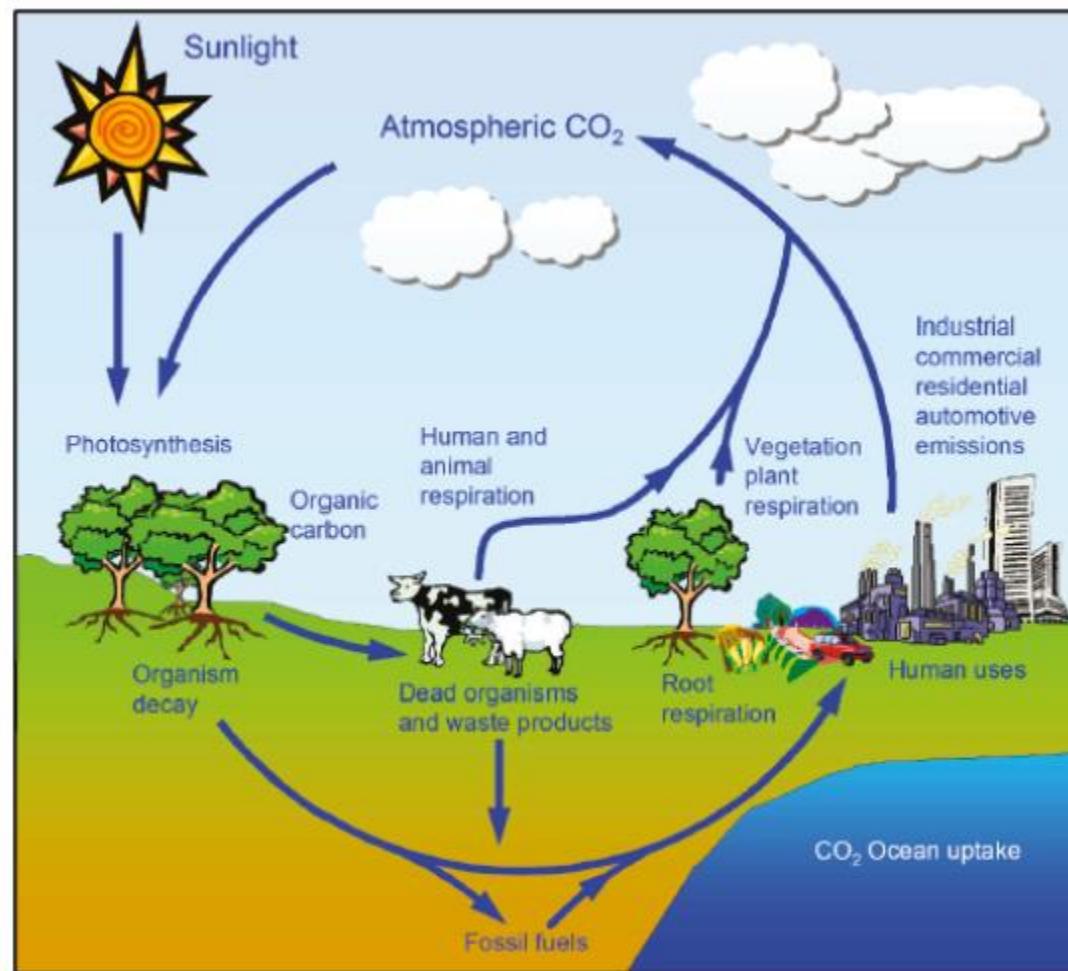


# ENVIRONMENTAL ENGINEERING

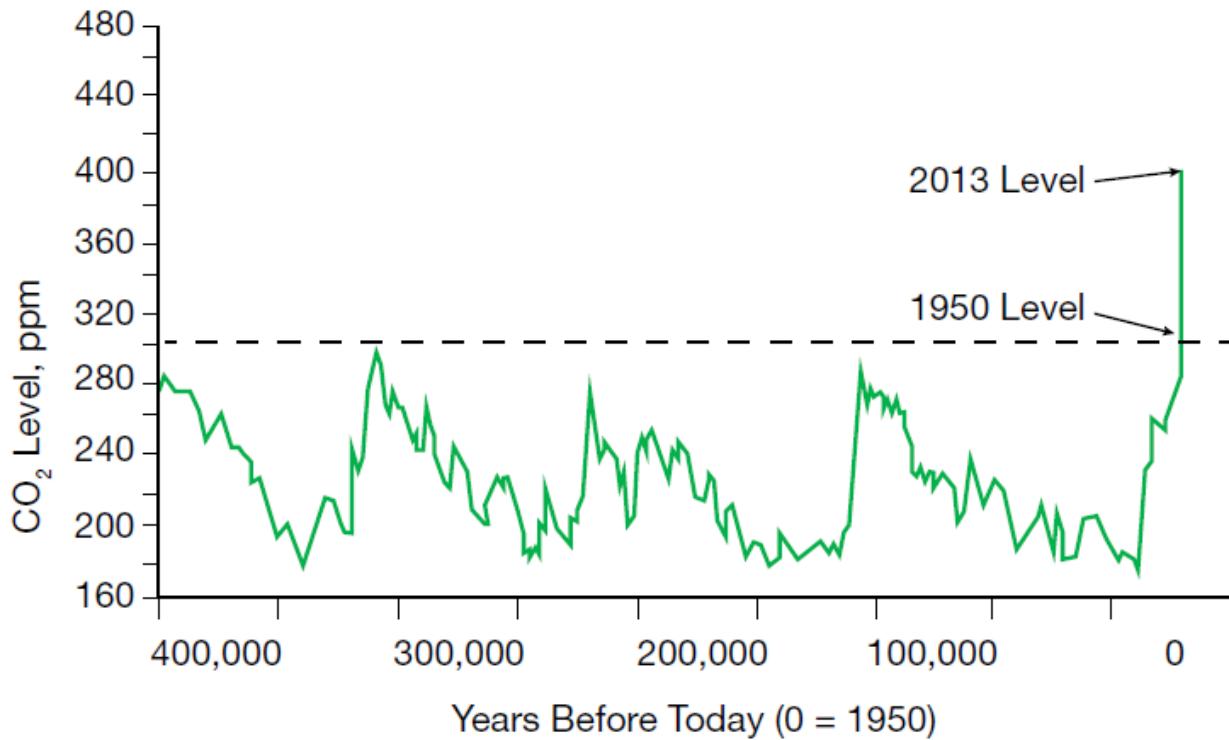
**AIR POLLUTION CONTROL – CARBON DIOXIDE CAPTURE, UTILIZATION & STORAGE**

# Natural Carbon Cycle

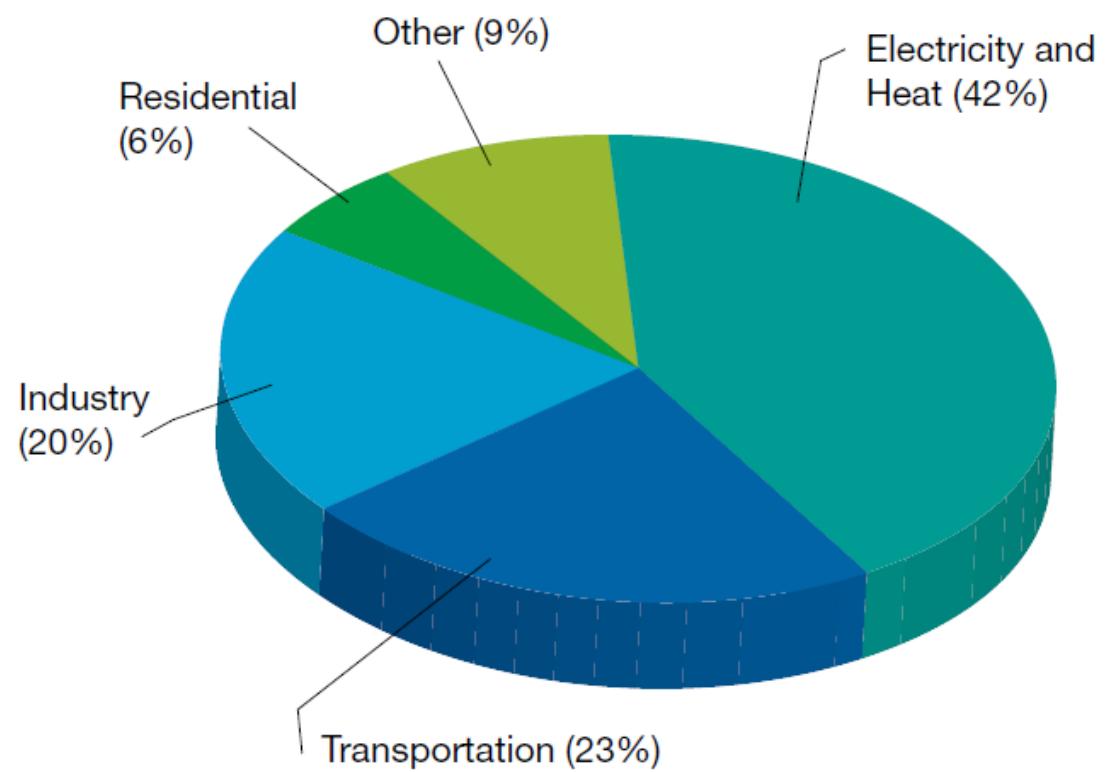


## Atmospheric CO<sub>2</sub> emissions

Atmospheric CO<sub>2</sub> concentrations have dramatically increased since 1950

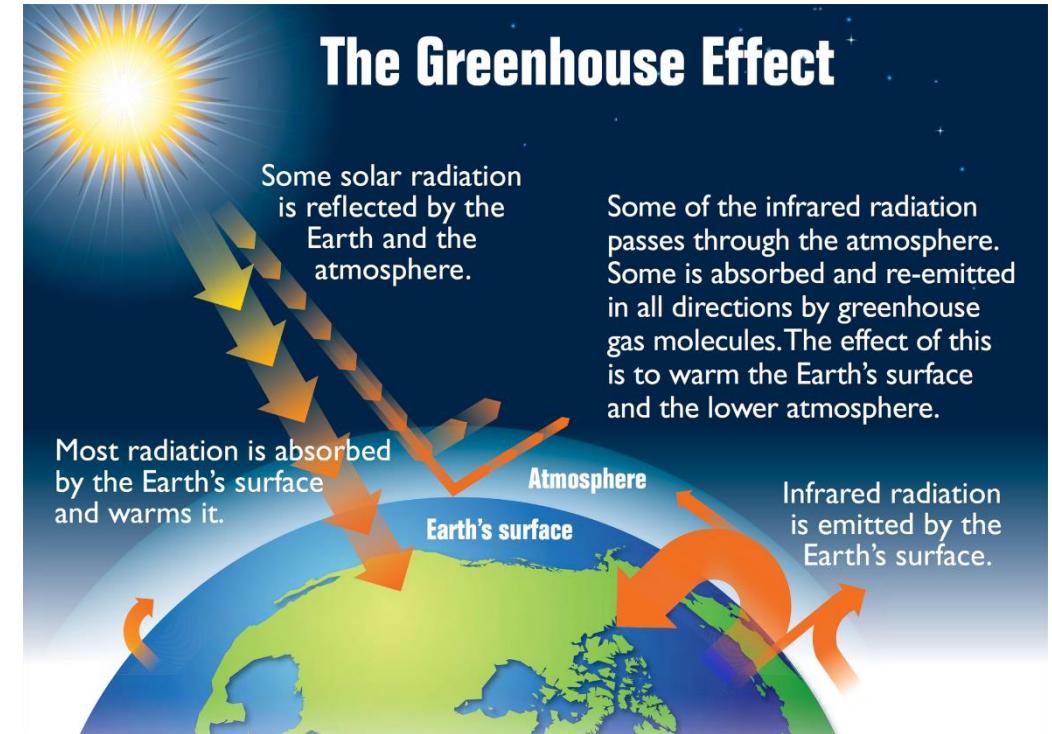
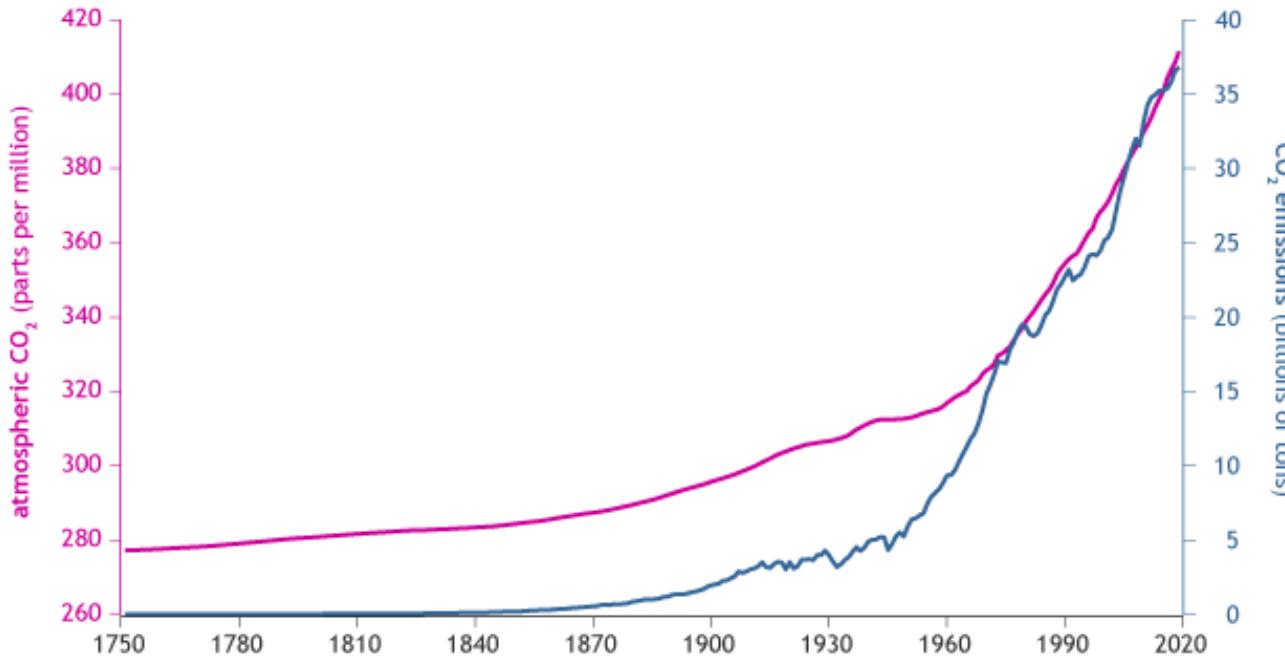


The production of electricity and heat is the leading source of CO<sub>2</sub> emissions

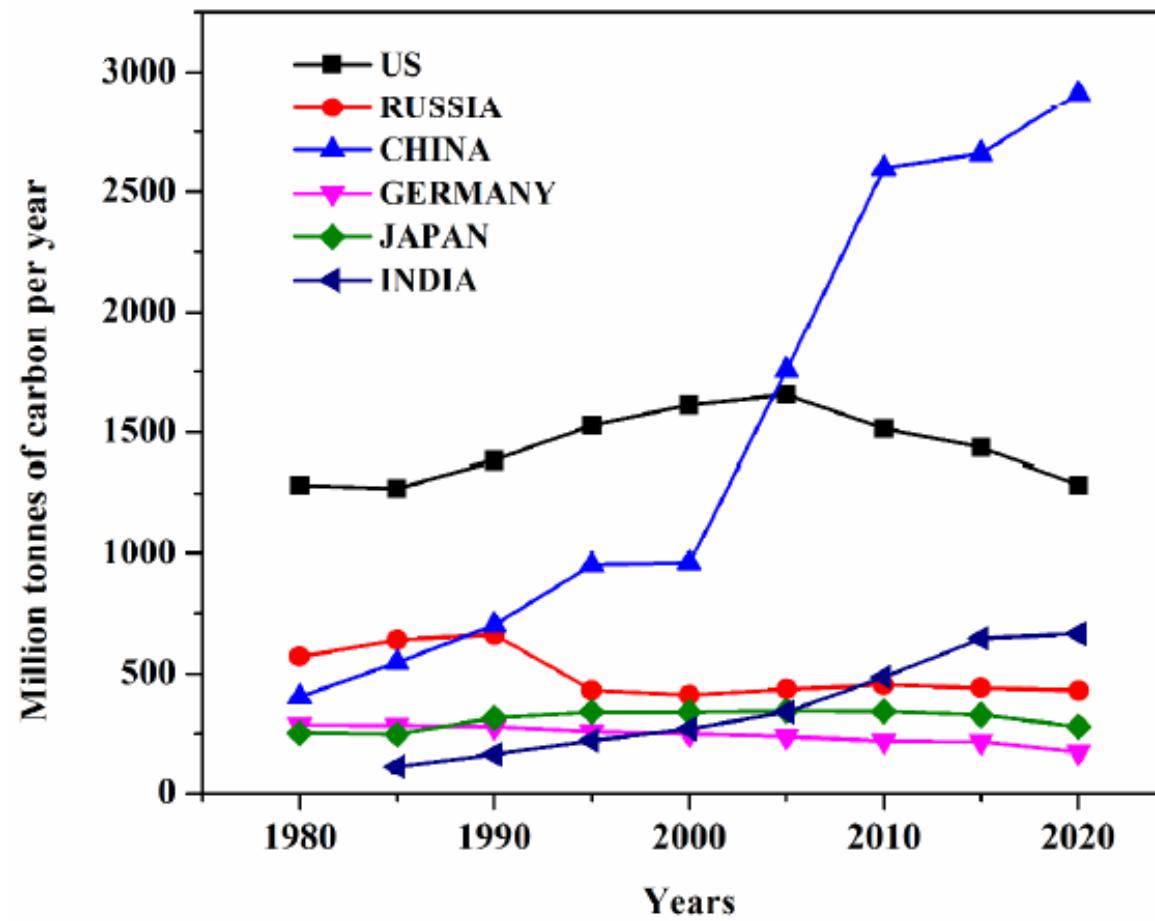


Source: CEP June 2016, 52

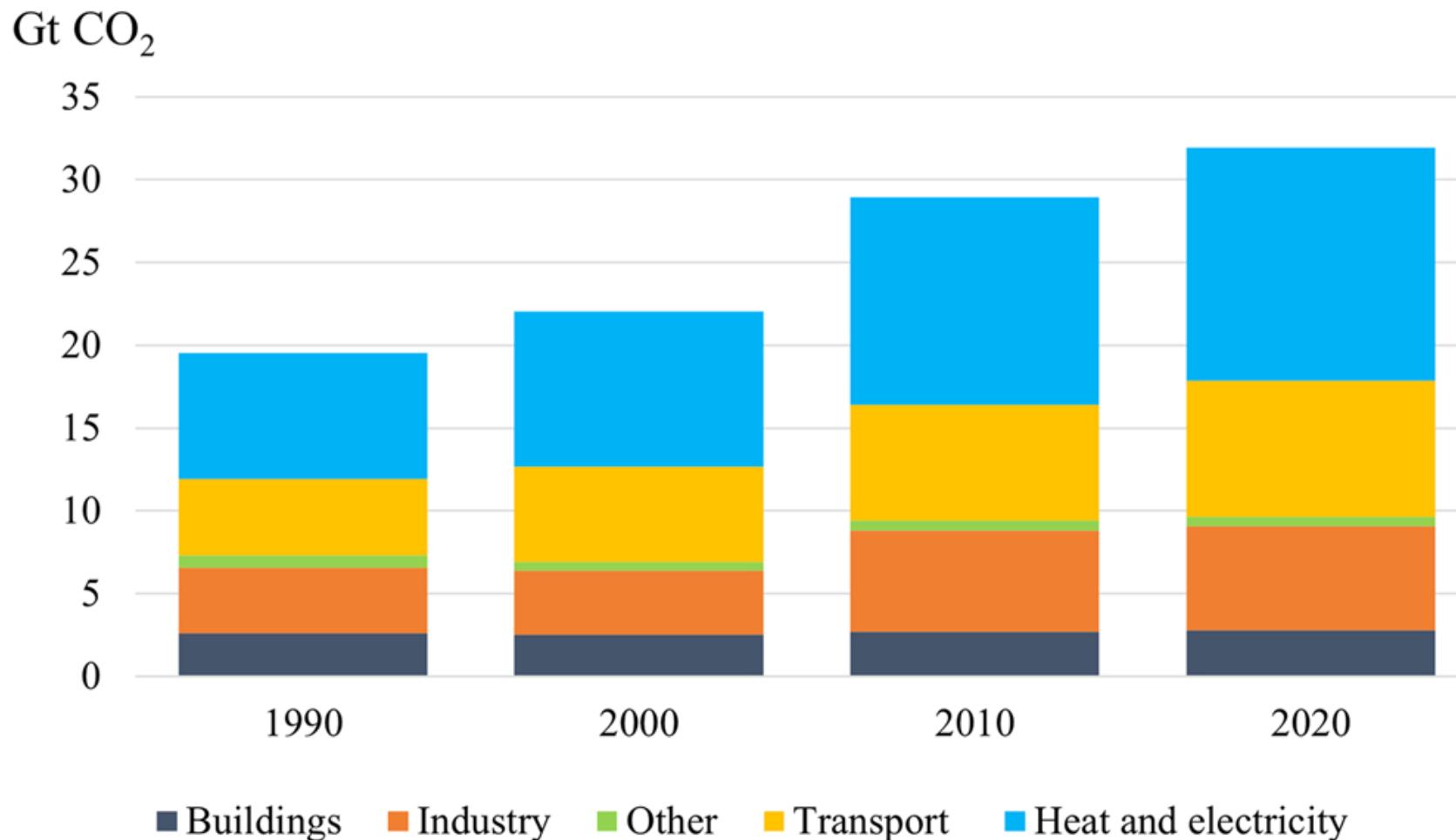
# Atmospheric CO<sub>2</sub>, Emissions and Greenhouse Effect



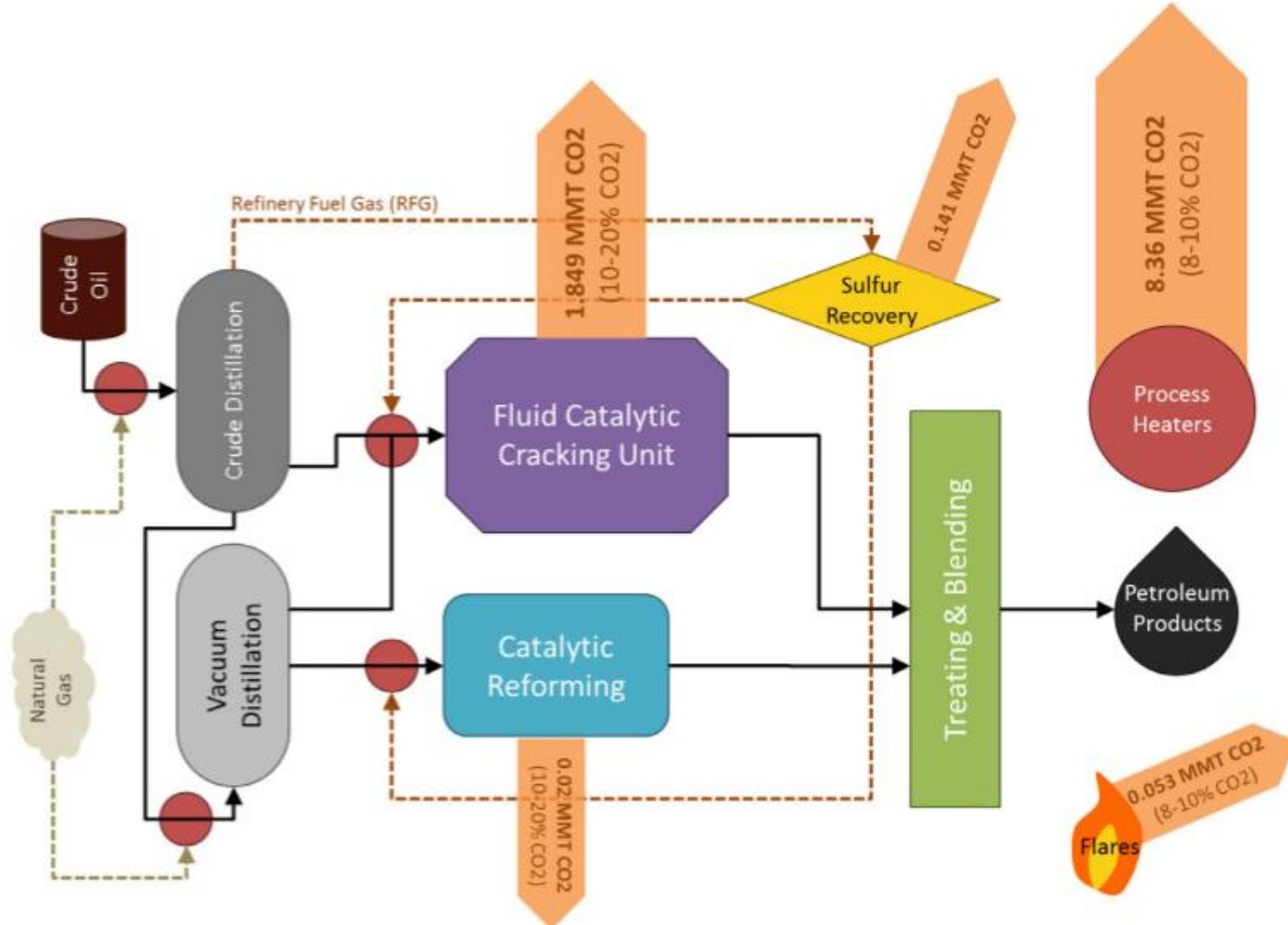
# Carbon Emissions of Selected Countries from 1980-2020



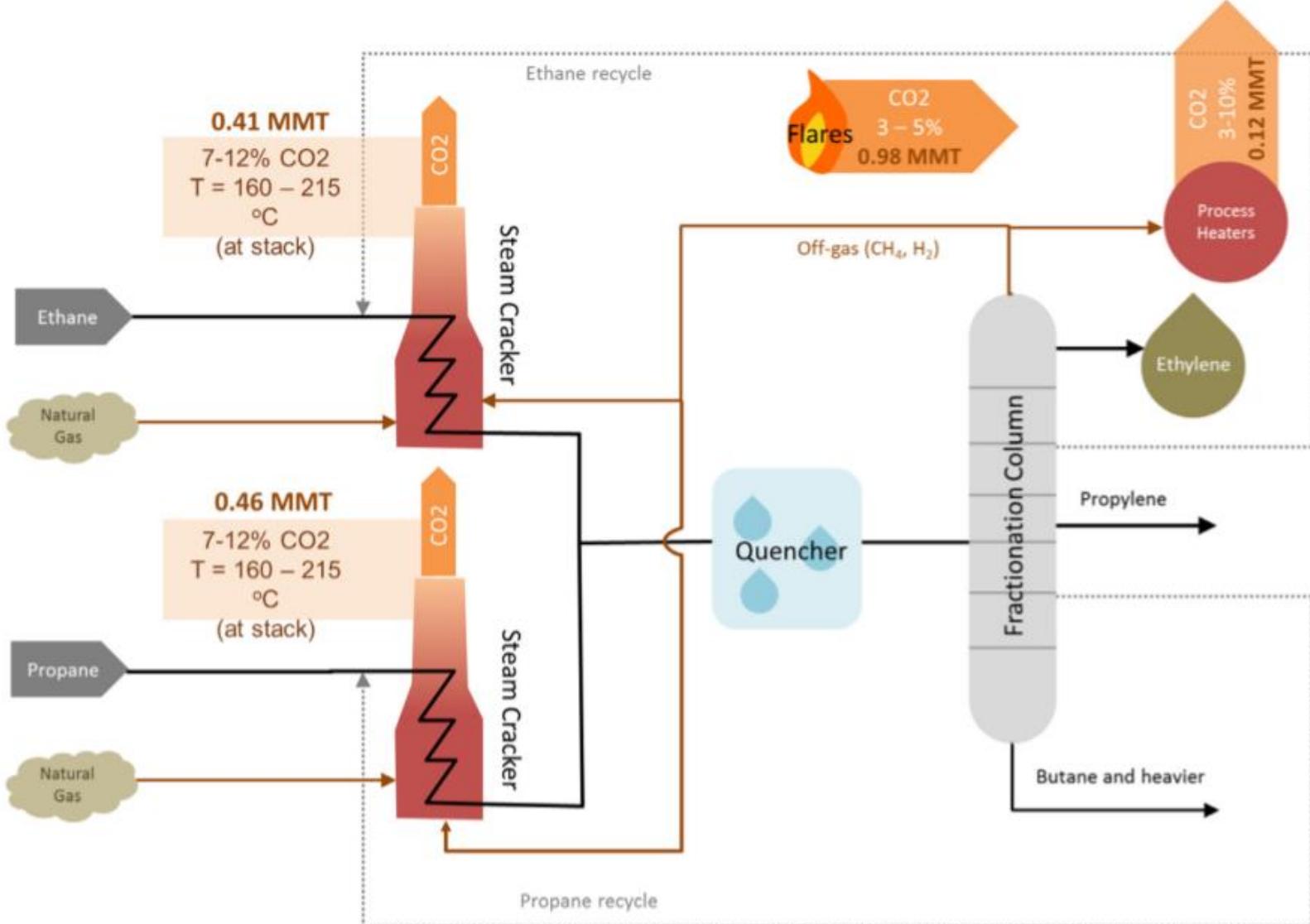
## Global CO<sub>2</sub> Emissions from Fuel Combustion by Sector



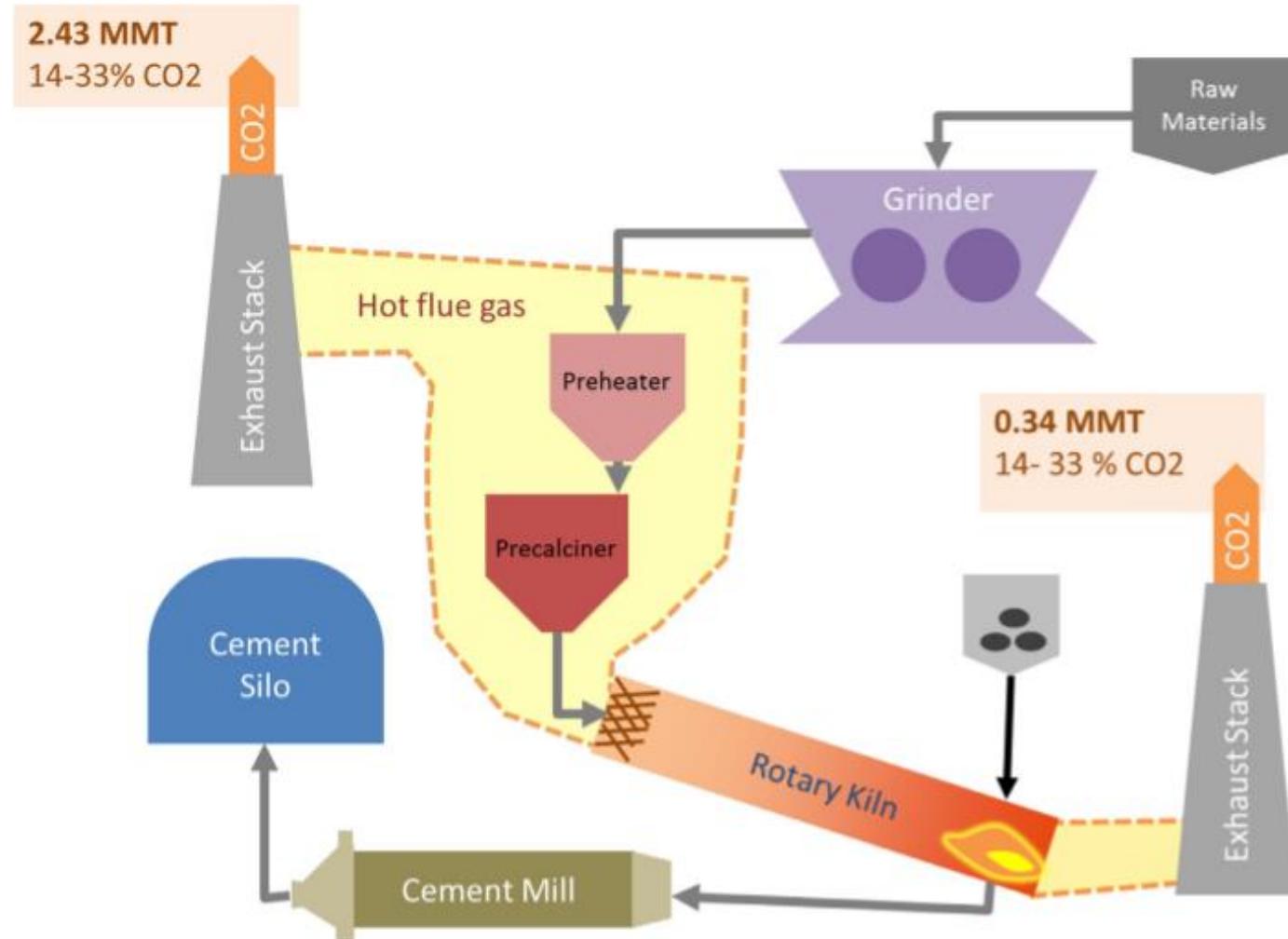
# Petroleum Refining



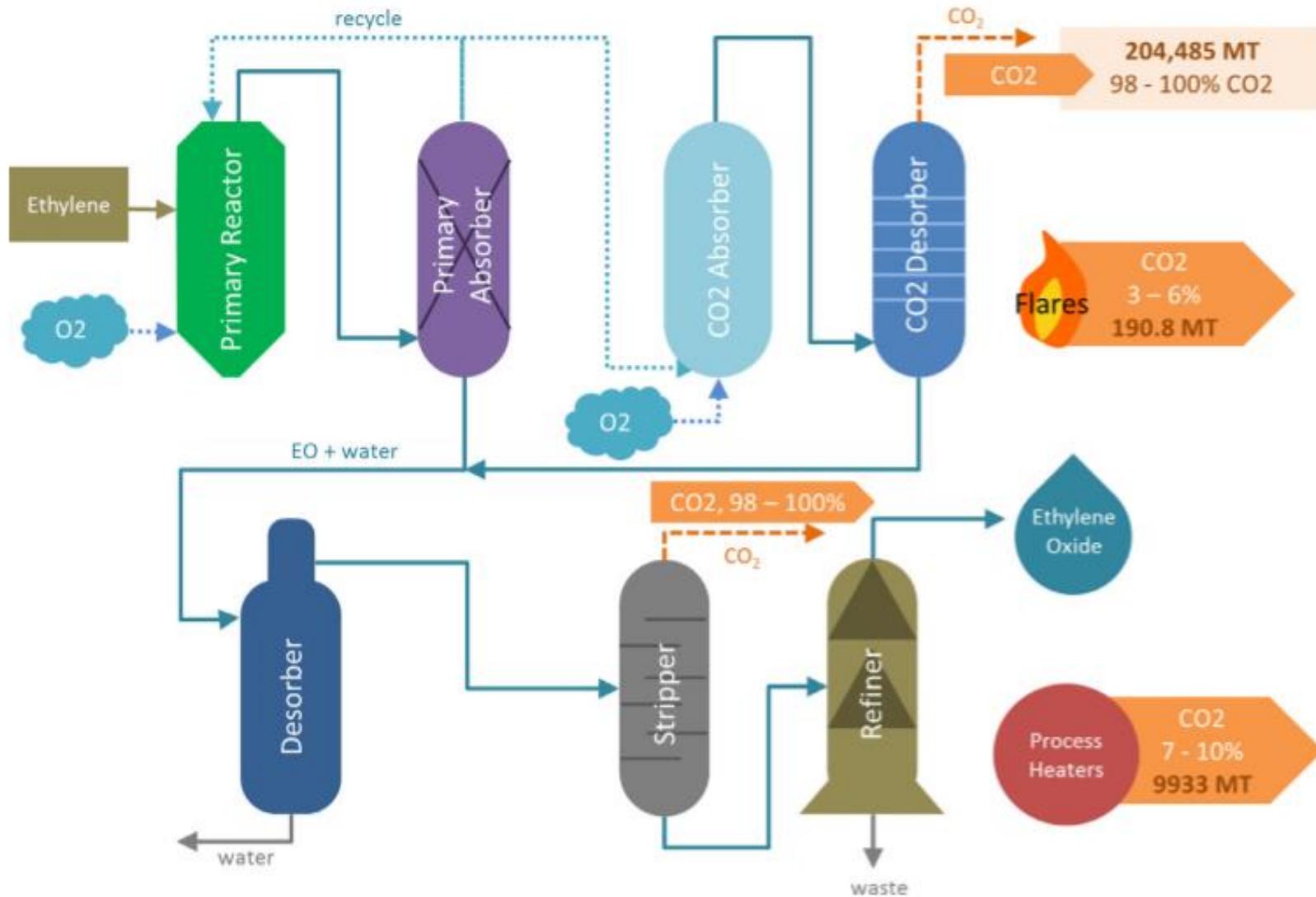
# Ethylene Production



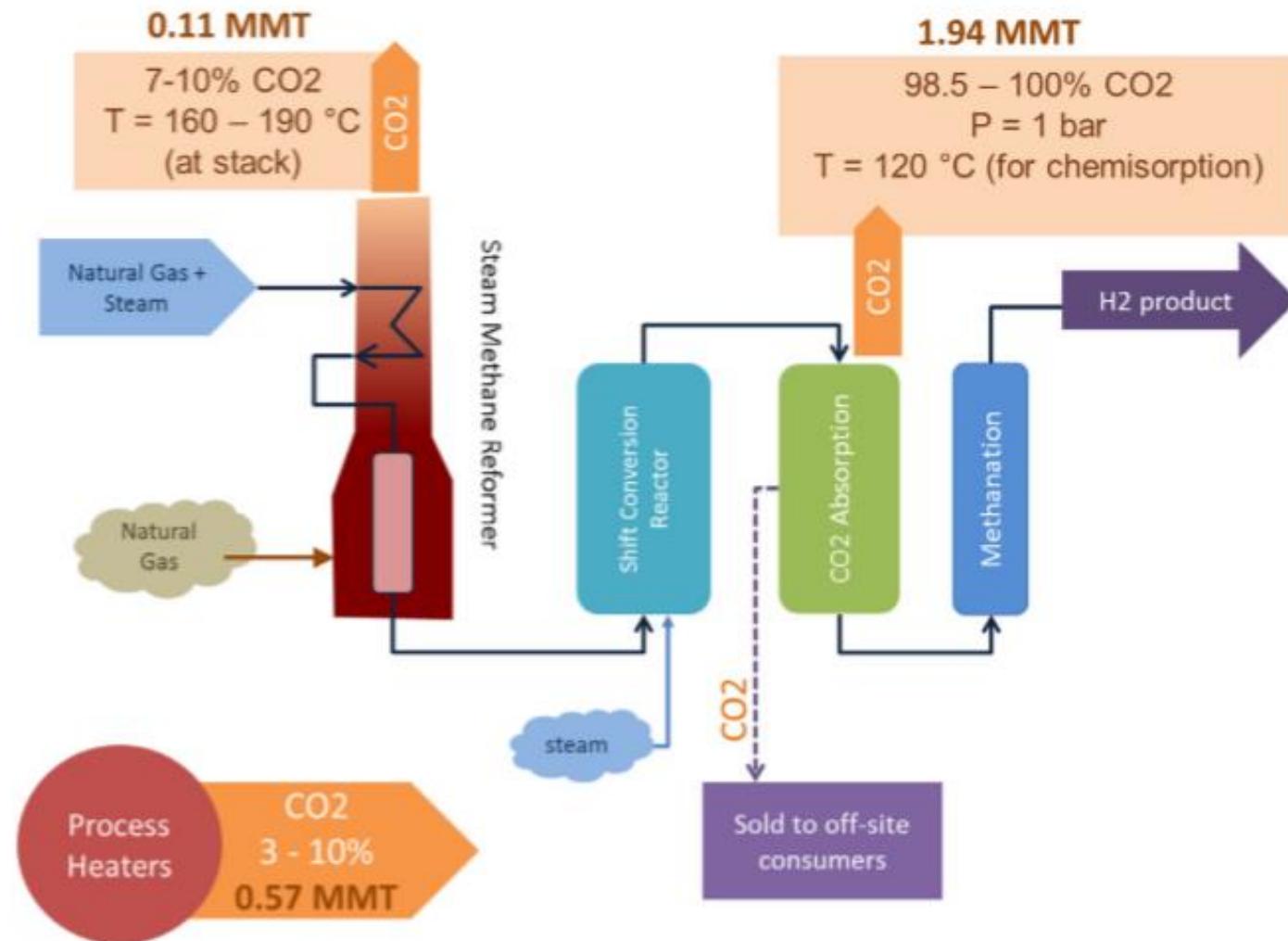
# Cement Production



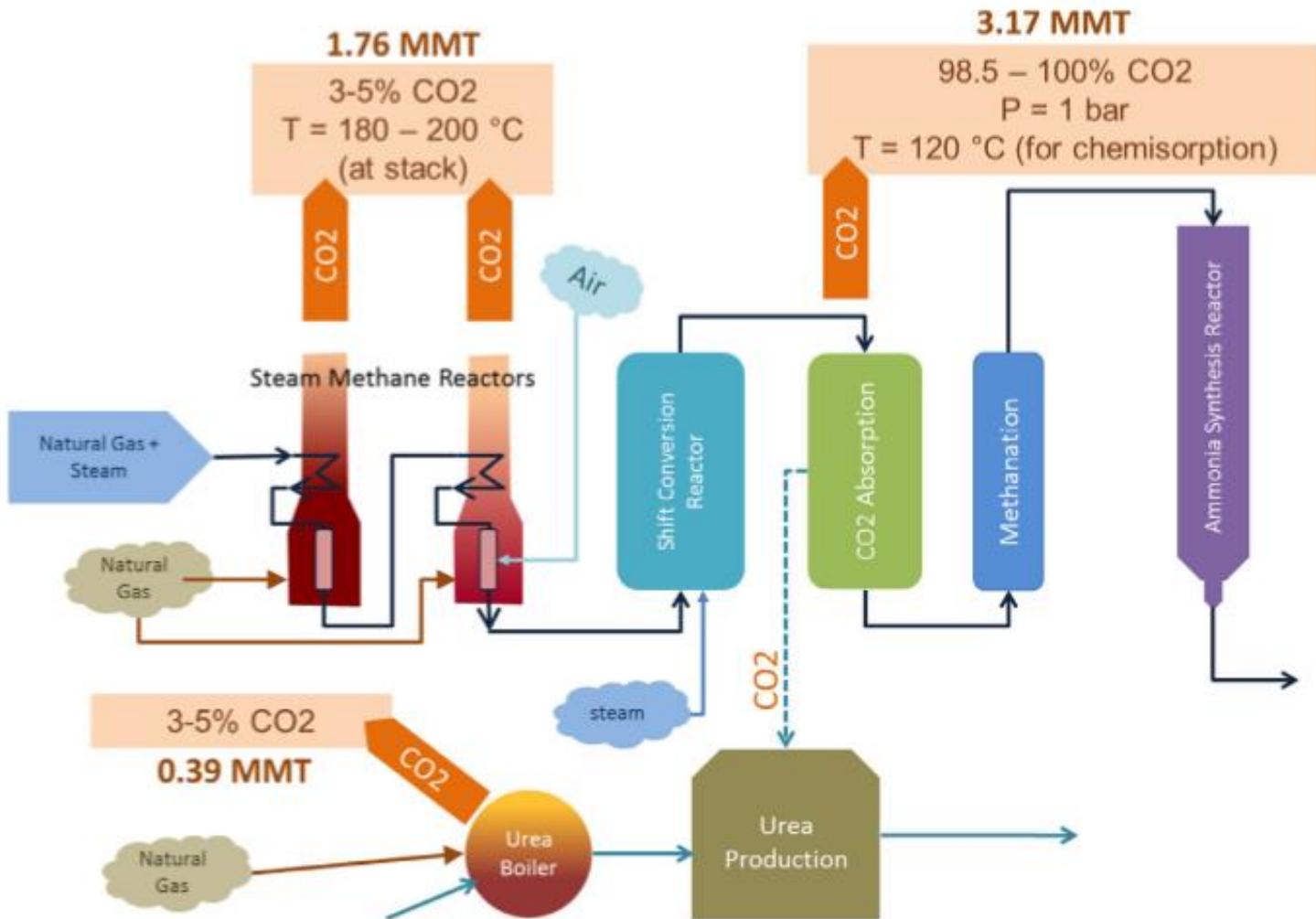
# Ethylene Oxide Production



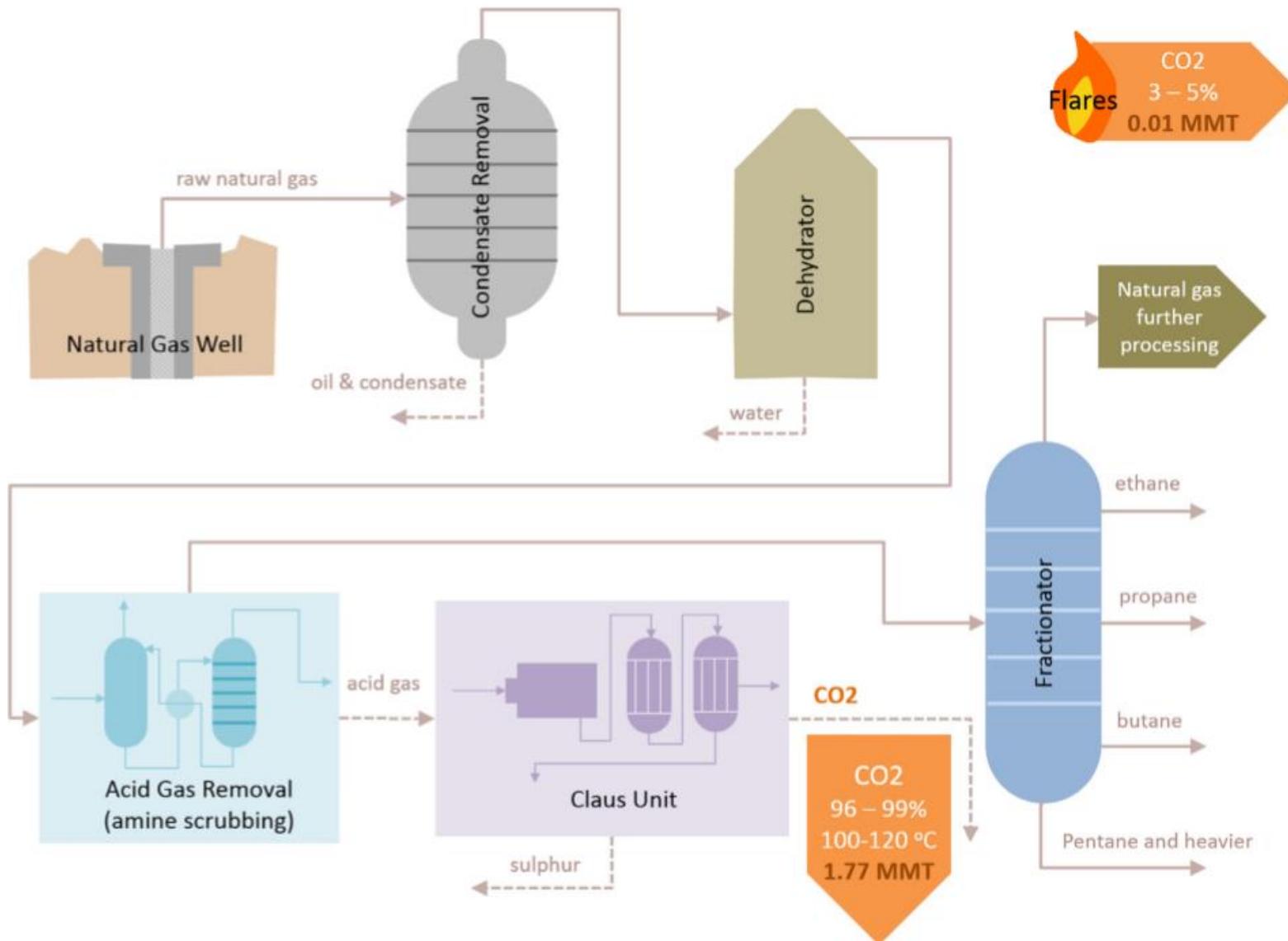
# Hydrogen Production



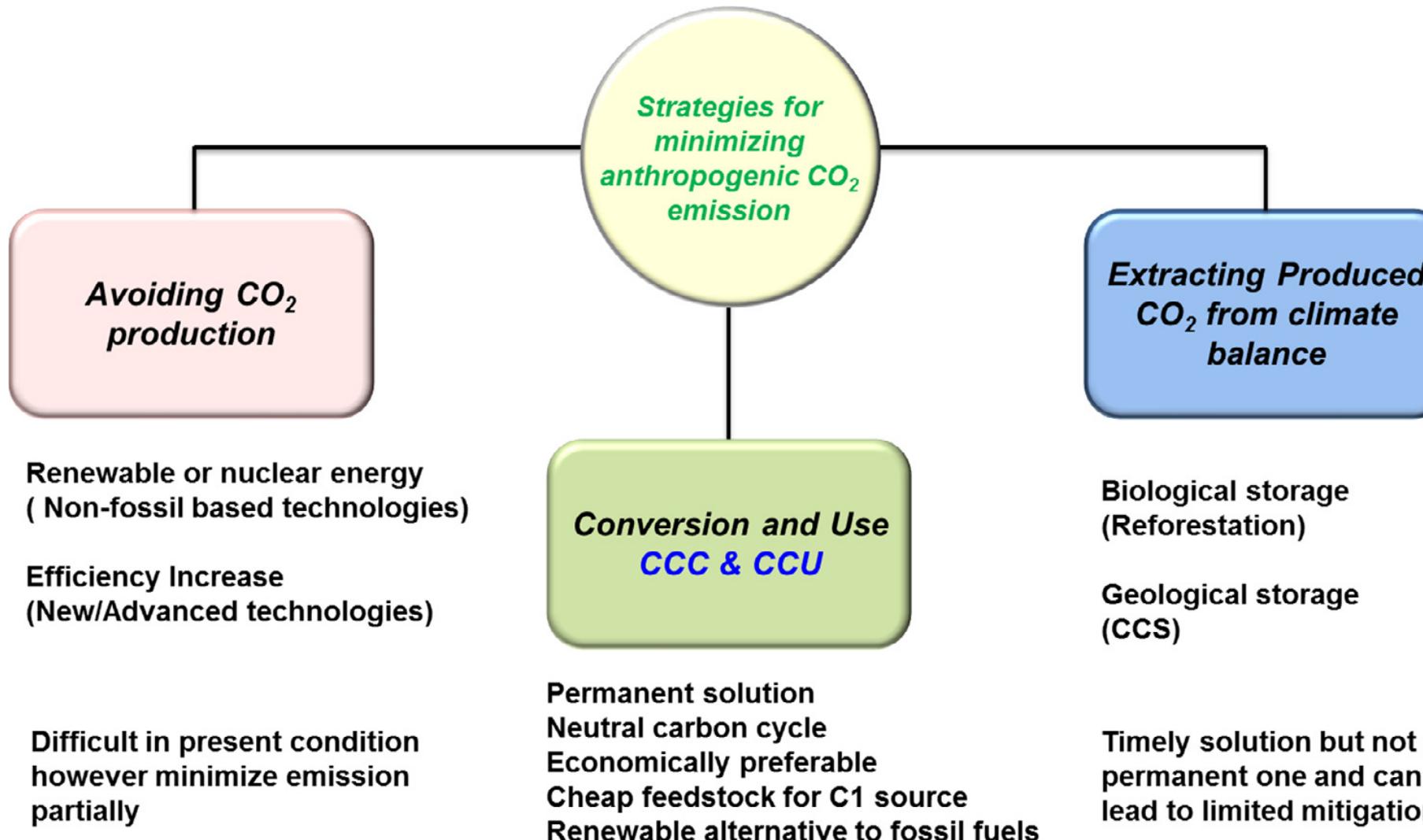
# Ammonia Manufacturing



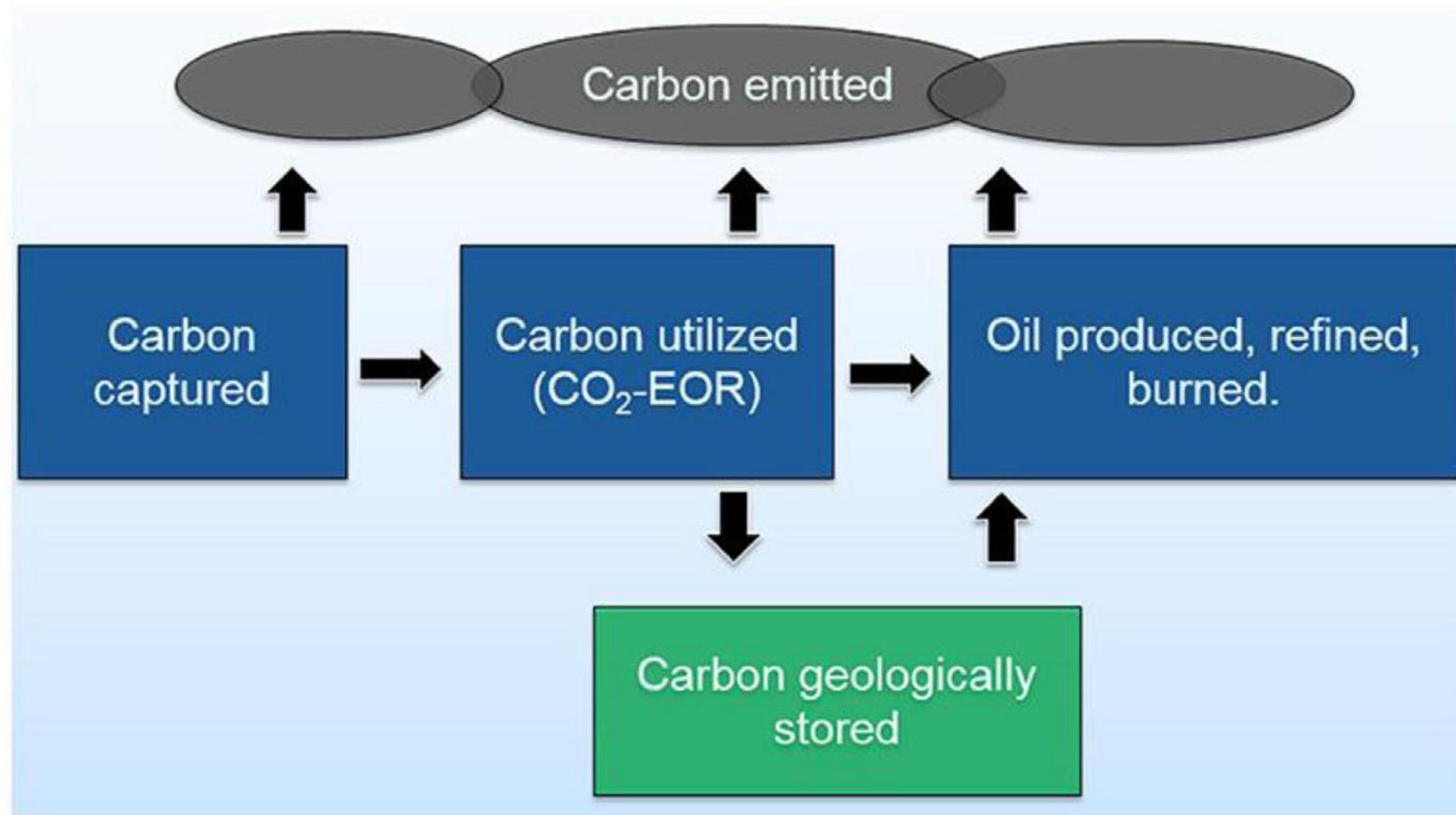
# Natural Gas Processing



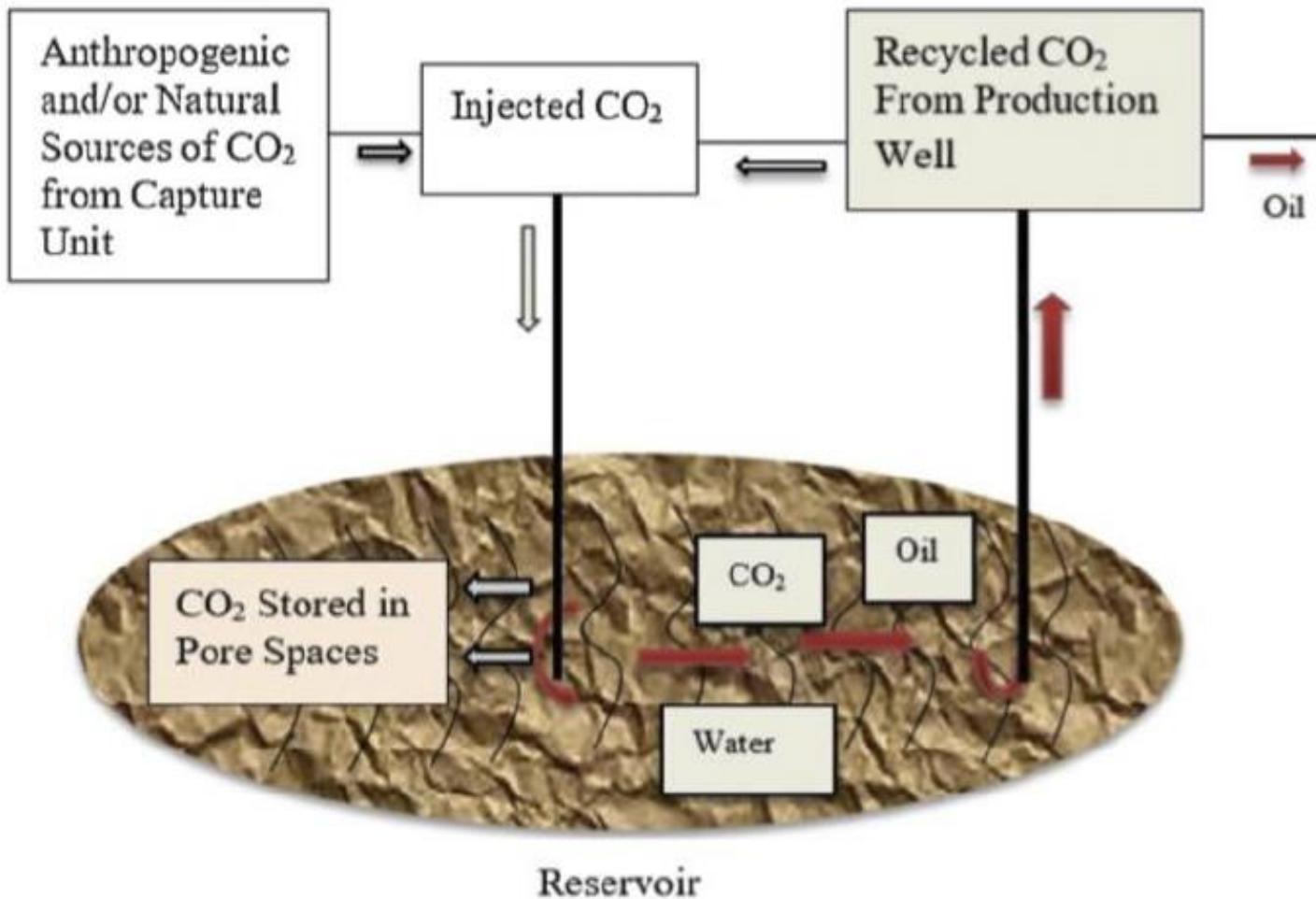
# Strategies for Minimizing Anthropogenic CO<sub>2</sub> Emissions



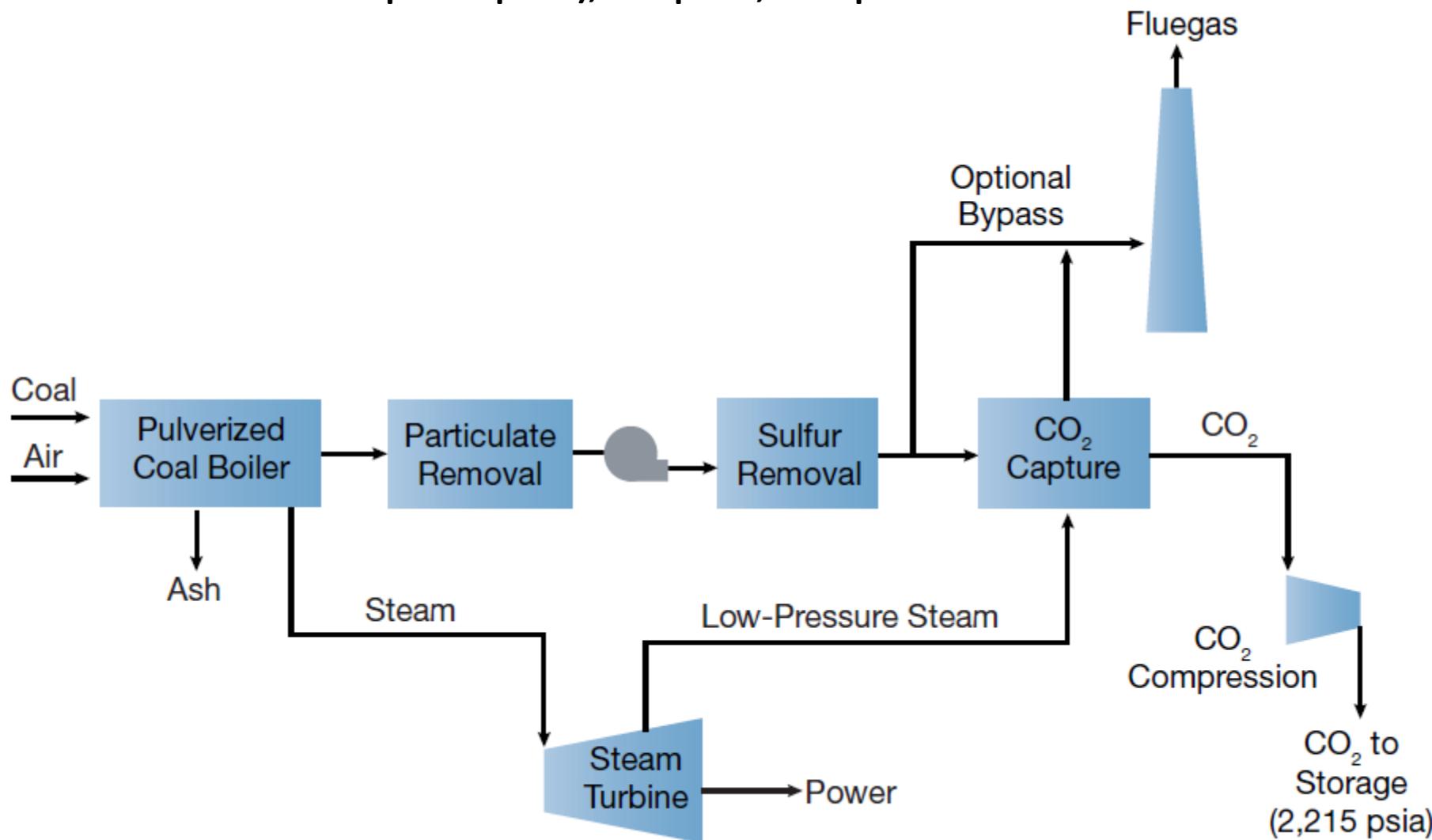
## Pathway for Produced CO<sub>2</sub> in CCS



# CO<sub>2</sub>-Enhanced Oil Recovery and Sequestration

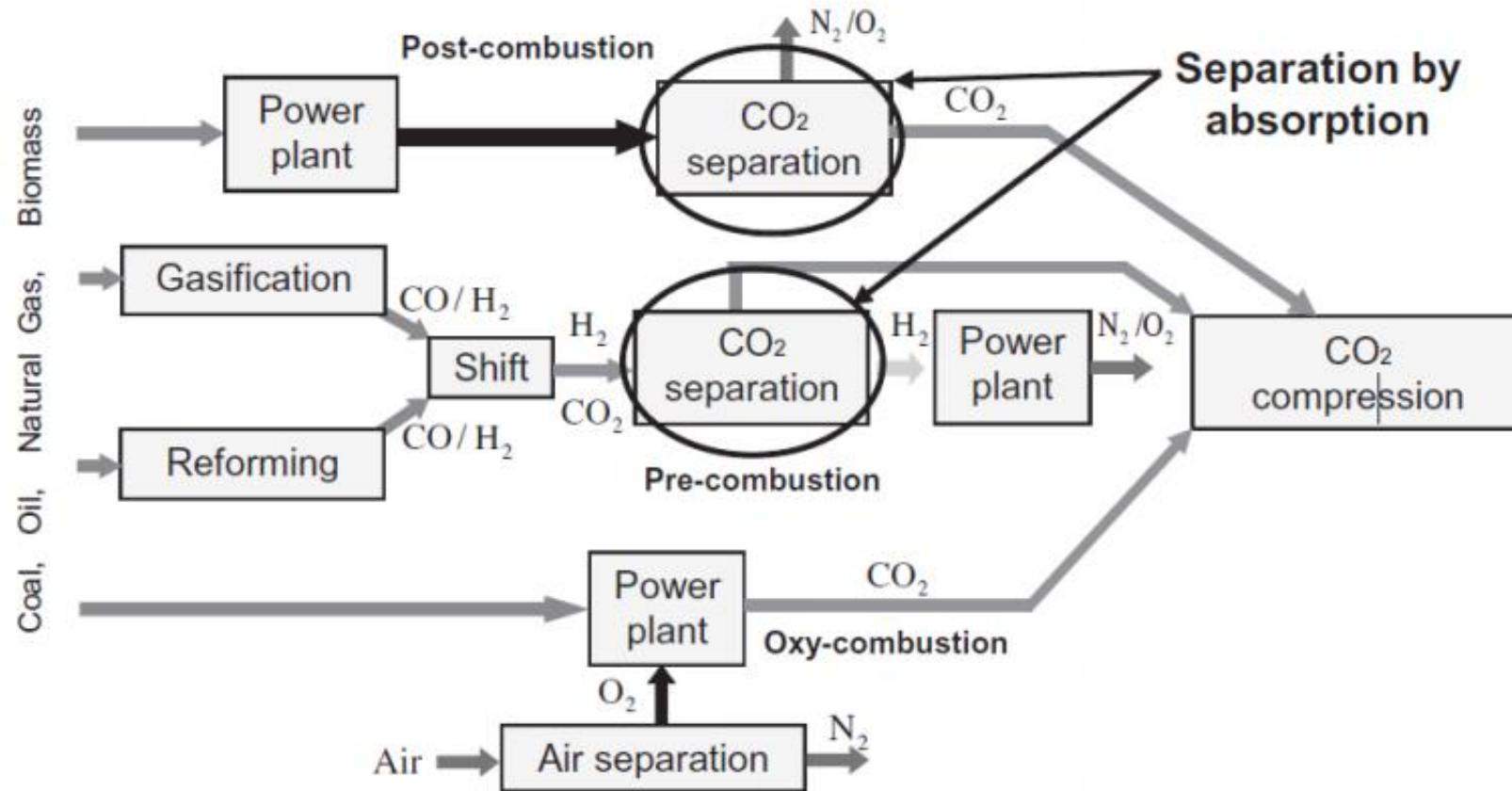


**Basic steps in CCS: capture (e.g., from flue gas of coal-fired power plant), compress, transport and store**



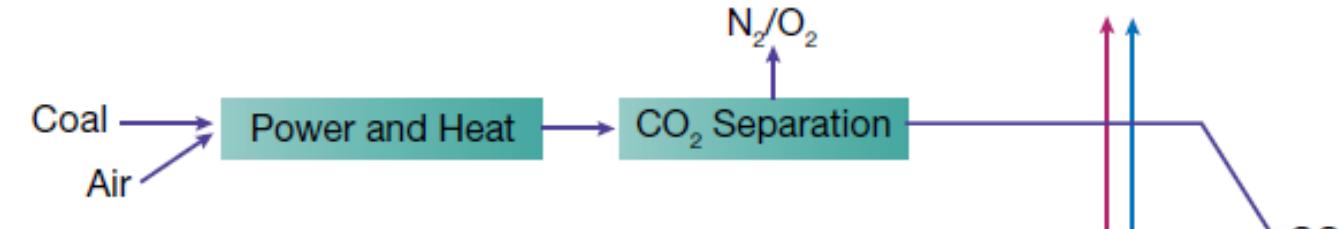
Source: CEP June 2016, 52

# $\text{CO}_2$ removal from flue gas in power plant

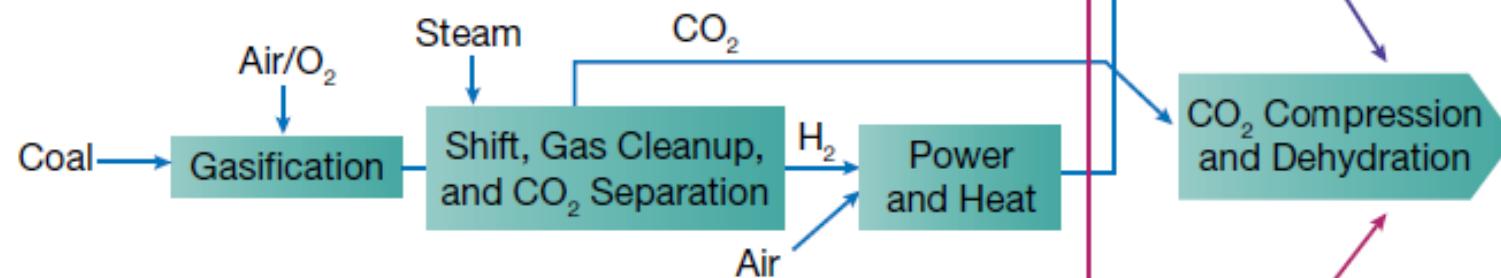


## Carbon capture technologies for power plants

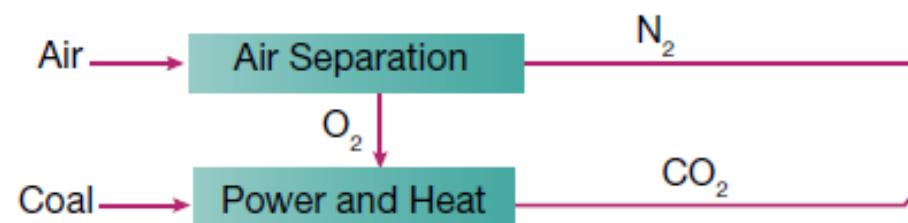
### Post-Combustion



### Pre-Combustion

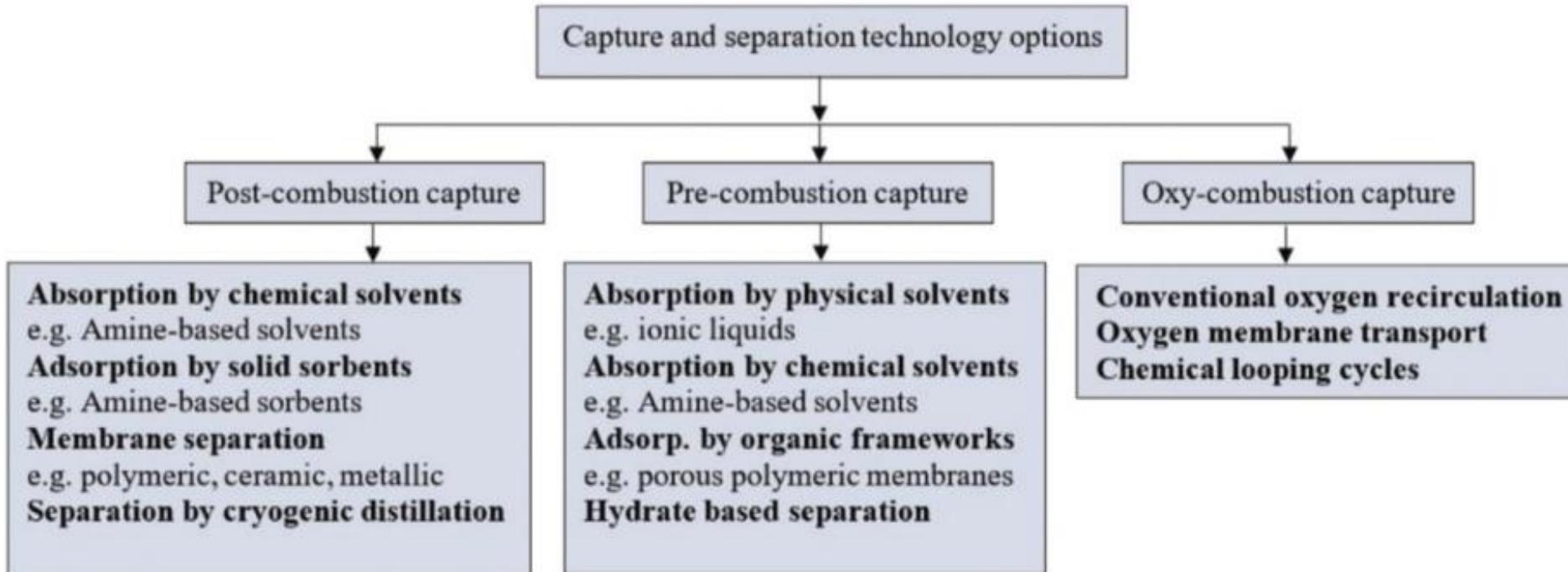


### Oxy-Combustion

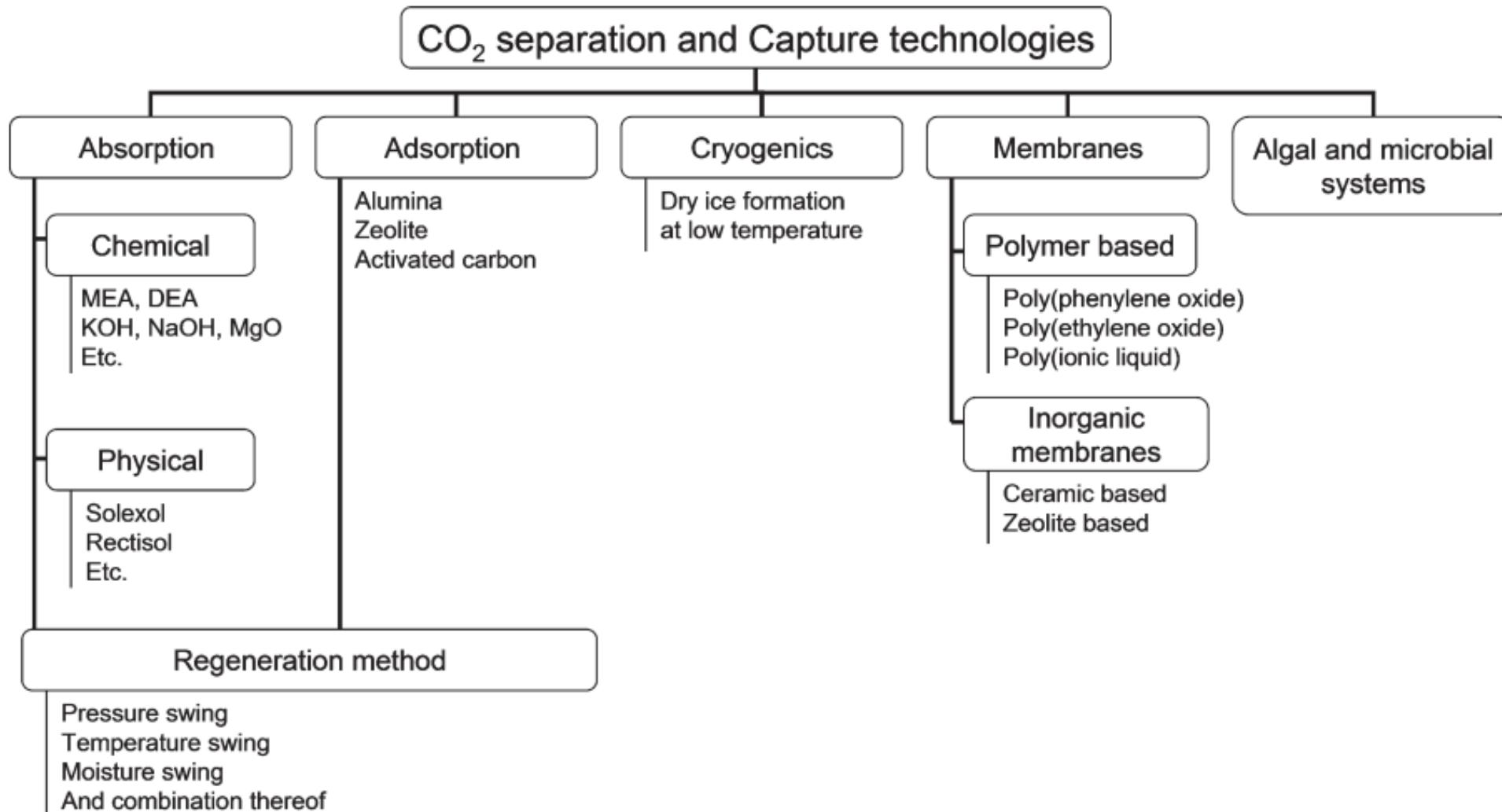


Source: CEP June 2016, 52

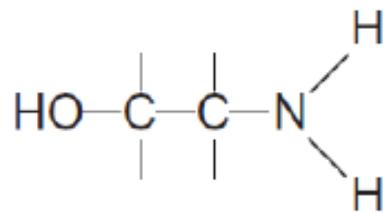
# CO<sub>2</sub> Capture in Power Generation



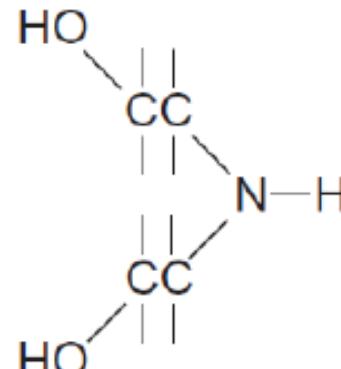
# CO<sub>2</sub> Removal Methods



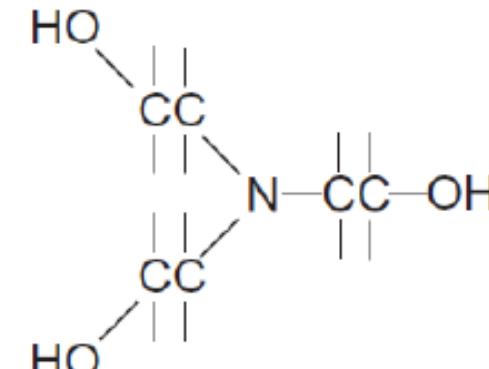
# Alkanolamine-Based Absorbents for Post-Combustion CO<sub>2</sub> Capture



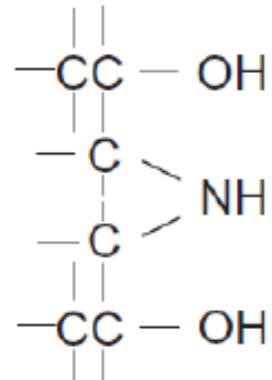
Monoethanolamine



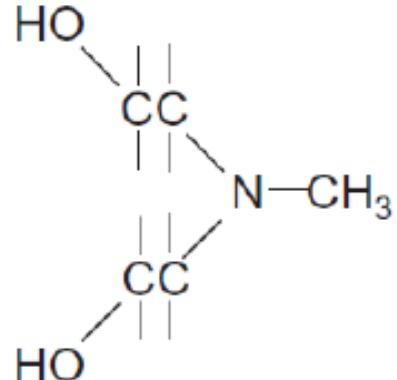
Diethanolamine



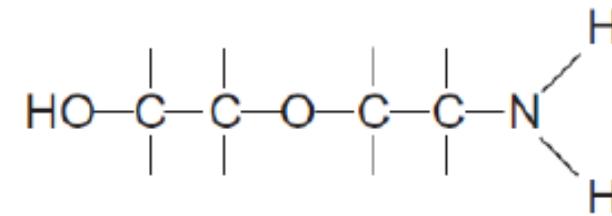
Triethanolamine



Diisopropanolamine

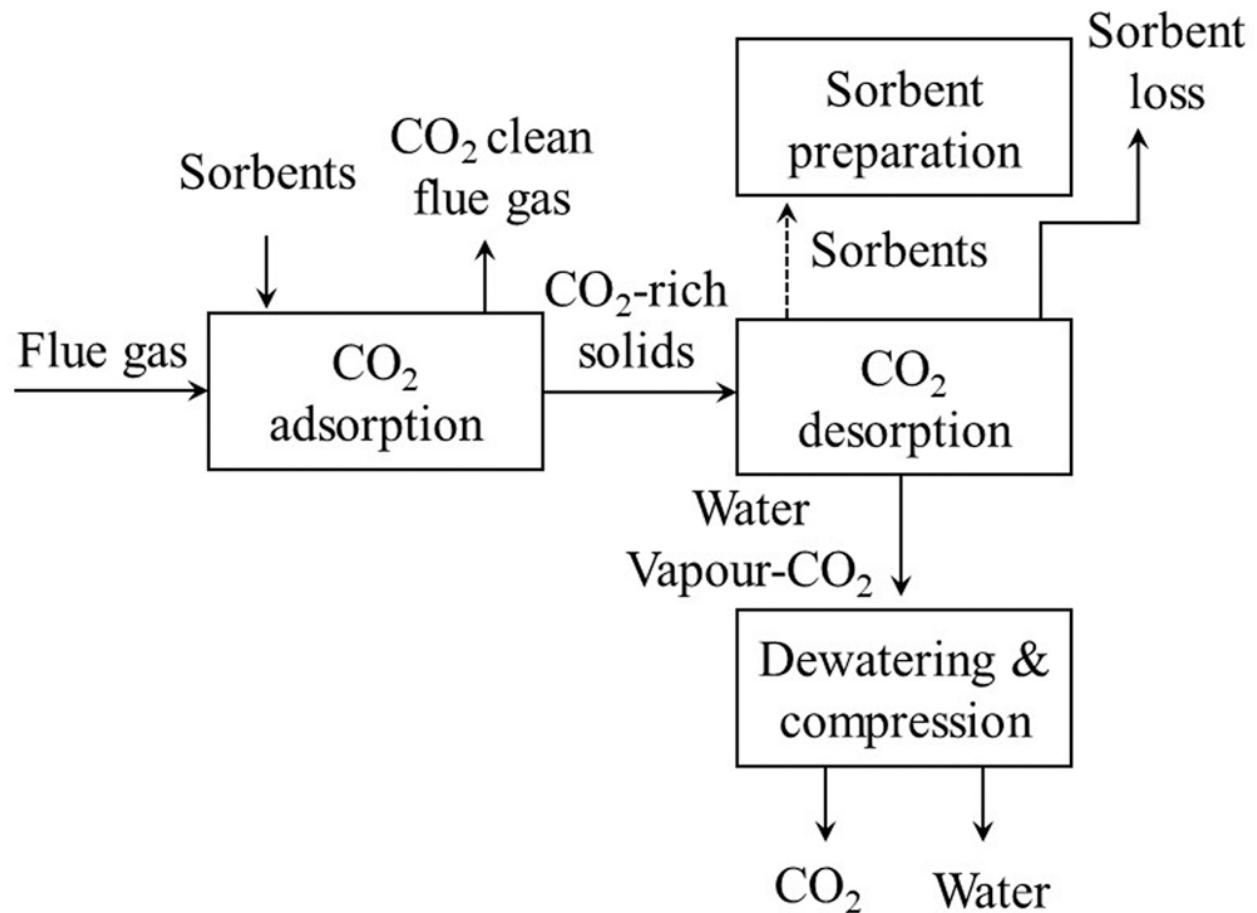


Methyl diethanolamine

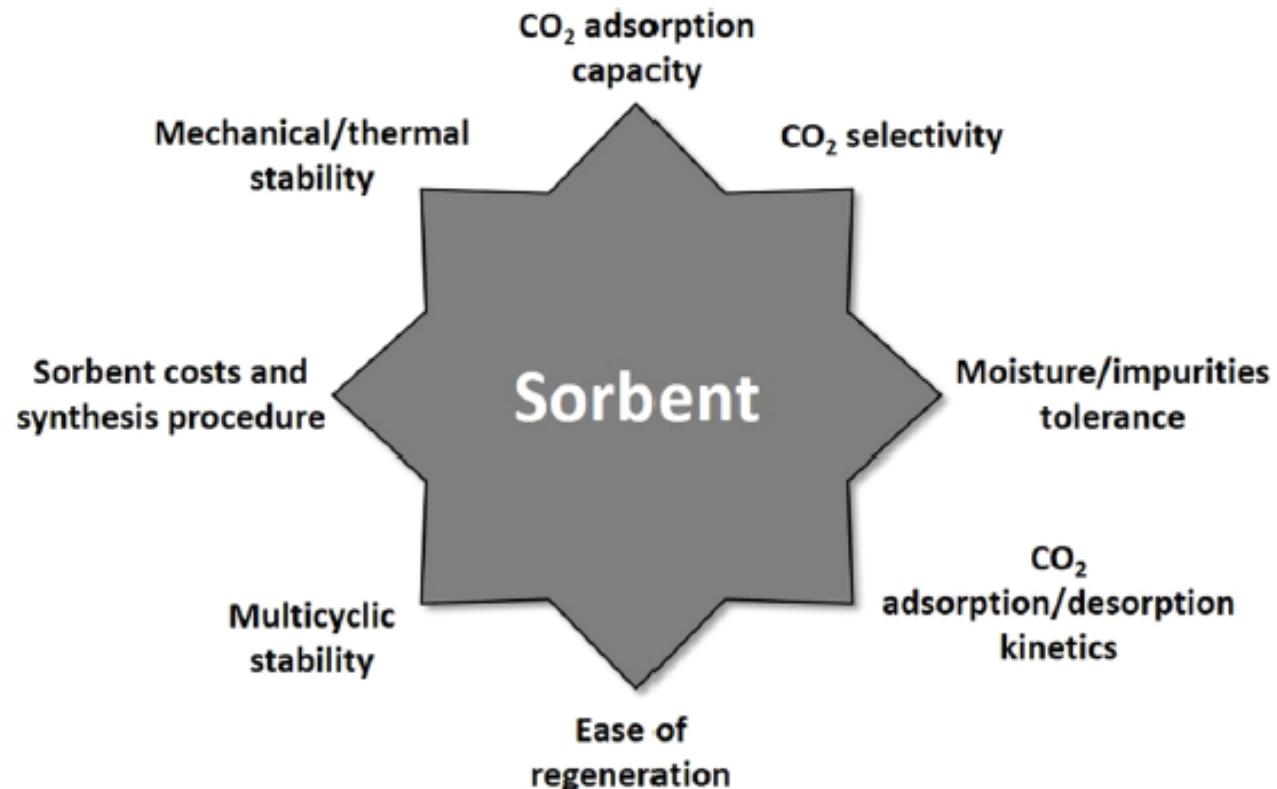


2 (2-aminoethoxy) ethanol

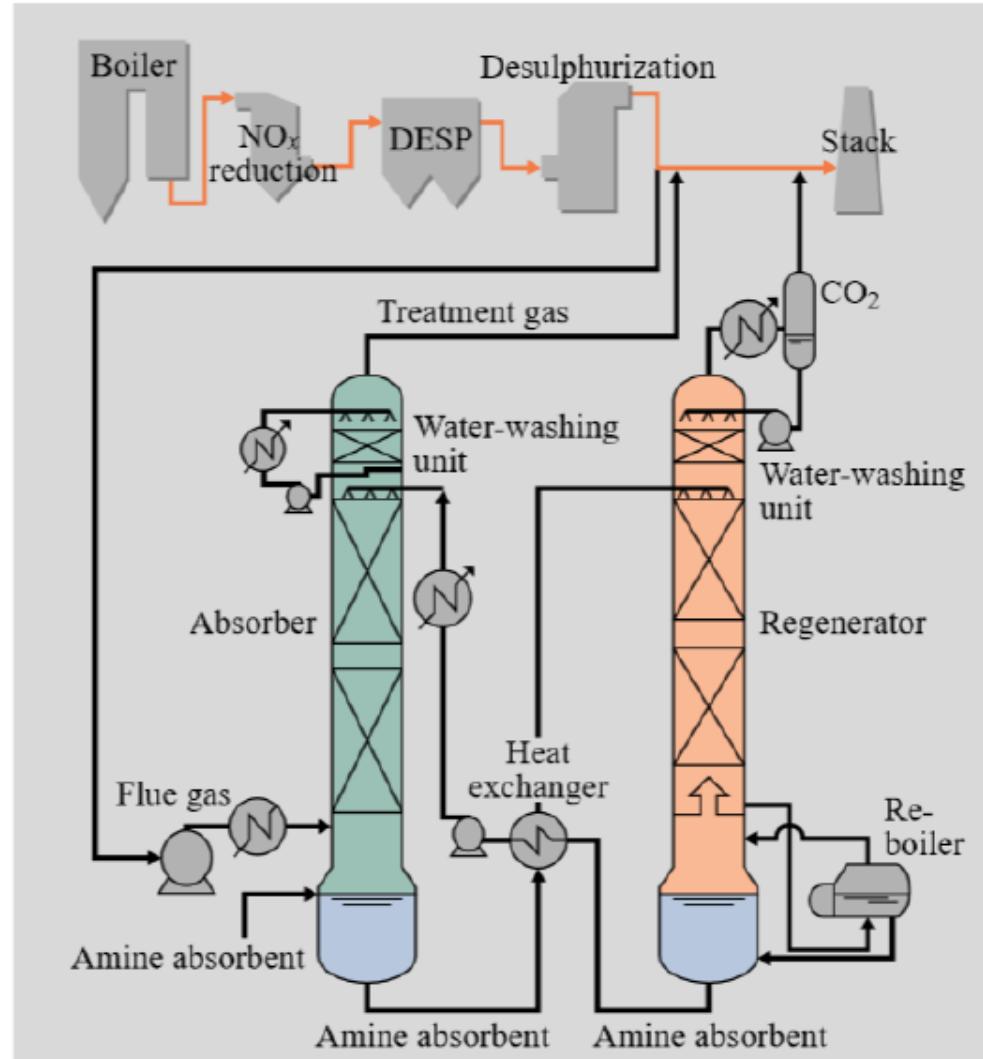
# Adsorption Process for CO<sub>2</sub> and Sorbent Regeneration



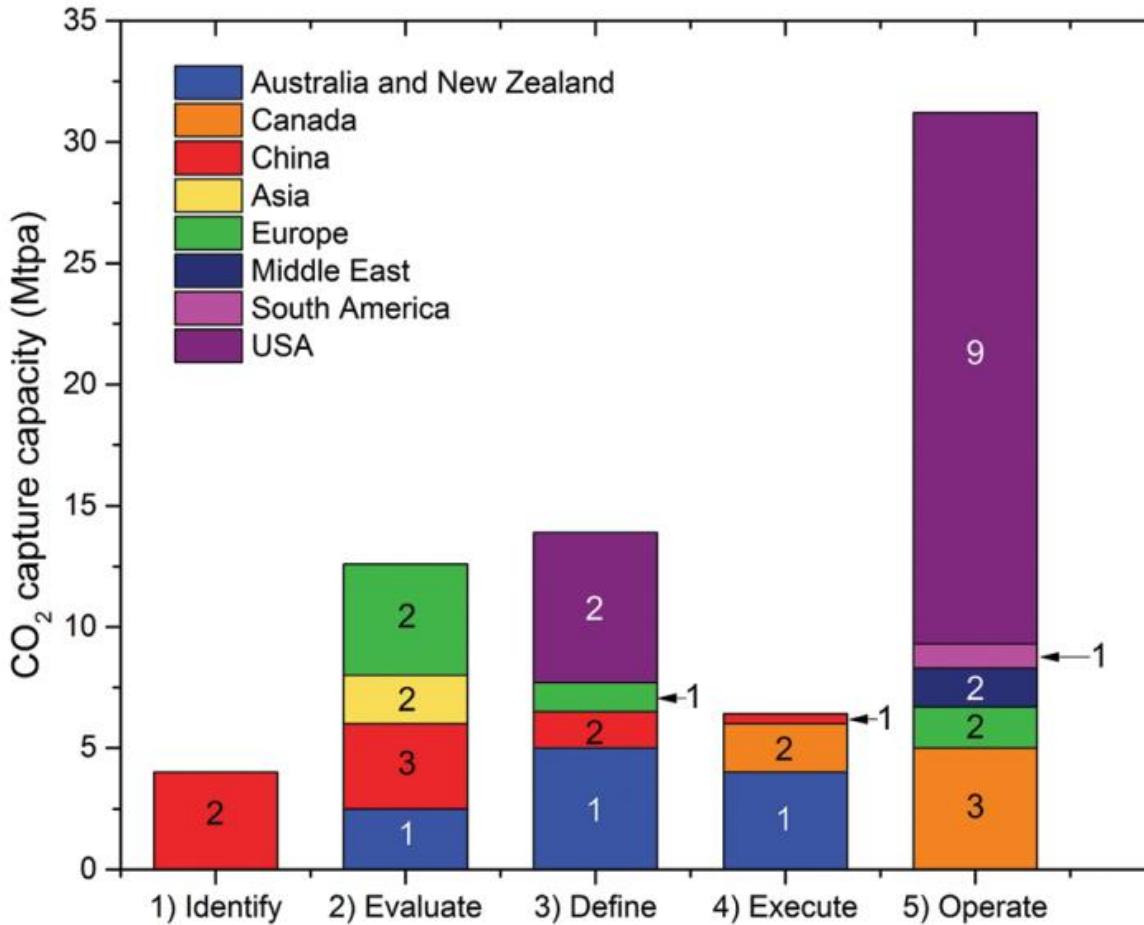
## Required Properties of Adsorbents



# Post-Combustion CO<sub>2</sub> Capture in Power Plant by Reactive Absorption



## CO<sub>2</sub> capture capacity of commercial-scale CCS projects

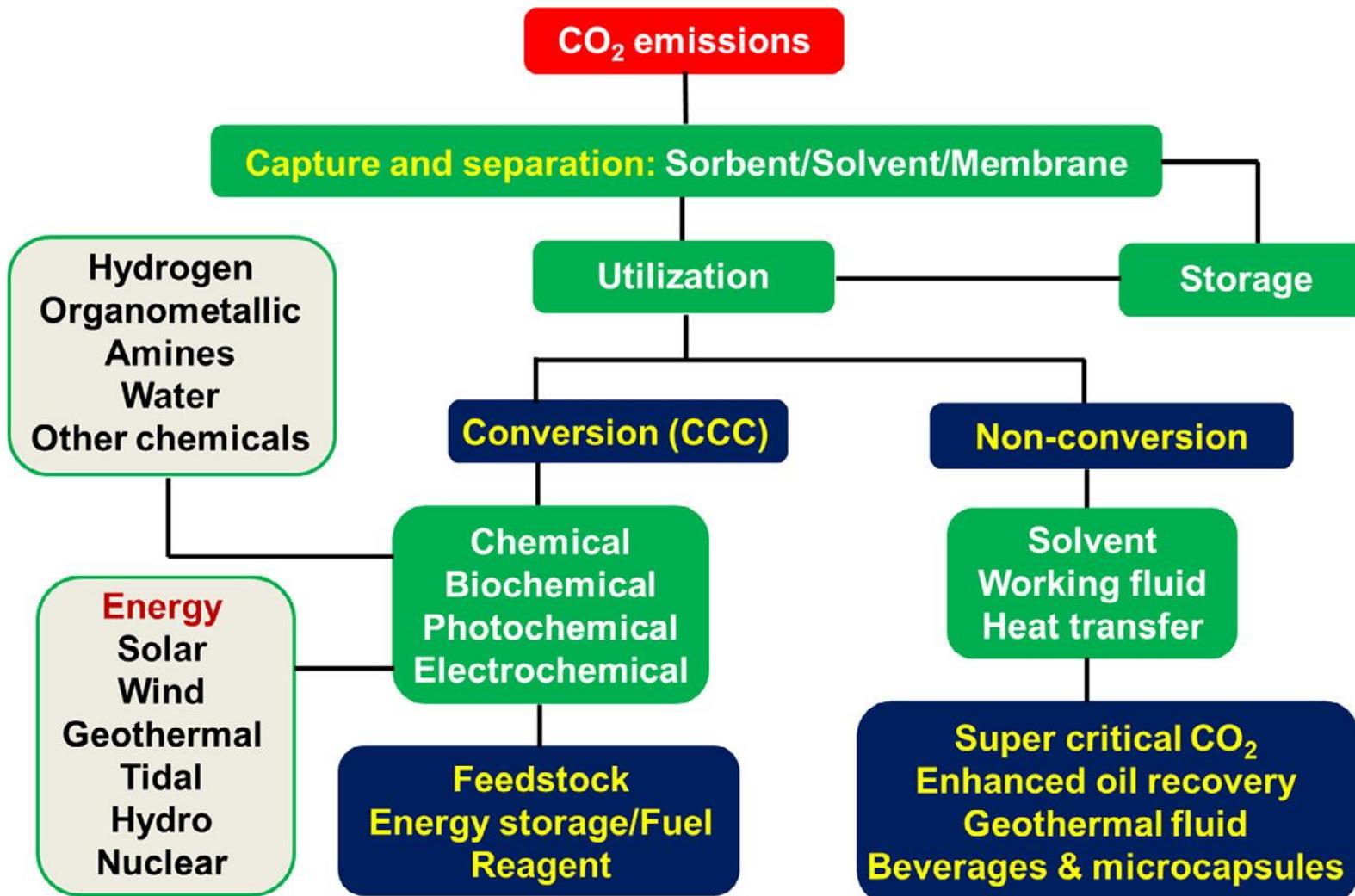


The number labelled on each proportion of capture capacity corresponds to the number of projects. Data from the Global CCS Institute.

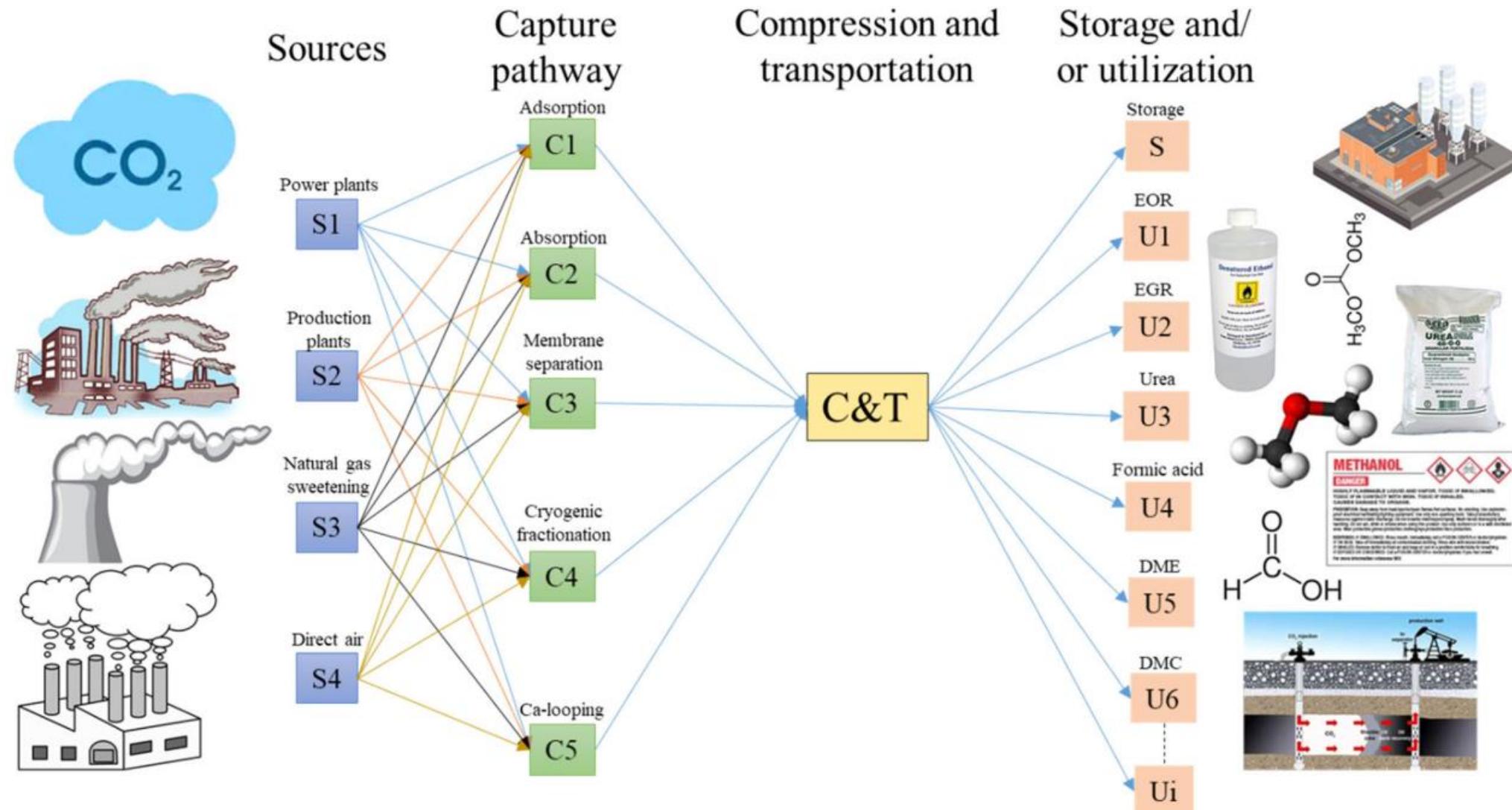
# CO<sub>2</sub> Removal Targets in the Industry

Process	Common cleanup targets
Hydrogen manufacture	<0.1% CO <sub>2</sub>
Ammonia manufacture	<16 ppm CO <sub>2</sub>
Natural gas purification	
Pipeline gas	<1% CO <sub>2</sub>
LNG feedstock	<50 ppm CO <sub>2</sub>
Synthesis gas for chemical production (H <sub>2</sub> /CO)	<500 ppm CO <sub>2</sub>
Coal gasification	~500 ppm CO <sub>2</sub>
Ethylene manufacture (steam cracker gas treating)	~1 ppm CO <sub>2</sub>
Power plants	
NGCC power plant	<0.5% CO <sub>2</sub>
Coal fired power plant	<1.5% CO <sub>2</sub>

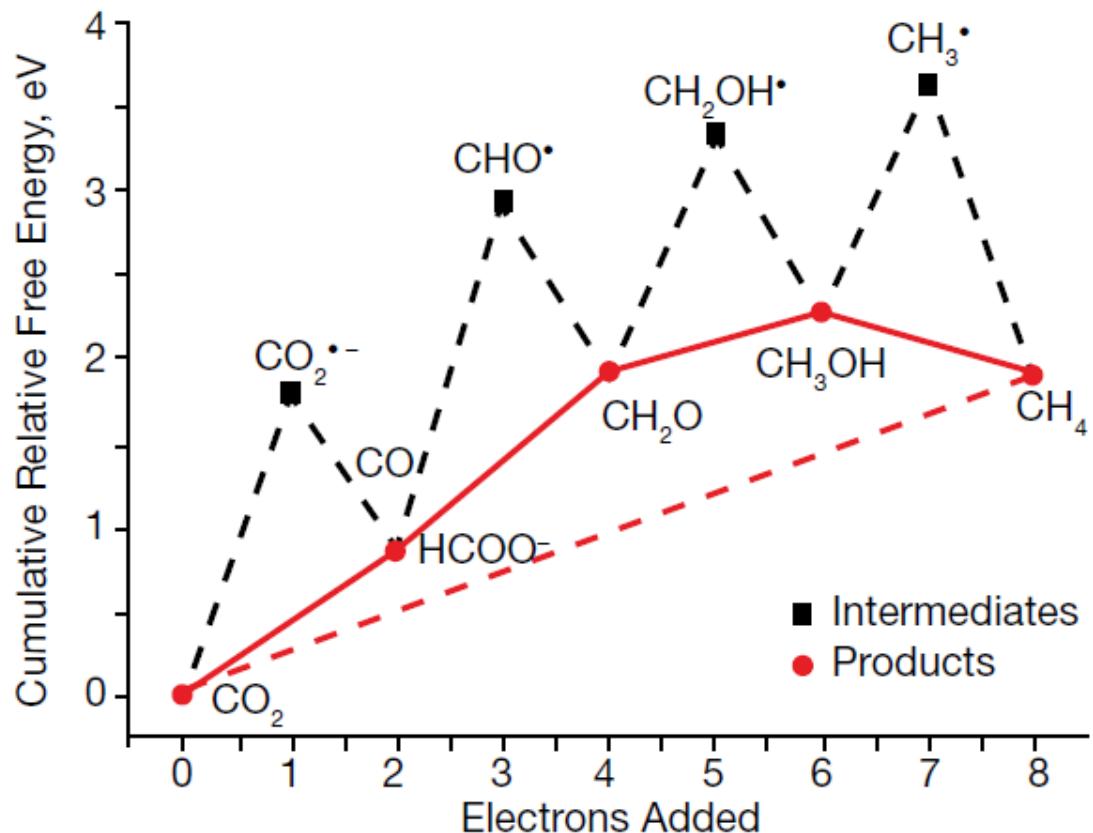
# CO<sub>2</sub> Capture and Utilization Process



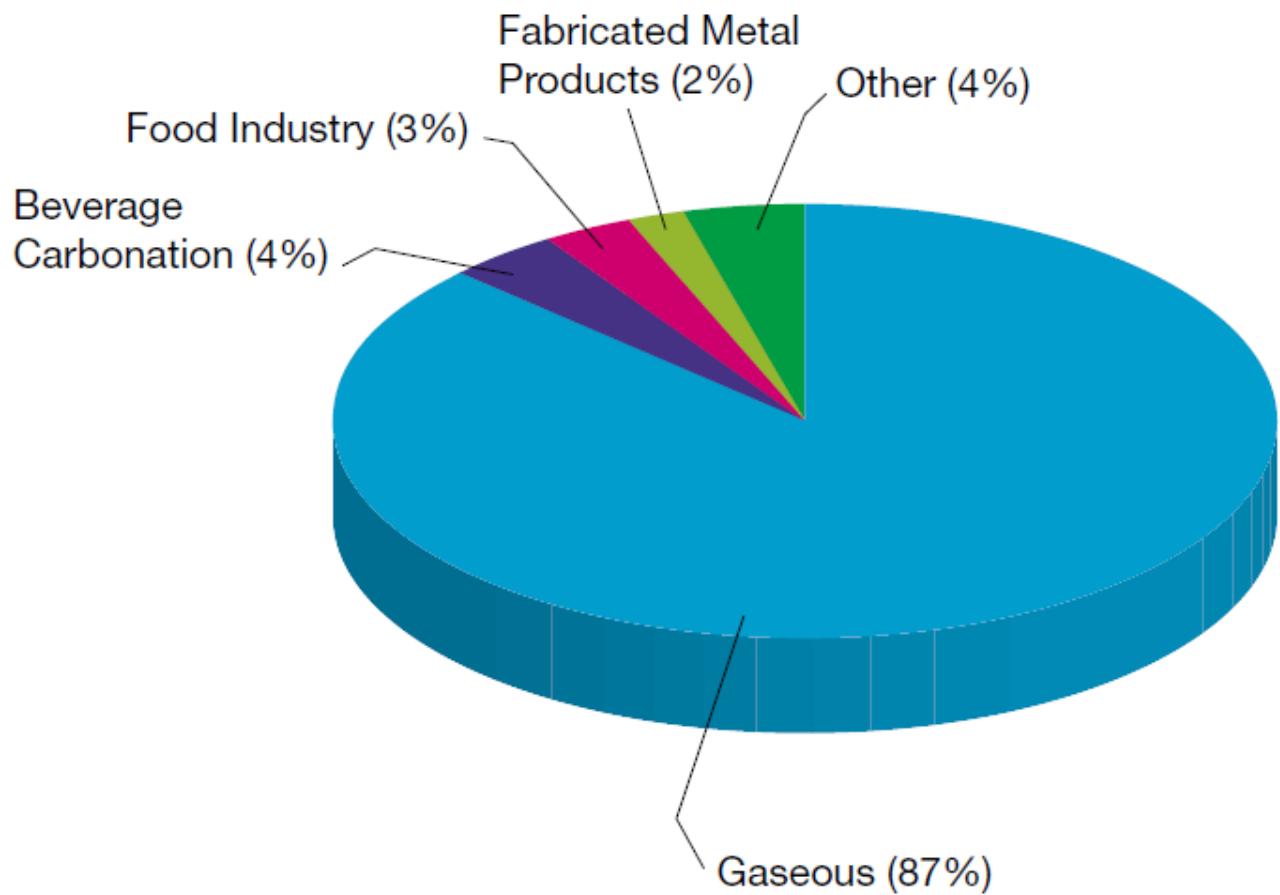
# A General Superstructure of CCU



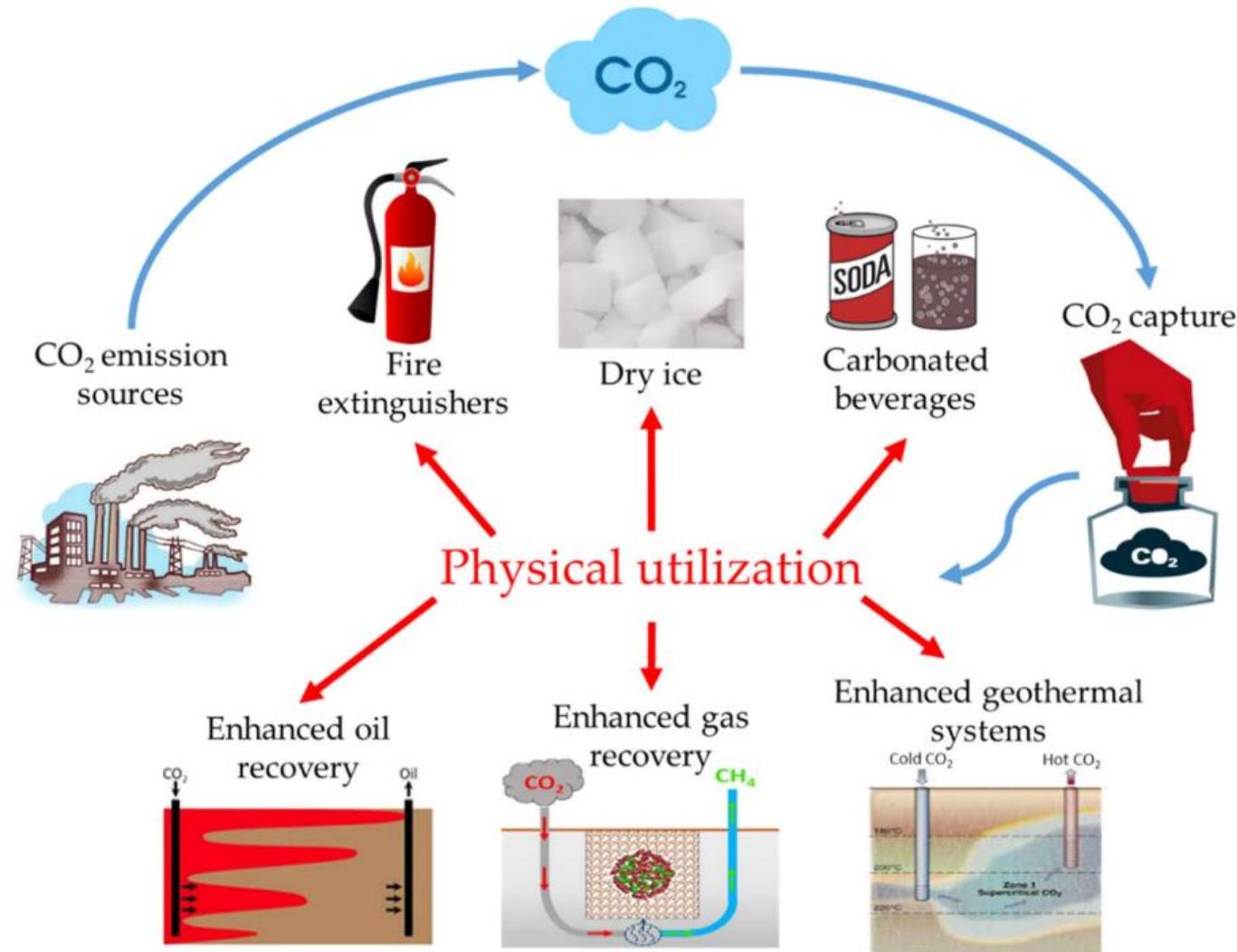
Converting  $\text{CO}_2$  into chemical products involves an energy penalty



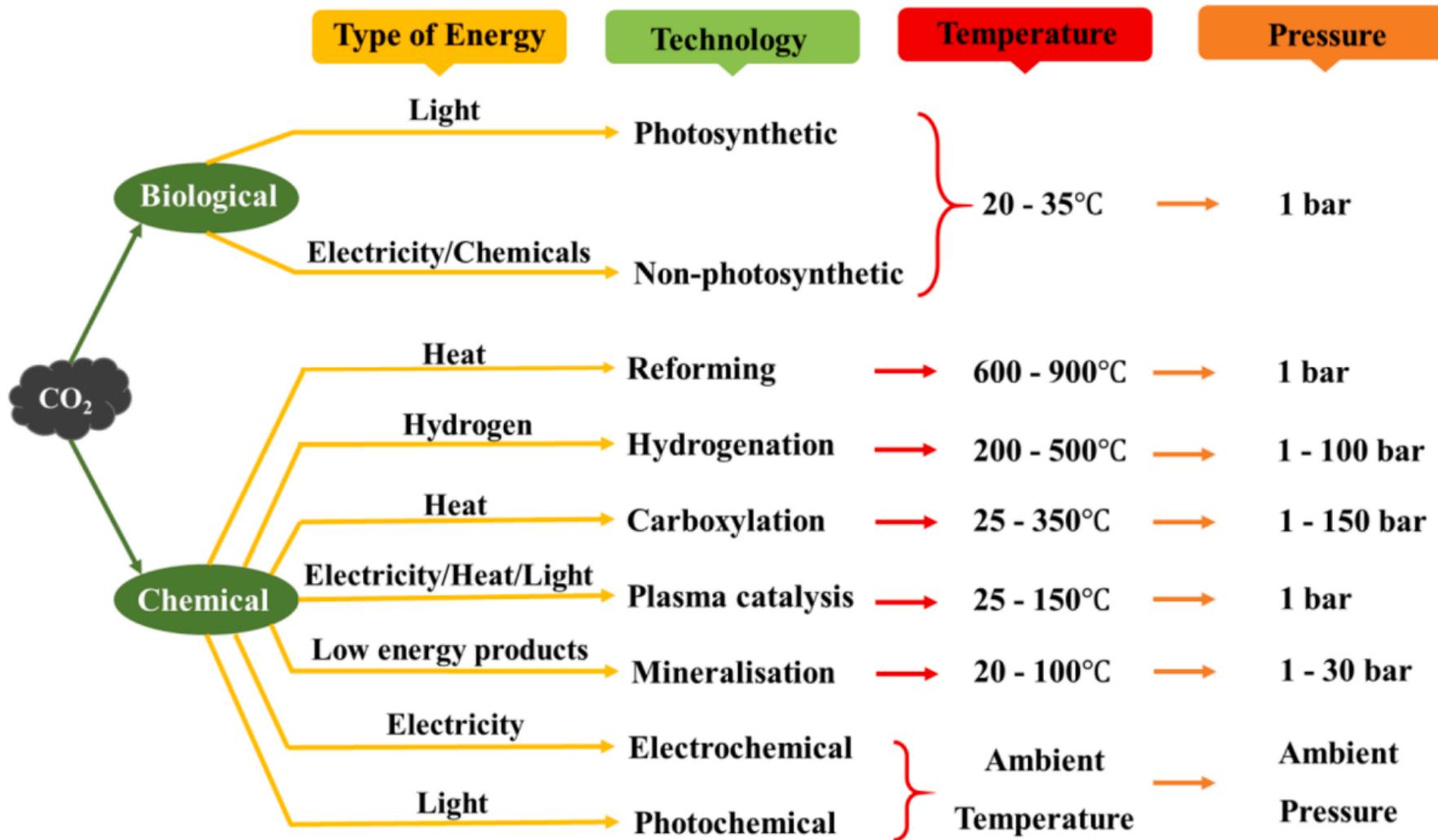
Most industrial  $\text{CO}_2$  is used in gaseous form for enhanced oil recovery



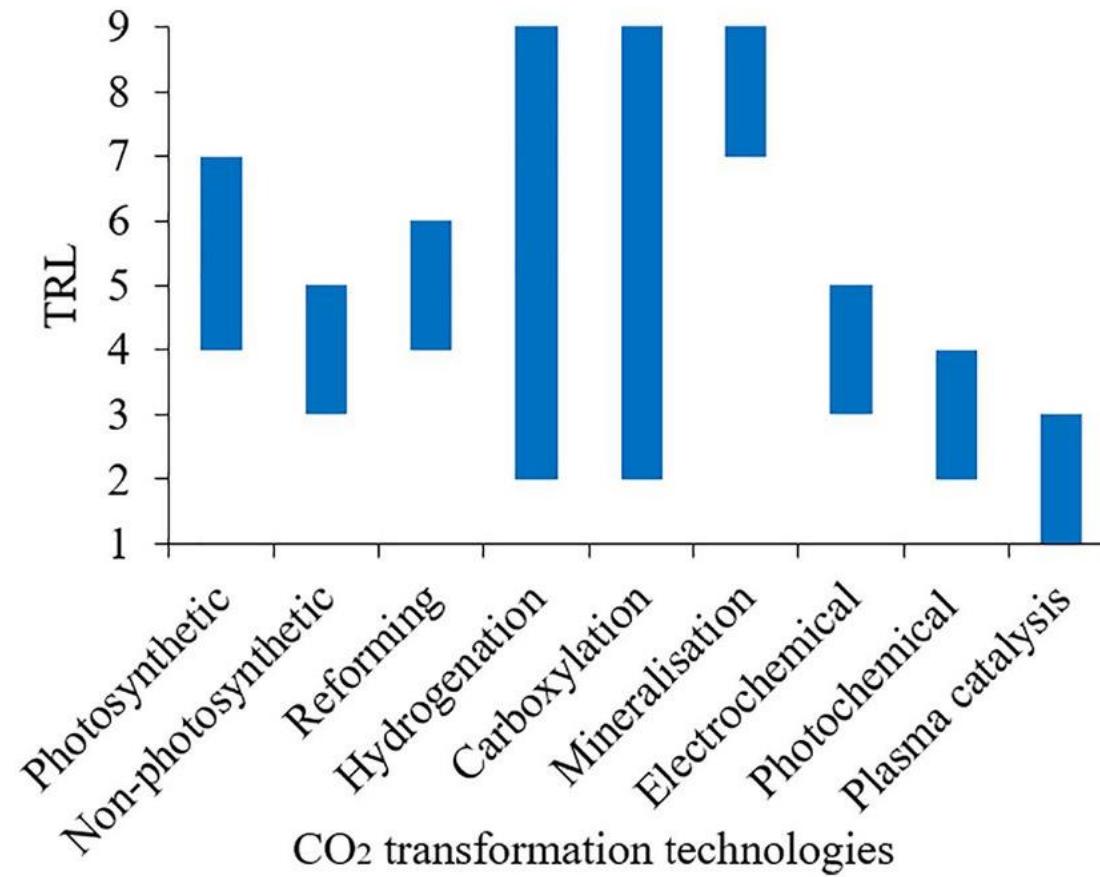
# Physical CO<sub>2</sub> Utilization Processes



# Chemical and Biological CO<sub>2</sub> Transformation Technologies



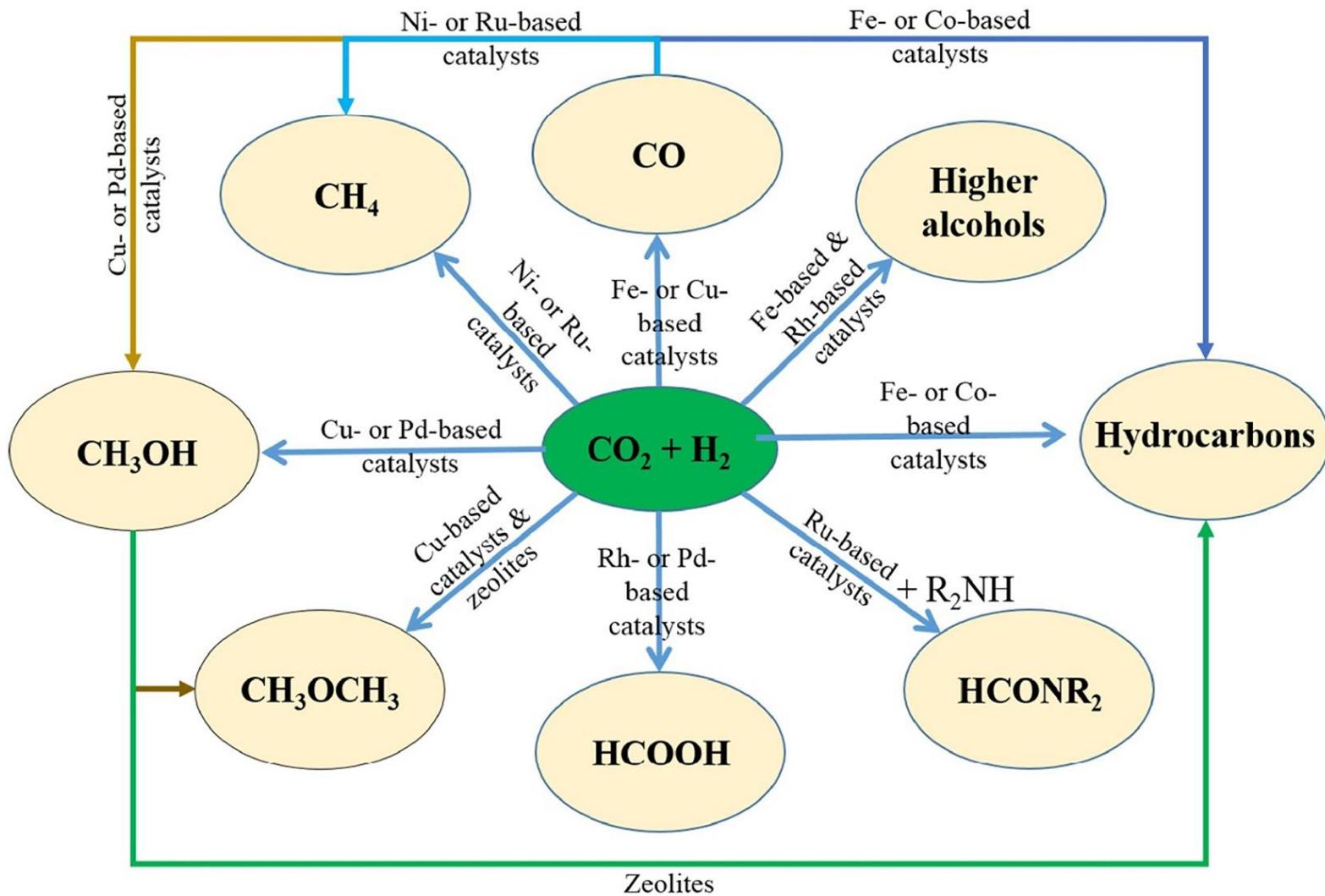
# Technology Readiness Level of Chemical CO<sub>2</sub> Transformation Technologies



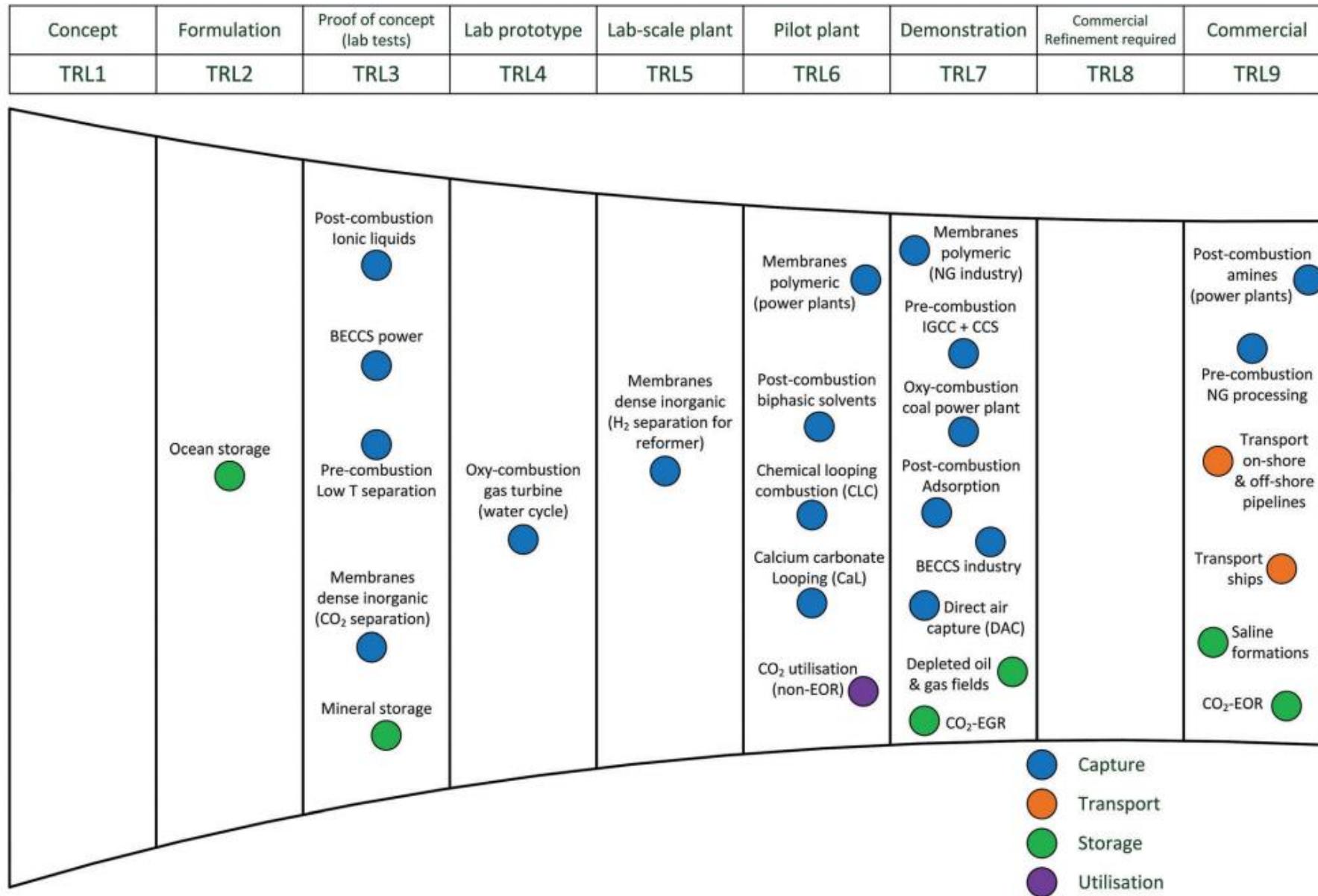
## TRL of Hydrogenation and Carboxylation Based on the Products

Technology	Product	TRL
Hydrogenation	Methanol	7–9
	Methane	7–9
	Liquid fuels via FTS	5–8
	Formic acid	3–5
	DME	2–3
	Formaldehyde	2–3
Carboxylation	Urea	7–9
	Polymers	6–7
	Cyclic carbonates	5–7
	Carboxylic acids	2–4

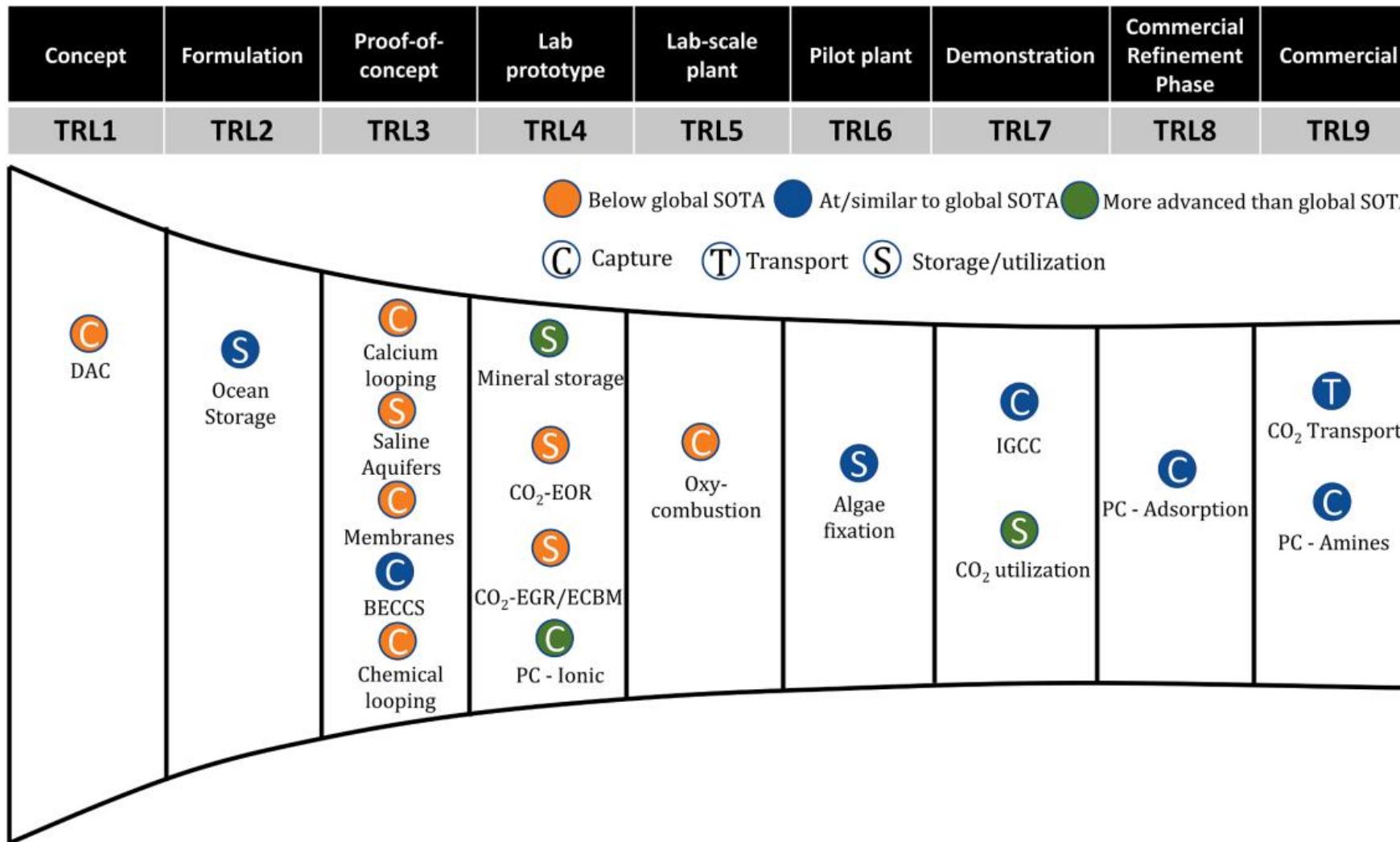
## Catalysts for CO<sub>2</sub> hydrogenation



# TRL of CCUS Technologies Worldwide

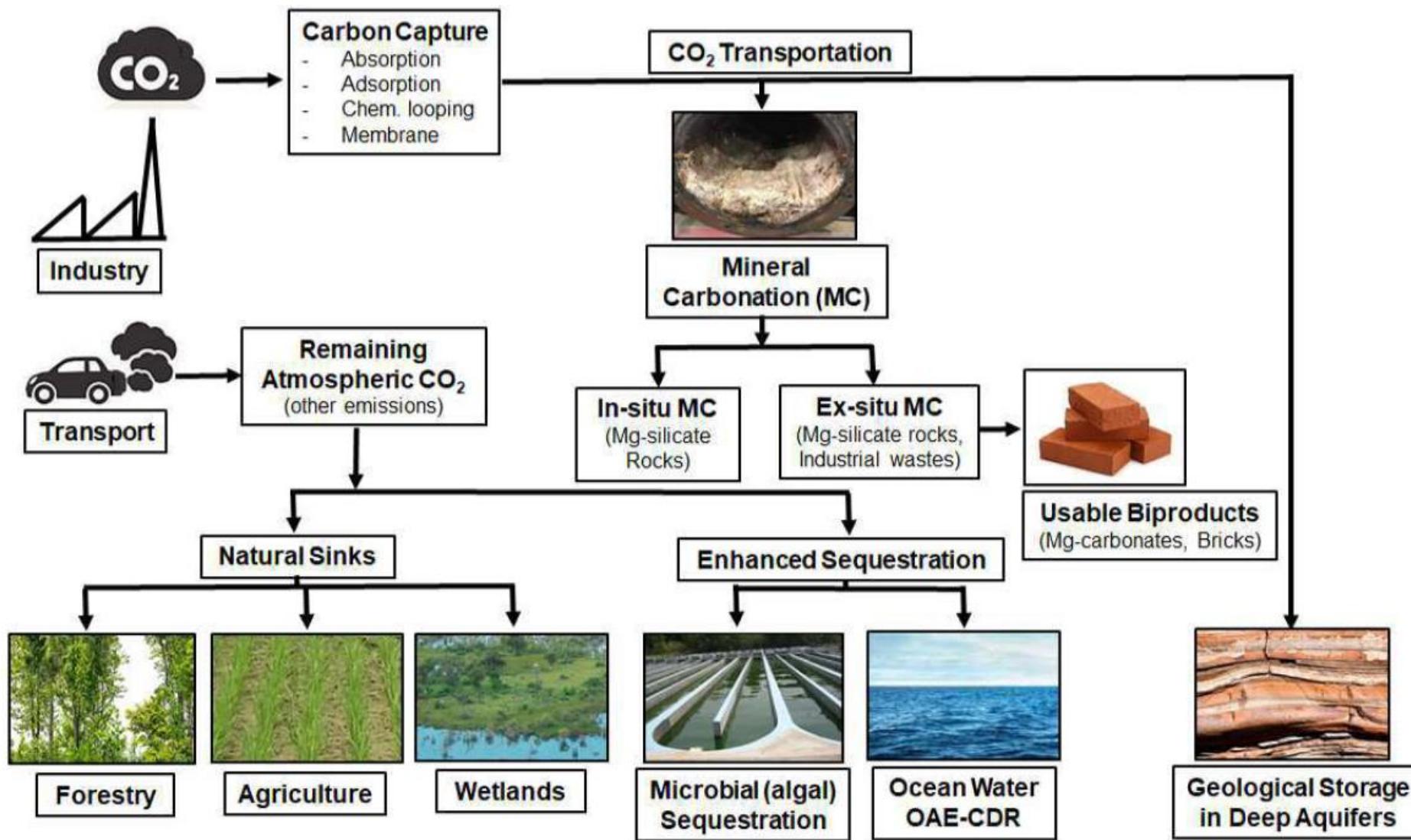


# TRL of CCUS Technologies Available in India

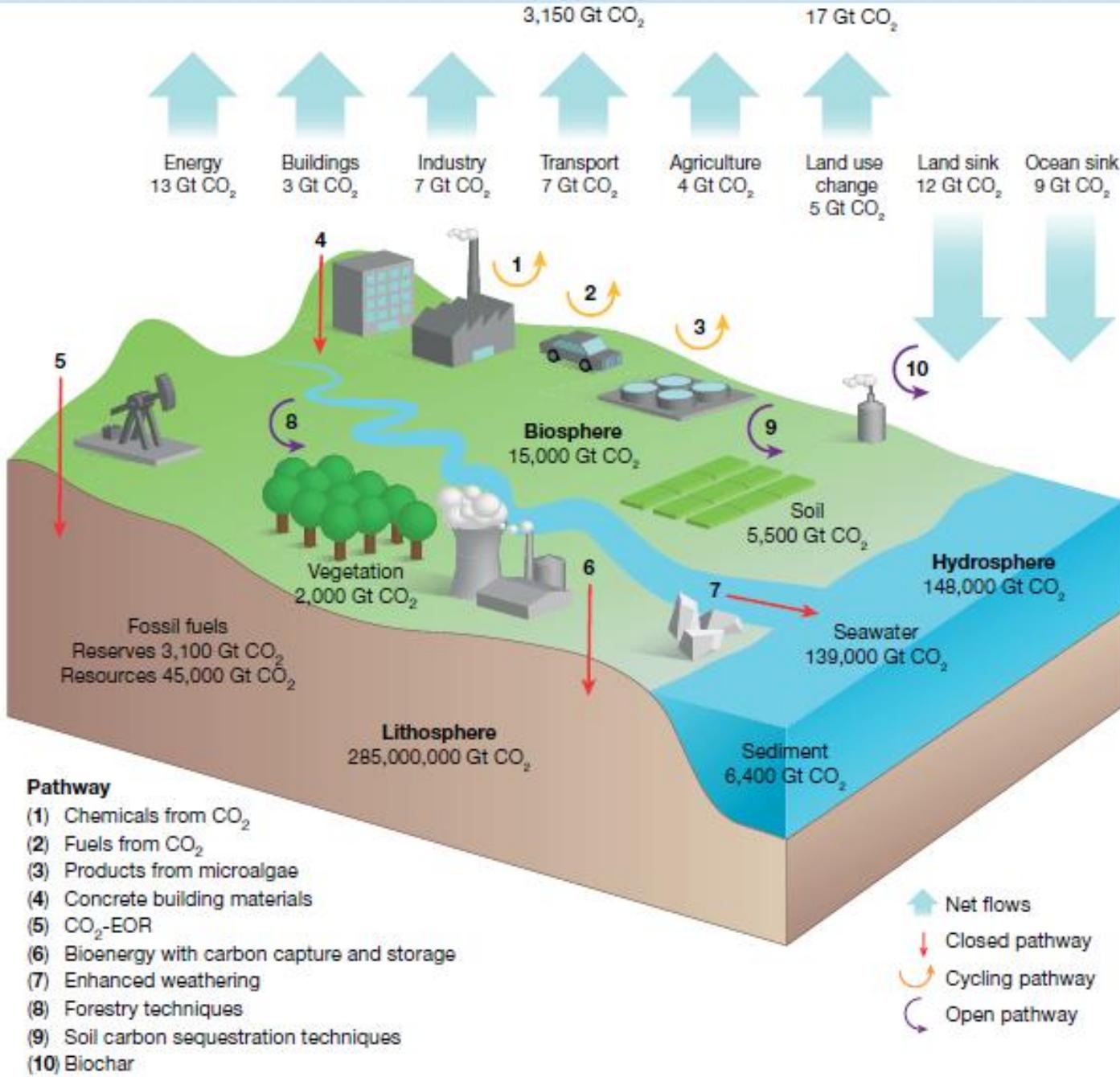


Colour schemes compare technology stages with the global state-of-the-art (SOTA).

# Strategies to be Adopted by India for Development of CCS Technologies



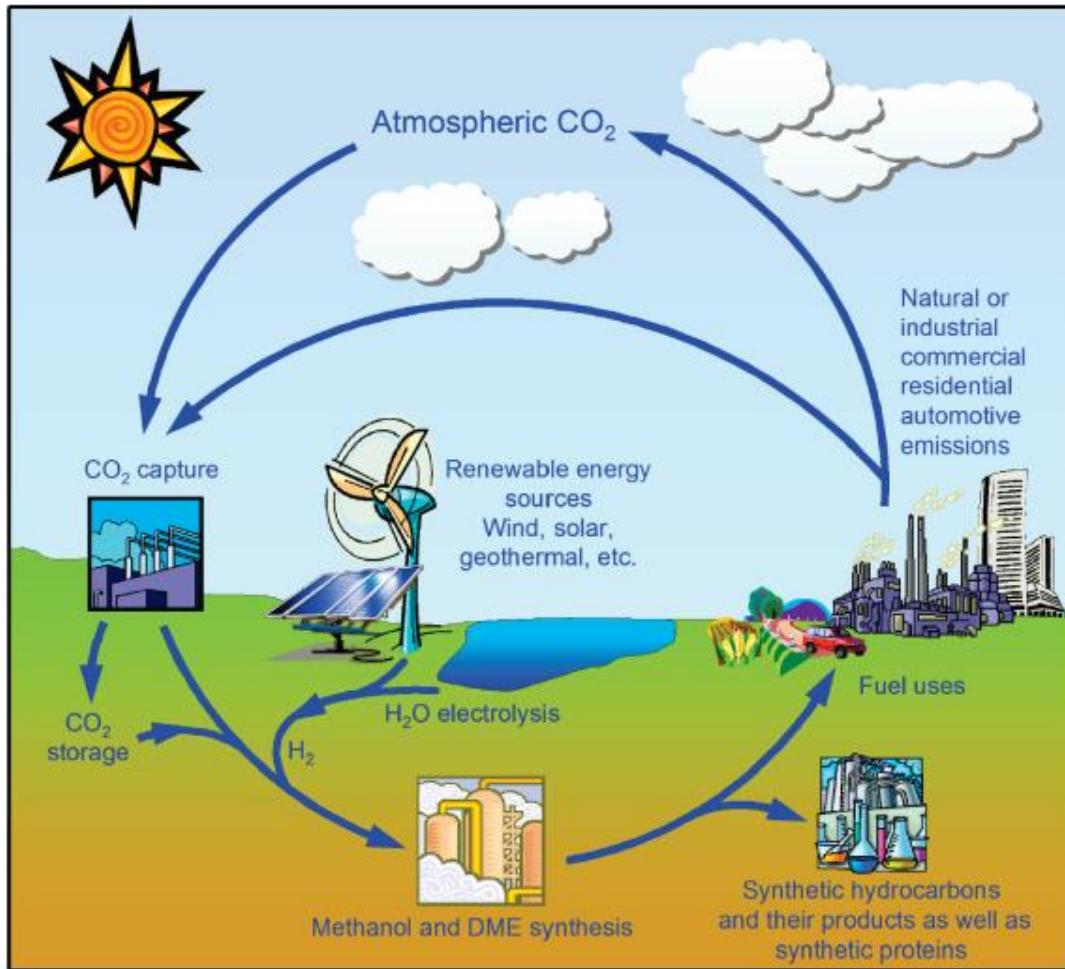
## Ten CO<sub>2</sub> Utilization and Removal Pathways



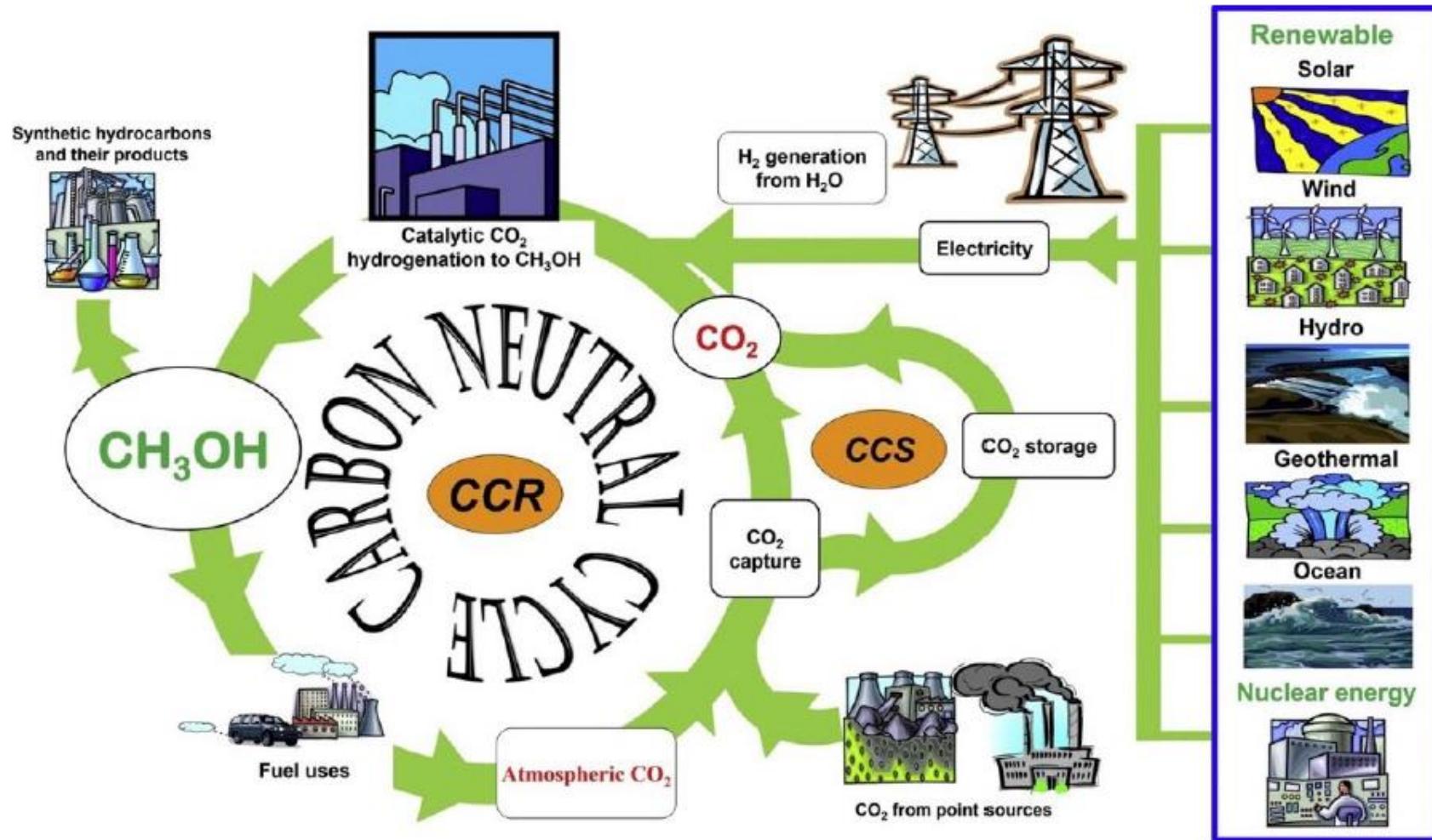
**Table 1 | Ten CO<sub>2</sub> utilization and removal pathways**

Pathway <sup>a</sup>	Removal and/or capture <sup>b</sup>	Utilization product	Storage <sup>c,d</sup> and likelihood of release (high/low)	Emission on use <sup>e</sup> or release during storage <sup>g</sup>
(1) Chemicals from CO <sub>2</sub>	Catalytic chemical conversion of CO <sub>2</sub> from flue gas or other sources into chemical products	CO <sub>2</sub> -derived platform chemicals such as methanol, urea and plastics	Various chemicals (days/decades) – high	Hydrolysis or decomposition
(2) Fuels from CO <sub>2</sub>	Catalytic hydrogenation processes to convert CO <sub>2</sub> from flue gas or other sources into fuels	CO <sub>2</sub> -derived fuels such as methanol, methane and Fischer-Tropsch-derived fuels	Various fuels (weeks/months) – high	Combustion
(3) Products from microalgae	Uptake of CO <sub>2</sub> from the atmosphere or other sources by microalgae biomass	Biofuels, biomass, or bioproducts such as aquaculture feed	Various products (weeks/months) – high	Combustion (fuel) or consumption (bioprodct)
(4) Concrete building materials	Mineralization of CO <sub>2</sub> from flue gas or other sources into industrial waste materials, and CO <sub>2</sub> curing of concrete	Carbonated aggregates or concrete products	Carbonates (centuries) – low	Extreme acid conditions
(5) CO <sub>2</sub> -EOR	Injection of CO <sub>2</sub> from flue gas or other sources into oil reservoirs	Oil	Geological sequestration (millennia) – low <sup>g</sup>	n.a.
(6) Bioenergy with carbon capture and storage (BECCS)	Growth of plant biomass	Bioenergy crop biomass	Geological sequestration (millennia) – low <sup>g</sup>	n.a.
(7) Enhanced weathering	Mineralization of atmospheric CO <sub>2</sub> via the application of pulverized silicate rock to cropland, grassland and forests	Agricultural crop biomass	Aqueous carbonate (centuries) – low	Extreme acidic conditions
(8) Forestry techniques	Growth of woody biomass via afforestation, reforestation or sustainable forest management	Standing biomass, wood products	Standing forests and long-lived wood products (decades to centuries) – high	Disturbance, combustion or decomposition
(9) Soil carbon sequestration techniques	Increase in soil organic carbon content via various land management practices	Agricultural crop biomass	Soil organic carbon (years to decades) – high	Disturbance or decomposition
(10) Biochar	Growth of plant biomass for pyrolysis and application of char	Agricultural or bioenergy crop biomass	Black carbon (years to decades) – high	Decomposition

# George Olah's Anthropogenic Chemical Carbon Cycle



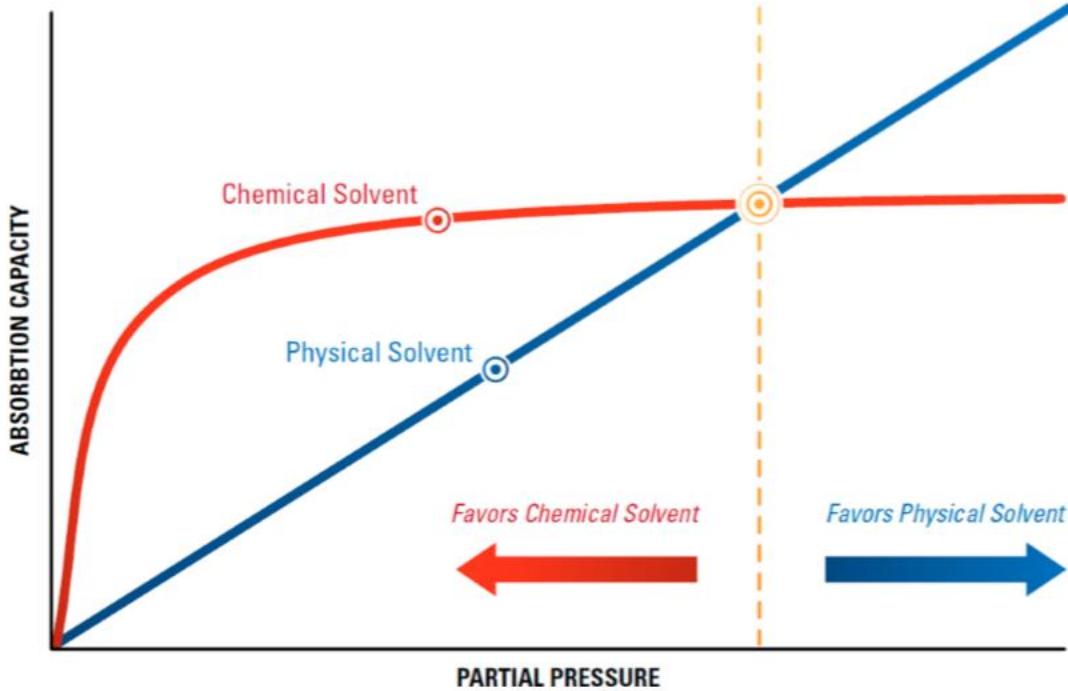
# Anthropogenic Chemical Carbon Cycle and Circular Methanol Economy



**THANK YOU**

# **CO<sub>2</sub> REMOVAL BY ABSORPTION**

# Physical & chemical solvents for absorption



e.g., relationship between absorption capacity and  $\text{CO}_2$  partial pressure

# Chemical or reactive absorption

Absorbed solutes are converted into other species and high product solubility is useful. Selective removal of solute is possible, but solvent regeneration is difficult.

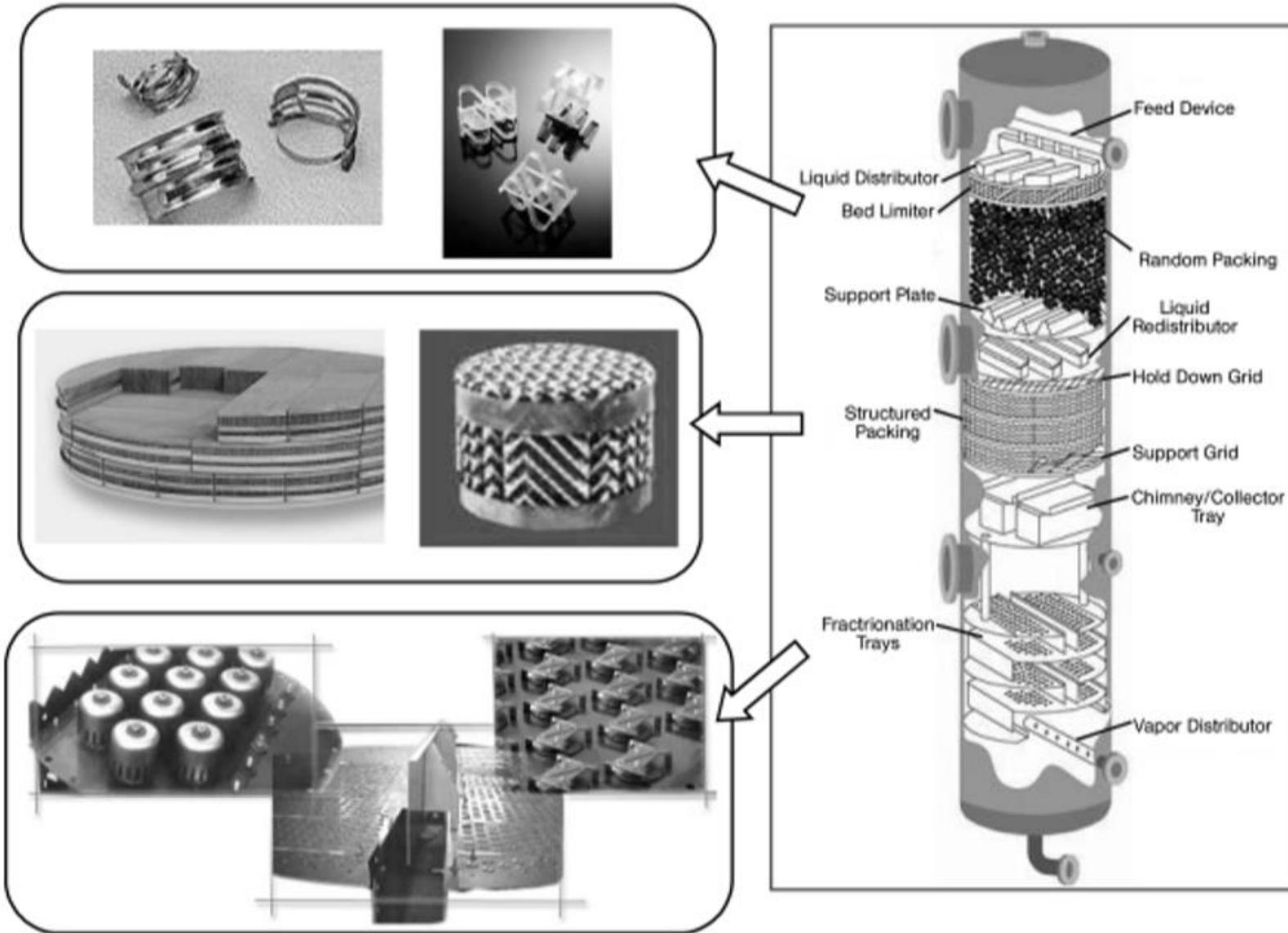
*e.g., chemical solvent-based CO<sub>2</sub> capture technologies*

existing commercial technology	solvent
	ammonia
EFG Plus <sup>SM</sup>	amine base
KM-CDR	
Kerr-McGee	piperazine

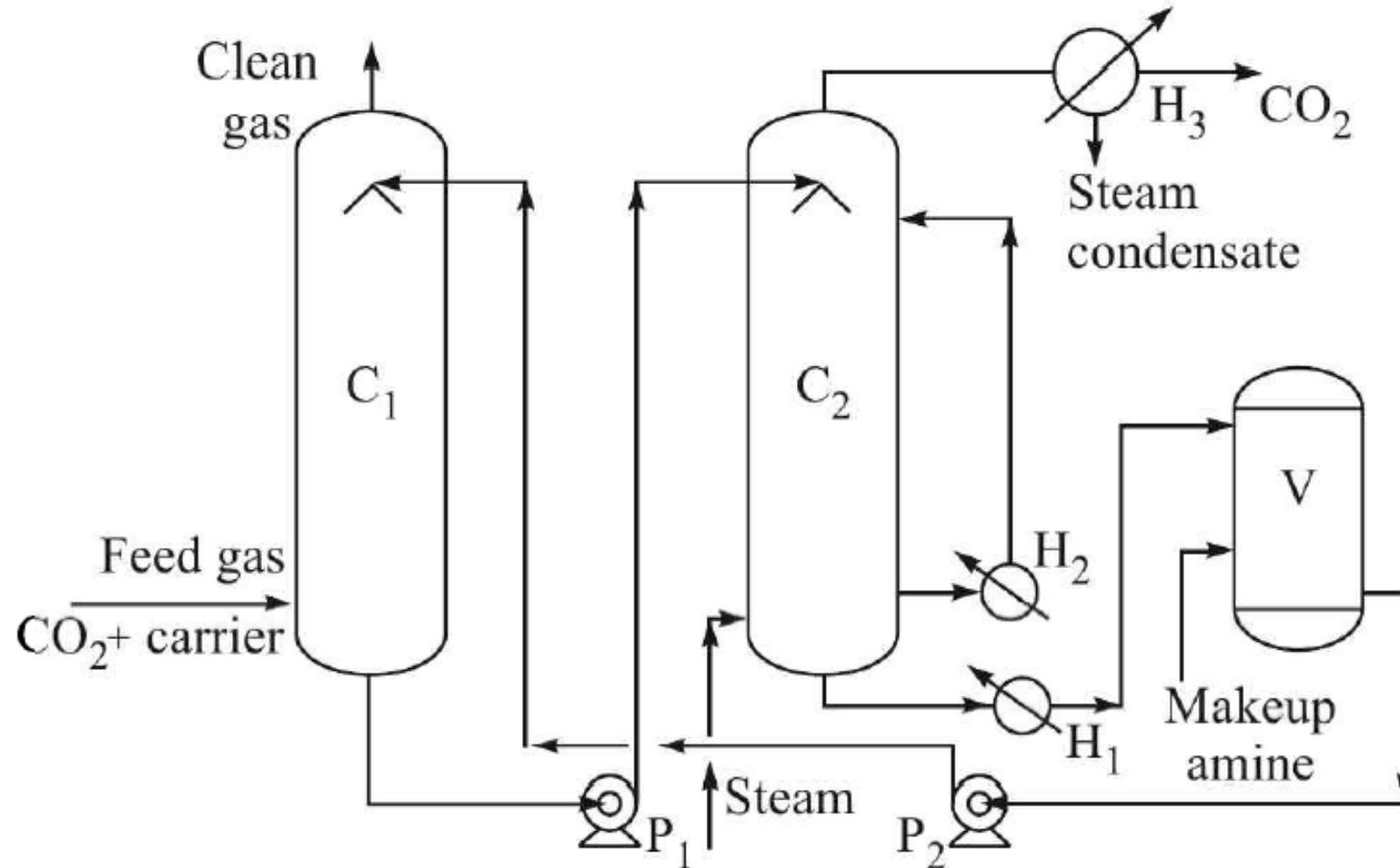
# Reactive absorption units

Unit group criterion	Unit type
Both phases in a continuous form	<ul style="list-style-type: none"><li>• packed columns</li><li>• thin-film contactors</li><li>• wetted-wall columns</li><li>• contactors with flat surface</li><li>• laminar jet absorber</li><li>• disc (sphere) columns</li></ul>
A disperse gas phase and a continuous liquid phase	<ul style="list-style-type: none"><li>• plate columns</li><li>• plate columns with packing</li><li>• bubble columns</li><li>• packed bubble columns</li><li>• mechanically agitated columns</li><li>• jet absorbers</li></ul>
A disperse liquid phase and a continuous gas phase	<ul style="list-style-type: none"><li>• spray columns</li><li>• venturi scrubbers</li></ul>

# Reactive absorption column and internals



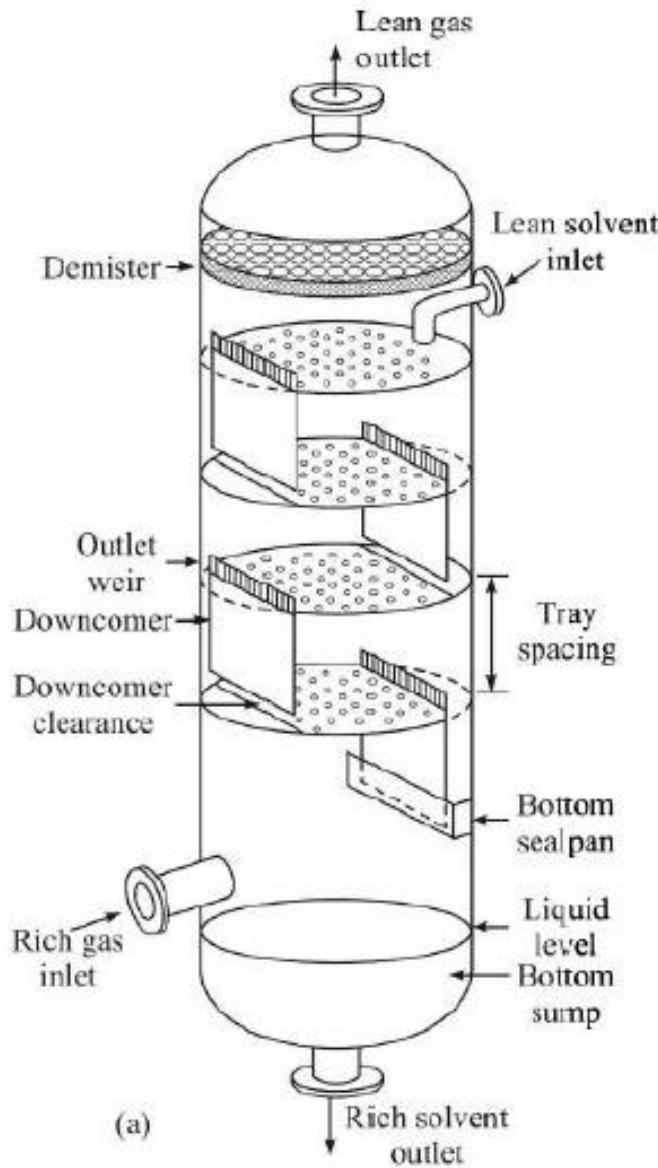
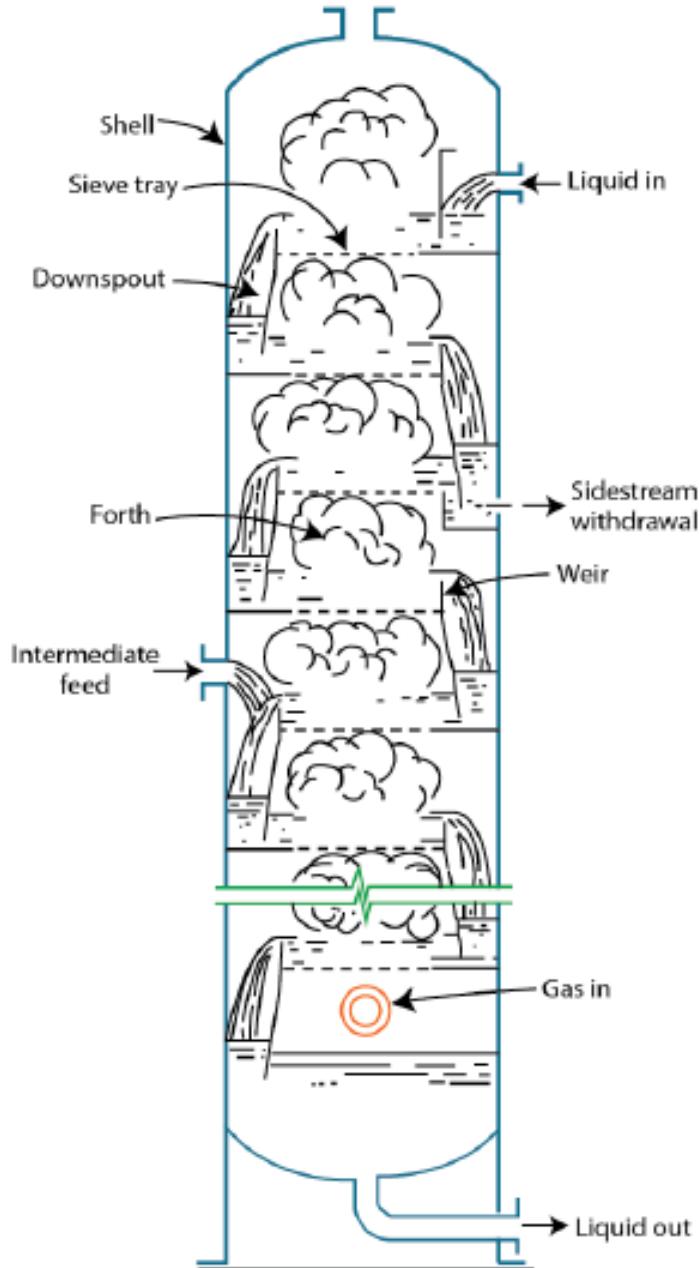
# Example of reactive absorption of CO<sub>2</sub> and amine regeneration



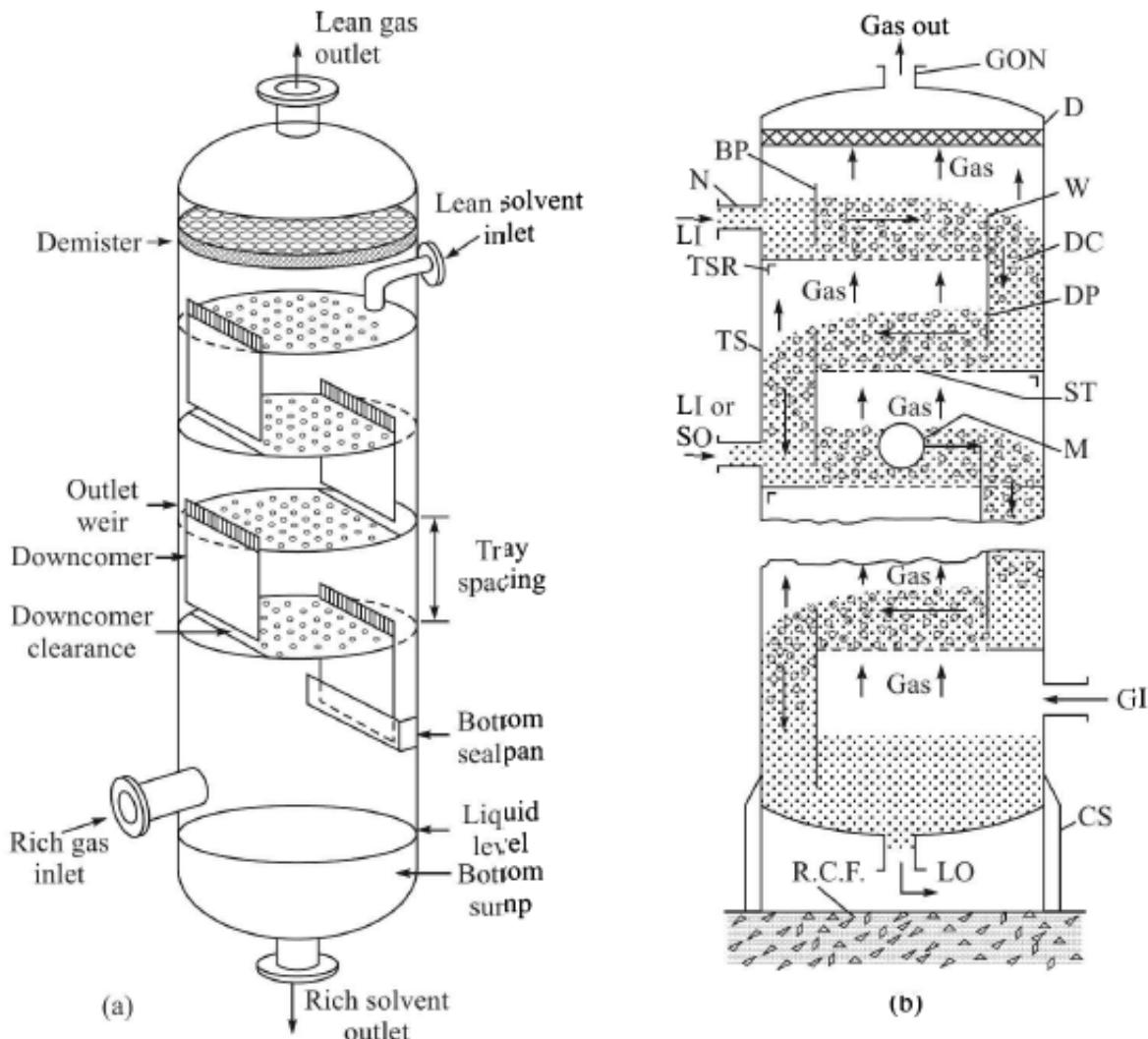
# Common range of values of mass transfer parameters in commercial gas-liquid contactors

Contacting equipment	Superficial gas velocity (m/s at normal condition)	Mass transfer parameters		
		$k_L \times 10^4$ (m/s)	$k_y \times 10^3$ (kmol/s.m <sup>2</sup> .Δy)	$\bar{a}$ (m <sup>2</sup> /m <sup>3</sup> )
Sieve tray	0.02– 0.5	1– 20	0.5–6.0	100–200
Packed column	0.1–1.2	1– 20	0.03–2.0	10–350
Bubble column	0.1–0.3	0.4–3.0	0.5–2.0	50–600
Spray column	0.05–3.0	0.7–1.5	0.5–2.0	10–100
Mechanically agitated contactor	0.05 –3.0	0.3 – 4.0		100–1000

# Schematic diagram of plate contactor

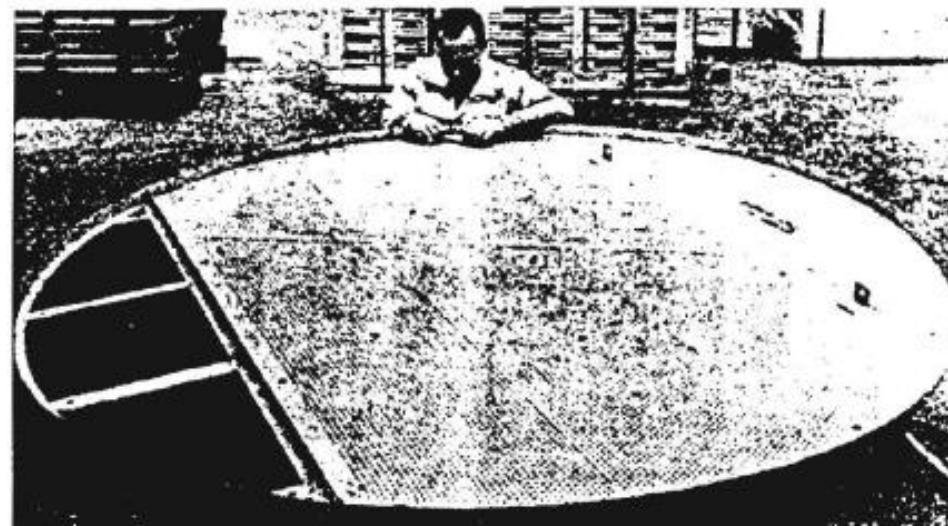
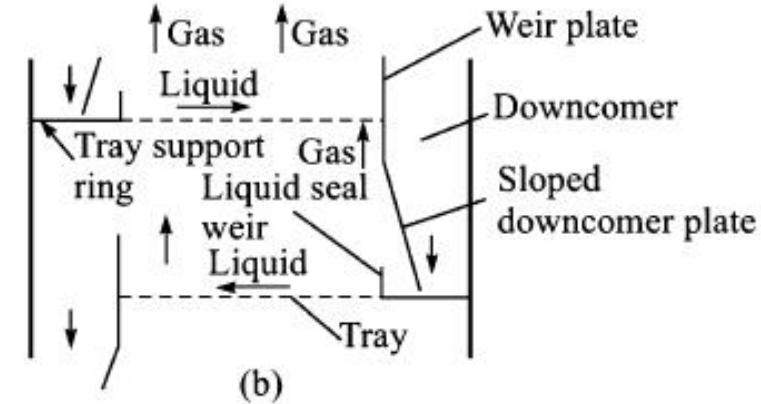
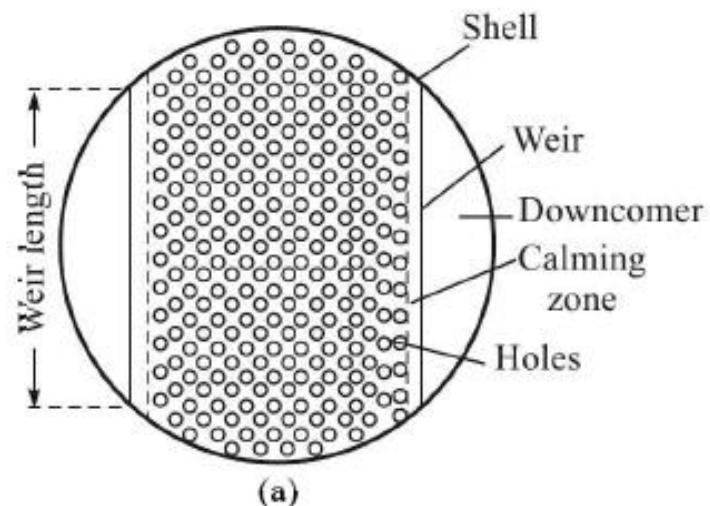


# Sieve tray column



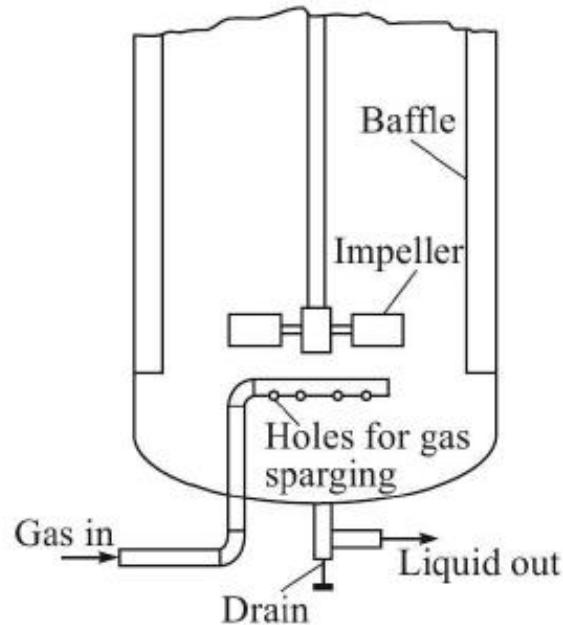
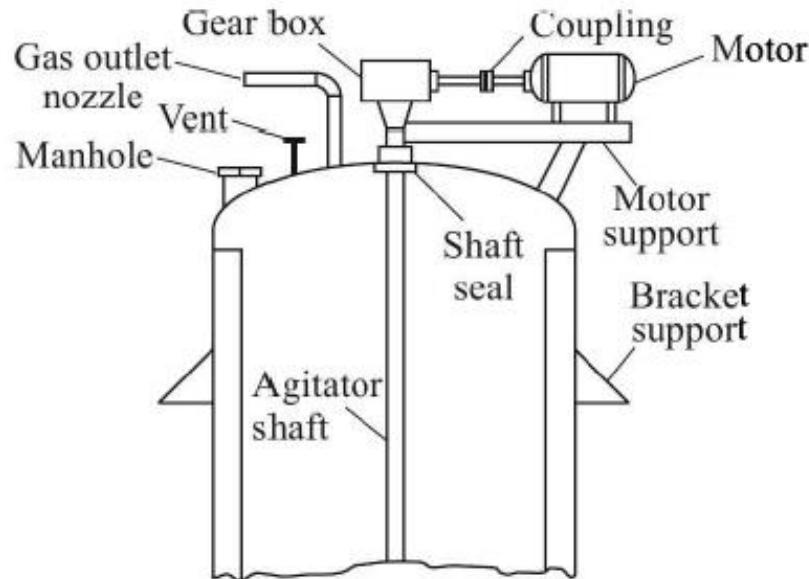
**Figure 5.1** (a) Schematic of a 'sieve tray' column and (b) sectional sketch of a 'sieve tray' column [BP: baffle plate; CS: column support; D: demister; DC: downcomer; DP: downcomer plate; GI: gas inlet; GON: gas outlet nozzle; LI: liquid inlet; LI or SO: liquid inlet or side-stream outlet; M: manhole; N: nozzle; RCF: reinforced concrete foundation; ST: sieve tray; TS: tower shell; TSR: tray-support ring; W: weir].

# Sieve tray layout

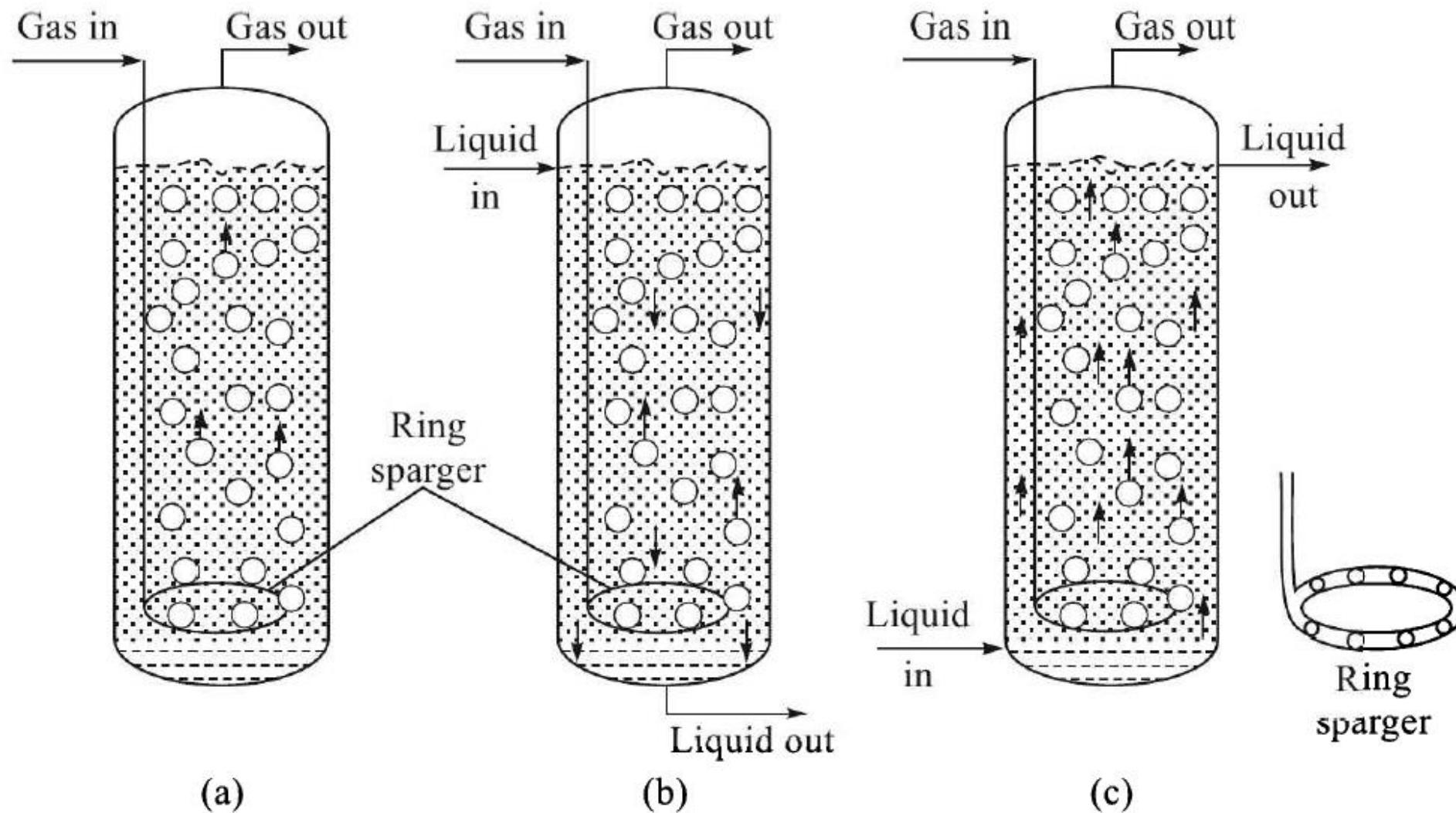


(c)

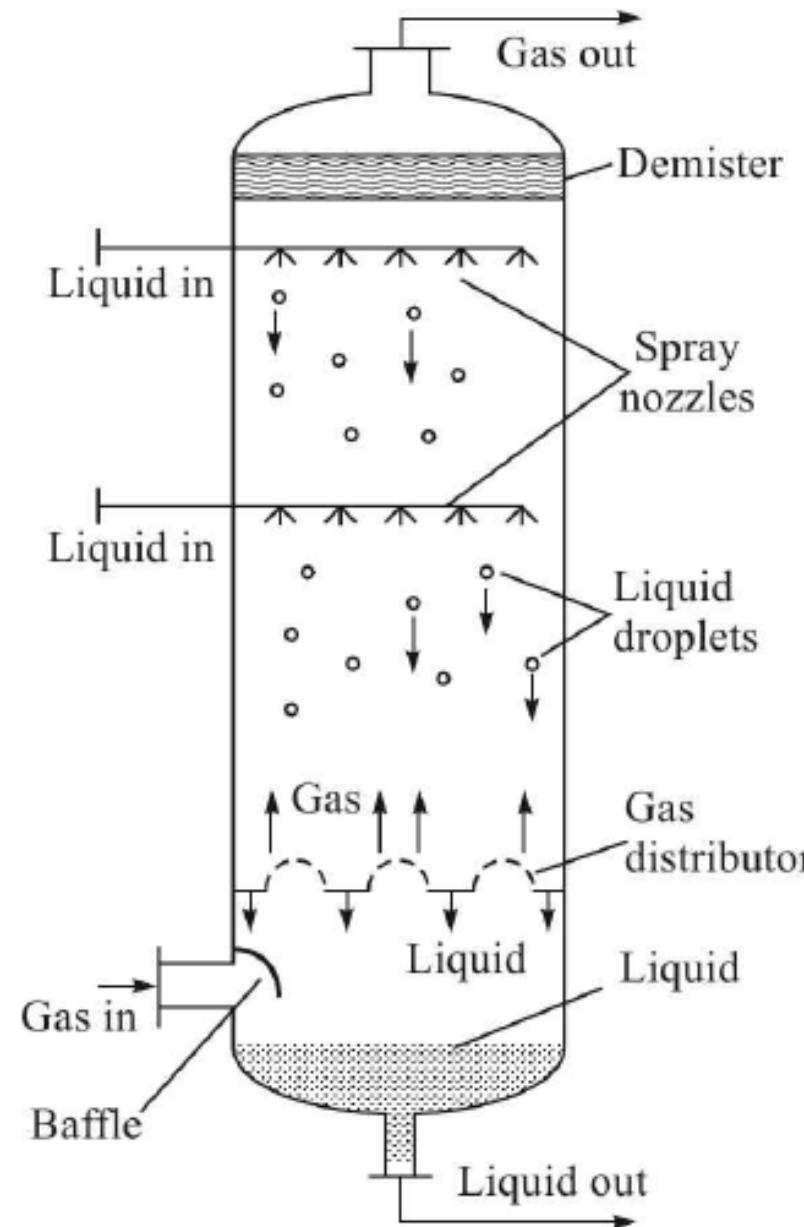
# Agitated vessel for gas absorption



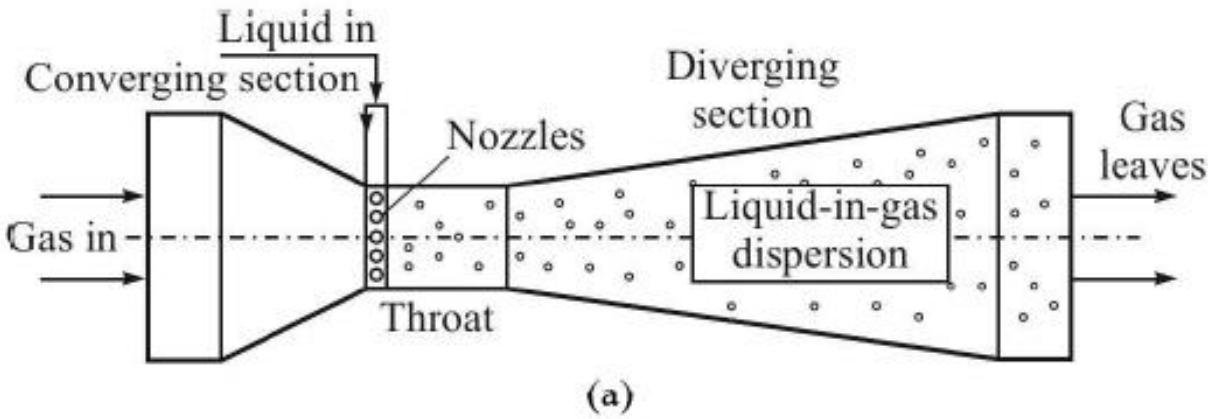
# Bubble columns – batch, countercurrent and cocurrent



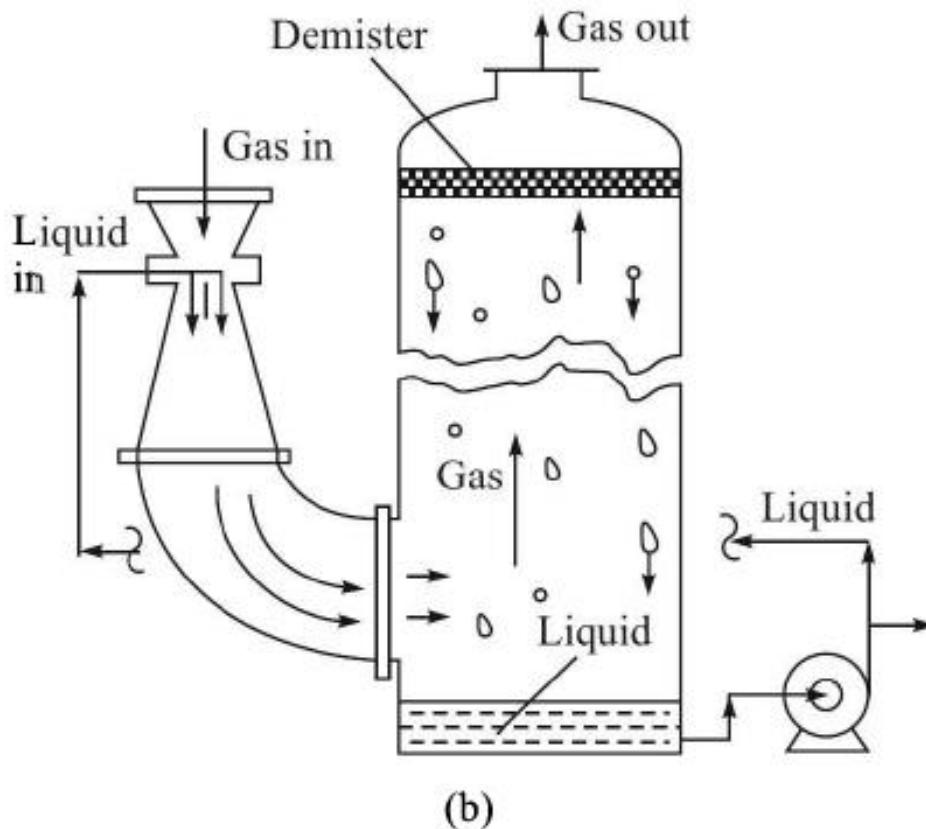
# A two-stage spray tower



# A venturi scrubber and cyclone

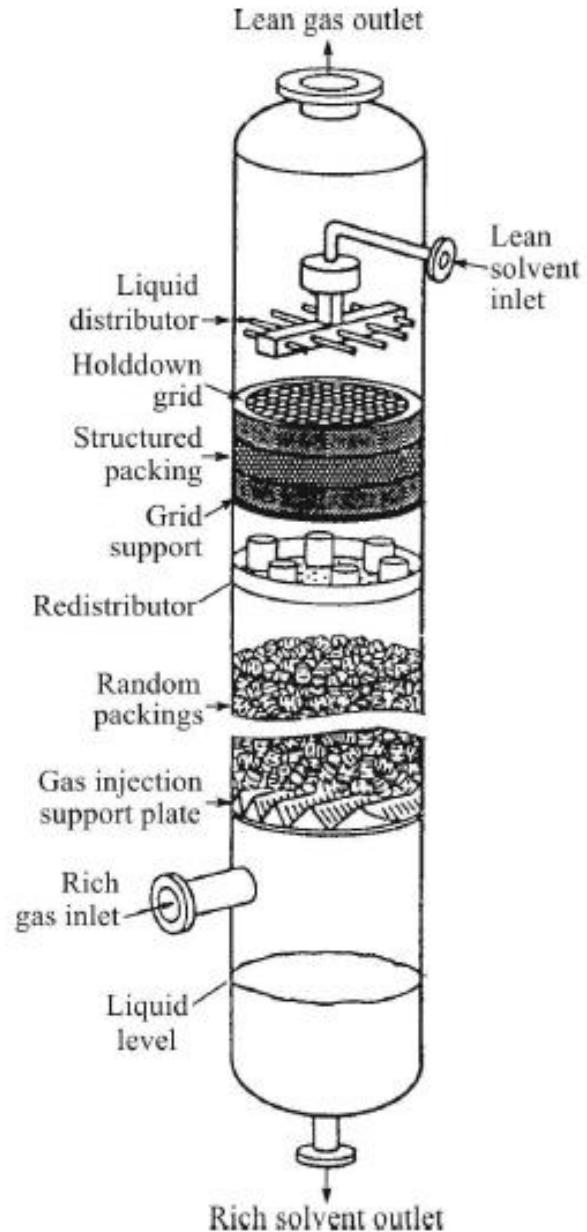


(a)



(b)

# A packed tower for gas-liquid contact



# First- and second-generation random packings



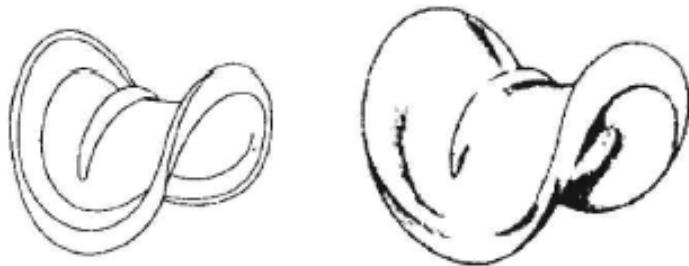
Raschig ring



Lessing ring



Cross-partition ring



Berl saddle



(a) Intalox saddle



(b) Pall ring



(c) Dumped intalox saddles



(d) Plastic pall ring (Glitsch)



(e) Metal 'Flexiring' (Koch Engg.)



(f) Norton 'Hy-Pak' ring (metal).



Plastic Tellerette

# Third-generation random packings



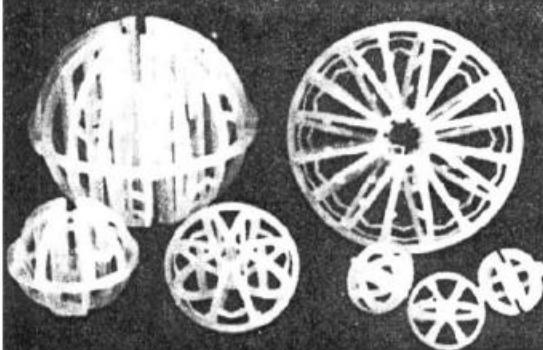
Intalox metal tower packing (IMTP)



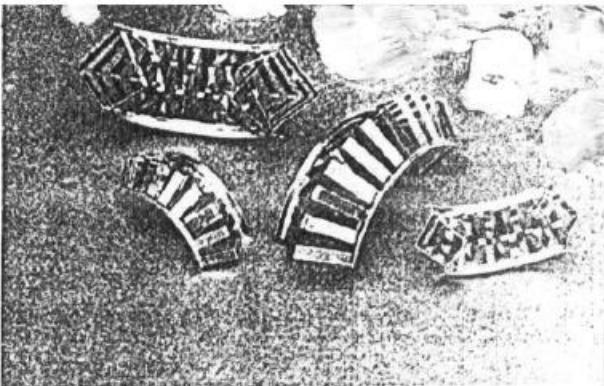
Nutter ring



Cascade Miniring



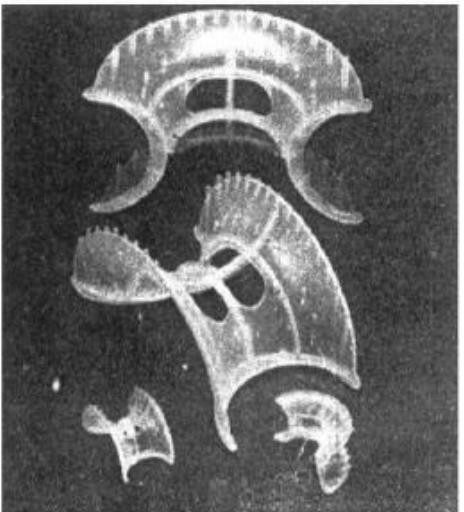
Jaeger 'Tri-packs' high performance packing  
made of corrosion-resistant plastic



Kock 'Fleximax' tower packing



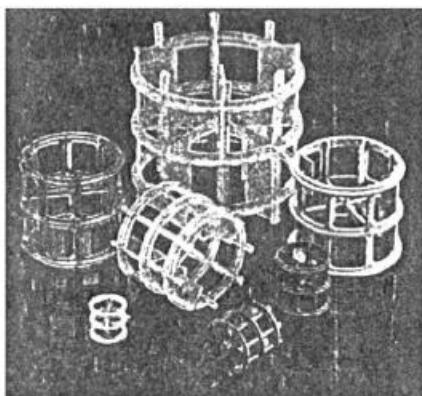
Metal Bialecki ring



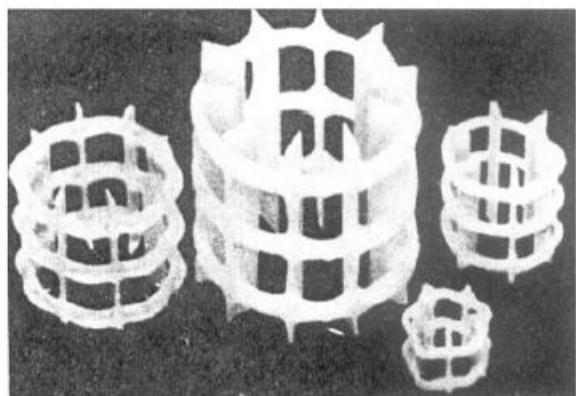
Koch 'Flexisaddles' (plastic)



Cascade Minirings  
(Jaeger)



Hiflow ring (Rauschert Ind.)

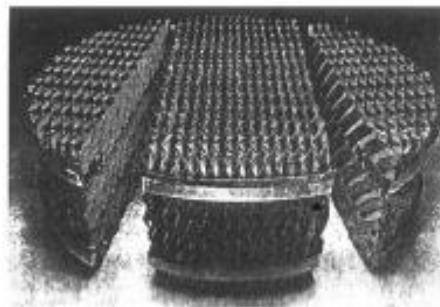


Nor-Pac, Plastic (NSW Corp.)

# Common high-performance structured packings

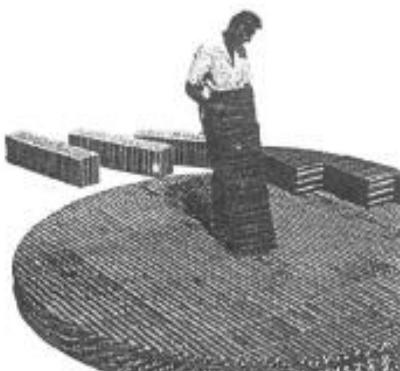


(a)

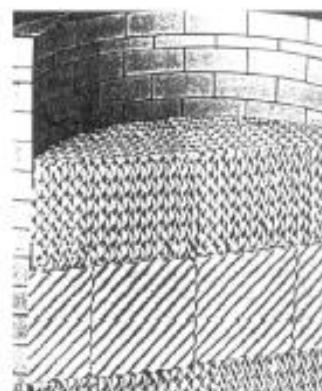


(b)

Intalox high performance corrugated structured packing (made from thin metal sheets).



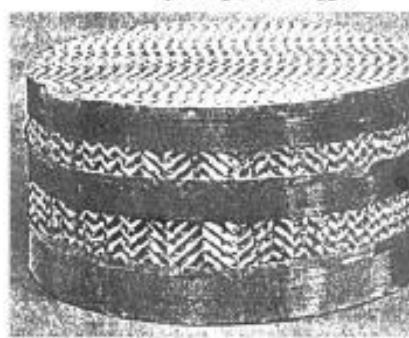
(c) The same as Figure 5.25(a) and (b).



(d) 'Flexeramic' corrugated structured packing (Koch Engg.).

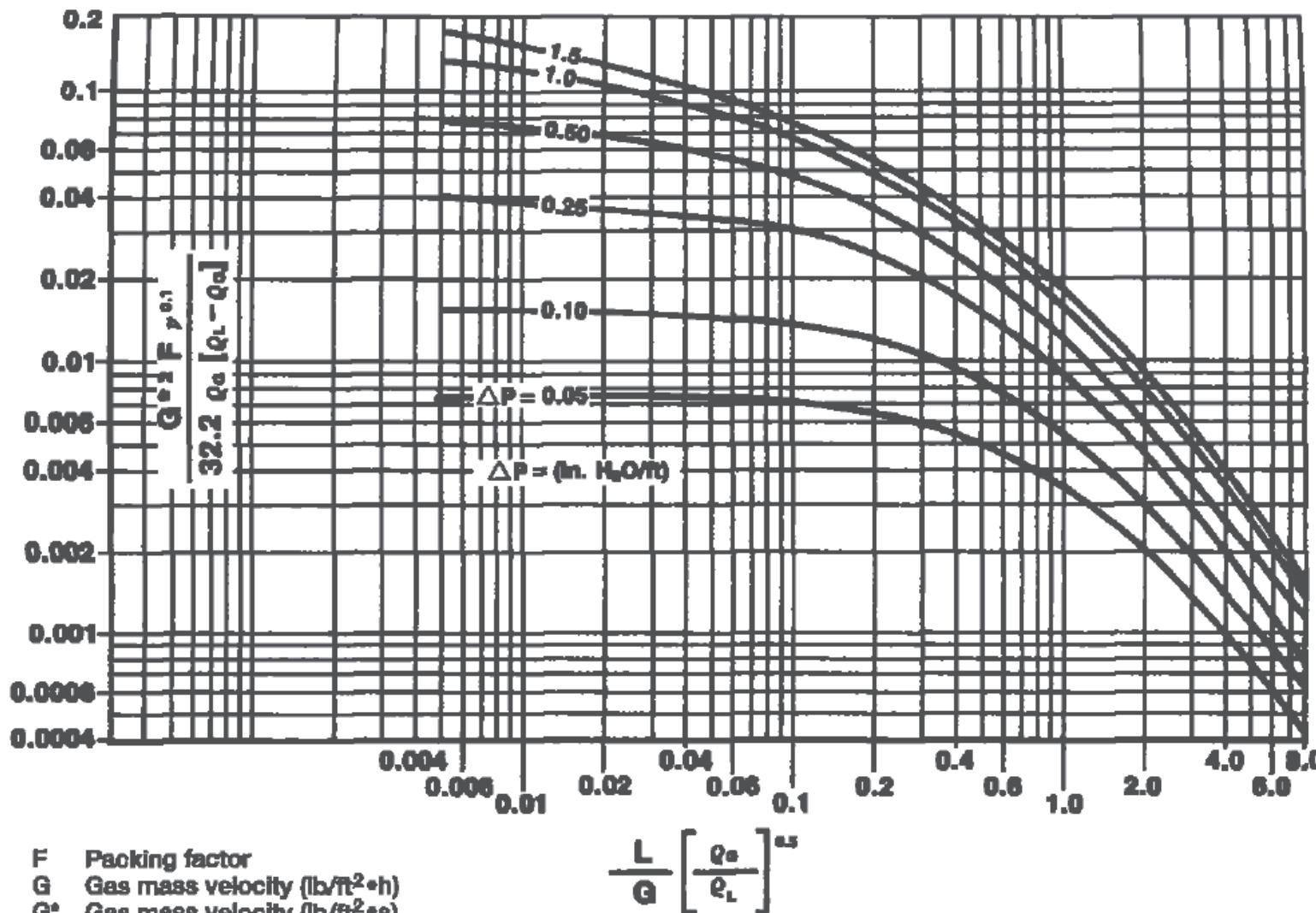


(e) 'Montz B1' Structured packing (Nutter Engg. Corporation).



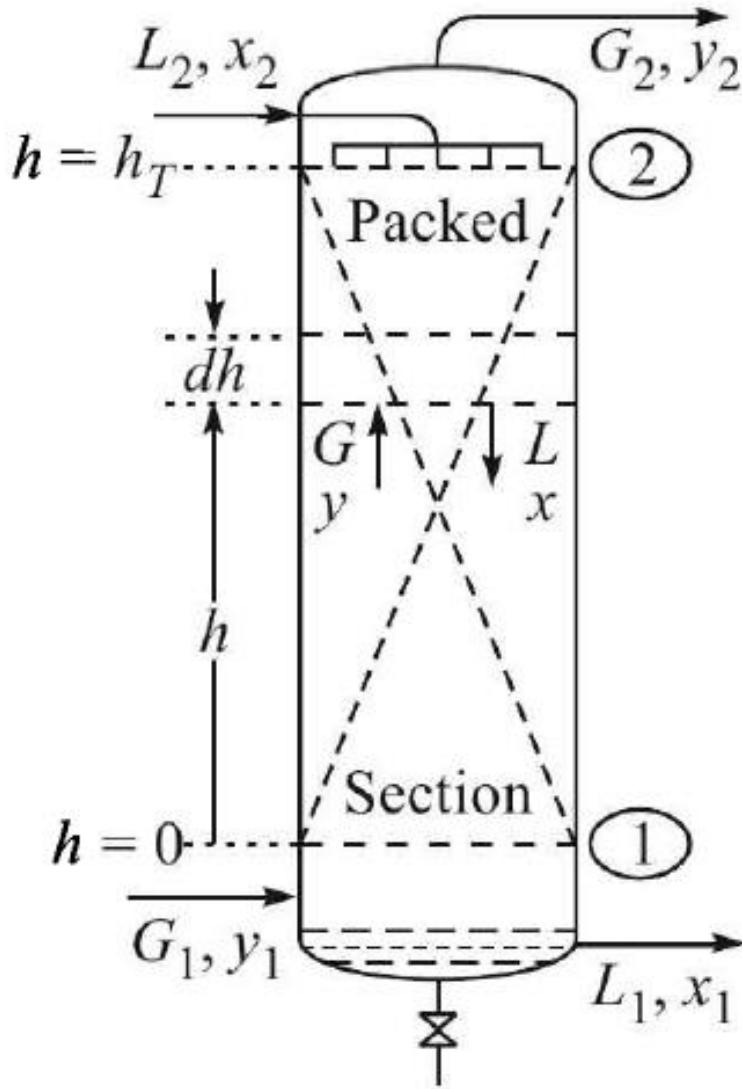
(f) Sulzer wire-gauge packing CY.

# Determination of diameter of packed tower



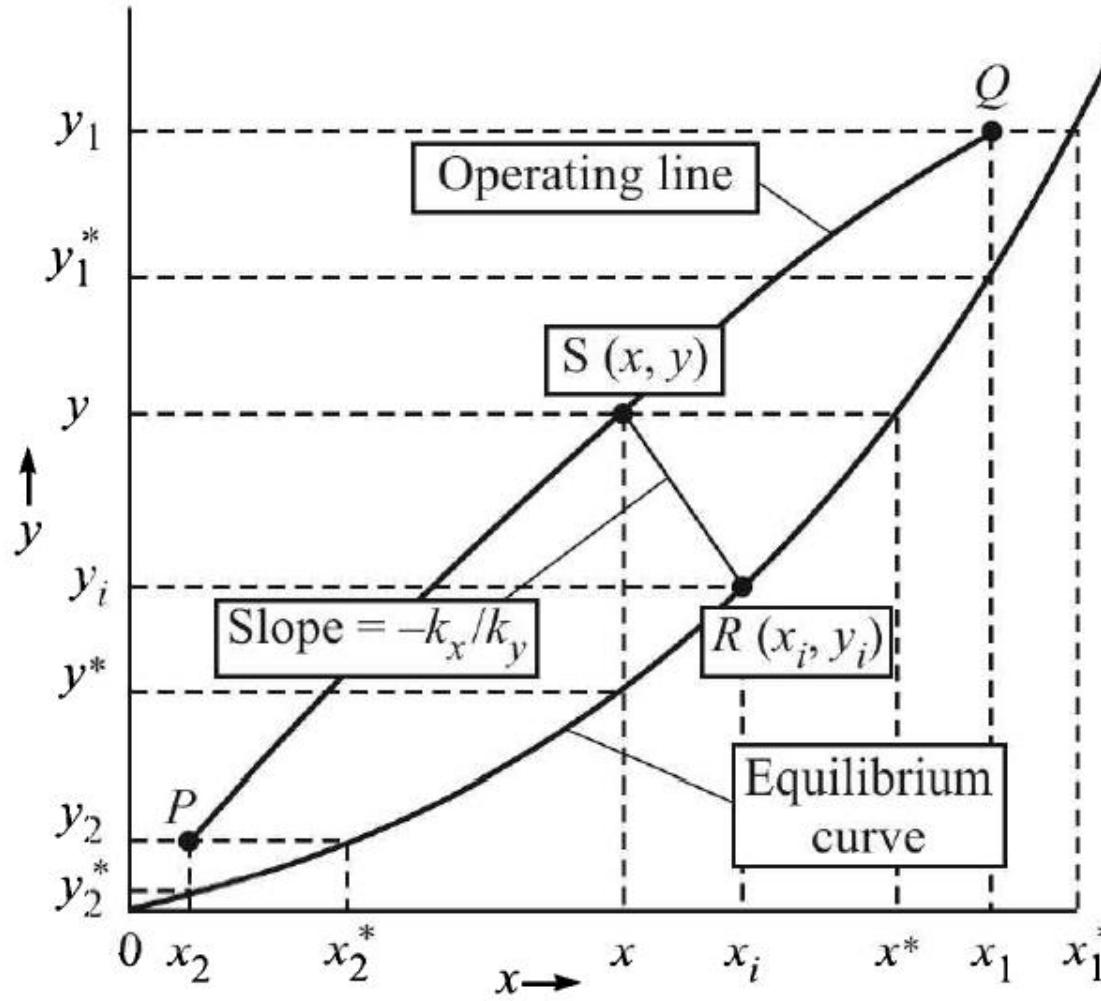
- $F$  Packing factor  
 $G$  Gas mass velocity ( $\text{lb}/\text{ft}^2 \cdot \text{h}$ )  
 $G'$  Gas mass velocity ( $\text{lb}/\text{ft}^2 \cdot \text{s}$ )  
 $L$  Liquid mass velocity ( $\text{lb}/\text{ft}^2 \cdot \text{h}$ )  
 $\nu$  Kinematic liquid viscosity (cst)  
 $\rho_G$  Gas density ( $\text{lb}/\text{ft}^3$ )  
 $\rho_L$  Liquid density ( $\text{lb}/\text{ft}^3$ )

# Differential section of packed column for mass balance



$$h_T = \int_0^{h_T} dh = - \int_{y_1}^{y_2} \frac{G' dy}{k_y \bar{a} (1-y)(y-y_i)} = \int_{y_2}^{y_1} \frac{G' dy}{k_y \bar{a} (1-y)(y-y_i)}$$

# Concentration terms in the equation for packed tower design



$$h_T = \int_{x_2}^{x_1} \frac{L' dx}{k_x \bar{a} (1-x)(x_i-x)} = \int_{y_2}^{y_1} \frac{G' dy}{k_G \bar{a} P (1-y)(y-y_i)} = \int_{x_2}^{x_1} \frac{L' dx}{k_L \bar{a} (C)_{av} (1-x)(x_i-x)}$$

$$h_T = \int_{y_1}^{y_2} \frac{G' dy}{k_y \bar{a} (1-y)(y_i-y)}$$

# Design method based on height of a transfer unit

$$h_T = H_{tG} N_{tG}$$

$$h_T = \frac{G'}{k_y a (1-y)_{iM}} \int_{y_2}^{y_1} \frac{(1-y)_{iM} dy}{(1-y)(y-y_i)} = H_{tG} \int_{y_2}^{y_1} \frac{(1-y)_{iM} dy}{(1-y)(y-y_i)}$$

$$H_{tG} = \frac{G'}{k_y \bar{a} (1-y)_{iM}} = \frac{G'}{k'_y \bar{a}}$$

$$h_T = H_{tL} N_{tL}$$

$$H_{tL} = \frac{L'}{k_x \bar{a} x_{iBM}} = \frac{L'}{k_x \bar{a} (1-x)_{iM}}; \quad N_{tL} = \int_{x_2}^{x_1} \frac{(1-x)_{iM} dx}{(1-x)(x_i - x)}$$

$$(1-x)_{iM} = \frac{(1-x) - (1-x_i)}{\ln \frac{1-x}{1-x_i}}$$

# Expressions for HTUs and NTUs

Driving force	Height of a Transfer Unit (HTU)			Number of Transfer Units (NTU)
	Symbol	DANB	ECD	
$y - y_i$	$H_{IG}$	$\frac{G'}{k_y \bar{a} (1-y)_M}$	$\frac{G'}{K_y' \bar{a}}$	$N_{IG}$ $\int_{y_2}^{y_1} \frac{(1-y)_M dy}{(1-y)(y-y_i)}$
$y - y^*$	$H_{IG}$	$\frac{G'}{K_y \bar{a} (1-y)_M^*}$	$\frac{G'}{K_y' \bar{a}}$	$N_{IG}$ $\int_{y_2}^{y_1} \frac{(1-y)_M^* dy}{(1-y)(y-y^*)}$
$Y - Y^*$	$H_{IG}$	$\frac{G'_s}{K_Y \bar{a}}$	$\frac{G'_s}{K_Y' \bar{a}}$	$N_{IG}$ $\int_{Y_2}^{Y_1} \frac{dY}{(Y - Y^*)}$
$x_i - x$	$H_{IL}$	$\frac{L'}{k_x \bar{a} (1-x)_M}$	$\frac{L'}{K_x' \bar{a}}$	$N_{IL}$ $\int_{x_2}^{x_1} \frac{(1-x)_M dx}{(1-x)(x_i - x)}$
$x^* - x$	$H_{IL}$	$\frac{L'}{K_x \bar{a} (1-x)_M^*}$	$\frac{L'}{K_x' \bar{a}}$	$N_{IL}$ $\int_{x_2}^{x_1} \frac{(1-x)_M^* dx}{(1-x)(x^* - x)}$
$X^* - X$	$H_{IL}$	$\frac{L'_s}{K_X \bar{a}}$	$\frac{L'_s}{K_X' \bar{a}}$	$N_{IL}$ $\int_{X_2}^{X_1} \frac{dX}{(X^* - X)}$

$$(1-y)_M = \frac{(1-y_i) - (1-y)}{\ln[(1-y_i)/(1-y)]}; \quad (1-y)_M^* = \frac{(1-y^*) - (1-y)}{\ln[(1-y^*)/(1-y)]}$$

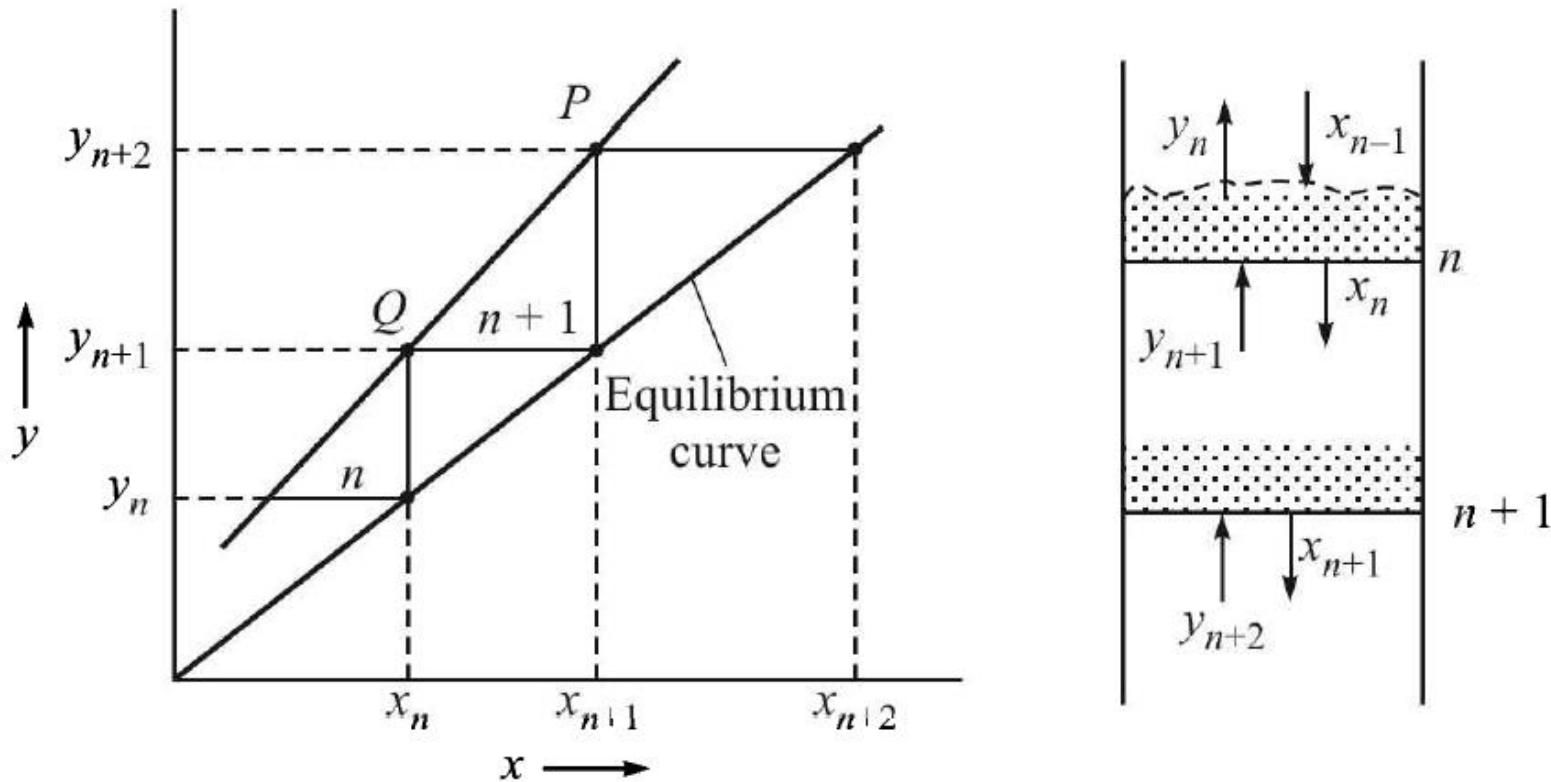
DANB: Diffusion of A through non-diffusing B; ECD: Equimolar counterdiffusion of A and B.

# Analytical determination of number of overall transfer units

$$N_{tOG} = \frac{\ln \left[ \left( \frac{y_1 - mx_2}{y_2 - mx_2} \right) (1 - \bar{S}) + \bar{S} \right]}{1 - \bar{S}}; \quad \bar{S} = 1/\bar{A} = mG/L$$

# Concept of height equivalent to theoretical plate (HETP)

$HETP = h_T/N_T$ ;  $h_T$  = height of packing, and  $N_T$  = number of ideal trays required



$$HETP = H_{tOG} \frac{\ln(mG'/L')}{(mG'/L') - 1} = H_{tOG} \frac{\ln(\bar{S})}{\bar{S} - 1}$$

# Other examples of reactive absorption

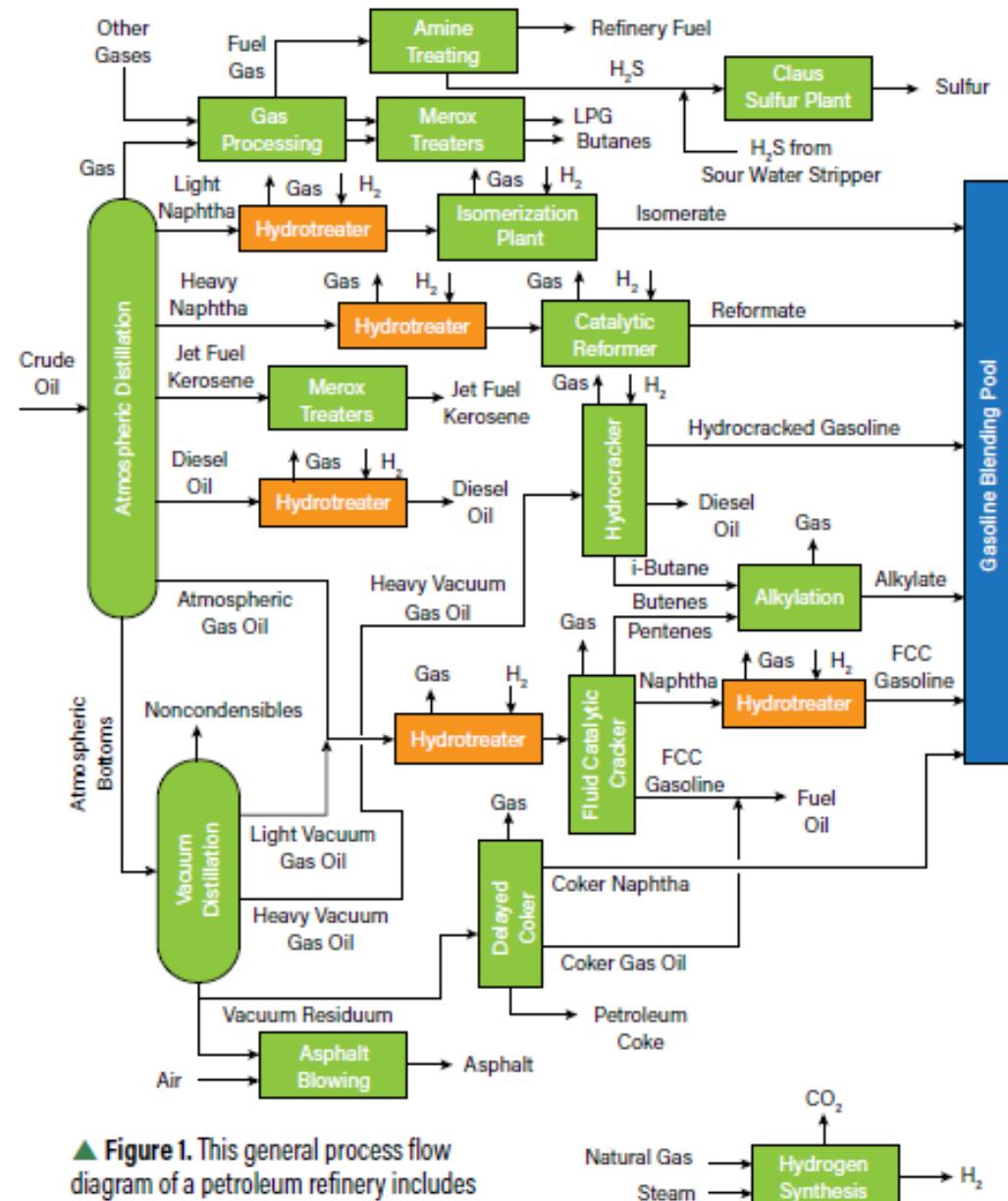
Aim of the process	Examples	Application area
Removal of harmful substances	<ul style="list-style-type: none"><li>• Coke oven gas purification</li><li>• Carbon dioxide removal by amines/ amine blends/ hot potassium carbonate solutions</li><li>• NO<sub>x</sub> removal</li></ul>	Gas purification
Retrieval/regeneration of valuable substances or non-reacted reactants	<ul style="list-style-type: none"><li>• Solvent regeneration</li></ul>	Gas separation
Production/preparation of particular products	<ul style="list-style-type: none"><li>• Sulfuric and nitric acid manufacture</li><li>• Formaldehyde preparation</li></ul>	Chemical synthesis
Water removal	<ul style="list-style-type: none"><li>• Water removal from natural gas</li><li>• Air drying</li></ul>	Gas drying
Conditioning of gas streams	<ul style="list-style-type: none"><li>• Synthesis gas conditioning</li></ul>	Gas separation/ gas purification
Separation of substances	<ul style="list-style-type: none"><li>• Olefin/paraffin separation</li></ul>	Separation of organic components

# **ENVIRONMENTAL ENGINEERING**

## **AIR POLLUTION CONTROL – SULFIDE COMPOUNDS IN GASES**

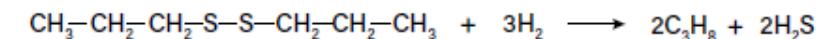
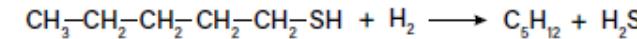
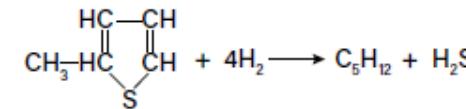
# **ENVIRONMENTAL ENGINEERING**

## **AIR POLLUTION CONTROL – SULFIDE COMPOUNDS IN GASES**

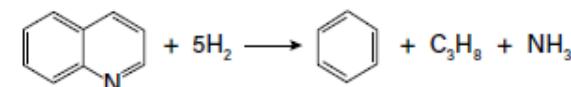
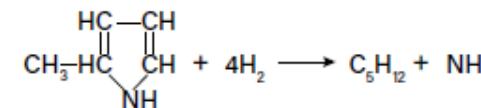


▲ Figure 1. This general process flow diagram of a petroleum refinery includes several hydrotreating units.

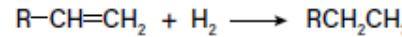
### Desulfurization



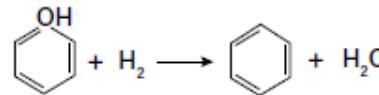
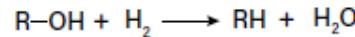
### Denitration



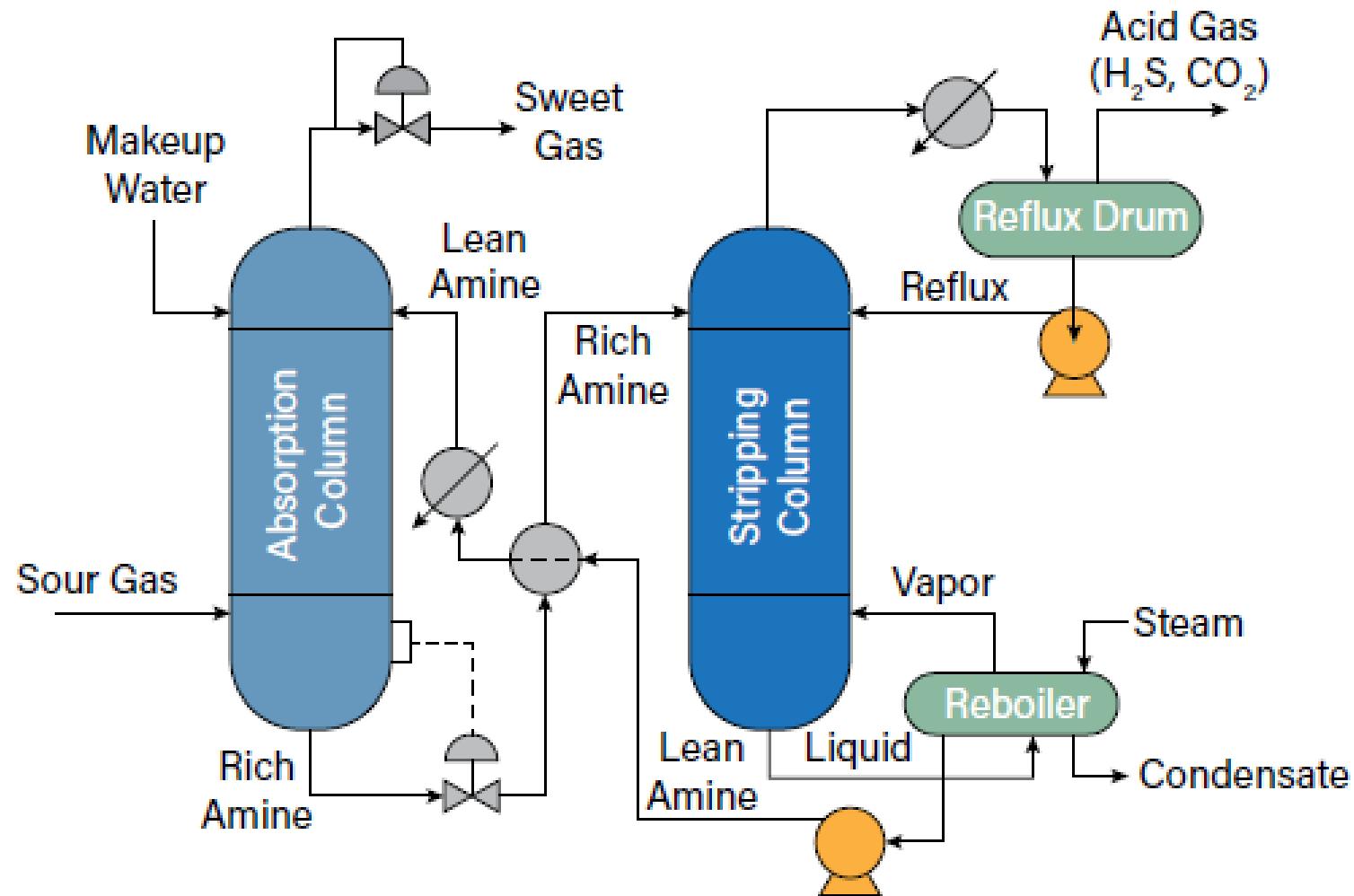
### Hydrocarbon Saturation



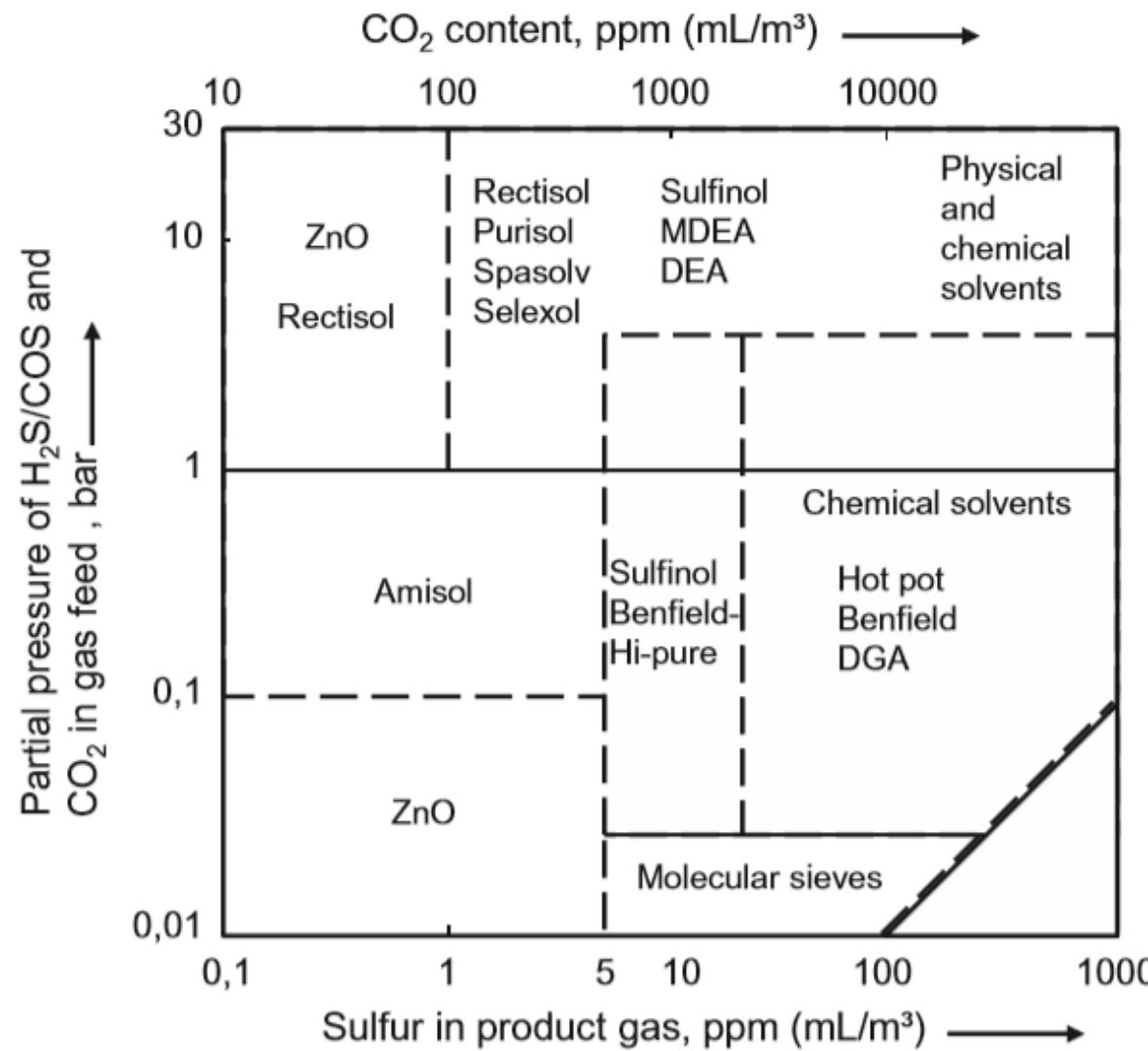
### Oxygen Removal



# Amine gas treating process



# Simultaneous H<sub>2</sub>S/COS and CO<sub>2</sub> Removal from Refinery Offgas



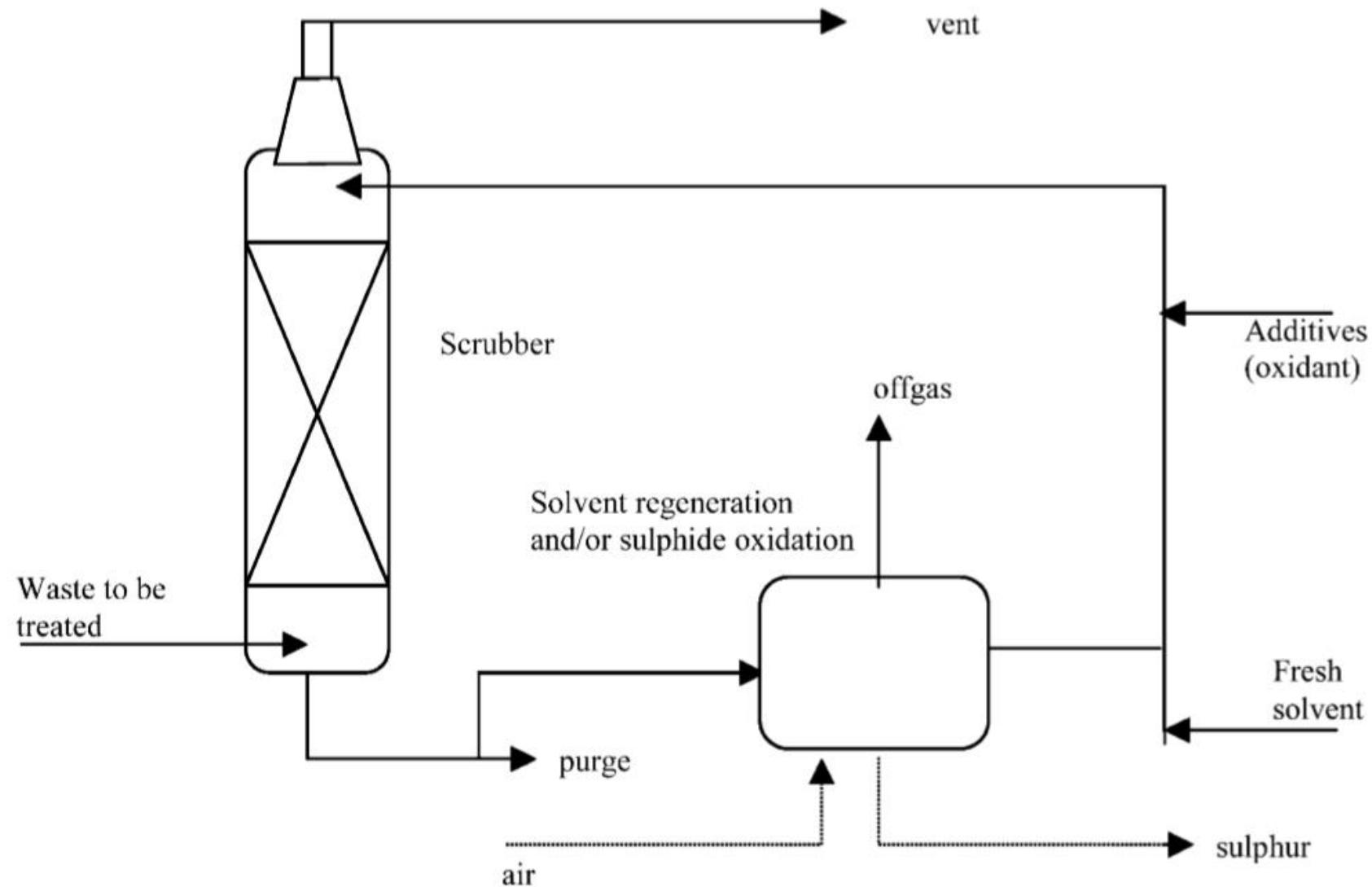
# Processes for Capturing CO<sub>2</sub>/H<sub>2</sub>S

Process	Licensor	Solvent
Result	CB&I TPA	MDEA or formulated MDEA
ADIP	Shell Global Solutions International B.V.	DIPA or MDEA
ADIP-X	Shell Global Solutions International B.V.	MDEA + additive
Advanced amines	Prosernat-IFP Group Technologies	High load DEA, selective MDEA, activated MDEA
aMDEA process	BASF AG	MDEA
Amine Guard FS	UOP LLC	Ucarsol (MDEA-based solvent)
Benfield	UOP LLC	Hot potassium carbonate
Fluor improved Econamine	Fluor Enterprises, Inc.	DGA

Summary of processes for purification of gases from sulphide compounds

	Primary process	Secondary process	Process name	Product
Sulphur recovery	Scrubbing/regeneration			H <sub>2</sub> S (and other sulphide compounds)
	Scrubbing/regeneration	Catalytic oxidation	Claus-type processes	Sulphur
	Scrubbing/regeneration	Chemical oxidation	Iron-redox processes	Sulphur
	Scrubbing/regeneration	Microbiological oxidation	Shell-TIOPAQ	Sulphur
	Condensation			Organosulphur compounds
	Membrane separation			H <sub>2</sub> S
Destruction	Thermal oxidation			SO <sub>2</sub>
	Catalytic oxidation			SO <sub>2</sub>
	Scrubbing	Oxidation	ICI ODORGARD	Sulphate solution
	Absorption	Oxidation		SO <sub>2</sub> or sulphur
	Biofiltration			

# Waste gas treatment by scrubbing and oxidation

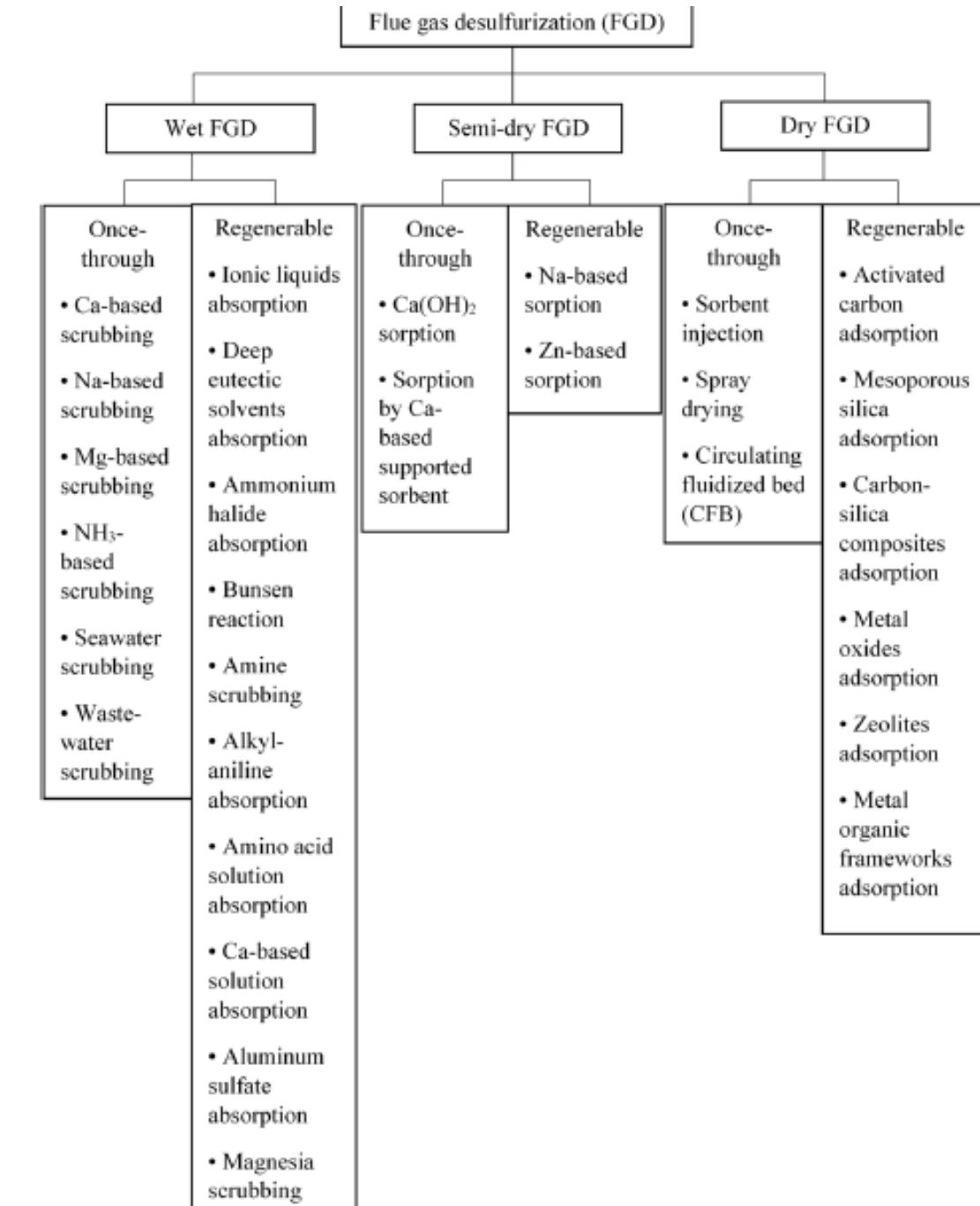


# **ENVIRONMENTAL ENGINEERING**

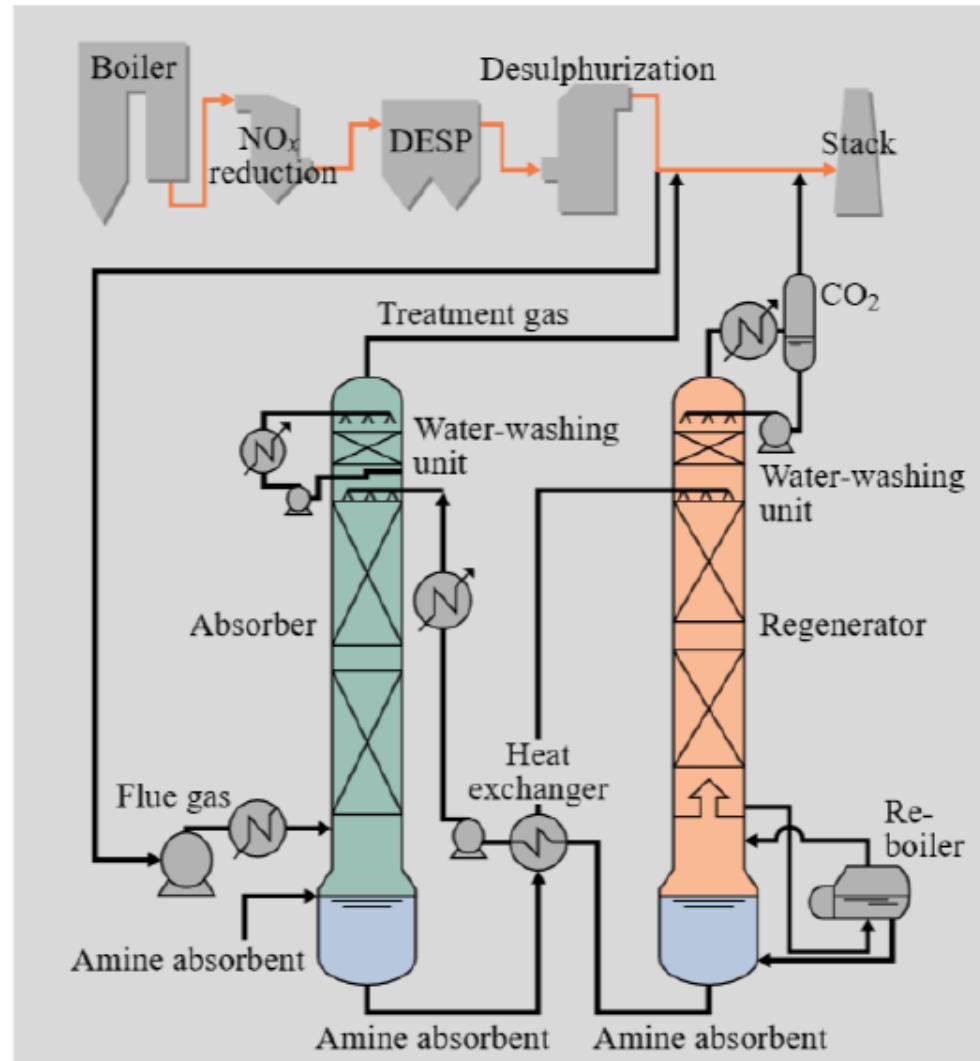
## **AIR POLLUTION CONTROL – SO<sub>x</sub>**

# Methods for reducing SO<sub>2</sub> emissions

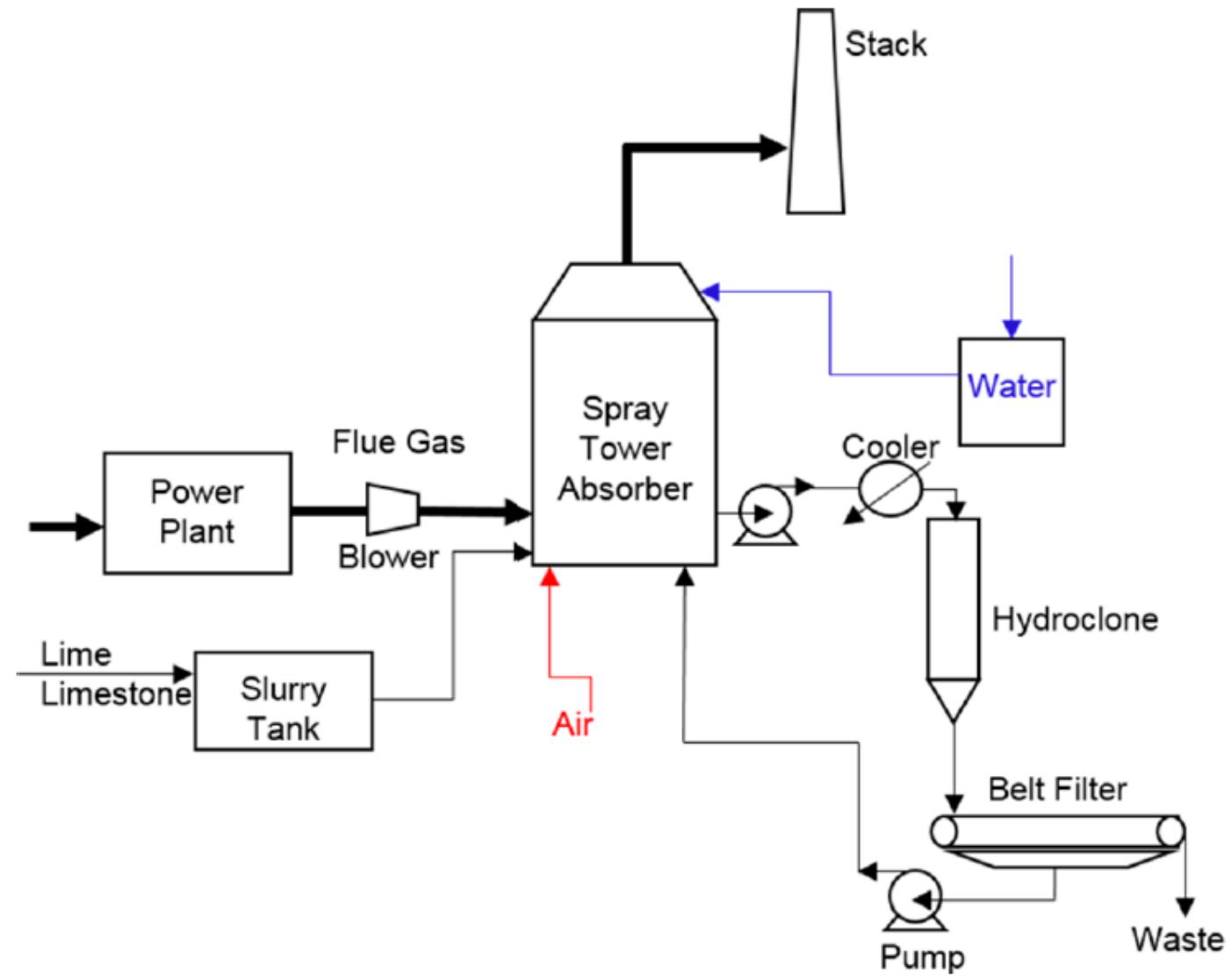
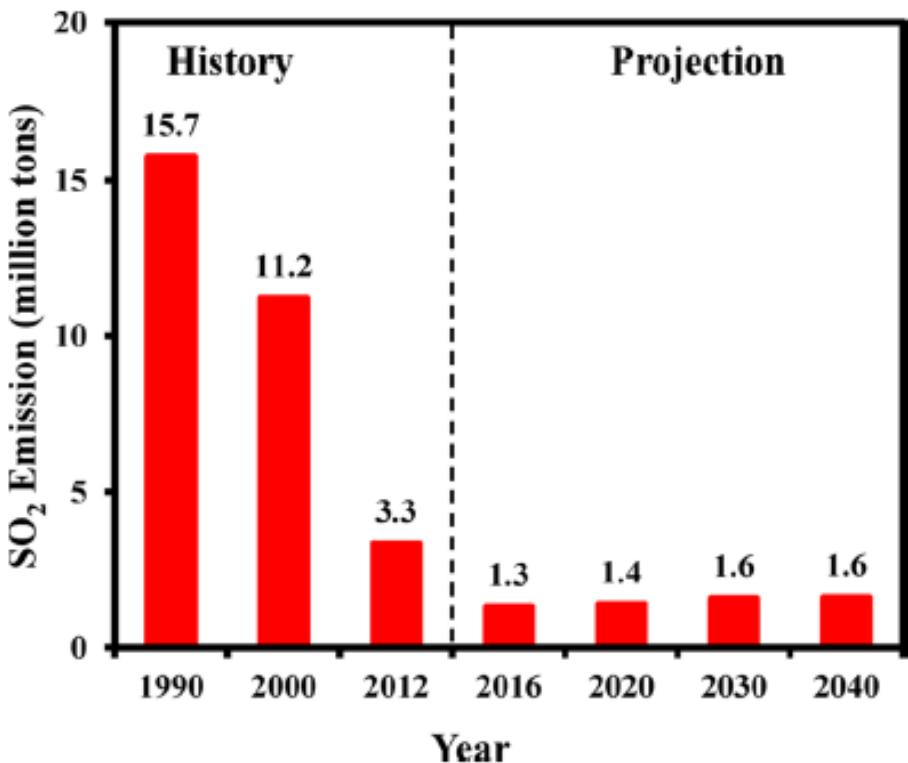
Method	Advantages	Disadvantages
Cleaner fuel	Lower sulfur content in fuel, lower SO <sub>2</sub> emission	High production cost, dependency on finite resource
Sulfur recovery unit	Production of saleable sulfur	Corrosion of treatment equipment due to presence of toxic gases, requirement of rich H <sub>2</sub> S stream
Coal washing	Longer fuel combustion, direct reduction in SO <sub>2</sub> emission	Higher operational cost, possible operational problem due to fuel properties alteration
Flue gas desulfurization (FGD)	Recycling of sorbent and reduction in waste handling (regenerative method), very high removal efficiency (wet method)	Wet method: visible plume, large area requirement Dry method: lower removal efficiency compared with wet method
Biological technologies	High efficiency, cost-effectiveness, convenient operation	High dependency on water, significant reduction of SO <sub>2</sub> removal in low water condition
Electron beam irradiation	High efficiency, resulting product can be used as a fertilizer	High cost and energy consumption, high safety protection required
Pulse corona discharge	No requirement for electron accelerator or high protection	Immature technology for SO <sub>2</sub> removal



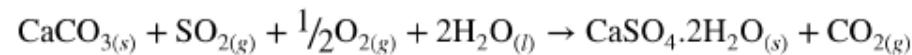
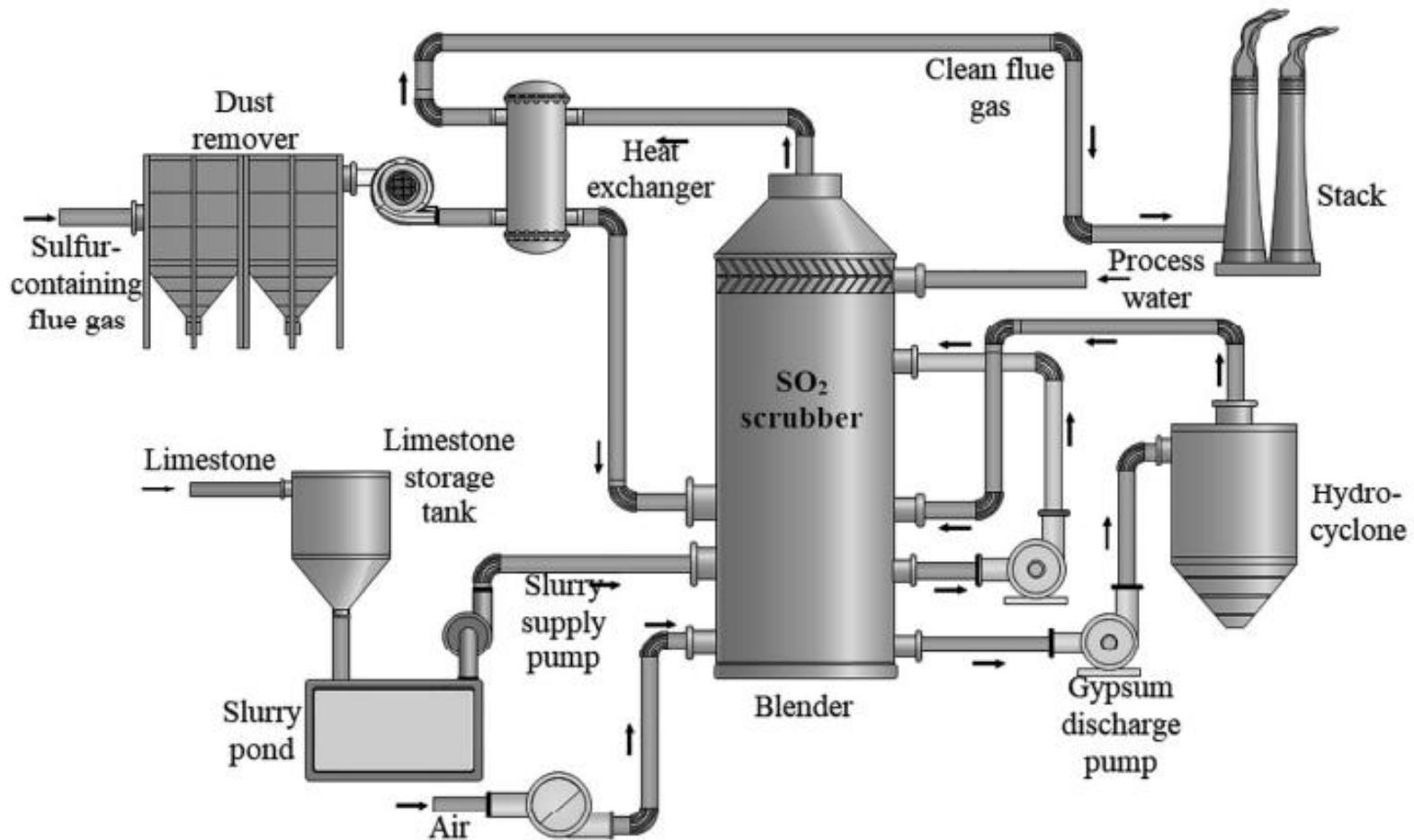
# Flue Gas Cleaning (DeNOx, DeSOx and ESP) in Power Plant



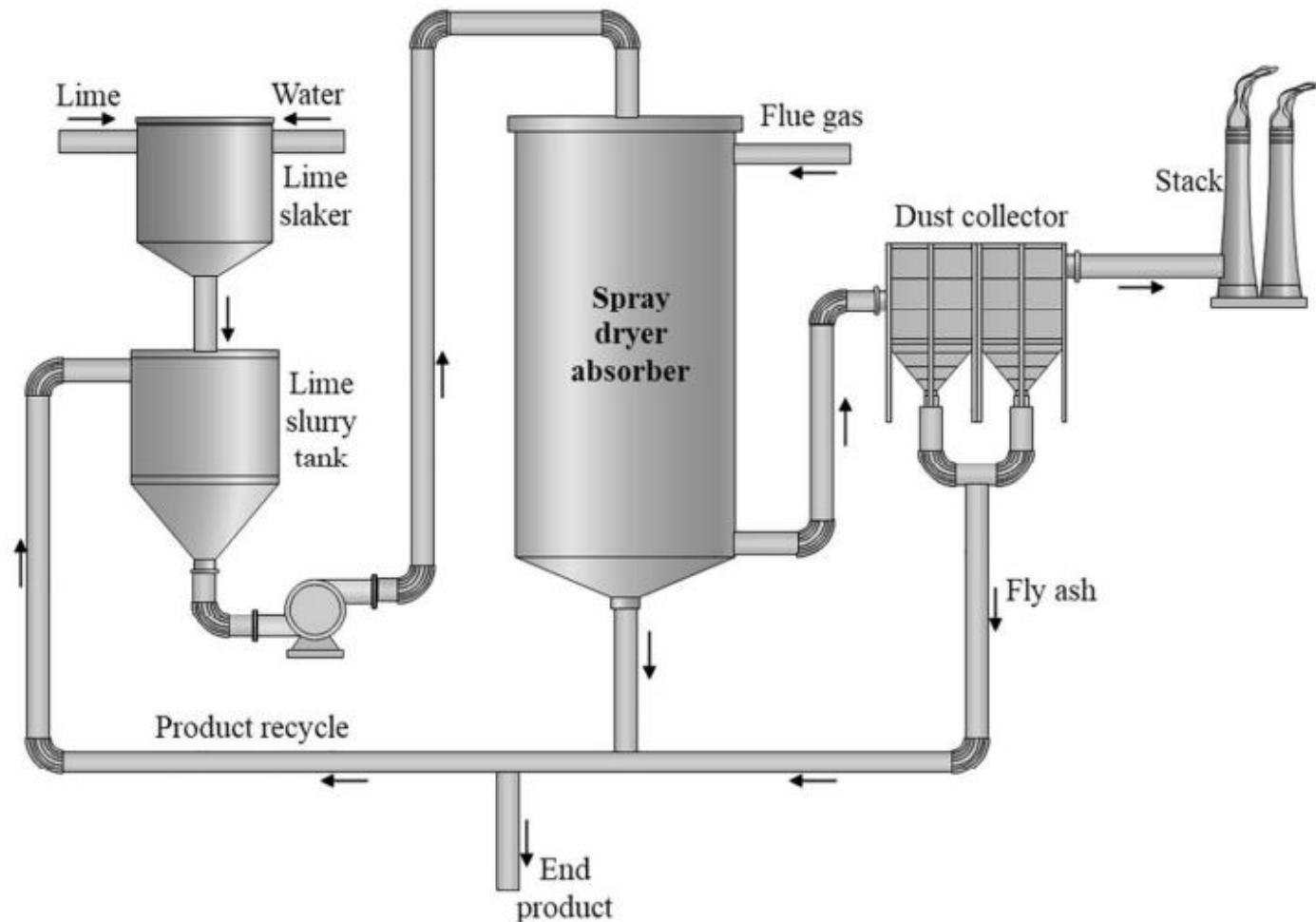
# $\text{SO}_2$ Emissions from Electricity Generation and Wet FGD Process



# Typical Limestone Wet FGD System

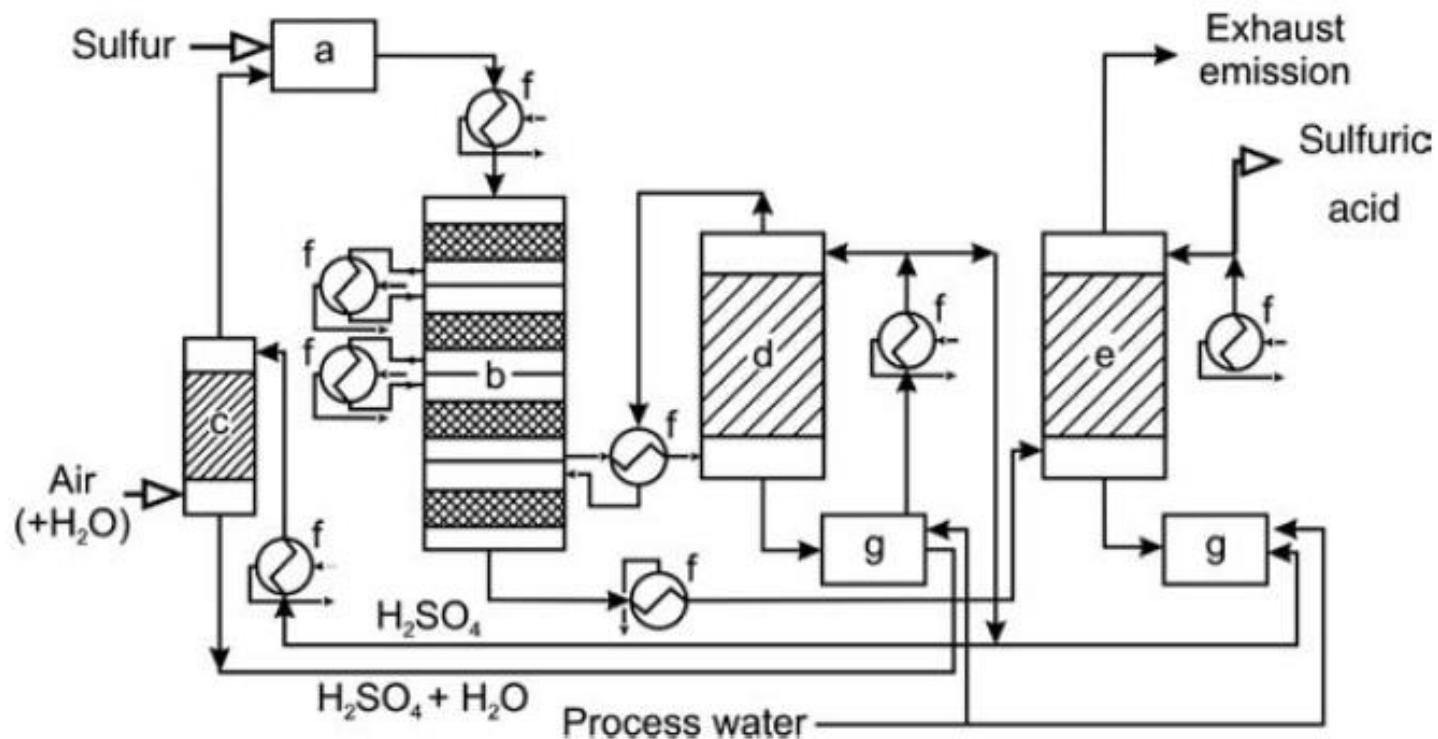


# Lime Spray Drying FGD Process



# Sulfuric acid production

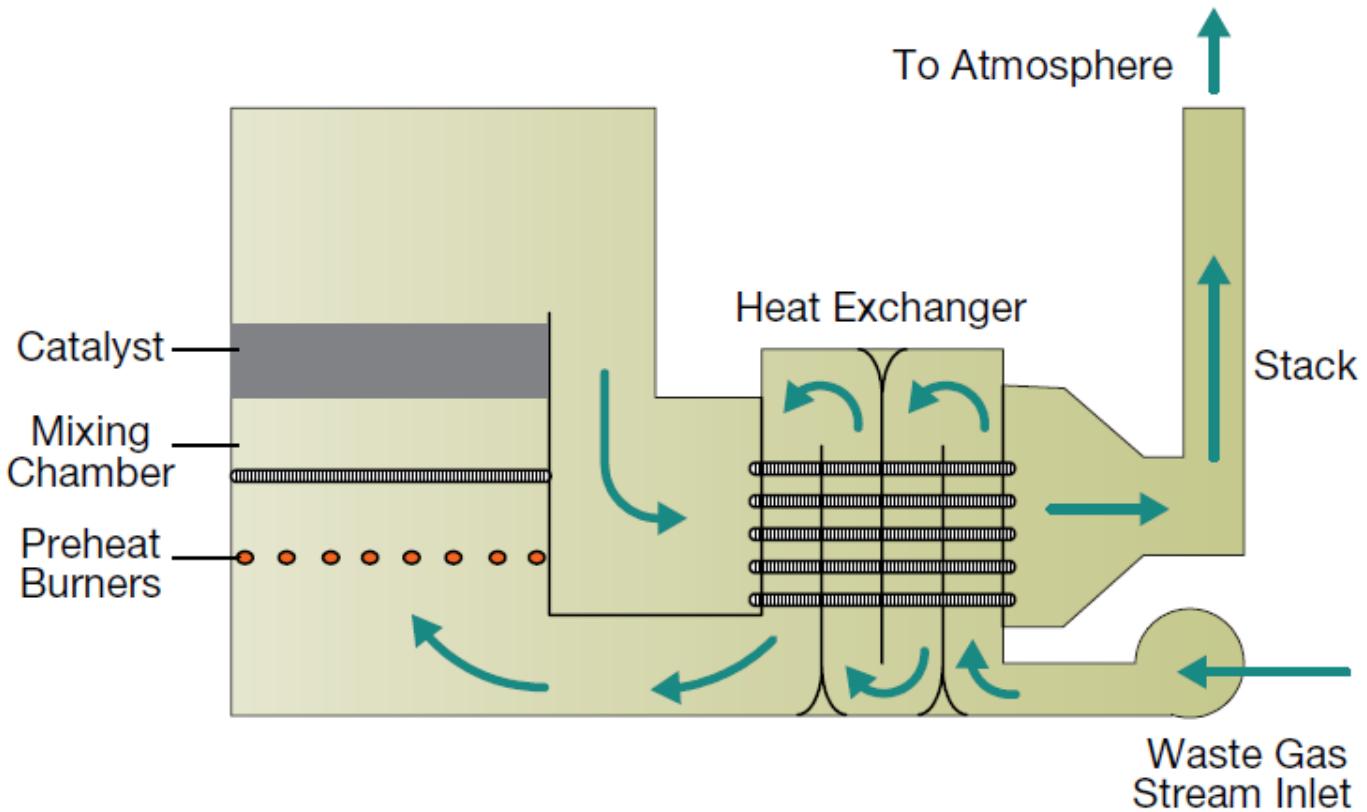
Figure 6.3.13 Simplified flow sheet of double absorption sulfuric acid plant; (a) combustion chamber for oxidation of sulfur, (b) reactor with four adiabatic beds, (c) dryer for air, (d) intermediate absorption of  $\text{SO}_3$ , (e) final absorption of  $\text{SO}_3$ , (f) heat exchanger, and (g) tank for sulfuric acid. Adapted from Baerns *et al.*, 2006).



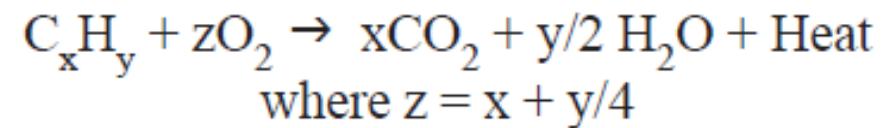
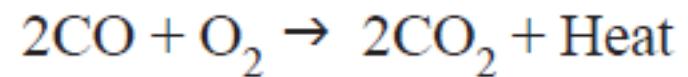
# **ENVIRONMENTAL ENGINEERING**

**AIR POLLUTION CONTROL – NO<sub>x</sub>, CO, VOC**

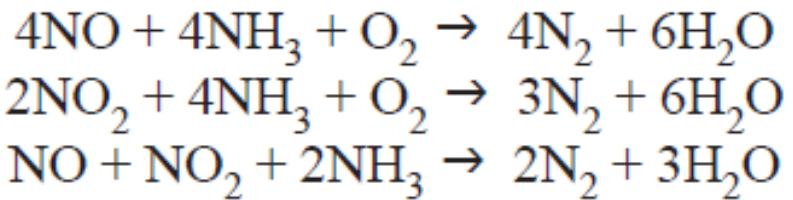
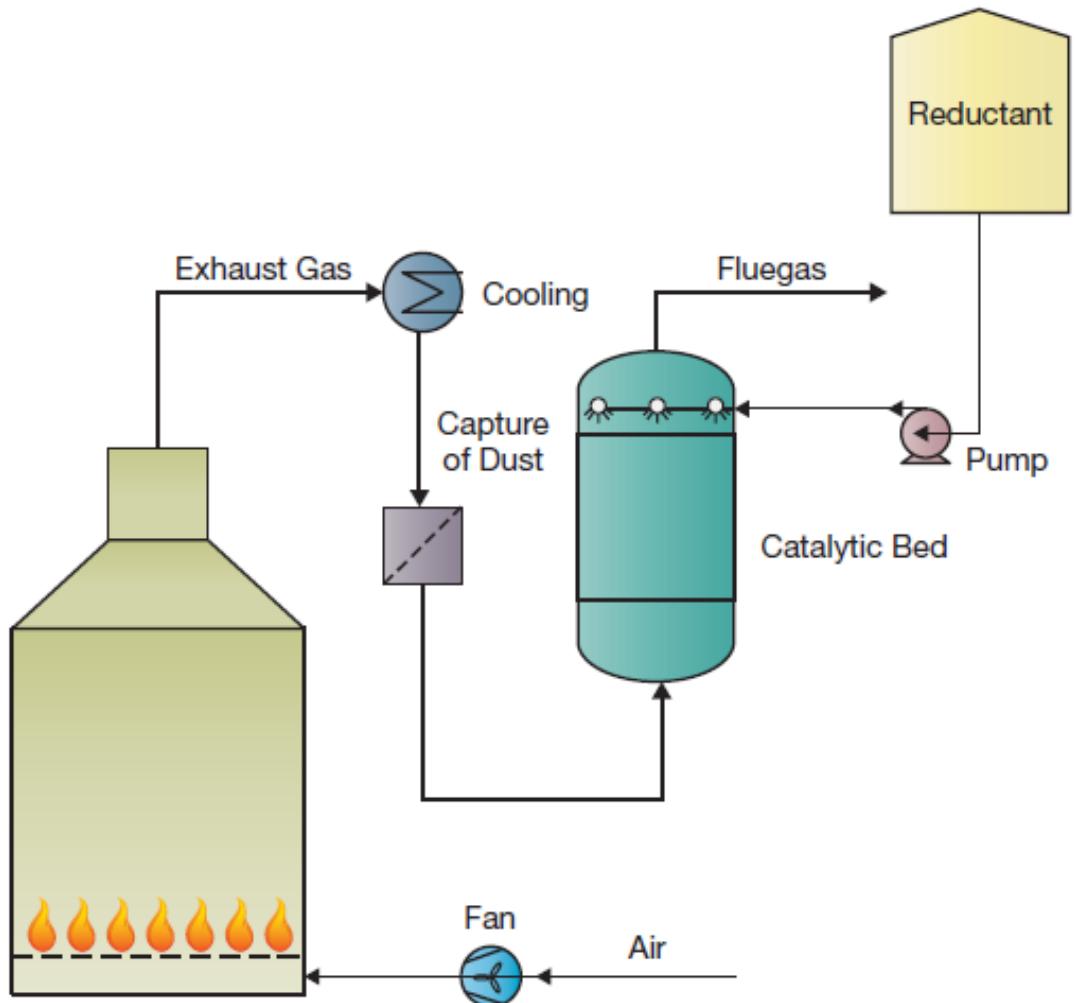
## Catalysis for Air Pollution Control – Catalytic Oxidation



▲ **Figure 1.** To ensure complete oxidation in a catalytic oxidizer, the waste gas stream is preheated in a heat exchanger and mixed thoroughly with oxygen before it enters the oxidation catalyst bed.

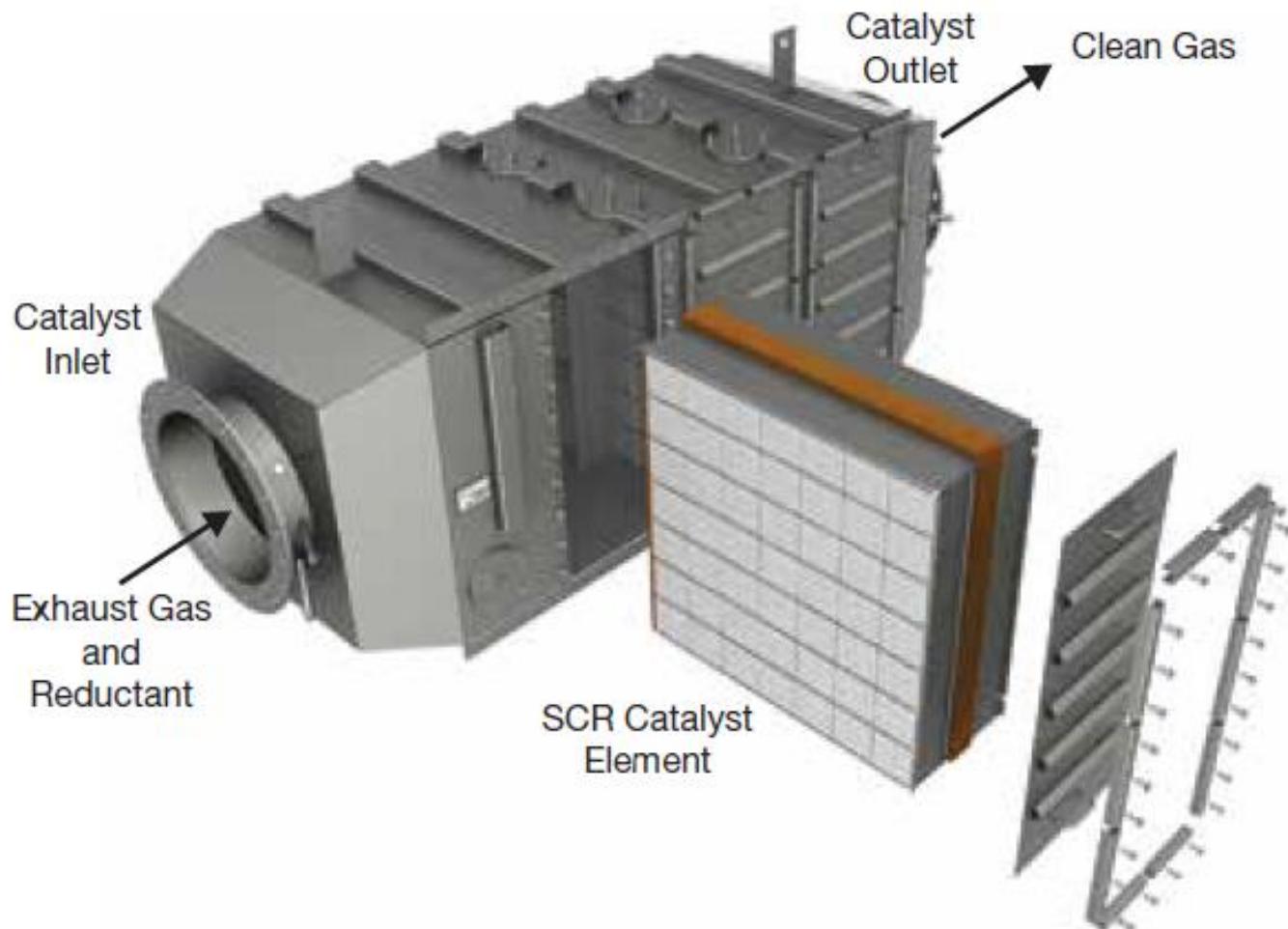


## Catalysis for Air Pollution Control – Selective Catalytic Reduction



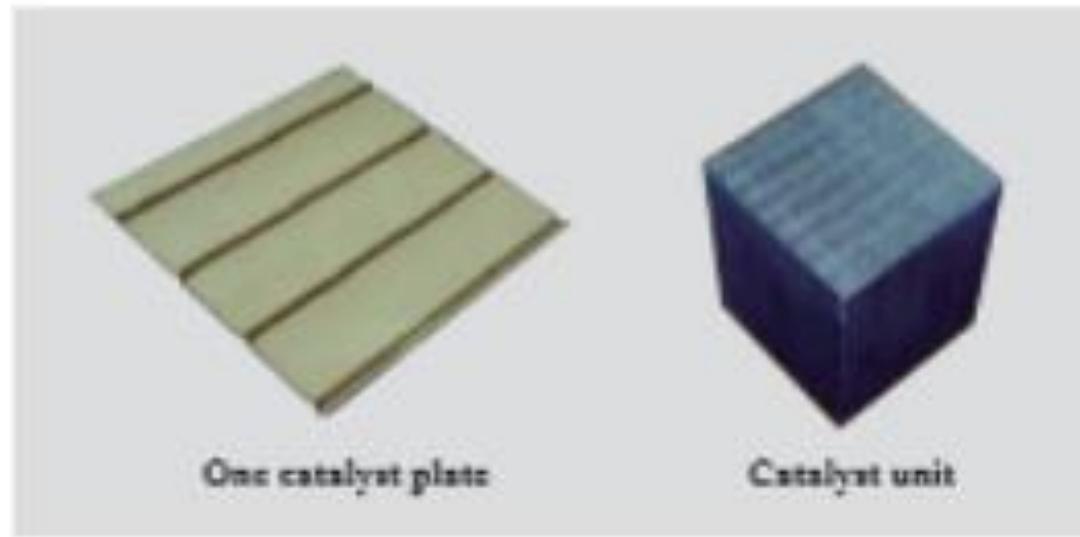
▲ **Figure 4.** Unlike other forms of catalytic pollution abatement, SCR requires the addition of a reductant, separate from the process stream, that must be pumped into the catalyst bed.

## Selective Catalytic Reduction – Honeycomb Configuration



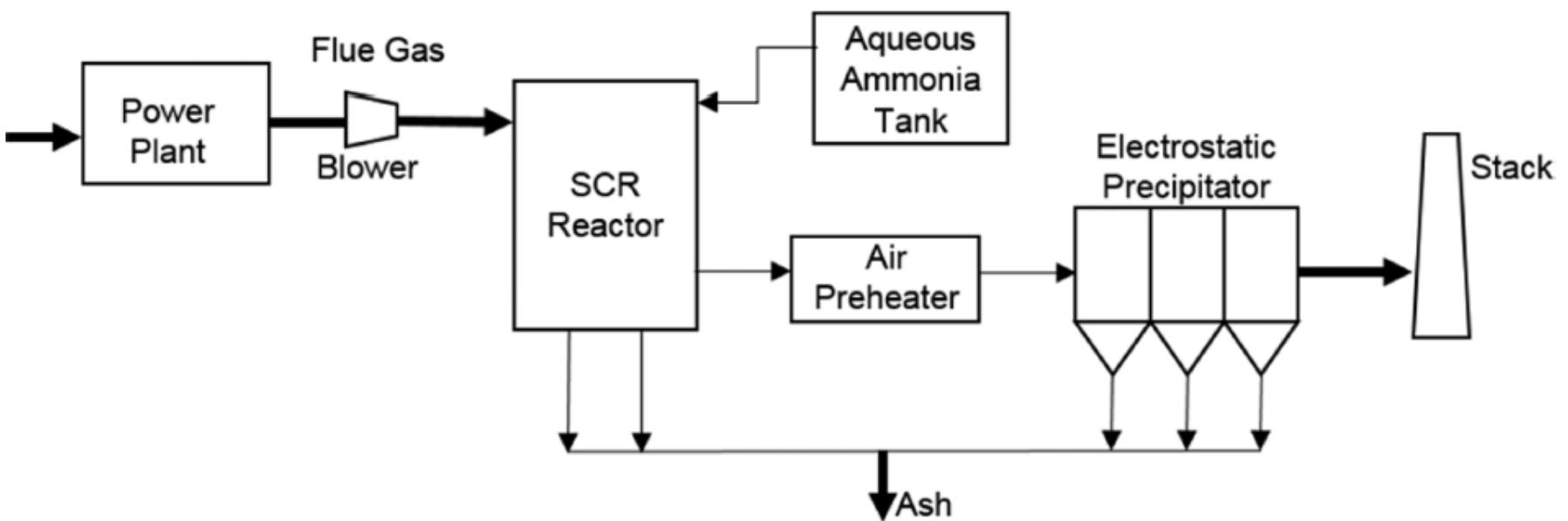
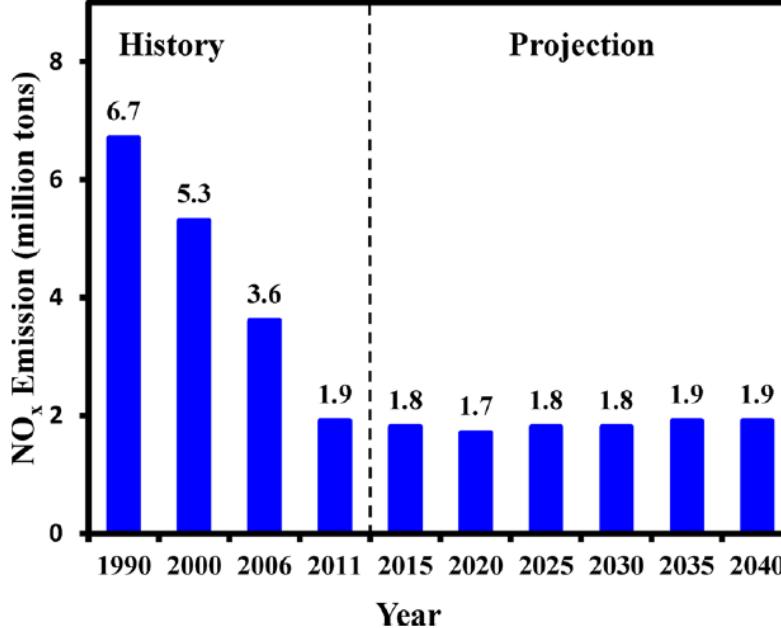
▲ **Figure 5.** This SCR catalyst housing is configured to accommodate up to three catalyst elements (only one is shown here). Photo courtesy of MIRATECH.

## Plate type catalyst for DeNOx

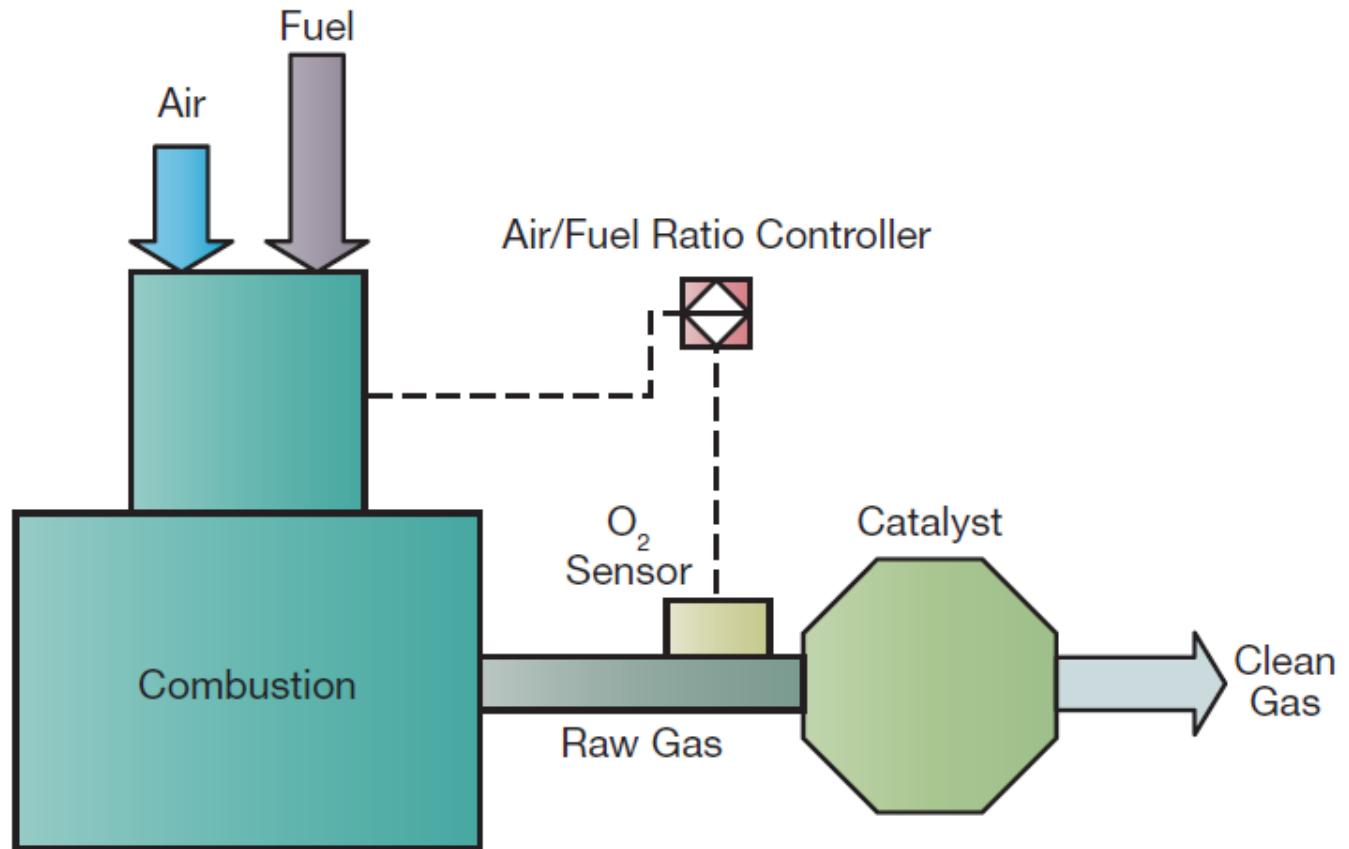


The reducing agent ammonia converts NOx into molecular N<sub>2</sub>

# $\text{NO}_x$ Emissions from Electricity Generation and Wet SCR Process

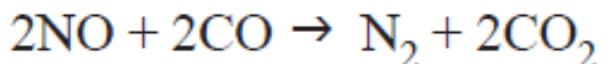


## Catalysis for Air Pollution Control – Nonselective Catalytic Reduction



Example:  
catalytic  
converter in  
automobiles

▲ **Figure 6.** The NSCR system requires a balance of air to fuel that is monitored by an oxygen sensor. Achieving the appropriate air-to-fuel ratio is key to effectively eliminating pollutants from the gas stream.



# Catalysis for Air Pollution Control – A Comparison of Methods

	Catalytic Oxidation	Selective Catalytic Reduction (SCR)	Nonselective Catalytic Reduction (NSCR)
Pollutants Controlled	CO VOCs	NOx	NOx CO VOCs
Additional Reactants	O <sub>2</sub> (from the atmosphere)	Anhydrous ammonia Aqueous ammonia Urea	O <sub>2</sub> (from the atmosphere) CO (from the exhaust stream)
Common Catalyst(s)	Platinum Palladium	Vanadium Titanium oxides Zeolite	Platinum Palladium Rhodium
Operating Temperature	600°F–800°F	Vanadium: 480°F–800°F Zeolite: 800°F–1,000°F	800°F–1,200°F
Concentration Achievable	CO: 2 ppmvd VOCs: 1 ppmvd	NOx: 2 ppmvd	NOx: 10 ppmvd CO: 2 ppmvd VOCs: 1 ppmvd
Other Technologies to Consider	Thermal Incineration	Dry Low-NOx (DLN) Burner Selective Non-Catalytic Reduction (SNCR) Steam/Water Injection	SCR + Thermal Incineration Catalytic Oxidation + SCR

# Control of Gaseous Pollutants

- Absorption
- Adsorption
- Oxidation
- Reduction

# Absorption

Primary application: inorganic gases

Example:  $\text{SO}_2$

Mass transfer from gas to liquid

Contaminant is dissolved in liquid

Liquid must be treated

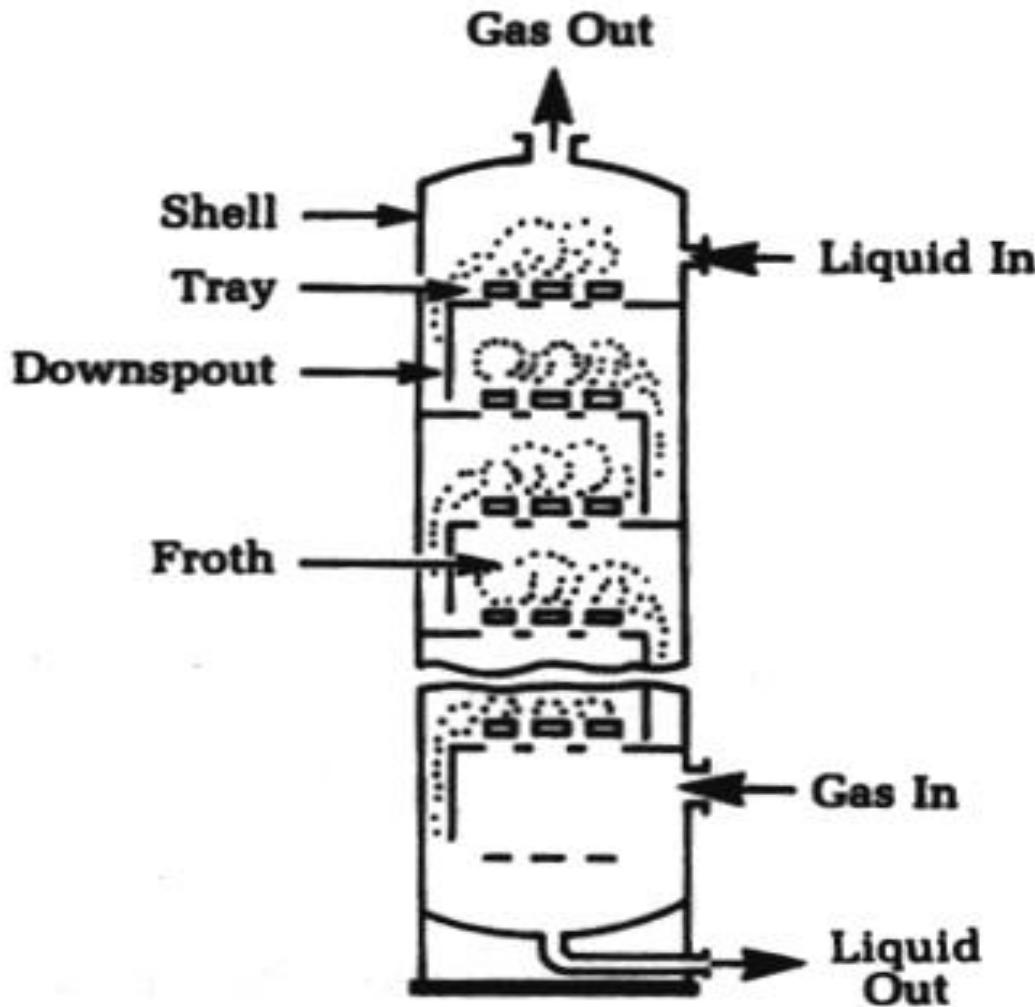
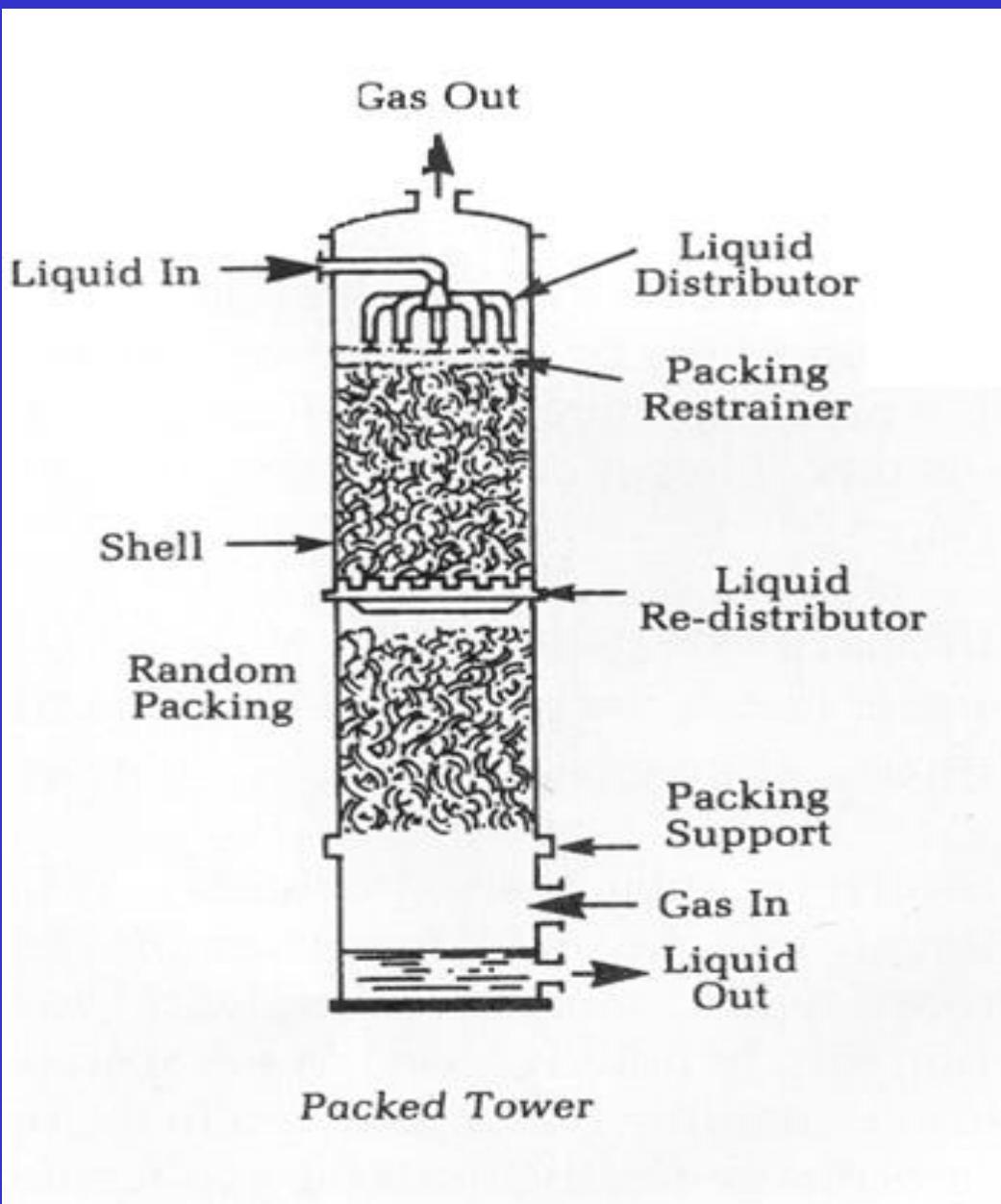


Plate Tower



# Adsorption

Primary application: organic gases

Example: trichloroethylene

Mass transfer from gas to solid

Contaminant is ‘bound’ to solid

Adsorbent may be regenerated

# Common Adsorbents

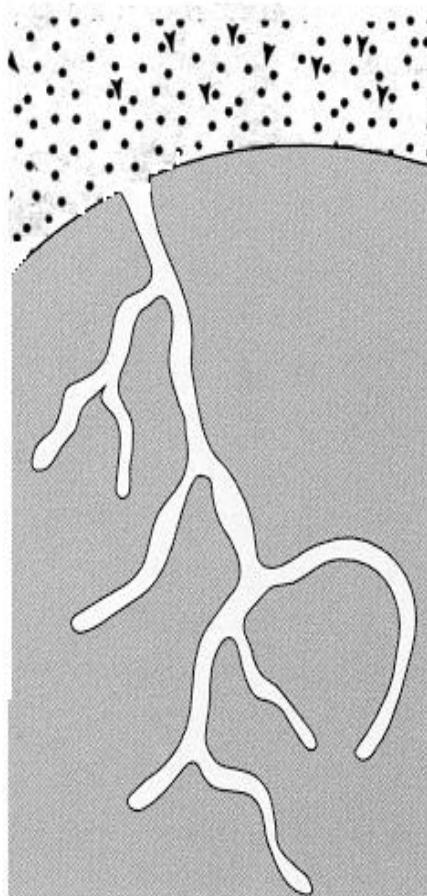
Activated carbon

Silica gel

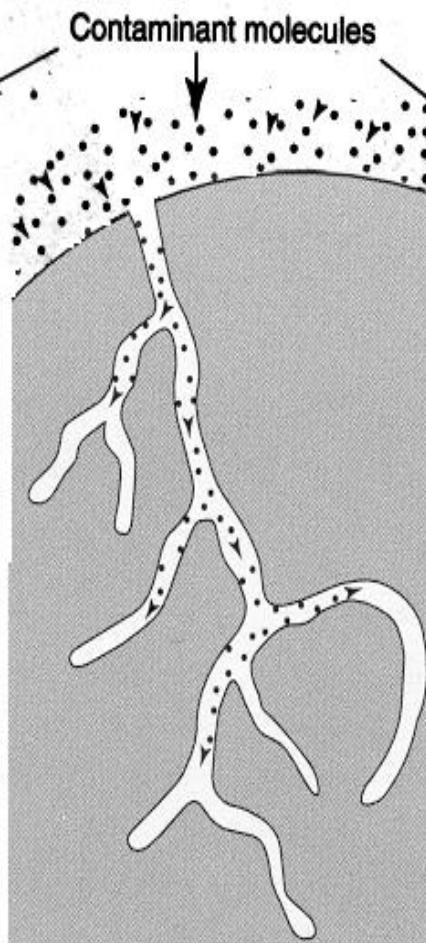
Activated alumina

Zeolites (molecular sieves)

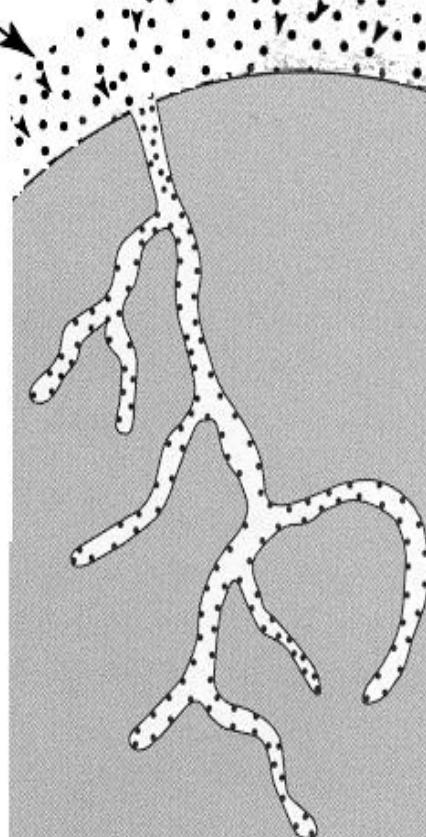
**Step 1: diffusion to adsorbent surface**

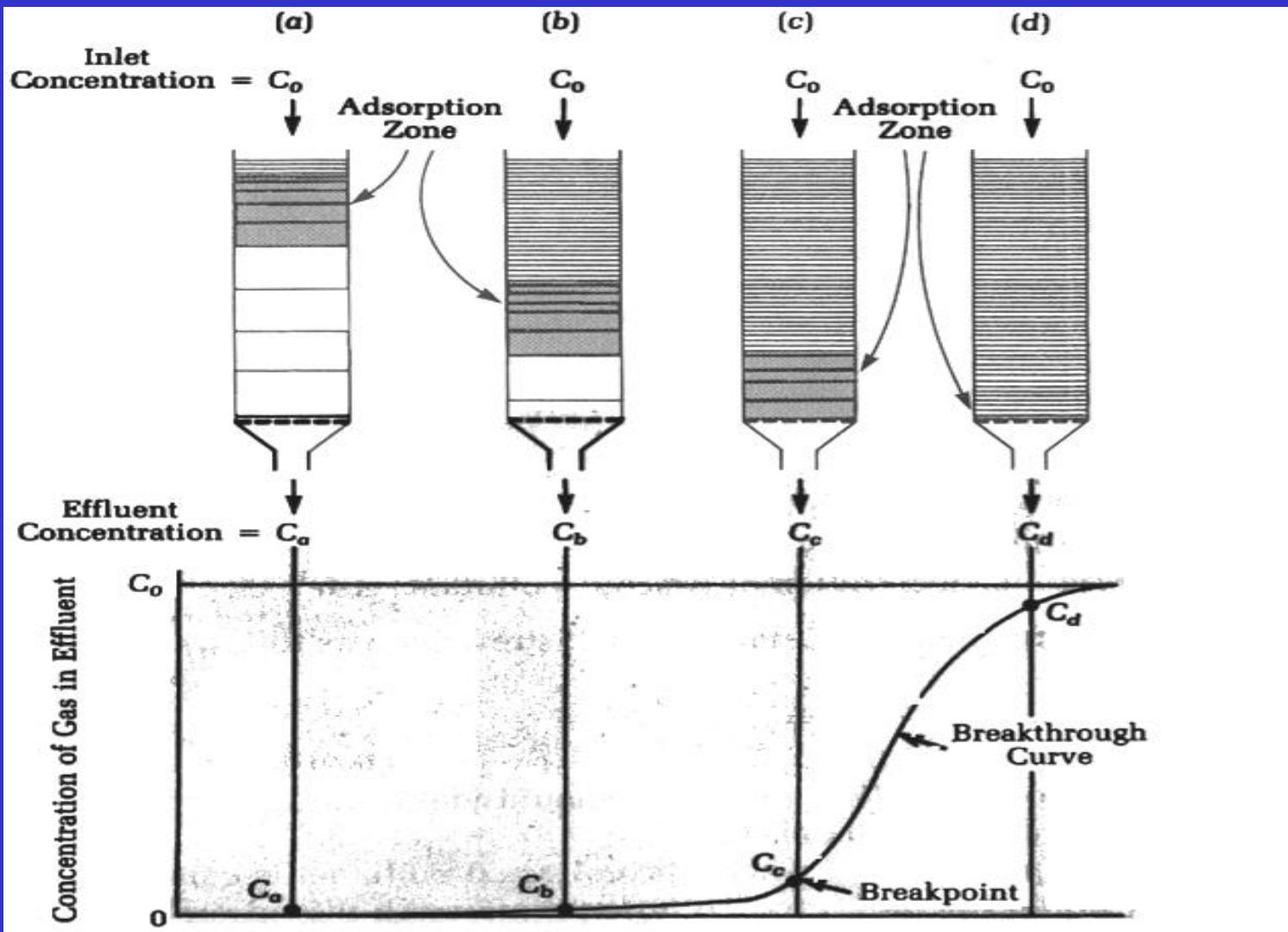


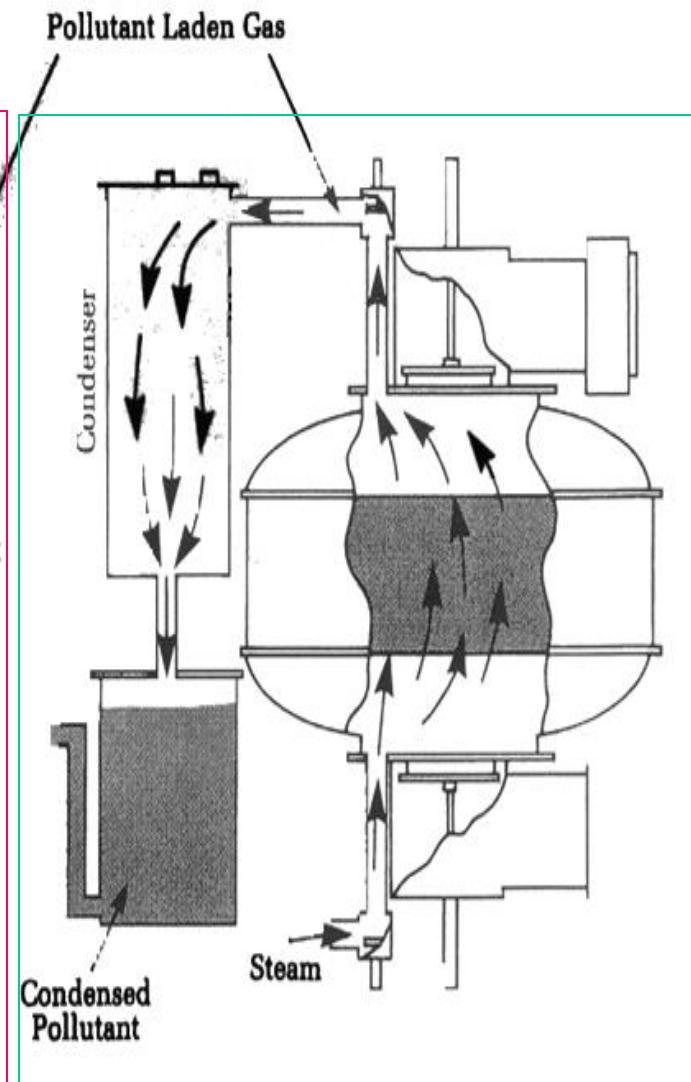
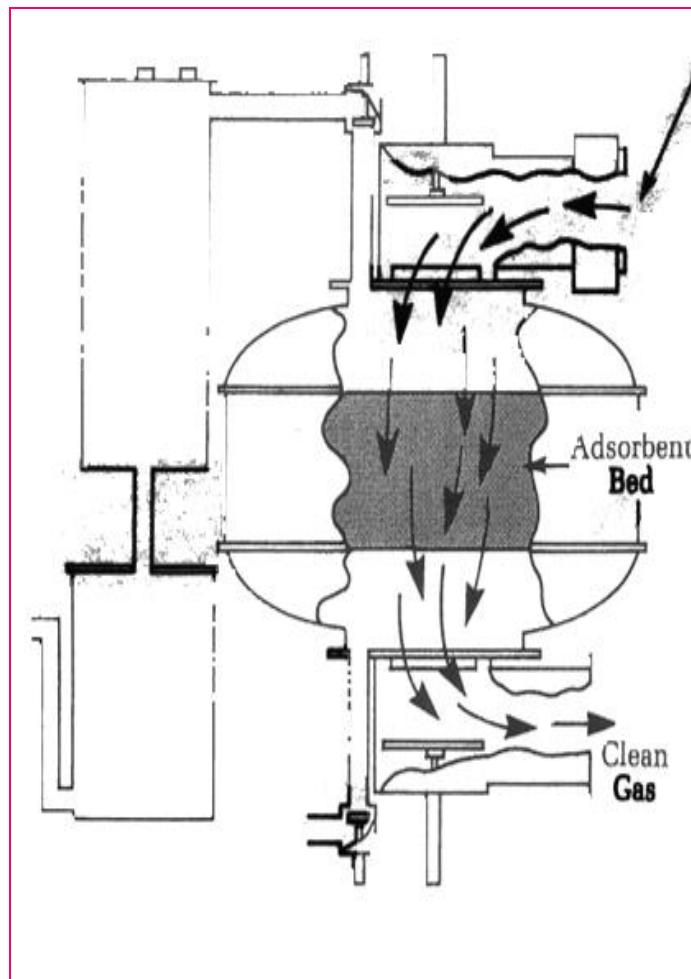
**Step 2: migration into pores of adsorbent**



**Step 3: monolayer buildup of adsorbate**







# Oxidation

- Thermal Oxidation
- Catalytic Oxidation

- A **thermal oxidizer** (or **thermal oxidiser**) is a process unit for air pollution control in many chemical plants that decomposes hazardous gases at a high temperature and releases them into the atmosphere.
- Thermal Oxidizers are typically used to destroy Hazardous Air Pollutants (HAPs) and Volatile Organic Compounds (VOCs) from industrial air streams.
- These pollutants are generally hydrocarbon based and when destroyed via thermal combustion they are chemically changed to form CO<sub>2</sub> and H<sub>2</sub>O.

# **Thermal Oxidation**

**Application: organic gases**

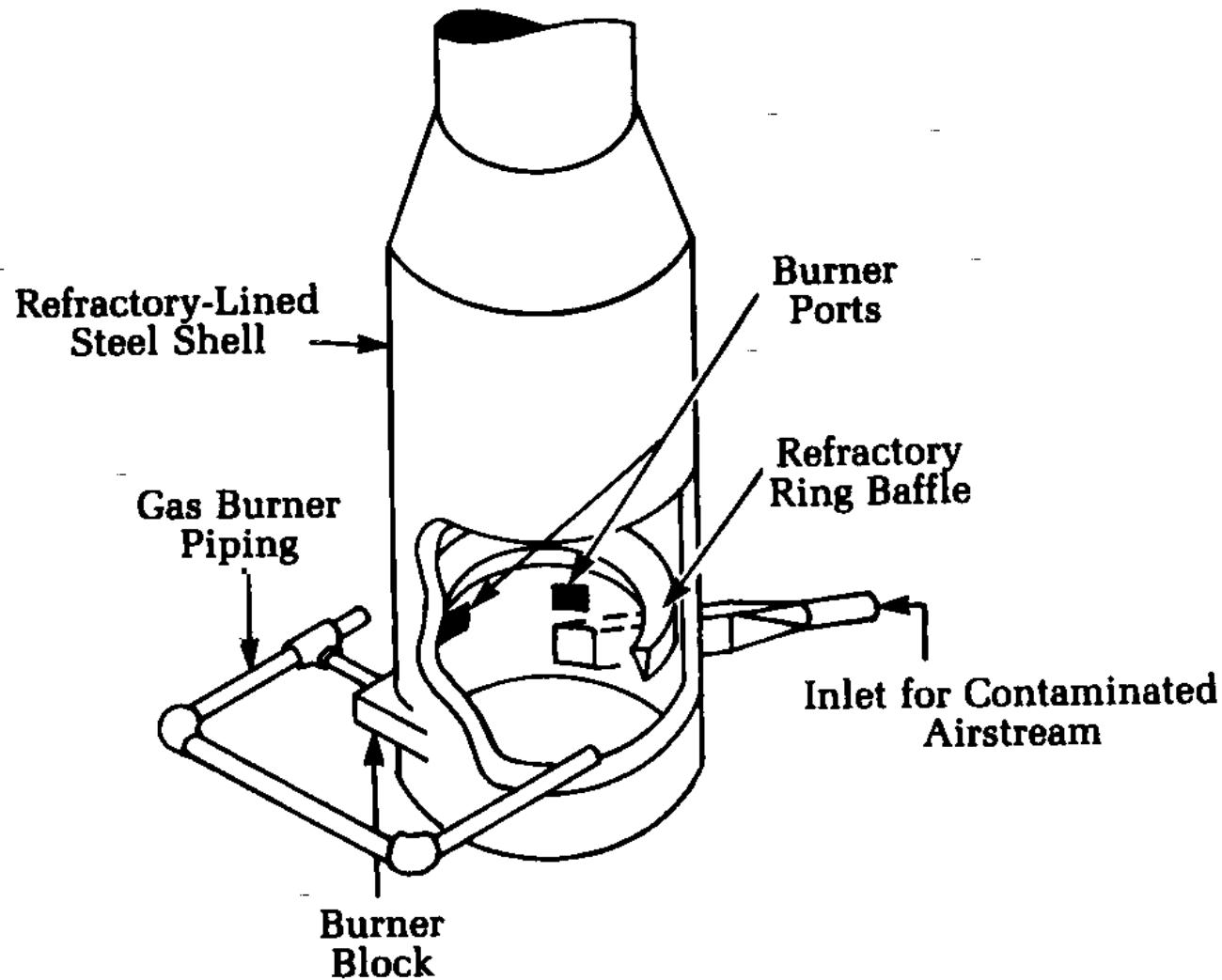
**Autogenous gases = 7 MJ/kg (heat value)**

**Operating temperatures: 700 - 1300 °C**

**Efficiency = 95 - 99%**

**By-products must not be more hazardous**

**Heat recovery is economical necessity**



# Catalytic Oxidation

- Catalytic oxidation is a relatively recently applied alternative for the treatment of VOCs in air streams resulting from remedial operations.
- The addition of a catalyst accelerates the rate of oxidation by adsorbing the oxygen and the contaminant on the catalyst surface where they react to form carbon dioxide, water, and hydrochloric gas.
- The catalyst enables the oxidation reaction to occur at much lower temperatures than required by a conventional thermal oxidation

# Catalytic Oxidation

Application: organic gases

Non-autogenous gases < 7 MJ/kg

Operating temperatures: 250 - 425 °C

Efficiency = 90 - 98%

Catalyst may be poisoned

Heat recovery is not normal

# Selective Catalytic Reduction (SCR)

**Application: NO<sub>x</sub> control**

**Ammonia is reducing agent injected into exhaust**

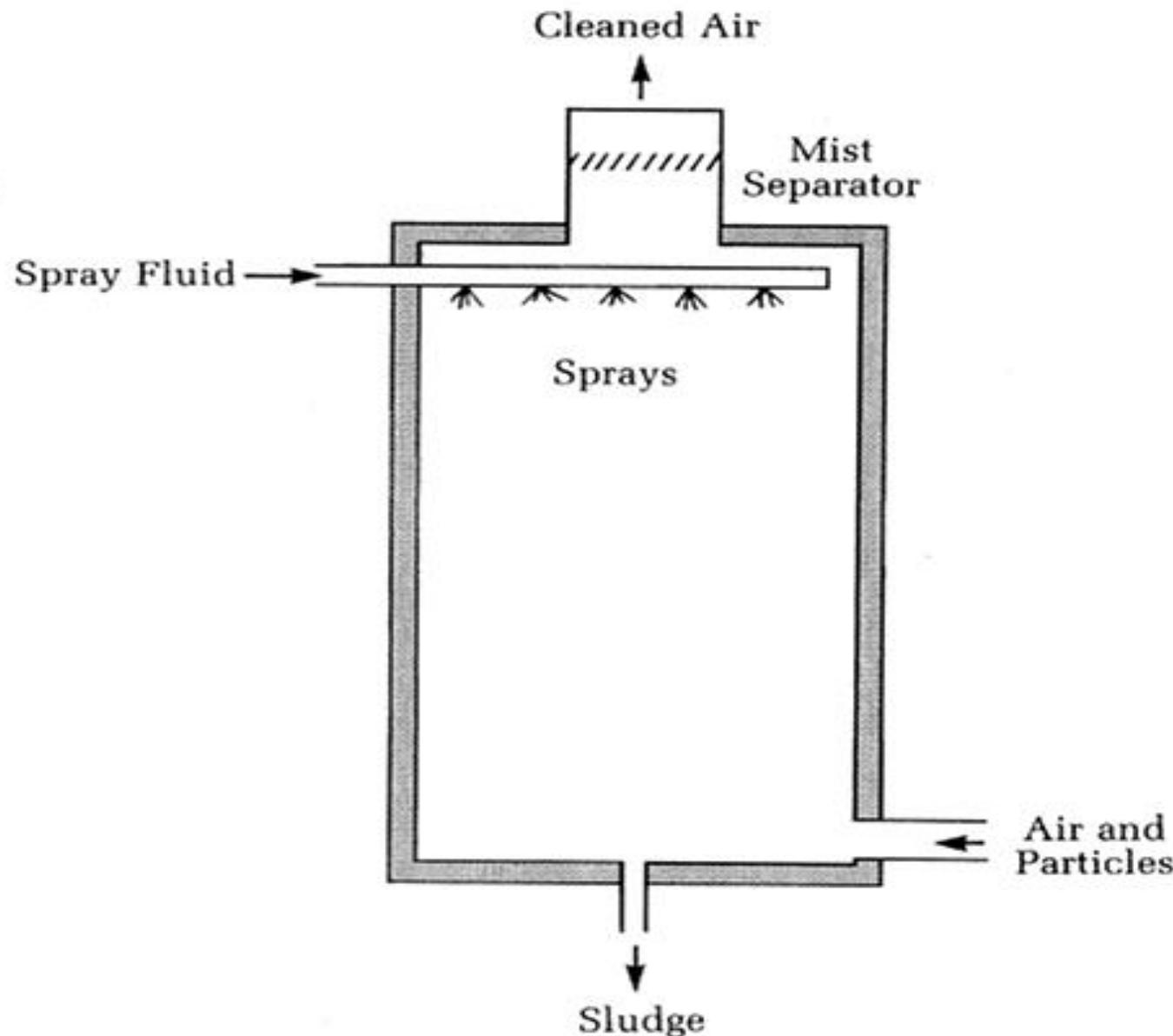
**NO<sub>x</sub> is reduced to N<sub>2</sub> in a separate reactor containing catalyst**

**Reactions:**



# Control of Particulate Pollutants

- Spray chamber
  - Cyclone
  - Bag house
  - Venturi
- Electrostatic Precipitator (ESP)



# Spray Chamber

# Spray Chamber

Primary collection mechanism:

Inertial impaction of particle into water droplet

Efficiency:

< 1% for < 1 um diameter

>90% for > 5 um diameter

Pressure drop: 0.5 to 1.5 cm of H<sub>2</sub>O

Water droplet size range: 50 - 200 um

# Spray Chamber

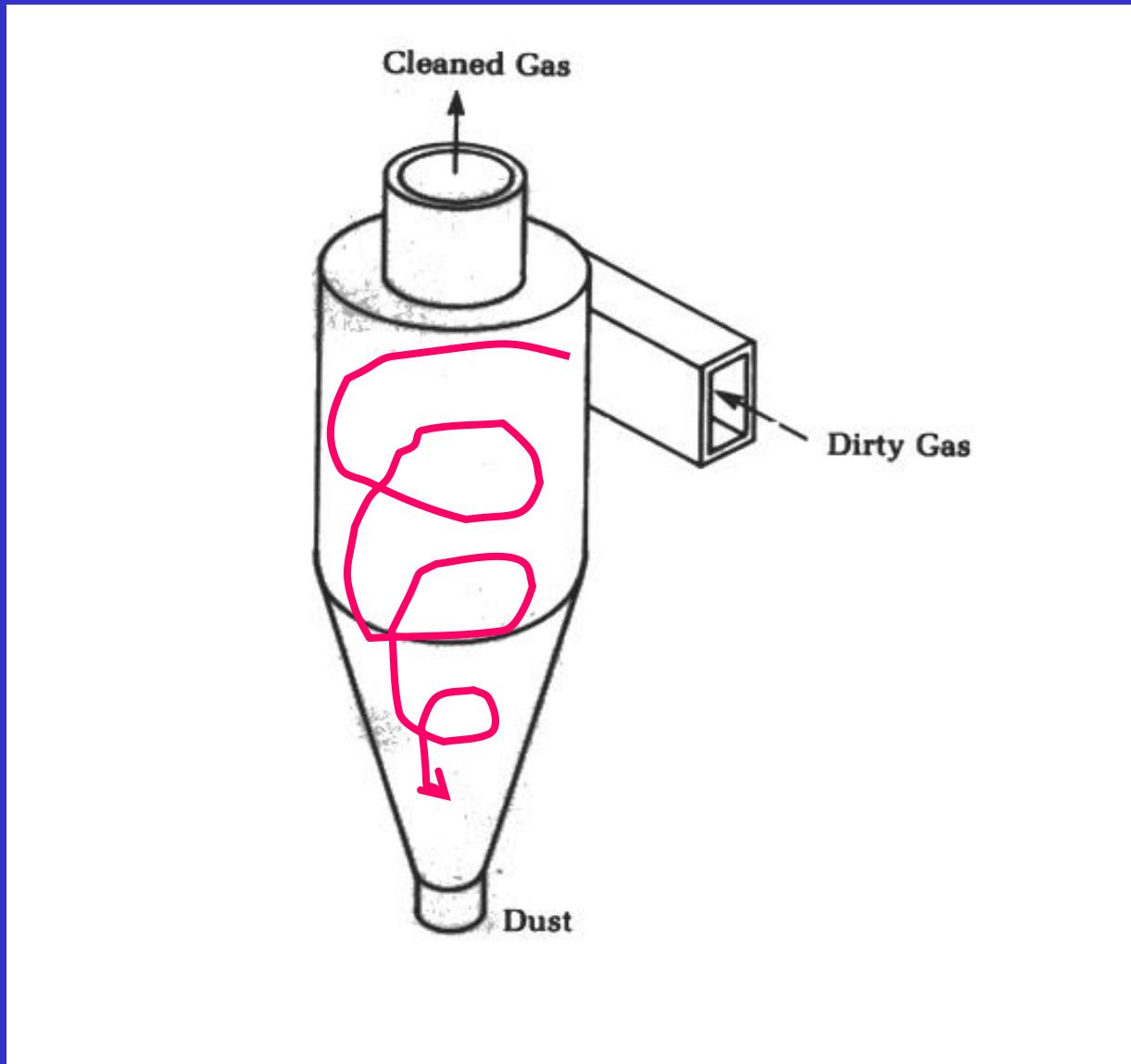
## Applications:

1. Sticky, wet corrosive or liquid particles

Examples: chrome plating bath

paint booth over spray

2. Explosive or combustible particles
3. Simultaneous particle/gas removal



# Cyclone

# Cyclone

## (Multi-clones for high gas volumes)

Primary collection mechanism:

Centrifugal force carries particle to wall

Efficiency:

<50% for <1 um diameter

>95% for >5 um diameter

# Cyclone

## (Multi-clones for high gas volumes)

Pressure drop: 8-12 cm of H<sub>2</sub>O

Applications:

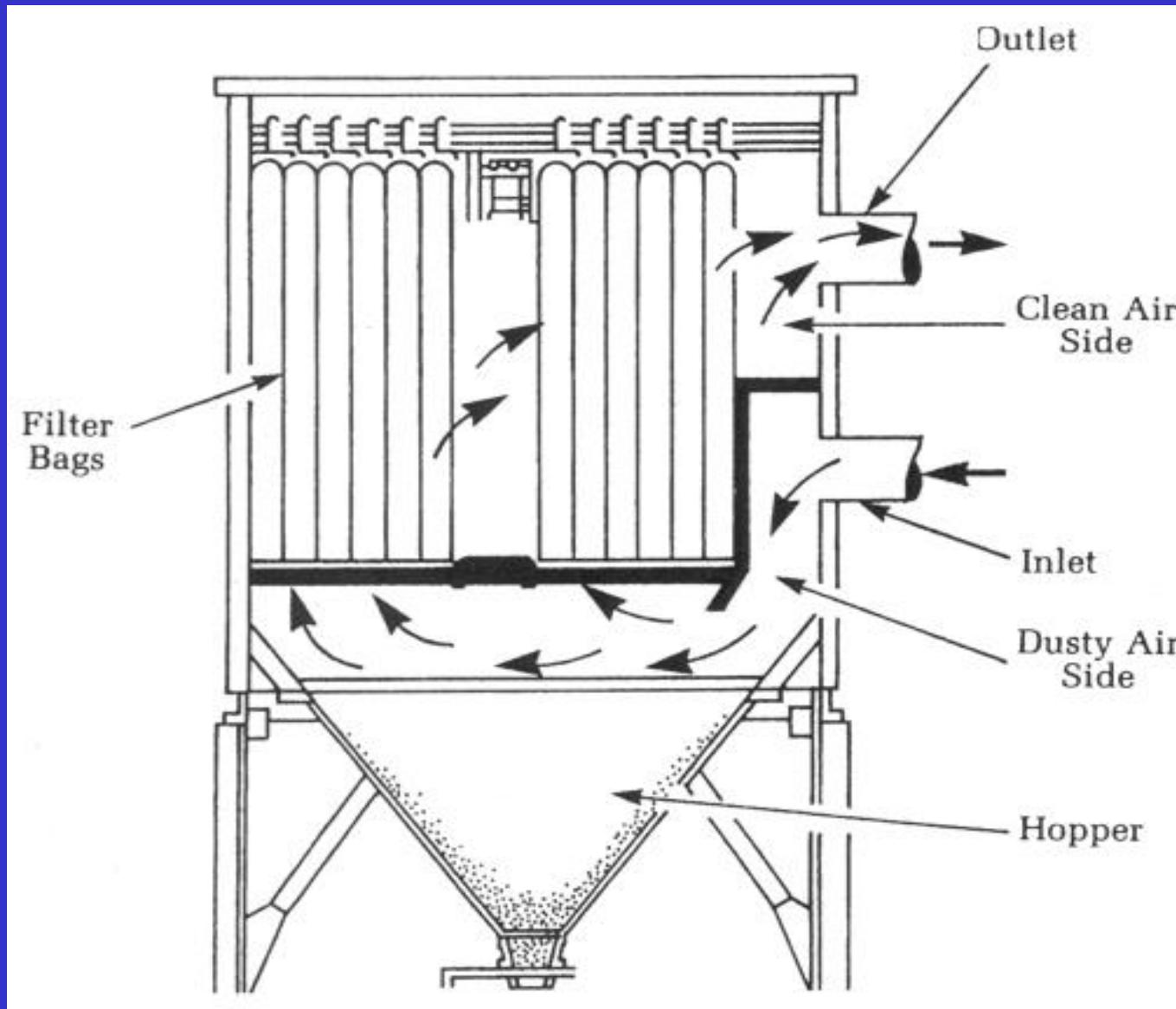
1. Dry particles

Examples: fly ash pre-cleaner

saw dust

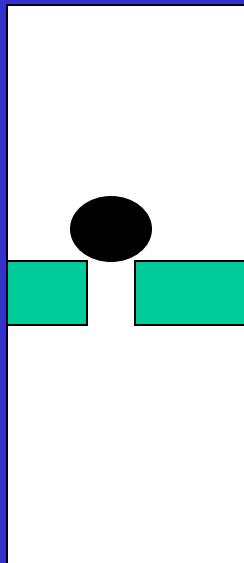
2. Liquid particles

Examples: following venturi

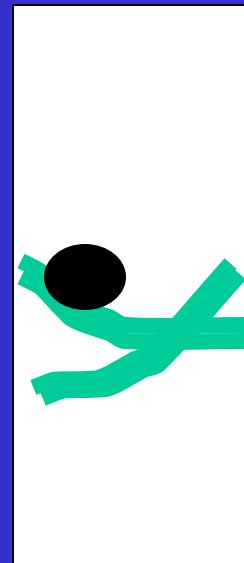


# Bag House

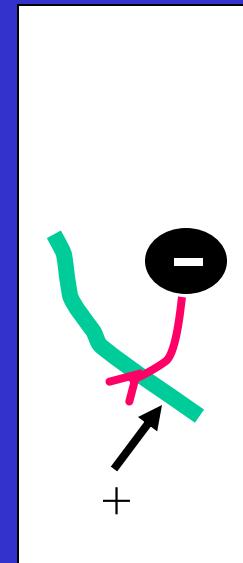
# Bag House Particle Collection Mechanisms



Screening



Impaction



Electrostatic

# Bag House

Efficiency:

>99.5% for <1 um diameter

>99.8% for >5 um diameter

Fabric filter materials:

1. Natural fibers (cotton & wool)

Temperature limit: 80 °C

2. Synthetics (acetates, acrylics, etc.)

Temperature limit: 90 °C

3. Fiberglass

Temperature limit: 260 °C

# Bag House

Bag dimensions:

15 to 30 cm diameter  
~10 m in length

Pressure drop: 10-15 cm of H<sub>2</sub>O

Cleaning:

1. Shaker
2. Reverse air
3. Pulse jet

# Bag House

Applications:

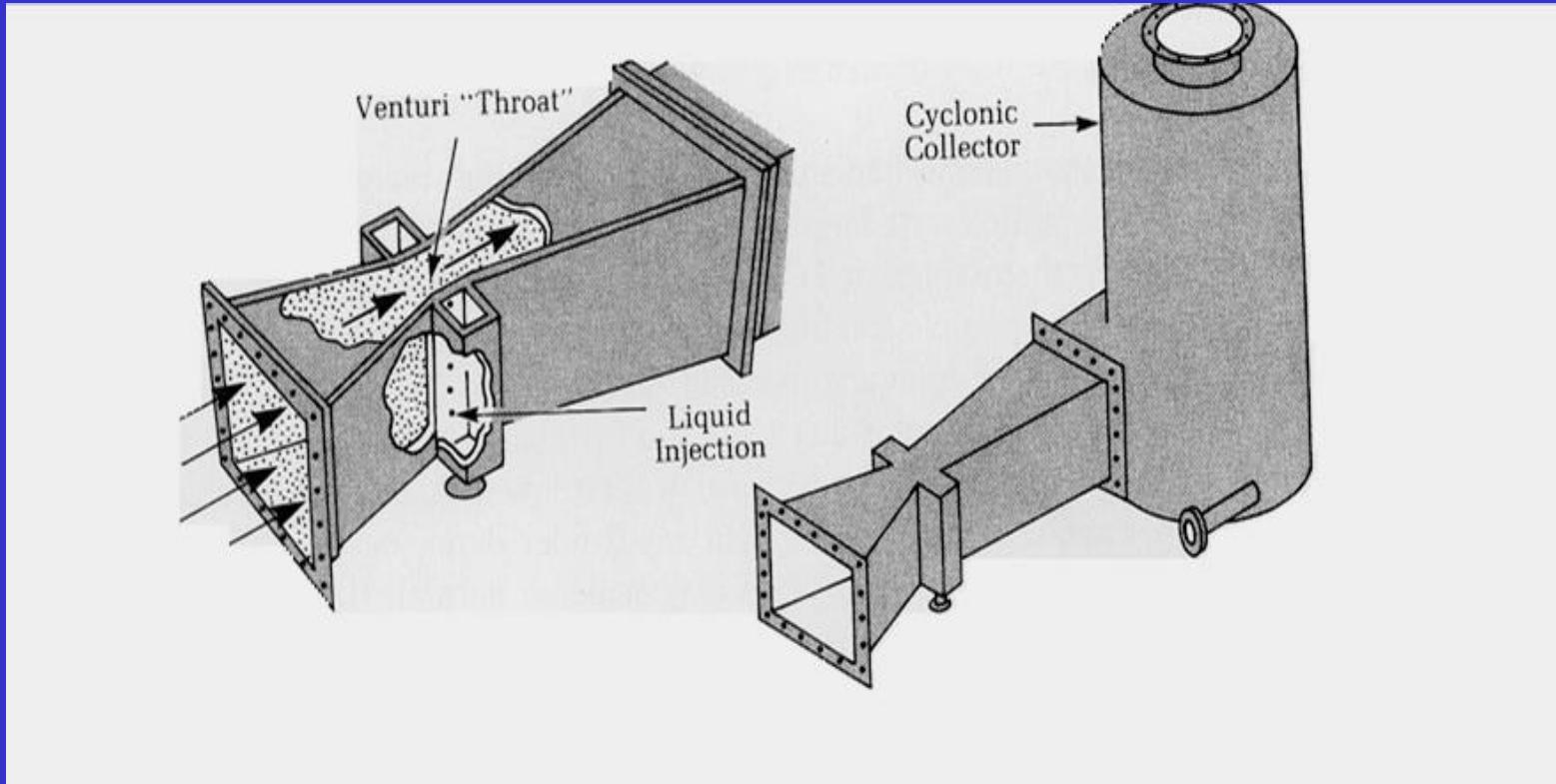
Dry collection

Fly ash

Grain dust

Fertilizer

May be combined with dry adsorption media  
to control gaseous emission (e.g. SO<sub>2</sub>)



# Venturi

# Venturi

Primary collection mechanism:

Inertial impaction of particle into water droplet

Water droplet size: 50 to 100  $\mu\text{m}$

Water drop and collected particle are removed by cyclone

# Venturi

Efficiency:

>98% for >1 um diameter

>99.9% for > 5 um diameter

Very high pressure drop: 60 to 120 cm of H<sub>2</sub>O

Liquid/gas ratios: 1.4 - 32 gal/1000 ft<sup>3</sup> of gas

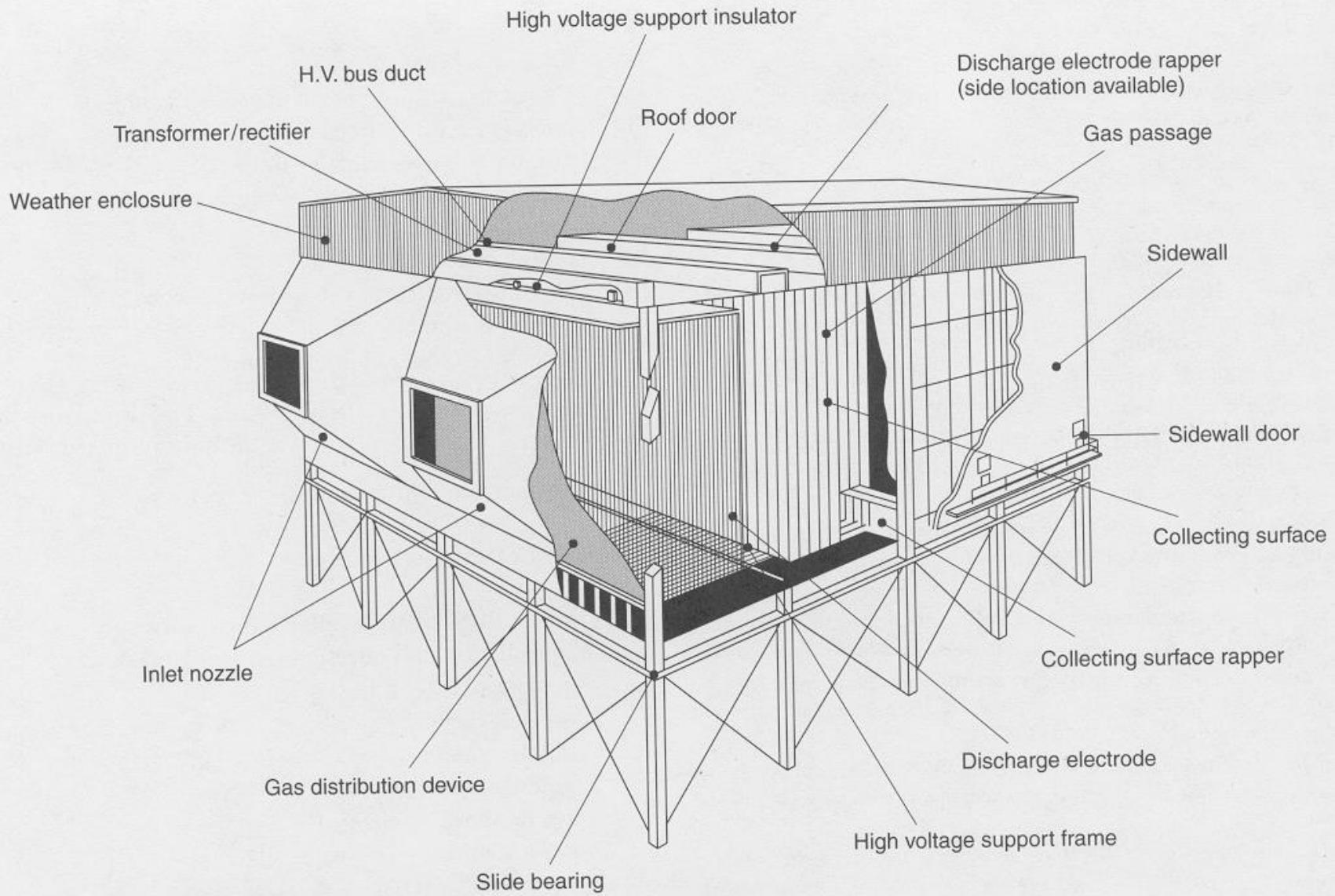
# Venturi

Applications:

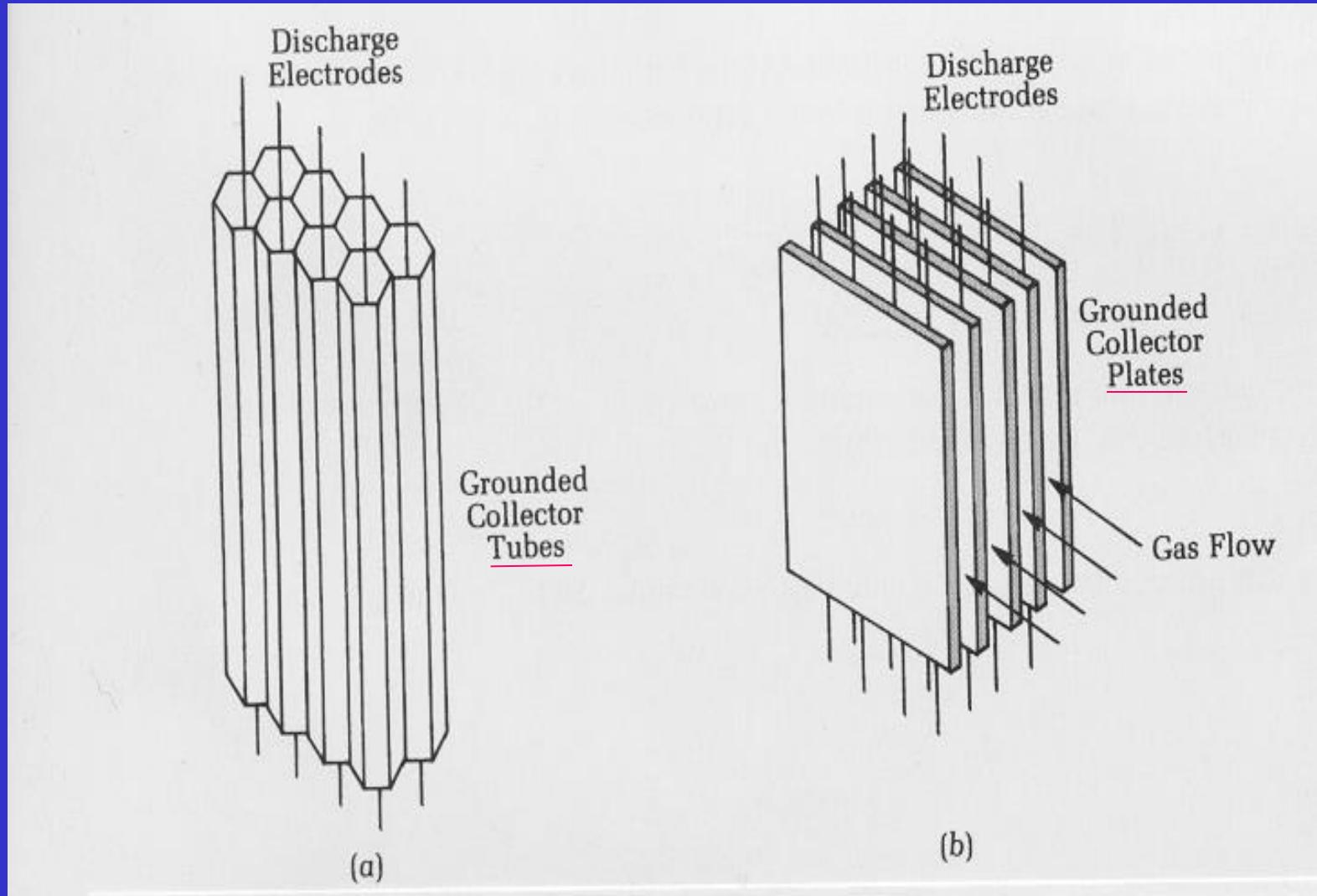
Phosphoric acid mist

Open hearth steel (metal fume)

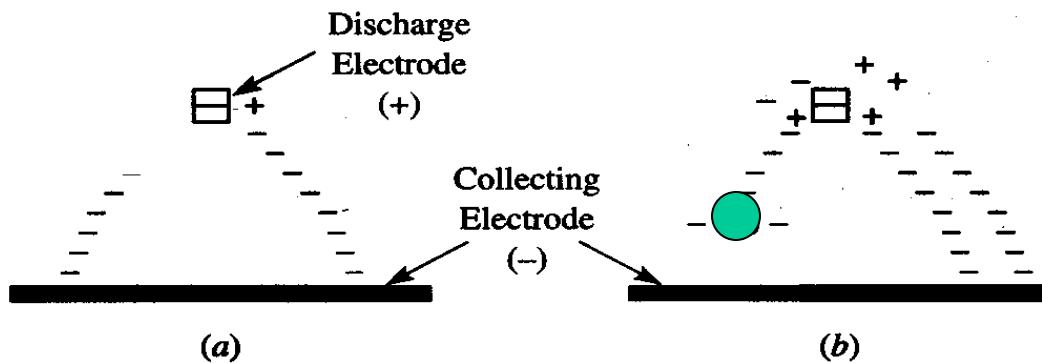
Ferro-silicon furnace



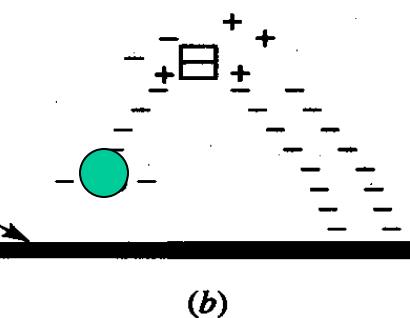
# Electrostatic Precipitator (ESP)



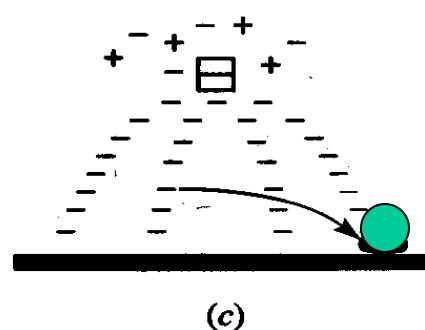
ESP Tube (a) and Plate (b) collectors



(a)



(b)



(c)

## ESP Collection Mechanism

# Electrostatic Precipitator (ESP)

Efficiency:

>95% for >1 um diameter

>99.5% for > 5 um diameter

Pressure drop: 0.5 to 1.5 cm of H<sub>2</sub>O

Voltage: 20 to 100 kV dc

Plate spacing: 30 cm

Plate dimensions: 10-12 m high x 8-10 m long

Gas velocity: 1 to 1.5 m/s

Cleaning: rapping plates

# Electrostatic Precipitator (ESP)

Applications (non-explosive):

1. Fly ash
2. Cement dust
3. Iron/steel sinter

# Flue Gas Desulfurization (FGD)

Predominant Processes (all non-regenerative):

1. Limestone wet scrubbing
2. Lime wet scrubbing
3. Lime spray drying

Typical scrubbers: venturi, packed bed and plate towers and spray towers

# Flue Gas Desulfurization (FGD)

Spray dryer systems include a spray dryer absorber and a particle-collection system (either a bag house or an ESP)

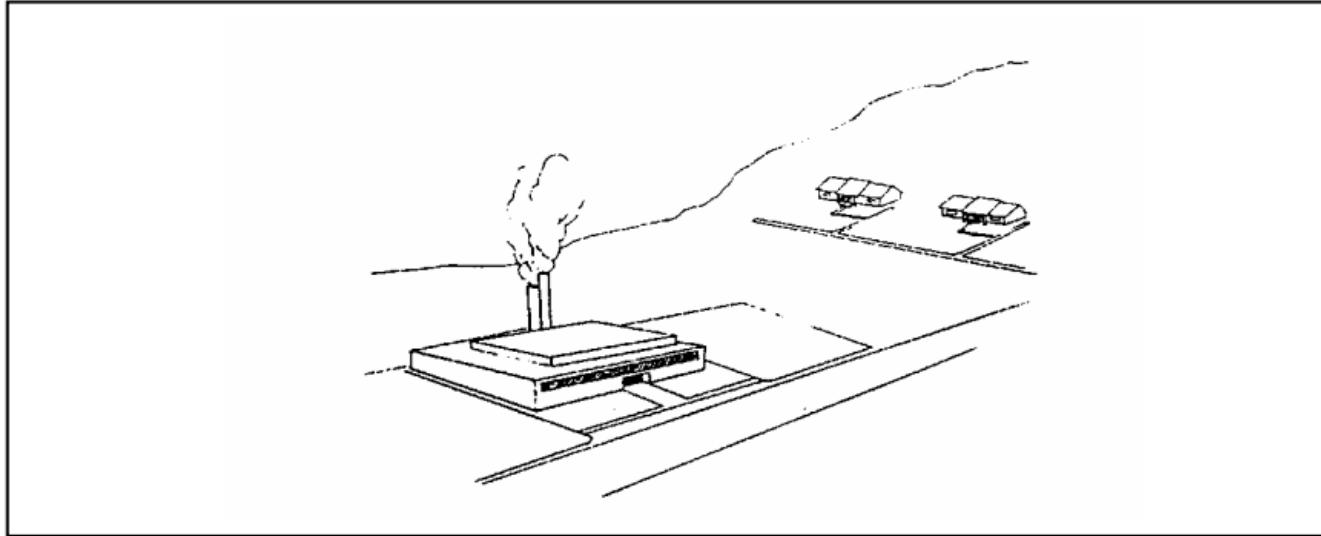
In 1990 the average design efficiency for new and retrofit systems was 82% and 76% respectively

# Flue Gas Desulfurization (FGD)

Overall reactions:



# Transport and Dispersion of Air Pollution



*Air Pollution meteorology studies how pollutants are delivered and dispersed into the ambient air.*

*Stable atmospheric conditions usually occur when warm air is above cooler air, inhibiting vertical mixing. This condition is commonly referred to as an atmospheric inversion.*

## Atmospheric Stability

While wind speed and direction generally relate to the horizontal movement of air, atmospheric stability relates to the forces that move air vertically. The vertical movement of air, or atmospheric stability, is most directly affected by high- and low-pressure systems that lift air over terrain and mix it with the upper atmosphere. The mechanisms that are specifically responsible for the vertical movement of air are atmospheric temperature and pressure. Everything on earth absorbs, stores and reradiates the sun's energy. Some parts of the earth, or different types of surfaces heat more readily than others. This is known as differential heating. For example, a plowed field heats more quickly than a large lake, which can store large amounts of energy, but heat up slower.

Differential heating of the earth affects the air above it. The air directly above a heated surface will also become heated as the heat moves to an area of less heat. This warming occurs due to two basic principles; conduction and convection. Conduction is the transfer of heat that takes place when something touches a heated surface. In this case, the air touches the heated earth and gains some of that heat. Convection is the vertical mixing of the air.

A parcel of air, for example, that is warmer than the surrounding air masses will expand, rise and cool. As the air expands, it decreases in both temperature and pressure. A parcel of cool air, however, behaves in the opposite manner.

As warm air rises, it cools; as cool air descends, it warms.

Air circulates on the earth in a three-dimensionally movement not only vertically and horizontally. This movement is called turbulence. Turbulence occurs from two different processes: (1) *mechanical* or (2) *thermal turbulence*. Thermal turbulence results from atmospheric heating and mechanical turbulence from the movement of air past an obstruction. Both types of turbulence usually occur in during any atmospheric air movements, although one type or the other may dominate under certain circumstances. For example; on clear sunny days with light winds, thermal turbulence is dominant. Where as, mechanical turbulence is dominant on windy night with neutral atmospheric stability. The net effect of turbulence is to enhance the pollutant dispersion process. However, mechanical turbulence can cause downwash from a pollution source, which can result in high concentrations of pollutants, immediately downwind.

## **Adiabatic and Environmental Lapse Rate**

The temperature in the troposphere decreases with height up to an elevation of about 10 kilometers. Decreasing temperature with height is described as the lapse rate. On average this decrease is  $-0.65^{\circ}\text{C}/100\text{ m}$  and is stated as the normal lapse rate. If a parcel of air were lifted in the atmosphere, then allowed to expand and cool or compress and warm, with a change in atmospheric pressure and no interchange of heat, it would be an adiabatic process. The air parcel must also be unsaturated and the rate of adiabatic cooling or warming remains constant. The rate of heating or cooling for unsaturated air is  $10^{\circ}\text{C}/1000\text{ meters}$ , with the water remaining in the gaseous state, and is referred as the dry adiabatic lapse rate.

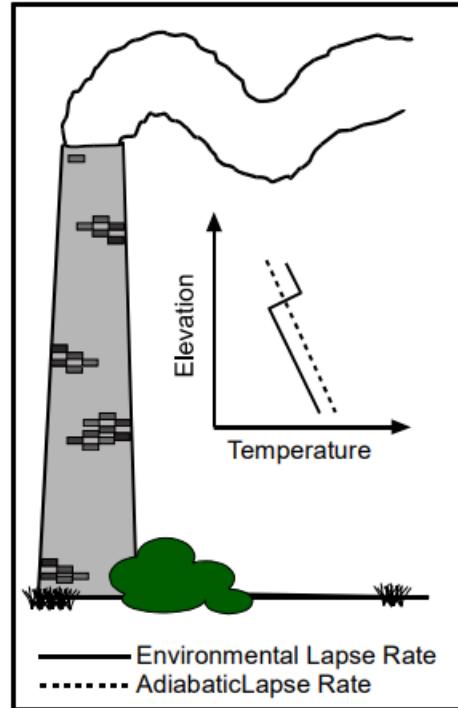
Individual vertical temperature measurements can vary considerably from either the normal or dry adiabatic lapse rate. This change of temperature with height for a specific measured location is the environmental lapse rate. The environmental lapse rate values characterize the atmospheric stability and have a direct bearing on the vertical air movement and pollutant dispersion (Godish, 1997).

A critical relationship exists between atmospheric stability and pollutant concentrations. Pollutants that cannot be transported or dispersed into the upper atmosphere quickly become trapped at ground level and pose a significant risk to human health and the environment. This relationship can be visualized in the behavior of emission plumes from industrial smoke stacks. Six types of air pollution plumes illustrate the relationship between atmospheric stability and pollutant emissions: looping plumes, fanning plumes, coning plumes, lofting plumes, fumigating plumes, and trapping plumes.

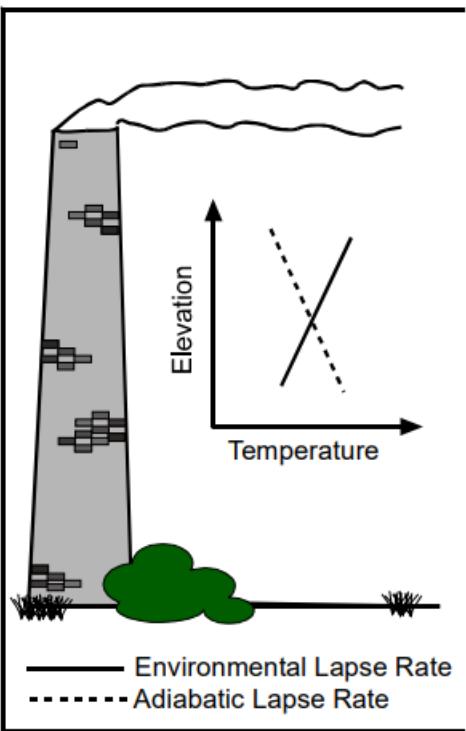
*Types of Smokestack Plumes:*

- *Looping*
- *Fanning*
- *Coning*
- *Lofting*
- *Trapping*
- *Fumigating*

**Looping plumes.** Pollution that is released into an *unstable* atmosphere forms looping plumes. Rapid changes in temperature and pressure may result in plumes that appear billowing and puffy. While unstable conditions are usually favorable for pollutant dispersion, high concentrations of air pollution forced down by cooling air can be harmful if trapped at ground level. This can occur on sunny days with light to moderate winds, which combine with rising and sinking air to cause the stack gases to move up and down in a wavy pattern producing a looping plume (Godish, 1997).

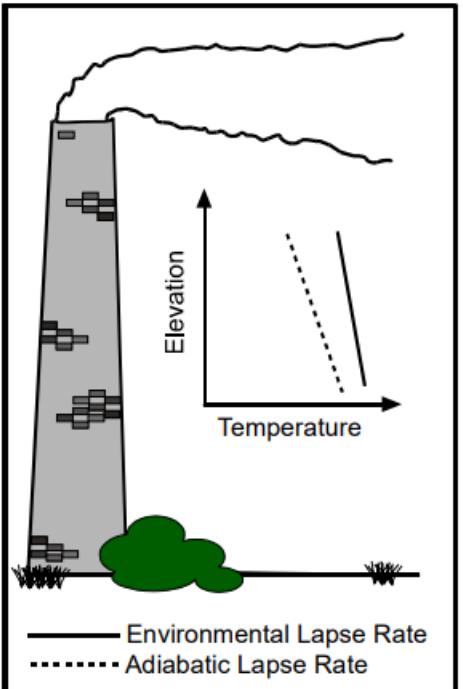


**Fig. 3-4. Looping Plume**



**Fig. 3-5. Fanning Plume**

**Fanning plumes.** A fanning plume occurs during *stable* conditions and is characterized by long, flat streams of pollutant emissions. Because atmospheric pressure is stable, there is neither a tendency for emissions to rise nor descend permitting (horizontal) wind velocity to transport and disperse the pollutant. Fanning plumes are usually seen during the early morning hours just before the sun begins to warm the atmosphere and winds are light (Godish, 1997).



**Fig. 3-6. Coning Plume**

**Coning plumes.** *Neutral* or slightly unstable conditions create a coning plume that is distinguished by large billows or puffs of pollutants. Coning plumes are typically formed on partly cloudy days when there is an alternate warming and cooling of the atmosphere. Warm gases released into cool, ambient air mix, expand, and rise into the upper atmosphere (Godish, 1977).

**Lofting plumes.** When the atmosphere is relatively *stable*, warm air remains above cool air and creates an inversion layer. Pollutants released below the inversion layer will remain trapped at ground level and, in the absence of any atmospheric instability, prevent the upward transport of the pollutant. When there is little or no vertical mixing, pollutants tend to form in high concentrations at ground level. When conditions are unstable or neutral above the inversion layer, stack gases above that level form a lofting plume that can effectively disperse the pollutant into the upper atmosphere (Godish, 1997).

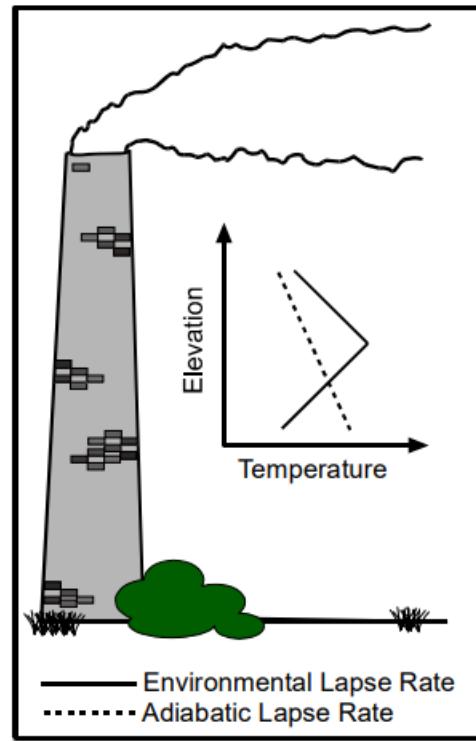
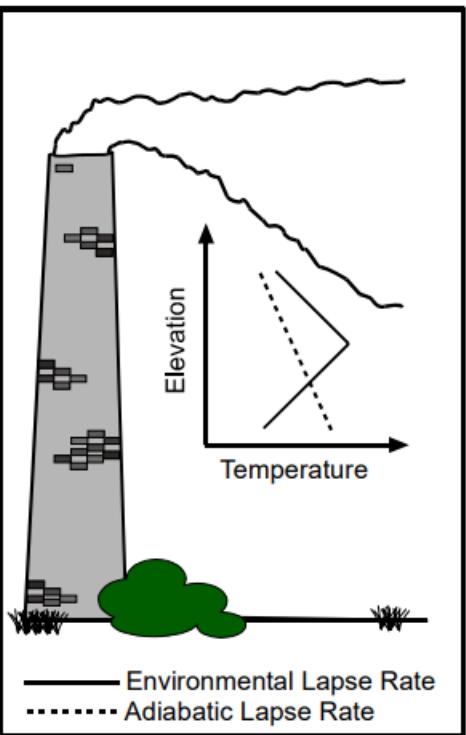
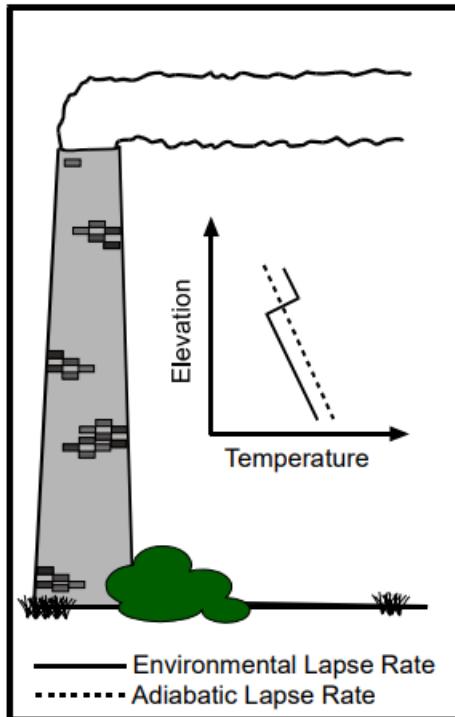


Fig. 3-7. Lofting Plume



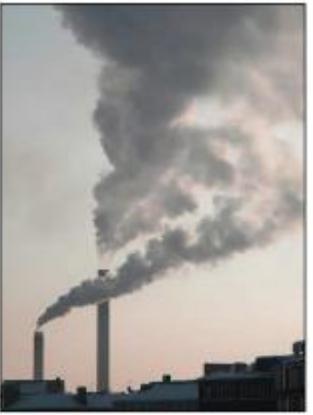
**Fig. 3-8. Fumigating Plume**

**Fumigating plumes.** In the early morning, if the plume is released just below the inversion layer, a very serious air pollution episode could develop. When pollutants are released below the inversion layer, gaseous emissions quickly cool and descend to ground level. This condition is known as fumigation and results in a high concentration of pollution that can be damaging to both humans and the environment alike. This atmospheric condition characterizes the most destructive type of air pollution episode possible



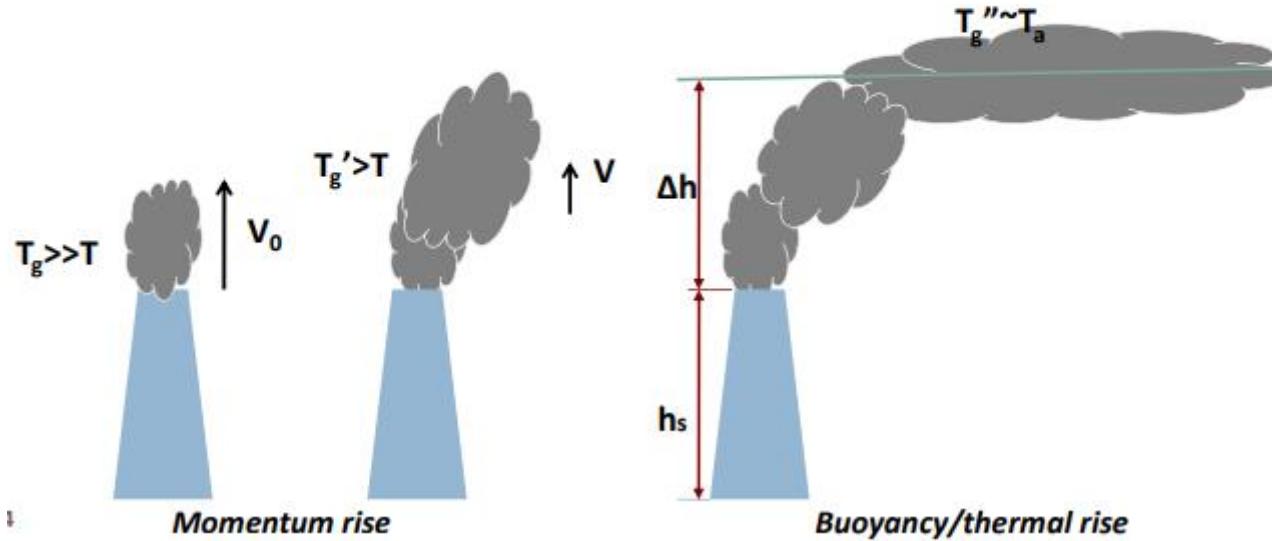
**Fig. 3-9. Trapping Plume**

**Trapping plumes.** A trapped plume, on the other hand, is produced on clear, sunny days or clear nights with light winds. A trapped plume is the result of an *unstable* air mass that creates an inversion layer both above and below the plume. A trapped plume, in contrasted with a fumigating plume, is one of the most favorable types of plume for pollutant dispersion. Temperature inversions, both above and below the plume, protect ground sources from potential exposure while winds at altitude disperse and dilute the pollutant (Godish, 1997).



## TRANSPORT AND DISPERSION OF AIR POLLUTANTS

Gases leaving the tops of stacks rise higher than the stack top when they are either of lower density than the surrounding air (**buoyancy rise**) or ejected at a velocity high enough to give the exit gases upward kinetic energy (**momentum rise**).



After this initial stage, the **dispersion of pollutants** in the atmosphere is the result of the following three mechanisms: 1) general air motion that transports pollutants downwind, 2) turbulent velocity fluctuations that disperse pollutants in all directions and 3) diffusion due to concentration gradients.

**Turbulence** is highly irregular motion of the wind.

There are basically two different causes of turbulent eddies: **mechanical turbulence** and **convective turbulence**. While both of them are usually present in any given atmospheric condition, either mechanical or convective turbulence prevails over the other.

**Mechanical turbulence** is caused by physical obstructions to normal flow such as mountains, building, trees,... The degree of mechanical turbulence depends on wind speed and roughness of the obstructions.

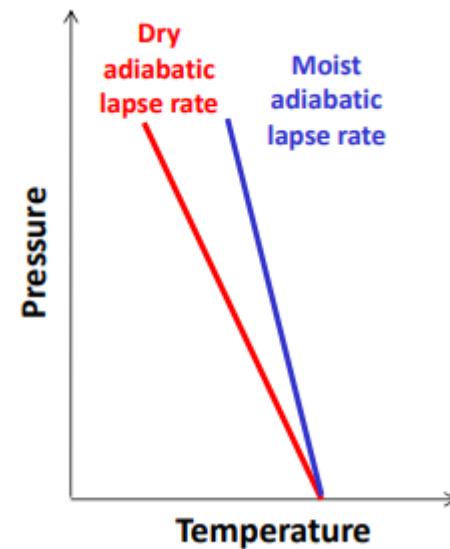
**Convective turbulence** results from different heating-cooling of surfaces and air masses. The higher the temperature difference, the greater the turbulence is.

Atmospheric eddies cause a breaking apart of atmospheric parcels which mixes polluted air with relatively unpolluted air, causing polluted air at lower and lower concentrations to occupy successively larger volumes of air. Thus, the level of turbulence in the atmosphere determines its dispersive ability.

## ATMOSPHERIC STABILITY

One of the most important characteristics in intensity of turbulence in the atmosphere is its **stability**. Stability is the tendency to resist vertical motions or to suppress existing turbulence).

The atmospheric stability is related to the variation with altitude of **temperature**, **pressure** and **humidity**.

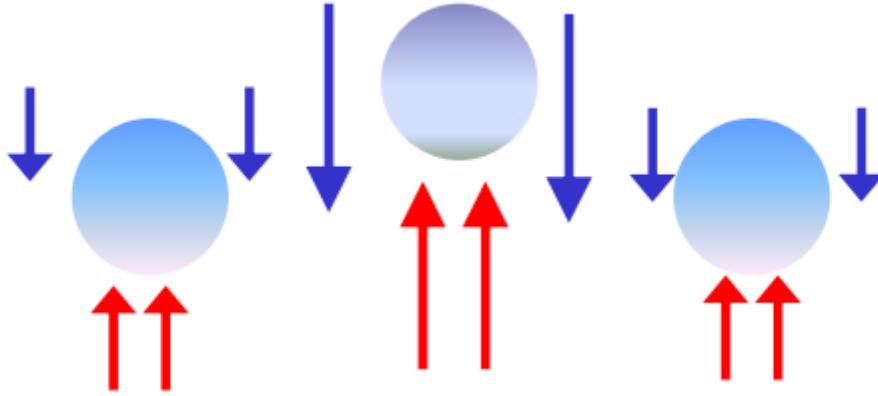


Holding other conditions constant, the temperature of air increases as atmospheric pressure increases and conversely decreases as pressure decreases. With respect to the atmosphere, where air pressure decreases with rising altitude, the normal temperature profile of the troposphere is one where temperature decreases with height. An air parcel that becomes warmer than the surrounding air begins to expand and cool. As long as the parcel's temperature is greater than the surrounding air, the parcel is less dense than the cooler surrounding air. Therefore, it rises, or is buoyant. As the parcel rises, it expands thereby decreasing its pressure and, therefore, its temperature decreases as well. The initial cooling of an air parcel has the opposite effect.

Assuming that:

1. The air parcel is a relatively well-defined body of air that it does not mix with the surrounding air
2. The exchange of heat between the air parcel and its surrounding is minimal: it does not gain or lose heat (**adiabatic process**) and,
3. This raising (falling) air parcel cools (heats) without reaching its dew point, that is, without saturation, any water in it remains in a gaseous state (**dry air**).

Likewise, the rate of cooling (or warming) of the air parcel forced to rise or descend is about  $-9.76$  ( $+9.76$ )  $^{\circ}\text{C}\cdot\text{km}^{-1}$ . This is the **dry adiabatic profile** or **dry adiabatic lapse rate (DALR)**.

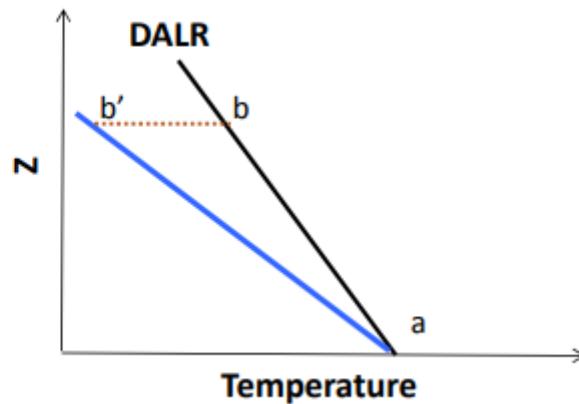


*Warm air rises and cools, while cool air descends and warms*

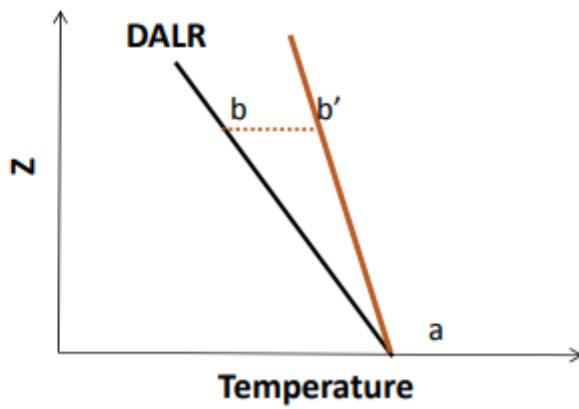
The extent to which an air parcel rises or falls depends on the relationship of its temperature to that of the surrounding air.

Thus, the **degree of stability** of the atmosphere can be determined from comparing the DALR and the **environmental lapse rates**.

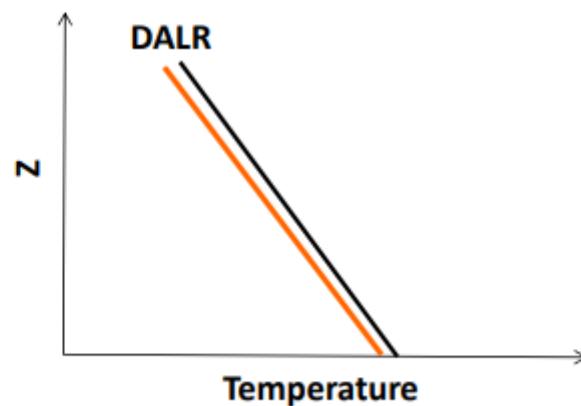
Comparing the temperature of the parcel to that of the surrounding environment, it is seen that in rising from  $a$  to  $b$ , the parcel undergoes the temperature change of the DALR. Since the rate of the surrounding environment is steeper than the DALR (**superadiabatic**), at  $b$  the parcel is warmer than the environment  $b'$ , and the resulting acceleration is upward. The parcel will continue to rise. This atmosphere is enhancing the vertical motion (**unstable**).



However, when the lapse rate of the surrounding environment is not as steep as the dry adiabatic lapse rate (**subadiabatic**), in the forced ascent of the air parcel up the slope from *a* to *b* it cools less than the DALR; thus, at *b* parcel is cooler than the environment *b'*, therefore, it will sink back to its original level. This atmosphere resists upward or downward motion (**stable**).



When the lapse rate of the surrounding environment is the same as the dry adiabatic lapse rate (**adiabatic**), the vertical movement is neither encouraged nor hindered. The atmosphere is in a state of **neutral** stability.



Summing up, according to the vertical temperature profiles there are three categories of stability:

- **Neutral conditions**  $\Gamma_{\text{env}} = \Gamma_{\text{DALR}}$

Occur on windy days or when there is a cloud cover such as that strong heating or cooling of the earth's surface does not occur.

✓ Mechanical turbulence

- **Unstable conditions**  $\Gamma_{\text{env}} > \Gamma_{\text{DALR}}$

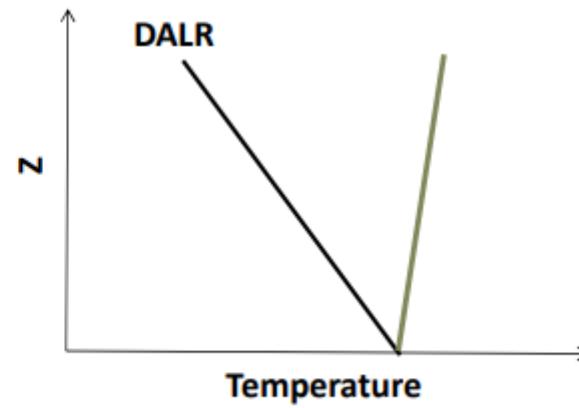
Develop on sunny days with low wind speeds.

✓ Mechanical turbulence + thermal induced turbulence

- **Stable conditions**  $\Gamma_{\text{env}} < \Gamma_{\text{DALR}}$

Occur at night when there is little or no wind.

When air temperature increases with altitude an inversion occurs. Inversions are directly related to pollutant concentrations in the ambient air, since they inhibit vertical movements and the dispersion of air pollutants. The most common inversion type is **radiation inversion** and occurs when the earth's surface cools rapidly.



## STABILITY AND PLUME BEHAVIOR

The stability of the air (vertical air movement) together with the horizontal air flow influences the behavior of plumes from stacks. Thus, watching smoke plumes provides a clue to the turbulence of the atmosphere, and knowing the stability yields important information about the dispersion of pollutants.

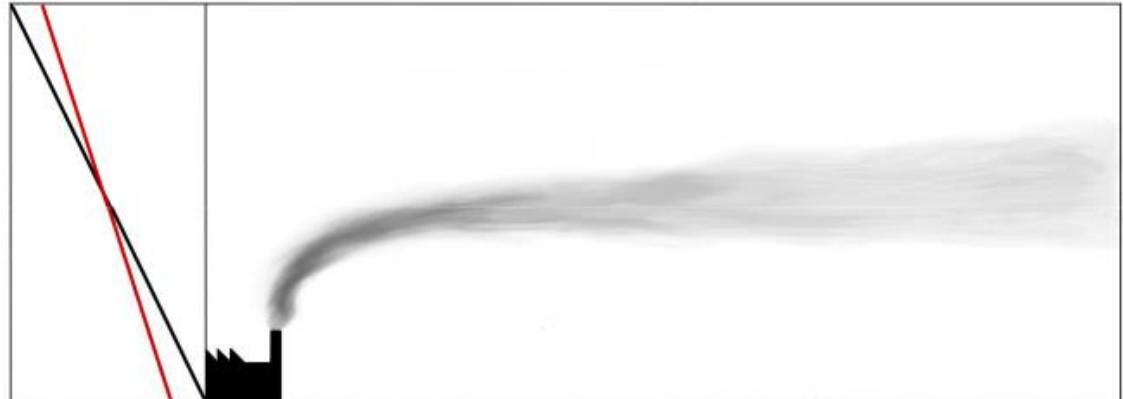
Next figure depicts early morning conditions. The winds are light, and a radiation inversion extends from the surface to above the height of the stack. In this **stable** environment, there is little up and down motion, so the smoke spreads horizontally rather than vertically. The smoke plume resembles the shape of a fan: **fanning smoke plume**.



Later in the morning, the surface air warms quickly and destabilizes as the radiation inversion gradually disappears. In **neutral** conditions, the **coning smoke plume** occurs.

If daytime heating of the ground continues, the depth of atmospheric instability increases. Light-to-moderate winds combine with rising and sinking air to cause the smoke to move up and down in a wavy pattern, producing a **looping smoke plume**.

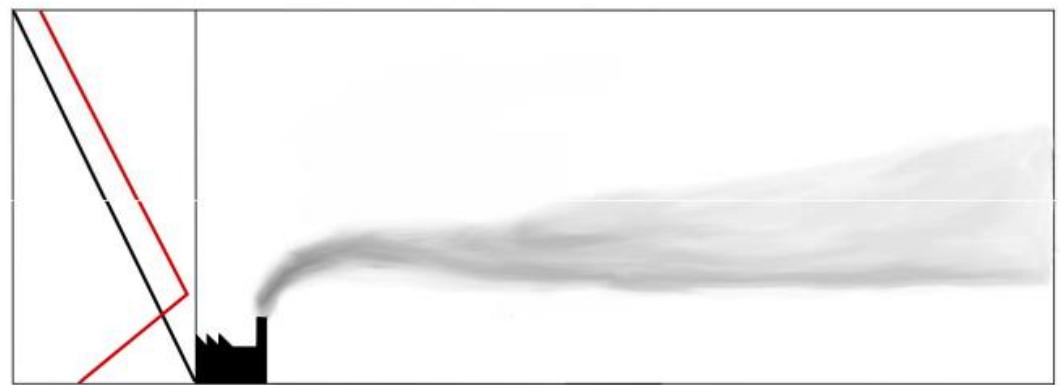
While **unstable** conditions are generally favorable for pollutant dispersion, momentarily high-ground level concentrations can be registered if the plume loops downward to the surface: **fumigation**.



Coning (top) and looping (bottom)

A major problem for pollutant dispersion is an **inversion** layer, which acts as a barrier to vertical mixing. The height of the stack in relation to the height of the inversion layer influence ground-level pollutant concentrations during an inversion.

When conditions are unstable above an inversion the release of a plume above the inversion results in effective dispersion without noticeable effects on ground level concentrations around the source. This condition is known as **lofting**.



If the plume is released under an inversion layer, a serious air pollution situation could develop. As the ground warms in the morning, air below an inversion layer becomes unstable. When the instability reaches the level of the plume that it is still trapped below the inversion layer, the pollutants can be rapidly transported down toward the ground. This is known as **fumigation**.

If the air below the inversion is neutral, vertical movements are blocked and the plumes are trapped below this layer. This is **trapping** (not shown). It should therefore be apparent why taller chimneys have replaced many of the shorter ones. Although these tall stacks can prevent fumigation and trapping, thus improving the air quality in their immediate area, they may also contribute to larger scale problems by allowing the pollutants to be swept great distances downwind.

