Chapter 11 Adverse Effect of Powders

11.1 Introduction

- *Dust explosion*
- *Respirable dust*
- *Nanoparticle hazard in human body (?)*
- *Particulate contamination in fine industries and hospitals...*

11.2 Fire and Explosion Hazards of Fine Powders

(1) Introduction

Explosion

- *Flammable gas: fuel concentration, local heat transfer conditions, oxygen concentration, initial temperature*
- *Dusts: + particle size distribution, moisture content*

(2) Combustion Fundamentals

1) Flames

- *Flammable materials + oxygen + ignition source*
- *Stationary flame vs. explosion flame*

  according to the behavior of flame front

2) Explosion and Detonation

- *Generation of gaseous combustion products*

  → rapid gas expansion or

  → rapid pressure increase

- *Detonation vs. deflagration*

  Determined by flame speed (< or > speed of sound) which is governed by heat of combustion*

  degree of turbulence

  ignition energy

* Accompanying pressure shock waves

3) Ignition - Simple Analysis for Ignition

Energy balance for fuel-air mixture:

Δ $$Q_{input} + (- \quad H)\left[Z\exp\left(-\frac{E}{RT}\right)\right]C_{\;m,\,fuel} =$$

Heat input *Heat generated*

ρ $$V[C_{\;m,\,fuel} C_{p,\,fuel} + (1-C)_{\;m_{air}} C_{p,\,air}]\frac{dT}{dt} + hA(T - T_s), \;\; J/s$$

heat accumulation *heat dissipated*

where C: volumetric concentration of fuel

ρ *: molar density*

V: volume of fuel-and-air mixture element

A: surface area of the element

* Figure 12.1

$T_B \rightarrow$ *Ignition temperature*

Figure 12.2 Effect of heat input

Figure 12.3 Autoignition (spontaneous ignition)

4) Flammability Limits

- *Upper and lower flammability limit,* C_{fL}, C_{fU}

in volume % fuel

- *Minimum oxygen for combustion*

For C_3H_8 $C_{fL} = 2.2\%$, *by volume*

$$MOC = C_{fL} \cdot \left[\frac{moles\ O_2}{moles\ fuel}\right]_{Stoich}$$

$$= 2.2 \cdot 5 = 11\% \;\; O_2 \;\; by\ volume$$

Worked Example 12.1

Worked Example 12.2

(3) Combustion in Dust Clouds

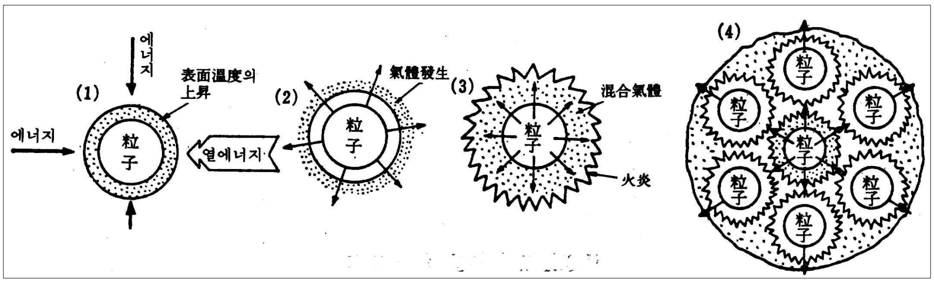
- Powders : High surface area / small size (small heat capacity)

Where special attention is required against dust explosion

Particles	*Grain flour, coal, metals, plastics, sugar, pharmaceuticals*
Industries	*Plastics, food processing, metal processing, pharmaceuticals, agricultural, chemicals and coals*
Processes	*Dilute pneumatic conveying, spray drying (heat and dilute suspension)*

· *Organic dust :*

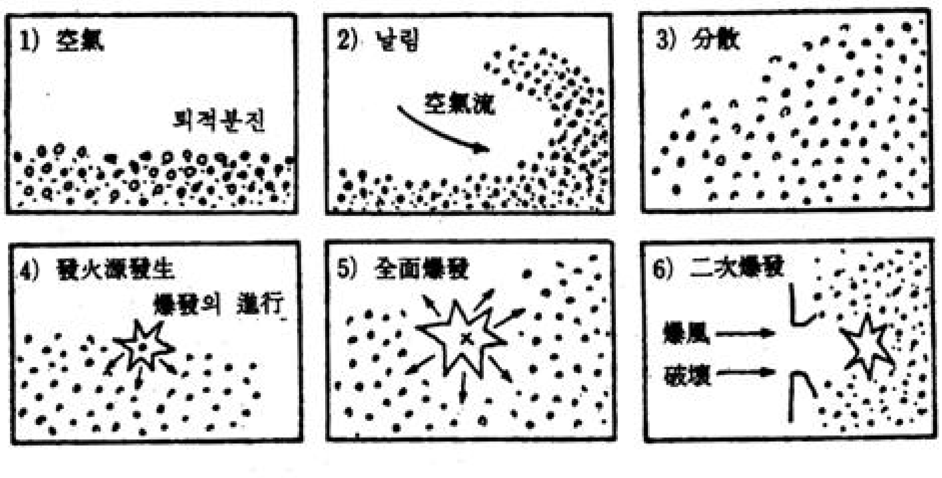
heating → emission of combustible gases → explosion



분진폭발 기구

· *Metals :*

Protective oxide films → breaking by sudden heating



- Primary vs. secondary explosion

↓

Pressure wave of small explosion → increase in resuspending particles

∵ *Pressure wave precedes the flame.*

1) Fundamental to Specific to Dust Cloud Explosion

Particle size : very important

- *Dispersion (cloud form)*
    - *More explosive when suspended (individual particles contact with air)*
    - *Cloud state is more explosive than bed state...*

- *High surface area for reaction*

$$(-\Delta H) r'' \left[\frac{moles\ fuel}{m^2 fuel \cdot s}\right]\left(\frac{m^2 fuel}{m^3 reactor}\right) = (-\Delta H) r'' \left[\frac{m^2 fuel}{m^3 fuel}\right]\left(\frac{m^3 fuel}{m^3 reactor}\right)$$

$$= (-\Delta H) r'' \left(\frac{6}{x}\right) C$$

- *Low specific heat of reaction → high heat up rate: low heat capacity*

2) Characteristics of Dust Explosion

Little data on powder properties

i) Minimum dust concentration

분 진	하 한 농 도 (g/㎥)
◈ 수지류	
요소계	70 ~140
페놀계	25 ~175
리그닌계	40 ~65
비닐계	20 ~40
폴리스틸렌계	20
초산셀룰로오스	35 ~40
셀락	14 ~20
합성고무	30
◈ 역청탄	30 ~38
◈ 금속	
마그네슘	20 ~50
알루미늄	35 ~40
철(카보닐법)	105
철(수소환원)	120 ~250
안티몬	190 ~220
지르코늄	190
망간	210 ~350
아연	300

ii) Minimum oxygen for combustion (MOC)

iii) Minimum ignition temperature

분 진	발 화 온 도 (℃)
면화	470
목분	430
헥사메틸렌, 테트라민	310
페놀수지	460
초산셀룰로오스 성형분	320
합성고무(硬)	320
무수프탈산	650
분쇄알파펄프	480
비닐수지	550
폴리스틸렌수지	490
비닐성형분	690
리그닌수지	450
셀락, 로진, 고무	390
펜타에스리톨	450

발화도분류

발화도	분진의 발화온도
I 1	270℃ 이상인 것
I 2	200℃ 이상 270℃ 이하인 것
I 3	150℃ 이상 200℃ 이하인 것

분진 / 발화도	폭연성 분진	가연성 분진	
		전도성	비전도성
I 1	마그네슘, 알루미늄 알루미늄부론즈	아연, 코크스, 카본블랙	소맥, 고무, 염료 페놀수지, 폴리에틸렌
I 2	알루미늄(수지)	철, 석탄	코코아, 리그닌, 쌀겨
I 3			유황

iv) Minimum ignition energy

Ignition energy

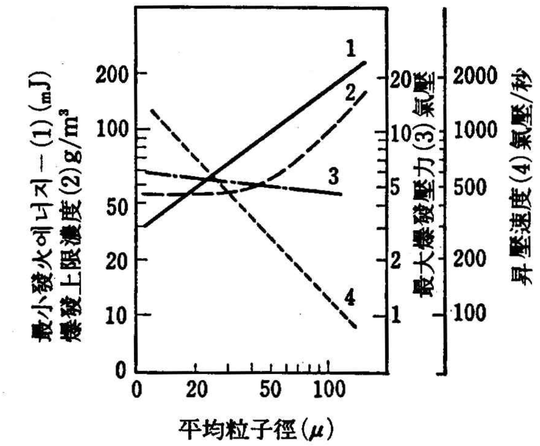
금속시료	운상(雲狀)		층상(層狀)	
	노출 전	노출 6주 후	노출 전	노출 6주 후
티탄(Ti)	15mJ	25mJ	8×10^{-6}J	8×10^{-6}J
티탄(Ti)	10mJ	15mJ	2×10^{-6}J	8×10^{-6}J
지르코늄(Zr)	5mJ	15mJ	1×10^{-6}J	1×10^{-6}J
지르코늄(Zr)	15mJ	125mJ 로서 발화 않음	3×10^{-6}J	1×10^{-6}J

(v) Maximum explosion pressure

(vi) Maximum rate of pressure rise

Germany, Canada, Switzerland, Australia, UK

$$\left(\frac{dp}{dt}\right)_{\max} V^{1/3} = K_{ST}$$



알루미늄의 평균 입경과 폭발변수와의 관계

Table 12.1

Table 11.2 - Explosion class (K_{ST})

<u>Index of explosibility</u>, US Bureau of Mines

$$= \frac{\times \qquad \times}{\times \qquad \times}$$

$$= \frac{\times}{\times}$$

* *Index of explosibility = 발화감도 × 폭발격렬도*

폭발정도와 폭발지수와의 관계

폭발의 강도	발화용이도	폭발강도	폭발지수
약한 폭발	< 0.2	< 0.5	< 0.1
중간정도의 폭발	0.2 ~ 1.0	0.5 ~ 1.0	0.1 ~ 1.0
강한 폭발	1.0 ~ 5.0	1.0 ~ 2.0	1.0 ~ 10
극히 강한 폭발	> 5.0	> 2.0	> 10

US NFPA (National Fire Protection Association)

- For gas, vapor and dusts...

$\left(\frac{dp}{dt}\right)_{max}$ *in* bar/s *is classified by three classes...*

$0 < \left(\frac{dp}{dt}\right)_{max} < 345, \quad 345 < \left(\frac{dp}{dt}\right)_{max} < 690, \quad 690 < \left(\frac{dp}{dt}\right)_{max}$

** Test conditions : as close as possible to plant conditions*

(3) Control of the Hazard (12.3.4)

1) Introduction

- Change the process to eliminate the dust

- Design the plant to withstand the pressure generated by any explosion

- Remove the oxygen to below MOC

- Add moisture to the dust

- Add diluent powder to the dust

2) Ignition Sources

Flames / Smouldering / hot surfaces / welding and cutting / friction and impact / electric spark / spontaneous heating

3) Venting

- Simple and inexpensive method

Figure 12.6

Worked Example 12.3

4) Suppression

- Discharging a quantity of inert gas and inert powder into the vessel

** Suppression systems*

Automatic venting/advance inerting/automatic shutdown

5) Inerting

- N_2 and CO_2
- Oxygen concentration < MOC

6) Minimize Dust Cloud Formation

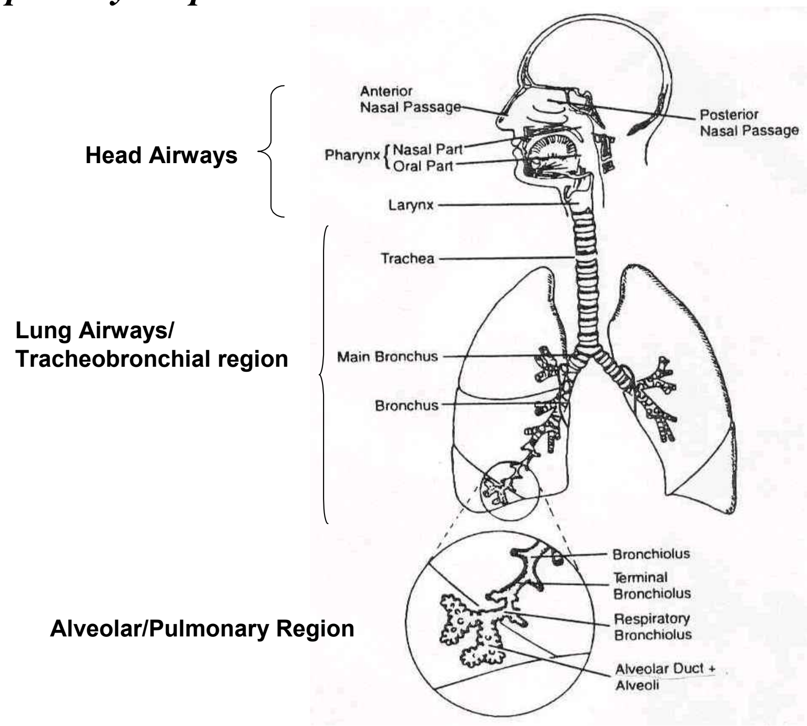
- Use of dense phase conveying
- Use cyclone and filters instead of settling vessels
- Dot not allow the powder stream to fall freely through the air

7) Containment

분진 취급공정의 위험성 평가표

구분	평가요소	위험장소(설비명) 평가점				중요도	평가점	합격점
		1	2	3	4			
물성치	1. 최소점화에너지(mj)	> 10	10 ~1	1 ~0.1	> 0.1	3		
	2. 발화온도(℃)	> 450	450 ~200	200 ~100	> 100	2		
	3. 인화점(℃)	> 70	70 ~20	20 ~0	0 <	6		
	4. 고유저항(Ωcm)	> 10^9	10^{10}	10^{11}	> 10^{12}	3		
	5. 폭발한계비	< 1	1 ~10	10 ~20	< 20	4		
	6. 입경범위(micron)	150 ~170	100 ~150	75 ~100	< 75	3		
	7. Kst(bar/m/s)	0	≤200	201 ~300	> 300	5		
사용조건	8. 사용온도(인화점 기준)	거의 없다	드물다	가끔 있다	자주 있다	5		
	9. 사용압력(kg/㎠)	< 대기압	대기압 ~2	2 ~10	> 10	2		
	10. 사용량(규정값의 배수)	< 1.5	1/5 ~10	10 ~100	> 100	3		
	11. 건물구조	옥외	창문이 많은 건물	창문이 적은 건물	밀폐	5		
	12. 환기조건	> 40	40 ~100	20 ~5	< 5	5		
설비사양	13. 장비노화도 (사용시간, 내식성 고려)		보통		심하다	2		
	14. 설비의 독립성(닥트류)	밀폐	일부 공용		여러개공용	2		
	15. 개방 또는 밀폐	기계작동	가끔 개방	정기개방	개방	4		
	16. 누출의 용이성	없음	회전체만 있음	회전왕복체	복잡한 동작 기계	3		

11.3 Respiratory Deposition



- *Hazard: chemical composition and the site deposited of particles*
- *Change in geometry and transient flow condition*
- *Rely to a greater extent on experimental and empirical data*

(1) Respiratory System

- *Head airway region(extrathoracic or nasopharyngeal)*

  Nose, mouth, pharynx, larynx
- *Tracheobronchial(lung airway) region - inverted tree*

  Trachea, bronchi, bronchiole, terminal bronchiole
- *Alveolar(pulmonary) region - gas exchange*

  Respiratory bronchiole, alveolar duct, alveolar sac, alveoli

Respiratory system of a normal adult

- *10-25m^3 (12-30kg) air/day is being processed.*
- *Surface area for gas exchange : 75m^2*
- *Tidal air: 0.5 -1.5 L inhaled and exhaled per breath*

12-36 breaths/min

Reserve air: 2.4 L

Not exhaled during normal breath

1/2-exhaled by forced exhalation

- 23 branchings - 16 in tracheobronchial regions

7 in alveolar region

<u>Fate of deposited particles</u>

- Head and lung airways: mucociliary (mucus+ciliary) action to pharynx

Clearance time : hours

- Alveolar region: no protective layer

· Insolubles: dissolved or engulfed by macrophages

dissolved or transported to lymph nodes or mucosiliary escalator

clearance time: months or years

· Solubles: pass through thin membrane into bloodstream

** Fibrogenic dusts(silica): gradual scarring or fibrosis in alveolar region*

Characteristics of Selected Regions of the Lung[a]

[a]Based on Weibel's model; regular dichotomy average adult lung with volume. 4.8 l at about three-fourths maximal inhalation. Table adpated from Lippamann(1995).

[b]At a flow rate of 1 l/s.

Airway	Generation	Number per Generation	Diameter (mm)	Length (mm)	Total Cross Section (cm^2)	Velocity[b] (cm/s)	Residence Time[b] (ms)
Trachea	0	1	18	120	2.5	390	30
Main bronchus	1	2	12	48	2.3	430	11
Lobar bronchus	2	4	8.3	19	2.1	460	4.1
Segmental bronchus	4	16	4.5	13	2.5	390	3.2
Bronchi with cartilage in wall	8	260	1.9	6.4	6.9	140	4.4
Terminal bronchus	11	2×10^3	1.1	3.9	20	52	7.4
Bronchi with muscle in wall	14	16×10^3	0.74	2.3	69	14	16
Terminal bronchiole	16	66×10^3	0.60	1.6	180	5.4	31
Respiratory bronchiole	18	260×10^3	0.50	1.2	53	1.9	60
Alveolar duct	21	2×10^6	0.43	0.7	3,200	0.32	210
Alveolar sac	23	8×10^6	0.41	0.5	72000	0.09	550
Alveoli		300×10^6	0.28	0.2			

(2) Deposition

- *Mostly by impaction, settling and diffusion*

1) Effect of deposition mechanism

- *Impaction[a]:*
  - *Effective where direction change*
  - *Effective for larger particles with higher velocity and in larger airways (bronchial region)*
- *Settling[b]:*
  - *Effective larger particles with lower velocity and in smaller and horizontal airways(distal airways)*
- *Brownian diffusion[c]:*
  - *Effective submicron particles with lower velocity and in smaller and horizontal airways (distal airways)*
- *Interception :*
  - *Usually unimportant except for long fibers*

µ *cf. 200 m long and 1 m wide →* d_{pa} *= 3 m*

Relative Importance of Setting, Impaction, and Diffusion Mechanisms for Deposition of Unit-Density Particles at Selected Regions of the Lung

[a]Stopping distance st airway velocity for steady flow of 1.0 L/s.

*[b]Setting distance = setting velocity * residence time in each airway st a steady flow of 1.0 L/s.*

[c]Rms displacement during time in each airway at a steady flow of 1.0 L/s.

Airway	Stopping Distance[a] / Airway Diameter			Setting Distance[b] / Airway Diameter			Rms Displacement[c] / Airway Diameter		
	0.1㎛	1㎛	10㎛	0.1㎛	1㎛	10㎛	0.1㎛	1㎛	10㎛
Trachea	0	0.0008	0.068	0	0	0.0052	0.0004	0.0001	0
Main bronchus	0	0.0013	0.109	0	0	0.0041	0.0003	0.0001	0
Segmental bronchus	0	0.0031	0.272	0	0	0.0022	0.0005	0.0001	0
Terminal bronchus	0	0.0017	0.149	0	0.0002	0.021	0.0029	0.0006	0.0002
Terminal bronchiole	0	0.0003	0.028	0	0.0018	0.156	0.011	0.0022	0.0006
Alveolar duct	0	0	0.0023	0.0004	0.017	1.52	0.039	0.0079	0.0023
Alveolar sac	0	0	0.0007	0.0012	0.047	4.13	0.067	0.013	0.0040

2) Total Deposition

The total deposition fraction (DF) in the respiratory system according to ICRP model is

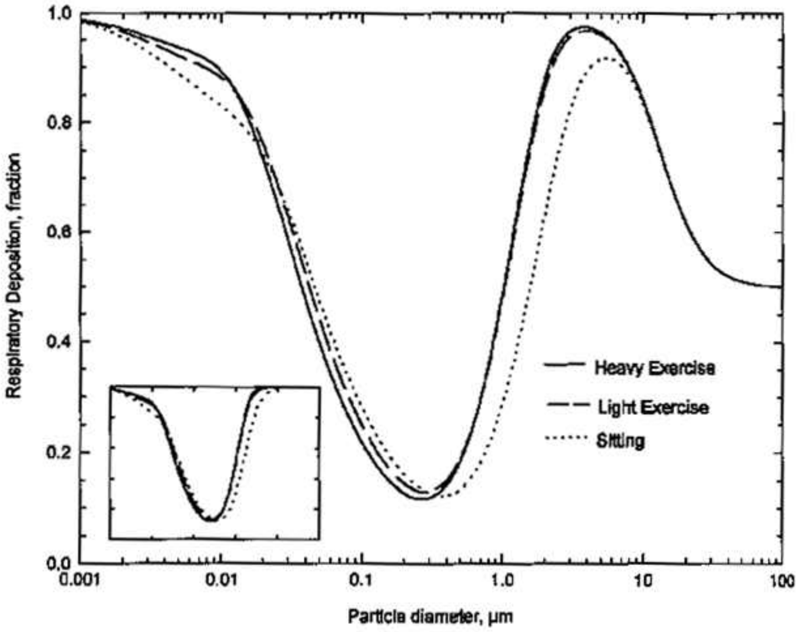
$$DT = IF\left(0.0587 + \frac{0.911}{1+\exp(4.77+1.485\ln x)} + \frac{0.0943}{1+\exp(0.503+2.58\ln x)}\right)$$

$$\text{where}\ \ IF = 1 - 0.5\left(1 - \frac{1}{1+0.00076x^{2.8}}\right)$$

IF=Inhalable fraction: fraction that would reach the nose or mouth

x *in* μm

ICRP: International Commission on Radiological Protection



Predicted total respiratory deposition at three levels of exercise based on ICRP deposition model. Average data for males and females. Inset does not include the effect of inhalability

3) Regional Deposition

Head region

- *Sedimentation/impaction : dominant*

$$DF_{HA} = IF\left(\frac{1}{1+\exp(6.84+1.183\ln x)} + \frac{1}{1+\exp(0.924-1.885\ln x)}\right)$$

Tracheobronchiole region

- *Sedimentation/impaction/diffusion : dominant*
- *Significant mixing of inhaled air with reserve air*

$$DF_{TB}=\left(\frac{0.00352}{x}\right)[\exp(-0.234(\ln x+3.40)^2)+63.9\exp(-0.819(\ln x-1.61)^2)]$$

<u>*Alveolar region*</u>

- *Gas exchange by molecular diffusion*
- *Sedimentation from trapped reserve air*

$$DF_{AL}=\left(\frac{0.0155}{x}\right)[\exp(-0.416(\ln x+2.84)^2)+19.11\exp(-0.482(\ln x-1.362)^2)]$$

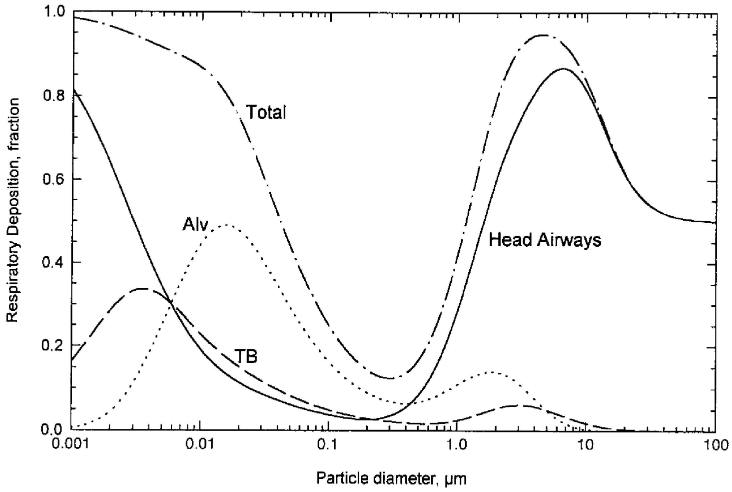
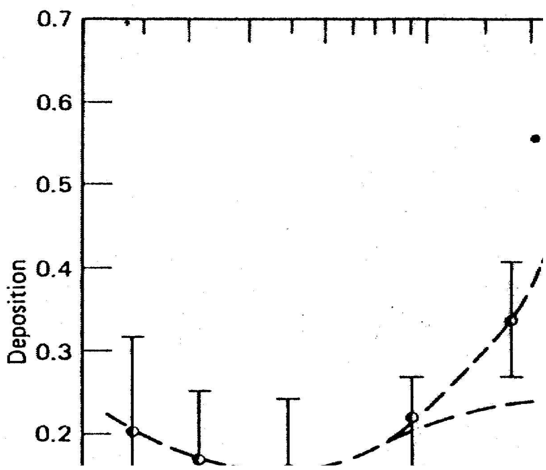


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.



For calculation of DF

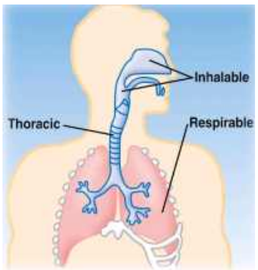
see http://aerosol.ees.ufl.edu/respiratory/section07.html

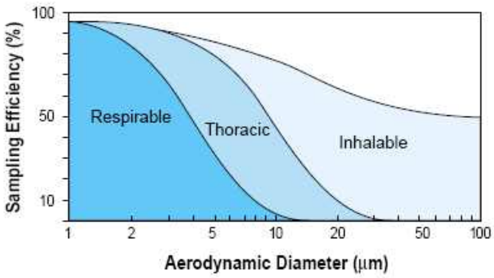
(3) Inhalable and Respirable Fraction

Inhalable fraction : fraction that would reach the nose or mouth

Respirable fraction : fraction that would reach the alveolar region

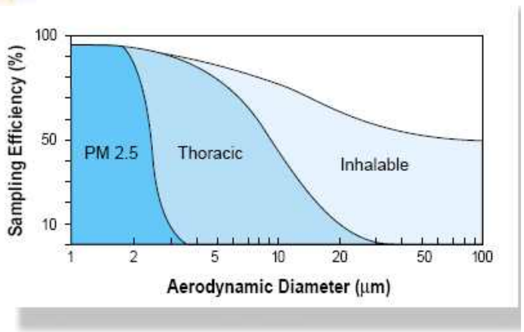
Thoracic fraction : fraction that would reach the tracheobronchial region





Conventional curves as agreed upon by ISO, ACGIH and CEN for the inhalable, thoracic and respirable fractions (1993/94).

- Respirable fraction: 50% cut-off at 4 μm (Stage 1)
- Thoracic fraction: 50% cut-off at 10 μm (Stages 1+2)
- Inhalable fraction: 50% efficiency at 100 μm (Stages 1+2+3)



- PM 2.5: 50% cut-off at 2.5 μm Curve defined by the U.S. EPA/1997 (Stage 1)
- Thoracic fraction: 50% cut-off at 10 μm (Stages 1+2)
- Inhalable fraction: 50% efficiency at 100 μm (Stages 1+2+3)

Example.

크기가 0.5um인 입자의 DF 값을 계산해 보자.

$$x := 0.5$$

$$IF := 1 - 0.5\left(1 - \frac{1}{1 + 0.00076x^{2.8}}\right) = 1$$

$$DF := IF\cdot\left(0.0587 + \frac{0.911}{1 + \exp(4.77 + 1.485\ln(x))} + \frac{0.0943}{1 + \exp(0.503 + 2.58\ln(x))}\right) = 0.154$$

$$DFHA := IF\cdot\left(\frac{1}{1 + \exp(6.84 + 1.183\ln(x))} + \frac{1}{1 + \exp(0.924 - 1.885\ln(x))}\right) = 0.099$$

$$DFTB := \frac{0.00352}{x}\left[\exp\left[-0.234(\ln(x) + 3.40)^2\right] + 63.9\exp\left[-0.819(\ln(x) - 1.61)^2\right]\right] = 7.107\times10^{-3}$$

$$DFAL := \frac{0.0155}{x}\left[\exp\left[-0.416(\ln(x) + 2.84)^2\right] + 19.11\exp\left[-0.482(\ln(x) - 1.362)^2\right]\right] = 0.082$$