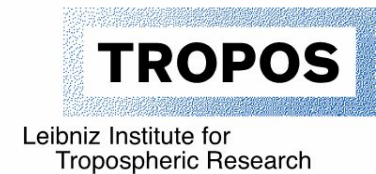


Atmospheric Aerosol Physics, Physical Measurements, and Sampling

Particle Filter

SAMLAC
San Juan, Puerto Rico
November 2018



Principle

The "ideal filter" should have a 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
- Gravitational settling
- External forces (electrical forces)

These deposition mechanisms depend on 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

Filter Type

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.

Deposition efficiency and pressure drop both increase as a function of the actual filter loading and consequently a function of time.

The theoretical description of particle transport in filters is complex.

The two most important types of filters are:

- fiber filters
- membrane filters

Filter Type Selection

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

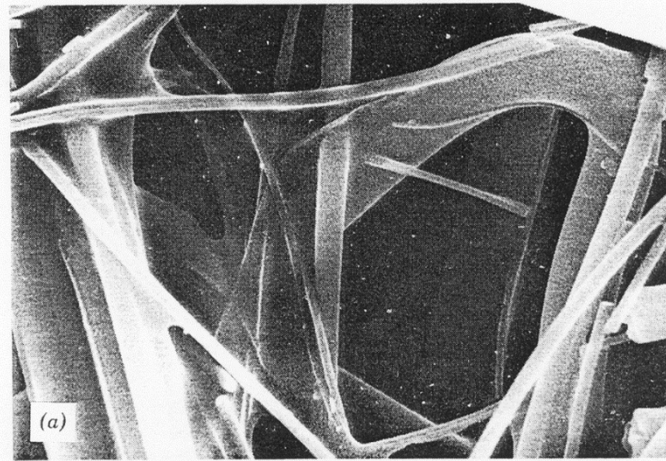
NO MATERIAL IS PERFECT FOR ALL PURPOSES

Fiber Filter

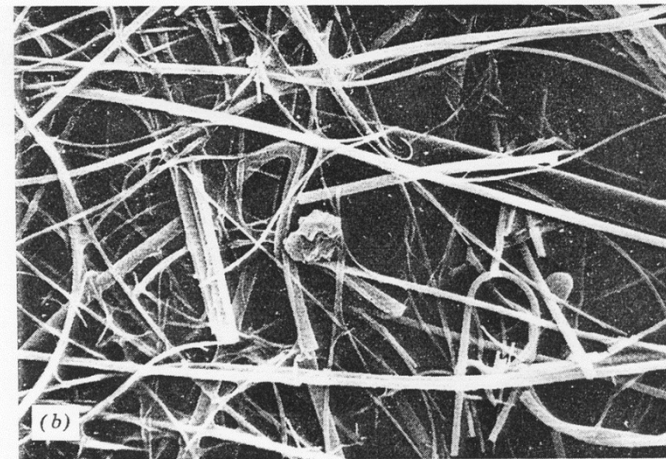
- Fiber Filters consist of layers of fine e.g. glass or plastic fibers
- The fiber orientation is such that the fiber axis are perpendicular to the flow direction
- Depending on the actual application, fiber diameters vary in the range between 0.3 and 100 μm
- The fiber volume fraction (or solidity or packing density) α is in the order of 1 to 30%: Fiber filters mainly consist of air

$$\alpha = \frac{\text{fiber volume}}{\text{filter volume}} = 1 - \text{porosity}$$

- Fiber filter thickness ranges between 150 and 500 μm
- For fiber filters, particles also deposit inside the filter
- For gas cleaning applications such as gas filtration in clean rooms, mainly fiber filters are used



1 μm
■

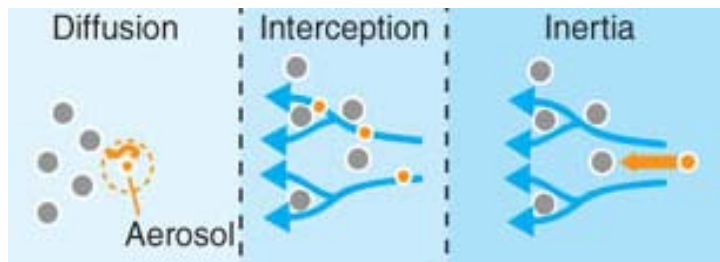


Scanning electron microscope photograph of a high efficiency glass fiber filter. Magnification (a) 4150 X, (b) 800 X.

Filter Mechanisms

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

- Inertial impaction
- Interception
- Diffusion
- Settling
- External forces (electrical forces)



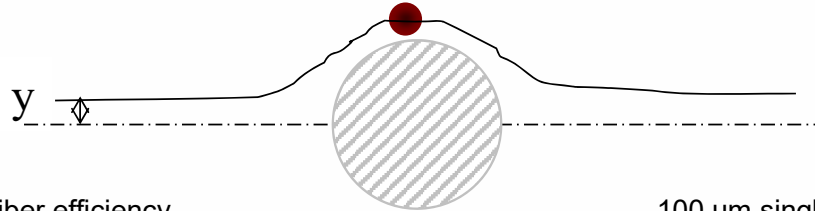
For a given face velocity, the efficiency of these mechanisms depends on the fiber diameter as well as particle size and shape.

The overall efficiency of a filter made of many fibers increases with the filter packing density and thickness.

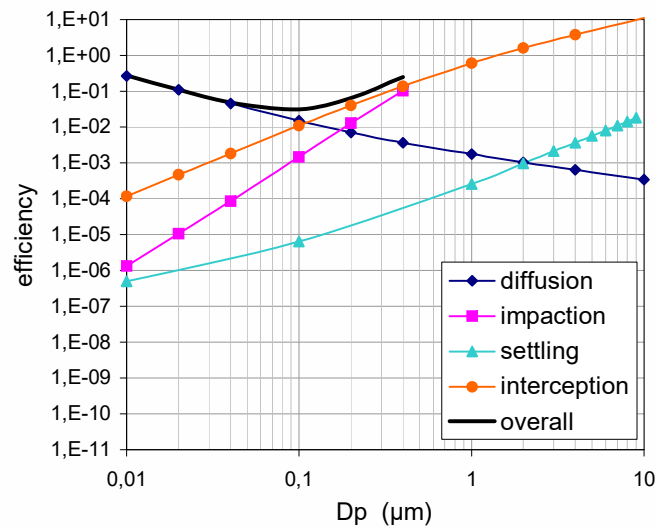
Fiber filter single fiber efficiency e for:

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

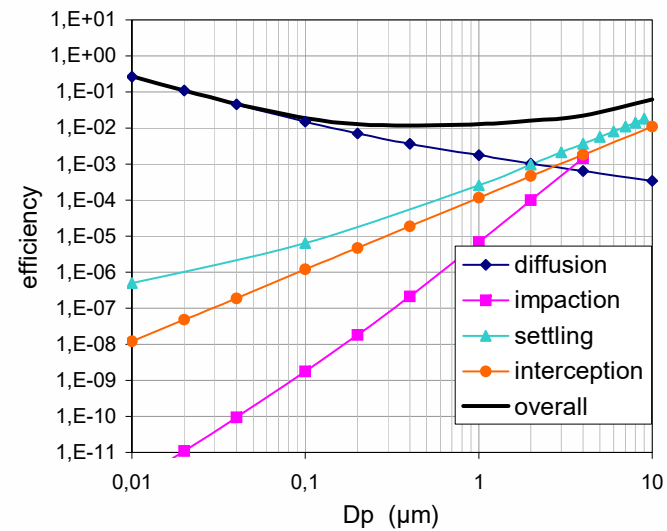
e = number of particles captured / number of particles captured without flow deviation e is the number of fiber radii for which all particles are captured ($e = y / R_f$)



1 um single fiber efficiency



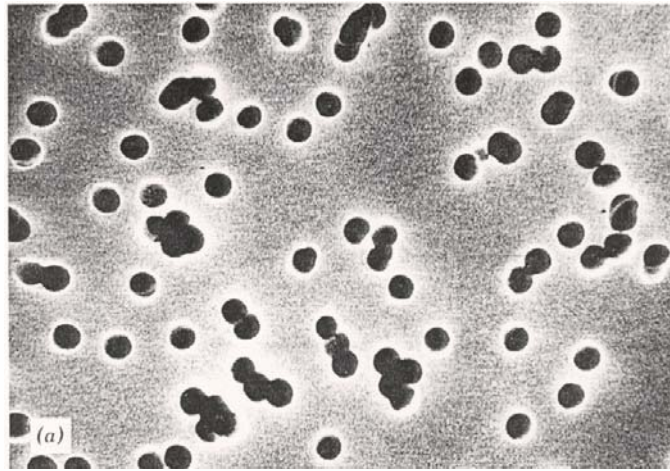
100 um single fiber efficiency



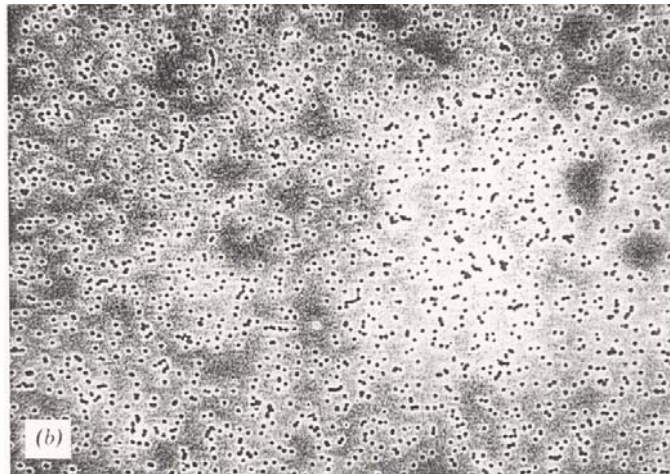
Filter type	Applications	😊	😞
Fiber filters (in general)	Air quality	<ul style="list-style-type: none"> • low pressure drop • high loading capa. 	<ul style="list-style-type: none"> • lower efficiency for subμm particles • penetration
Cellulose filters	IC, dust (ashless)	<ul style="list-style-type: none"> • cheap • easy extraction 	<ul style="list-style-type: none"> • moisture sensitive
Borosilicate glass filters	Wide scope (without binder)	<ul style="list-style-type: none"> • resists to 500°C 	<ul style="list-style-type: none"> • resists to 500°C • water vapor uptake
Quartz fiber filters	Sampling for chemical analyses: IC, AAS, carbon, PAHs	<ul style="list-style-type: none"> • reasonable moisture uptake • resists to > 800°C 	<ul style="list-style-type: none"> • may be friable

Membrane Filter

- Membrane filters consist of thin (100 and 200 μm) porous plastic foils or films with cylindrical pores
- The usually cylindrical pores of straight-through pore membrane filters 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

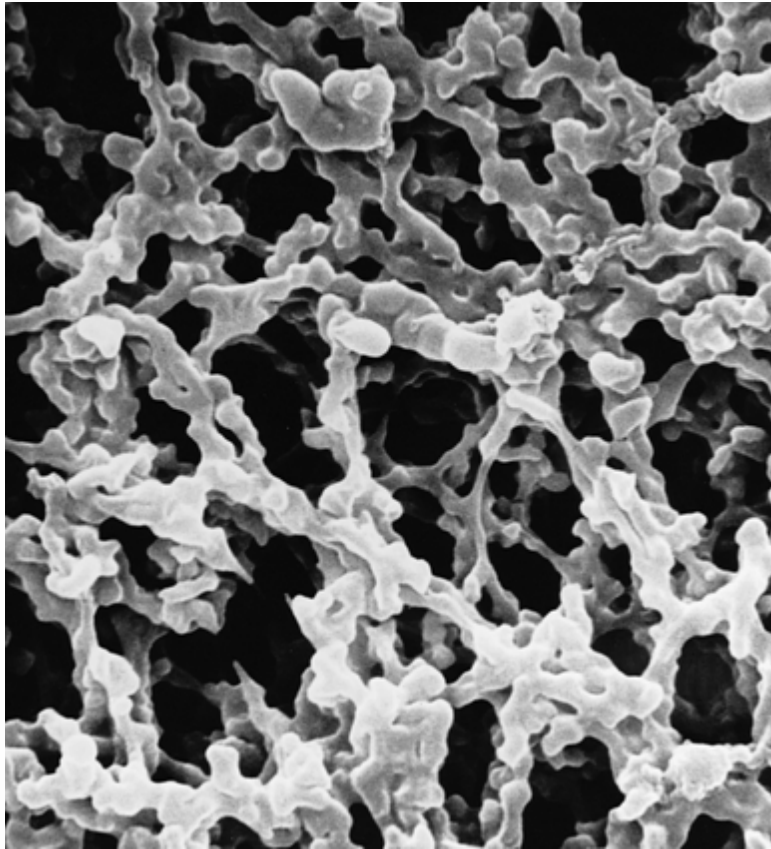


■ 1 μm

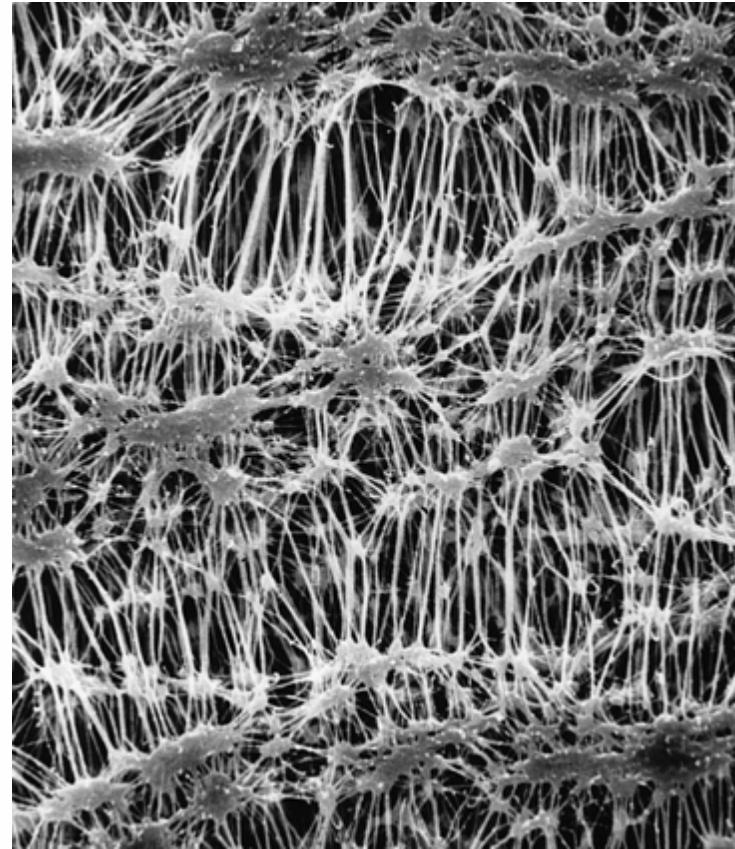


Scanning electron microscope photograph of a 0,8- μm Pore size capillary pore membrane filter. Magnification (a) 4150 X, (b) 800 X.

PTFE



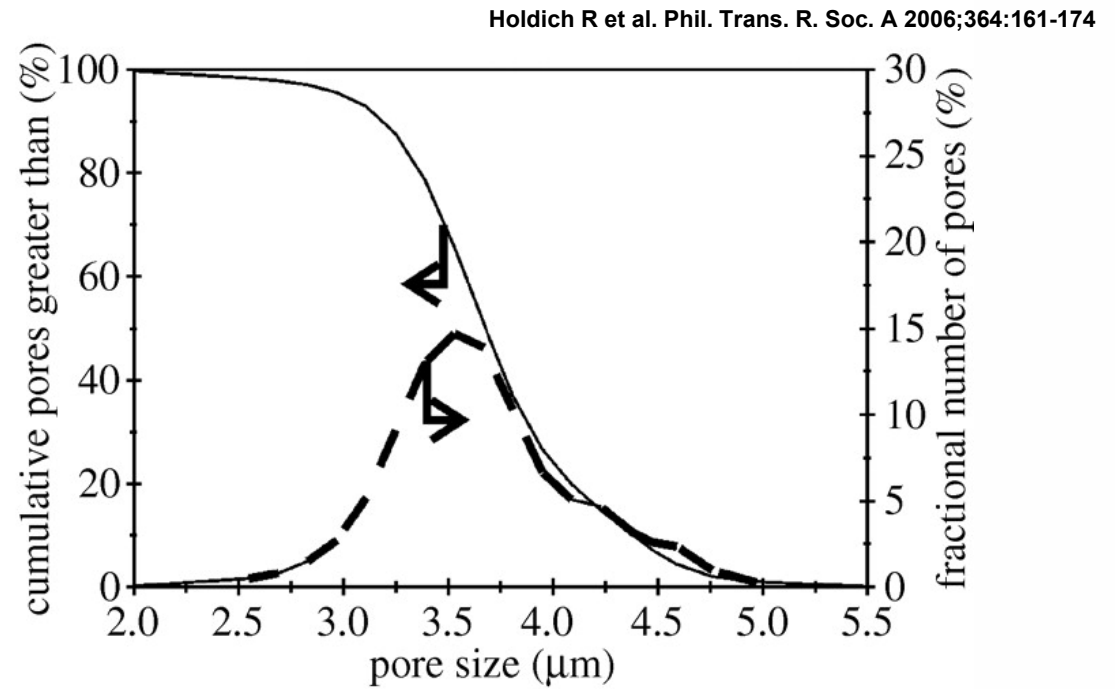
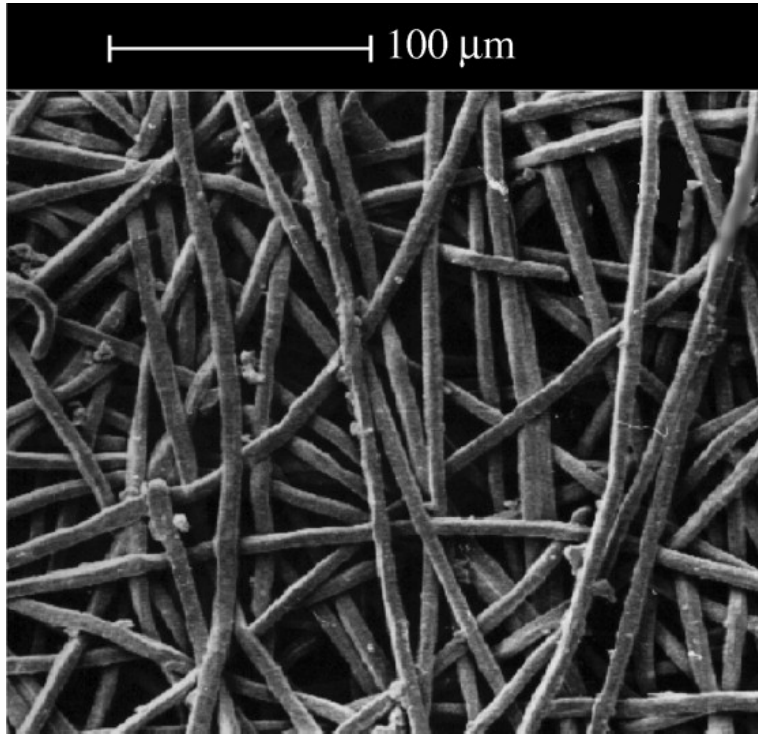
Mixed cellulose acetate and nitrate



■ 1 μm

Scanning electron microscope photograph of two popular membrane filters.

- Porous membrane filter pore sizes are defined from the “bubble point test” 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.



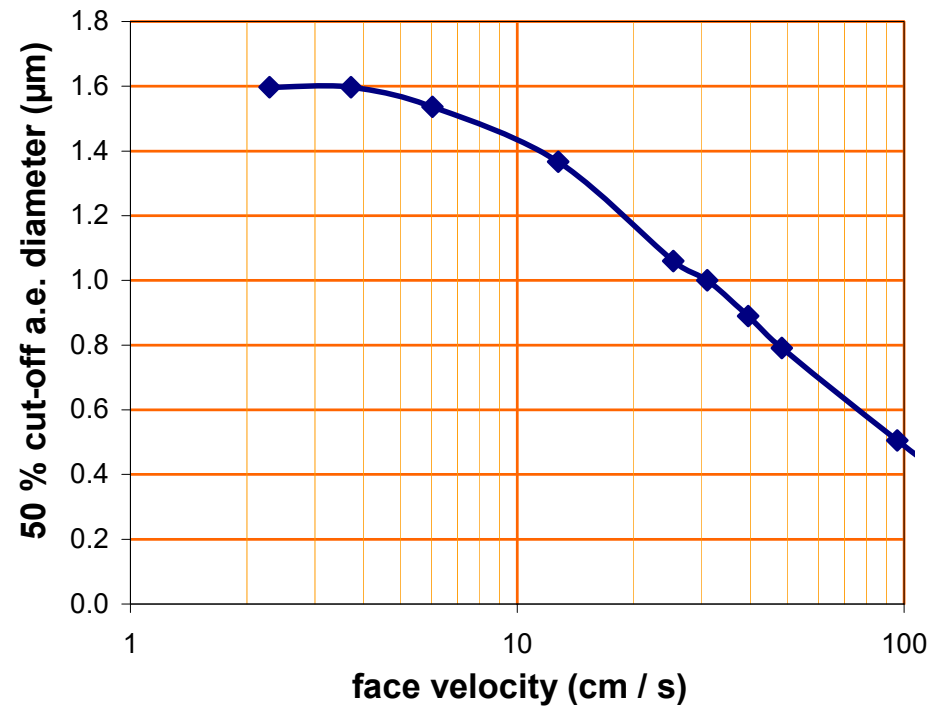
Picture of the surface of a tortuous pore channel microfiltration membrane and the pore size distribution provided by a technique based on ASTM-316.

PTFE membrane filter:



2 μm pore size Teflon membrane at 23 cm/s

→ 99.98 % efficiency for $D_p > 35 \text{ nm}$

5 μm pore size polycarbonate membrane

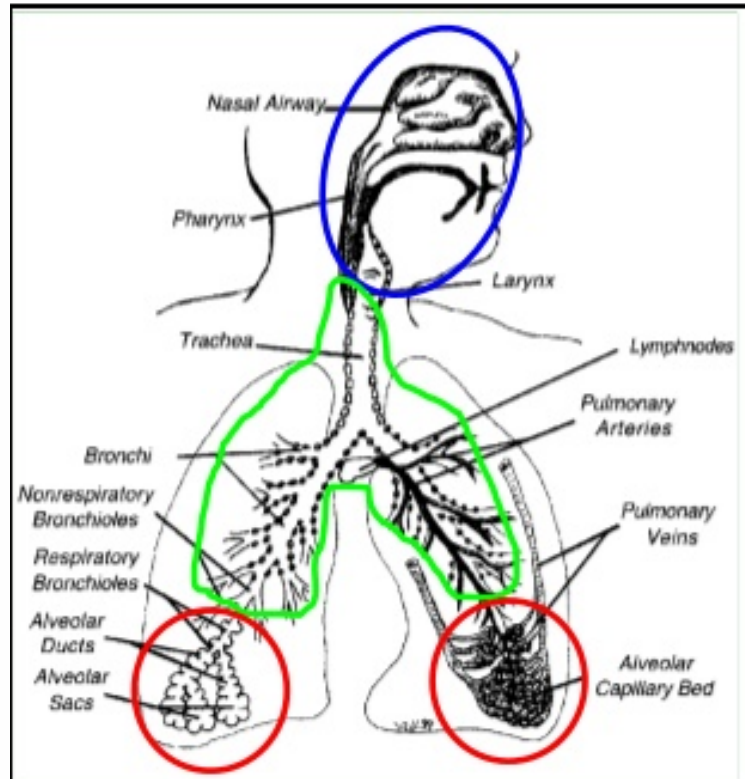


from John et al., 1983, *Atmos. Env.* 17, 373 - 382

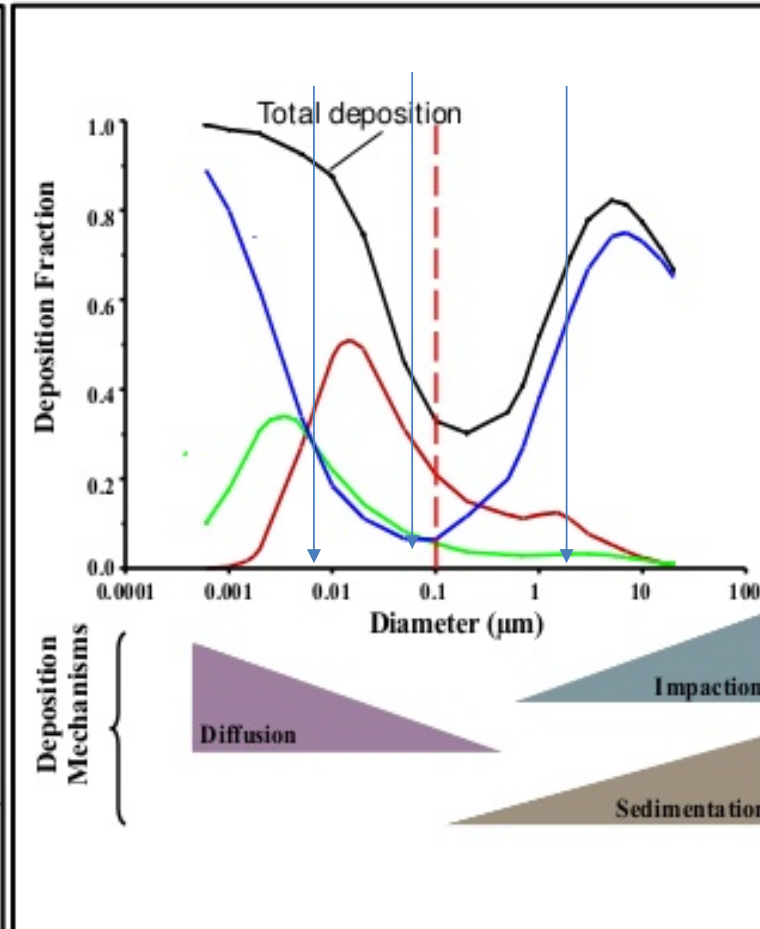
Filter type	Applications		
Membrane filters (in general)	Particle sampling for surface analytical techniques	<ul style="list-style-type: none"> • efficiency • “solidity” 	<ul style="list-style-type: none"> • high pressure drop • low loading capa.
Cellulose mixed esters nitrate, acetate PVC	Sampling of metals, asbestos, etc (NIOSH methods)	<ul style="list-style-type: none"> • cheaper than other membranes 	<ul style="list-style-type: none"> • moisture uptake • electrostat. charges
Teflon	Gravimetry, NAA, XRF, XRD	<ul style="list-style-type: none"> • inert • no moisture uptake • low blanks 	
Polycarbonate	Ideal for microscopy, PIXE	<ul style="list-style-type: none"> • flat, uniform surf. • no moisture uptake • low blanks • semitransparent • size dependent eff. 	<ul style="list-style-type: none"> • may be friable • electrostat. charges • size dependent eff.

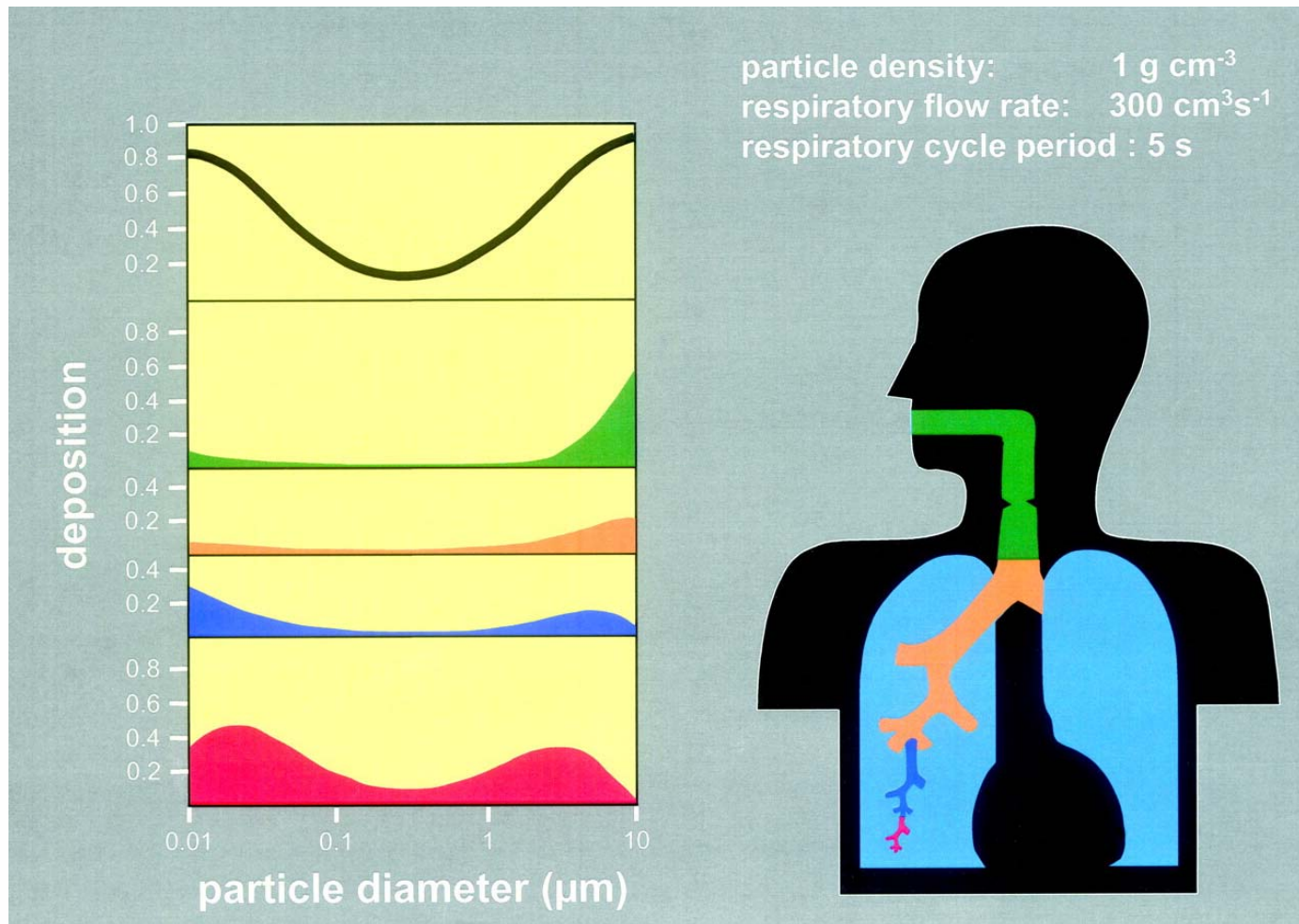
Fractional Deposition of Inhaled Particles in the Human Respiratory Tract

(ICRP Model, 1994; Nose-breathing)



Inhalable < 100um
Thoracic < 30um
Respirable < 10um

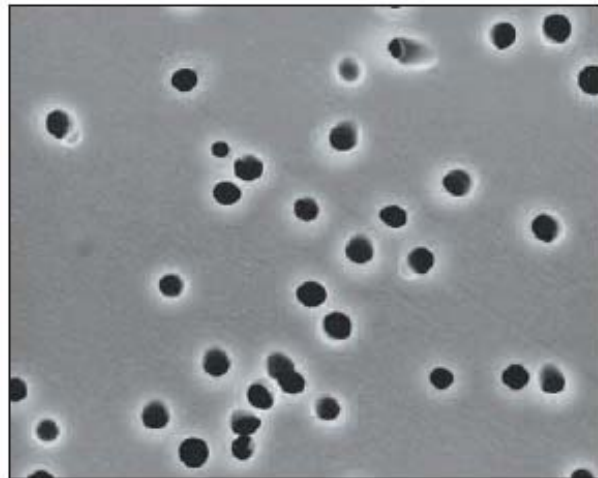




Total and regional deposition of unit-density spheres in the human respiratory tract predicted by the ICRP deposition model for oral inhalation at rest. (Heyder; *Proc Am Thorac Soc* **2004**, 1, 315-320. © 2004 The American Thoracic Society)

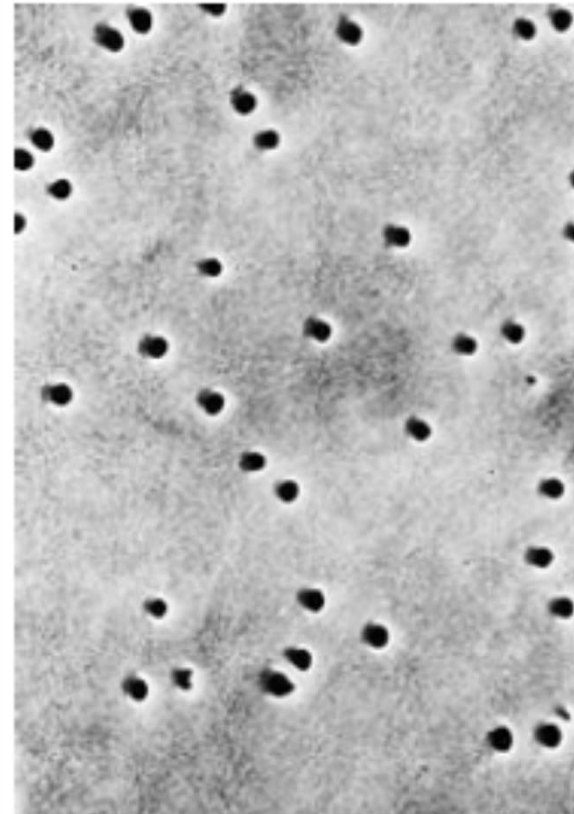
Discussion

Thin films with discrete pores formed through charged particle bombardment (or irradiation) and chemical etching



Polycarbonate (Advantec)

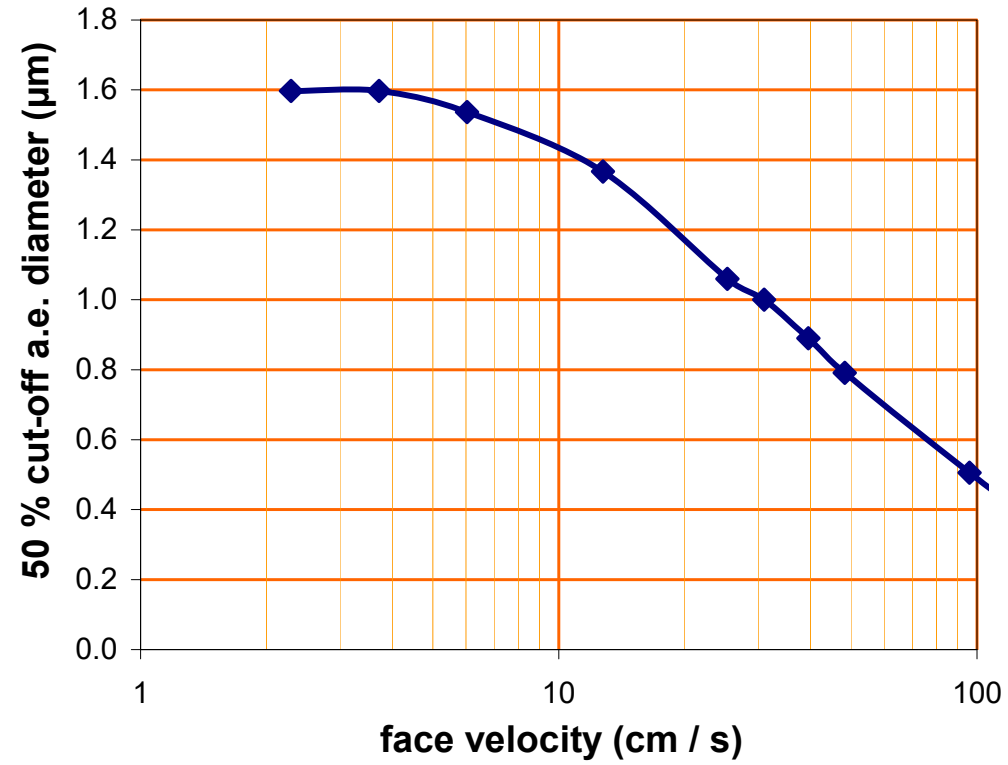
■ 1 μm



Polycarbonate film (Nuclepore)

Polycarbonate membrane filter:

5 μm pore size polycarbonate membrane



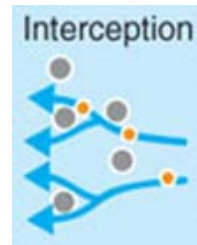
from John et al., 1983, *Atmos. Env.* 17, 373 - 382

Mechanisms for the deposition of particles on a polycarbonate membrane are:

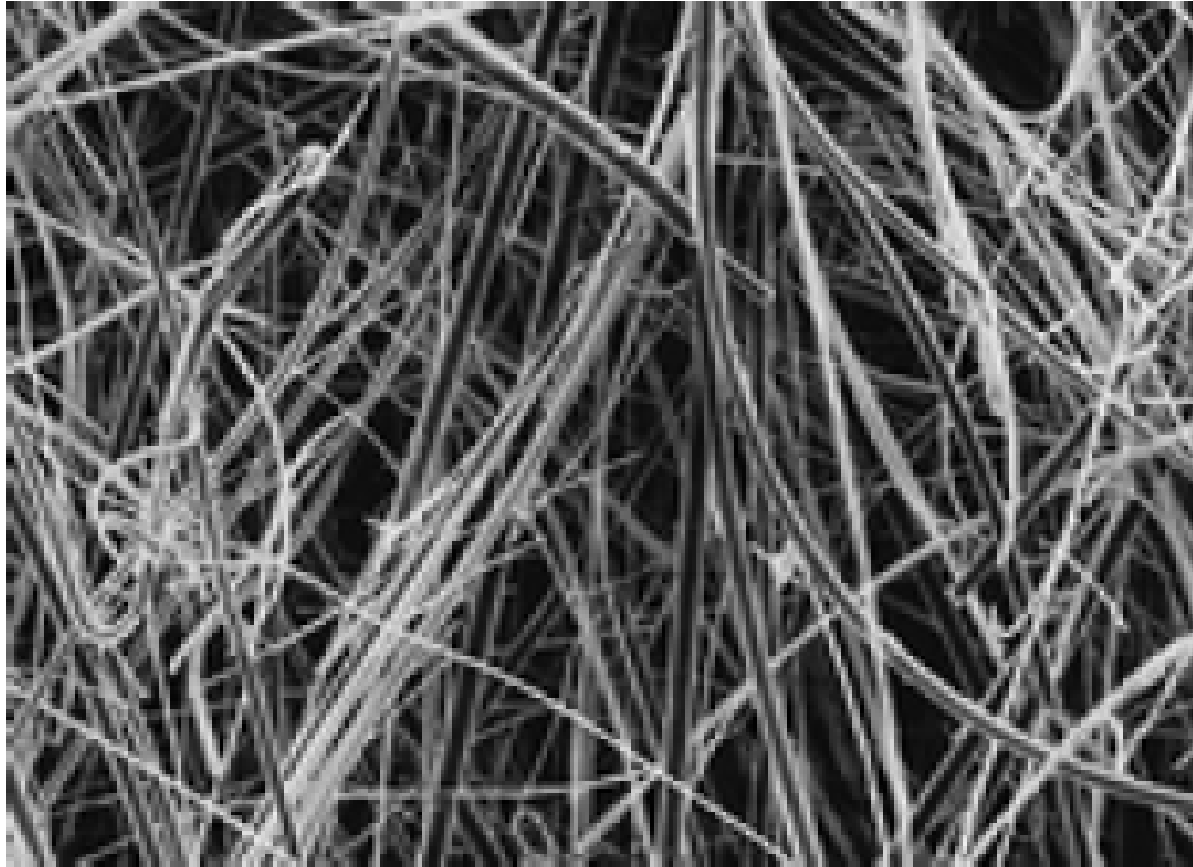
- Inertial impaction



- Interception

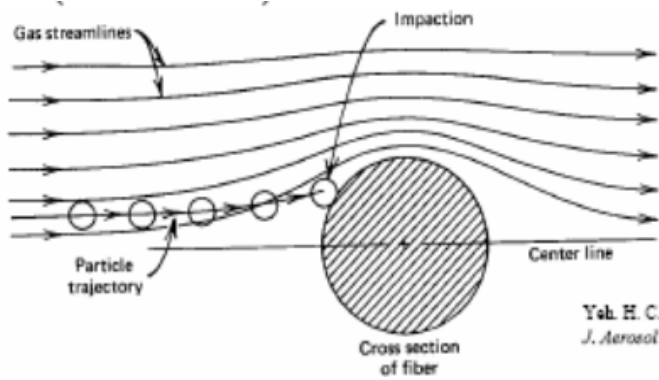


Glass Fiber Filter:

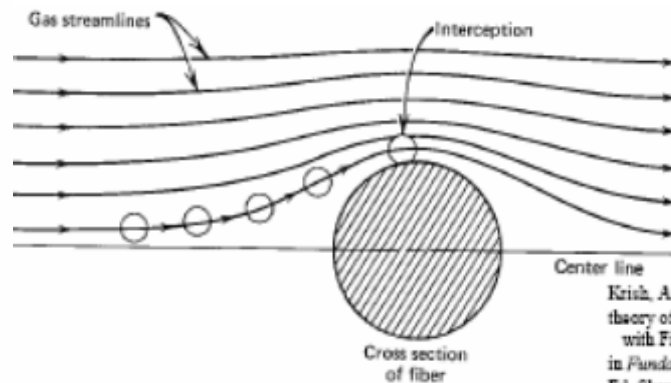
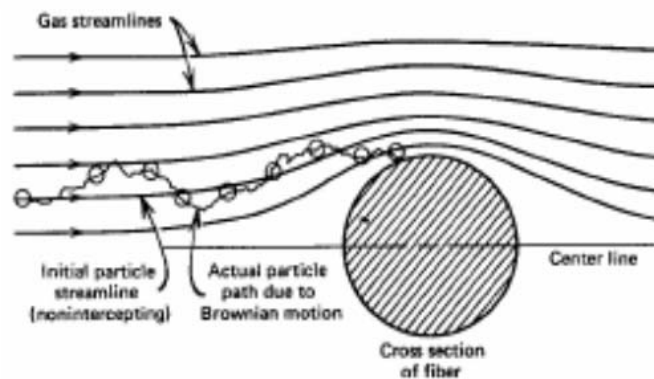


■ 1 μm

Fiber volume fraction (or solidity or packing density) α is in the order of 1 to 30%



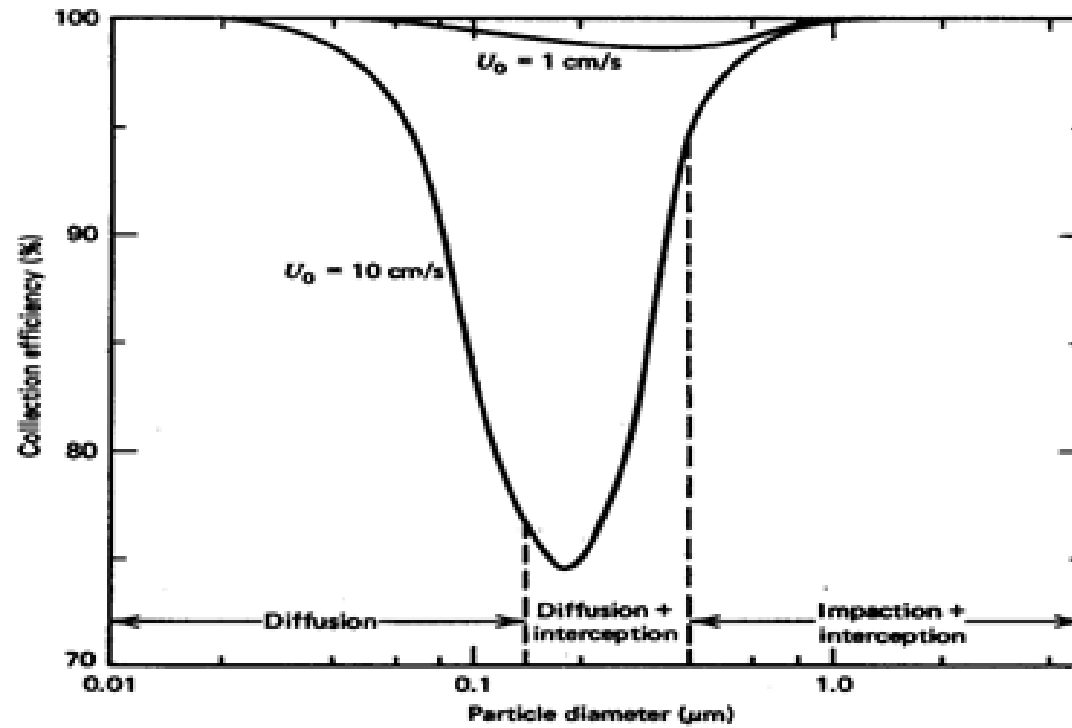
Yeh, H. C. and Liu, B. Y. H.,
J. Aerosol Sci., 5:191-217, 19



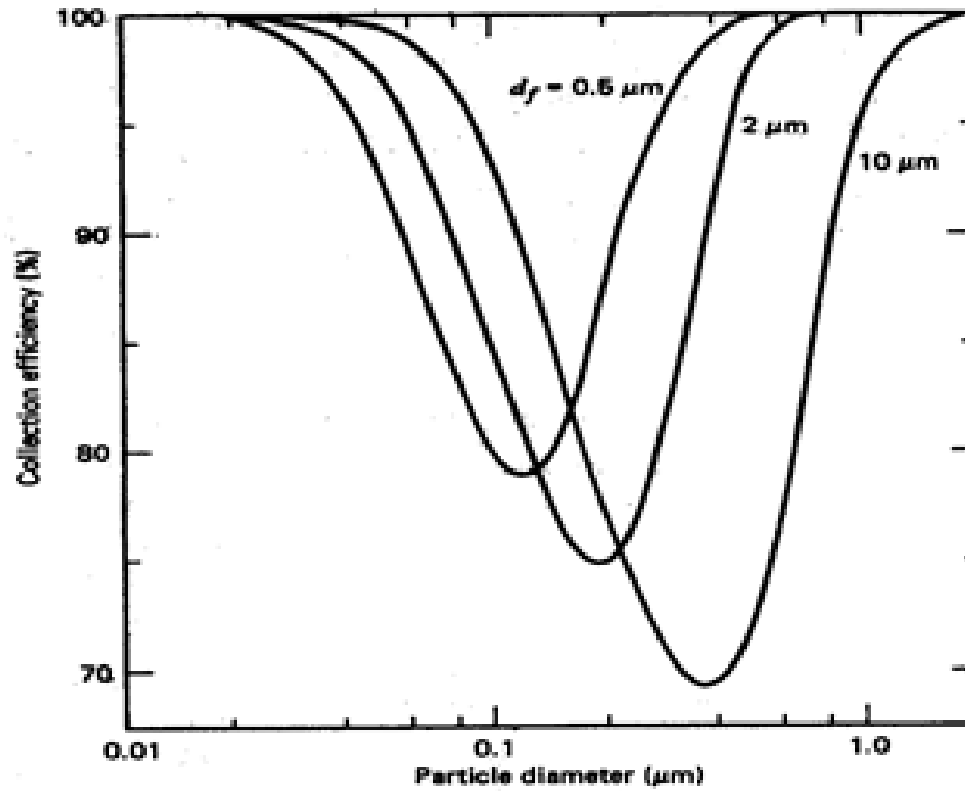
Krish, A. A. & Stechkina, I. B., "The
 theory of Aerosol Filtration
 with Fibrous Filters",
 in *Fundamentals of Aerosol Science*,
 Ed. Shaw, D. T., Wiley, 1976.

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

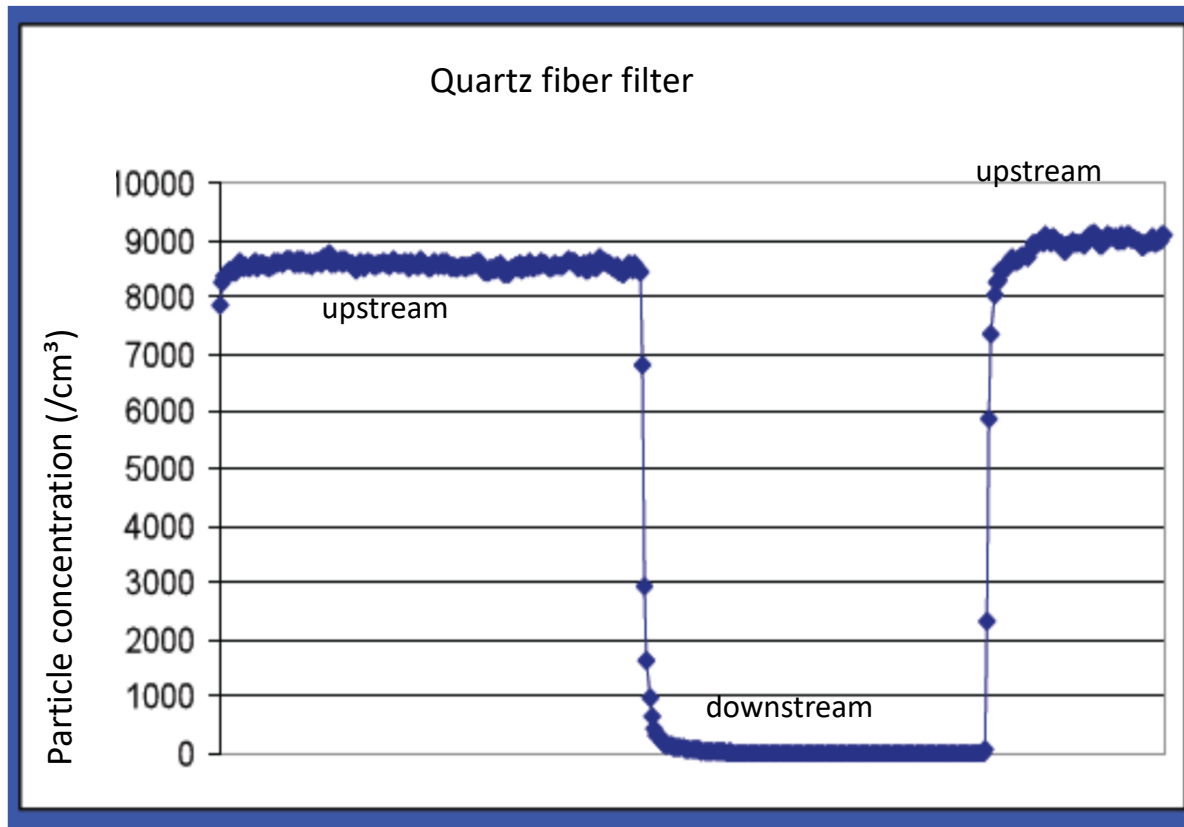
- Inertial impaction
- Interception
- Diffusion
- Settling (sedimentation)
- External forces (electrical forces)



Efficiency versus particle size for face velocities of 1 and 10 cm/s, filter thickness of 1 mm, solidity of 0.05 and fiber diameter of $2\mu\text{m}$



For a given face velocity, the efficiency of these mechanisms depends on the fiber diameter as well as particle size and shape.

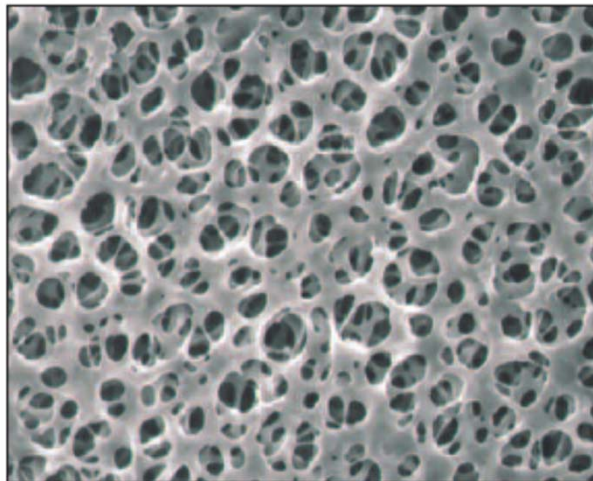


The overall efficiency of a filter made of many fibers increases with the filter solidity and thickness.

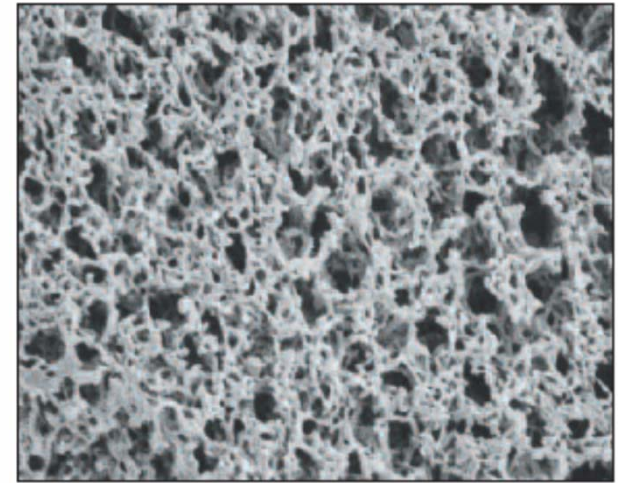
Membrane filters:



Hydrophobic PTFE



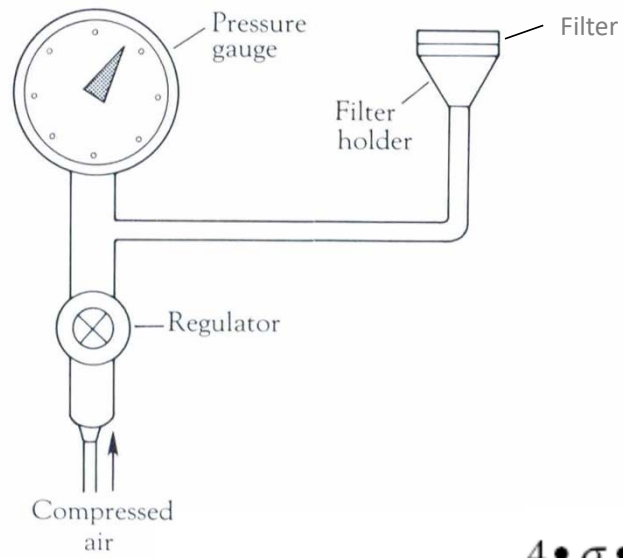
Cellulose Acetate



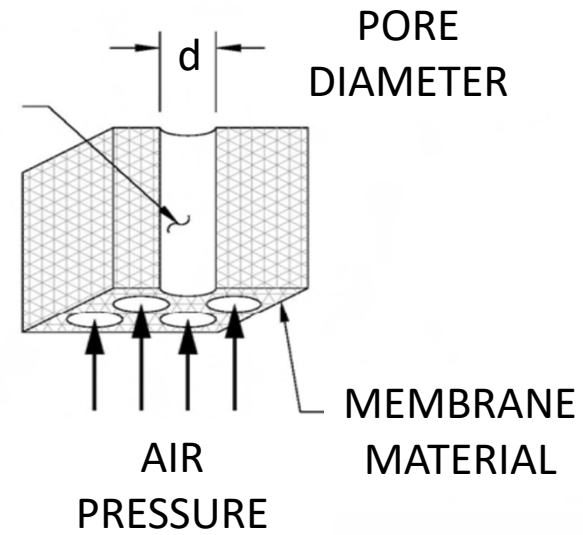
Nylon

▪ 1 μm

Bubble point test:



WATER-FILLED
MEMBRANE
PORE



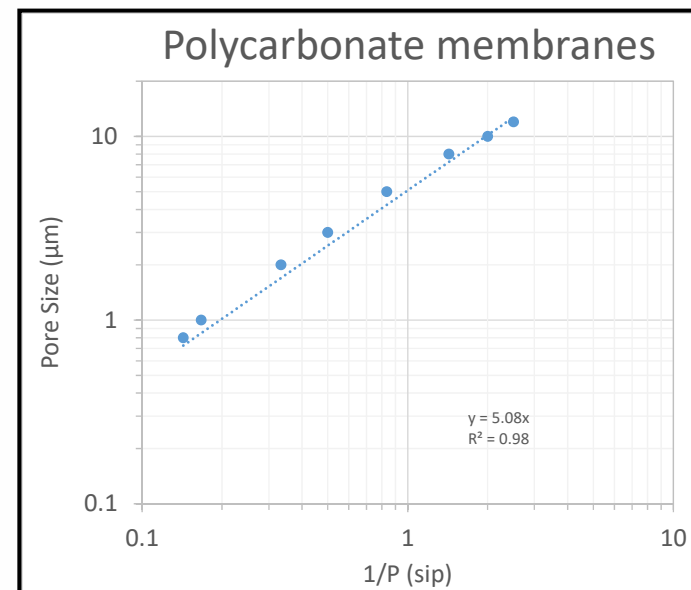
$$P_{bp} = \frac{4 \cdot \sigma \cdot \cos \theta}{d_{cap}}$$

Where:

P_{bp}	=	bubble point pressure
σ	=	surface tension at the air-liquid interface
θ	=	liquid-membrane contact angle
d_{cap}	=	capillary diameter

SPECIFICATIONS: POLYCARBONATE MEMBRANE, CODE K

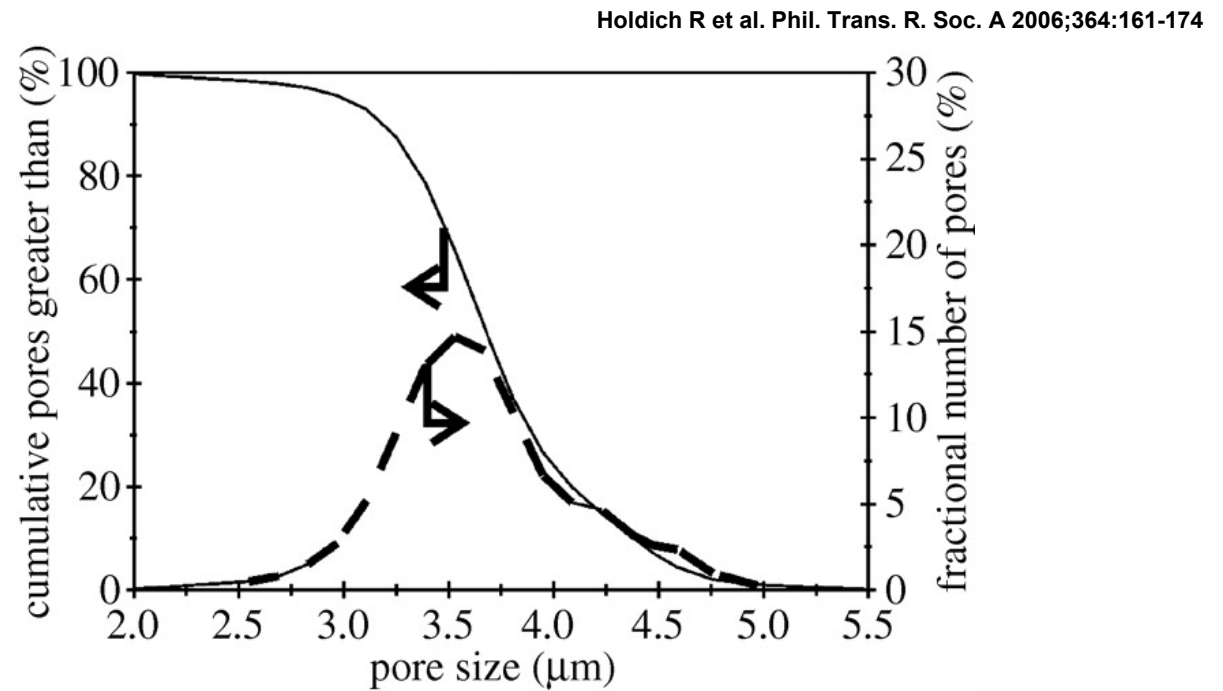
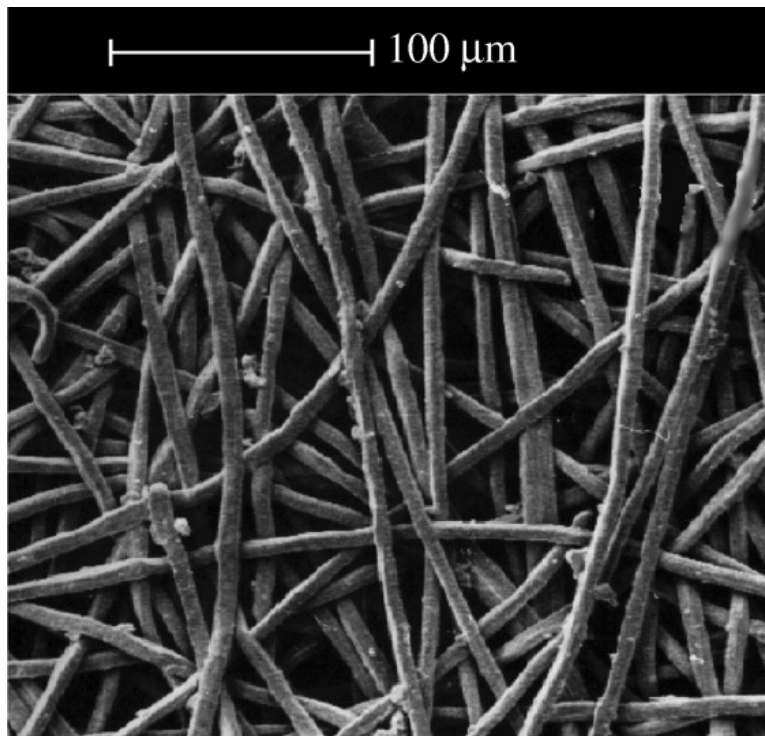
Pore Size (μm)	Bubble Point ¹		Flow Rate ²		Nominal Thickness (μm)
	MPa	psi	Water (mL/min/cm ²)	Air (L/min/cm ²)	
0.10	≥ 0.21	≥ 30	2.5	1.5 ³	6
0.20	≥ 0.14	≥ 20	10	3 ³	10
0.40	≥ 0.083	≥ 12	33	7.5 ³	10
0.80	≥ 0.048	≥ 7	90	18 ³	9
1.00	≥ 0.041	≥ 6	130	20 ⁴	11
3.00	≥ 0.014	≥ 2	440	37.5 ⁴	9
8.00	≥ 0.0048	≥ 0.7	1000	30 ⁴	7



SPECIFICATIONS: HYDROPHOBIC PTFE MEMBRANE, CODE T

Pore Size (μm)	Bubble Point ¹		Flow Rates ²		Porosity ³ (%)	Maximum Operating Temperature ($^{\circ}\text{C}$)	Thickness (μm)
	MPa	psi	Acetone (mL/min/cm ²)	Air (L/min/cm ²)			
0.10	≥ 0.12	≥ 17.4	27.0	-	68	260	70
0.20	≥ 0.091	≥ 13.2	55.0	-	74	260	80
0.50	≥ 0.063	≥ 9.1	100	-	78	260	75
0.80	≥ 0.039	≥ 5.7	200	-	76	260	75
1.00	≥ 0.031	≥ 4.5	300	-	79	260	75
3.00	≥ 0.013	≥ 1.9	750	-	83	260	75

- Porous membrane filter pore sizes are defined from the “bubble point test” 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.



Picture of the surface of a tortuous pore channel microfiltration membrane and the pore size distribution provided by a technique based on ASTM-316.