Advanced Waste Gas Treatment

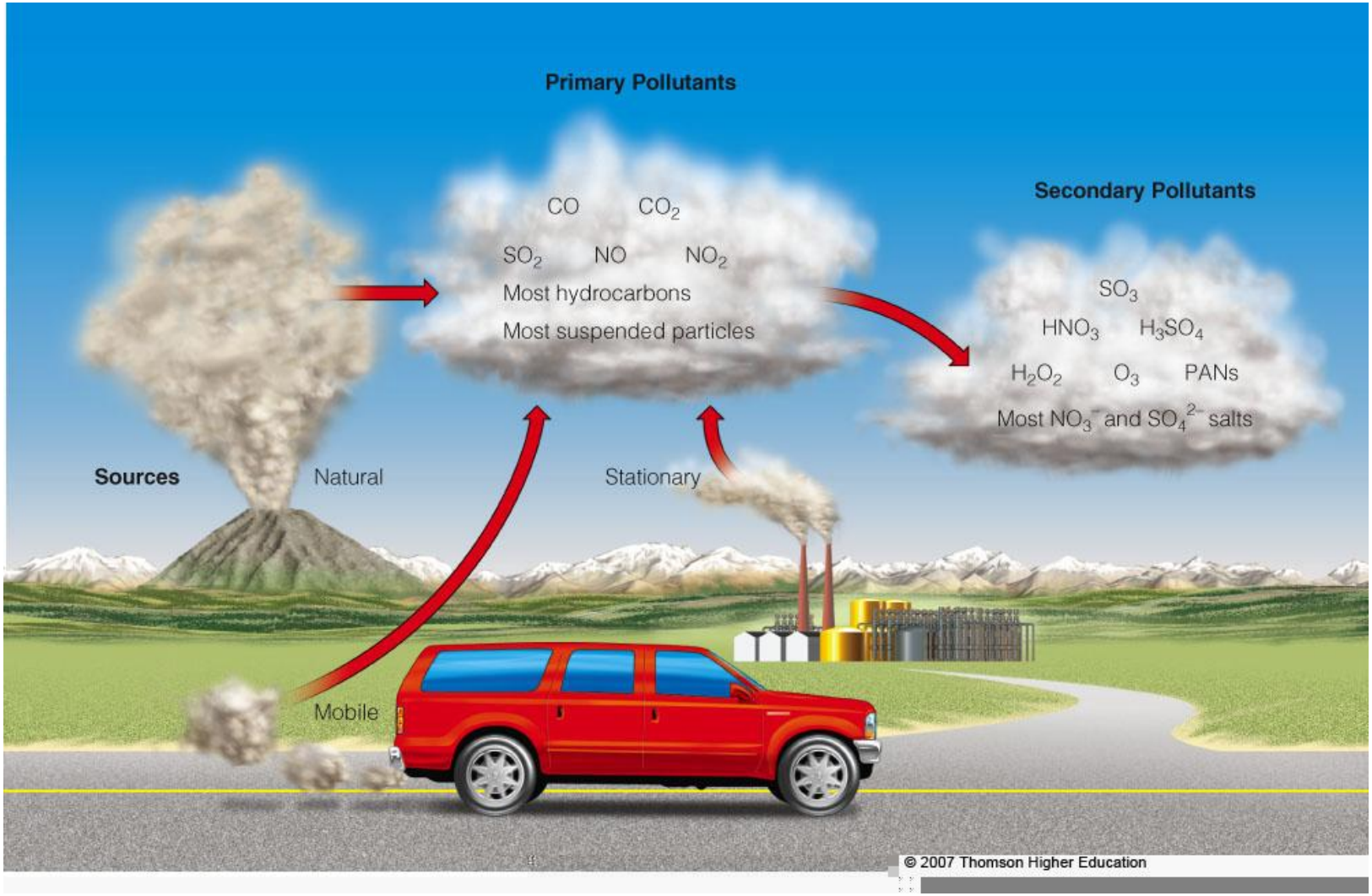
Introduction

Atmospheric dispersion

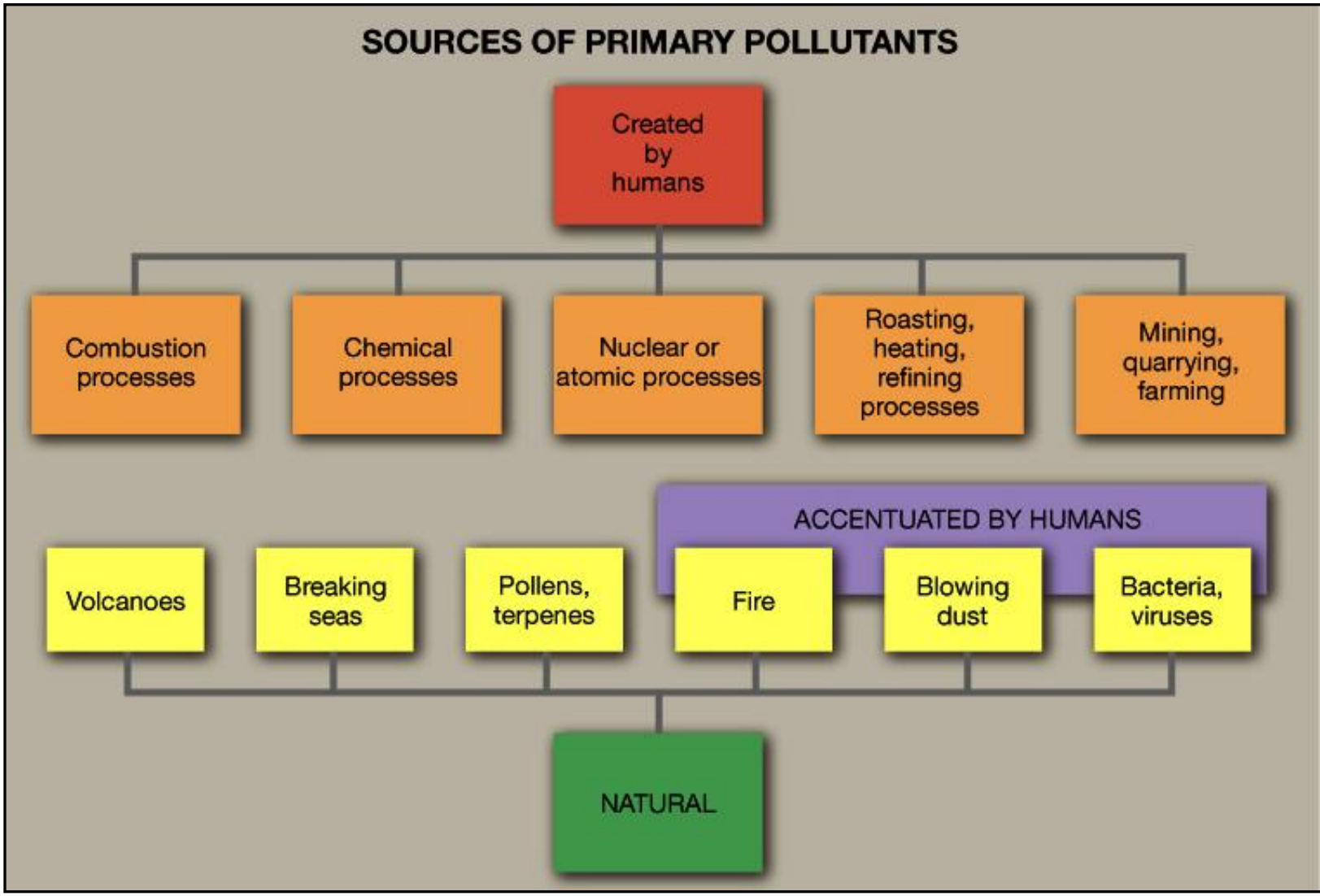
Gases
Sox, Nox, VOC …

Particulate matter

1. Introduction

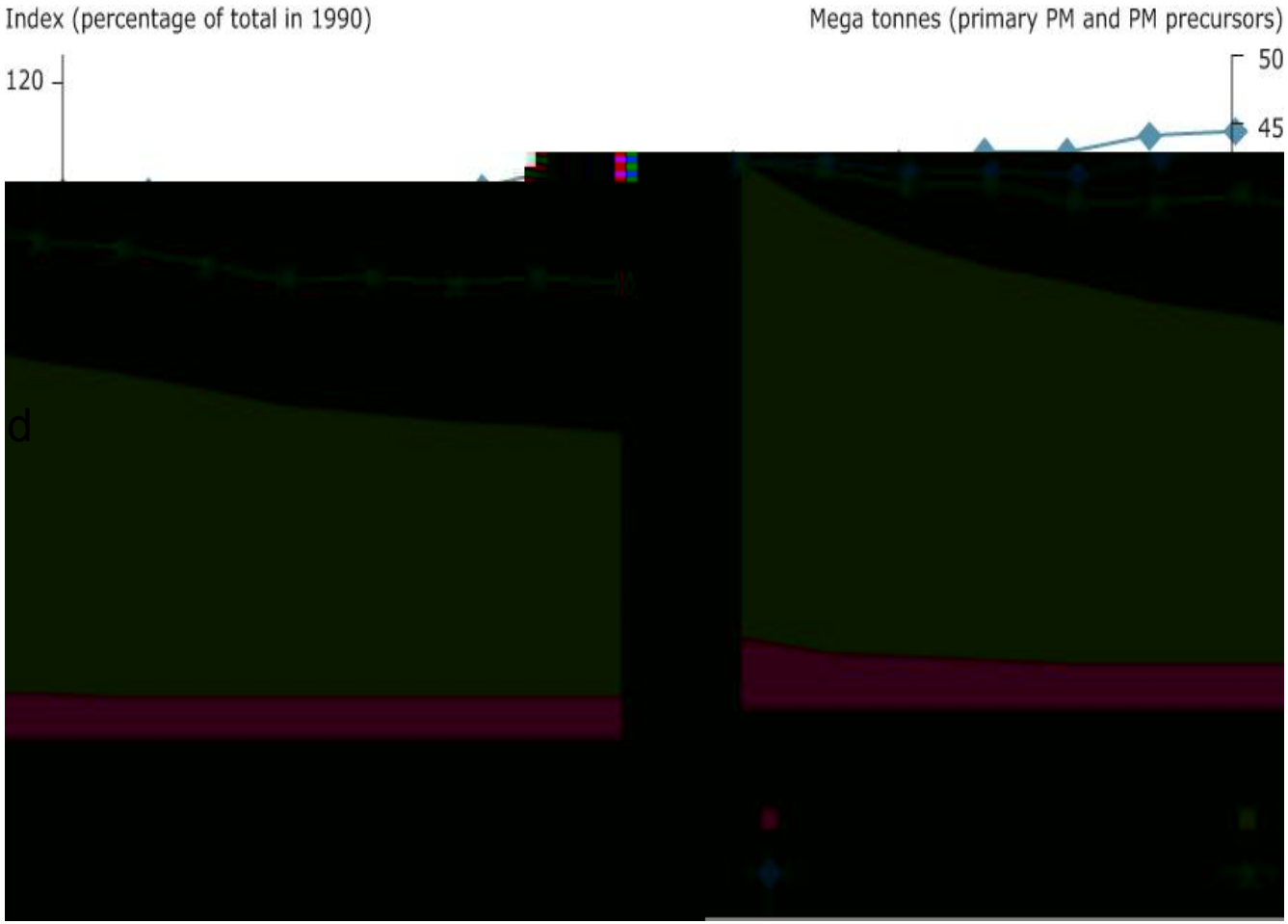


SOx
NOx
VOC
CO
NH3
PM
…



Emissions of primary and secondary PM10 (1990-2004) in Europe

- Primary and secondary emissions declined by 45%
- SO2 and NOx remain important contributors to total PM10 formation



- Outdoor versus Indoor

Ç sources: buiding materials; heat production (cooking);
– furniture; tobacco; consumer products; chemicals from
– biological origin (mycoto

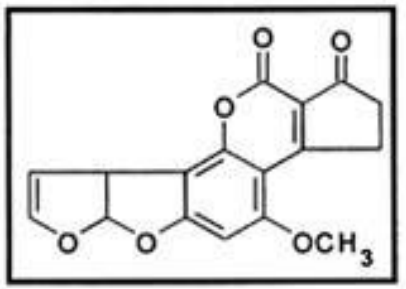


Figure 2. Structure of Aflatoxin B_2

Ç influx from outdoor

Ç concentrations higher

Ç various chemicals: PAHs
– Formaldehyde, nicotine, …

Flow measurement

Pitot–Static Tube

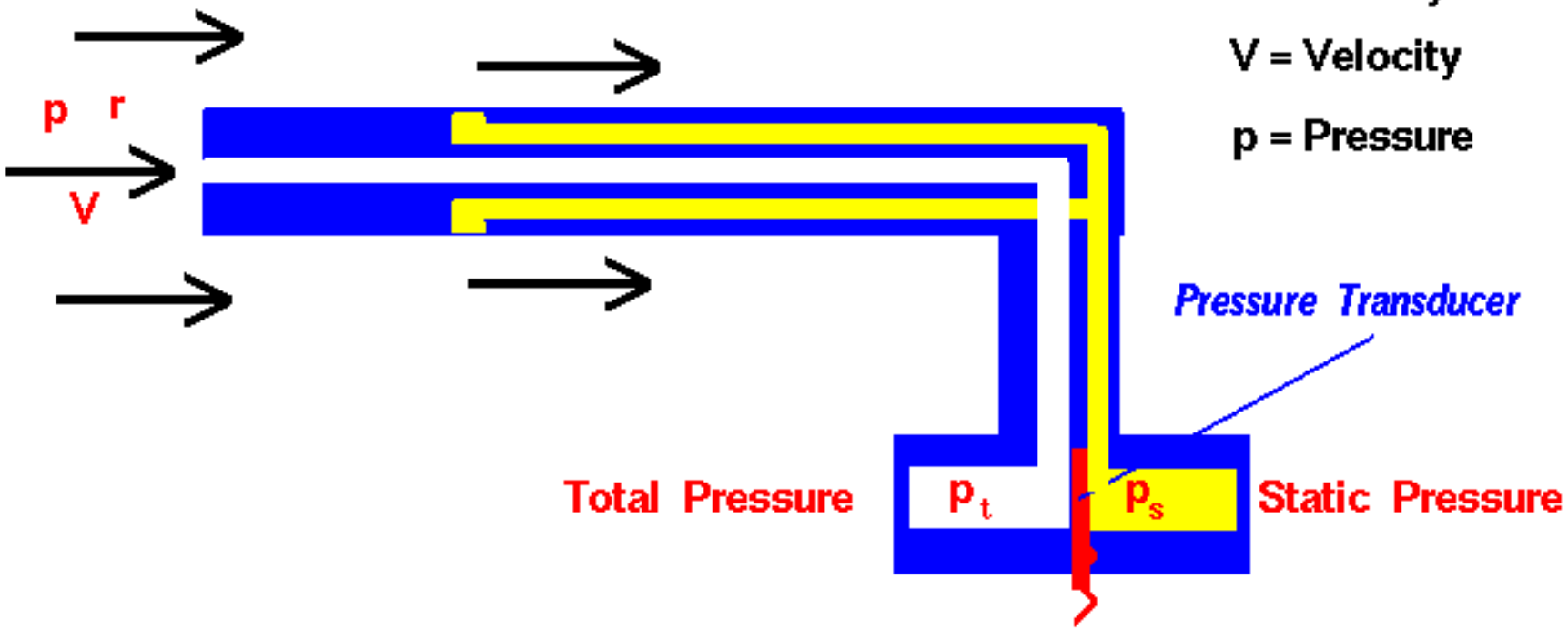
Prandtl Tube

Glenn Research Center

r = Density

V = Velocity

p = Pressure



Measure difference in total and static pressure

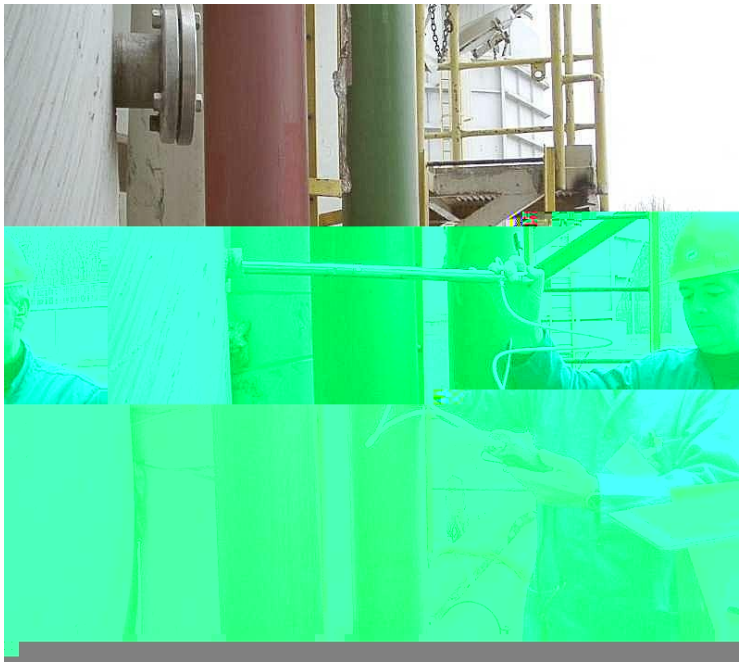
Bernoulli's Equation:

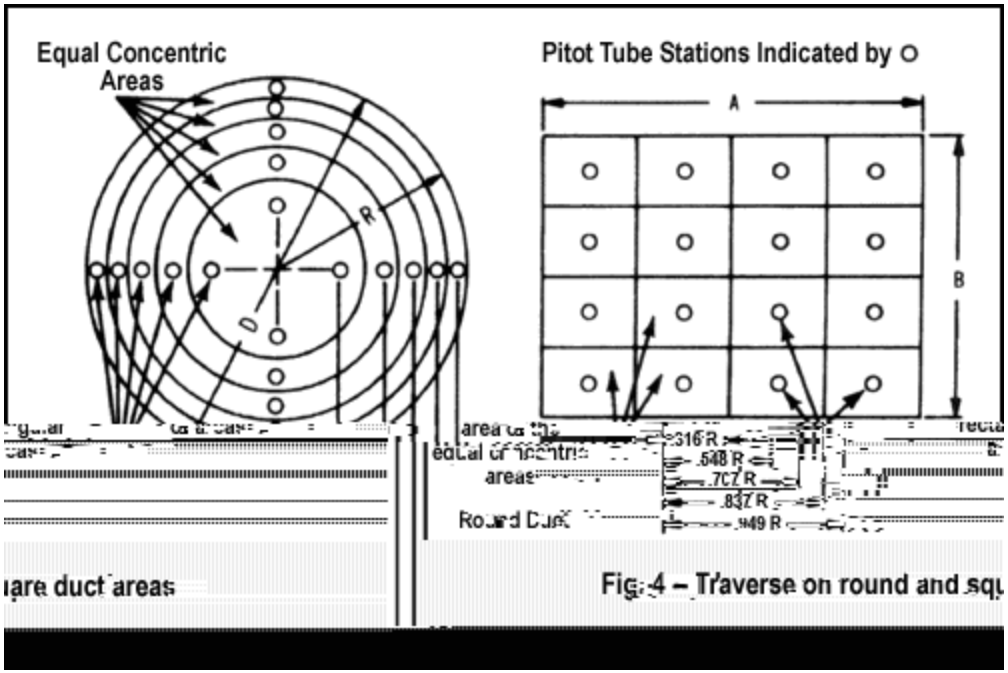
static pressure + dynamic pressure = total pressure

$$\left(p_s + r \times \frac{V^2}{2} \right) = p_t$$

Solve for Velocity:

$$V^2 = \frac{2(p_t - p_s)}{r}$$




Equal Concentric
Areas
Pitot Tube Stations Indicated by
A
B
R
.316 R
.548 R
.707 R
.837 R
.949 R
areas
Round Duct
are duct areas
Fig. 4 – Traverse on round and squ

AIR: compressibility: DRY
Standard conditions (273 K; 101.3 kPa)

T [°C]	p [kPa]
0	0,60
10	1,21
20	2,32
30	4,22
40	7,36
50	12,33
60	19,92
70	31,17
80	47,36
90	70,11
100	101,32

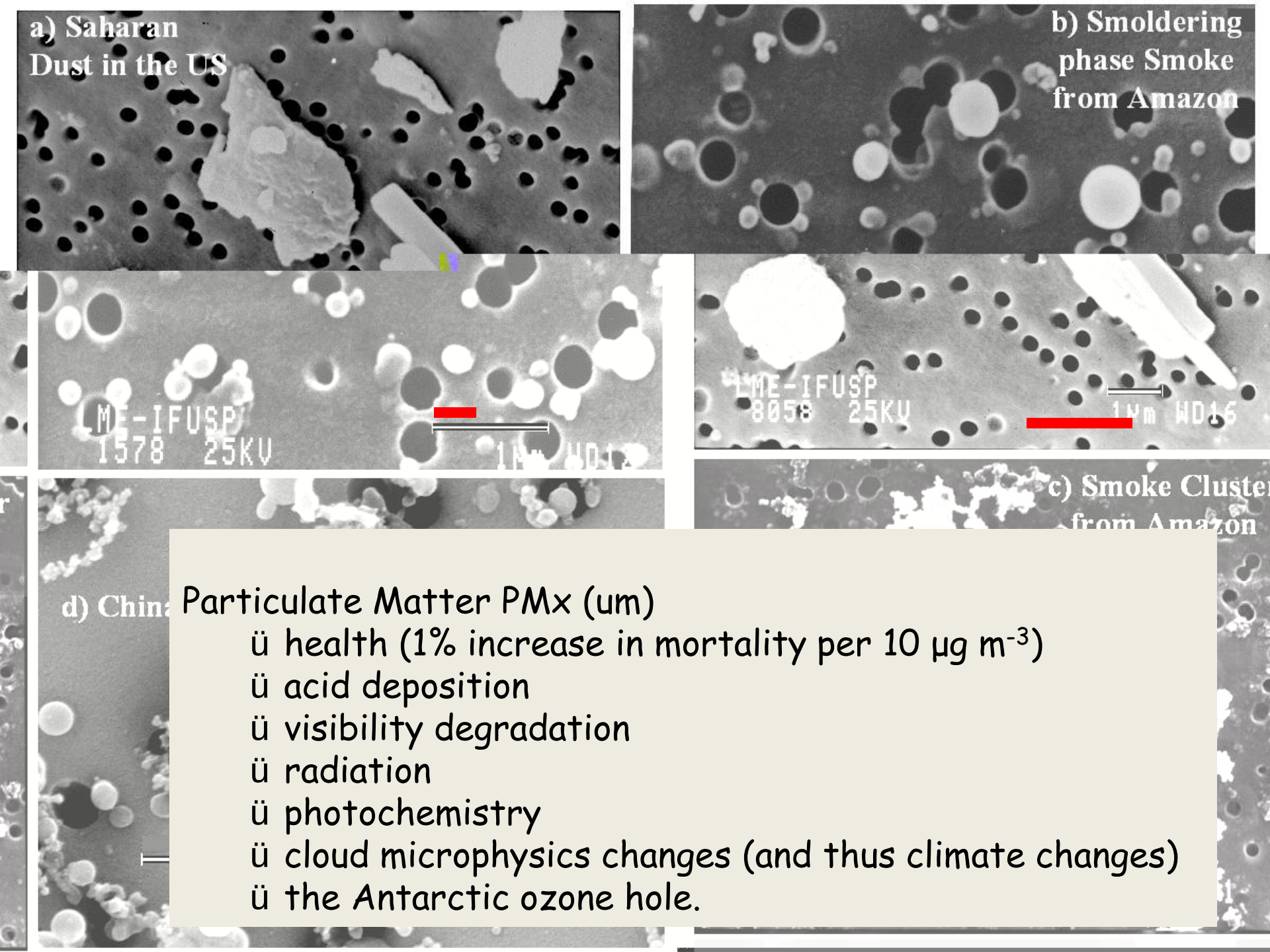
DATA:

volumetric flow	10000	m^3/h
temperature:	65	°C
conc.	15	mg/m^3
r.h.	100	%

Regulation:

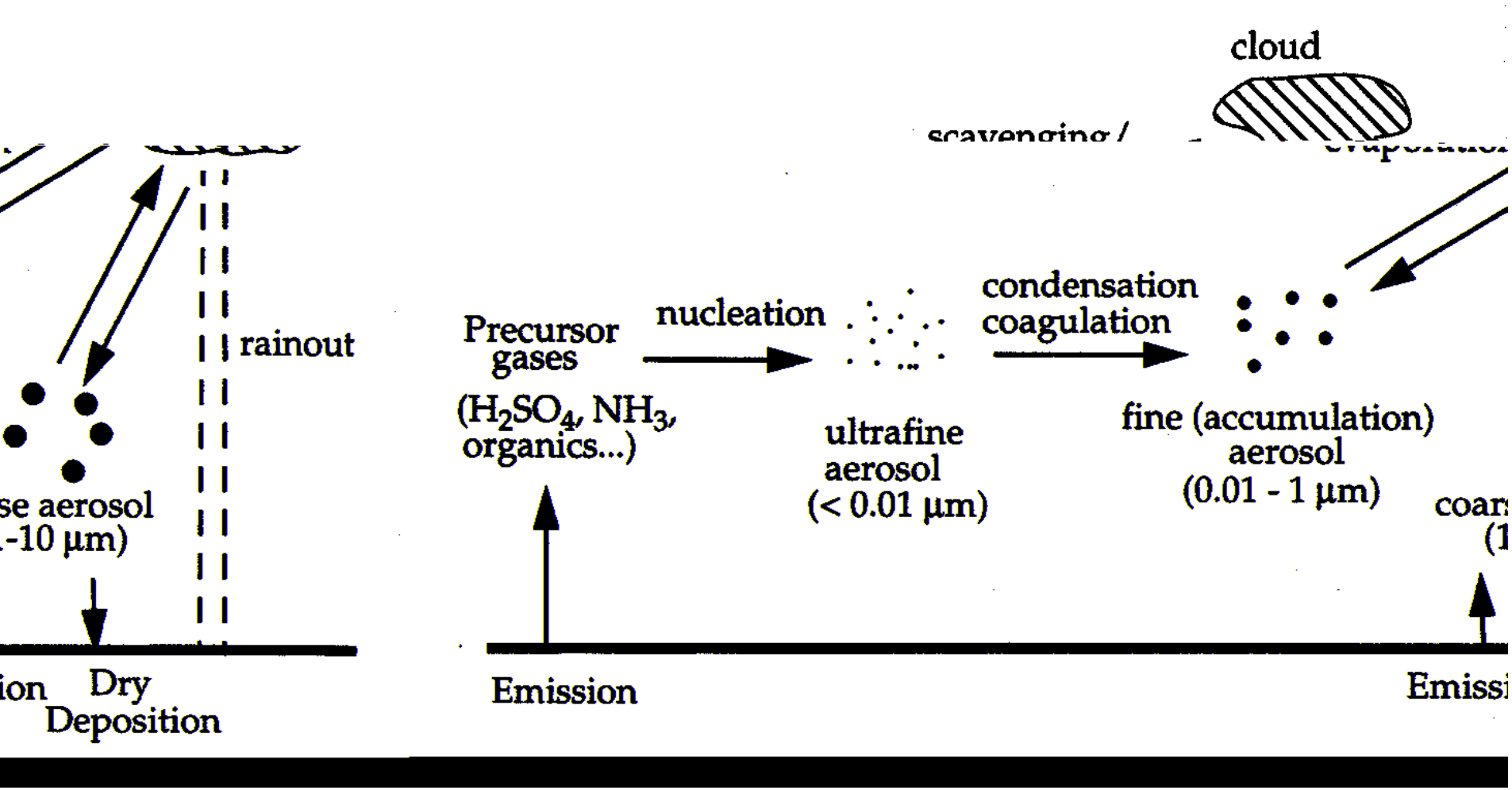
mass threshold:	100	g/h
max. Conc. emission	20	g/m^3

Does this emission complies regulation?
What would be the max rh in order to comply.



Particulate Matter PMx (um)

- ü health (1% increase in mortality per 10 μg m^{-3})
- ü acid deposition
- ü visibility degradation
- ü radiation
- ü photochemistry
- ü cloud microphysics changes (and thus climate changes)
- ü the Antarctic ozone hole.


cloud
rainout
Precursor gases
(H_2SO_4, NH_3, organics...)
nucleation
ultrafine aerosol
(< 0.01 µm)
condensation
coagulation
fine (accumulation) aerosol
(0.01 - 1 µm)
Dry Deposition
Emission

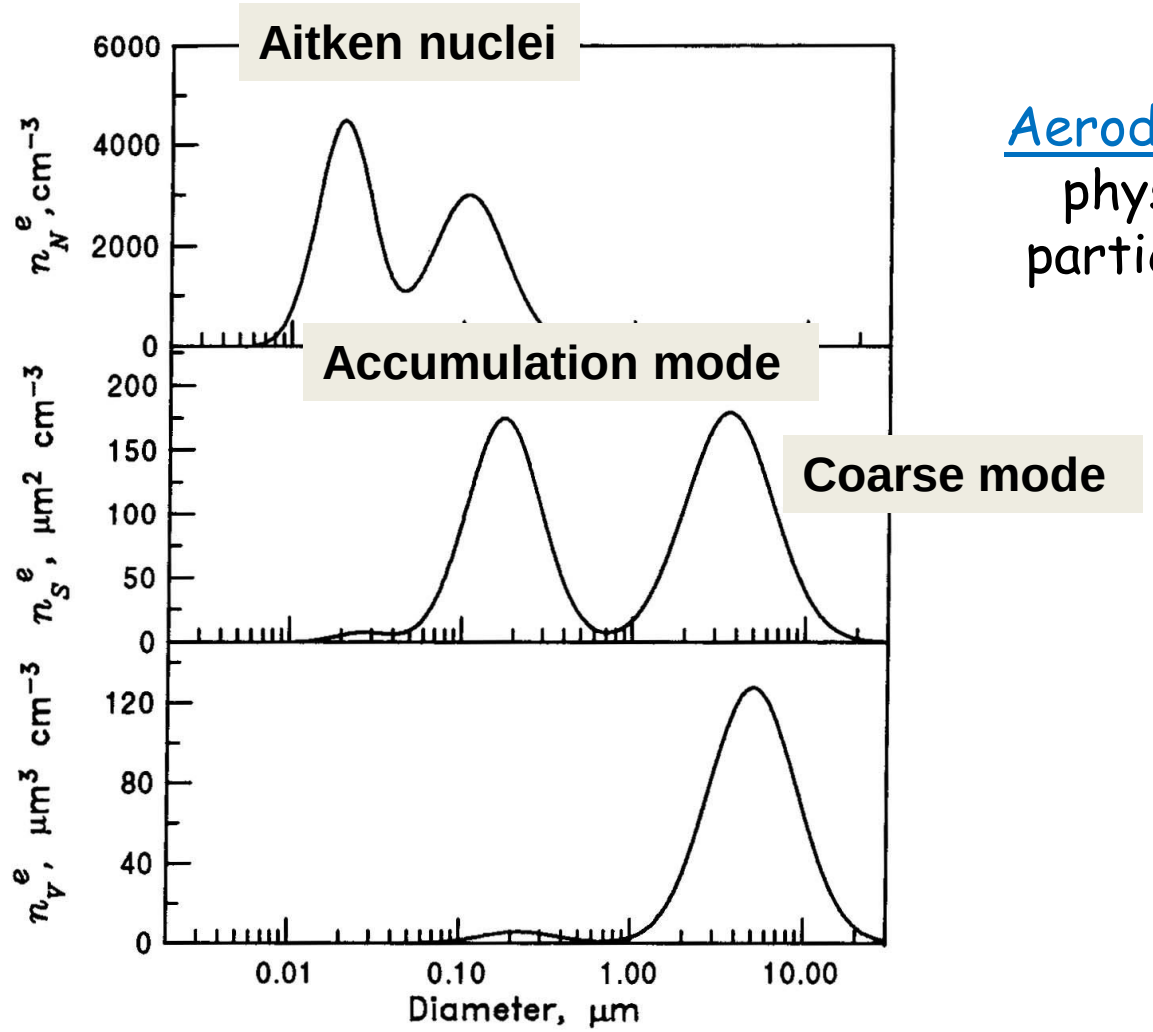
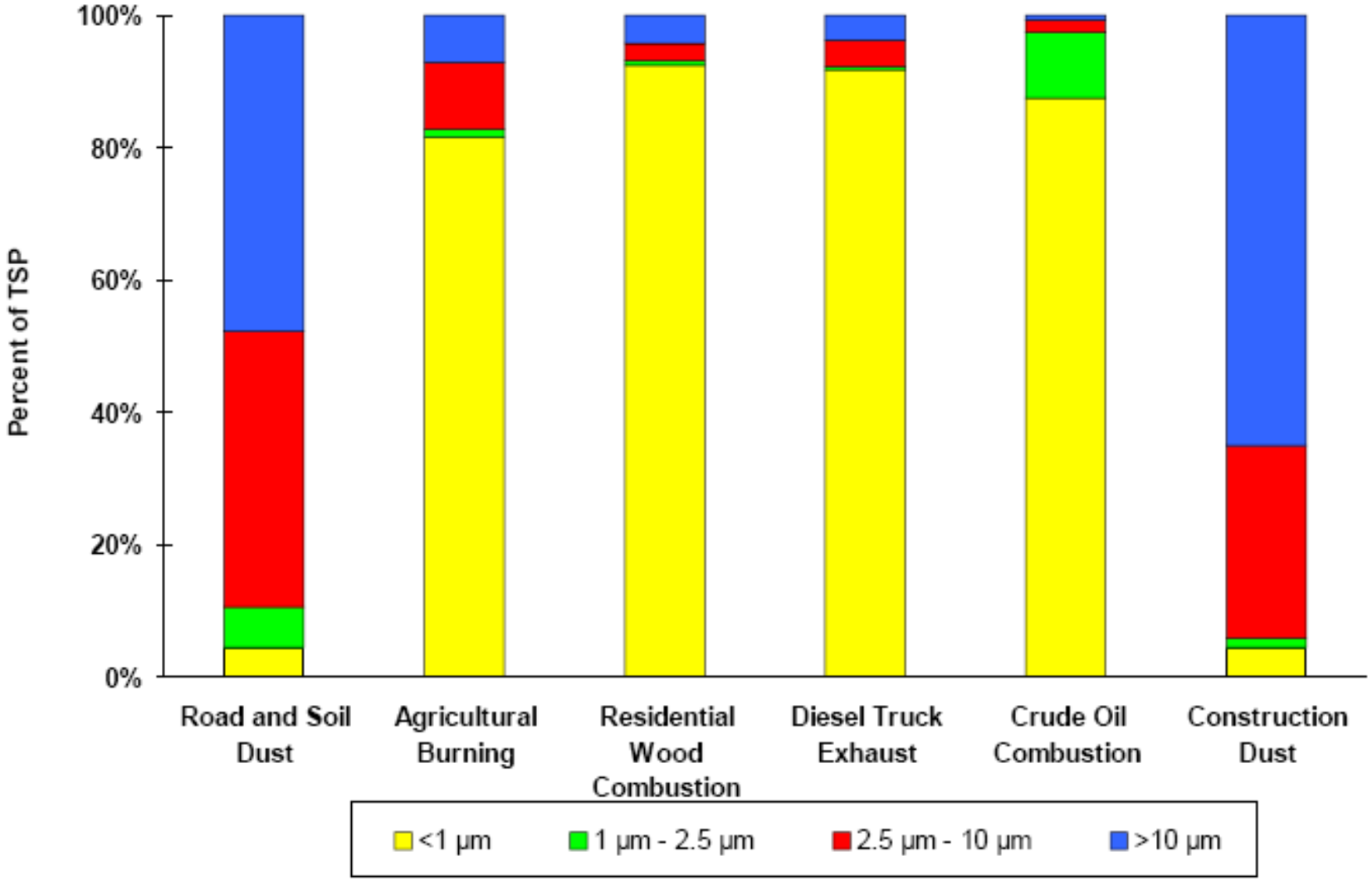


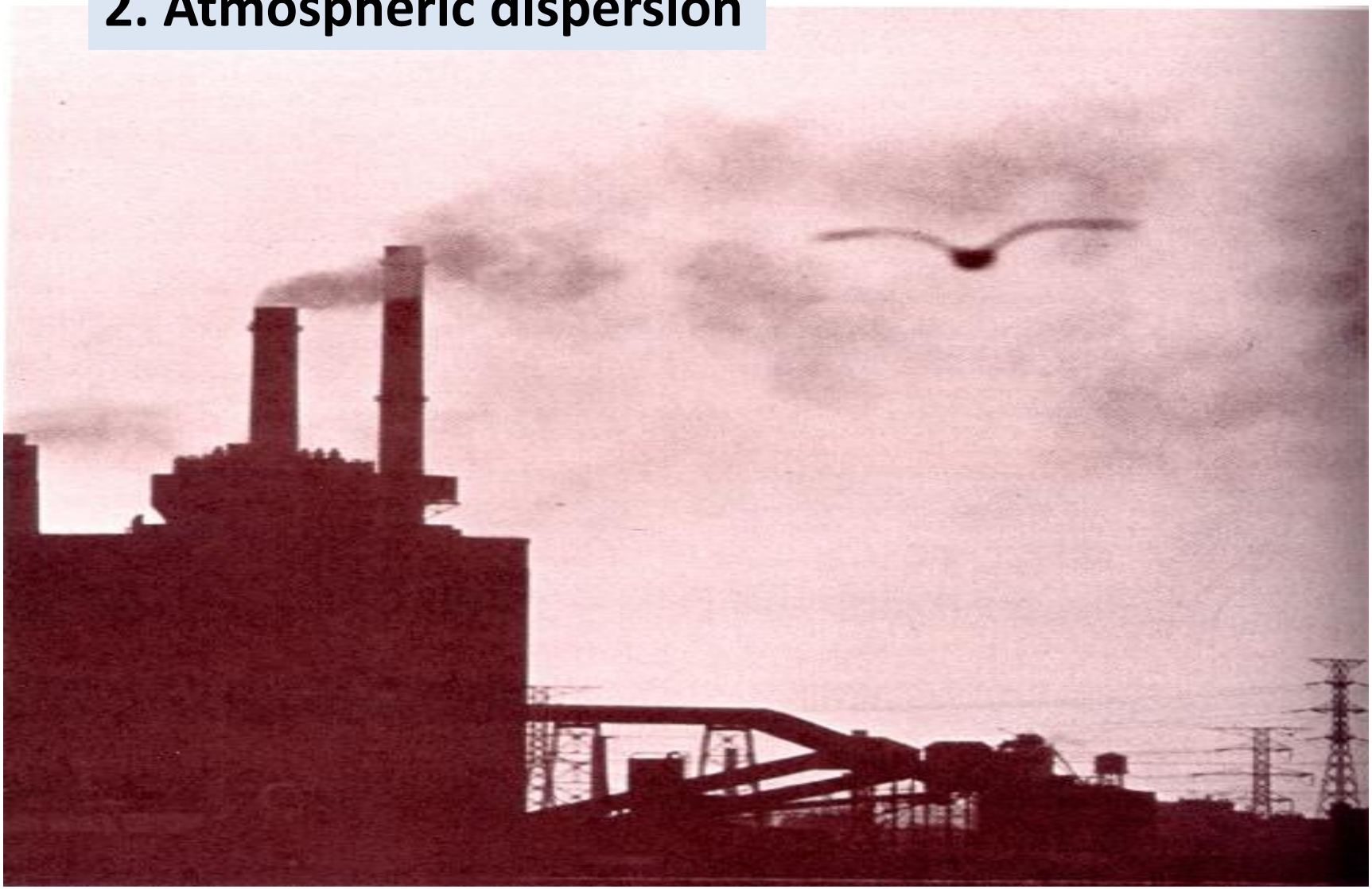
FIGURE 7.6 The same aerosol distribution as in Figures 7.4 and 7.5 expressed as a function of log D_p and plotted versus log D_p. Also shown are the surface and volume distributions. The areas below the three curves correspond to the total aerosol number, surface, and volume, respectively.

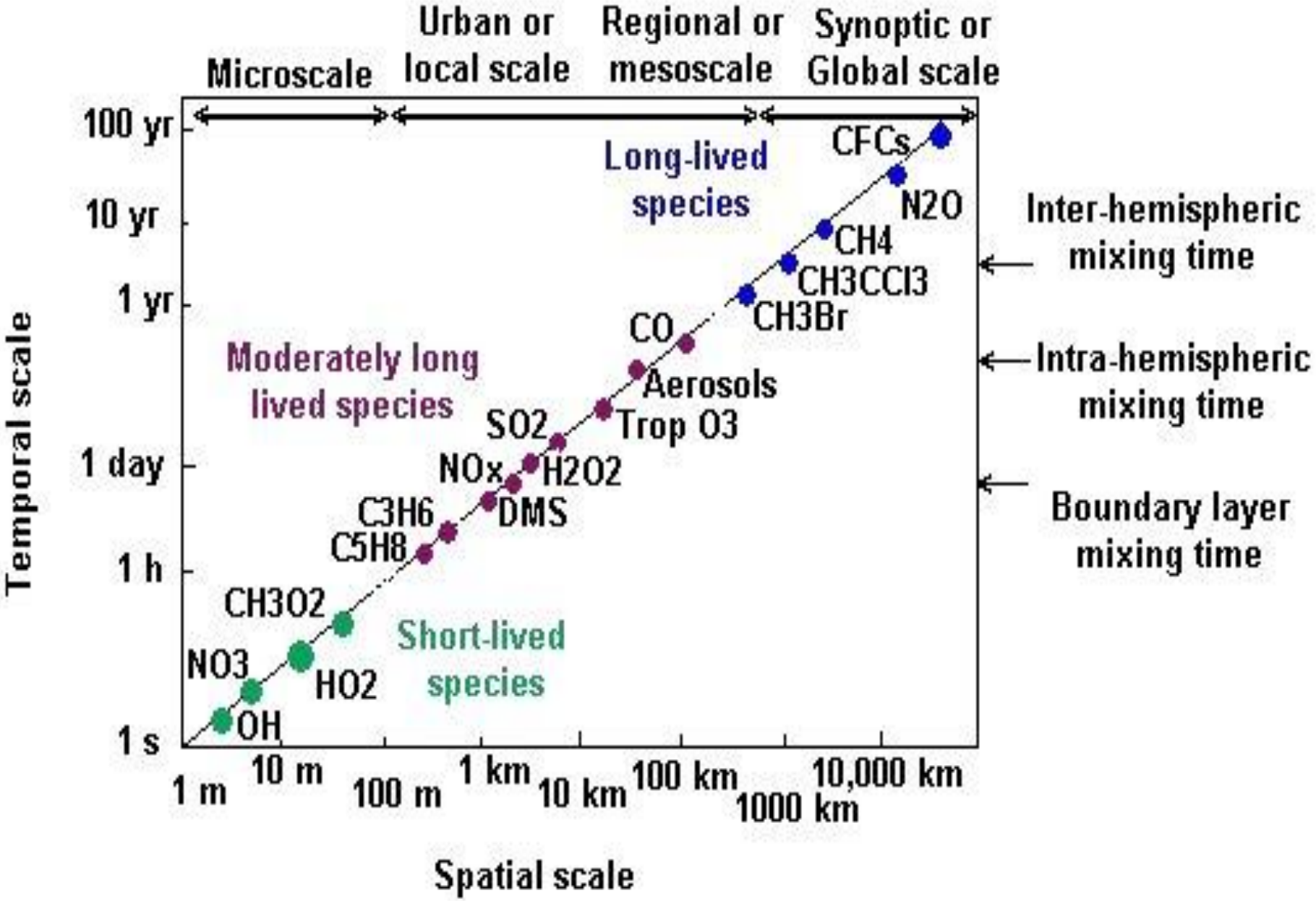
Aerodynamic diameter is a physical property of a particle in a viscous fluid such as air

Size Distributions of Several Particulate Source Emissions



2. Atmospheric dispersion




Microscale
Urban or local scale
Regional or mesoscale
Synoptic or Global scale
100 yr
10 yr
1 yr
1 day
1 h
1 s
Temporal scale
Long-lived species
CFCs
N2O
CH4
CH3CCl3
CH3Br
Moderately long lived species
CO
Aerosols
Trop O3
SO2
NOx
H2O2
DMS
C3H6
C5H8
Short-lived species
CH3O2
NO3
HO2
OH
Inter-hemispheric mixing time
Intra-hemispheric mixing time
Boundary layer mixing time
1 m
10 m
100 m
1 km
10 km
100 km
1000 km
10,000 km
Spatial scale

Assumptions for Model Development

Steady-State Conditions	Mass Conservation	Boundary Conditions
Constant emission rate	No deposition	No lower bounding surface (earth's surface)
Constant wind speed and direction	No chemical transformation	No upper bounding surface (elevated inversion)
	No radioactive decay	

Factors in Modeling a Continuous Source

$$\text{Concentration} = (\text{Emission Rate})(\text{Dilution})(\text{Dispersion})$$

Source parameter

$$\frac{\text{mass}}{\text{volume}} = \left(\frac{\text{mass}}{\text{time}}\right)\left(\frac{1}{\frac{\text{length}}{\text{time}}}\right)\left(\frac{1}{\text{length}}\right)^2$$

meteo

thermal, mechanical roughness

Basic Dispersion Equation

$$C(x,y,z) = Q\left(\frac{1}{u}\right)\frac{1}{\sqrt{2}\,\sigma_y}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\frac{1}{\sqrt{2}\,\sigma_z}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

$$C(x,y,z) = \frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)\right]$$

Dispersion Equation Including Source Height, *h*

$$C(x,y,z;h) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{(z-h)^2}{\sigma_z^2}\right)\right]$$

h = effective height = geometric + plume rise

Dispersion Equation Accounting for a Reflecting Lower Barrier

$$C(x,y,z;h) = \frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}+\frac{(z-h)^2}{\sigma_z^2}\right)\right]$$

$$+\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}+\frac{(z+h)^2}{\sigma_z^2}\right)\right]$$

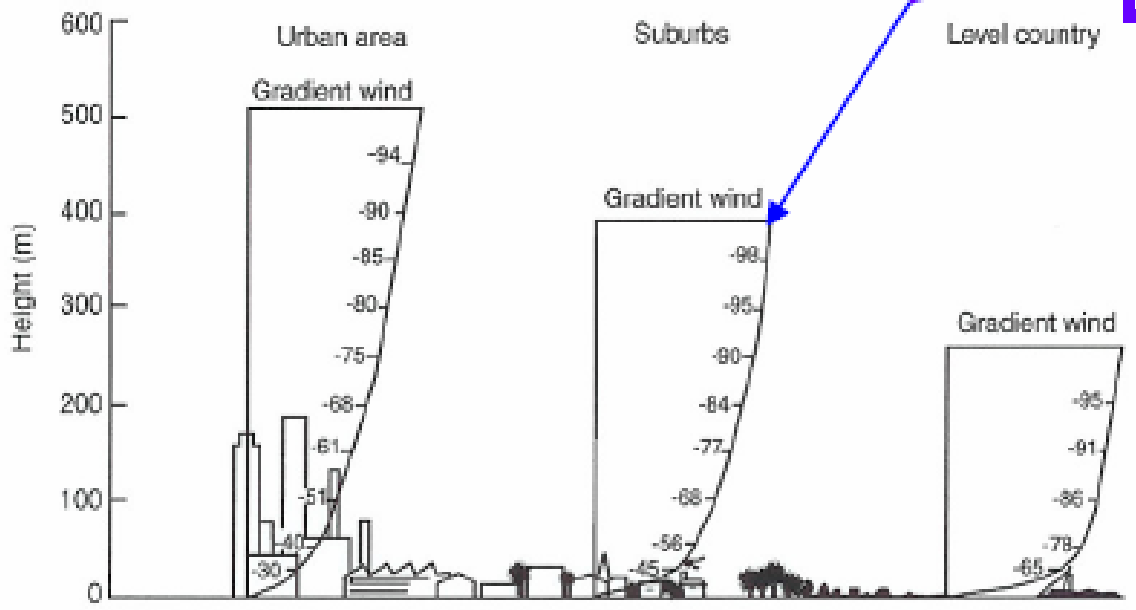
or

$$C(x,y,z;h) = \frac{Q}{2\ u\sigma_y\sigma_z}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right\}$$

The two components in describing wind → speed and direction, are affected by:

- Horizontal pressure gradients
- Horizontal temperature gradients
- Friction related to surface roughness

Maximum height of wind profiles indicate where effects of surface roughness end and where "gradient wind" (GW) begins



Numbers refer to % of the GW

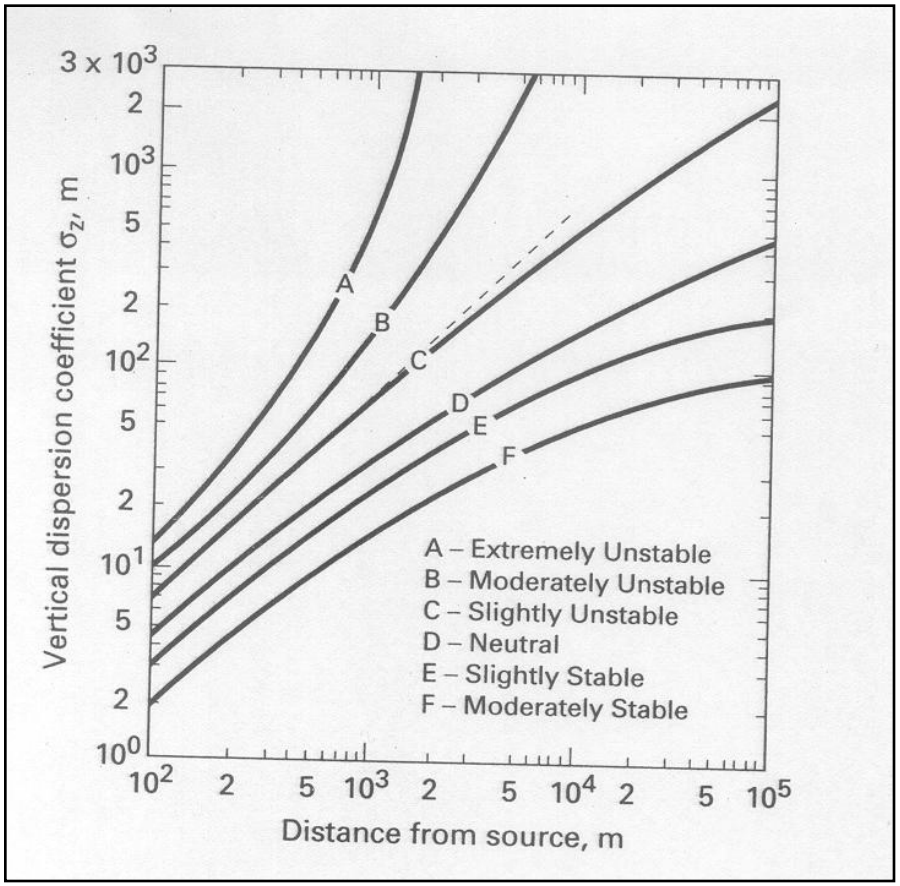
GW → blow parallel to the isobars (caution: though not necessarily equal to geostrophic winds)

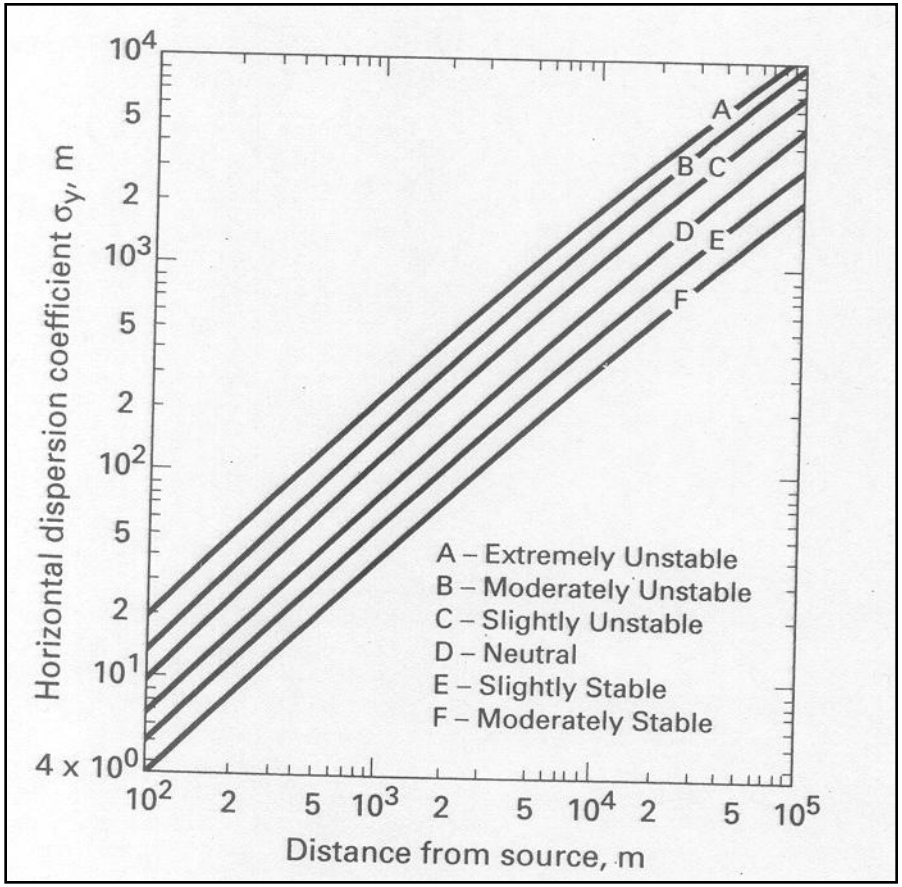
From Air Pollution: Its Origin and Control" by Wark, K., Warner, C.F. and Davis,W.T.

Class	S > 0	S < 0	u (m s^{-1})
E1	$\geq$ 2.75		$\leq$ 11
E2	1.75 < < 2.75		$\leq$ 11
E3	$\leq$ 1.75	$\leq$ 2	$\leq$ 11

Bultynck-Malet classes $\sigma_y = A\, x^a \qquad \sigma_z = B\, x^b$

class	A	a	B	b
E1	0,235	0,796	0,311	0,711
E2	0,297	0,796	0,382	0,711
E3	0,418	0,796	0,520	0,711
E4	0,586	0,796	0,700	0,711
E5	0,826	0,796	0,95	0,711
E6	0,946	0,796	1,321	0,711
E7	1,073	0,698	0,819	0,669


Vertical dispersion coefficient σ_z, m
3 x 10^3
2
10^3
5
2
10^2
5
2
10^1
5
2
10^0
A
B
C
D
E
F
A – Extremely Unstable
B – Moderately Unstable
C – Slightly Unstable
D – Neutral
E – Slightly Stable
F – Moderately Stable
10^2 2 5 10^3 2 5 10^4 2 5 10^5
Distance from source, m


Horizontal dispersion coefficient σ_y, m
10^4
5
2
10^3
5
2
10^2
5
2
10^1
4 x 10^0
A
B
C
D
E
F
A – Extremely Unstable
B – Moderately Unstable
C – Slightly Unstable
D – Neutral
E – Slightly Stable
F – Moderately Stable
10^2 2 5 10^3 2 5 10^4 2 5 10^5
Distance from source, m

$$H = h + \frac{u_s.d}{u}\left[1.5 + 2.68\times10^{-3}.P.d.\frac{T_s - T_a}{T_s}\right]$$

H = effective height of plume (m)
h = stack height (m)
u_s = stack exit velocity (m/s)
u = wind velocity (m/s)
d = diameter (m)
P = pressure (mbar)
T_s= gas temperature at exit of stack (K)
T_a= ambient air temperature at stack height (K)

Building downwash

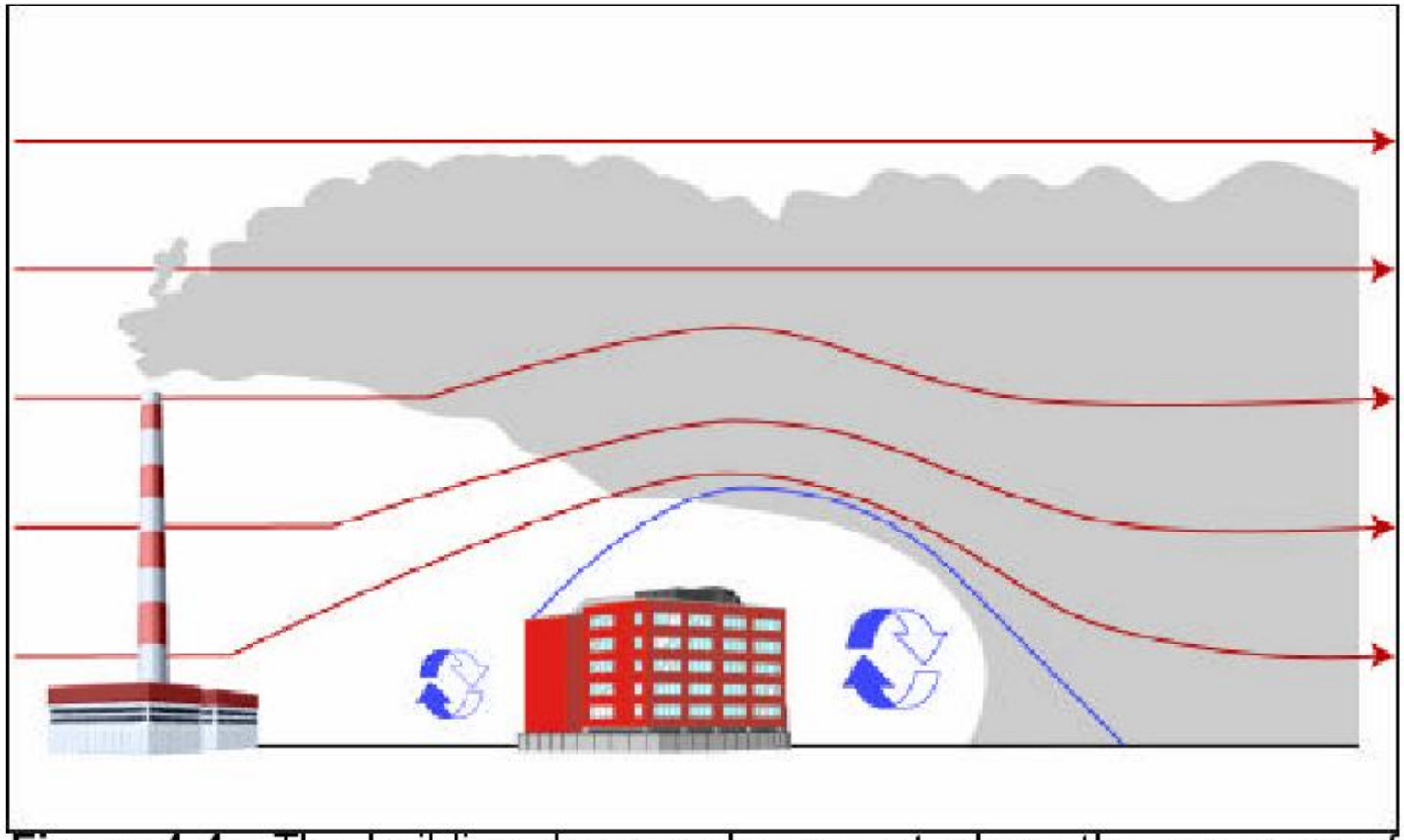


Figure 4.4 - The building downwash concept where the presence of buildings forms localized turbulent zones that can readily force pollutants down to ground level.

OVERVIEW

- Basic principles: bi-Gaussian; dispersion parameters;

- For 1 set of meteorological conditions

- Applicable for evaluation of annual average situations
  - emission data
  - meteorological data:
    - wind direction
    - wind speed
    - stability class

- calculation of averages; percentiles …

Macromedia Flash Player 6

CALRoads View

An air dispersion modeling package for predicting air quality impacts of pollutants near roadways, CALRoads View features three mobile source dispersion models:

CAL3QHC -
Estimates total air pollutant con
PM) near highways from both m
vehicles. Also estimates the le
formed by idling vehicles at sig

CAL3QHCR -
An enhanced version of CAL3C
process up to a year of hourly
and vehicular emissions, traffic
signalization (ETS) data for eac

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3. VOC removal

3.1. Introduction

3.2. Phase-transfer removal technology

3.3. Thermal/chemical removal technology

3.4. Biological removal technology

3.1. Introduction

VOCs:

- USA:

“organic compounds that have a vapour pressure more than 13.3 Pa at 25 °C (ASTN test method D3960–90)

- European Union:

“organic compounds with a vapour pressure above 10 Pa at 20 °C (European VOC Solvents Directive 1999/13/EC)

-Australian National Pollutant Inventory:

“chemical compound based on carbon chains or rings (and also containing hydrogen) with a vapour pressure greater than 2 mm of mercury (0.27kPa) at 25 C, excluding methane”

VOC removal from waste gases:

(1) Selective removal by phase transfer:

gas changes into liquid: **condensation**

gas transferred to liquid: **absorption**

gas transferred to a solid surface: **adsorption**

gas transfer through a **membrane**

(2) Removal by VOC **oxidation** :

$$C_xH_y + (x + 0.25\,y)\,O_2 \;\longrightarrow\; x\,CO_2 + 0.5y\,H_2O$$

- <u>Types of oxidation</u>:
  - chemical/thermal
  - biological
- <u>Site of oxidation</u>:
  - in gas phase: without phase transfer
  - in another phase: after phase transfer

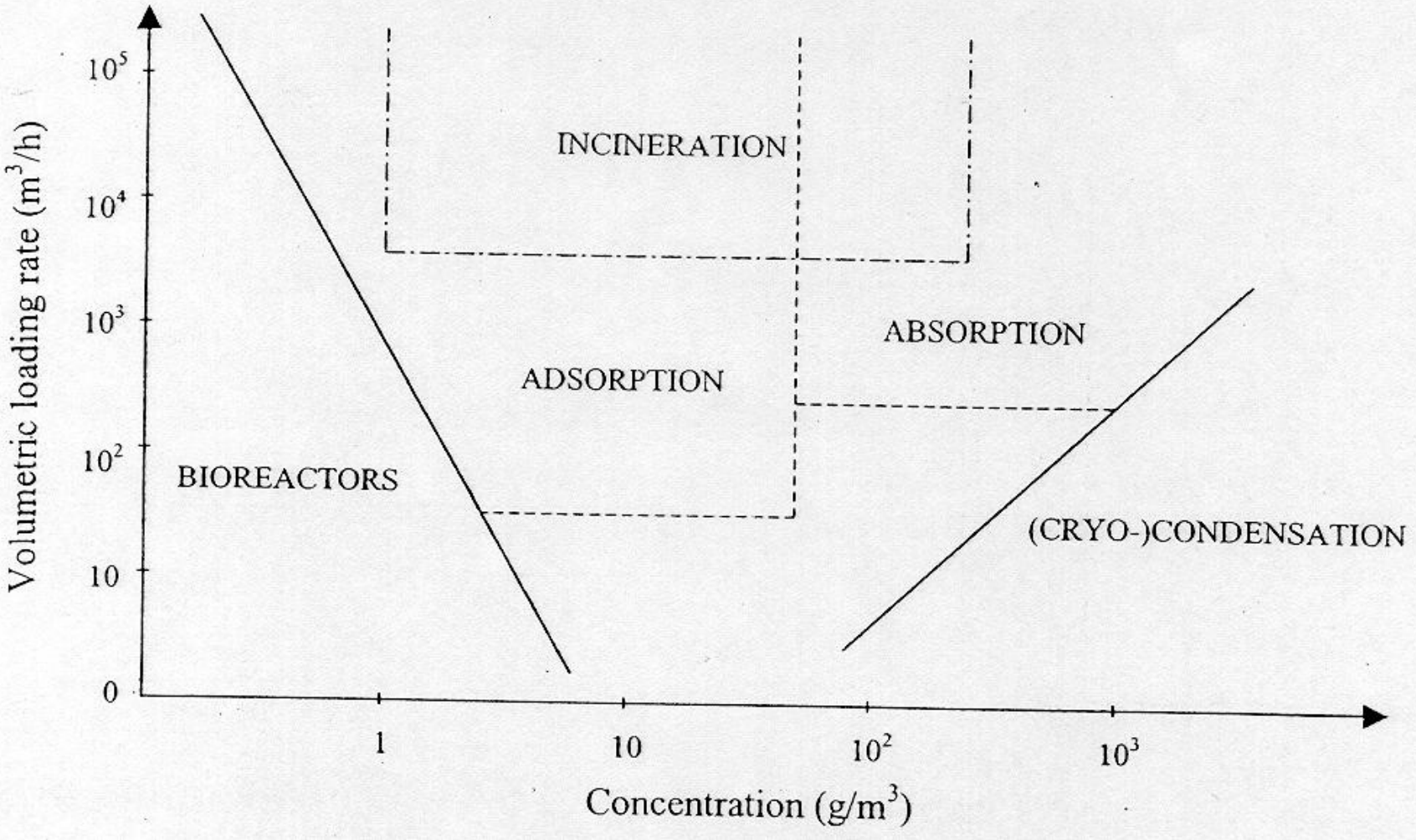
3.2. Phase transfer removal technology

4 technologies :
- condensation
- absorption
- adsorption
- membrane separation

Choice of technology determined by:

-Technical aspects:
- nature of VOC
- concentration VOC
- flow rate of waste gas
- temperature and pressure of waste gas

- Economics



Selection of VOC abatement technique depending on air flow rate and pollutant concentration

Condensation

Principle: cooling until VOCs are condensing:

Efficiency depends on:

- vapour pressure of compounds (‘condensability’)
- concentration or partial pressure of compounds
- temperature

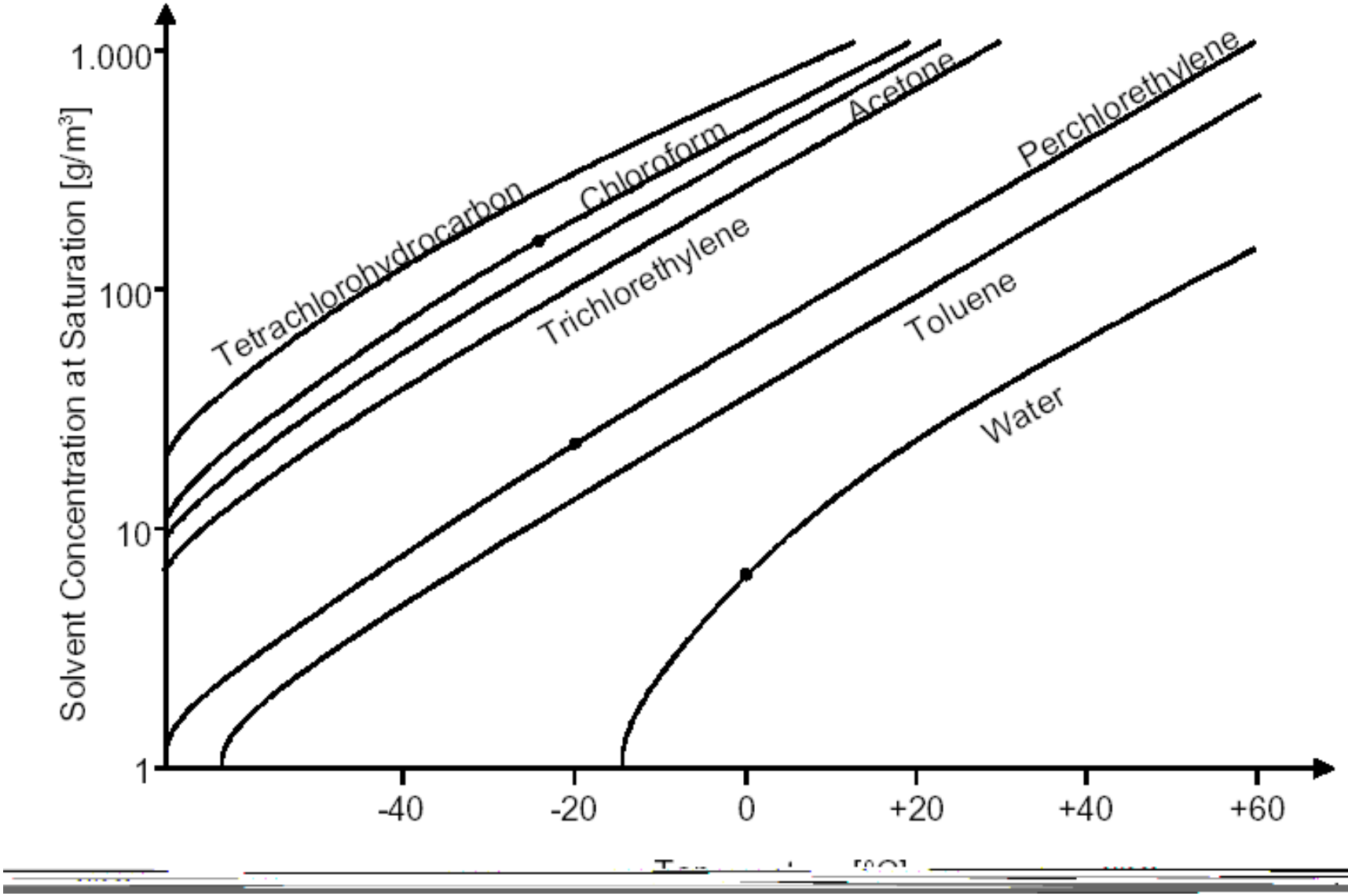
Two processes:

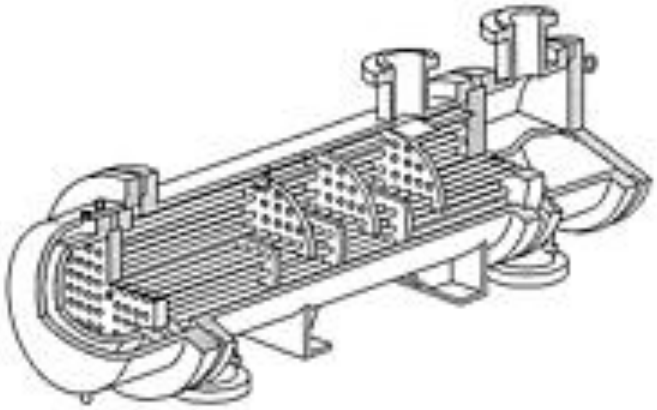
- indirect condensation:

  - Condensation of VOCs on a cooled surface
  - no direct contact with cooling agent
  - advantage: liquid product (condensate) is only VOCs

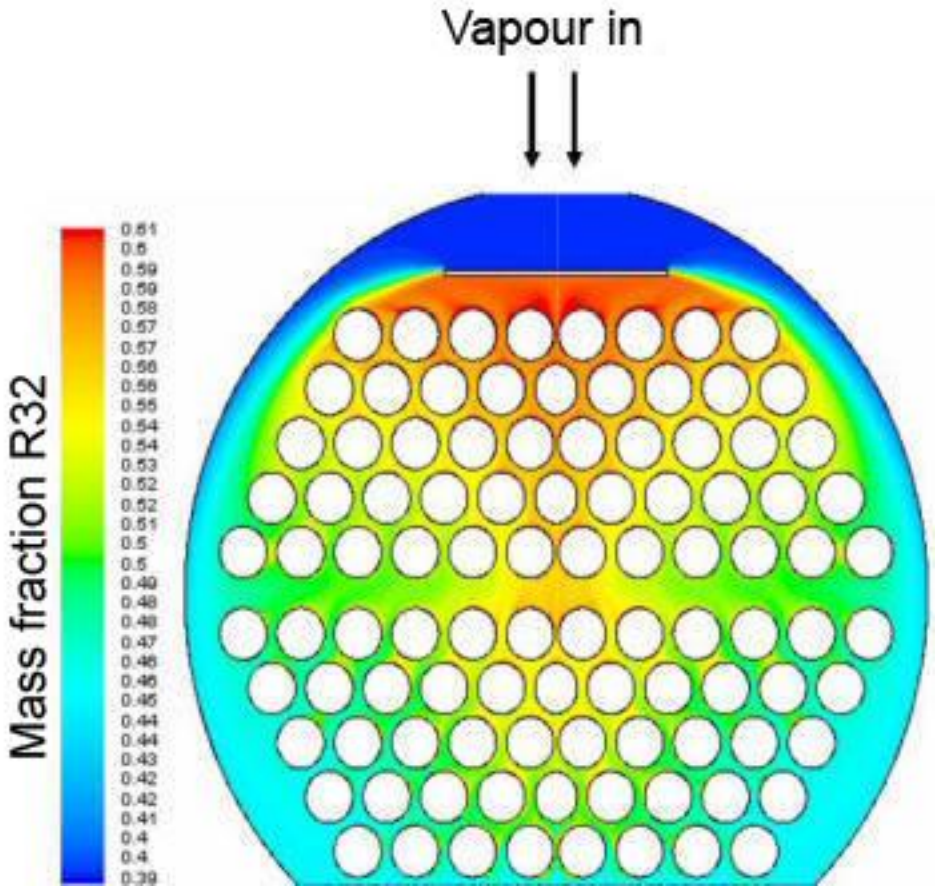
- direct condensation:

  - Condensation of VOCs through contact with cooling agent
  - gas and cooling agent in countercurrent
  - disadvantage: need of separation after process


1.000
100
10
1
Solvent Concentration at Saturation [g/m³]
Tetrachlorohydrocarbon
Chloroform
Acetone
Trichlorethylene
Perchlorethylene
Toluene
Water
-40
-20
0
+20
+40
+60



1
2
3
4
5


Vapour in
Mass fraction R32
0.61
0.6
0.59
0.59
0.58
0.57
0.57
0.56
0.56
0.55
0.54
0.54
0.53
0.52
0.52
0.51
0.5
0.5
0.49
0.48
0.48
0.47
0.46
0.46
0.45
0.44
0.44
0.43
0.42
0.42
0.41
0.4
0.4
0.39

Absorption:

Principle: selective transfer of VOCs into a liquid (absorbent)

Absorption = scrubbing = gas to liquid transfer

Two variants:
- Physical absorption or scrubbing: no chemical reaction
- Chemical absorption or scrubbing: with chemical reaction in liquid

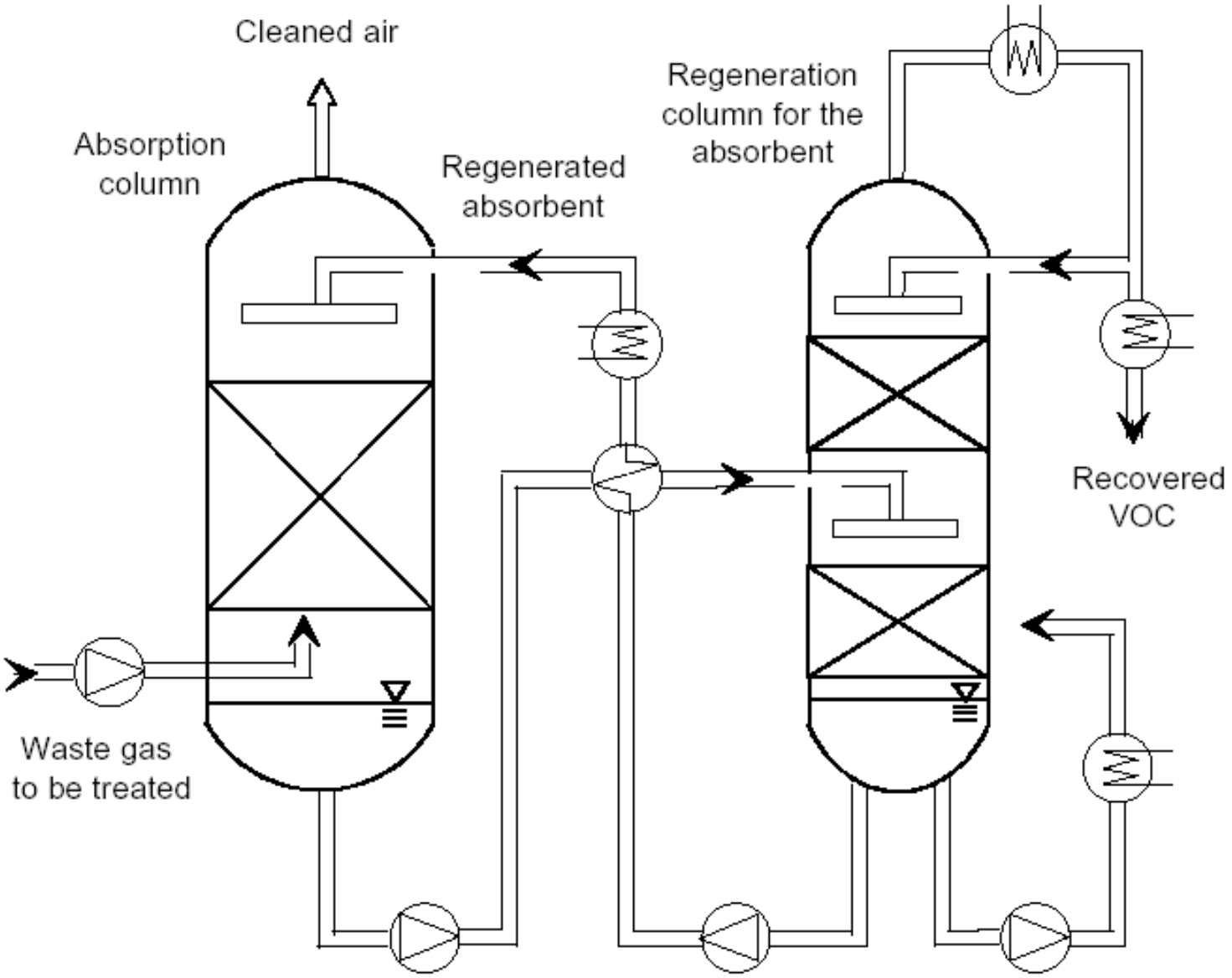
Absorption operation:

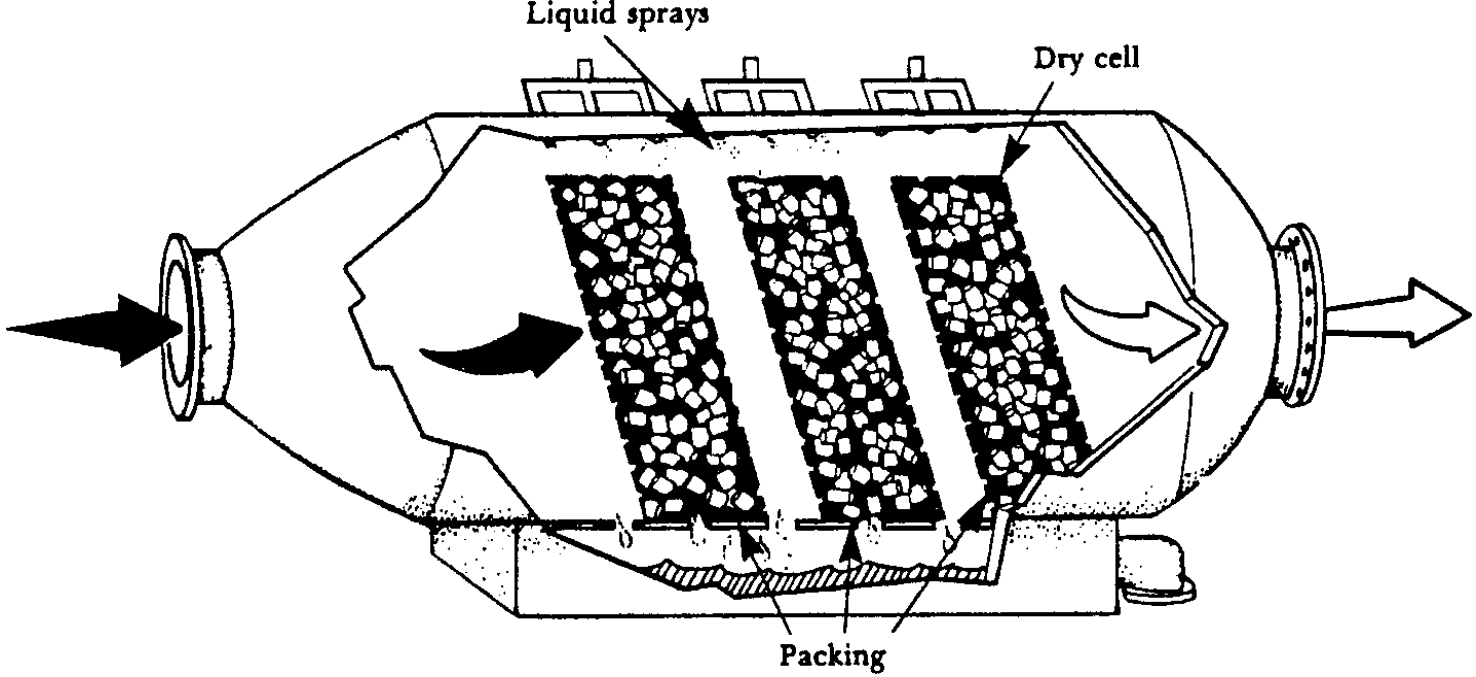
- absorber: countercurrent gas/liquid contact
  gas to liquid transfer of VOCs

- in combination with desorption:
  regeneration of the solvent = absorbens:
  separation of VOCs from the absorbens
  recovery of VOCs

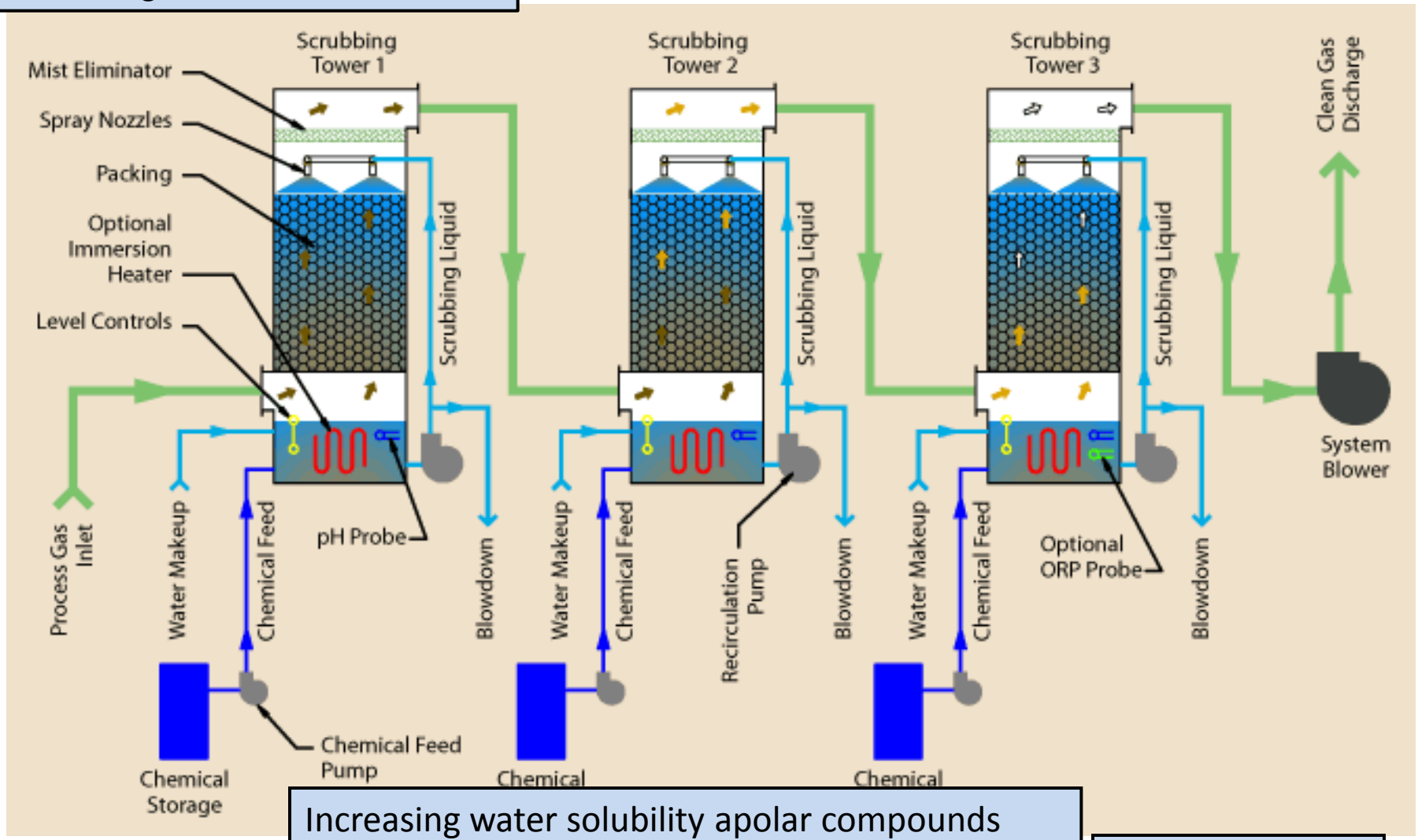
Choice of absorbent depends on:

- solubility of VOCs in absorbent (+ vapour pressure-> Henry)
- potential to separate from VOCs in regeneration step
  (difference in vapour pressure)
- low viscosity
- general criteria:
  - Availability
  - Price
  - Safety
  - Non-toxicity
  - Non-corrosivity


Cleaned air
Absorption column
Regenerated absorbent
Regeneration column for the absorbent
Recovered VOC
Waste gas to be treated


Liquid sprays
Dry cell
Packing

Multi stage chemical scrubber



Increasing water solubility apolar compounds

Amine removal

Safety back up

Acid / Oxidant / Alkaline
Ex. Rendering plant

Sector	Waste Gas Flow Rate [m^3/h]	Raw Gas Concentration [gC/m^3]	Clean Gas Concentration [mgC/m^3]	Efficiency [%]
In general	< 100,000	0.06 – 14	< 150	> 95
Pharmaceuti-cal industry	400	38	150	> 99
Aluminium coating	30,000	17	150	> 99

Adsorption:

Principle: selective transfer of VOCs onto an active surface
= gas to solid phase transfer

Physical process (0.5 kJ/mol, reversible)
Chemical process (50 kJ/mol, irreversible)

Typical (ad)sorbents:
- Activated carbon (AC)
- Zeolites

Sorbent Materials

- Activated Carbon
- Activated Alumina
- Silica Gel
- Molecular Sieves (zeolite)

Polar and **Non-polar** adsorbents

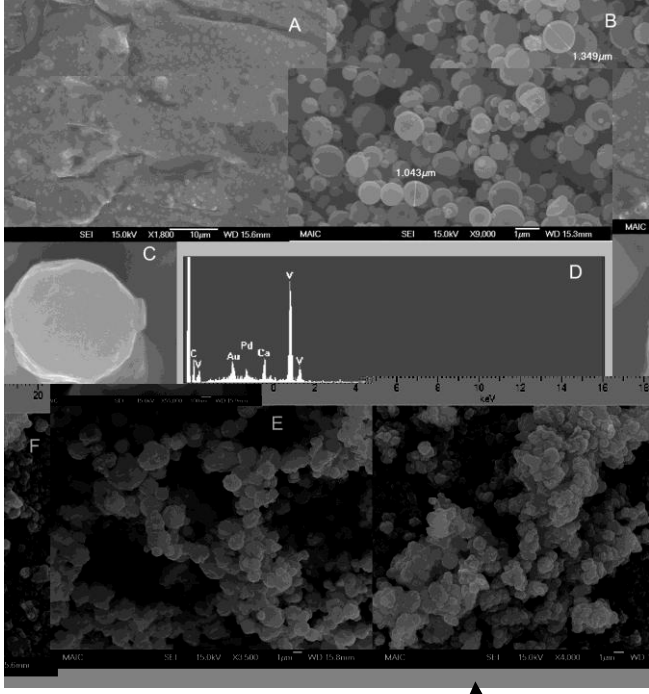
Properties of Activated Carbon

Bulk Density	350-550 kg/m^3
Heat Capacity	1.1-1.5 kJ/kg/K
Pore Volume	0.56-1.20 cm^3/g
Surface Area	600-1600 m^2/g
Average Pore Diameter	15-25 Å
Regeneration Temperature (Steaming)	100-140 ^oC
Maximum Allowable Temperature	150 ^oC

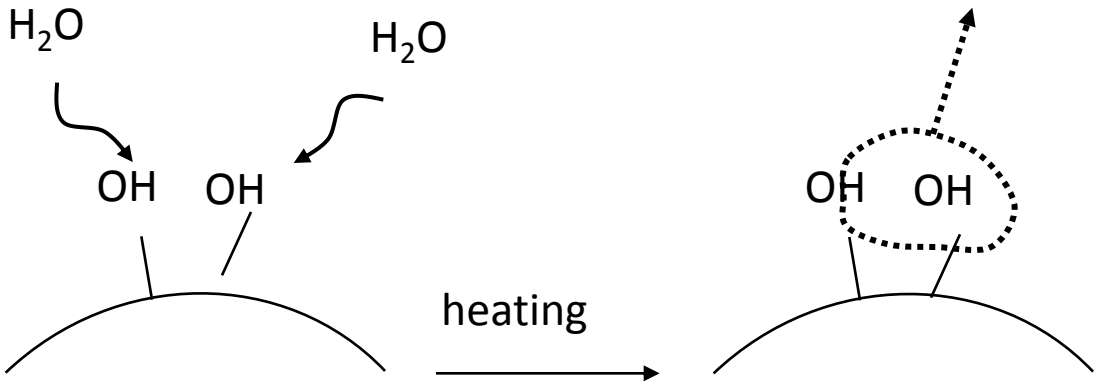
Q: If an activated carbon granule is a solid particle with1 mm diameter, what is the specific surface area (ρ = 0.7 g/cm³)?

Properties of Silica Gel

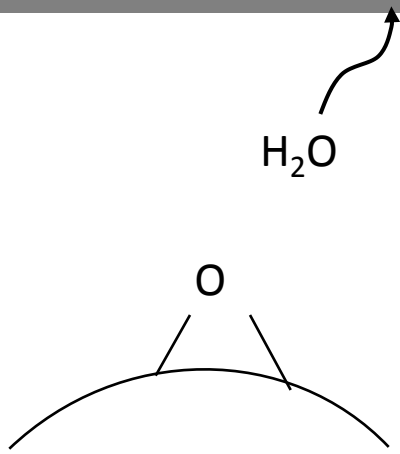
Bulk Density	700-890 kg/m^3
Heat Capacity	0.9-1.1 kJ/kg/K
Pore Volume	0.37 cm^3/g
Surface Area	750 m^2/g
Average Pore Diameter	22 Å
Regeneration Temperature	120-250 ^{o}C
Maximum Allowable Temperature	400 ^{o}C



What if it is heated over 250 ^{o}C?

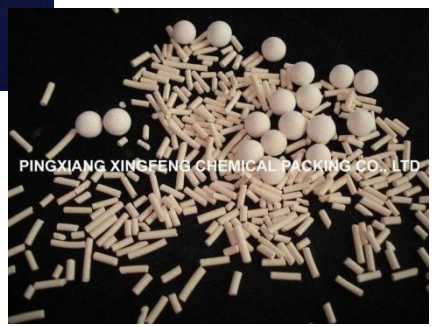


hydrophilic



Properties of Activated Alumina

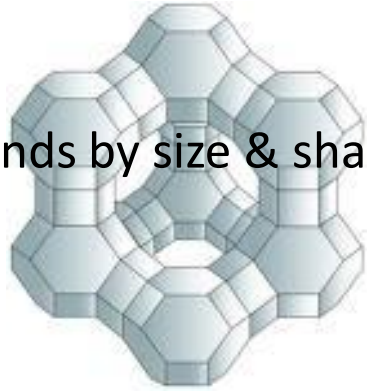
Bulk Density	
Granules	600-670 kg/m^3
Pellets	860-930 kg/m^3
Specific Heat	0.88-1.05 kJ/kg/K
Pore Volume	0.29-0.37 cm^3/g
Surface Area	210-360 m^2/g
Average Pore Diameter	18-48 Å
Regeneration Temperature (Steaming)	200-250 ^{o}C
Maximum Allowable Temperature	500 ^{o}C



Properties of Molecular Sieves

	Anhydrous Sodium Aluminosilicate	Anhydrous Calcium Aluminosilicate	Anhydrous Aluminosilicate
Type	4A	5A	13X
Density in bulk (kg/m^3)	44	44	38
Specific Heat (kJ/kg/K)	0.8	0.8	-
Effective diameter of pores (Å)	4	5	13
Regeneration Temperature (^{o}C)	200-300	200-300	200-300
Maximum Allowable Temperature (^{o}C)	600	600	600

- Crystalline zeolite
- Uniform pores to selectively separate compounds by size & shape

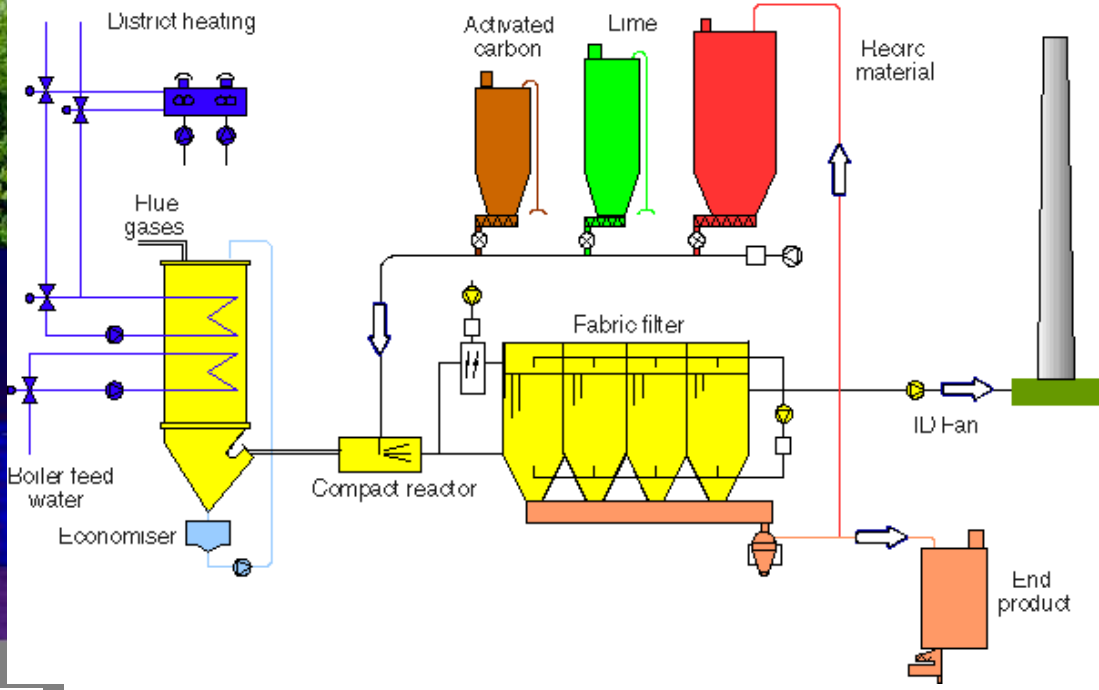


Desorption of adsorbent through:

- Steam (vapour) desorption (120-140°C)
  to be followed by VOC/water separation

- Hot gas desorption (150-350°C)
  inert gas: e.g. nitrogen

- Vacuum desorption


District heating
Activated carbon
Lime
Hearc material
Hue gases
Fabric filter
ID Fan
Boiler feed water
Compact reactor
Economiser
End product

HORUN
POCKET ACTIVATED CARBON FILTER
POCKET SYNTHETIC FIBER FILTER
HORUN
POCKET ELECTROSTATIC NONWOVEN FILTER

Choice of adsorbent:

- Adsorption potential for VOCs (surface/volume)

-Selectivity for VOCs

-Good desorption characteristics

-Low pressure drop

-High stability

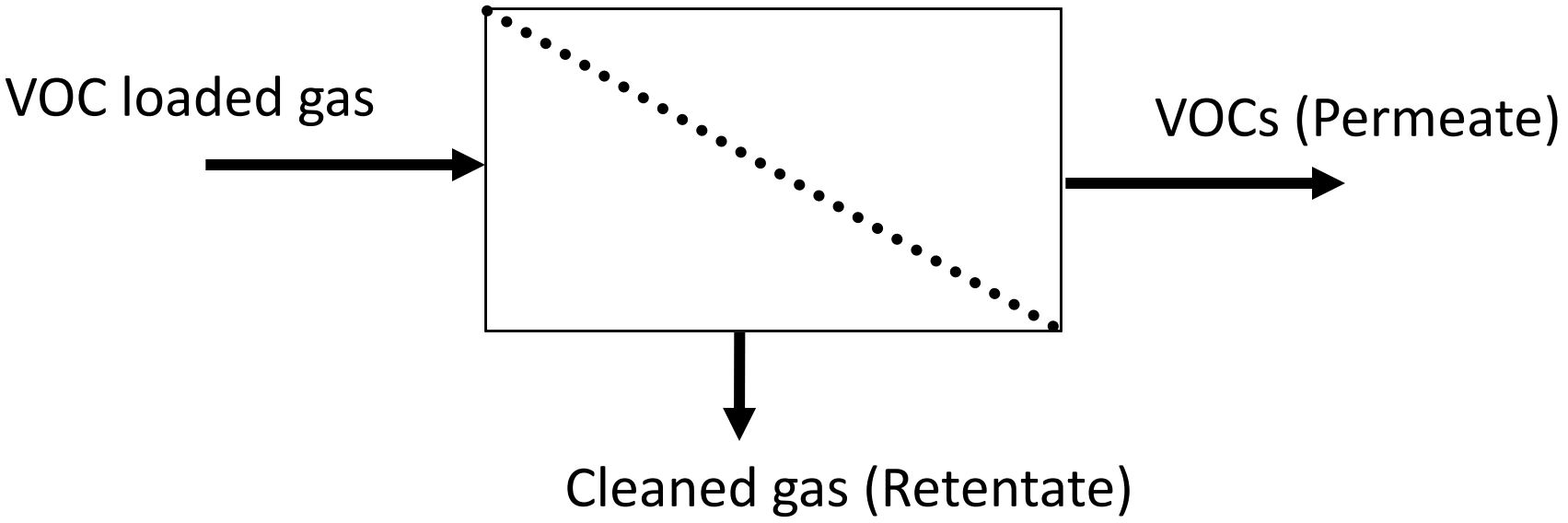
Adsorbent	Powder Density [kg/m³]	Specific Surface [m²/g]	Desorption Temperature [°C]
Active coke	300 - 500	1,000 – 1,500	100 - 150
Active coke narrow	400 - 500	600 – 1,000	100 - 150
[illegible]	[illegible]	[illegible]	[illegible]
n. a.			ca. 1,700
n. a.	Carbon molecular sieve	600 - 890	n. a.
- 300	Zeolite molecular sieve	650 - 750	800 - 1,100 - 200

Adsorbent	Powder Density [kg/m^3]	Specific Surface [m^2/g]	Desorption Temperature [°C]
Macro-porous polymers	800	n. a.	n. a.
Aluminium oxide	700 - 850	100 - 400	n. a.
Silicagel narrow porous	700 – 800	600 – 850	n. a.
Silicagel wide porous	400 - 800	250 - 350	n. a.

Membrane Separation:

Principle: selective transfer of VOCs through a barrier
= gas permeation

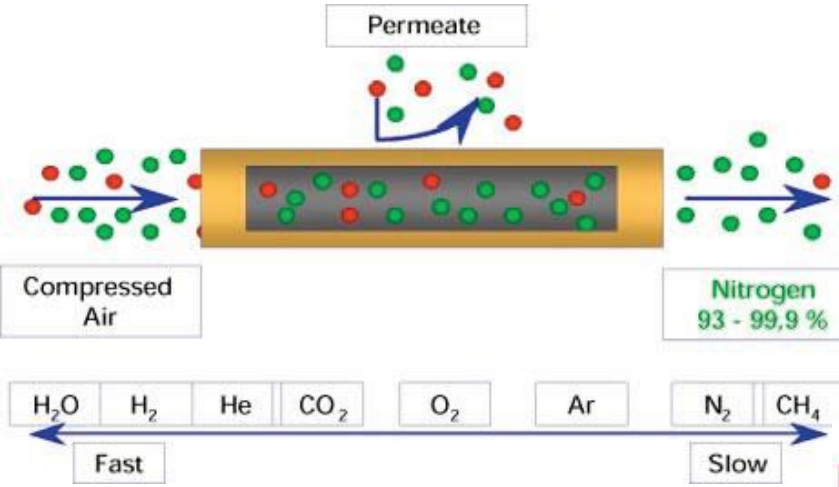
Relative new technique

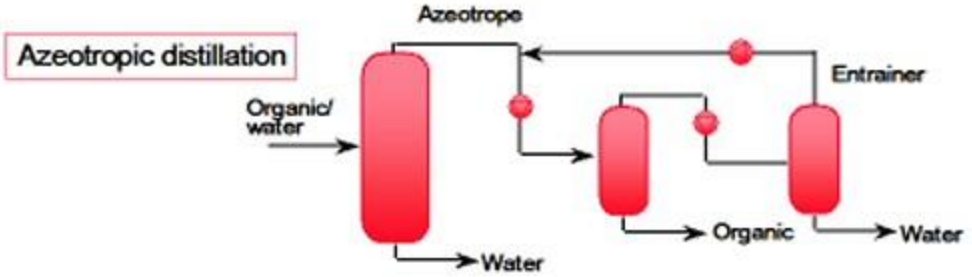


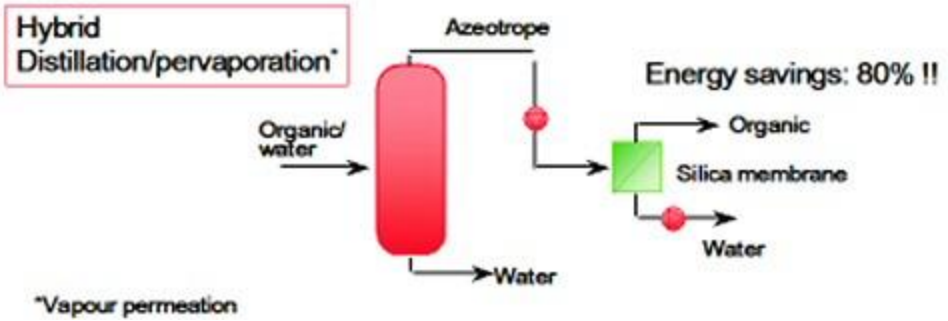
Way of operation:

- Pressure difference:
    - Pressure at the feed side
    - Vacuum at the permeate side

- Membranes:
    -Thin polymer films free of pores:
        silicon rubbers (1-3µm) on a support with high porosity:
        Composite membranes


Permeate
Compressed Air
Nitrogen
93 - 99,9 %
H_2O
H_2
He
CO_2
O_2
Ar
N_2
CH_4
Fast
Slow


Azeotropic distillation
Azeotrope
Entrainer
Organic/ water
Organic
Water
Water


Hybrid Distillation/pervaporation*
Azeotrope
Energy savings: 80% !!
Organic/ water
Organic
Silica membrane
Water
Water
*Vapour permeation

-In combination with:

-Recovery: condensation of the permeate

-Oxidation: incineration of the permeate

Process	Waste Gas Flow Rate [Nm^3/h]	NMVOC-Concentration in Raw Gas [gC/Nm^3]	NMVOC-Abatement Efficiency [%]
Permeation + catalytic incineration	300	100 – 1,500	99

3.3. Thermal/chemical removal technology

- Thermal incineration:
  - no catalyst
  - no heat regeneration
- Regenerative thermal incineration:
  - no catalyst
  - heat regeneration
- Catalytic incineration:
  - catalyst
  - no heat regeneration
- Catalytic regenerative incineration:
  - catalyst
  - heat regeneration

- **Thermal incineration**:

Principle: VOCs with additional fuel (and oxygen) into combustion chamber at 700-1000°C

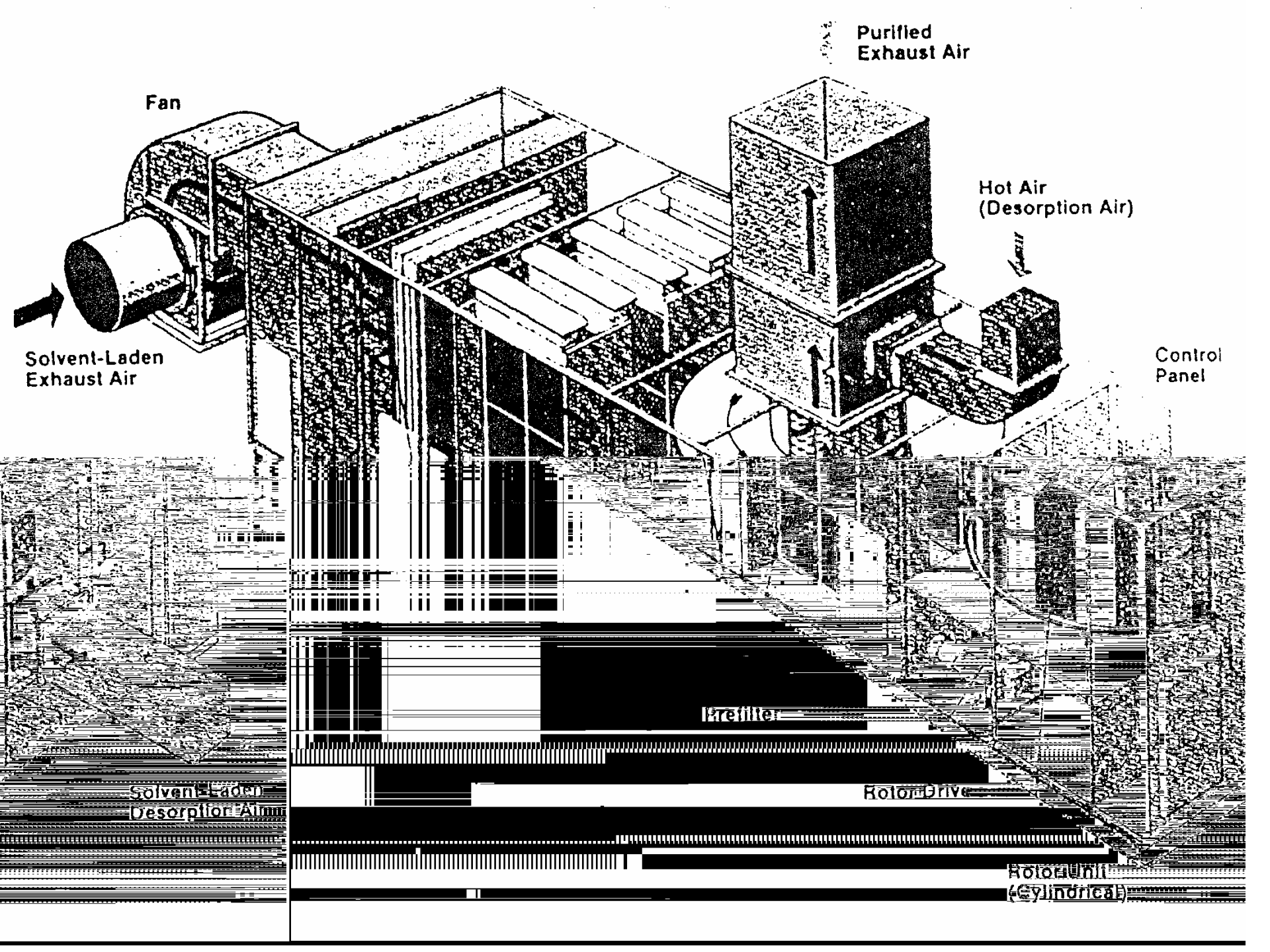
Usually with heat recovery from the combustion waste gas (300-400°C):

- primary heat recovery:
  recovered heat for preheating of gas to be treated
- secondary heat recovery:
  recovered heat for other purposes: e.g. steam

Parameters to be considered:

-Temperature
- Too low: CO instead of CO_2
- Too high: NO_x production

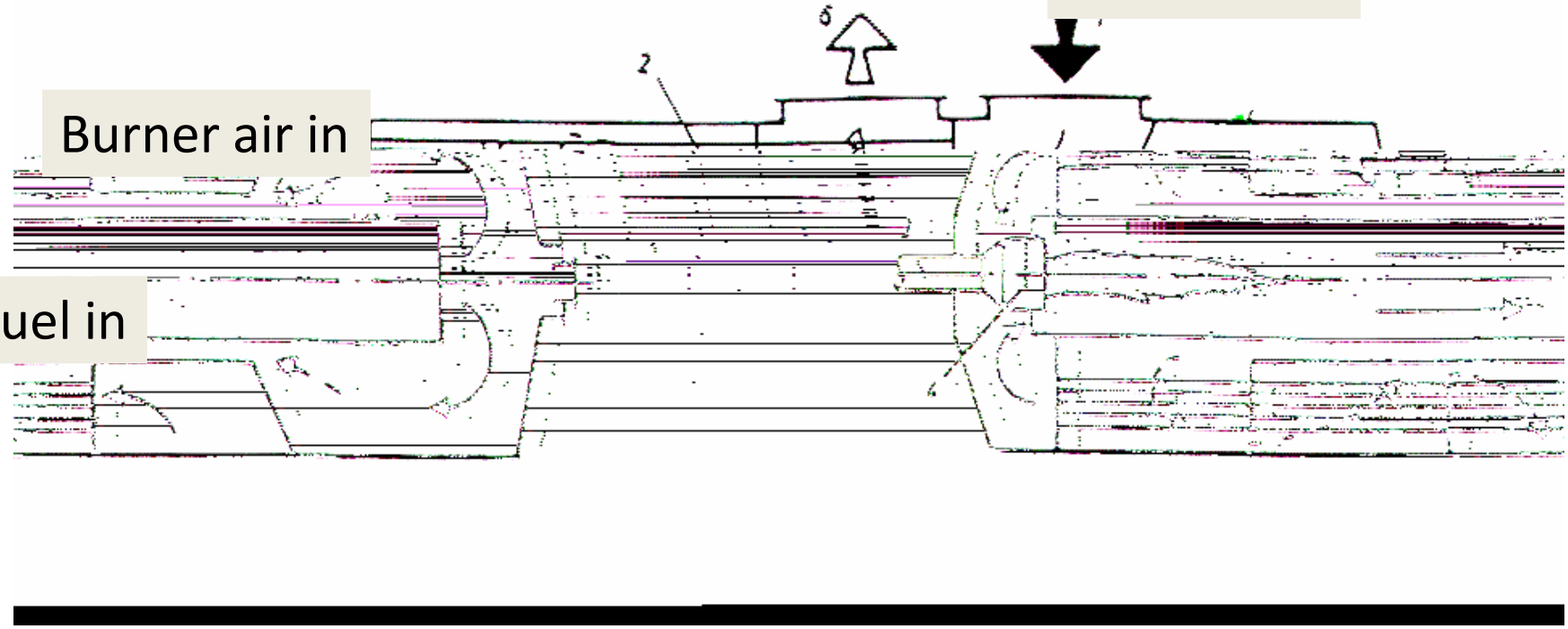
- Waste gas flow rate
- Concentration and type of VOCs:
  -Heat content determines amount of additional fuel
- Homogenity in combustion chamber:
  -concentration and temperature distributions
- Residence time in combustion chamber
- Oxygen content in waste gas (addition necessary?)


Purified
Exhaust Air
Fan
Hot Air
(Desorption Air)
Solvent-Laden
Exhaust Air
Control
Panel
Prefilter
Solvent-Laden
Desorption Air
Rotor Drive
Rotor Unit
(Cylindrical)

Waste Gas Flow Rate [m^3/h]	Raw Gas Concentration [gC/m^3]	Clean Gas Concentration [mgC/m^3]	Abatement Efficiency [%]
5,000 - 60,000	≤ 20	5	99.8
500 – 40,000	≤ 20	< 20	99.8
200 – 60,000	≤ 20	< 20	99.5
50,000	≤ 18	10	n. a.

Clean air out

Waste air in



Burner air in

Fuel in

- Regenerative thermal incineration:

Principle: similar as with thermal incineration but with heat regeneration

Thermal incineration can use heat exchangers:

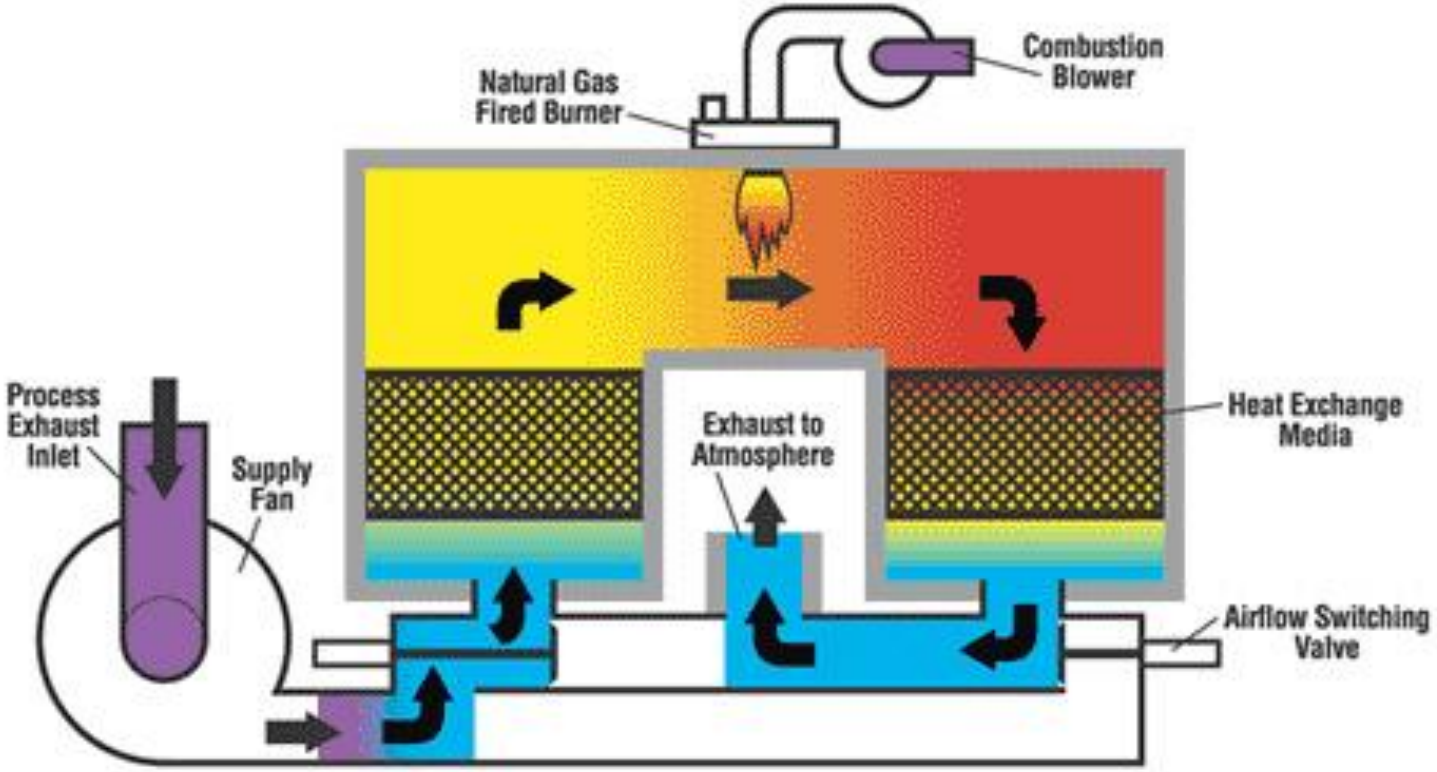
thermal incineration with heat recuperation

energy utilisation: 60-70%

Regenerative incineration uses beds to accumulate and restore heat (heat accumulators)

e.g. ceramics

energy utilisation: 90-95%


Natural Gas
Fired Burner
Combustion
Blower
Process
Exhaust
Inlet
Supply
Fan
Exhaust to
Atmosphere
Heat Exchange
Media
Airflow Switching
Valve

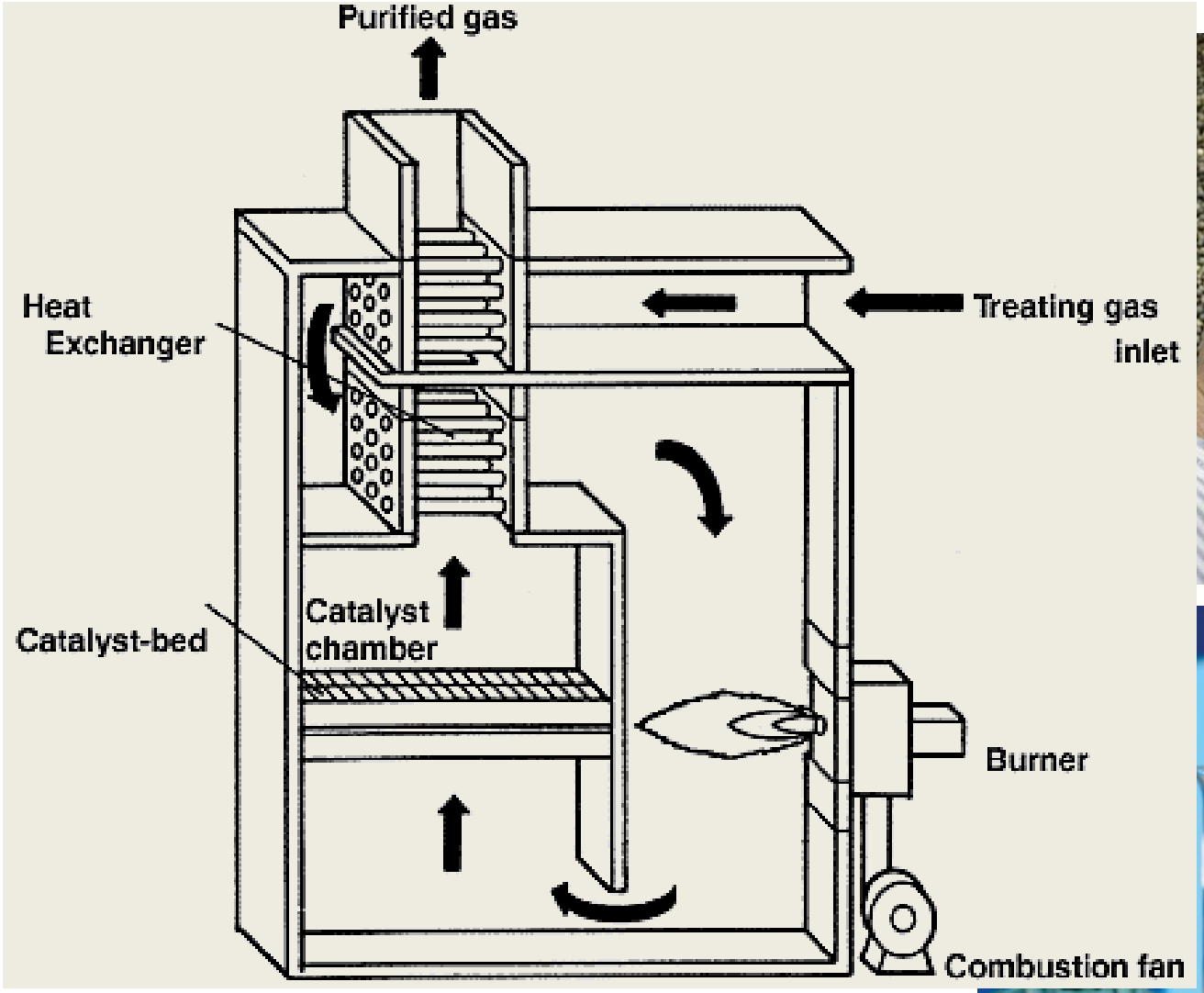
- **Catalytic incineration:**

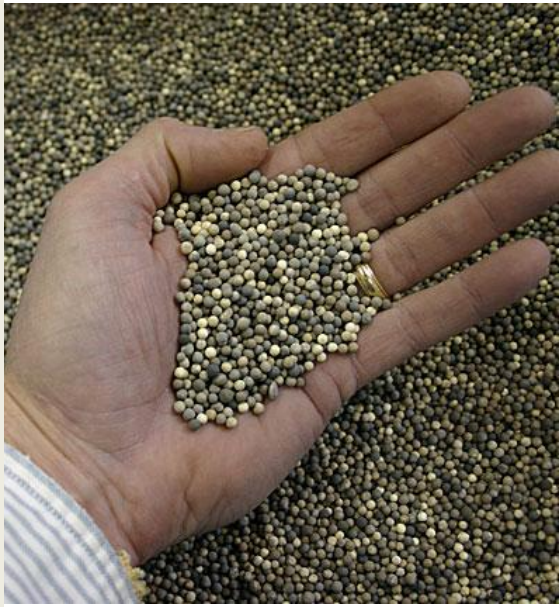
Principle: VOCs oxidized in the presence of a catalyst
at 200-400°C

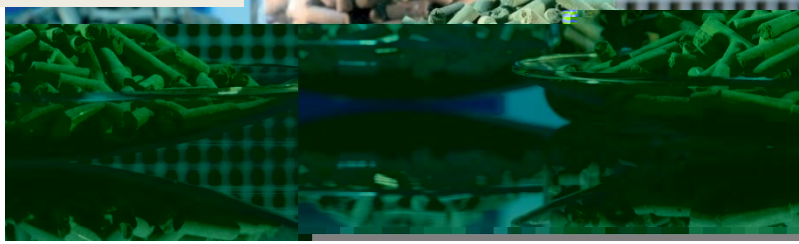
Main differences with thermal incineration:

- lower temperatures
- shorter residence times
- presence of a catalyst

Waste Gas Flow Rate [m^3/h]	Raw Gas Concentration [gC/m^3]	Clean Gas Concentration [mgC/m^3]	Rate of Heat Recovery [%]	Abatement Efficiency [%]
15,000 – 200,000	≤ 3.8	2	> 85	99
3,000 – 16,000	≤ 7	≤ 20	n. a.	n. a.
5,000 – 250,000	n. a.	n. a.	n. a.	95
5,000 – 30,000	≤ 3	5	95	n. a.
5,000 – 20,000	≤ 1.7	50 ± 20	97	n. a.
55,000	≤ 9	n. a.	90	99
90,000	≤ 11	n. a.	90	99
≤ 20,000	≤ 6	n. a.	n. a.	n. a.


Purified gas
Heat
Exchanger
Treating gas
inlet
Catalyst-bed
Catalyst
chamber
Burner
Combustion fan





3.4. Biological removal technology

Principle:

step 1: transfer from gas to microbiology

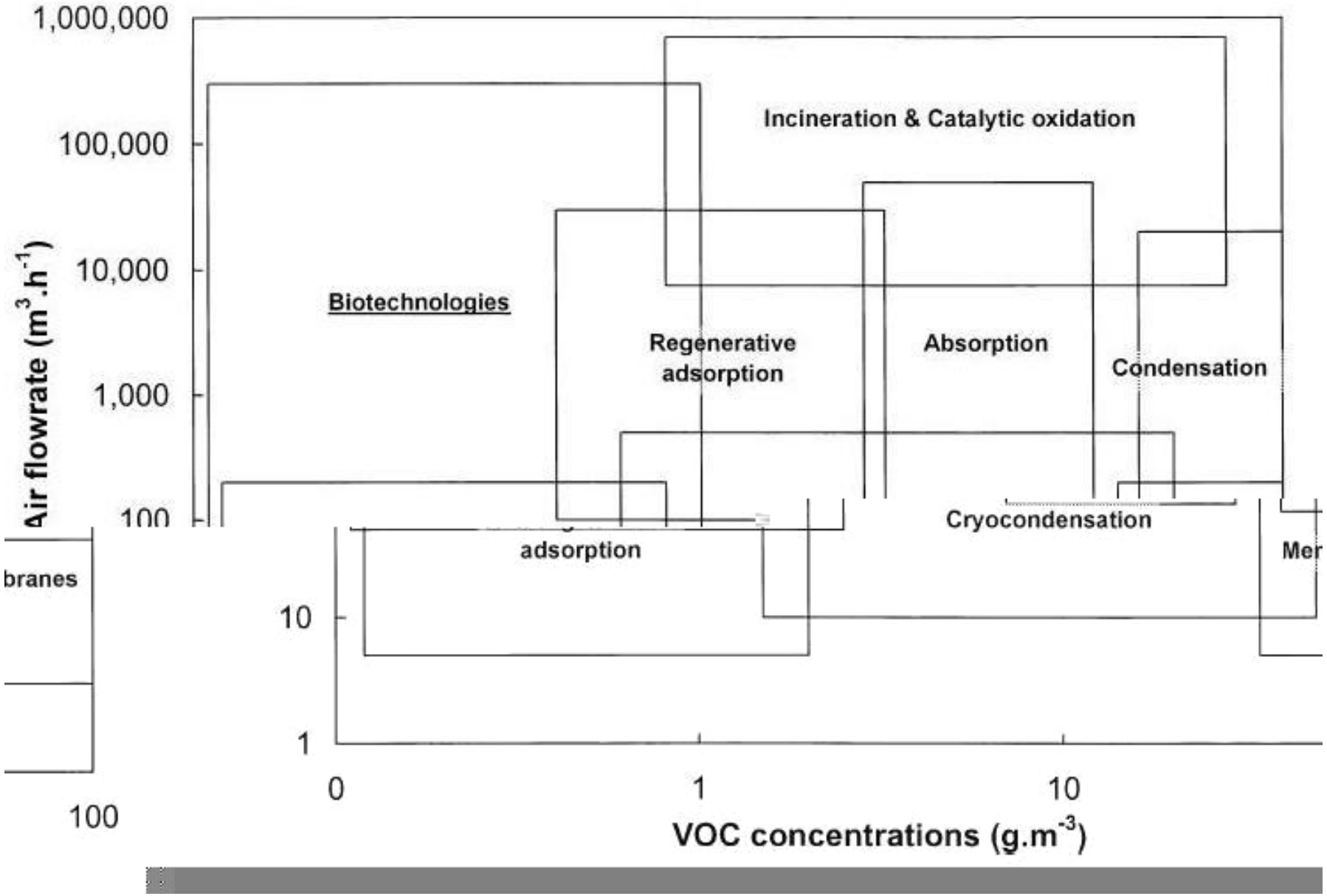
(bacteria, fungi, yeast)

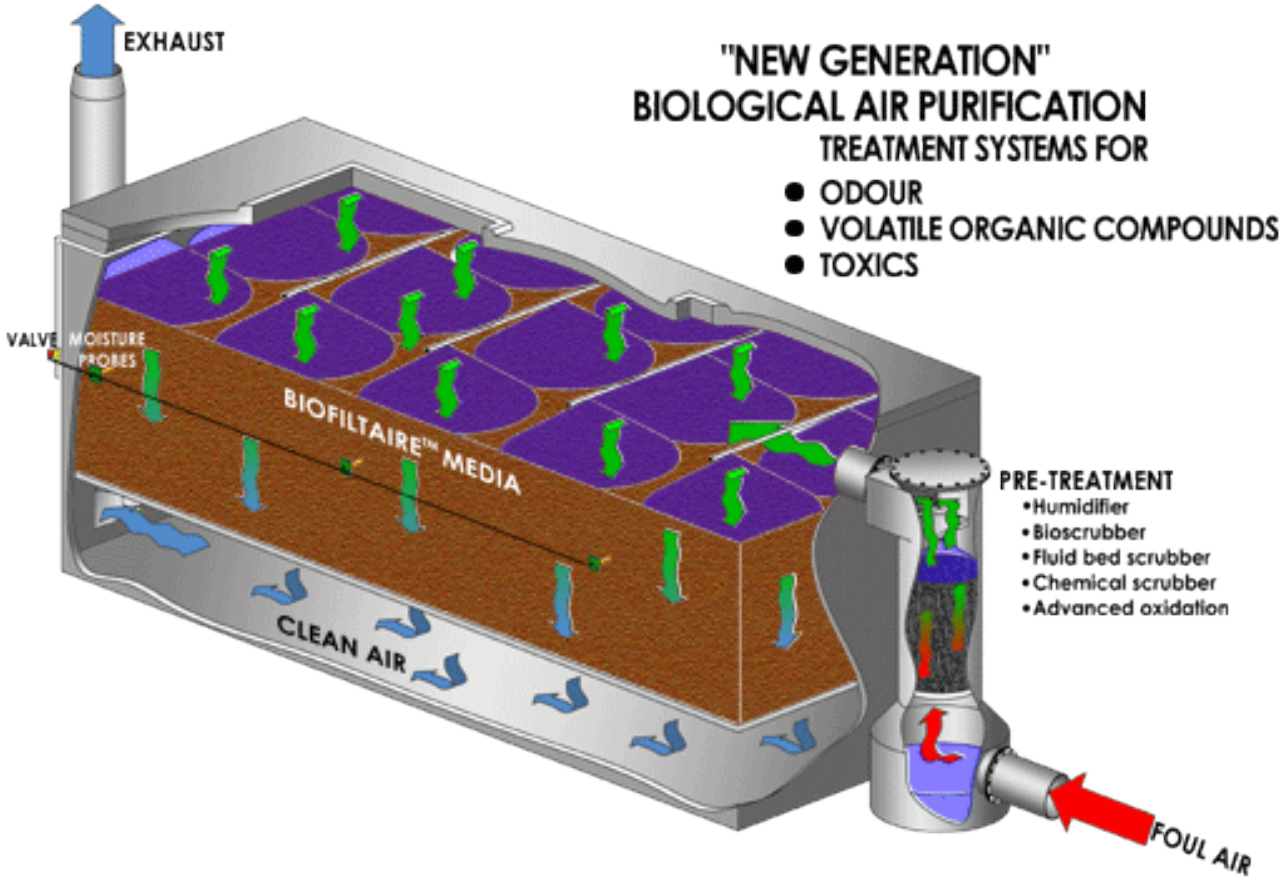
step 2: micro-organisms use VOC as feed

= oxidation van de VOC

Types of biological removal technology:

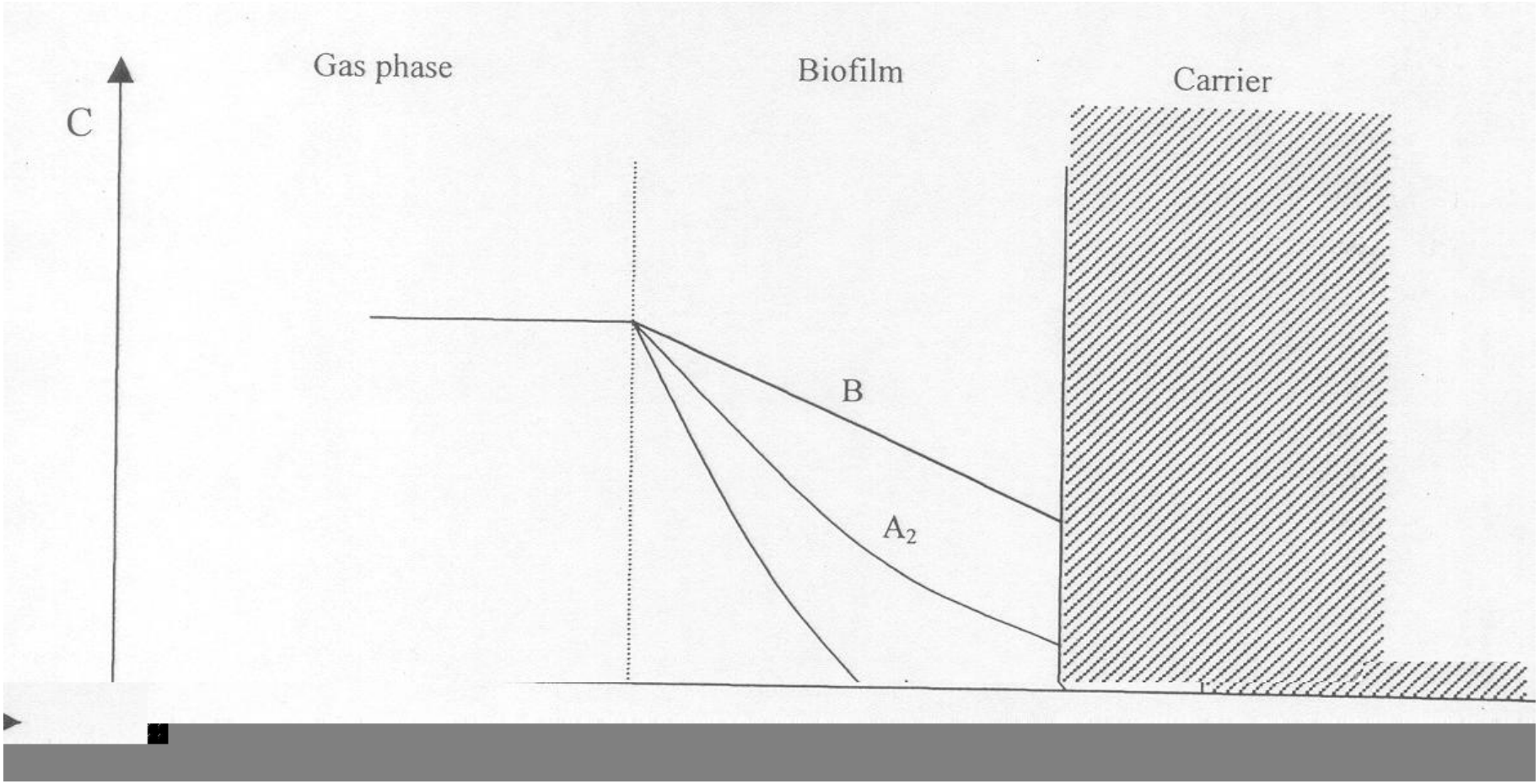
1. Biofilters
2. Bioscrubbers
3. Biotrickling filters


1,000,000
100,000
10,000
1,000
100
10
1
0
1
10
100
Air flowrate (m3.h-1)
VOC concentrations (g.m-3)
Incineration & Catalytic oxidation
Biotechnologies
Regenerative adsorption
Absorption
Condensation
Cryocondensation
adsorption
branes


EXHAUST
"NEW GENERATION"
BIOLOGICAL AIR PURIFICATION
TREATMENT SYSTEMS FOR
ODOUR
VOLATILE ORGANIC COMPOUNDS
TOXICS
VALVE
MOISTURE PROBES
BIOFILTAIRE™ MEDIA
CLEAN AIR
PRE-TREATMENT
•Humidifier
•Bioscrubber
•Fluid bed scrubber
•Chemical scrubber
•Advanced oxidation
FOUL AIR

Elements of the filter:

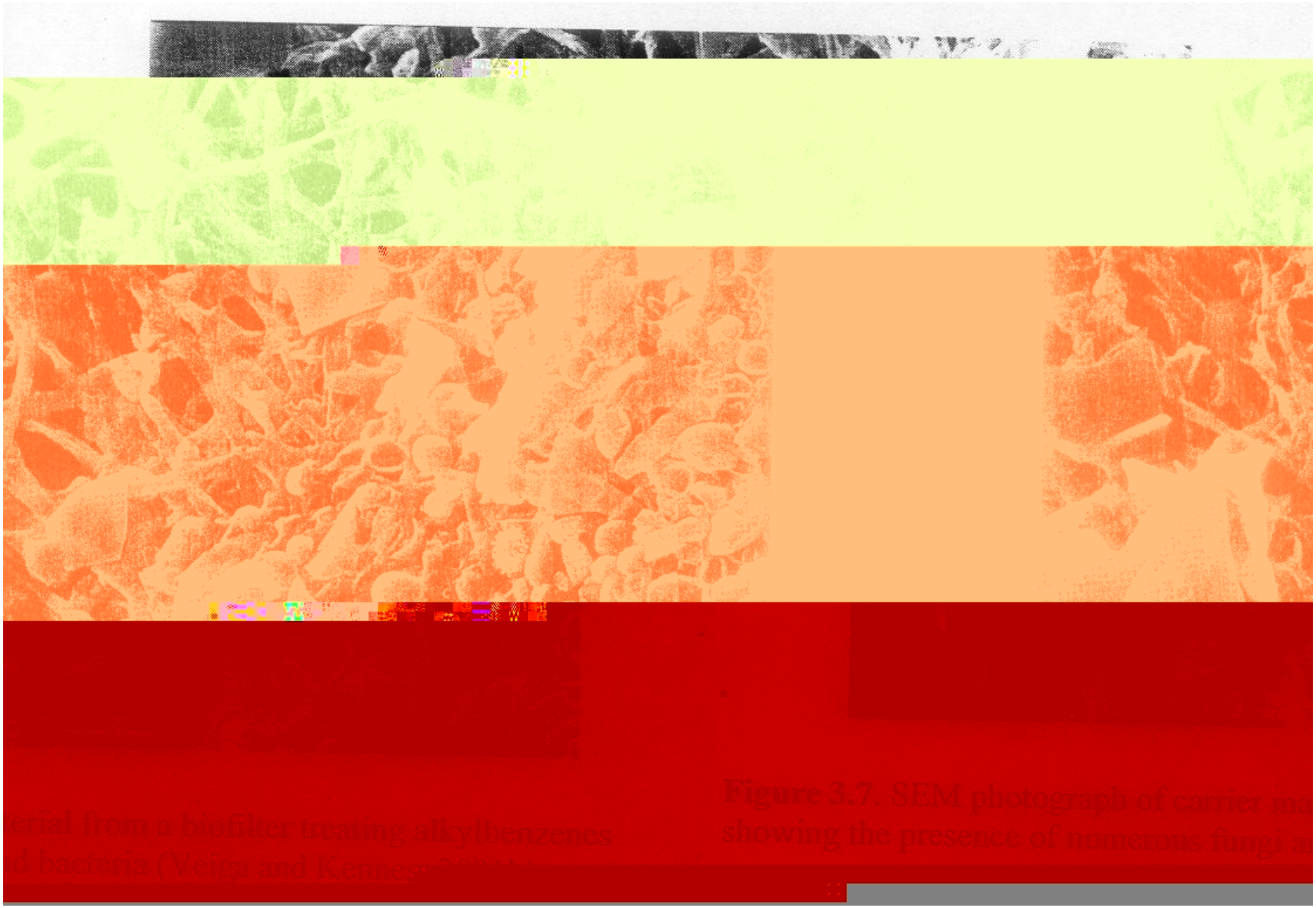
- carrier material: peat, compost, , …
- biofilm: living micro-organisms on
- gas phase: void volume



Process parameters:

- Temperature (20-42°C for biofilm)
- Gas to be handled:
    - Composition: biodegradability of VOCs
    - Concentration of VOCs
- Load:
    flow rate per reactor volume: volumetric load
    Residence time:
- Water with nutrients:
    - humidity
    - nutrients
    - pH
- Biofilm: Type of micro-organisms (inocculation)
- Pressure drop

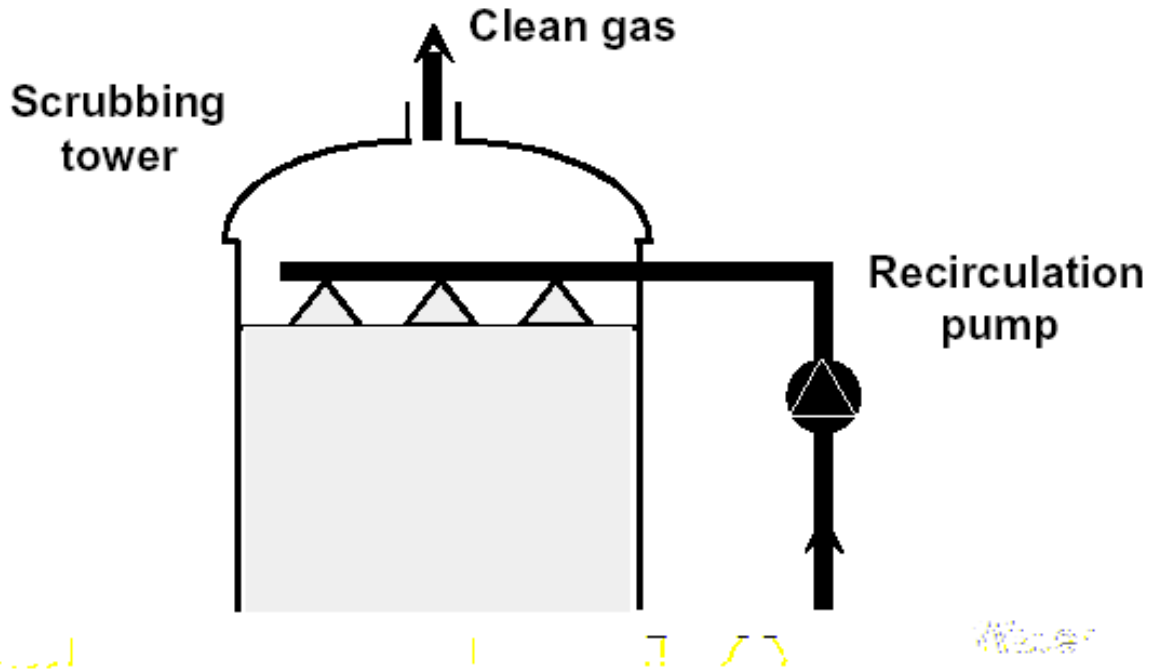
High Degradability	Medium Degradability	Low Degradability
Acetaldehyde	Acetonitrile	Dioxane
Butadiene	Benzene	1.1.1-Trichhloroethane
Cresols	Carbon disulfide	Trichloroethylene
Ethylbenzene	Hexane	Perchloroethylene
	Methanol	Methyl ethyl ketone
	Xylene	



Application Field	Waste Gas Flow Rate [m^3/h]	Raw Gas Concentration	Clean Gas Concentration	Abatement Efficiency [%]
Chemical industry	4,150	30 – 520 ppmC 555 – 740 o. u.	1 – 11 ppmC 105 – 104 o. u.	98 83
Oil mills	38,850	40 – 215 ppmC	35 – 96 ppmC	53
		4,540 o. u.	94 o. u.	98
			mgC/m^3	mgC/m^3
n. a.	Tobacco industry	25,000	2,000 o. u.	50 o. u

2 stage process:

- Scrubbing:
  absorption of VOCs from waste gas into water
    “scrubber”=“absorber”
- Oxidation:
  oxidation of VOCs in water in a separate basin:
    “active sludge basin”


Clean gas
Scrubbing tower
Recirculation pump
Activation basin
Water (excess)

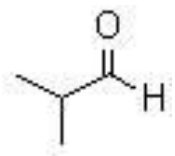
Parameters for scrubbing:

- type and concentration of VOCs
- air/water partitioning behaviour of VOC
- design of scrubber: mass tranfer efficiency

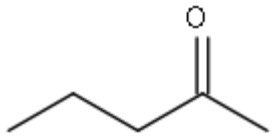
Parameters for basin:

- active organisms
- nutrients (N, P)
- pH

Reactor	Start-up period (day)	EC ($g\ m^{-3}\ h^{-1}$)	
		IBA	PENT



Bp 63 °C



Bp 101 °C

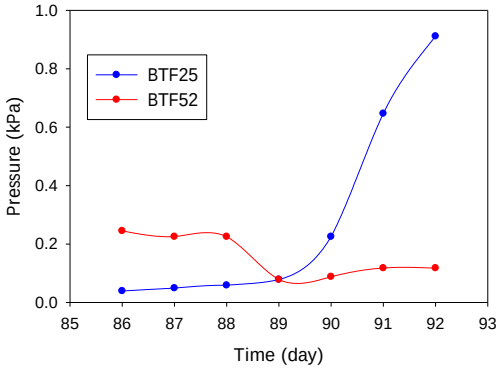
Luvsanjamba, M. et al. (2007), J. *Chemical Technology and Biotechnology*, 82 (1), 74-80

Operational stability (IBA & 2-pentanone)

BTF25

Higher biomass accumulation →

- Fast pH drop
- Foaming
- Clogging



BTF52

Lower biomass accumulation →

- Higher elimination capacity
- Stable long-term performance

-In between biofilter and bioscrubber:

-Cfr. Biofilter:

- Phase transfer and oxidation in 1 unit
- But: - recirculating liquid with nutrients
  - most cases: synthetic support

-Cfr. Bioscrubber:

- Recirculating liquid
- But: - micro-organisms are fixed in filter
  - phase transfer and oxidation in 1 unit

4. Removal of NO_x and SO_x

4.1. SO_x removal

Source of SO_x: S-containing fuels

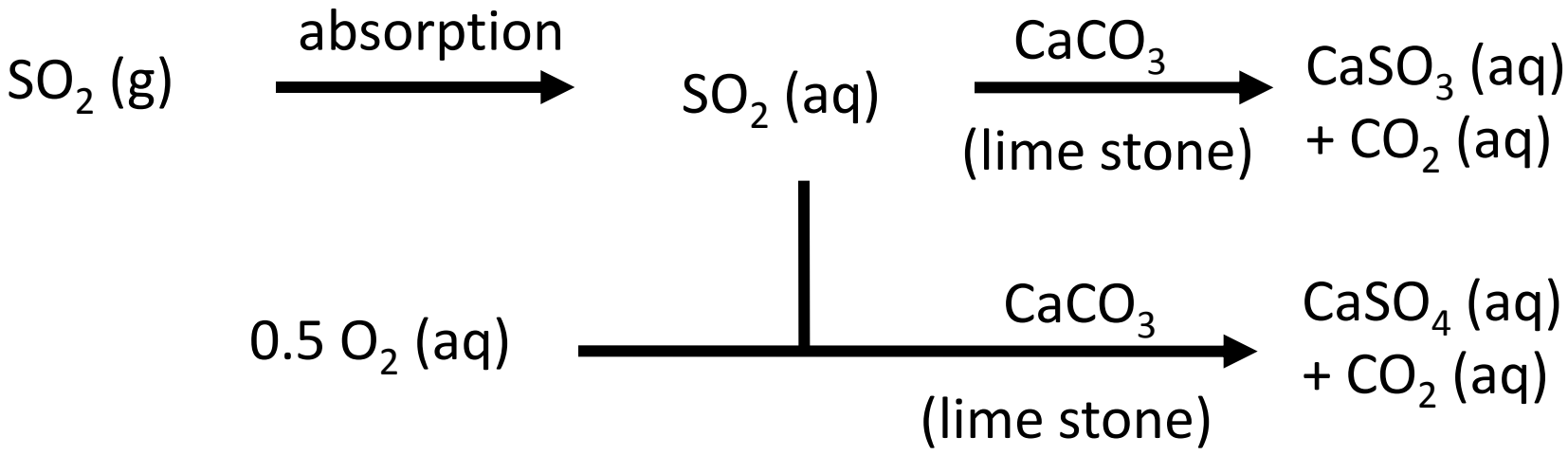
Solutions:

- S reduction in fuel (preventive)
- SO_x removal in waste gas

SO_x removal in waste gas:

- Phase transfer to liquid: absorption
  followed by reaction in liquid
- Phase transfer to liquid: adsorption
  - without reaction on surface (physical)
  - with reaction on surface (chemical)
- Reaction in gas phase
  - oxidation: SO_x into H_2SO_4
  - reduction: SO_x into S

- Phase transfer to liquid: absorption followed by reaction in liquid



$$CaSO_3\,(aq) + CO_2\,(aq) \xrightarrow{2\,H_2O} CaSO_3 \cdot 2H_2O\,(s) + CO_2\,(g)$$

$$CaSO_4\,(aq) + CO_2\,(aq) \xrightarrow{2\,H_2O} CaSO_4 \cdot 2H_2O\,(s) + CO_2\,(g)$$

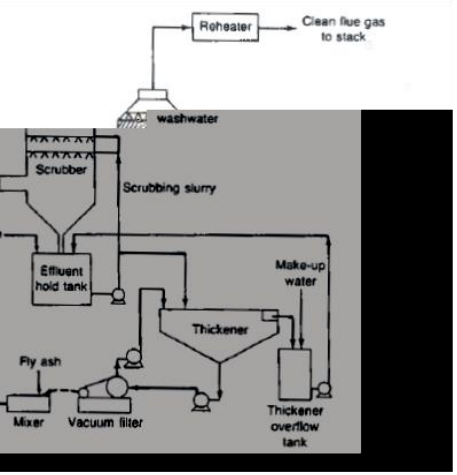
In summary:

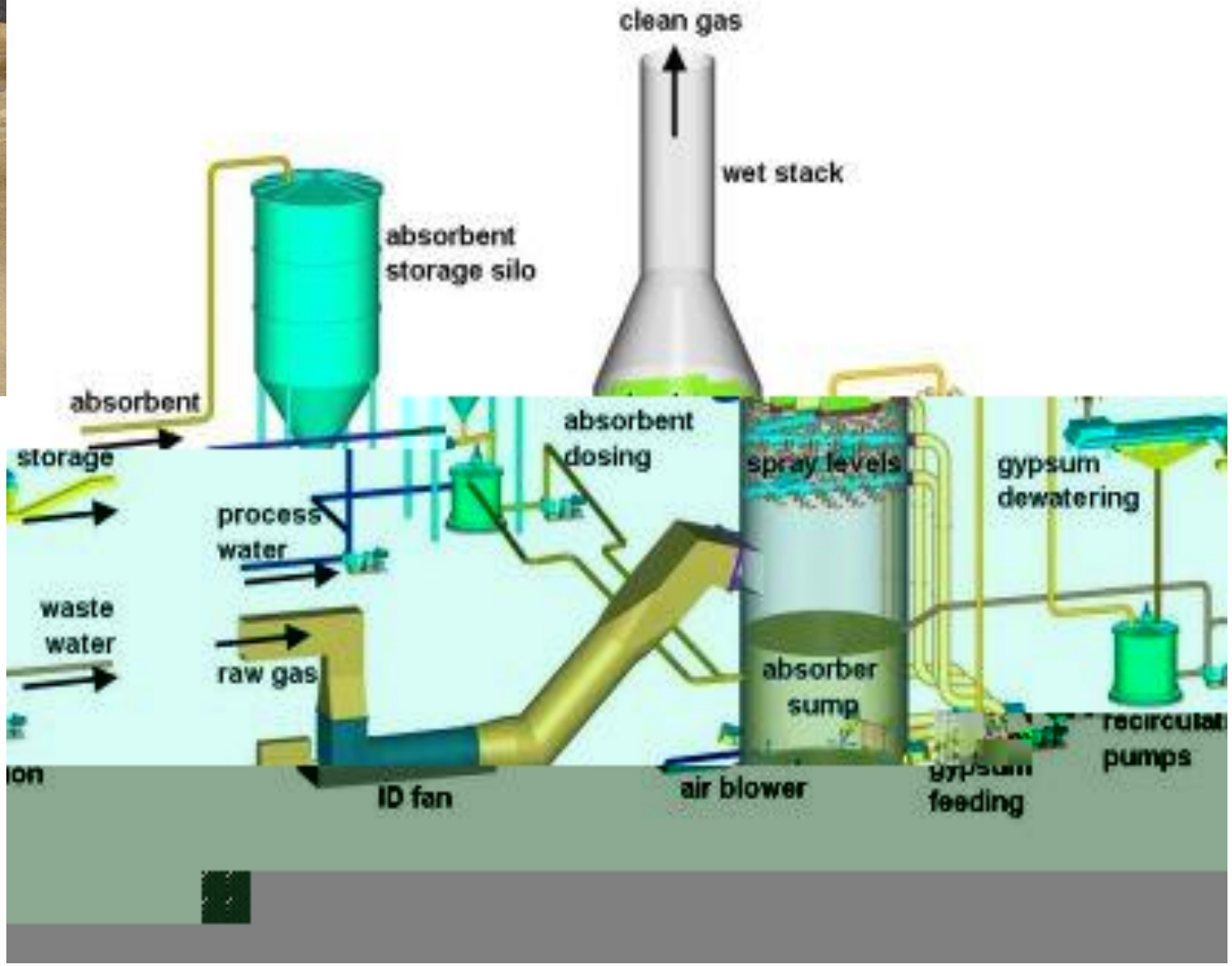
- SO_x converted into gypsum (solid product)

- Requires :
  - absorber
  - tank for lime stone addition
  - tank to thicken the slurry

Comparable processes:

- $Ca(OH)_2$
- NaOH


Reheater
Clean flue gas to stack
washwater
Scrubber
Scrubbing slurry
Effluent hold tank
Make-up water
Thickener
Fly ash
Mixer
Vacuum filter
Thickener overflow tank


clean gas
wet stack
absorbent storage silo
absorbent
storage
absorbent dosing
spray levels
gypsum dewatering
process water
waste water
raw gas
absorber sump
recirculat pumps
ID fan
air blower
gypsum feeding

- Phase transfer to solid surface: adsorption

-Without reaction on surface

Comparable to adsorption of VOC:

Phase transfer van gas naar een actief oppervlak:

- activated charcoal
- alkalized alumina

SO_2 can be thermally desorbed: concentrated

- conversion as with lime stone based absorption but <u>dry</u>:

- high temperature: $CaCO_3$ splits CaO and CO_2
- products: $CaSO_3$ and $CaSO_4$ dry
- particle collection needed

- Reaction in gas phase
  - oxidation: SO_x into SO_4^{2-}

Step 1 : oxidation and formation of solids

$$SO_2\,(g) + H_2O\,(g) + 2\,NH_3\,(g) + 0.5\,O_2\,(g) \longrightarrow (NH_4)_2SO_4\,(s)$$

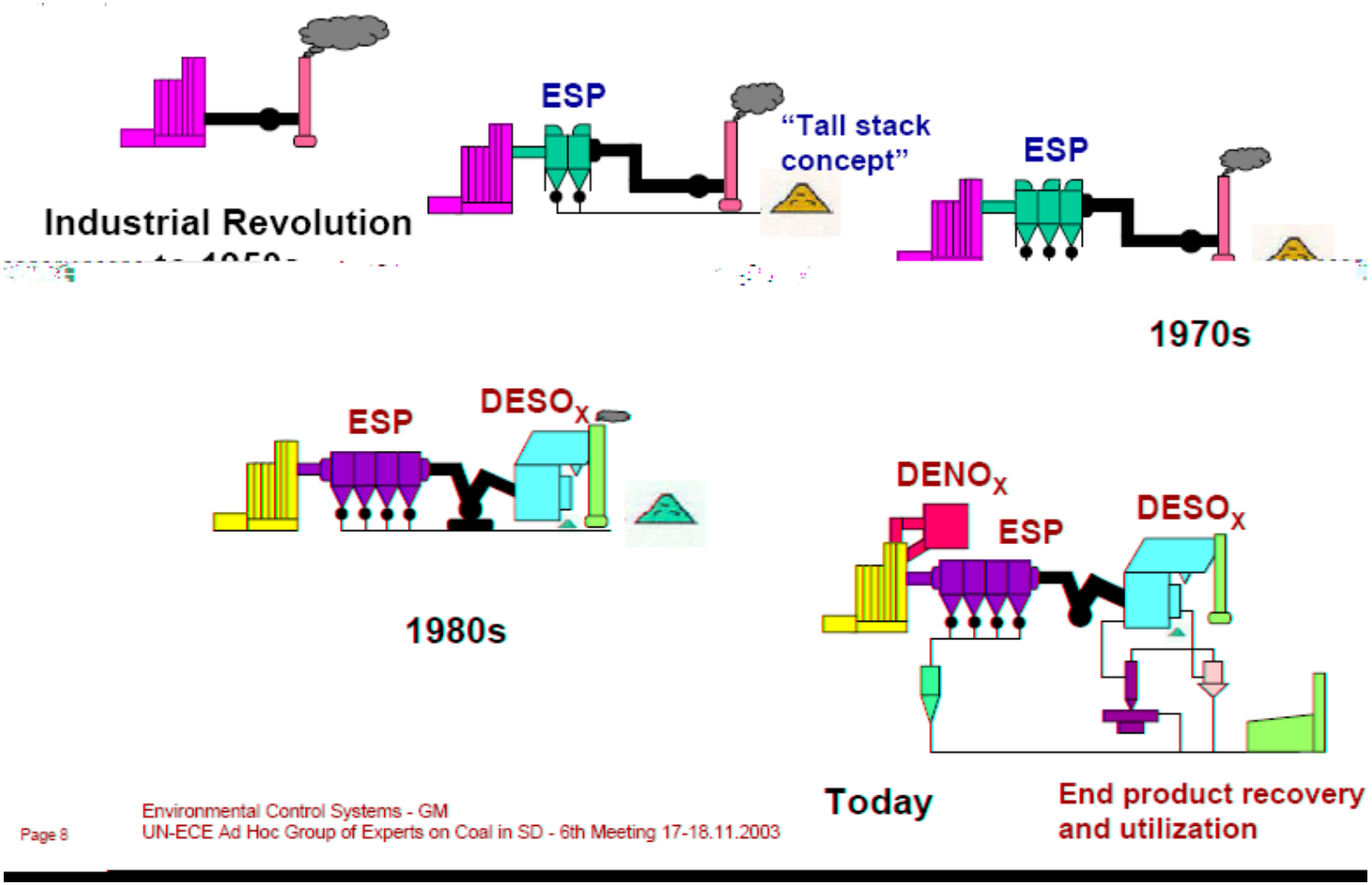
Step 2 : captation of solid particles

- Reaction in gas phase
    - reduction: SO_x into S

Step 1 : reduction with catalyst

$$SO_2\,(g) + 2\,H_2S \xrightarrow{Fe_2O_3\,(s)} 3\,S\,(g) + 2\,H_2O$$

Step 2 : condensation of S vapours: $S\,(g) \longrightarrow S\,(liq)$


Industrial Revolution
ESP
"Tall stack concept"
ESP
1970s
ESP
DESOX
1980s
DENOX
ESP
DESOX
Today
End product recovery and utilization
Page 8
Environmental Control Systems - GM
UN-ECE Ad Hoc Group of Experts on Coal in SD - 6th Meeting 17-18.11.2003

NOx reduction by:

- circulation of combustion gases
- staged combustion
- SCR: selective catalytic reduction
- NSCR: non-selective catalytic reduction

- Circulation of combustion gases
    - cold
    - low oxygen content

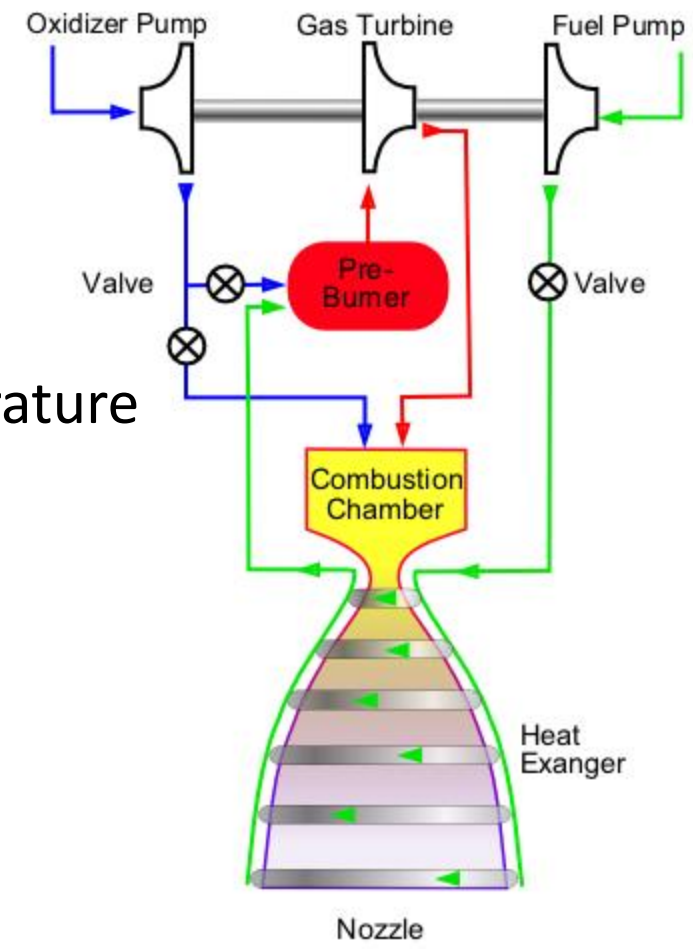
Results in thermal NO_X reduction
Applicable for fuels with low N-content (natural gas)
Reduction up to 70-80% is possible

- staged combustion

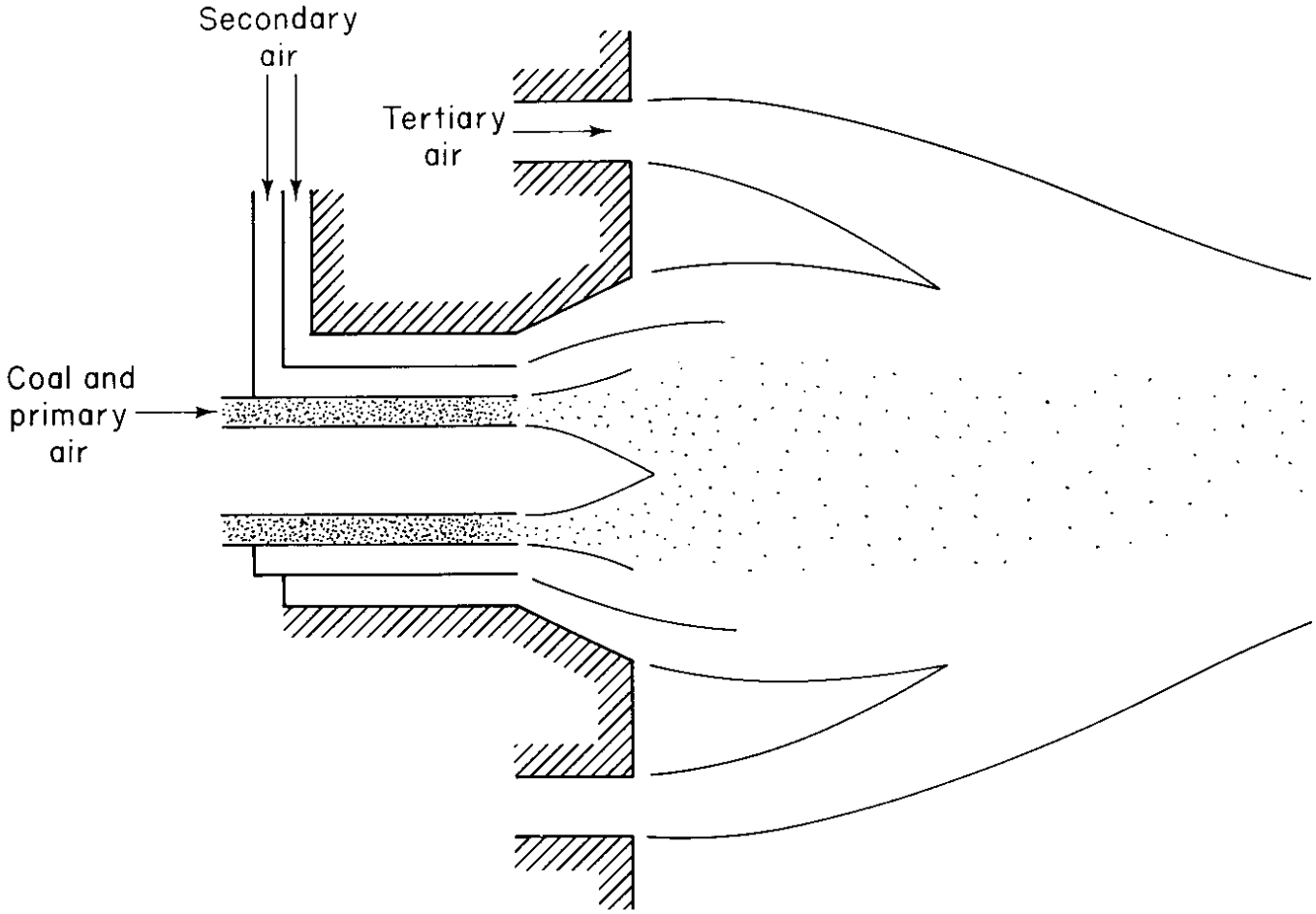
Combustion in several stages:

gradual dosage of air (oxygen)

- first step(s): low O_2 level, low temperature
  - thermal NO_x reduction
  - no “fuel NO_x “
- next step(s): more O_2:
  - thermal NO_x reduction
  - formation of “fuel NOx “



- **Low-NOx burner**: inhibit NOx formation by controlling the mixing of fuel and air; lean excess air and off-stoichiometric combustion



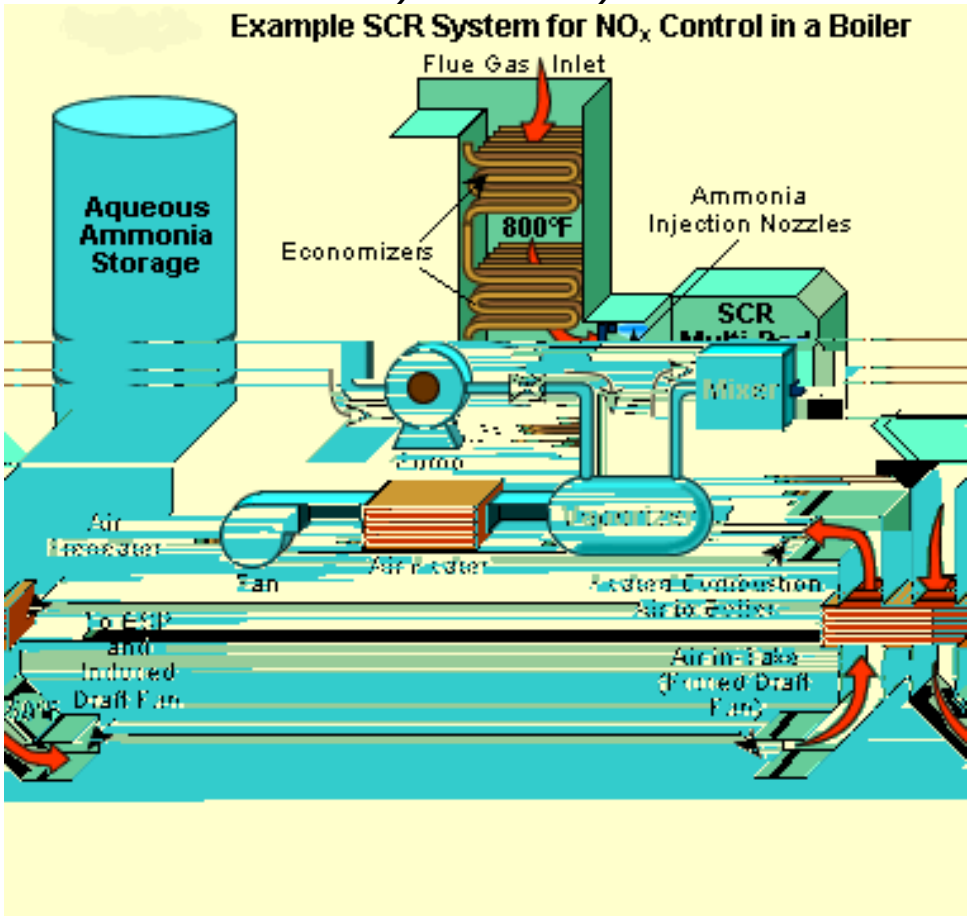
- **Gas reburning**: injection of natural gas into the boiler above the main burner to create a fuel-rich reburnreburn

- SCR: selective catalytic reduction = DENOX

$$4\ NO + 4\ NH_3 + O_2 \longrightarrow 4\ N_2 + 6\ H_2O$$

$$6\ NO_2 + 8\ NH_3 \longrightarrow 7\ N_2 + 12\ H_2O$$

- With catalyst:
  e.g. Vanadium/Wolfram oxides on TiO_2
- Temperature: 300-400°C



- NSCR: non-selective catalytic reduction

Similar to SCR, but

- no catalyst
- reductans can be ammonia or ureum
- temperature is higher:
  - ammonia: 900-1100°C
  - ureum: 550-1030°C

5. Removal of particulate matter

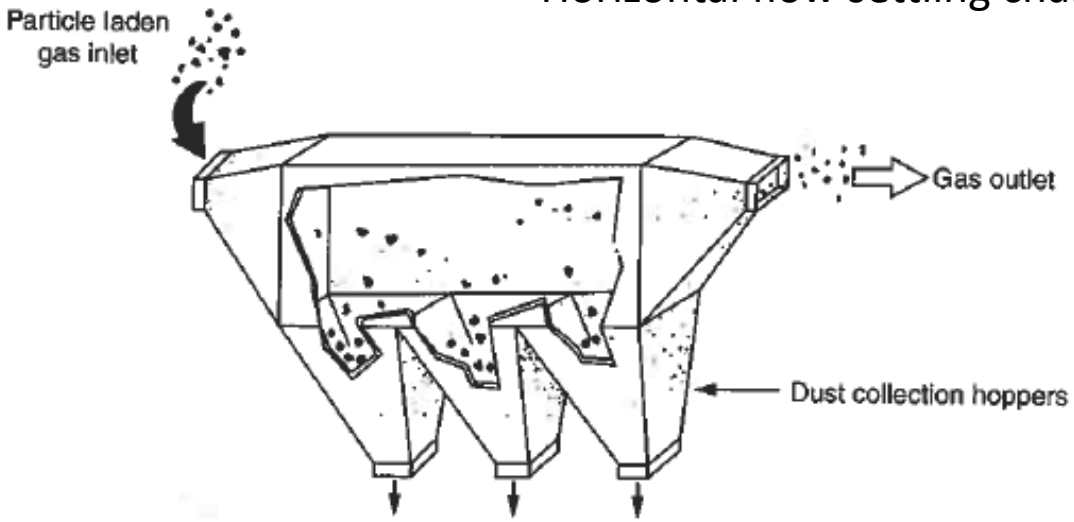
	Coarse Particles (PM_{10}) (2.5<d<10µm)	Fine Particles ($PM_{2.5}$) (d<2.5µm)
Composition	smoke, dirt and dust from factories, farming, from roads mold, spores, and pollen	toxic organic compounds heavy metals
Origin	crushing and grinding rocks and soil then blown by wind	- driving automobiles - burning plants - smelting (purifying) - and processing metals

Removal technology:

- Gravitation chambers
- Cyclones
- Filters
- Electrostatic precipitators
- Scrubbers

- Gravitation chambers

Horizontal flow settling chamber.

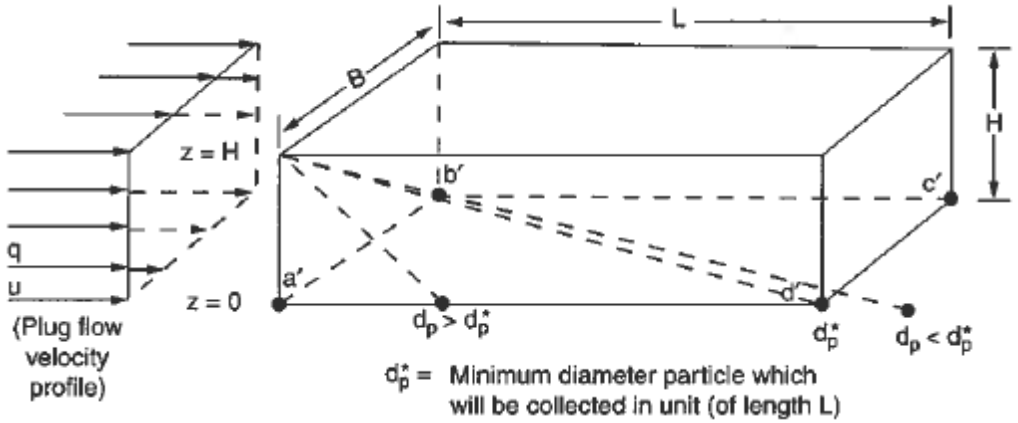


Howard settling chamber (multi

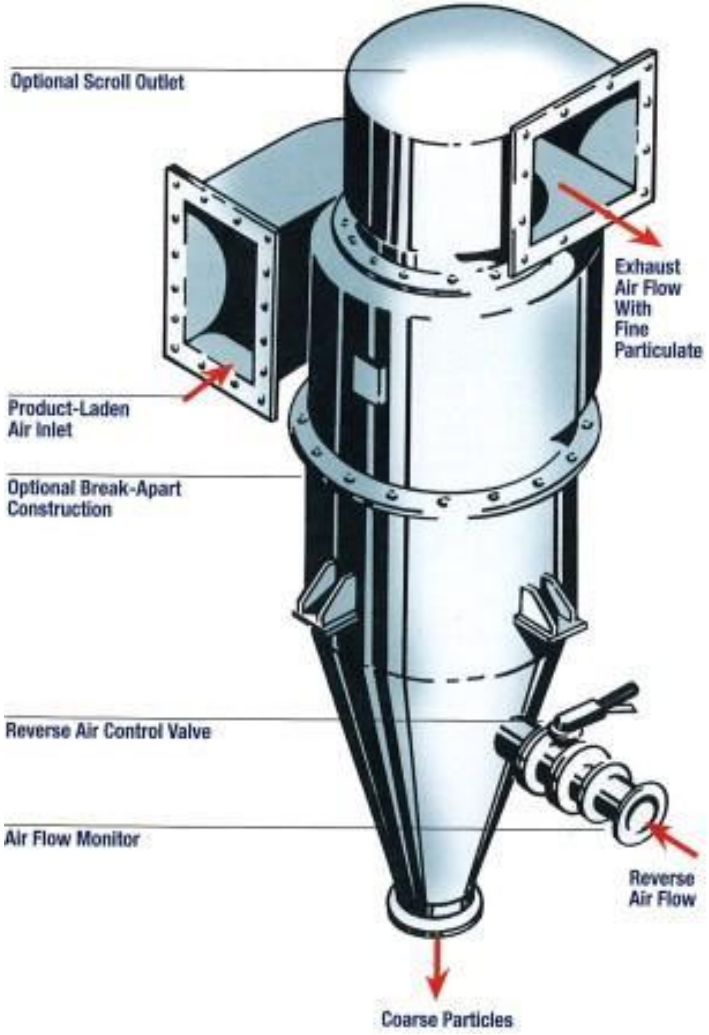
- Gravitation chamber mainly used as a first pretreatment:

- Advantages:

  - Simple
  - Low pressure drop
  - Low maintenance cost



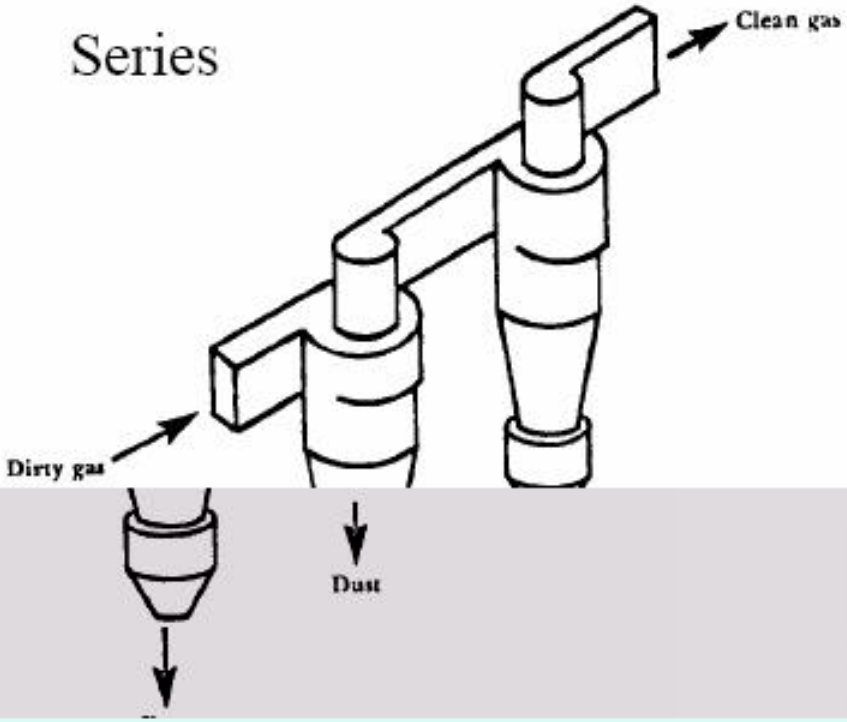
- Cyclones


Optional Scroll Outlet
Exhaust Air Flow With Fine Particulate
Product-Laden Air Inlet
Optional Break-Apart Construction
Reverse Air Control Valve
Air Flow Monitor
Reverse Air Flow
Coarse Particles

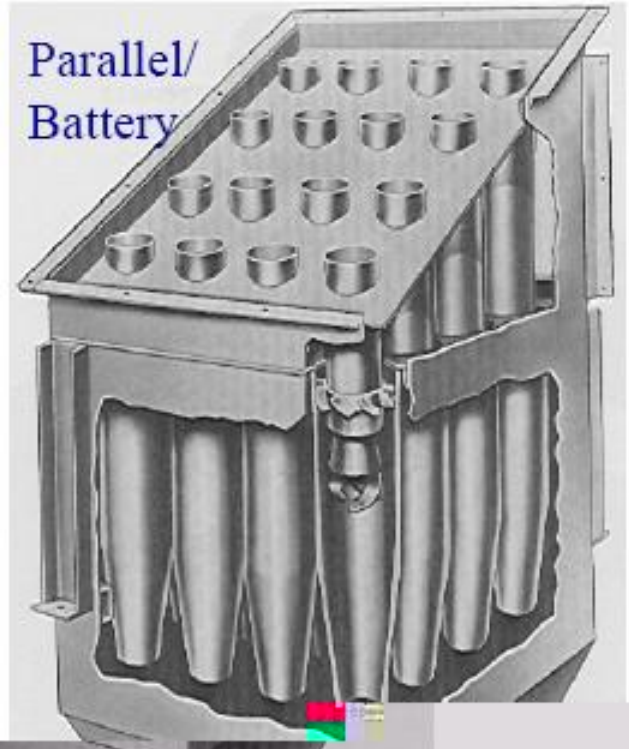
Cyclone
clean air outlet
inner cylinder
airflow path
outer wall
dusty air inlet
dust deposited on wall
dust outlet
small cyclone on truck

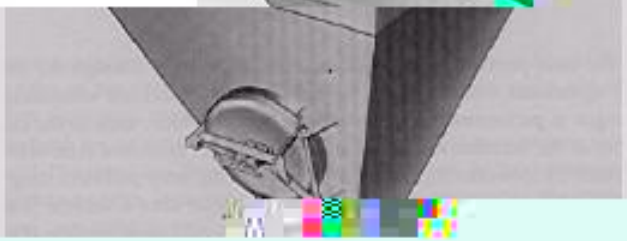
Arrangement

Series



Parallel/
Battery





Air Pollution Control Equipment,
Theodore & Buonicore, *CRC Press*, 1988

- Based on centrifugal force

- Efficiency depends on
    - particle size
    - particle density
    - gas speed
    - diameter of cyclone

- Larger pressure drop: higher operating cost

Principle: sudden change in velocity

Application: very coarse particles (> 75 um)

Efficiency: low

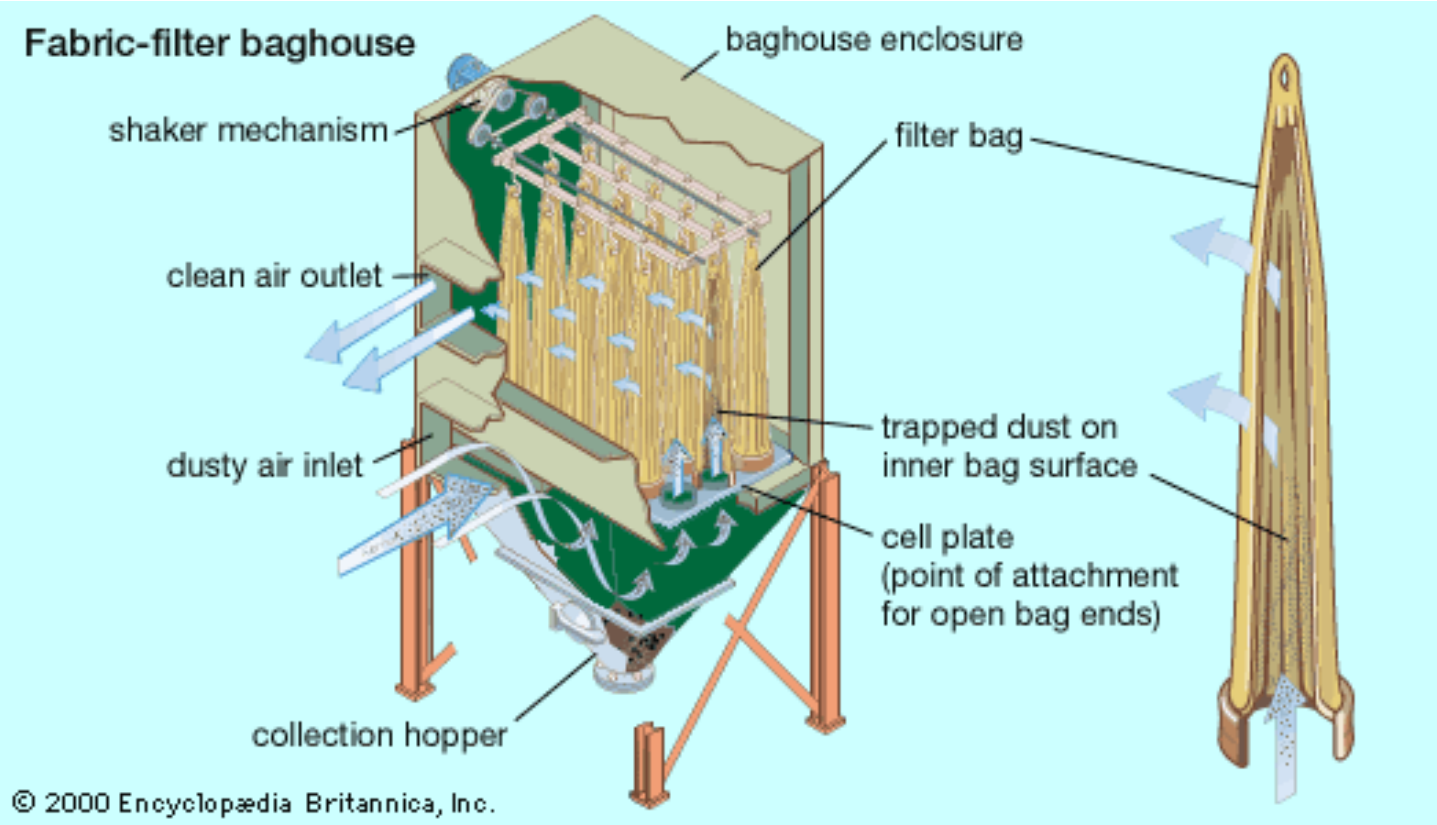
Initial cost: inexpensive

Operating cost: low

Necessary space: **large**

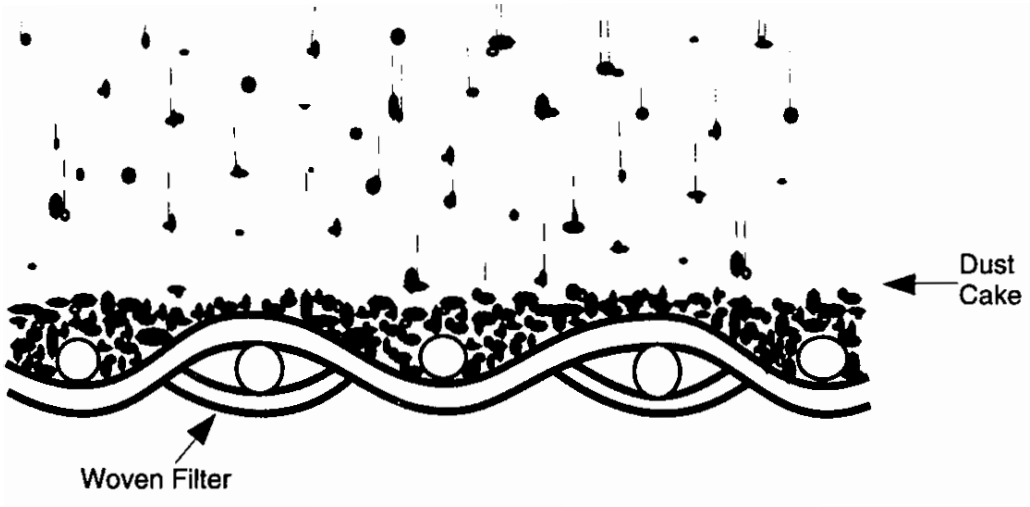
- Filters

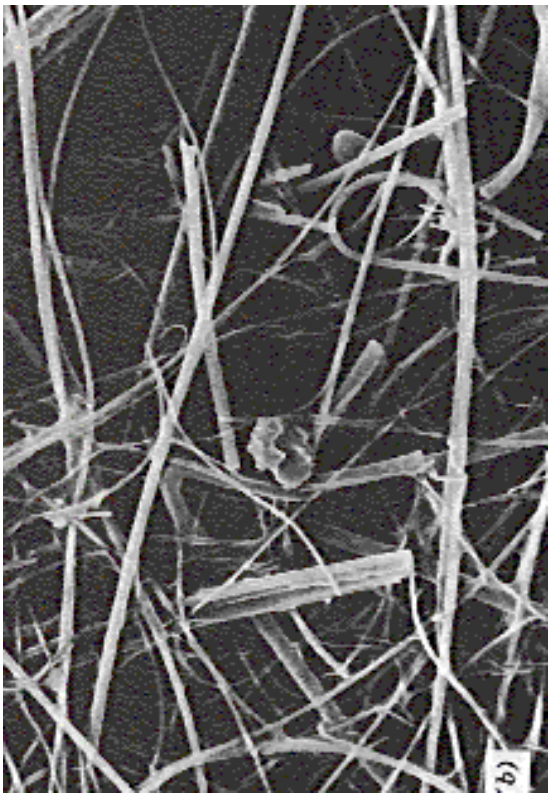
Removal by
- Shaking
- blowing



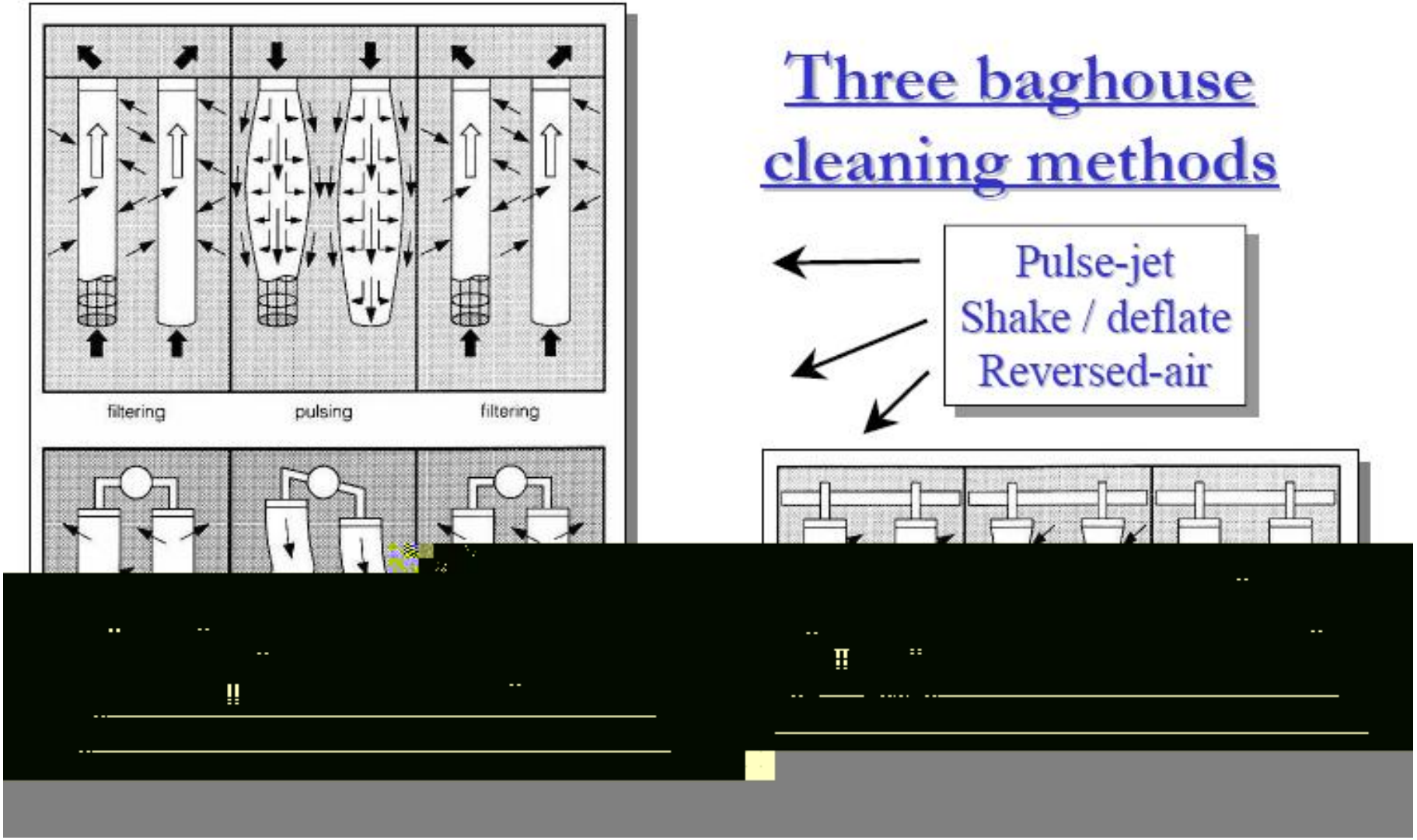
Shaker

Frequency:	4 Hz
Amplitude:	5 – 8 cm

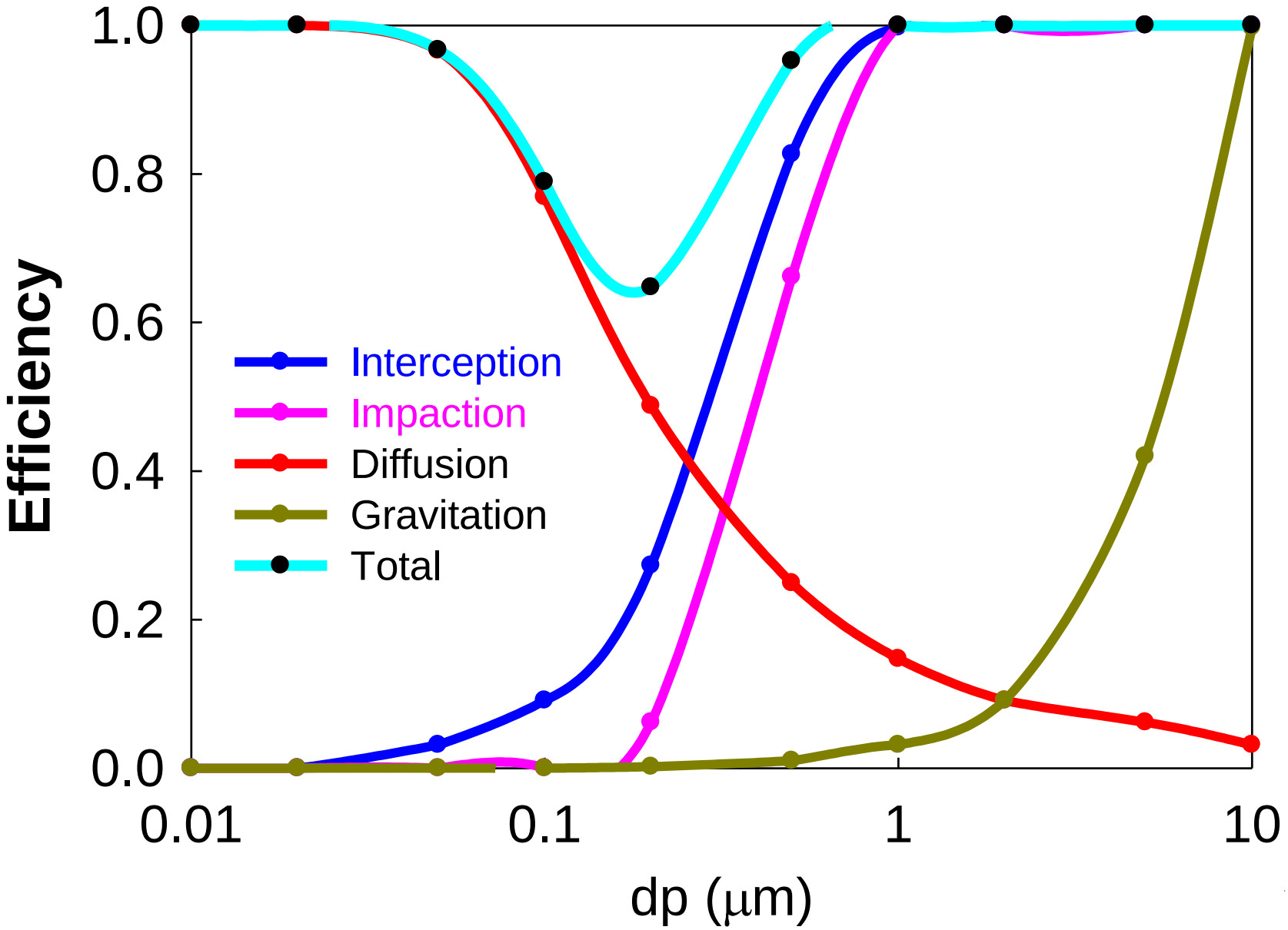

Dust
Cake
Woven Filter



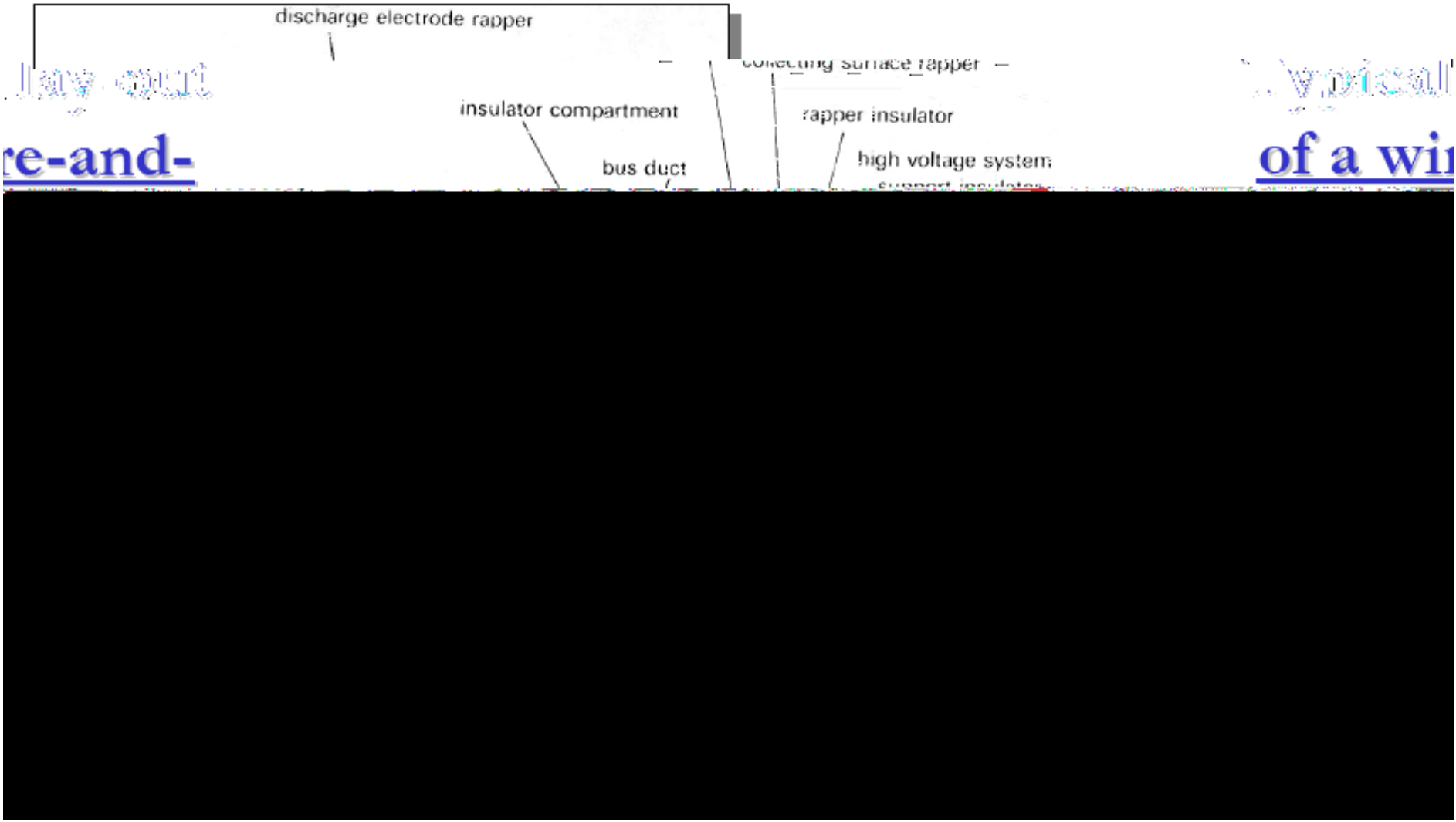
Three baghouse cleaning methods



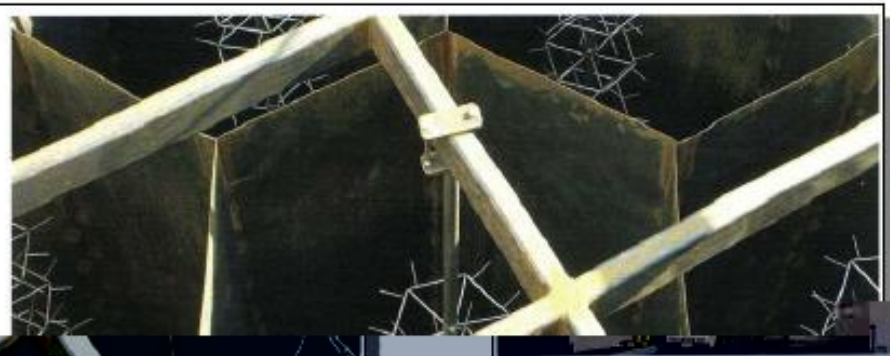
Filter efficiency for individual mechanism and combined mechanisms



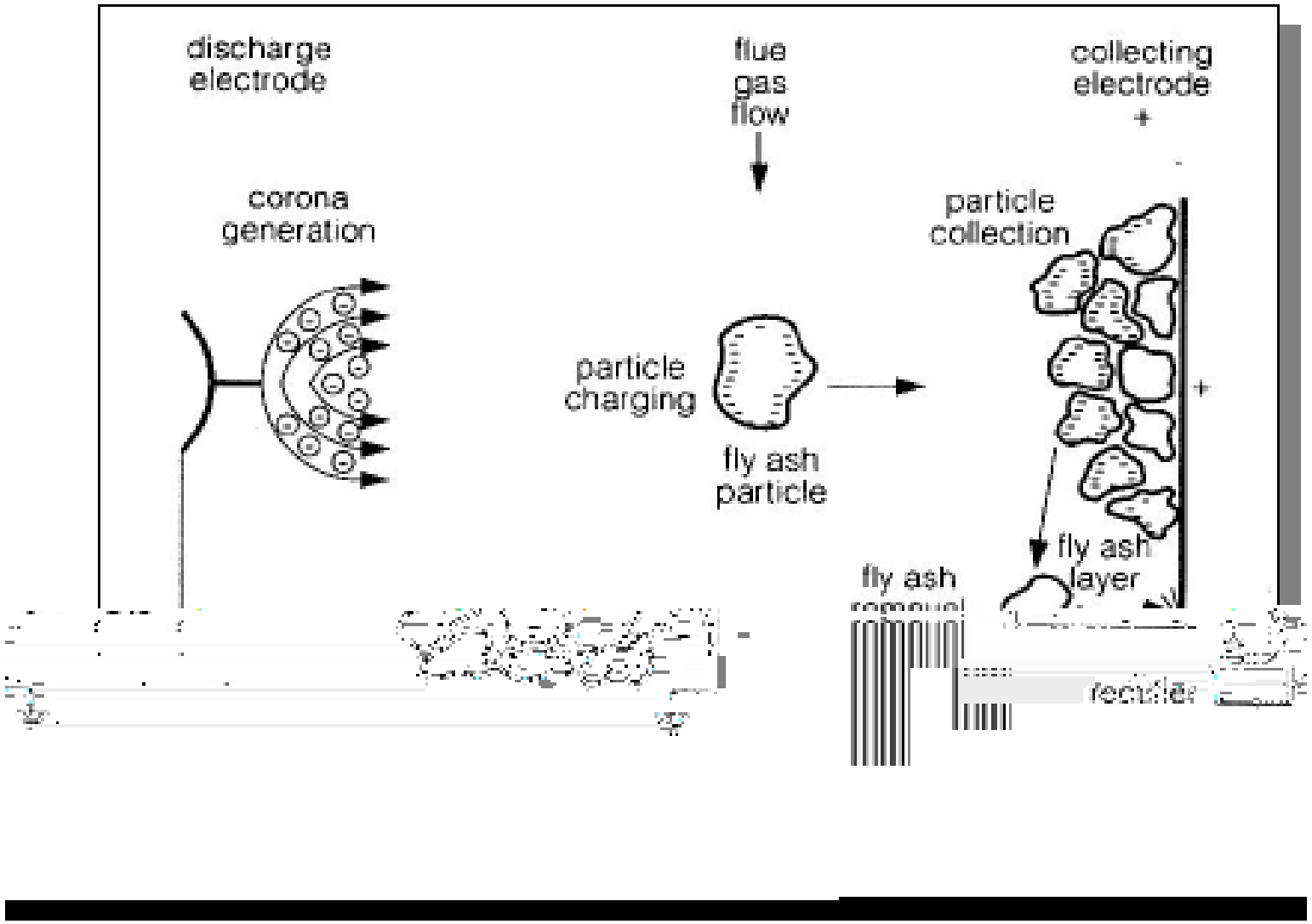
- **Electrostatic precipitators : 'wire and plate' concept**

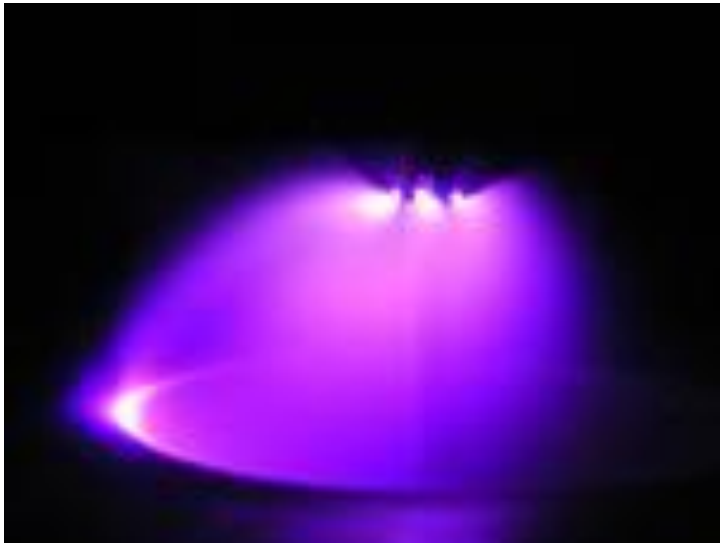


An ESP at Kotka Finland

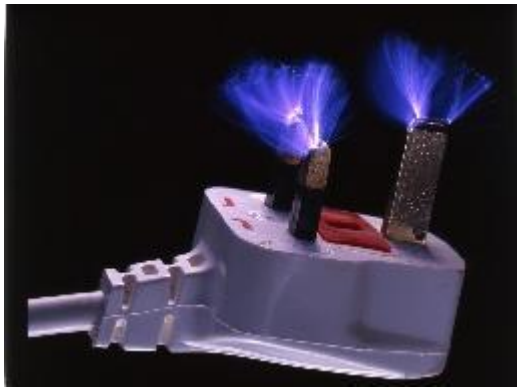


Sähkösuodattimen kennostoa rakennusvaiheessa. Keskellä ovat emissioelektrodit.


discharge electrode
flue gas flow
collecting electrode
+
corona generation
particle collection
particle charging
fly ash particle
+
fly ash layer
fly ash
recycle

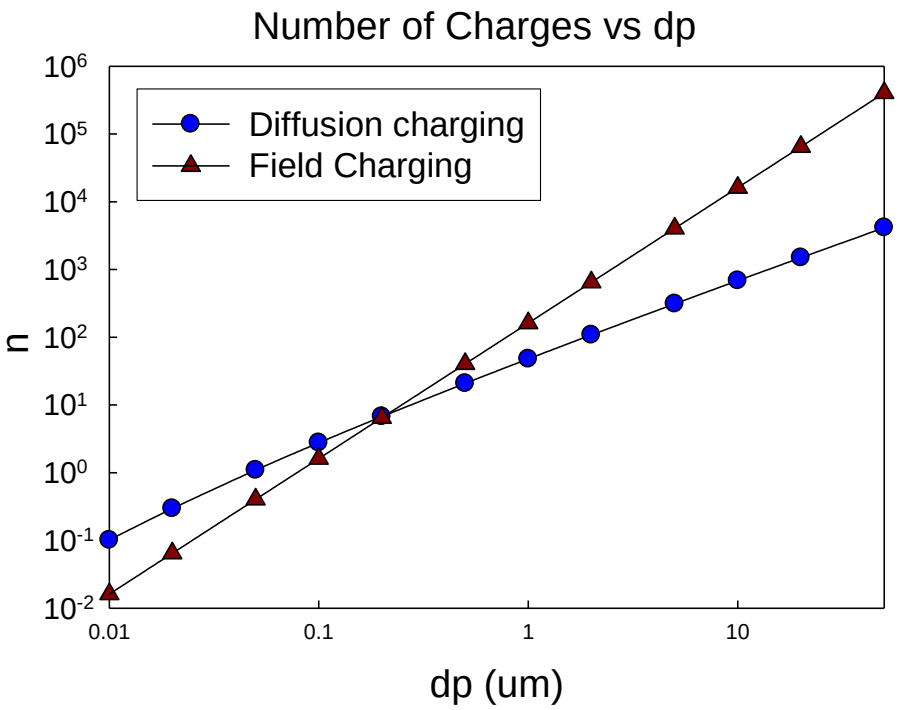


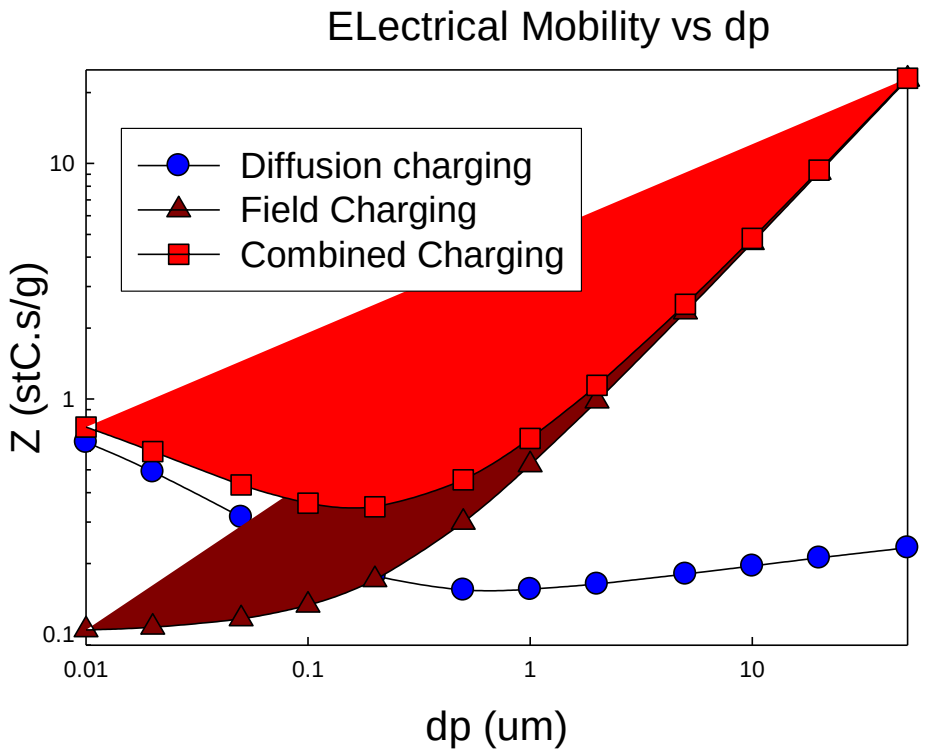
Glow discharge



Tuft glow

spark


Number of Charges vs dp
Diffusion charging
Field Charging
n
dp (um)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0.01
0.1
1
10


ELectrical Mobility vs dp
Diffusion charging
Field Charging
Combined Charging
Z (stC.s/g)
dp (um)
10
1
0.1
0.01
0.1
1
10

Operation:

- Electrodes produce electron current to positive plates
  (electric field by high voltage: 50 000 V)
- Electrons collid with particles:
  = creation of negatively charged particles
- Negatively charged particles move to positive plates
  = collection of particles
- Particles mechanically removed from collector plates
- Global system: set of plates/collectors

- Expensive but efficient,
  especially for smaller particles (0.01 μm)

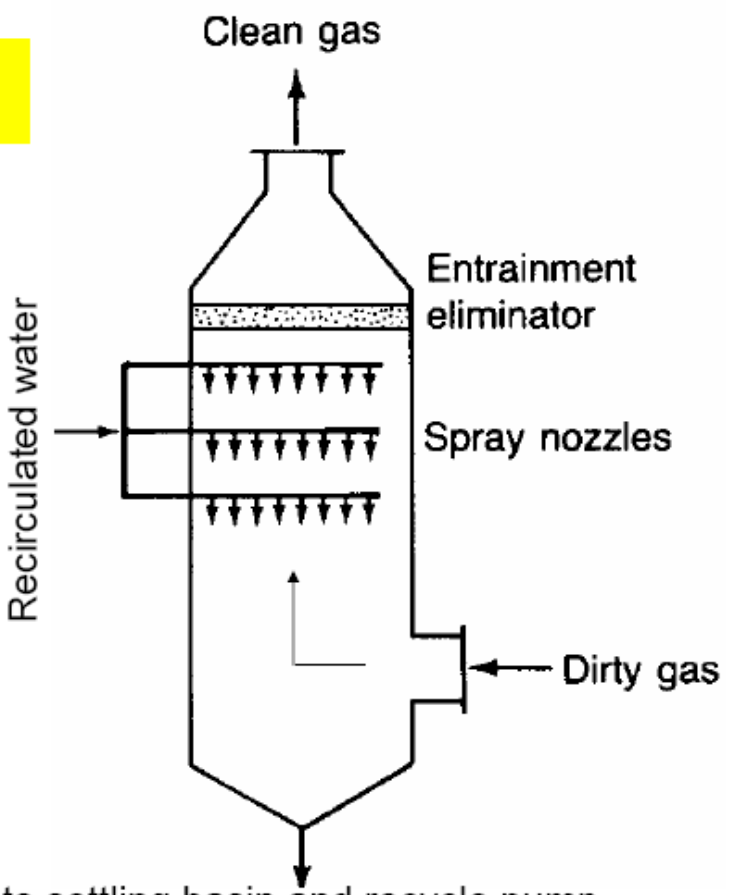
- Scrubbers

Spray Chamber

Collecting medium:

- Liquid drops
- Wetted surface

Impaction	
> 90%	> 5 um
60 – 80 %	3 – 5 um
< 50 %	3 um
Gas flow	1-50 m^3/s



Vertical spray chamber (countercurrent flow)