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THEORIES OF ELECTROSTATIC LUNG DEPOSITION OF INHALED AEROSOLS

C. P. YU

Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Amherst, NY 14260, U.S.A.

Abstract—Most airborne dust particles in the atmosphere of an industrial workplace are electrically charged. The electric charges carried by these particles are found to increase the amount of inhaled particles deposited in the lung. In this paper, the physics of charged particle deposition is reviewed. It is shown that for environmental aerosols with particle concentrations below 10^5 particles cm^{-3}, the electrostatic image force acting on the particle due to particle-wall interaction is responsible for the observed deposition enhancement. An expression for deposition efficiency by the image force is derived and is used for a deposition calculation in the lung. Comparisons with available total deposition data in humans show very good agreement.

INTRODUCTION

IT HAS BEEN recently observed that most airborne dust particles in the atmosphere of an industrial workplace are electrically charged to levels above Boltzmann equilibrium (JOHNSTON *et al.*, 1985). The electric charges carried by these particles can influence the deposition of inhaled particles in the lungs. Experimental studies in a hollow lung cast (CHAN *et al.*, 1978) and *in vivo* experiments in humans (MELANDRI *et al.*, 1977; TARRONI *et al.*, 1980; MELANDRI *et al.*, 1983) and animals (FRASER, 1966; VINCENT *et al.*, 1981; FERIN *et al.* 1983; JONES *et al.*, 1983) have all shown a significant increase in deposition due to the particle charge. In this paper, the fundamental physics of charged particle deposition is reviewed. A computational model is also developed to predict the amount and site of deposition in the human respiratory tract under various conditions.

PHYSICS OF DEPOSITION

The physics of charged-particle deposition for spherical particles was previously reviewed by JOHN (1980). Consider an aerosol particle carrying charge q in the presence of an electric field E. The electrical force qE acting on the particle will cause the particle to move and a final velocity $v = BqE$ will be attained by the particle when the viscous drag force on the particle becomes equal to the electrical force, where B is the particle mechanical mobility. For a spherical particle of diameter d, B is found to be

$$B = \frac{C}{3\pi\eta d}, \quad (1)$$

where η is the viscosity of air, C is the slip correction factor.

There are two electrical forces which cause particles to deposit on the surface of an enclosure. One is the image force due to the interaction between a particle and the wall.

The other is the space charge force due to the mutual repulsion between particles with like charge. While the image force is a single particle effect, the space charge force depends upon the particle concentration in the system. To determine which one of these forces is important in affecting lung deposition, we shall first examine inter-particle distance in relation to airway sizes. For an aerosol consisting of uniformly distributed particles in space at a number concentration $N = 10^5$ particles cm^{-3}, the inter-particle distance $\lambda = N^{-1/3} = 0.021$ cm. This distance is less than the smallest airway diameter in the human lung (see Table 1). Consequently, at such concentrations or greater we expect multi-particle interactions to be present in all airways. However, as will be seen below, a detailed analysis of deposition efficiency in an airway shows that only the image force is the predominantly controlling force for deposition at this concentration level, because the amount of deposition in an airway depends not only upon the number concentration of particles but also upon the residence time of particles in the airway.

Consider a system of unipolarly charged particles of same sign suspended in the air within a cylindrical cavity of radius R. The particles are assumed to have uniform size, each carrying a charge q, and the initial number concentration is N. Owing to mutual particle repulsion, the particles will be dispersed radially and collected by the wall. It has been previously shown (YU, 1977) that particle number concentration $\bar{N}$ in the cylinder will remain uniform, but it will decrease with time t according to the relation

TABLE 1. VALUES OF α AT DIFFERENT AIRWAY GENERATIONS FOR 1 μm AEROSOL PARTICLES EACH CARRYING 100 ELEMENTARY CHARGES BREATHED INTO A WEIBEL'S LUNG AT 1000 cm^3 TIDAL VOLUME AND 15 RESPIRATIONS MIN^{-1}. (α indicates the ratio of deposition efficiency by the space charge force to the image force.)

Generation No.	τ_e	R (cm)	α	
			$N = 10^5$ cm^{-3}	$N = 10^7$ cm^{-3}
0	0.992×10^{-9}	0.90	0.502	50.2
1	1.168×10^{-9}	0.61	0.174	17.4
2	1.368×10^{-9}	0.44	0.0727	7.27
3	1.616×10^{-9}	0.28	0.0209	2.09
4	6.760×10^{-9}	0.225	0.0282	2.82
5	1.456×10^{-8}	0.175	0.0221	2.21
6	3.080×10^{-8}	0.140	0.0186	1.86
7	6.320×10^{-8}	0.115	0.0167	1.67
8	1.312×10^{-7}	0.093	0.0144	1.44
9	2.680×10^{-7}	0.077	0.0131	1.31
10	5.392×10^{-7}	0.065	0.0126	1.26
11	1.096×10^{-6}	0.0545	0.0119	1.19
12	2.128×10^{-6}	0.0475	0.0122	1.22
13	4.024×10^{-6}	0.041	0.0121	1.21
14	7.616×10^{-6}	0.037	0.0137	1.37
15	1.480×10^{-5}	0.033	0.0150	1.50
16	2.688×10^{-5}	0.030	0.0167	1.67
17	5.096×10^{-5}	0.027	0.0187	1.87
18	0.864×10^{-4}	0.025	0.0211	2.11
19	1.576×10^{-4}	0.0235	0.0262	2.62
20	2.912×10^{-4}	0.0225	0.0346	3.46
21	5.120×10^{-4}	0.0215	0.0440	4.40
22	0.896×10^{-3}	0.0205	0.0554	5.54
23	1.520×10^{-3}	0.0205	0.0788	7.88

$$\frac{\bar{N}}{N}=\frac{1}{1+4\pi NR^3\tau_e}, \tag{2}$$

where τ_e is a dimensionless time, defined by

$$\tau_e=\frac{Bq^2t}{4\pi\varepsilon_0 R^3}. \tag{3}$$

Using equation (2), the deposition efficiency, T_s^*, due to the space charge force is then found to be

$$T_s^*=\frac{1}{\pi R^2}\int_0^R\left(1-\frac{\bar{N}}{N}\right)2\pi r\mathrm{d}r$$

$$=\frac{4\pi NR^3\tau_e}{1+4\pi NR^3\tau_e}. \tag{4}$$

For $4\pi NR^3\tau_e \ll 1$, we obtain

$$T_s^*=4\pi NR^3\tau_e. \tag{5}$$

The deposition efficiency due to the image force can be derived in the following manner: assuming that the wall is conducting, the image force on a particle at a distance r from the axis is (YU, 1977)

$$F=\frac{q^2r^2}{16\pi R^2\varepsilon_0(R-r)^2}. \tag{6}$$

Under the action of this force, the particle is drifted towards the wall with a velocity

$$v=\frac{\mathrm{d}r}{\mathrm{d}t}=BF. \tag{7}$$

From equation (7), YU (1977) has found deposition efficiency T_i^* due to the image force in the following form

$$T_i^*=1-x^2, \tag{8}$$

where x is a parameter related to τ_e, such that

$$\tau_e=4(x^{-1}-2\ln x-x). \tag{9}$$

For $\tau_e \ll 1$, a simplified result was obtained by PICH (1978) to give

$$T_i^*=(6\,\tau_e)^{\frac{1}{2}} \tag{10}$$

Let α be the ratio of T_s^* to T_i^*, then from equations (5) and (10) we obtain

$$\alpha=\left(\frac{32}{3}\right)^{\frac{1}{2}}\pi\,NR^3\,\tau_e^{\frac{1}{2}} \tag{11}$$

It is obvious that when $\alpha \gg 1$ deposition is contributed predominantly by the space charge force whereas for $\alpha \ll 1$ the major force for deposition is the image force. To obtain the values of α, we consider the case in which an aerosol of 1 μm particle diameter and 100 elementary charges per particle is breathed into a WEIBEL's lung

(1963) at 1000 cm^3 tidal volume and 15 respirations per minute. Table 1 shows the values of α as a function of airway generation number. It is seen that for $N = 10^5$ particles cm^{-3}, α is very small compared with unity everywhere in the lung and its value exceeds unity when $N = 10^7$ particles cm^{-3}. Since most environmental aerosols have relatively low number concentrations, we conclude that the image force acting on the charged particle is the predominant mechanism responsible for the deposition enhancement in the lung. This is the case, even when aerosol carries both signs of charge. In this paper, we shall only consider deposition due to such force.

Depending upon the particle size and location in the lung, deposition of charged particles is also caused by conventional mechanisms such as impaction, sedimentation and diffusion. Deposition efficiencies in an airway due to the combined action of the image force and one of the conventional mechanisms have been worked out for several cases (Yu and Chandra, 1977; Thiagarajan and Yu, 1979; Diu and Yu, 1980; Ingham, 1981). Typically, one finds that the image force contributes significantly to deposition only when the particles charge reaches an appreciable level.

Consider, for example, the case of a horizontal conducting cylinder of radius R, in which a charged aerosol of particle diameter d, mass density ρ_p and charge q is allowed to settle under gravity g. In this case, the particle is subjected to the vector addition of the image force and the gravity force, but the ratio of these two forces has the following order of magnitude:

$$\gamma = \frac{3q^2}{8\mu^2 \varepsilon_0 \rho_p g R^2 d^3}. \qquad (12)$$

Let the deposition efficiency by the combined mechanisms of the image force and gravity be T^*_{ig} and the deposition efficiency by gravity alone be T^*_g. The increment of deposition efficiency ΔT^*_i defined as

$$\Delta T^* = (T^*_{ig} - T^*_g)/(1 - T^*_g) \qquad (13)$$

is found to be a function of γ and τ_s (Luke *et al.*, 1985). τ_s is another dimensionless particle residence time derived from the particle settling velocity, $v_s = \pi \rho g d^3/(6B)$ such that $\tau_s = v_s t/(2R)$.

It is obvious from geometrical considerations that at $\tau_s = 1$, all the particles in the cylinder are deposited by settling ($T^*_g = 1$).

Figure 1 shows the result of ΔT^* versus γ at $\tau_s = 0.2$, which is approximately the value of τ_s for the case in which an aerosol of 1 μm diameter and unit density deposits in the lung by settling under the normal breathing condition. The curve for ΔT^* shown in Fig. 1 can be approximated by a dotted straight line which intersects the γ axis at $\gamma = \gamma_c \cong 10^{-3}$. Hence, for $\gamma < 10^{-3}$, ΔT^* is very small and T^*_{ig} is very small and T^*_{ig} is nearly equal to T^*_g. If we take $d = 1$ μm and $R = 0.02$ cm as the radius of the alveolar duct, we obtain a value of $q = q_c \sim 54$ elementary charges from equation (12). Thus, for $q < q_c$, the particle charge has a minor effect on deposition, and the deposition in lung is governed by the conventional mechanisms. This agrees very well with experimental observation by Tarroni *et al.* (1980) and Melandri *et al.* (1983).

Equation (12) also leads to two useful relationships of q_c at constant γ_c. These are: for constant R,

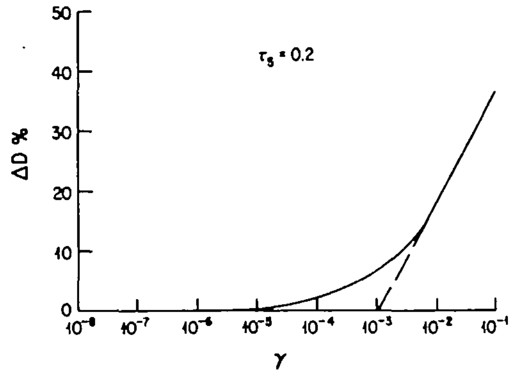

FIG. 1. ΔT^* vs γ for $\tau_s = 0.2$. The solid curve is the exact solution and the dotted line is the approximate result.

$$\frac{q_{c1}}{q_{c2}} = \left(\frac{\rho_{p1} d_1^3}{\rho_{p2} d_2^3}\right)^{1/2} \tag{14}$$

and for constant ρ_p and d,

$$\frac{q_{c1}}{q_{c2}} = \frac{R_1}{R_2}. \tag{15}$$

DEPOSITION MODEL

The deposition model of inhaled particles in the human respiratory tract previously developed for neutral particles (YU and DIU, 1983) is extended to include the effect of the image force on the particle. Because the particle is acted on by the vector sum of many forces, the determination of an exact expression for deposition efficiency in an airway would be very difficult. To simplify the analysis, we assume that the combined deposition efficiency for charged particles T can be written as the superposition of T_0 and T_i^*, i.e.

$$T = T_0 + T_i^*, \tag{16}$$

where T_0 is the efficiency of particle deposition of neutral particles due to conventional mechanisms (impaction, sedimentation and diffusion), and T_i^* is the contribution by particle charge due to the image force. In view of the result we obtained in Fig. 1, we may write

$$T_i^* = \left(\frac{Bl}{\pi \varepsilon_0 R^3 u_0}\right)^{1/2} (q - q_c), \tag{17}$$

where l is the airway length and u_0 is the mean velocity of the aerosol flow. Equation (17) differs from equation (10) because of the use of a parabolic velocity profile for the aerosol flow. In the small airways in which the effect of the image force is expected to be important, the parabolic velocity profile is a better description of the flow field.

Figure 2 shows the calculated increment of total deposition ΔT versus $|q/e|$ for unit density particles of diameters 0.3, 0.6 and 1.0 μm. The calculation was made for a

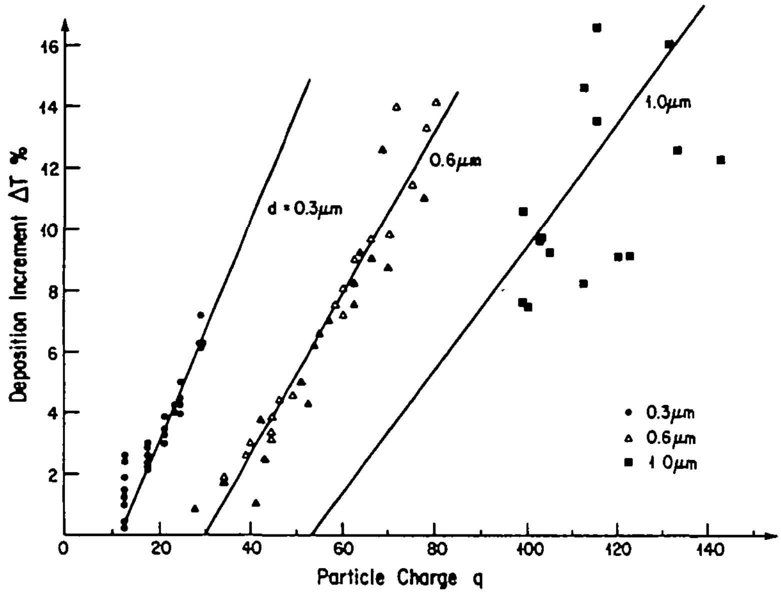

FIG. 2. ΔT vs Particles charge $|q/e|$ for three particle diameters at 0.3, 0.6 and 1.0 μm ($\rho_p = 1$ g cm^{-3}), the experimental data are by TARRONI *et al.* (1980) and MELANDRI *et al.* (1983). The calculated results are shown by solid lines.

WEIBEL (1963) lung of 3000 cm^3 initial volume, breathing through the mouth at 1000 cm^3 tidal volume and 15 respirations per minute without pause. The quantity ΔT is defined previously by TARRONI *et al.* (1980) and has the form

$$\Delta T = \frac{T - T_0}{1 - T_0}, \tag{18}$$

where T is the total deposition of charged particles and T_0 is the deposition for the same particles without charge.

In the calculation of ΔT, we have chosen $q_c = 54$ elementary charges for $d = 1.0$ μm ($\rho_p = 1$ g cm^{-3}) from the result obtained earlier. In principle, q_c can have different values at different airway generations because of the differences in residence time and airway diameter. Such a refinement has been ignored, because most deposition takes place in the alveolar region of the lung at this particle size. Using this simplification, we also obtain from equation (5) $|q_c/e| = 12$ and 30 for $d = 0.3$ and 0.6 μm, respectively. Figure 2 shows the calculated values of ΔT and they agree very well with the experimental data by TARRONI *et al.* (1980) and MELANDRI *et al.* (1983). For each particle size, ΔT increases linearly with q.

In Fig. 3, deposition increments as a function of charge for these three particle diameters are plotted for the tracheobronchial and alveolar regions of the lung. These increments are defined as the differences in deposition between charged and neutral particles in those regions divided by $1 - T_0$, so that the sum of the two increments gives the value of ΔT. The results show that charge-enhanced deposition takes place principally in the alveolar region. A more detailed illustration of the deposition site for

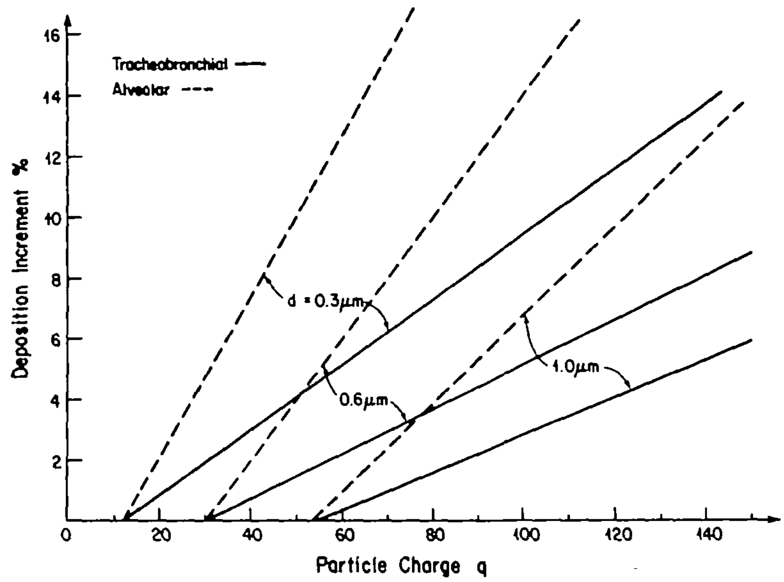

FIG. 3. Deposition increments in the tracheobronchial and alveolar regions versus particle charge $|q/e|$. The definition of deposition increment in each region is given in the text.

charged particles is shown in Fig. 4 for 0.6 μm particles at several levels of charge. At large particle diameter and high flowrate, however, CHAN *et al.* (1978) and CHAN and YU (1982) have observed a significant deposition enhancement in the tracheobronchial region for charged particles. In this case, the alveolar deposition for charged particles may become lower than the uncharged equivalents.

MELANDRI *et al.* (1983) investigated the effect of lung volume or functional residual

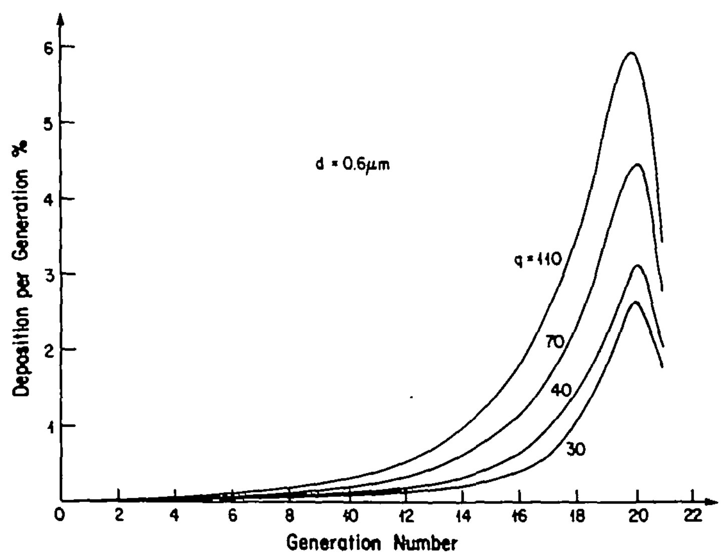

FIG. 4. Deposition profiles of 0.6 μm particles at various particle charge levels.

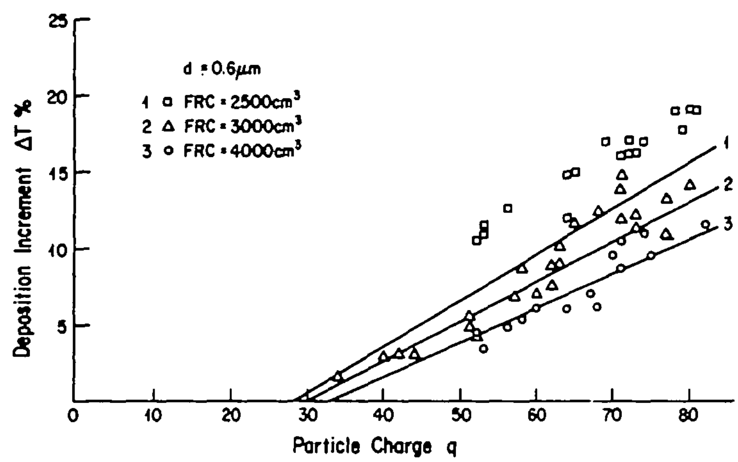

FIG. 5. ΔT vs particle charge q for several lung volumes. The experimental data are by MELANDRI *et al.* (1983). The calculated results are shown by solid lines.

capacity (FRC) on charged particle deposition. For smaller lung volumes of the same structure, the airway radii are smaller. From equations (9) and (11) we expect to have lower values of q_c and higher values of T_i^*. Consequently, for smaller lung volumes, the effect of particle charge on ΔT is larger. This observation is confirmed both experimentally and theoretically as shown in Fig. 5.

CONCLUSION

It has been shown from aerosol physics that particle charge can lead to a significant increase in aerosol deposition in the lung. For environmental aerosols at low concentrations ($N < 10^5$ particles cm^{-3}), the deposition increase is primarily due to the presence of the image force acting on the particle and the sign of charge has no effect on deposition. Because the particle charge level is moderate in most cases, the conventional mechanisms control the amount of deposition. As a consequence, there exists a charge level q_c for each particle size below which the effect of particle charge on deposition is unimportant. In this paper, we have obtained the values of q_c for particles in the size range where deposition is dominated by sedimentation. Further research is needed to determine q_c for other particle size ranges where diffusion or impaction deposition is most important.

It should also be noted that the theory presented above applies only to spherical, compact or isometric particles. For charged fibrous particles, such as asbestos dust, interaction between the particle and the airway wall may give rise to both a force and a torque on the particle. The net effects are not only a movement of the particle towards the wall but also a change in the particle orientation with respect to the flow field. Consequently, impaction, sedimentation and interception depositions of the particles are affected. Recent experimental data of JOHNSTON *et al.* (1985) and JONES *et al.* (1983) have shown that the electric charge carried by the asbestos dust will increase its deposition significantly in rat lungs. Quantitative theories are yet to be developed to explain this result.

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REFERENCES

CHAN, T. L., LIPPMANN, M., COHEN, V. R. and SCHLESINGER, R. B. (1978) Effect of electrostatic charges on particle deposition in a hollow cast of human larnyx-tracheobronchial tree. *J. Aerosol Sci.* **9**, 463–468.

CHAN, T. L. and YU, C. P. (1982) Charge effects on particle deposition in the human tracheobronchial tree. *Ann. occup. Hyg.* **26**, 65–75.

DIU, C. K. and YU, C. P. (1980) Deposition from charged aerosol flows through a pipe bend. *J. Aerosol Sci.* **11**, 397–402.

FERIN, J., MERCER, T. T. and LEACH, L. J. (1983) The effect of aerosol charge on the deposition and clearance of TiO_2 particles in rats. *Environ. Res.* **31**, 148–151.

FRASER, D. A. (1966) The deposition of unipolar charged particles in the lungs of animals. *Arch. environ. Hlth* **2**, 535–543.

INGHAM, D. B. (1981) Precipitation of charged particles in human airways. *J. Aerosol. Sci.* **12**, 131–135.

JOHN, W. (1980) Particle charge effects. Generation of Aerosols (Edited by WILLEKE, K.), Chapter 6, pp. 141–151. Ann Arbor Science, Ann Arbor, Missouri.

JOHNSTON, A. M., VINCENT, J. H. and JONES, A. D. (1985) Measurements of electric charge for workplace aerosols. *Ann. occup. Hyg.* **29**, 271–284.

JONES, A. D., JOHNSTON, A. M. and VINCENT, J. H. (1983) Static electrification of airborne asbestos dust. Aerosols in the Mining and Industrial Work Environments (Edited by MARPLE, V. A. and LIU, B. Y. H.), Chapter 46, pp. 613–632. Ann Arbor Science, Ann Arbor, Missouri.

LUKE, G. D., ASGHARIAN, B. and YU, C. P. (1985) Sedimentation of a charged aerosol inside cylindrical and spherical enclosures. International Symposium workshop on Particulate and Multi-phase Processes, 22-26 April 1985, Miami Beach, Florida, U.S.A.

MELANDRI, C., PRODI, V., TARRONI, G., FORMIGNANI, M., DE ZAIACOMO, T., BOMPANE, G. F. and MAESTRI, G. (1977) On the deposition of unipolar charged particles in the human respiratory tract. In: *Inhaled Particles IV* (Edited by WALTON, W. H.), pp. 193–200. Pergamon Press, Oxford.

MELANDRI, C., TARRONI, G., PRODI, V., DE ZAIACOMO, T., FORMIGNANI, M. and LOMBARDI, C. C. (1983) Deposition of charged particles in the human airways. *J. Aerosol Sci.* **14**, 657–669.

PICH, J. (1978) Comments on the paper: C. P. Yu's Precipitation of unipolarly charged particles in cylindrical and spherical vessels. *J. Aerosol Sci.* **9**, 275–278.

TARRONI, G., MELANDRI, C., PRODI, V., DE ZAIACOMO, T., FORMIGNANI, M. and BASSI, P. (1980) An indication on the biological variability of aerosol total deposition in humans. *Am. ind. Hyg. Assoc. J.* **41**, 826–831.

THIAGARAJAN, V. and YU, C. P. (1979) Sedimentation from charged aerosol flows in parallel-plate and cylindrical channels. *J. Aerosol Sci.* **10**, 405–410.

VINCENT, J. H., JOHNSTON, W. B., JONES, A. D. and JOHNSTON, A. M. (1981) Static electrification of airborne asbestos: a study of its cause, assessment and effects of airborne asbestos: a study of its cause, assessment and effects on deposition in the lungs of rats. *Am ind. Hyg. Assoc. J.* **42**, 711–721.

WEIBEL, E. R. (1963) *Morphometry of the Human Lung*. Academic Press, New York.

YU, C. P. (1977) Precipitation of charged particles in cylindrical and spherical vessels. *J. Aerosol Sci.* **8**, 237–241.

YU, C. P. and CHANDRA, K. (1977) Precipitation of submicron charged particles in human lung airways. *Bull. Math. Biol.* **39**, 471–478.

YU, C. P. and DIU, C. K. (1983) Total and regional deposition of inhaled aerosols in humans. *J. Aerosol Sci.* **14**, 599–609.

YU, C. P., ASGHARIAN, B. and LUKE, G. (1984) Sedimentation of charged particles in cylinders and spheres. Manuscript to be submitted to *Aerosol Sci. Tech.*