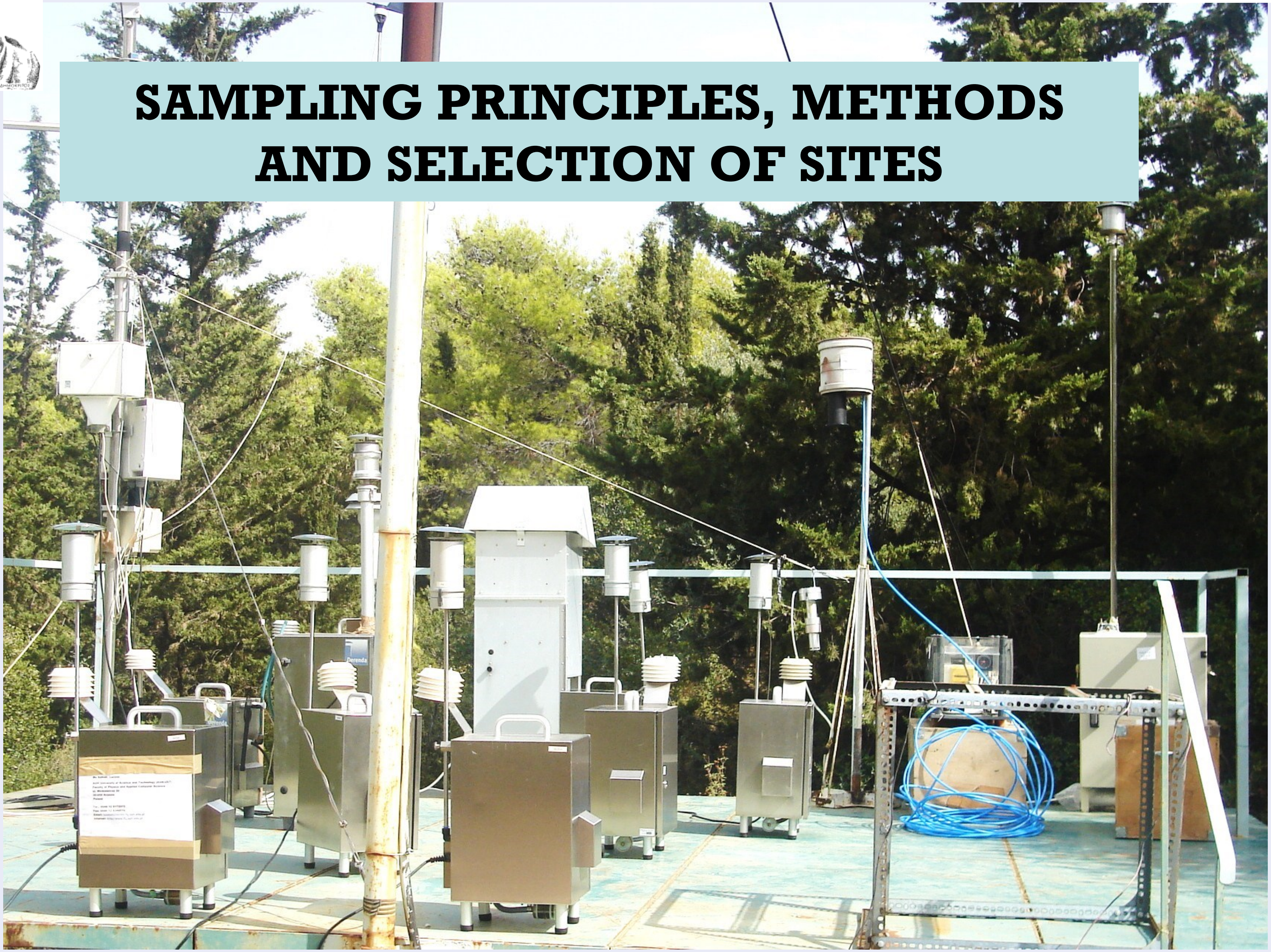
SAMPLING PRINCIPLES, METHODS AND SELECTION OF SITES



RER/1/013 Regional Training course ; Sacavém, Portugal, 02 –06 June, 2014

Inlets, Pre-Separators, and Transport Systems

Aerosol Sampling

Aerosol sampling systems consists usually of:

1. An inlet (or pre-selector) which samples a certain aerosol fraction

2. A transport system (pipes etc.) in which the aerosol is transported to instruments or collectors.

Particle losses can occur due to following processes:

a) sedimentation

b) impaction

c) diffusion

Inlets

Isokinetic inlet: The sampling velocity in the inlet tube is equal to the wind velocity outside ($U = U_0$).

Isoaxial inlet: The direction of the inlet tube faces directly the wind direction ($\Theta = 0$).

The sampling efficiency changes for ($U \neq U_0$) and ($\Theta \neq 0$) in dependence of the Stokes number.

$$\mathrm{Stk} = \frac{\tau \cdot U_0}{d} \qquad \textbf{with} \qquad \tau = \frac{\rho_P \cdot D_P^2 \cdot C_C}{18\eta}$$

τ = Relaxation time

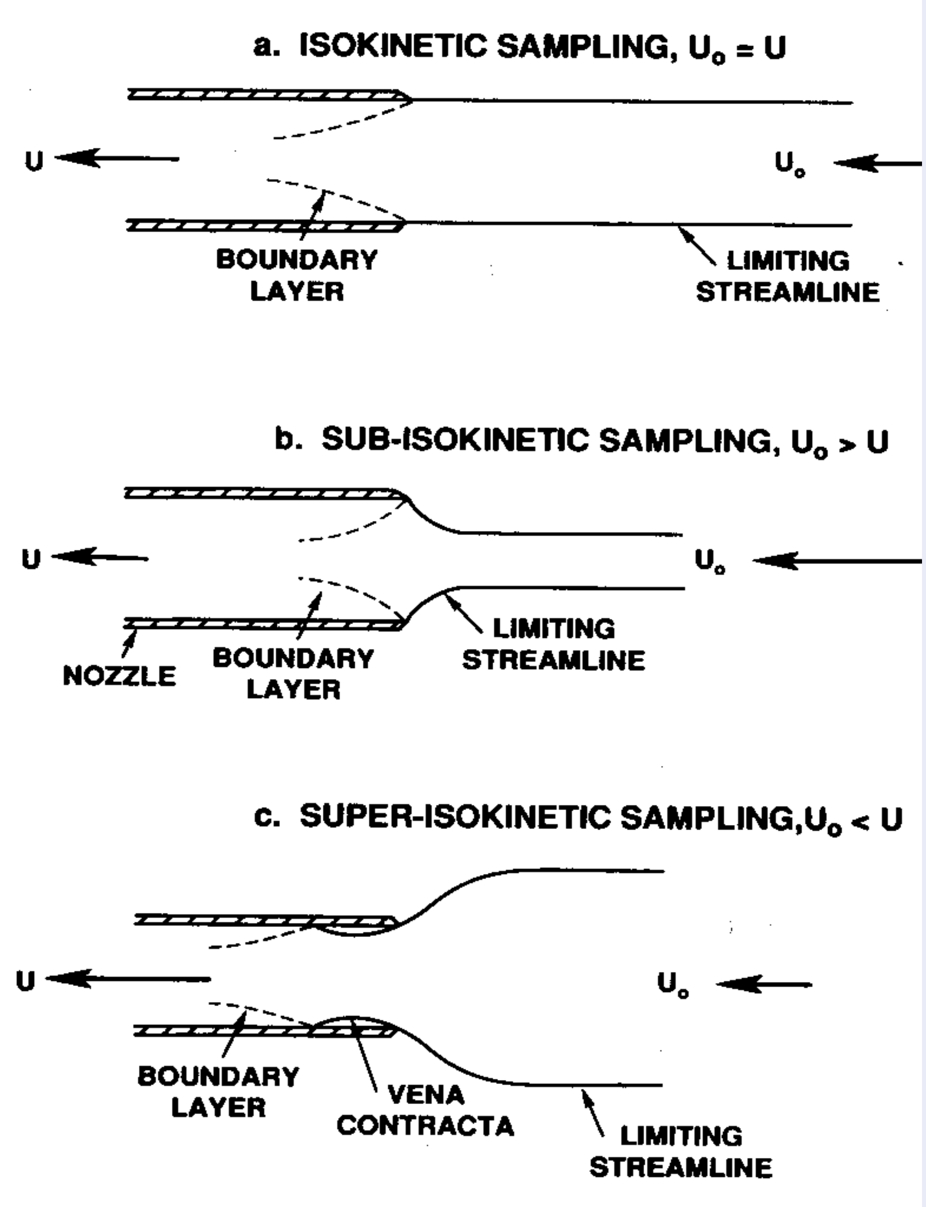
U_0 = Wind velocity

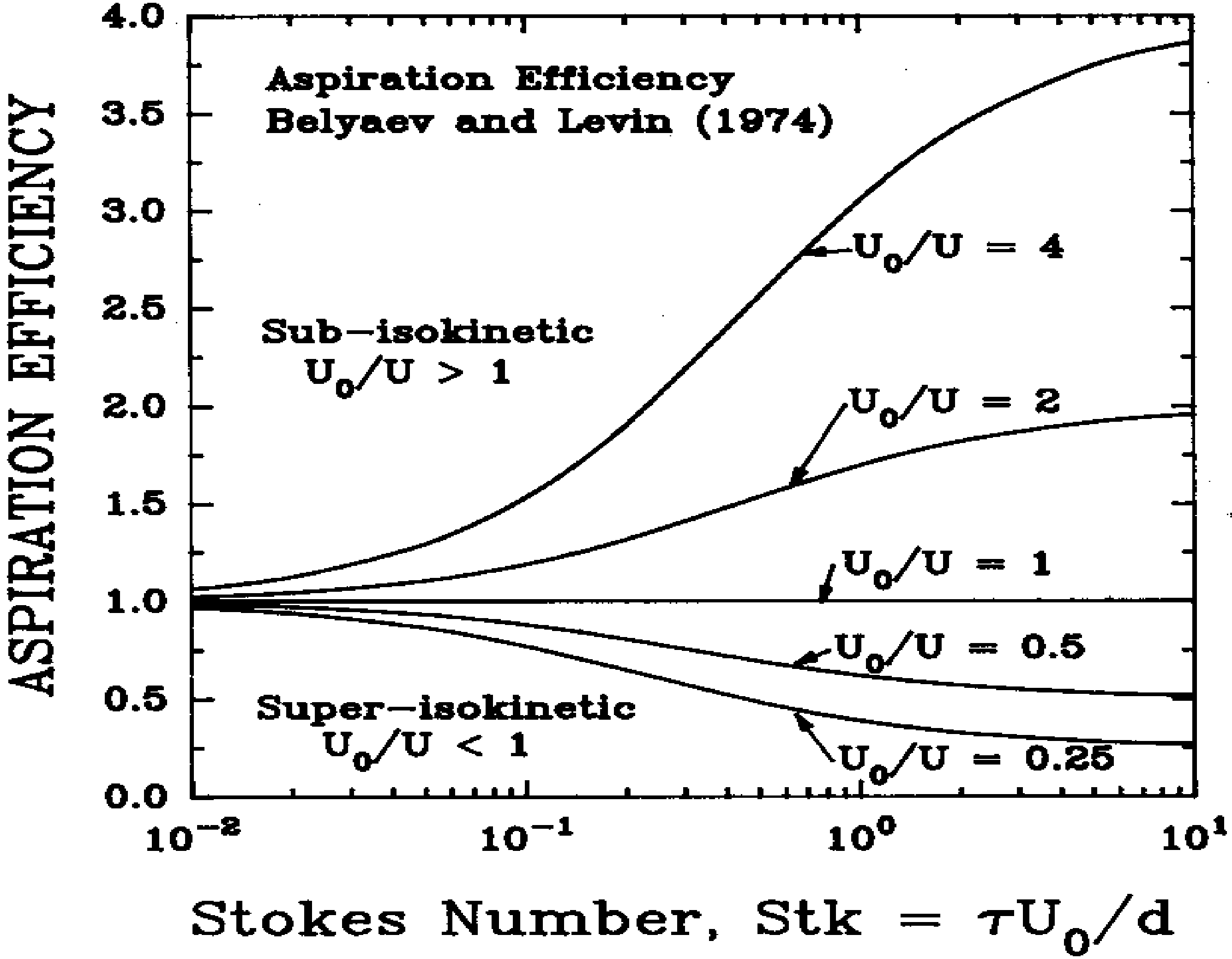
d = tube diameter

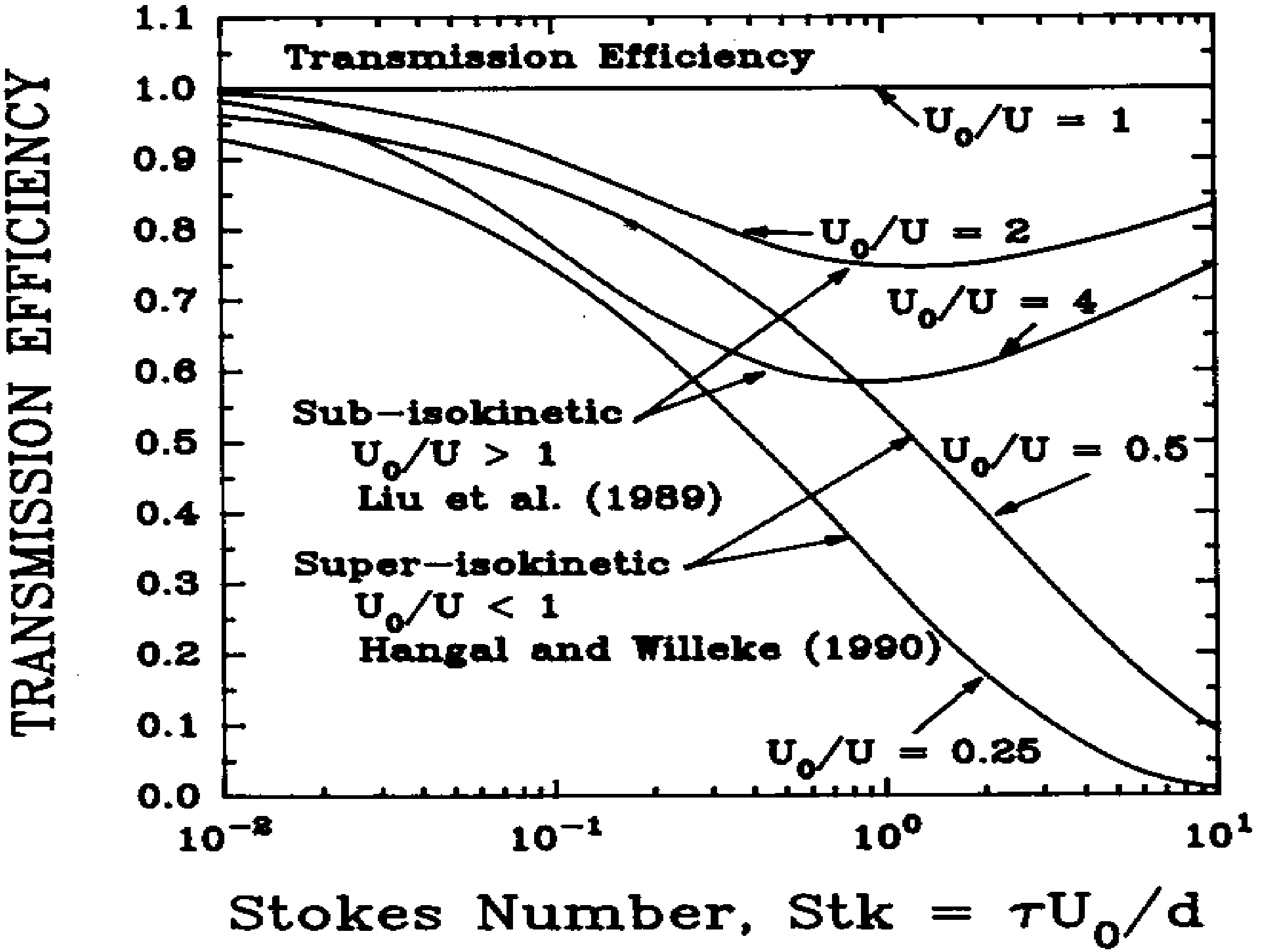
The Stokes number is the ratio between the particle stopping distance to characteristic dimensions of the flow profile.

The particle losses can be neglected for Stk < 0.01 and for $0.2 < U/U_0 < 5$.

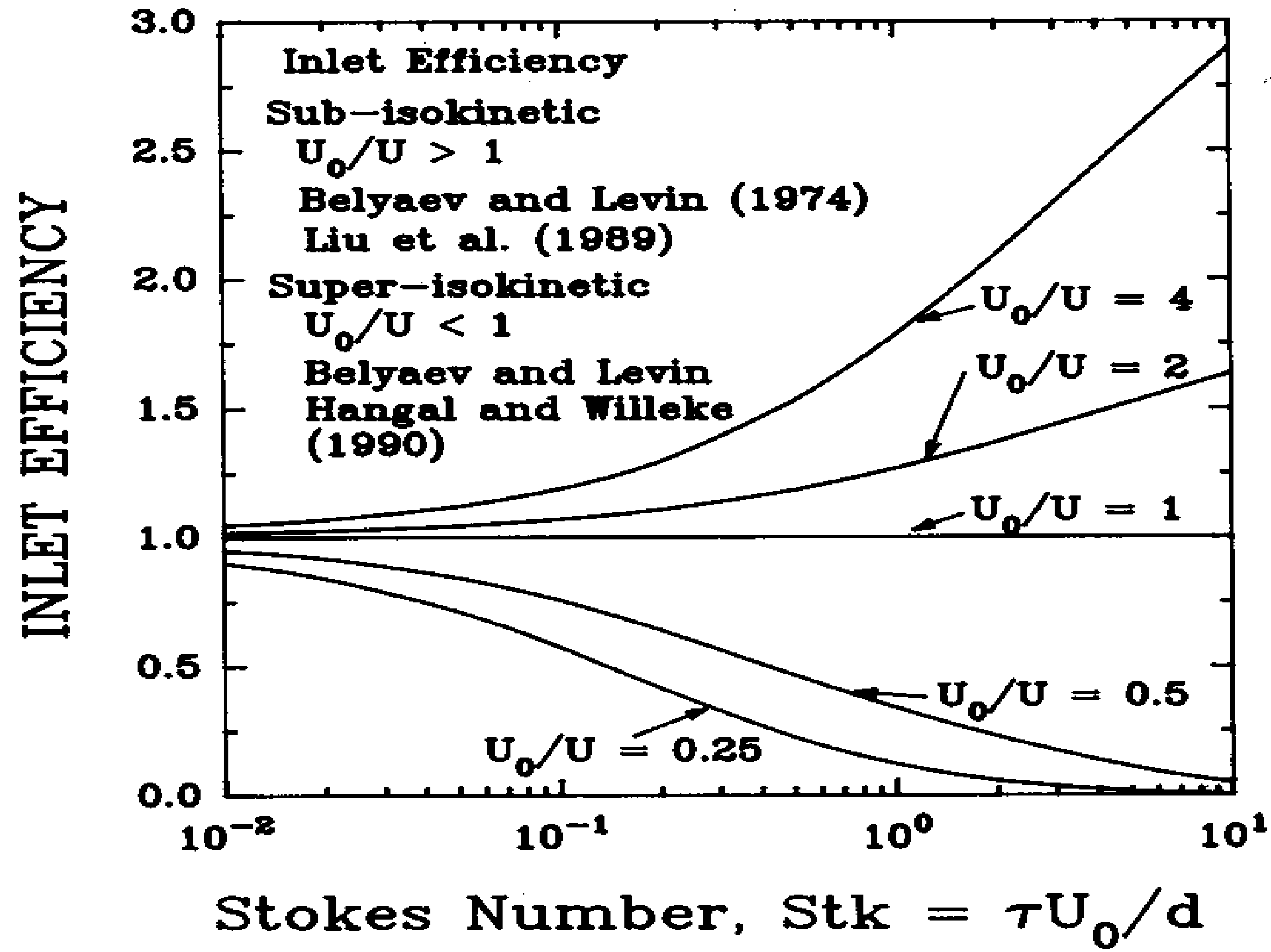
Isoaxial Sampling (Θ = 0)



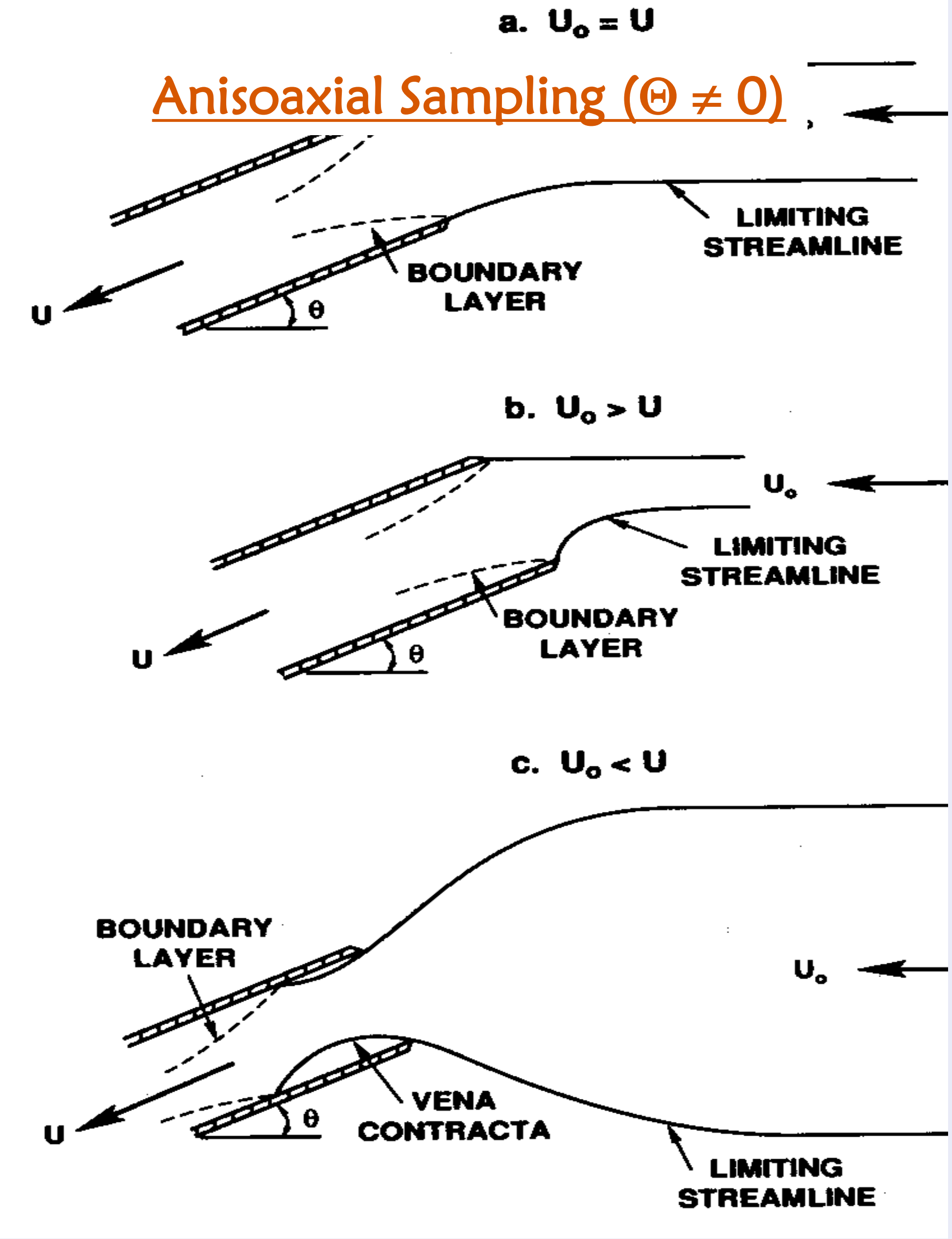

Aspiration Efficiency
Belyaev and Levin (1974)
ASPIRATION EFFICIENCY
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Sub–isokinetic
U0/U > 1
Super–isokinetic
U0/U < 1
U0/U = 4
U0/U = 2
U0/U = 1
U0/U = 0.5
U0/U = 0.25
10−2
10−1
10^0
10^1
Stokes Number, Stk = τU0/d

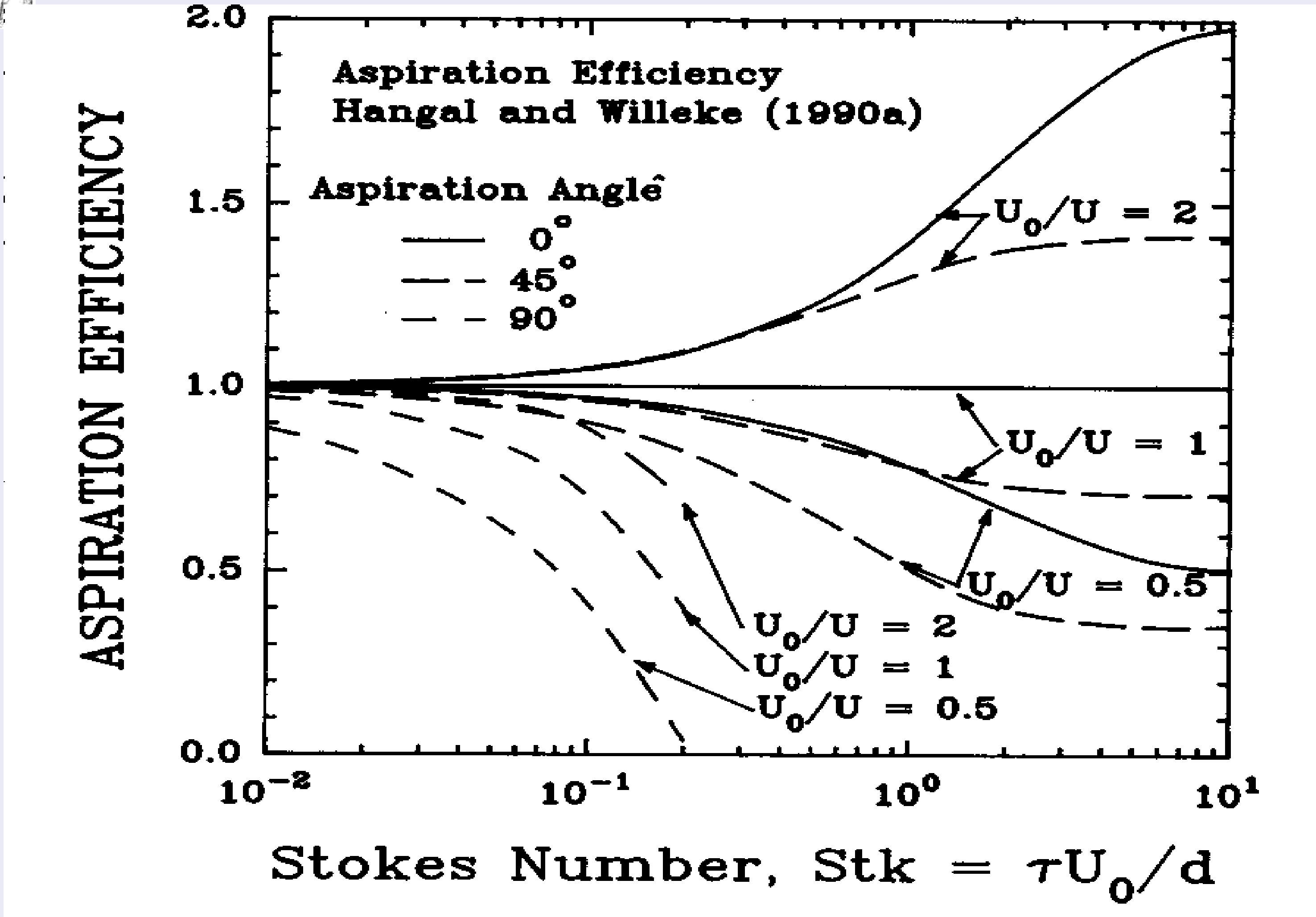


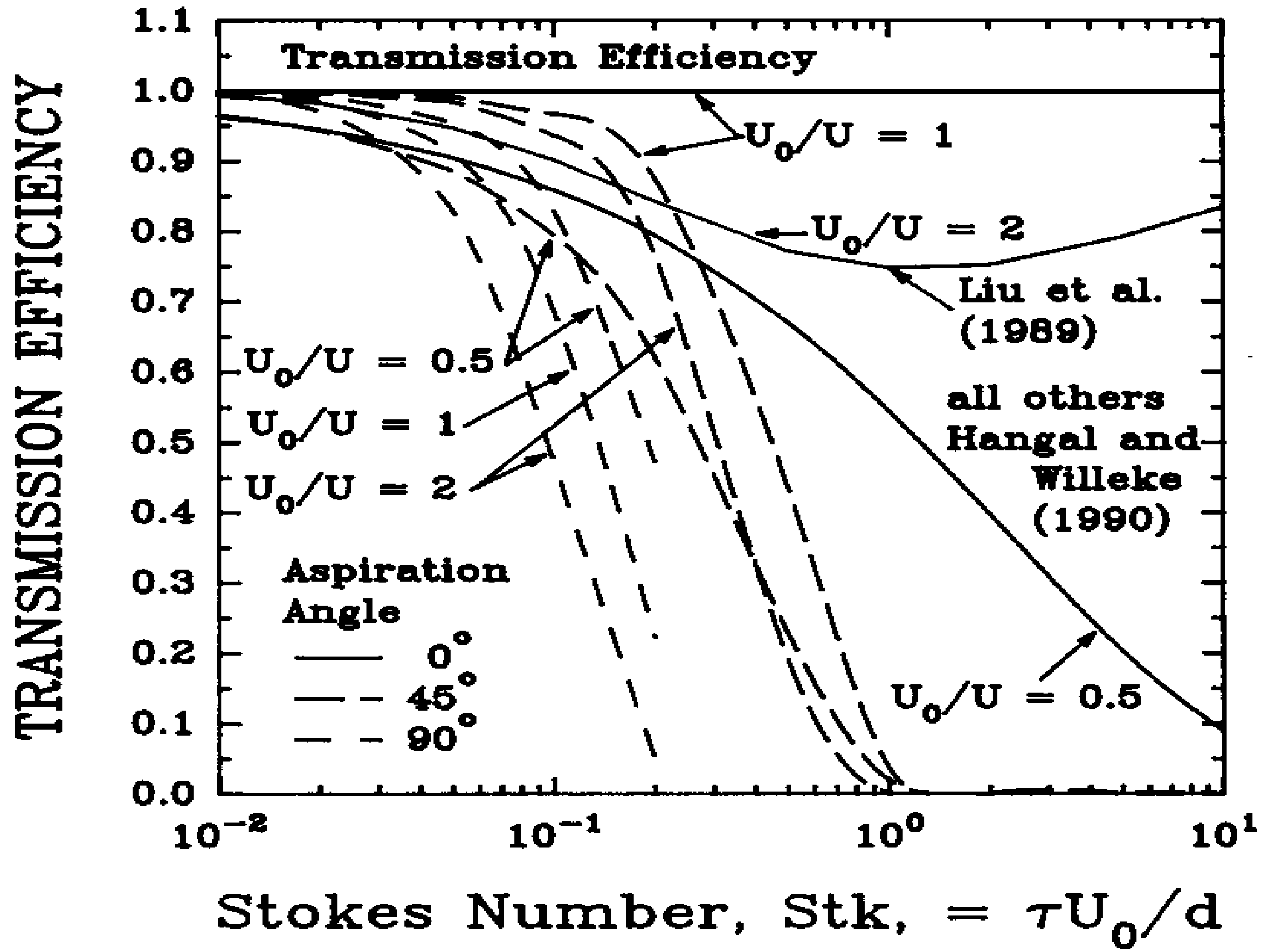
Transmission Efficiency
TRANSMISSION EFFICIENCY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$U_0/U = 1$
$U_0/U = 2$
$U_0/U = 4$
$U_0/U = 0.5$
$U_0/U = 0.25$
Sub–isokinetic
$U_0/U > 1$
Liu et al. (1989)
Super–isokinetic
$U_0/U < 1$
Hangal and Willeke (1990)
10^{-2}
10^{-1}
10^{0}
10^{1}
Stokes Number, Stk = $\tau U_0/d$

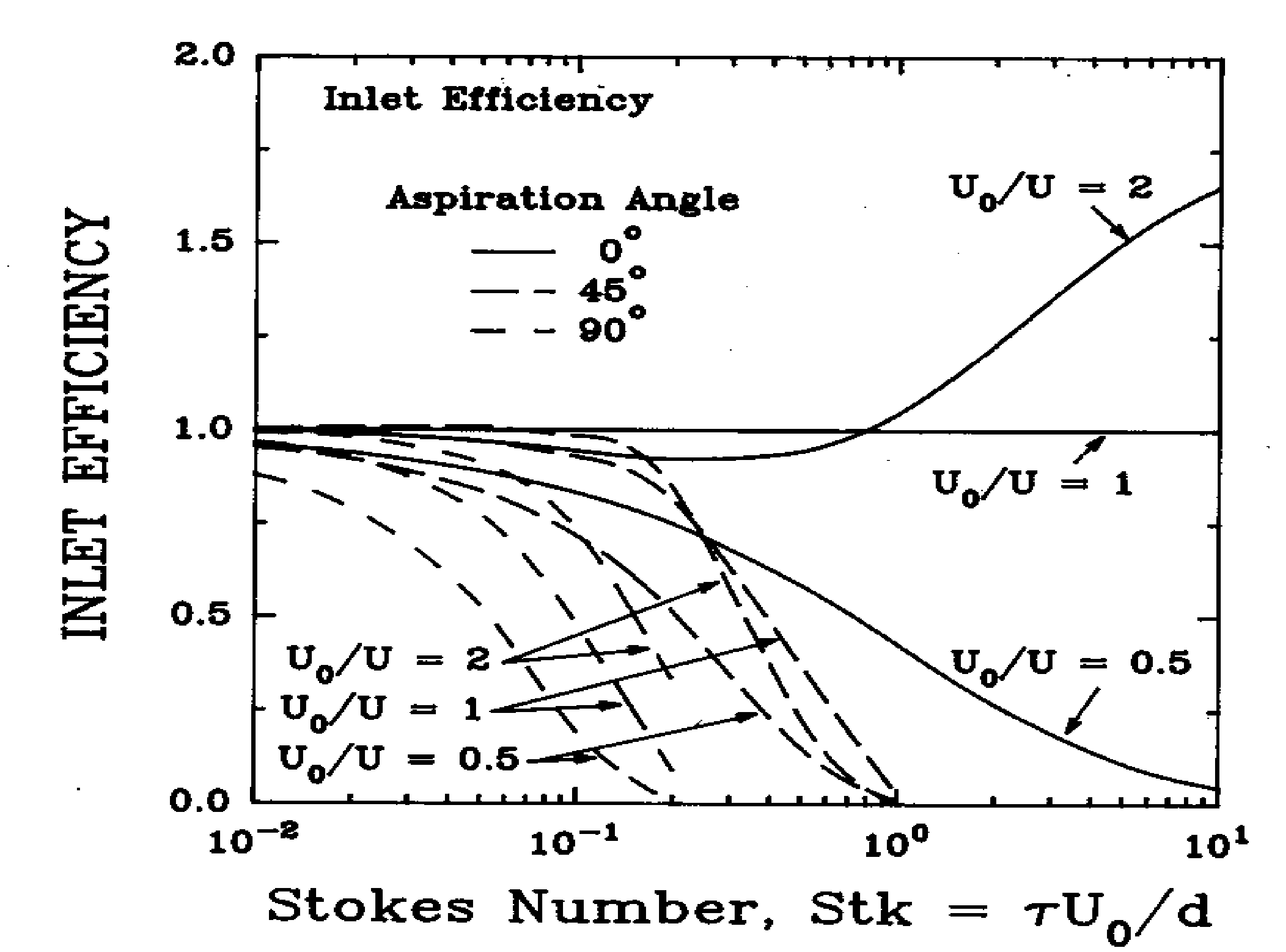

Inlet Efficiency
Sub–isokinetic
U0/U > 1
Belyaev and Levin (1974)
Liu et al. (1989)
Super–isokinetic
U0/U < 1
Belyaev and Levin
Hangal and Willeke
(1990)
U0/U = 4
U0/U = 2
U0/U = 1
U0/U = 0.5
U0/U = 0.25
INLET EFFICIENCY
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10−2
10−1
100
101
Stokes Number, Stk = τU0/d

Anisoaxial Sampling ($\Theta \neq 0$)




Aspiration Efficiency
Hangal and Willeke (1990a)
Aspiration Angle
0°
45°
90°
ASPIRATION EFFICIENCY
2.0
1.5
1.0
0.5
0.0
U0/U = 2
U0/U = 1
U0/U = 0.5
U0/U = 2
U0/U = 1
U0/U = 0.5
10^-2
10^-1
10^0
10^1
Stokes Number, Stk = τU0/d


Transmission Efficiency
TRANSMISSION EFFICIENCY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
U0/U = 1
U0/U = 2
Liu et al. (1989)
U0/U = 0.5
U0/U = 1
U0/U = 2
all others Hangal and Willeke (1990)
Aspiration Angle
0°
45°
90°
U0/U = 0.5
10^-2
10^-1
10^0
10^1
Stokes Number, Stk, = τU0/d



Inlet Efficiency
Aspiration Angle
0°
45°
90°
$U_0/U = 2$
$U_0/U = 1$
$U_0/U = 0.5$
$U_0/U = 2$
$U_0/U = 1$
$U_0/U = 0.5$
INLET EFFICIENCY
2.0
1.5
1.0
0.5
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
Stokes Number, Stk = $\tau U_0/d$

Pre-Separators:

Devices based on inertia are usually used as pre-separators:

a) impactors

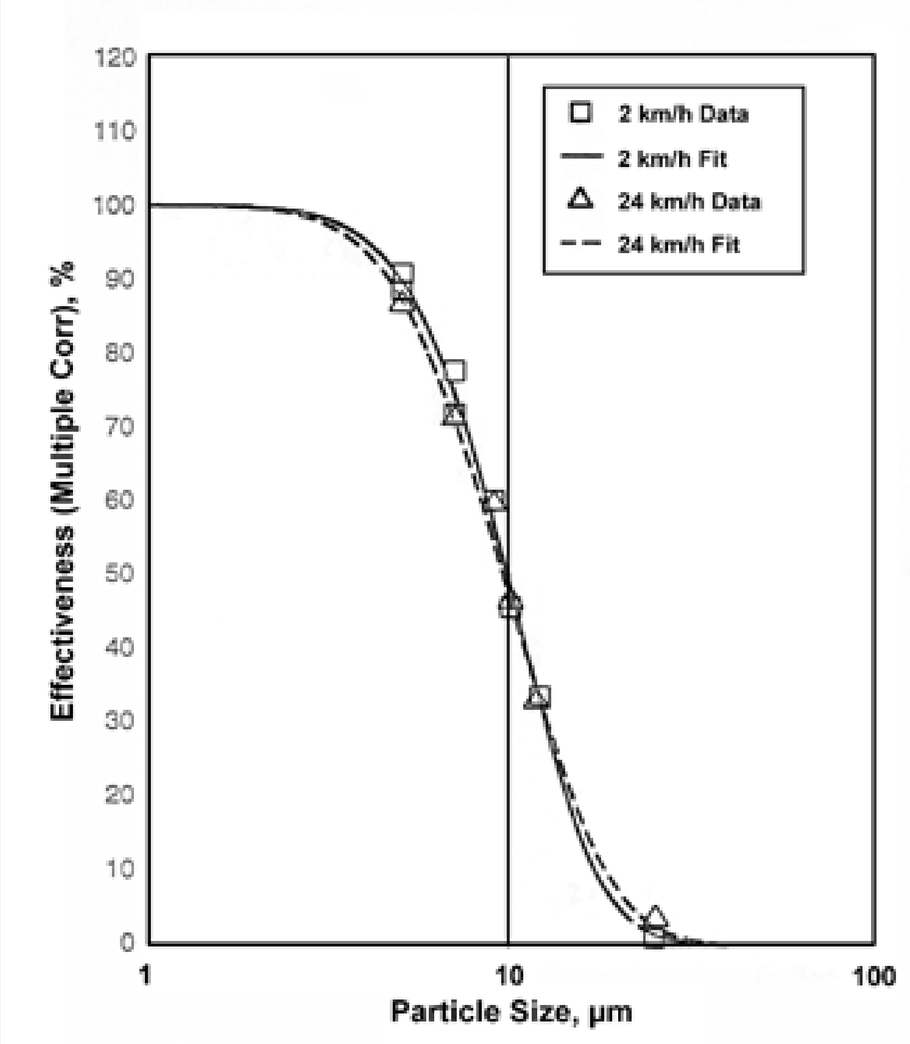
b) cyclones

Pre-separators are used to remove particles larger (or smaller) than a certain size from the aerosol.

Impactors can be theoretically better described than all other types of pre-separators.

Cyclones and other pre-separators must be calibrated to know their behavior.

Low flow PM10 inlet:



Penetration efficiency curve

Transport Systems:

Particle losses in transport systems can occur due to:

a) Inertia in bends (large particles)

b) Sedimentation in horizontal pipes (large particles)

c) Diffusion (small particles)

Recommendations:

For particles > 1 μm:

Pipes should be vertically orientated.

In cases when horizontal pipes cannot be avoided, the flow should be high.

Strong bends should be avoided.

Highly turbulent flows causes increased inertial losses

For particles < 0.1 μm:

Pipes should be kept as short as possible.

The transport system should designed for a laminar flow with the optimum Reynolds number of 2000.

Turbulent flows should be avoided, because of higher diffusional particle losses.

General Sampling Considerations

Sample air should be brought into the laboratory through a vertical stack with an inlet that is well above ground level.

For sites in level terrain, surrounded by no or low vegetation, a height of 5-10 m above ground level is recommended.

Because gas analysers may have incompatible requirements, a dedicated inlet stack may be required for the aerosol samples.

The size of the entrance configuration must be well designed to provide a high inlet sampling efficiency for aerosol particles over a wide range of wind speeds.

The sample flow should be laminar in the sample tube to avoid additional losses of small particles due to diffusion and turbulent inertial deposition. The ideal flow should have a Reynolds number of about 2000.

General Sampling Considerations

The inlet material should consist of conductive and non corrosive tubing material such as stainless-steel that are weather- and sunlight-resistant.

In tropical regions, the sample air must be either dried or diluted by particle-free dry air to avoid condensation in the sampling pipes.

The relative humidity should be kept below 40%.

Aerosol sampling equipment should be housed in a shelter that provides a controlled laboratory environment (temperature 15-30°C).

Filter

An important task in aerosol technology is to remove particles from the carrier gas they are suspended in utilizing filters.

Filters are used for as well gas cleaning as particle sampling (e.g. chemical characterization).

Filters are especially used for sub-micron particles and for low particles number concentrations.

Filters are characterized by their deposition efficiency *E*, (alternatively the penetration *P*) and their pressure drop Δp .

$$E = \frac{N_0 - N_1}{N_0} \qquad P = 1 - E$$

$$\Delta p = p_0 - p_1$$

N_0 = number concentration up-stream of the filter

N_1 = number concentration down-stream of the filter

P_0 = pressure up-stream of the filter

P_1 = pressure down-stream of the filter

The "ideal filter" should have an deposition efficiency of $E = 1$ together with a pressure $\Delta p = 0$.

Mechanisms for the deposition of particles on and/or inside filters are:

- Impaction
- Interception
- Diffusion
- Settling
- External forces (electrical forces)

These deposition mechanisms depend an the actual flow situation in the vicinity and/or inside the filter as well as particle size and shape.

The actual flow situation is characterized in terms of the filter face velocity:

$$u_0 = \frac{\dot{V}}{A}$$

$\dot{V}$ = aerosol volume flow rate

A = filter area

Particle deposition in filters is a function of particle size.

The deposition efficiency in filters always shows a minimum, i.e. a penetration maximum.

The position of the deposition efficiency minimum on the particle size axis depends on the filter itself.

The deposition efficiency is also a function of the actual filter loading and consequently a function of time.

With increasing time, both deposition efficiency and pressure drop increase.

The theoretical description of particle transport in filters is complex.

The two most important types of filters are:

- fiber filters
- membrane filter

Filter selection criteria include:

1. Mechanical stability
2. Chemical stability
3. Sampling efficiency
4. Flow resistance
5. Loading capacity
6. Blank values
7. Artifact formation
8. Compatibility with analytical protocols
9. Cost and availability

Filter media for atmospheric sampling include:

1. Cellulose fiber
2. Glass fiber
3. Quartz fiber
4. Teflon membrane
5. Etched polycarbonate membrane
6. Mixed cellulose ester membrane
7. Nylon membrane

NO MATERIAL IS PERFECT FOR ALL PURPOSES

B.3.1 Fiber Filters

Fiber Filters consist of layers of fine e.g. glass or plastic fibers.

The fiber orientation is such that the fiber axis are perpendicular to the flow direction.

Depending on the actual application, fiber diameters vary in the range between 0.3 und 100 μm.

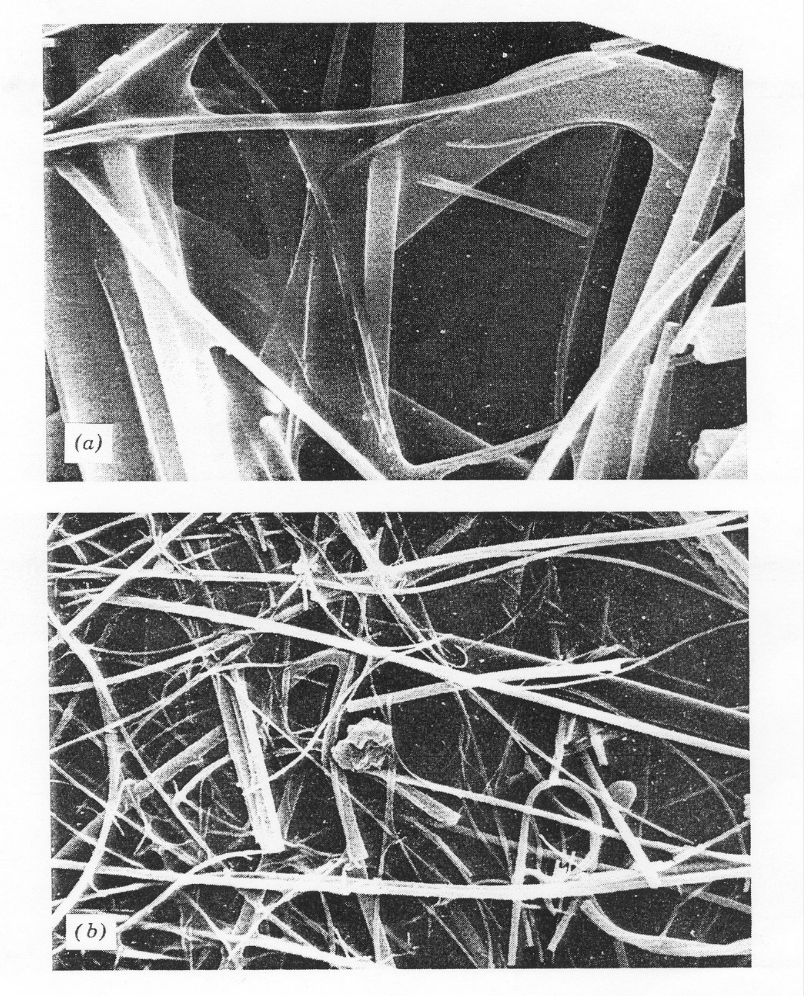
Fiber filter mainly consist of air.

The fiber volume fraction α is in the order of 1 to 30%.

$$\alpha = \frac{\text{fiber volume}}{\text{filter volume}}$$

For fiber filters, particles mainly deposit inside the filter.

Fiber filters are mainly used for gas cleaning applications such as gas filtration in clean rooms.

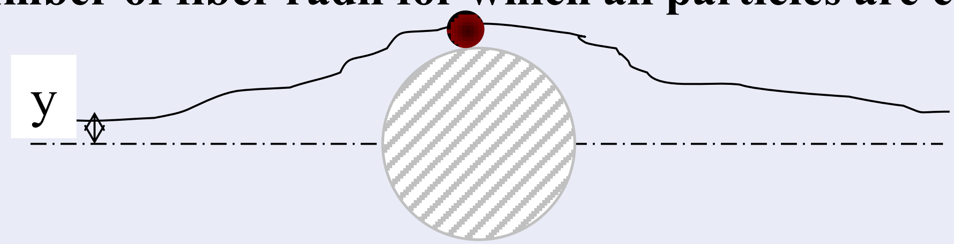


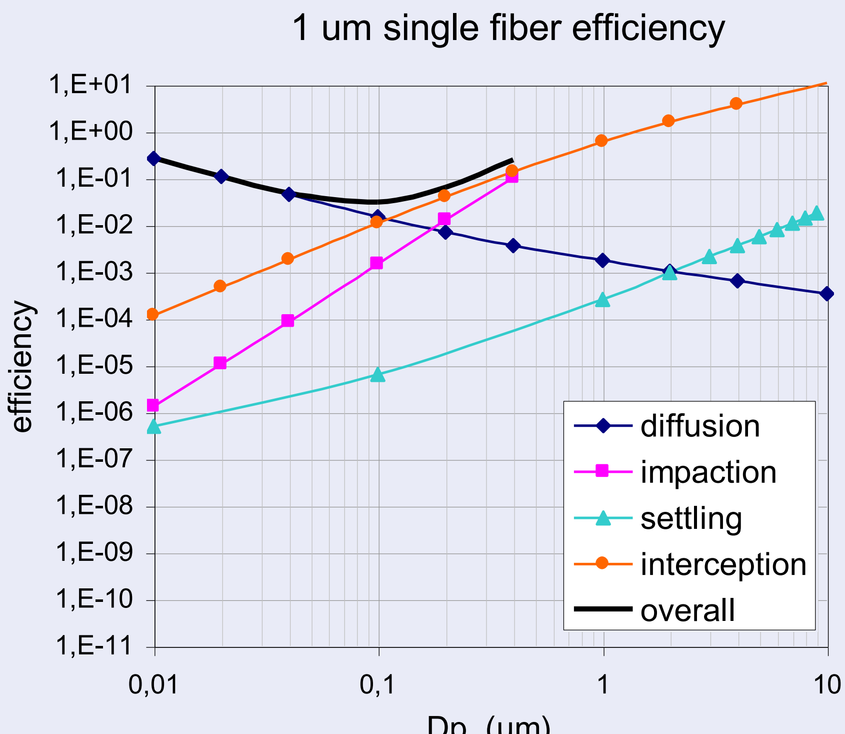
Scanning electron microscope photograph of a high efficiency glass fiber filter. Magnification (a) 4150 X, (b) 800 X .

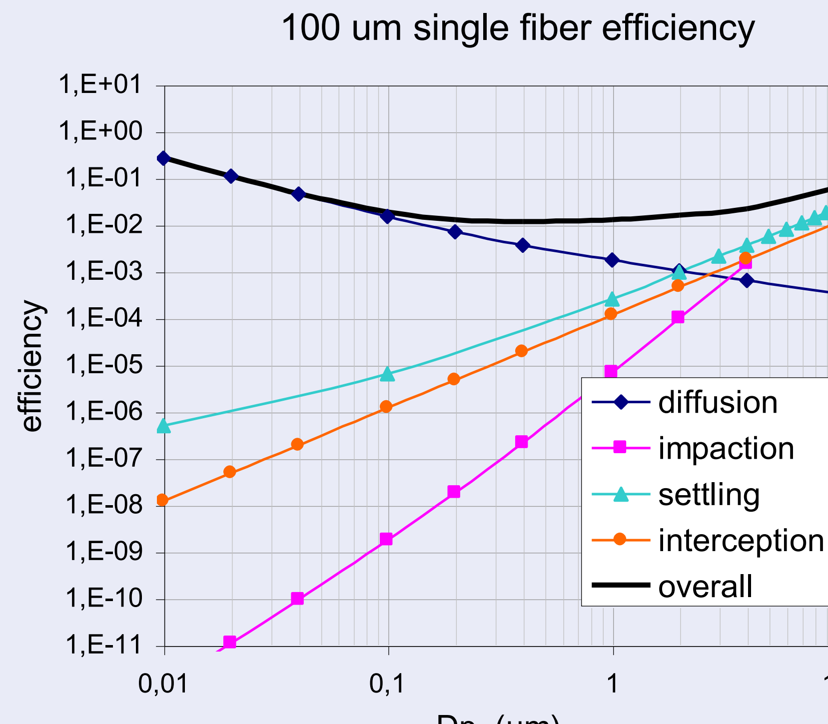
Fiber filter single fiber efficiency *e* for:

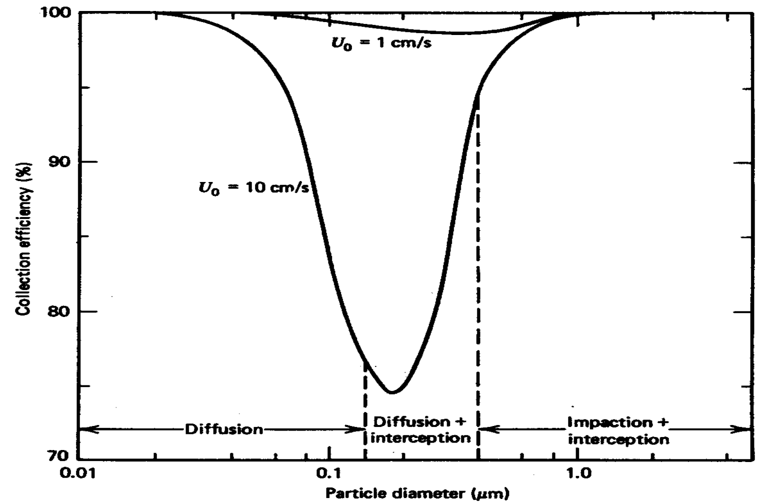
- **face velocity = 20 cm / s**
- **packing density = 0.05**

***e* is the number of fiber radii for which all particles are captured ($e = y / R_f$)**







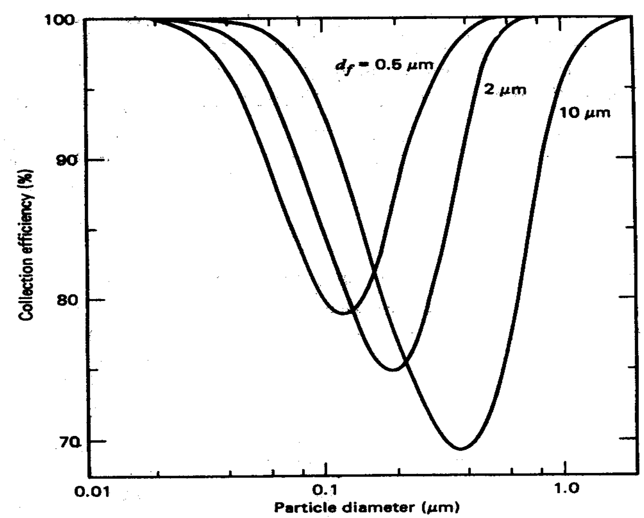


Efficiency versus particle size for face velocities of 1 and 10 cm/s; $t = 1$ mm, $\alpha = 0.05$, and $d_f = 2\ \mu$m.

α = solidity or packing density

= 1 – porosity

= fiber volume / filter volume



The effect of fiber size on filter efficiency as a function of particle size; $\alpha = 0.05$ and $U_0 = 10$ cm/s. Filter thickness has been adjusted so that all three filters have the same pressure drop

Filter type	Applications	☺	☹
Fiber filters (in general)	Air quality	• low pressure drop • high loading capa.	• lower efficiency for subμm particles • penetration
Cellulose filters	IC, dust (ashless)	• cheap • easy extraction	• moisture sensitive
Borosilicate glass filters	Wide scope (without binder)	• resists to 500°C	• resists to 500°C • water vapor uptake
Quartz fiber filters	Sampling for chemi--cal analyses: IC, AAS, carbon, PAHs	• reasonable moisture uptake • resists to > 800°C	• may be friable

Membrane Filter

Membrane Filters consist of thin porous plastic foils/films.

The usually cylindrical pores are produced by neutron bombardment and a subsequent etching process.

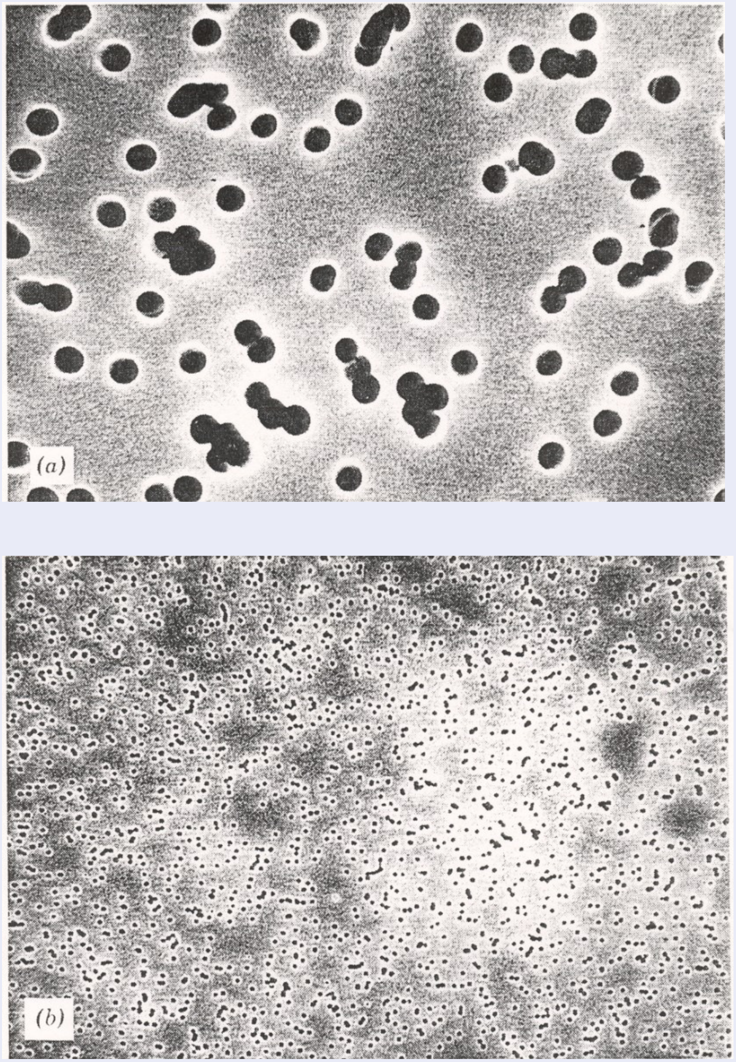
Depending on application, the pore diameters vary from a few ten nanometers up to a couple of micrometers.

Membrane filters are surface filters, i.e. particles are mainly deposited on the filter surface.

For particle diameters smaller than the pore diameter, the deposition efficiency is smaller than that of comparable fiber filters.

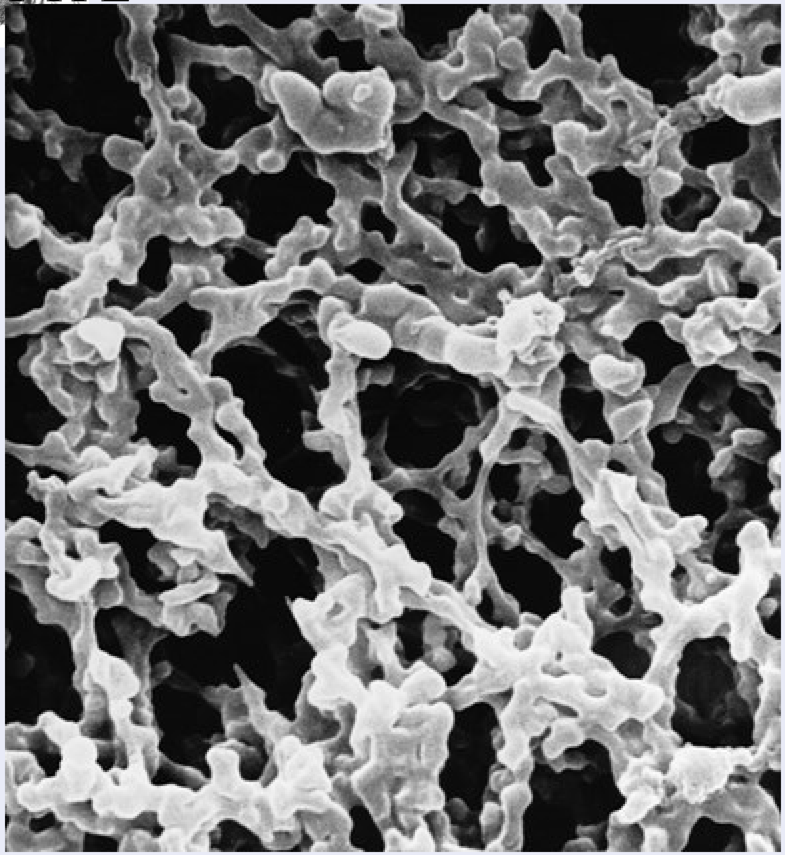
Membrane filters have a higher pressure drop than comparable fiber filters.

Membrane filters are mainly used for sampling applications such as particle size analysis utilizing electron microscopes.

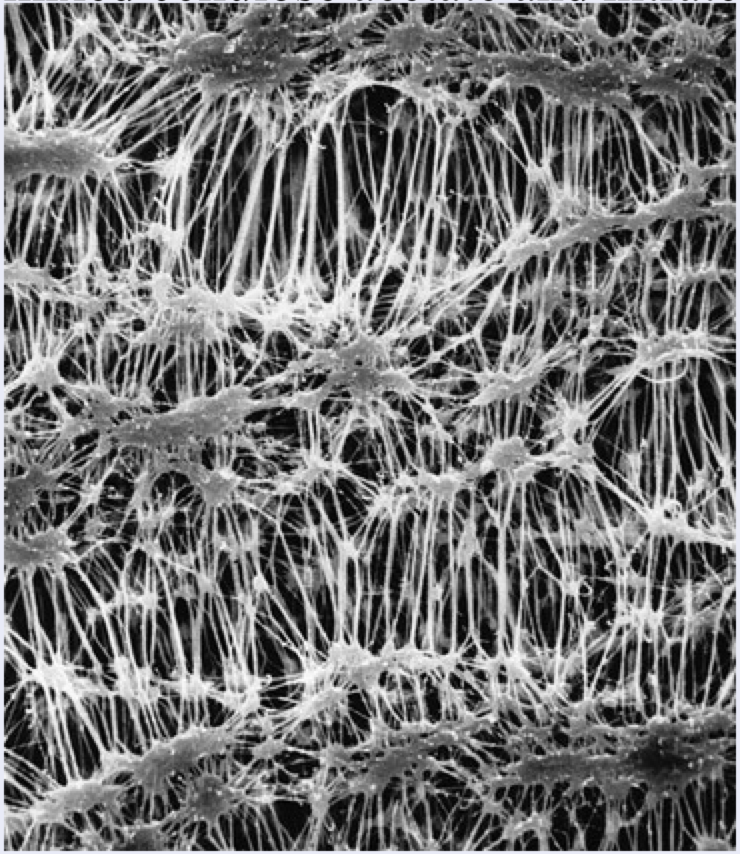


Scanning electron microscope photograph of a 0,8-μm Pore size capillary pore membrane filter. Magnification (a) 4150 X, (b) 800 X .

PTFE



mixed cellulose acetate and nitrate

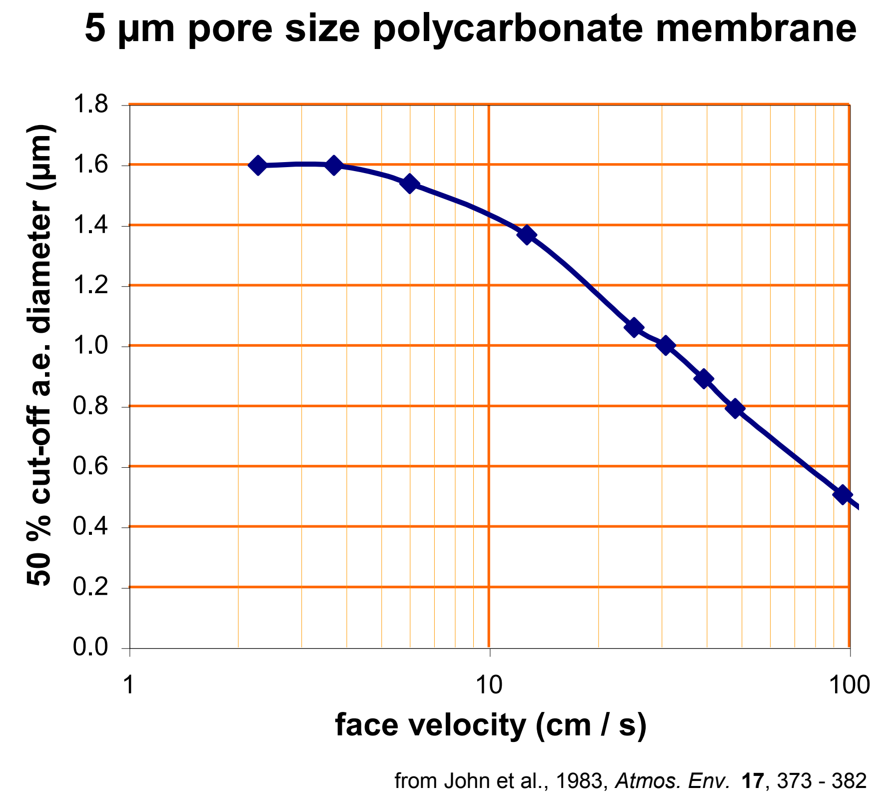


Scanning electron microscope photograph of two popular membrane filters .

Porous membrane filter pore sizes are defined from liquid filtration and do not match any of the physical filter pores, in contrast with straight –through pore membrane filters (like Nuclepore)

Particles are captured principally by Brownian motion and inertial impaction.

Polycarbonate membrane filter:



PTFE membrane filter:

2 µm pore size Teflon membrane at 23 cm/s

→ 99.98 % efficiency for Dp > 35 nm

Filter type	Applications	☺	☹
Membrane filters (in general)	Particle sampling for surface analyti- -cal techniques	• efficiency • “solidity”	• high pressure drop • low loading capa.
Cellulose mixed esters nitrate, acetate PVC	Sampling of metals, asbestos, etc (NIOSH methods)	• cheaper than other membranes	• moisture uptake • electrostat. charges
Teflon	Gravimetriy, NAA, XRF, XRD	• inert • no moisture uptake • low blanks	
Polycarbonate	Ideal for microscopy, PIXE	• flat, uniform surf. • no moisture uptake • low blanks • semitransparent • size dependent eff.	• may be friable • electrostat. charges • size dependent eff.