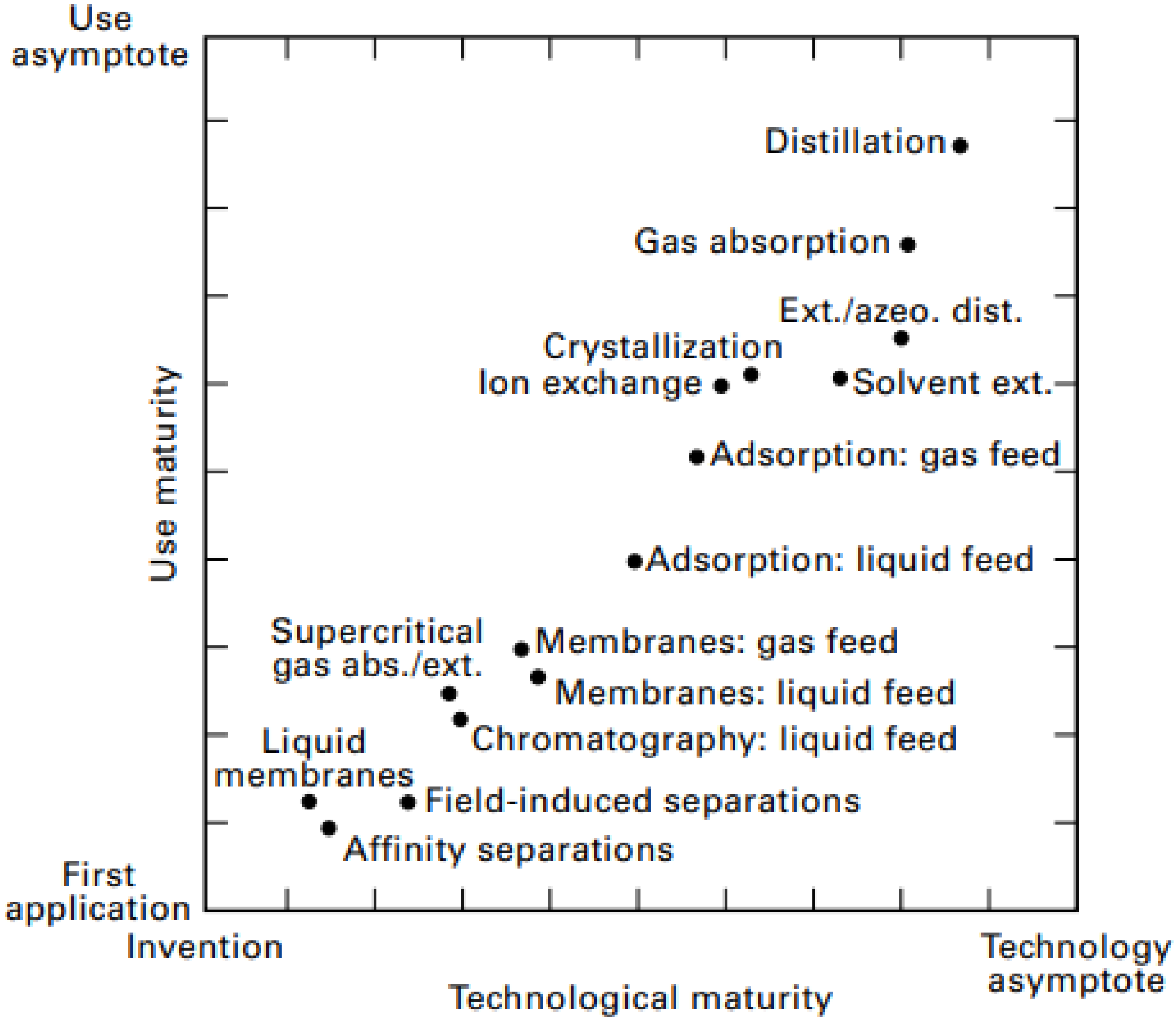


Figure 1.15 Technological and use maturities of separation processes [13].

Operations based on barriers are more expensive

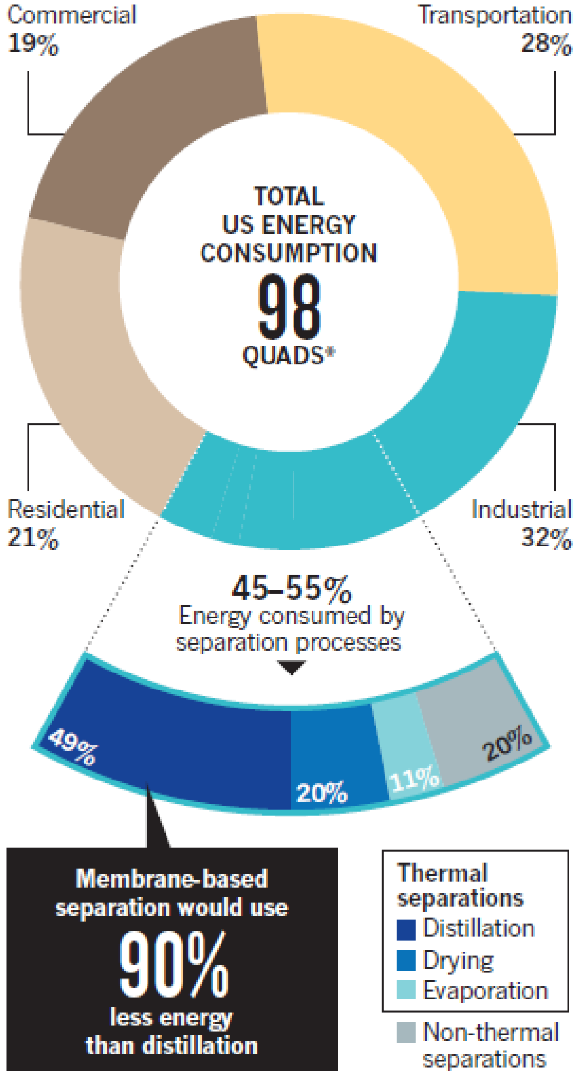
Seven chemical separations to change the world

Purifying mixtures without using heat would lower global energy use, emissions and pollution — and open up new routes to resources, say **David S. Sholl** and **Ryan P. Lively**.

- **Hydrocarbons from crude oil.**
- **Uranium from seawater**
- **Alkenes from alkanes**
- **Rare-earth metals from ores**
- **Benzene derivatives from each other**
- **Trace contaminants from water**
- **Greenhouse gases from dilute emissions**

CUTTING COSTS

Chemical separations account for about half of US industrial energy use and 10–15% of the nation's total energy consumption. Developing alternatives that don't use heat could make 80% of these separations 10 times more energy efficient.



*A quad is a unit of energy equal to 10^{15} British Thermal Units (1 BTU is about 0.0003 kilowatt-hours).

Summary

- Industrial chemical processes include equipment for separating chemicals in the process feed(s) and/or species produced in reactors within the process
- The extent of separation achievable by a separation operation depends on the differences in species properties.
- The more widely used separation operations involve the transfer of species between two phases, one of which is created by energy transfer or the reduction of pressure, or by introduction as an MSA.
- Separation operations are subject to the conservation of mass. The degree of separation is measured by a split fraction, SF, and/or a split ratio, SR.
- For a train of separators, component recoveries and product purities are of prime importance and are related by material balances to individual SF and/or SR values.
- The cost of purifying a chemical depends on its concentration in the feed. The extent of industrial use of a separation operation depends on its technological maturity