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懸浮微粒(氣膠)過濾與呼吸防護技術之應用

Factors Affecting Filter Penetration and Quality Factor of Particulate Respirators

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Factors Affecting Filter Penetration and Quality Factor of Particulate Respirators

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ABSTRACT

In the present study, a theoretical model was used to examine factors affecting the filtration characteristics of filters used for respiratory protection. This work was designed to support the particulate filter test requirements established in 1996. The major operating parameters examined in this work include face velocity, fiber diameter, packing density, filter thickness, and fiber charge density. Characteristics of the most penetrating particle size were also modeled with the same operating parameters.

The results showed that aerosol penetration through electret filter media increases with increasing face velocity and increasing fiber diameter, and decreases as packing density, filter thickness or fiber charge density increase. Face velocity and fiber charge density have more significant effects on filter quality than the other factors. Filter quality increases with decreasing face velocity or increasing fiber charge density. For electret filters, (1) the most penetrating particle size increases with increasing fiber diameter; (2) an increase in packing density, thickness, or fiber charge density would cause the most penetrating particle size to decrease, and (3) the most penetrating particle size through electret filters increases with increasing face velocity and decreasing filter thickness. On the other hand, for non-electret filter media, the most penetrating particle size increases with decreasing face velocity, and the filter quality factor is not affected by filter thickness.

Keywords: Respirator; Filter; Filtration model.

Introduction

- The process of filtration is complicated, and although the general principles are well known there is still a gap between theory and experiment.
- Therefore, filtration is still an active area for theoretical and experimental research.

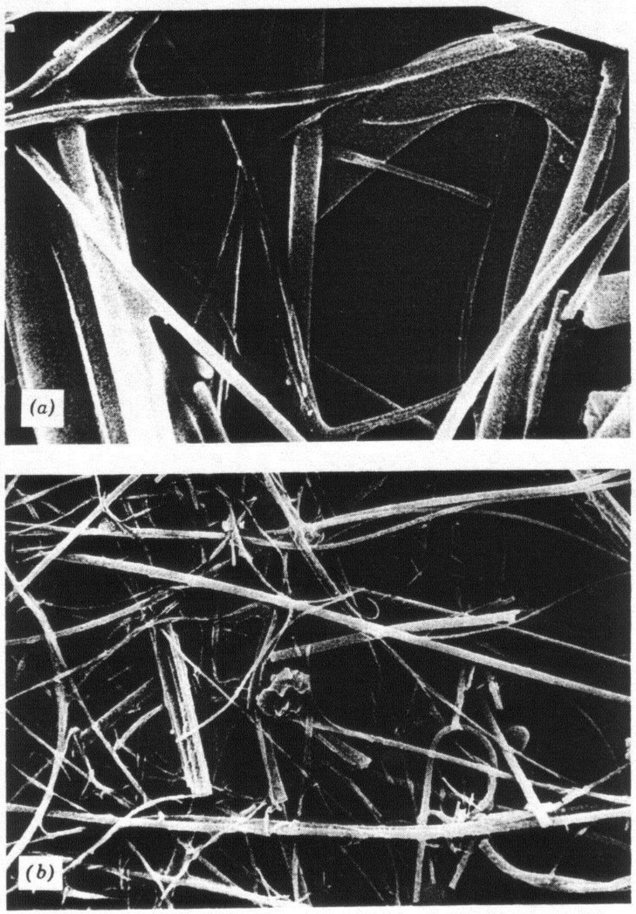
Filtration

(Particulate Control)

- Filter
- Cyclone
- Electrostatic Precipitator
- Scrubber

Types of filters (1)

Fibrous filter

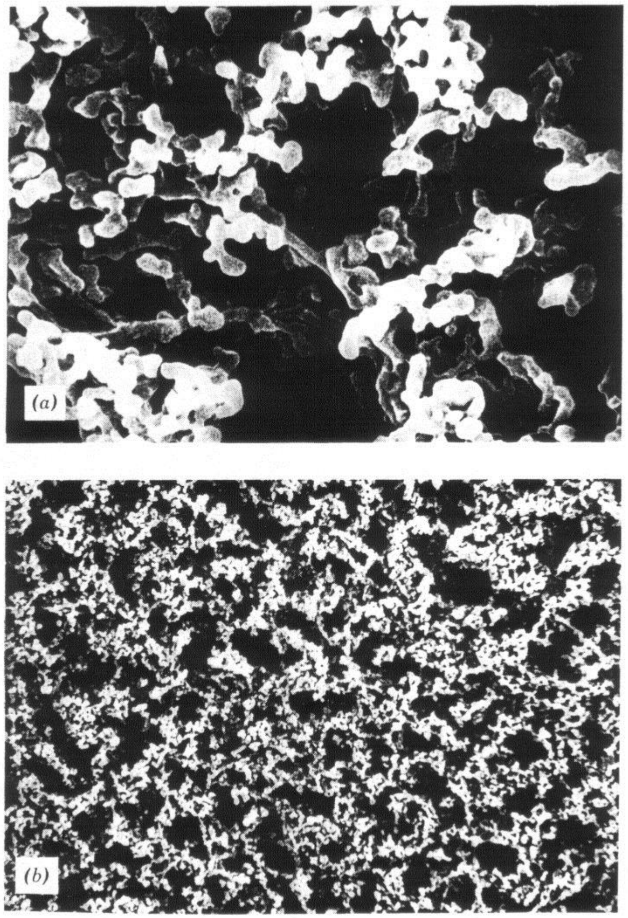


9.1 Scanning electron microscope photograph of a high-efficiency glass fiber
gnification of (a) 4150× and (b) 800×.

- A mat of fine fibers that arrange perpendicular to the direction of air flow
- (packing density)
  Have porosities from 70 to greater than 99%
- the fiber size: submicrometer to 100 μm
- cellulose fibers (wood fibers), glass fiber, and plastic fibers are the most common types.
- the air velocity through high-efficiency filters is usually quite low, about **10 cm/s**, therefore, it is often necessary to pleat the filter material.

Types of filters (2)

Porous membrane filter

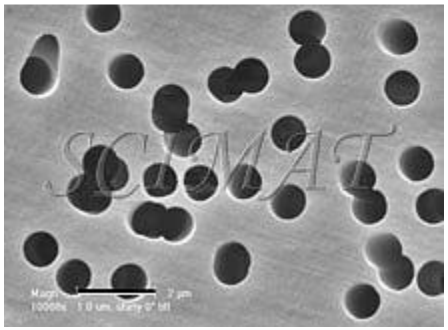


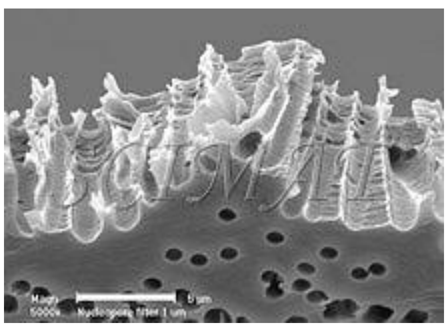
9.2 Scanning electron microscope photograph of a cellulose ester porous : filter with a pore size of 0.8 μm. Magnification of (*a*) 4150× and (*b*) 800×.

- have porosities from 50 to 90%
- have high efficiency and air resistance
- they are made from cellulose esters, sintered metals, polyvinyl chloride, Teflon™, and other plastics

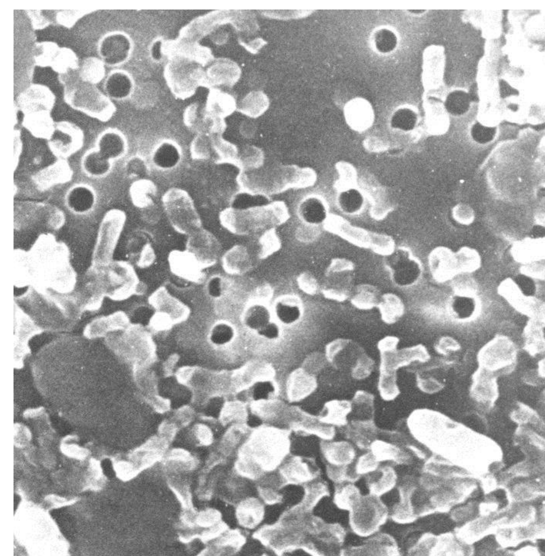
Types of filters (3)

Capillary pore membrane filter





- has an array of microscopic cylindrical holes of uniform diameter
- the efficiency for particles small than the pore size is not as good as that of porous membrane filters. Why??
- have smooth surface



Types of filters (4)

(Needlefelt)

Fabric filter (woven, non-woven)

- is used in industrial air cleaning for high-efficiency filtration **<u>at high dust concentrations</u>**
- has a **<u>low</u>** initial collection efficiency, but becomes highly efficient when a dust layer builds up on the fabric
- can operate at high temperatures

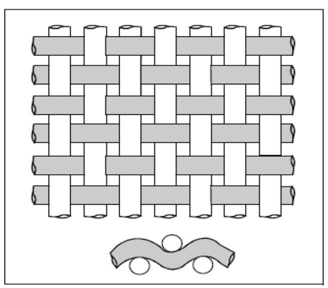


Figure 4-1. Plain weave or checkerboard

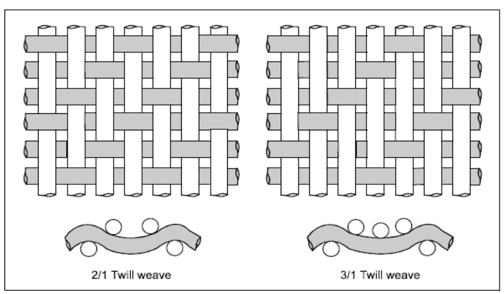


Figure 4-2. Twill weave patterns (2/1 and 3/1)

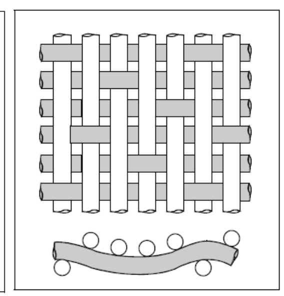
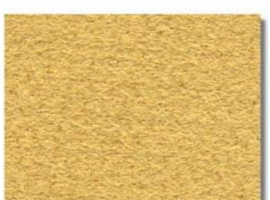
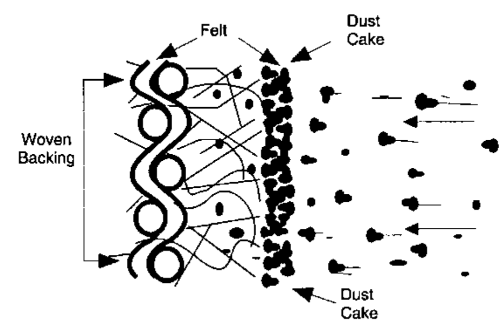


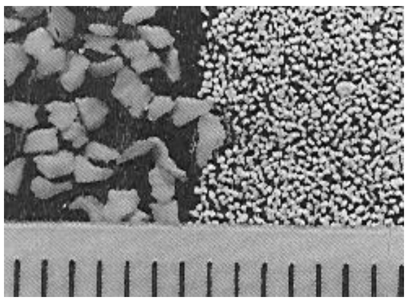
Figure 4-3. Sateen weave (satin weave)

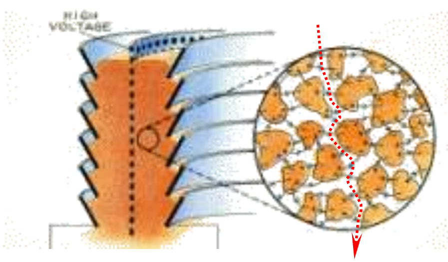




Types of filters (5)

Granular-bed filter





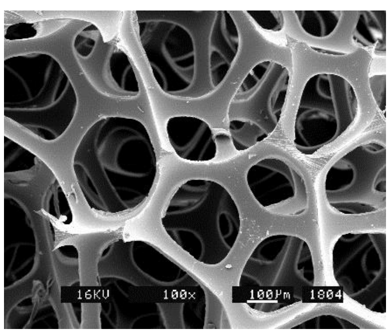
- a bed of fine granules
- is used primary for corrosive aerosols and aerosols at high temperatures
- See Tien (1989) for details.
- 蕭美芳，顆粒床過濾與負載特性，台灣大學，碩士論文，2008。

Types of filters (6)

Others

☞Cigarette filter

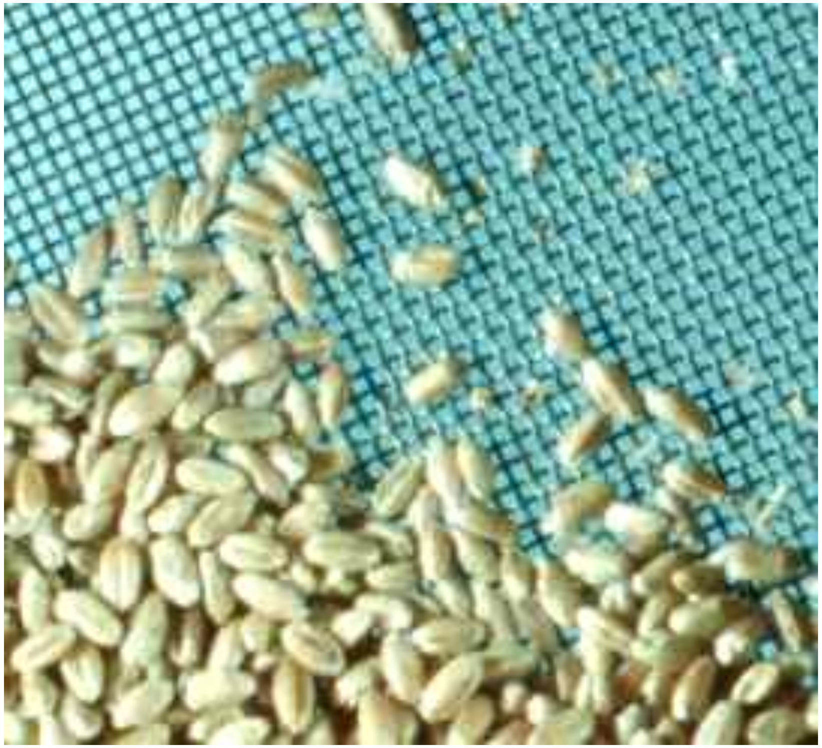
☞林宛筠， 不同纖維方向的濾嘴對主流煙微粒收集效率之影響，台灣大學，碩士論文，2002。



☞Foam filter

☞賴全裕，氣懸微粒分徑採樣器的研發--以海綿為分徑材質，台灣大學，碩士論文，1995。

Q: Does a filter work like a microscopic sieve (to collect particles larger than the sieve spacing)?



Filtering?
Sieving?

This view may be appropriate for the liquid filtration, but it is not how aerosol filtration works.

Airborne Particulate Cleanliness Classes

Class limits are given for each class name. The limits designate specific concentrations (particles per unit volume) of airborne particles with sizes equal to and larger than the particle sizes shown.

Class Name		Class limits									
		0.1μm		0.2μm		0.3μm		0.5μm		5μm	
		Volume units		Volume units		Volume units		Volume units		Volume units	
SI	English	(M^3)	(A^3)	(M^3)	(A^3)	(M^3)	(A^3)	(M^3)	(A^3)	(M^3)	(A^3)
M1		350	9.91	75.7	2.14	30.9	0.875	10.0	0.283		
M1.5	1	1240	35.0	265	7.50	106	3.00	35.3	1.00		
M2		3500	99.1	757	21.4	309	8.75	100	2.83		
M2.5	10	12400	350	2650	75.0	1060	30.0	353	10.0		
M3		35000	991	7570	214	3090	87.5	1000	28.3		
M3.5	100			26500	750	10600	300	3530	100		
4				75700	2140	30900	875	10000	283		
4.5	1000							35300	1000	247	7.00
5								100000	2830	618	17.5
5.5	10000							353000	10000	2470	70.0
6								1000000	28300	6180	175
6.5	100000							3530000	100000	24700	700
7								10000000	283000	61800	1750

What is the aerosol number concentration (#/cm^3) in this room ?

10^2, 10^3, 10^4, 10^5 (#/cm^3)

Determine the number of molecules in 1 cm³ of air at 760 mmHg pressure and 20°C.

☞ 1 mole of gas occupied 22.4 L volume at S.T.P. conditions.

☞ $$V_{20^\circ C} = 22.4\left(\frac{273+20}{273}\right) = 24.04L$$

☞ $$\frac{N_A}{V} = \frac{6.02\times10^{23}}{24.04\times10^{3}} = 2.50\times10^{19}\,molecules/cm^3$$

What do you see？

Dry Ice?
Liguid N?

The earth's atmosphere near the surface is composed primarily of Nitrogen and Oxygen. Together, the two comprise about 99% of the gas in the atmosphere. Here's a listing of the key components of the lower atmosphere...

Nitrogen - 78.084%
Oxygen - 20.95%
Argon - 0.934%
Carbon Dioxide - 0.036%
Neon - 0.0018%
Helium - 0.0005%
Methane - 0.00017%
Hydrogen - 0.00005%
Nitrous Oxide - 0.00003%
Ozone - 0.000004%

In addition, **water vapor** is variable but typically makes up about **1-4%** of the atmosphere.

- Name 7 gases or vapors you can see!

Fluorine

Chlorine!

Bromine!

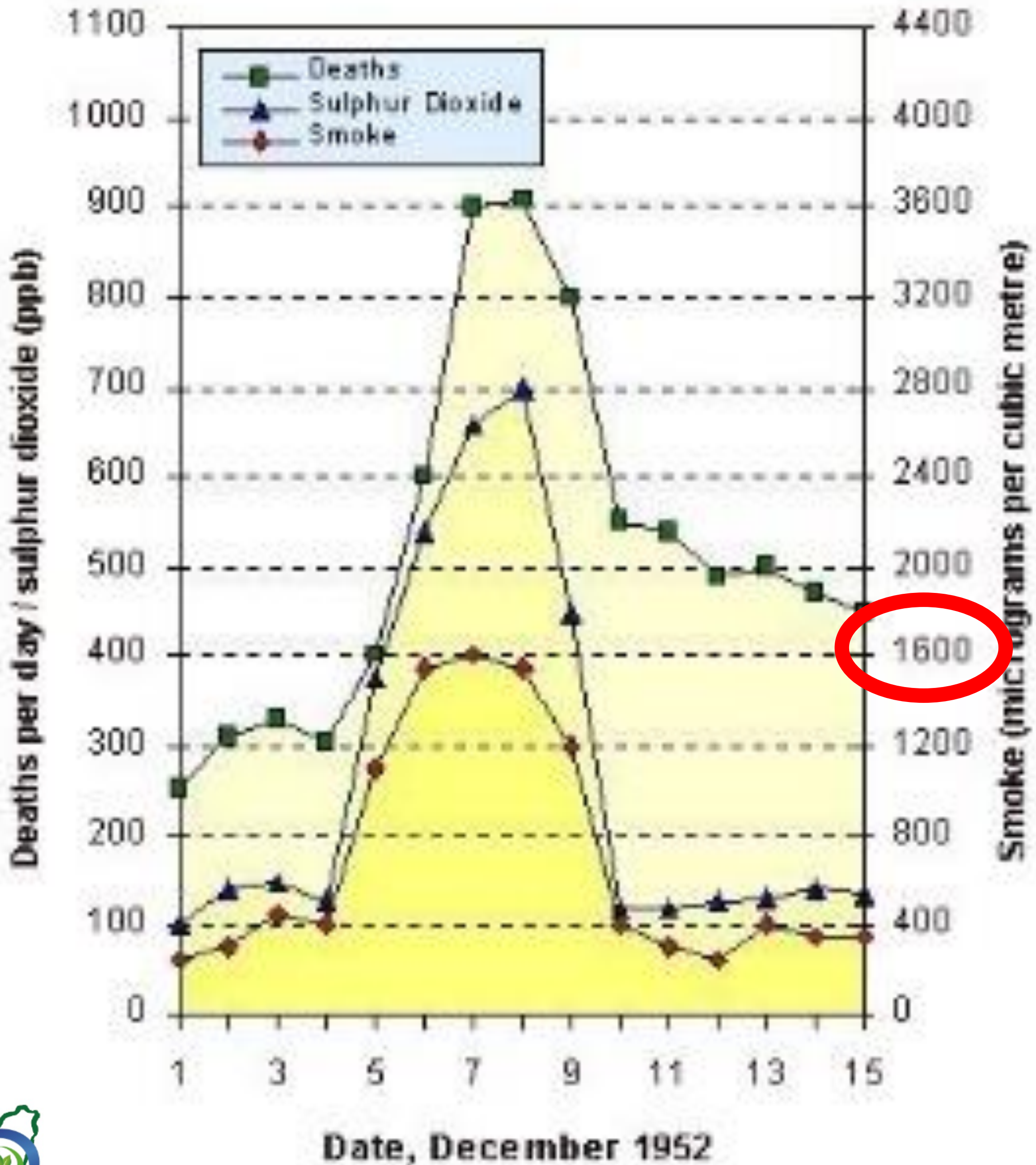
Iodine!

Ozone

Nitrogen dioxide!

??????

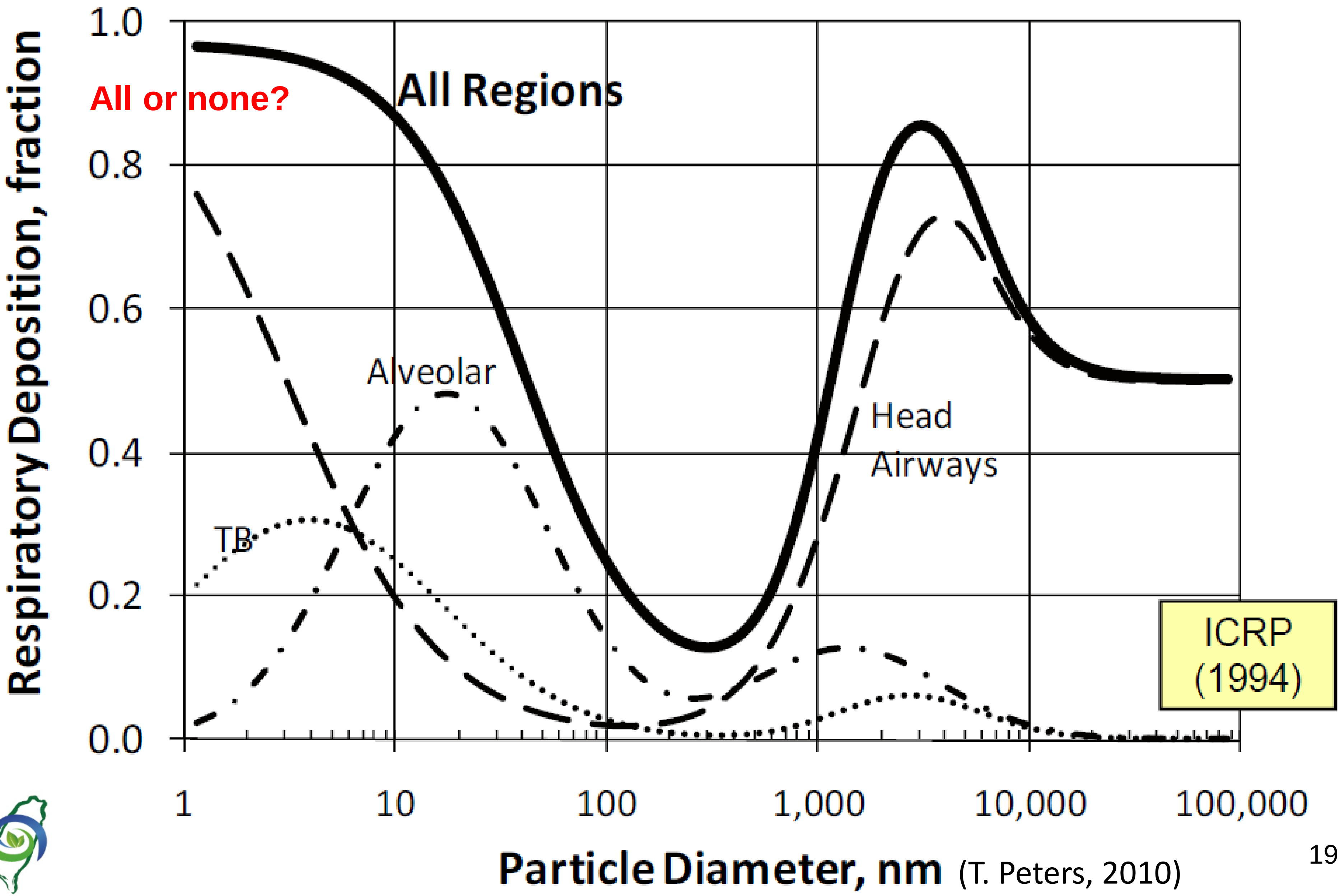
MW ↑ toxicity ↑



Dec. 4, 1952

The **great London smog** lasted for five days and led to around ***4000*** **more deaths** than usual. The first Clean Air Act was eventually introduced in 1956. (Beaver Committee Report)

Respiratory Deposition



(T. Peters, 2010)

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A Sampling Train for Rapid Measurement of Regional Lung Deposition

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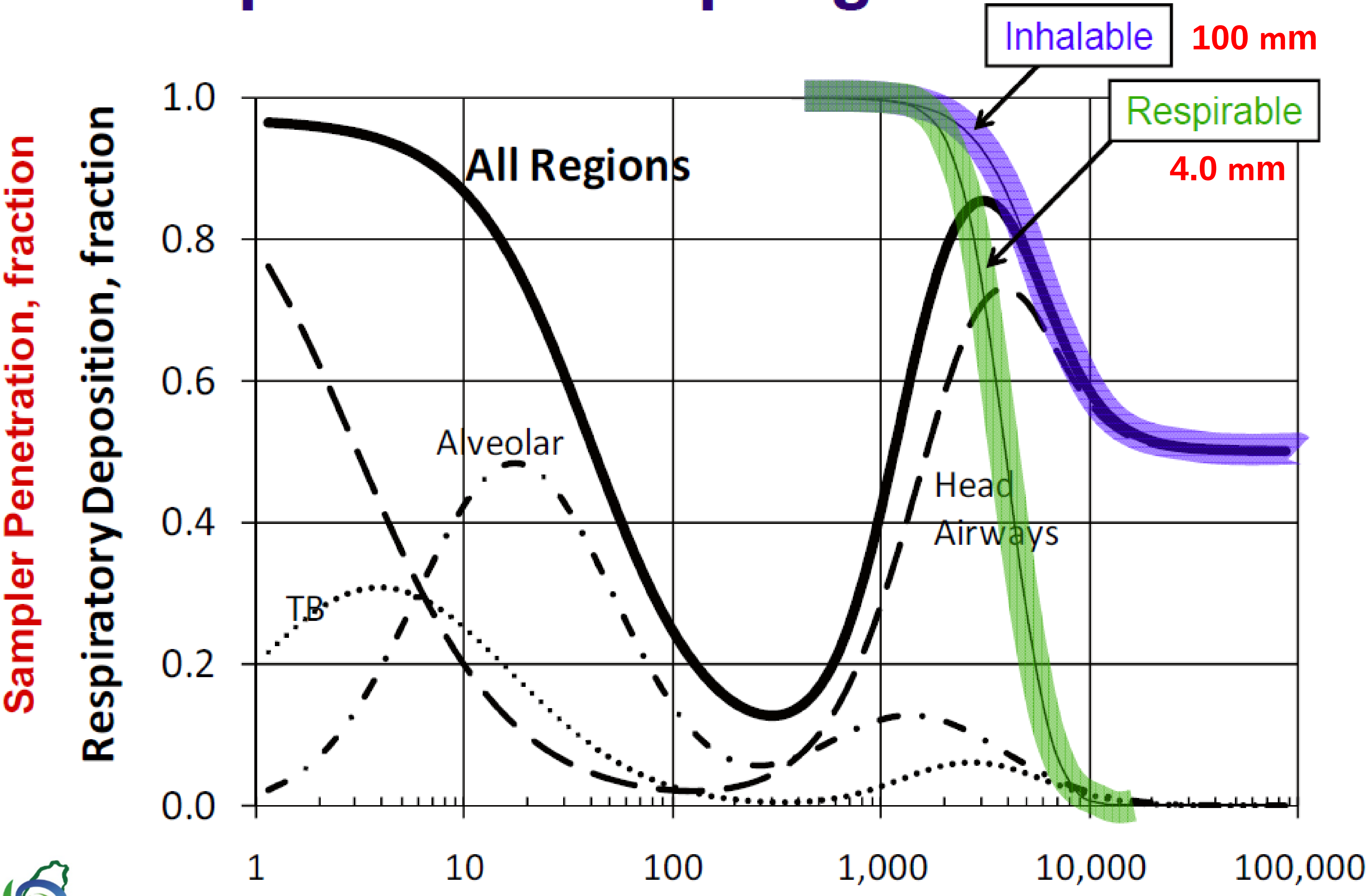
ABSTRACT

An experimental system for rapid measurement of regional lung deposition of Di-2-ethylhexyl sebacate (DEHS) aerosol particles was established in the present study. The principal goal was to identify the most relevant components of the sampling train and the proper instruments to be employed. After completing the search for an optimal sampling train and instruments, a human subject test was performed. Overall, the sampling train consisted of a mouthpiece, flow meter, and particle counter. The mouthpiece was attached to a Fleisch pneumotachograph. Several TSI condensation particle counters (CPCs), a PC-LabCard and a personal computer were employed to measure and record the counts of test particles at 100 Hz. A cylinder-piston breathing machine was built to generate a series of "standard" breathing patterns. For non-human subject tests, an acrylic tube, 5 cm diameter × 60 cm length, packed with a piece of 100 ppi foam disks was used as a substitute for the human respiratory tract. The optimal sampling train was determined to be a 1TH Fleisch pneumotachograph with a CPC model 3025A because of its short response time and low flow fluctuation. A healthy non-smoking man volunteered to be the subject, and was asked to follow breathing patterns generated by a cylinder-piston breathing machine. The local deposition efficiency was calculated for 1 μm DEHS particles of each 50 cm^3 volumetric region. The deposition data showed a good agreement with previous studies. Compared to the conventional bolus system, the advantage of the rapid measurement system developed in this work is its simplicity, low exposure, and high efficiency.

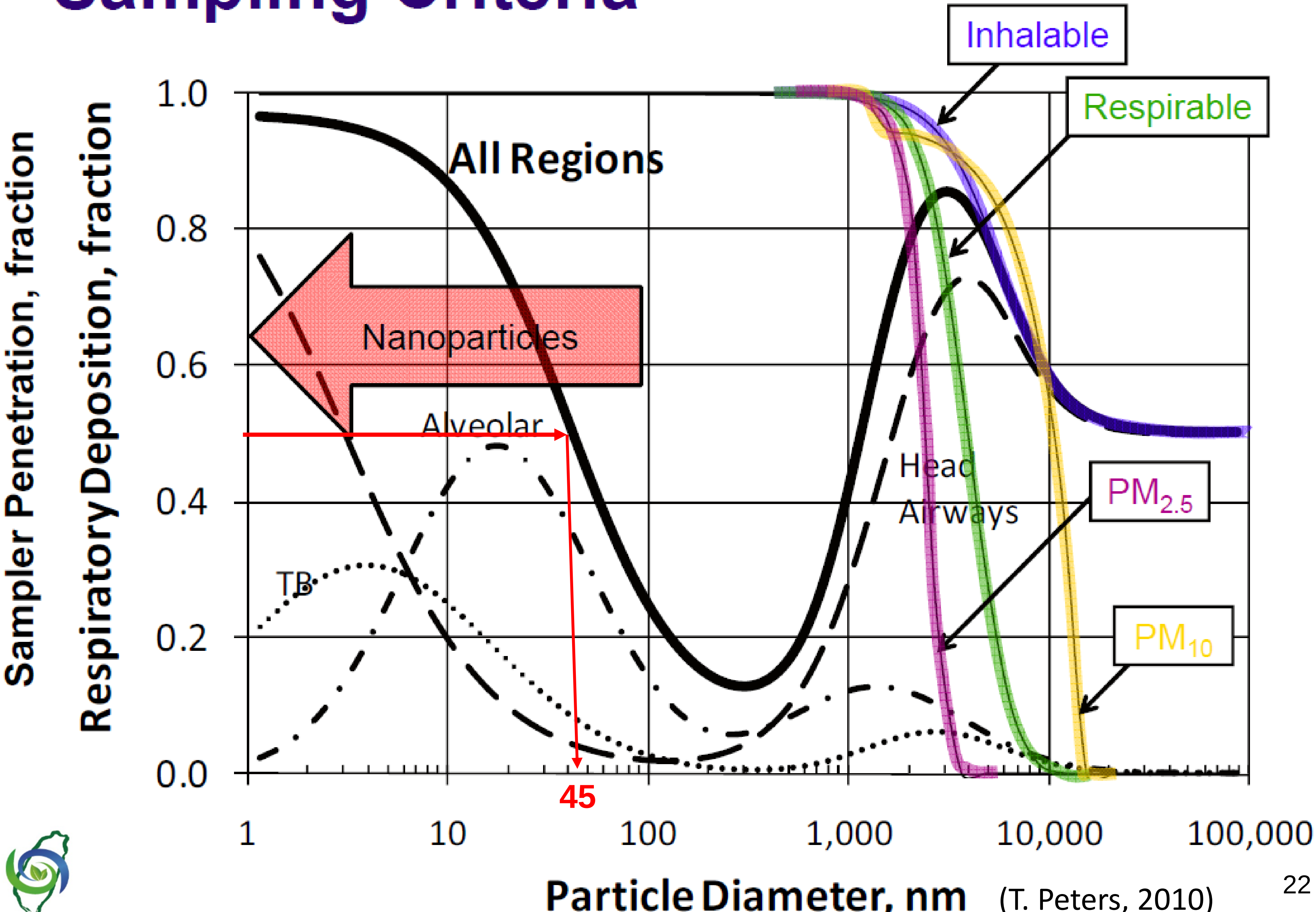
Keywords: Lung deposition; Pneumotachograph; Aerosol sampling.

Occupational Sampling Criteria



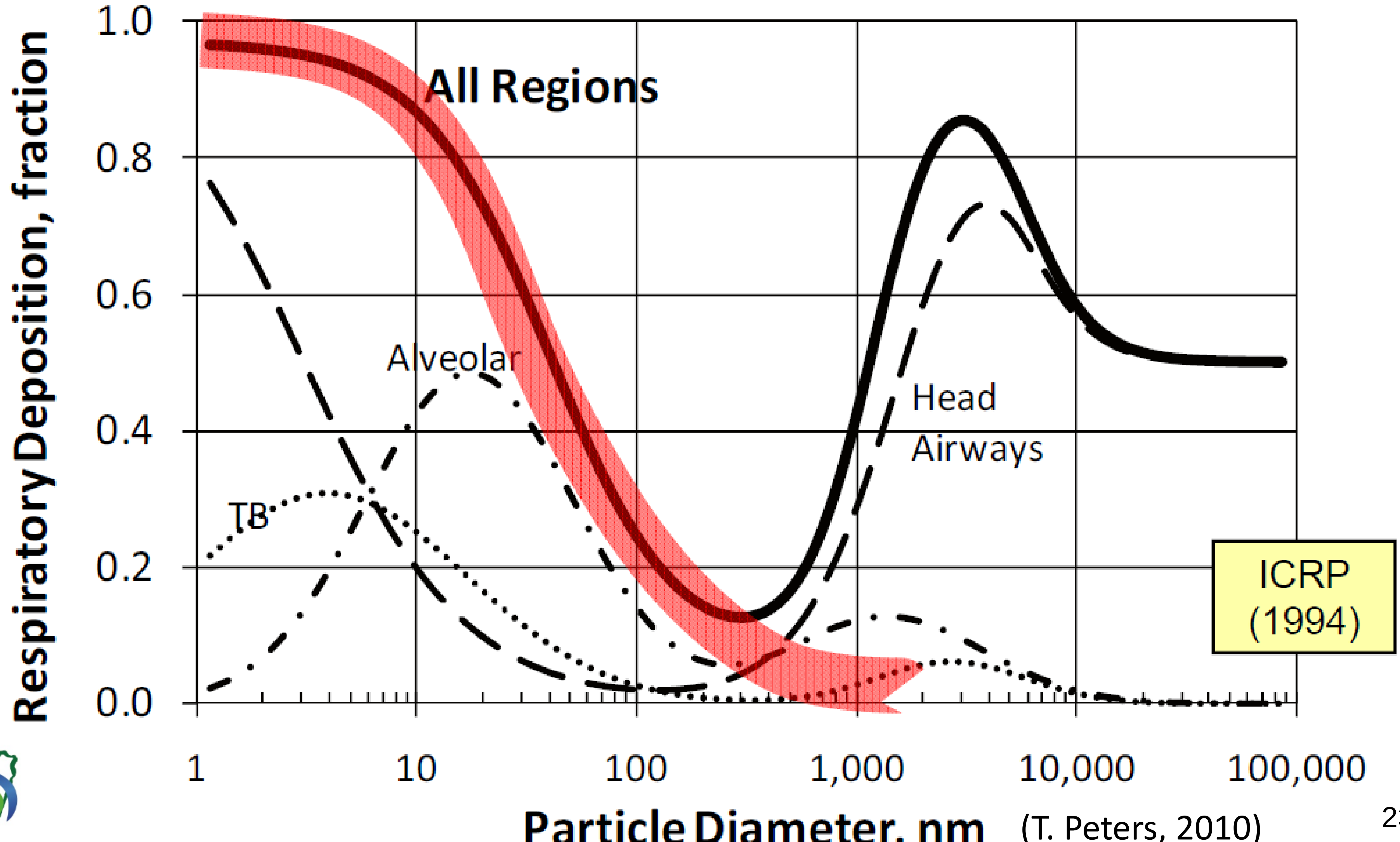
(T. Peters, 2010)

Sampling Criteria



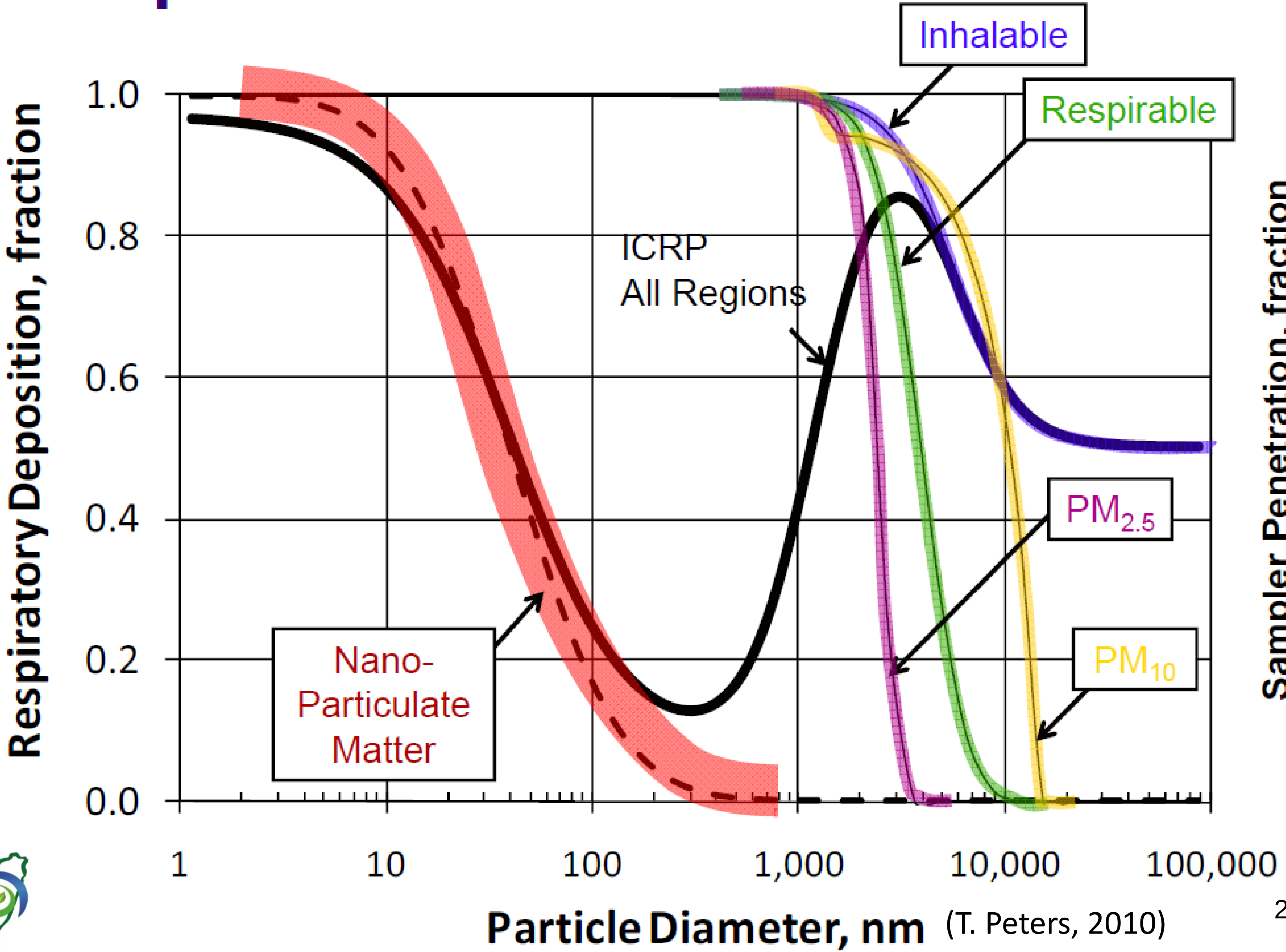
(T. Peters, 2010)

Basis For New Criterion
Deposition In All Regions For <300 nm



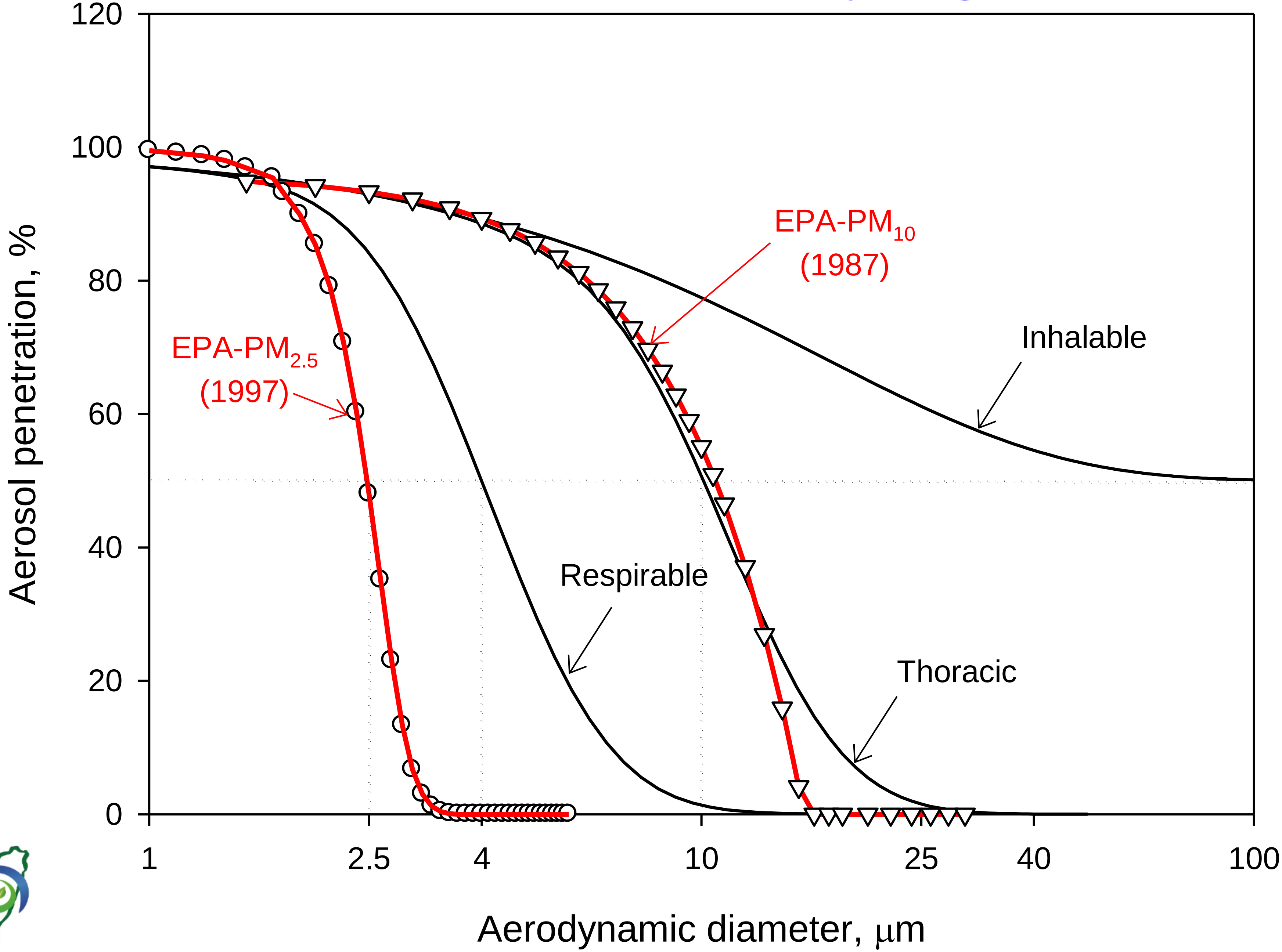
(T. Peters, 2010)

Nanoparticulate Matter Criterion

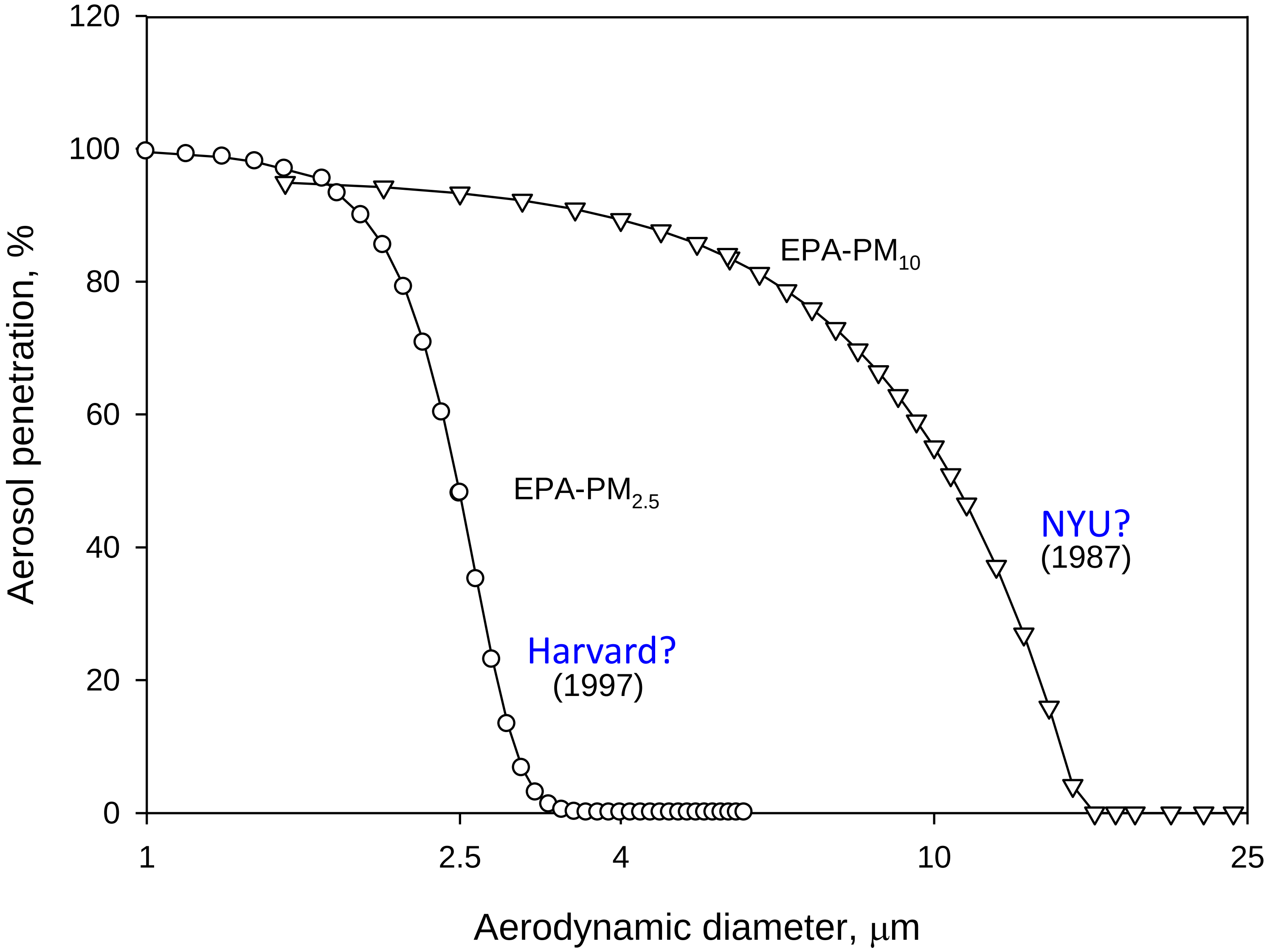


(T. Peters, 2010)

Size-selective sampling

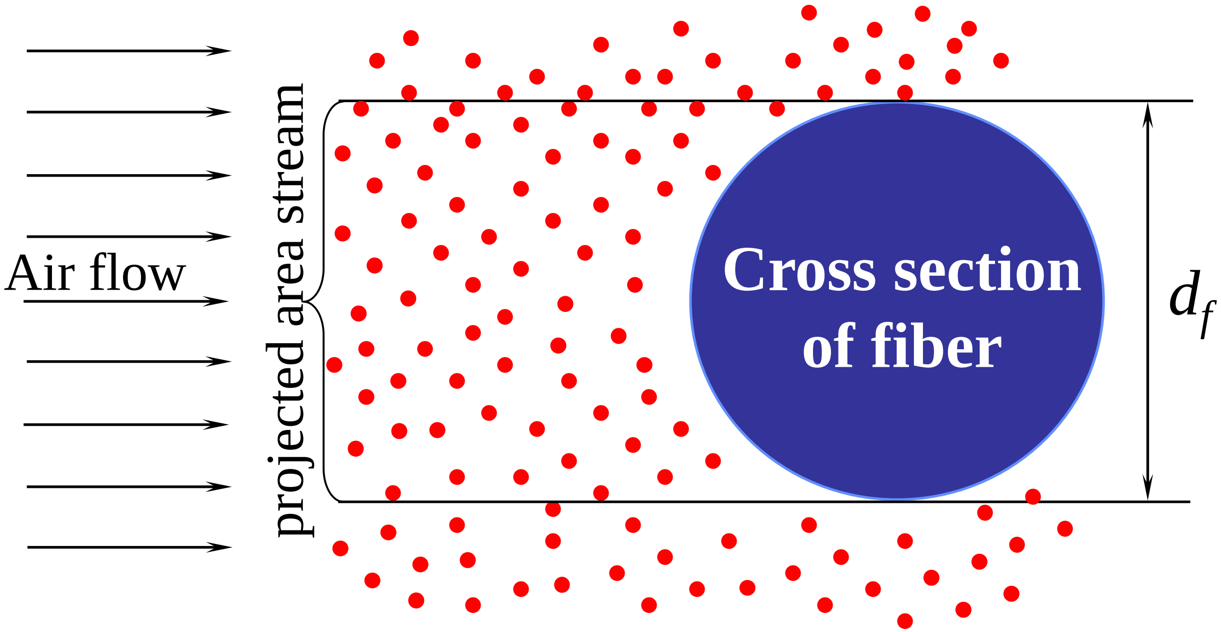


Size-selective sampling



Single Fiber Efficiency, E_Σ

The fraction of particles approaching a fiber in the region defined by the projected area of the fiber that are ultimately collected on the fiber



$$E_\Sigma = \frac{\text{number collected on unit length}}{\text{number geometrically incident on unit length}}$$

Assumptions:

- A particle sticks if it contacts the fiber.
- The flow inside a filter will be laminar.

The overall efficiency of a filter, $\boldsymbol{E}$, is a function of $\boldsymbol{E_\Sigma}$

Assuming all fibers in the filter have the same diameter, d_f

- Total length $\boldsymbol{L}$ of fiber in a unit volume

$$L = \frac{4\alpha}{\pi d_f^2}$$

Packing density/solidity, α

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

Number of particle collected when *a unit volume of aerosol* passes through an element of *unit cross section* and thickness ***dt***

$$n_c = NE_\Sigma \overbrace{d_f L}\, dt$$

$$\boxed{n_c = N\gamma dt}$$

☞ $$\gamma = E_\Sigma d_f L = \frac{4\alpha E_\Sigma}{\pi d_f}$$

$$\boxed{L = \frac{4\alpha}{\pi d_f^2}}$$

How do you determine E_Σ?

Filter Efficiency

$$P = 1 - E = e^{-\gamma t} = \exp\left(\frac{-4\alpha E_\Sigma t}{\pi d_f}\right)$$

Deposition Mechanisms

1. **Interception**
2. **Inertial impaction**
3. **Diffusion**
4. **Gravitational settling**
5. **Electrostatic attraction**

mechanical collection mechanisms

Coulombic attraction
Dielectrophoretic force
Image force

The five deposition mechanisms form the basis set of mechanisms for all types of aerosol particle deposition, including *deposition in a* ***lung***, *in a* ***sampling tube***, or *in an* ***air cleaner***.

1. Interception

- ☞when a particle follows a gas streamline that happens to come with one particle radius of the surface of a fiber.
- ☞For pure interception, it is assumed that the particles follow the streamline perfectly; that is, they have negligible inertia, settling, and Brownian motion.
- ☞Interception is the only mechanism that is not a result of a particle departing from its original gas streamline.

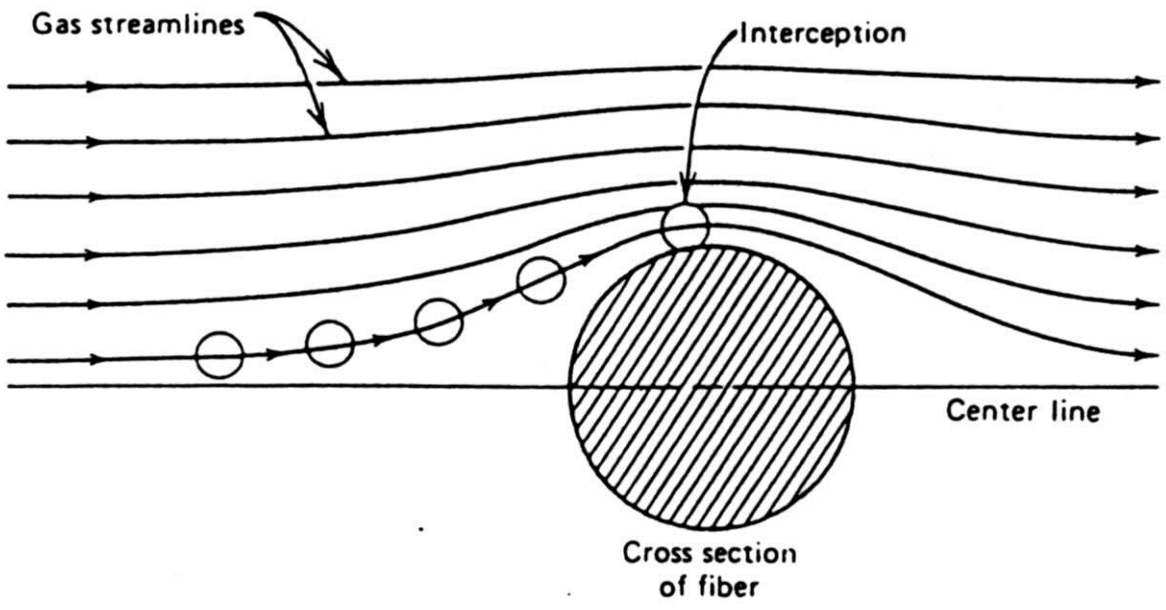
1. Interception (Lee and Ramamurthi, 1993)

$$E_R = \frac{(1-\alpha)R^2}{\mathrm{Ku}(1+R)} \quad \text{where} \quad \boxed{R = \frac{d_p}{d_f}}$$

$$Ku = -\frac{\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

Kuwabara hydrodynamic factor

Compensates for the effect of distortion of the flow field around a fiber because of its proximity to other fibers.



Q: Effect of increasing velocity? Increasing *R*?

2. Inertial impaction (Yeh and Liu, 1974)

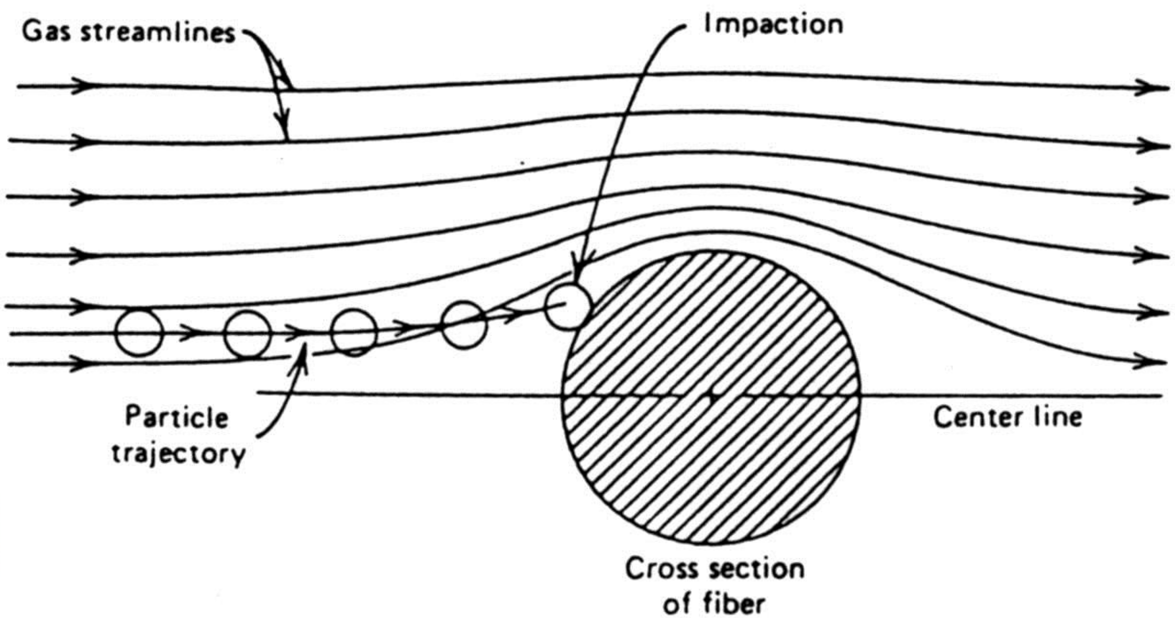
$$E_I = \frac{(\mathrm{Stk})J}{2\mathrm{Ku}^2}$$

Q: How to have a larger *Stk*?

1. a greater particle inertia
2. a greater particle velocity
3. a more abrupt curvature of streamlines

$$Stk = \frac{\tau U_0}{d_f} = \frac{\rho_p d_p^2 C_c U_0}{18\eta d_f}$$

$$J = \left(29.6 - 28\alpha^{0.62}\right)R^2 - 27.5R^{2.8} \qquad \text{for } R<0.4$$

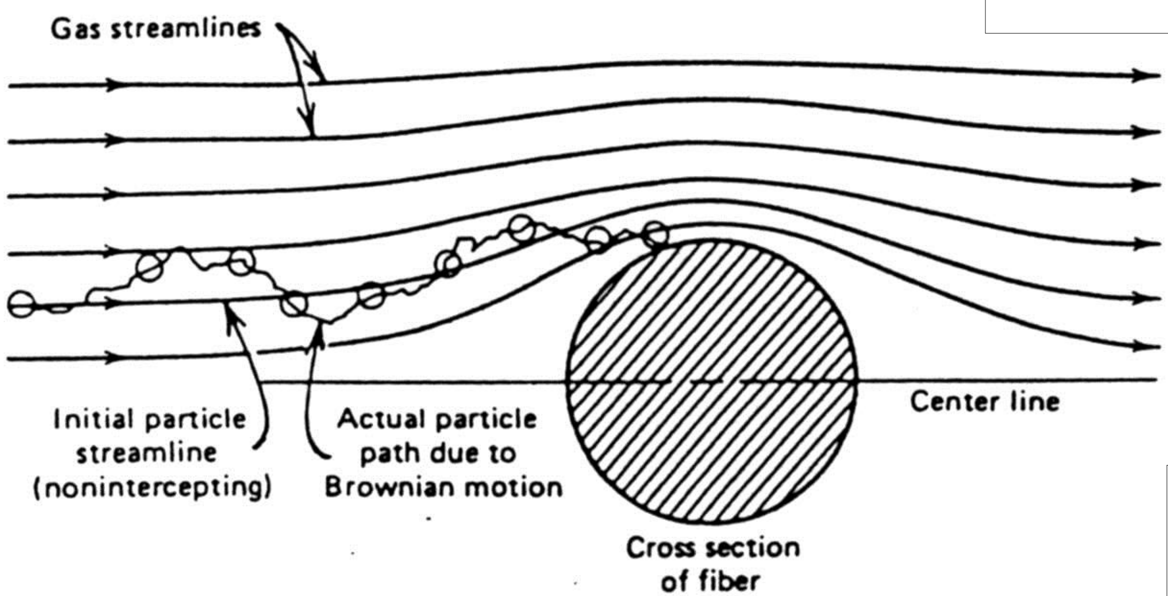


3. Diffusion (Kirsch and Fuchs, 1968)

$$E_D = 2\mathrm{Pe}^{-2/3}$$

$$Pe = \frac{d_f U_0}{D}$$ Peclet number

☞ near the size of minimum efficiency, it is necessary to include an interaction term to account for enhanced collection of diffusing particles due to interception of the diffusing particles.



$$E_{DR} = \frac{1.24R^{2/3}}{(\mathrm{Ku\,Pe})^{1/2}}$$

The only mechanism that increases as *dp* decreases.

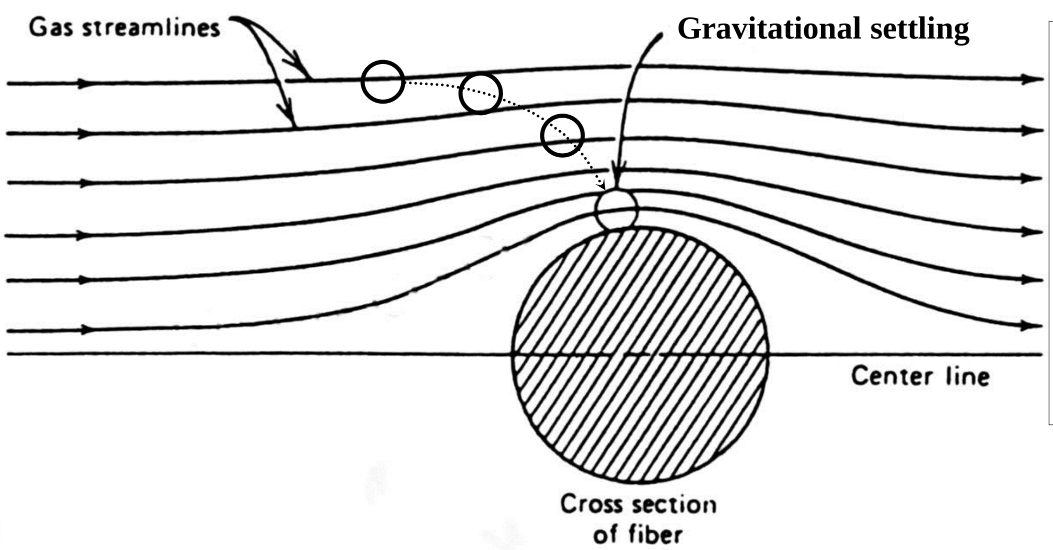
4. Gravitational settling

$$G = \frac{V_{TS}}{U_0} = \frac{\rho_g d_p^2 C_c g}{18\eta U_0}$$

$$E_G \approx G(1+R)$$ for $\boldsymbol{U_o}$ and $\boldsymbol{V_{TS}}$ are in the same direction

$$E_G \approx -G(1+R)$$ gas flow in the direction opposite to $\boldsymbol{V_{TS}}$

When flow is horizontal, E_G is much less – on the order of G^2.



☞E_G is small compared with other single fiber mechanisms, unless the particle size is large and U_0 is low.

5. Electrostatic attraction

☞can be extremely important, but is difficult to quantify.

① Coulombic attraction （庫侖力）

charged particles v.s. charged fibers

② Dielectrophoretic force （介電力）

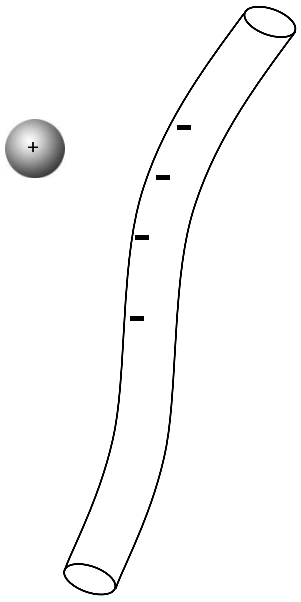
uncharged particles v.s. charged fibers

③ Image force （感應力）

charged particles v.s. uncharged fibers

5. Electrostatic attraction

① Columbic force（庫侖力）

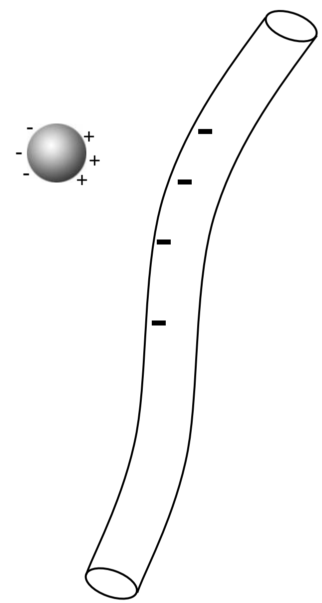


$$E_{c,n} = \left(\frac{1-\alpha}{Ku} \right)^{1/8} \frac{\pi N_{c,n}}{1 + 2\pi N_{c,n}^{1/4}}$$

$$N_{c,n} = \frac{ne\sigma C_c}{3\pi\varepsilon_0 \left(1+\varepsilon_f\right) \eta d_p U_0}$$

5. Electrostatic attraction

② Dielectrophoretic force（介電力）



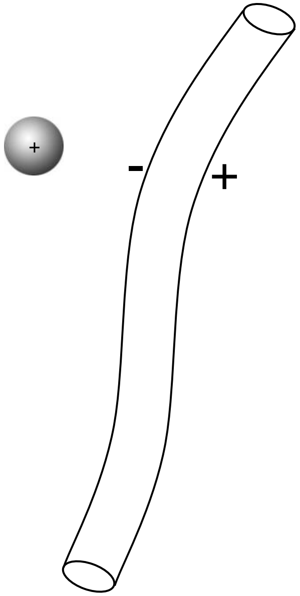
$$E_P = \left(\frac{1-\alpha}{Ku}\right)^{2/5} \frac{\pi N_d}{1+2\pi N_d^{2/3}}$$

$$N_d = \frac{(\varepsilon_p - 1) 2\sigma^2 d_p^2 C_c}{(\varepsilon_p + 2) 3\varepsilon_0 (1+\varepsilon_f)^2 \eta d_f U_0}$$

5. Electrostatic attraction

③ Image force（感應力）

$$E_m = 1.5\left[\frac{\left(\varepsilon_f - 1\right)}{\left(\varepsilon_f - 1\right)}\frac{Q_p^2}{12\pi^2\eta U_0\varepsilon_0 d_p d_f^2}\right]^{1/2}$$



Electret filter

- ☞ Filter composed of charged fiber.
- ☞ With high particle collection efficiency and low pressure drop.
- ☞ Charges will lose when exposed to ionizing radiation, high temperature, high humidity, or aerosol particles.

Total Filter Efficiency

$$P = 1 - E = e^{-\gamma t} = \exp\left(\frac{-4\alpha E_{\Sigma} t}{\pi d_f}\right)$$

$$E_{\Sigma} = 1 - (1 - E_R)(1 - E_I)(1 - E_D)(1 - E_{DR})(1 - E_G)$$

Valid for
005 < α < 0.2
0.1 < U_0 < 200 cm/s
0.1 < d_f < 50 μm
Re_f < 1

$$E_{\Sigma} \approx E_r + E_I + E_D + E_{DR} + E_G$$

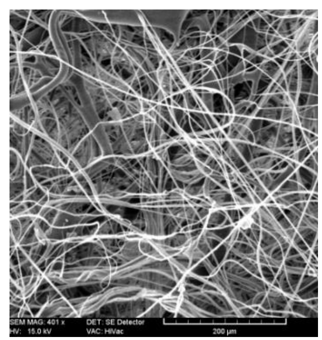
theoretically incorrect!

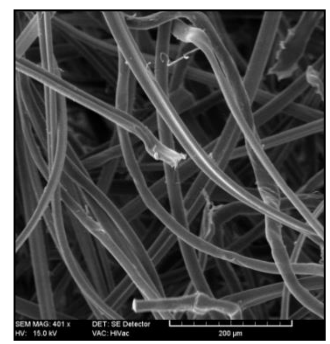
when only one mechanism predominates and the others are less than 0.01.

Total Filter Efficiency

E_Σ tend to overestimate efficiency because:

1. the fibers are not all perpendicular to the airflow
2. the fibers may be clumped together
3. packing density is not uniform





☞The use of the effective fiber diameter which is based on pressure drop measurement avoids this problem.

Filter Quality Factor (Figure of Merit, FOM)

A useful criterion for comparing different types of filters and filters of different thickness.

$$q_F = \frac{\ln\left(\dfrac{1}{P}\right)}{\Delta p}$$

P : aerosol penetration
Δp : pressure drop

Comparisons of q_F must be made for the same face velocity and test aerosol particle size.

Q: what does the best filter should be?

$d_f = 4\,\mu m,\ \alpha = 0.08,\ \chi = 0.2\,mm$

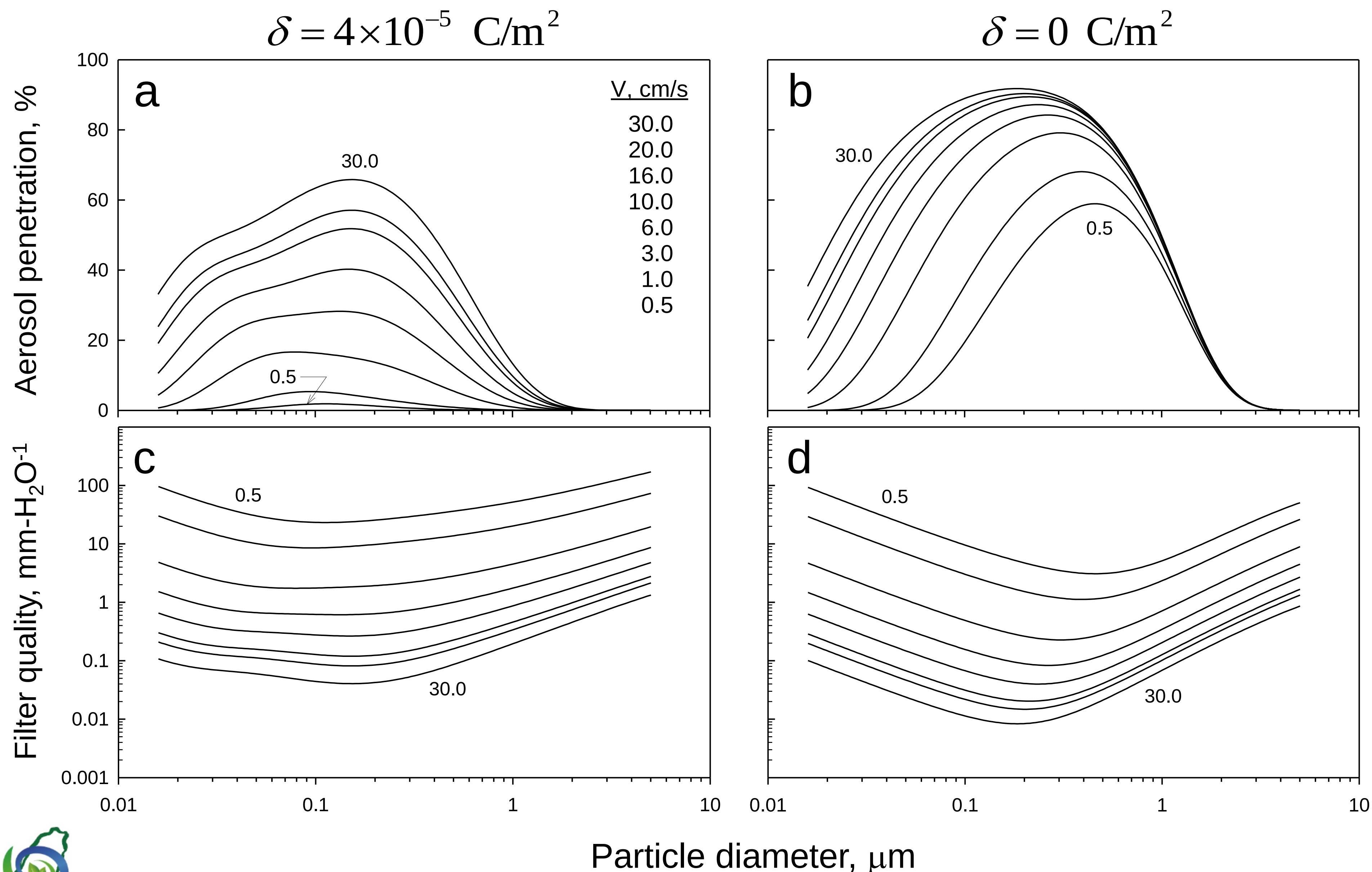


FIGURE 1. Effect of face velocity on aerosol penetration and filter quality

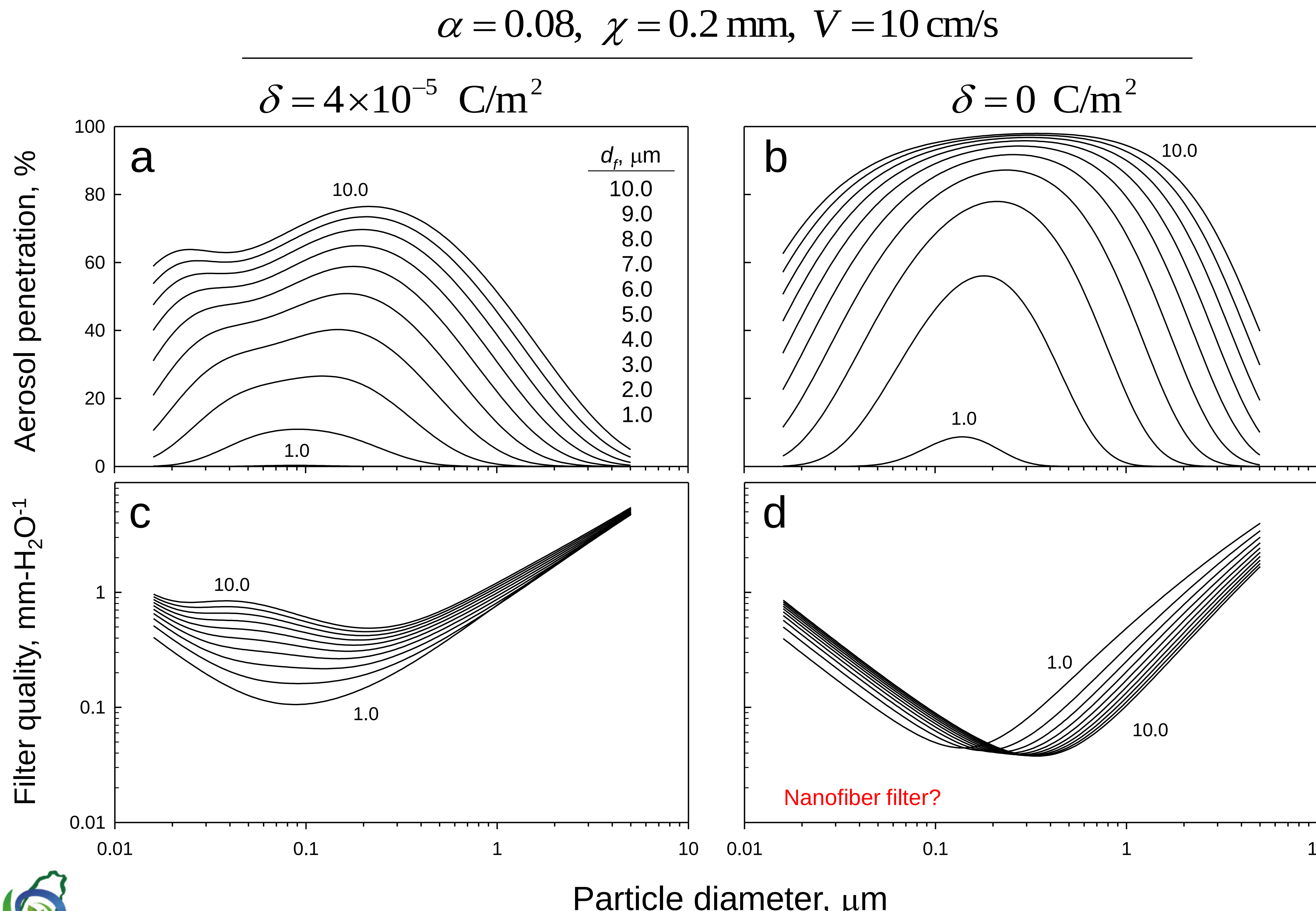


FIGURE 2. Effect of fiber diameter on aerosol penetration and filter quality

$$d_f = 4\,\mu\text{m},\ \ \chi = 0.2\ \text{mm},\ \ V = 10\ \text{cm/s}$$

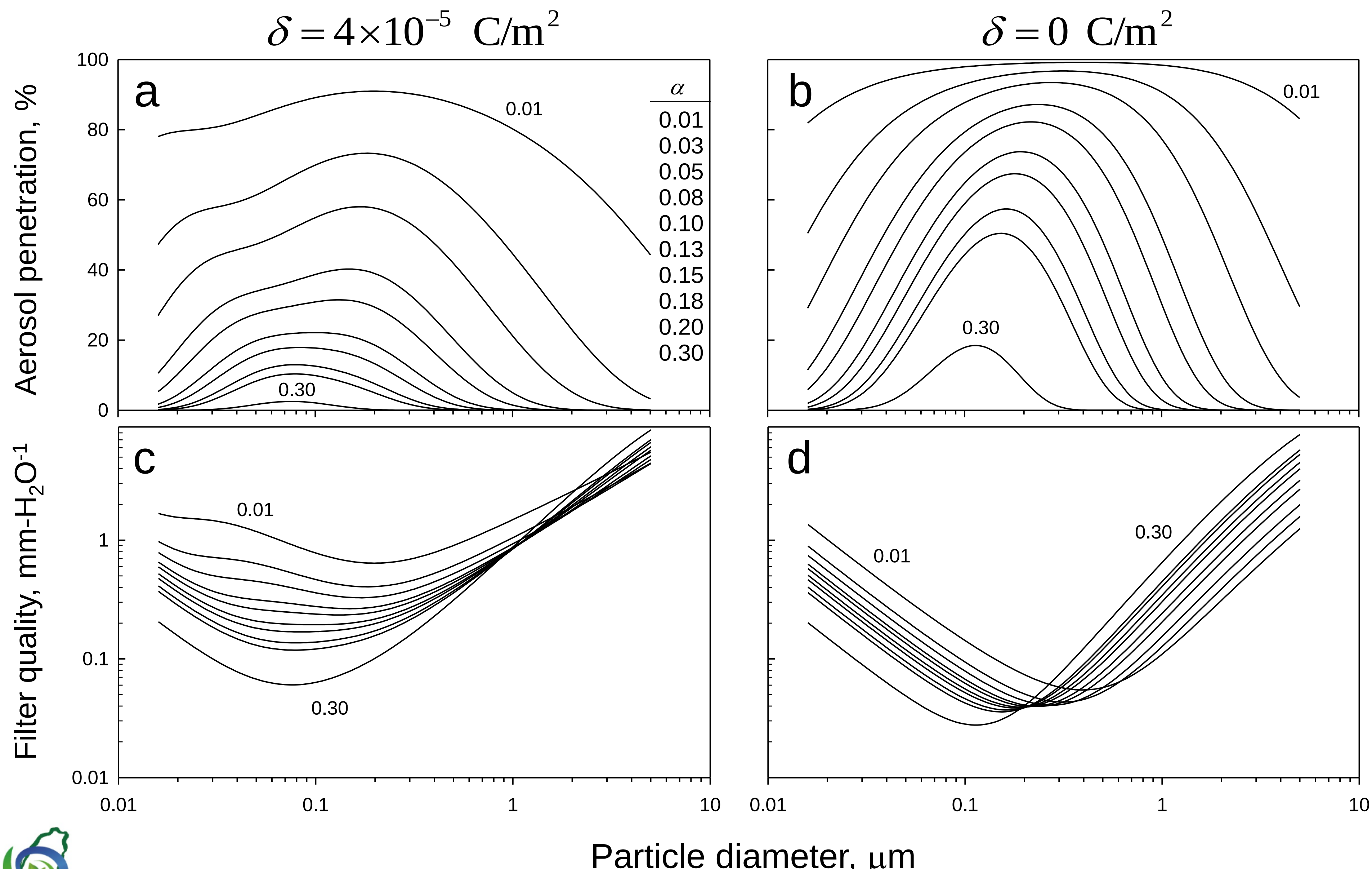


FIGURE 3. Effect of packing density on aerosol penetration and filter quality

$d_f = 4\ \mu m,\ \alpha = 0.08,\ V = 10\ cm/s$

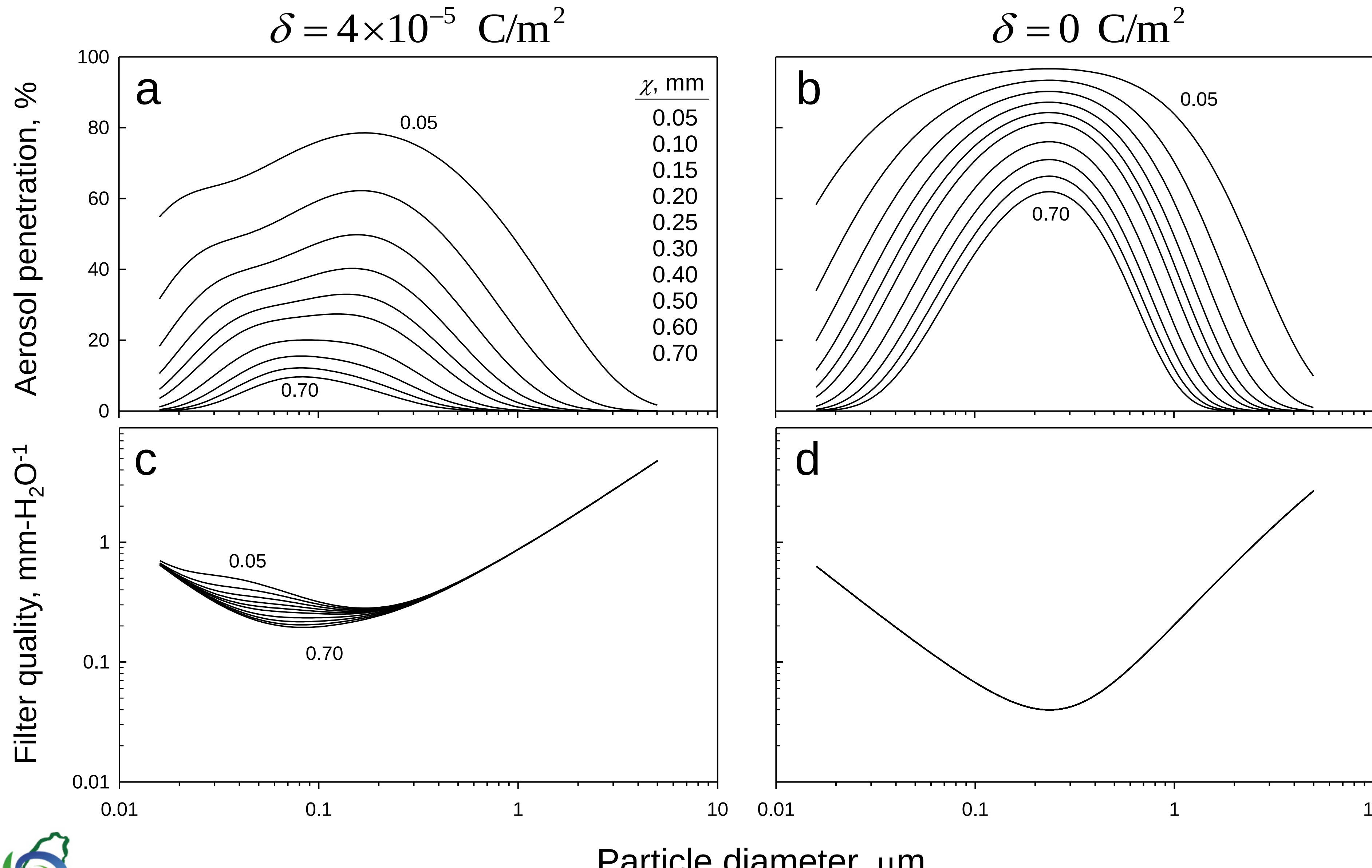


FIGURE 4. Effect of filter thickness on aerosol penetration and filter quality

$$d_f = 4\,\mu\text{m},\;\; \alpha = 0.08,\;\; \chi = 0.2\,\text{mm}$$

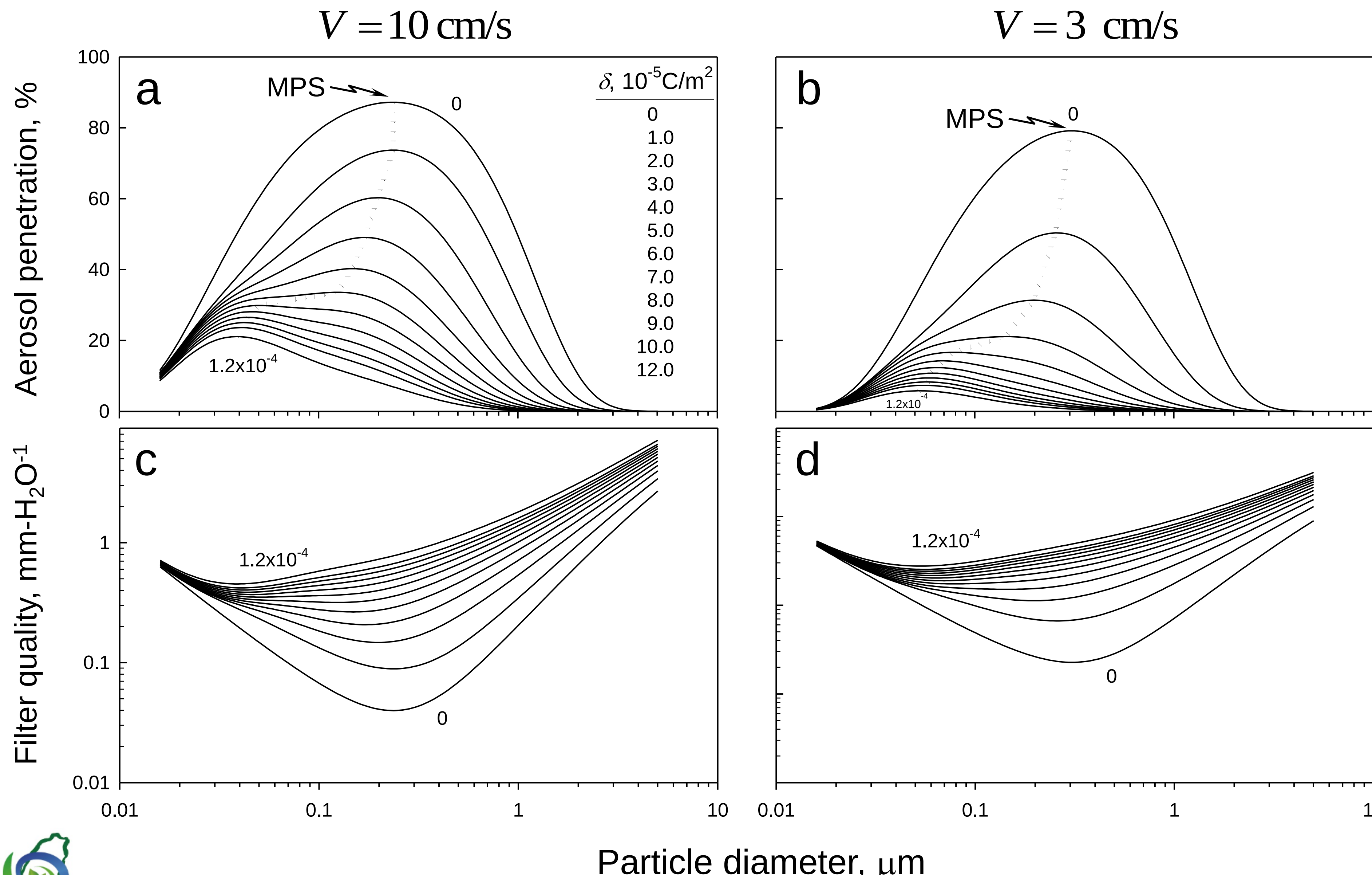
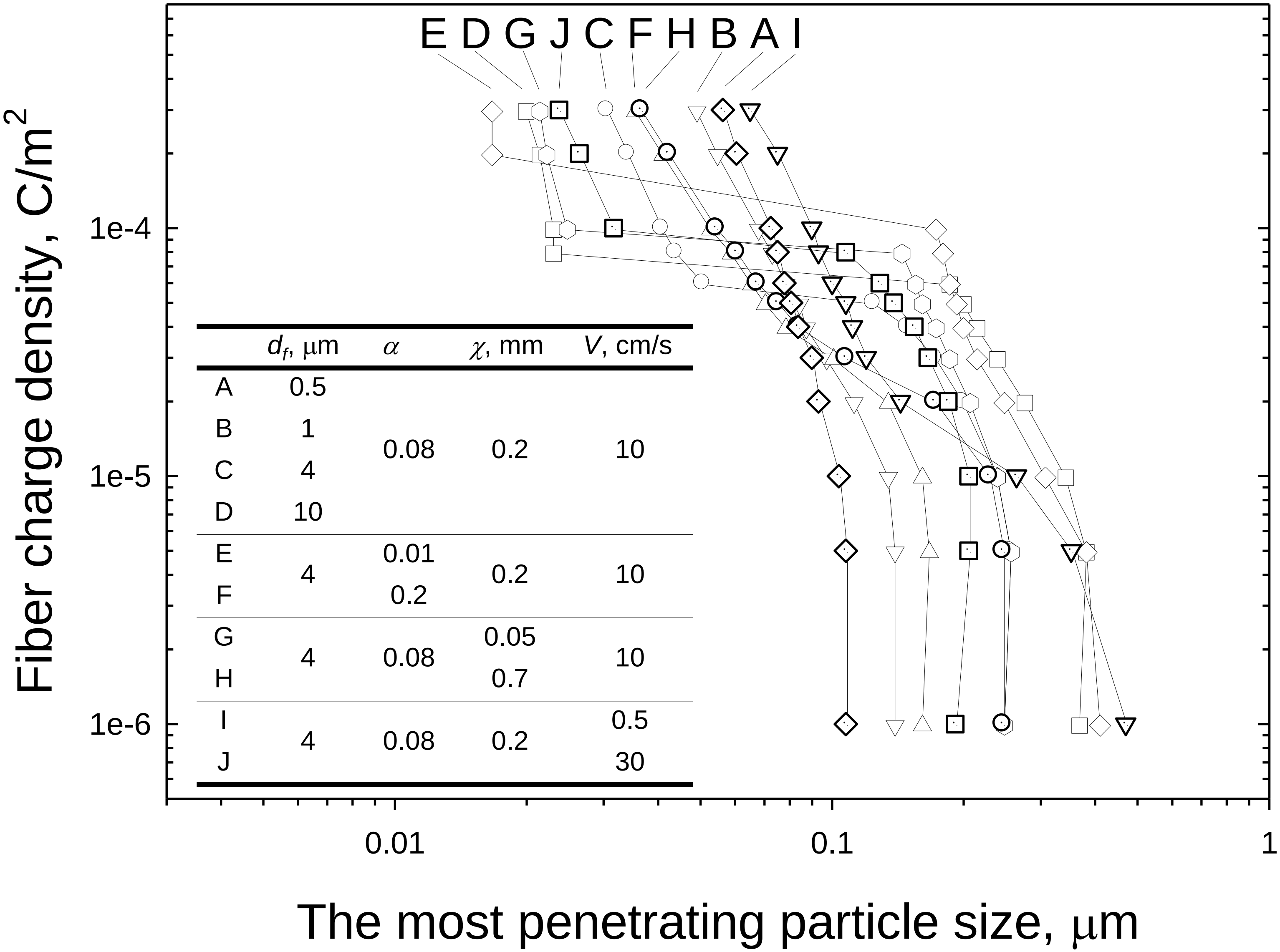


FIGURE 5. Effect of charge density on aerosol penetration and filter quality



	d_f, μm	α	χ, mm	V, cm/s
A	0.5	0.08	0.2	10
B	1			
C	4			
D	10			
E	4	0.01	0.2	10
F		0.2		
G	4	0.08	0.05	10
H			0.7	
I	4	0.08	0.2	0.5
J				30

FIGURE 6. Effect of charge density on the most penetrating particle size.

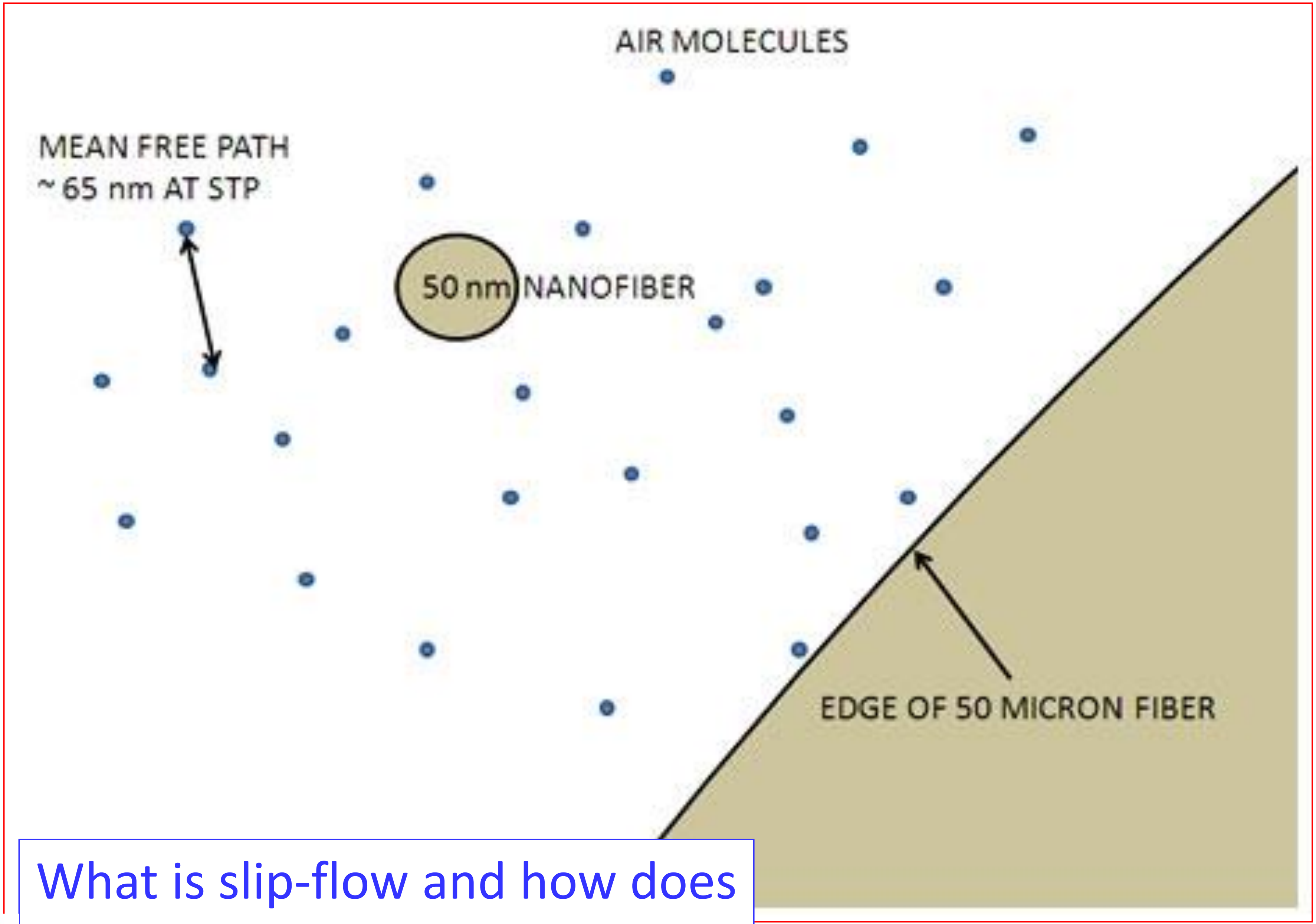
Table 1. Effect of operational factors on aerosol penetration, filter quality, and MPS within the simulated range.

Parameters	Unit	Aerosol penetration	Filter quality	Most penetrating particle size
Face velocity	cm/s	↑	↓↓↓	↑, ↓*
Fiber diameter	μm	↑	↑	↑
Packing density	—	↓	↓	↓
Filter thickness	mm	↓	—	↓, —*
Charge density	C/m^2	↓	↑↑	↓

* : mechanical filter

HEPA filter???

$PM_{2.5}$或PM_{10}效率99%???



What is slip-flow and how does it affect filter performance?

Nano-fiber filter?

Theoretically simple, but ……

Melt blown?

Electrospinning?

Thanks for your attention!