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Airborne Particle Deposition in Cleanrooms:

Deposition Mechanisms

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Airborne particle deposition in cleanrooms: Deposition mechanisms

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Abstract

This article discusses the mechanisms of particle deposition onto cleanroom surfaces. The main mechanism for particles above about 0.5µm is gravitational settling. Turbulent deposition and electrostatic attraction can also occur at all particle sizes, and for particles below 0.5µm Brownian diffusion is important. Measurements of particle deposition rates (PDRs) were made of particles ≥10µm on witness plates orientated in different directions and exposed in different ventilation conditions, and it was concluded that over 80% of particles were deposited by gravitational sedimentation, and probably more than half of the remainder by turbulent deposition.

Introduction

Cleanrooms are classified by the airborne particle concentration according to the method given in ISO 14644-1:1999. However, the concentration of airborne particles does not directly measure the likely amount of surface and product contamination, and the best method is by determining the particle deposition rate (PDR) onto a surface adjacent to the product. Discussion of this will be contained in a further article.

There has been a considerable amount of research into the behaviour of particles in air and their deposition onto surfaces, as demonstrated in the publications of Hinds (1999) and Lui (2010). Investigations of particle deposition in cleanrooms have also been reported but these have been mainly concerned with deposition of small particles (≤1µm) during semiconductor manufacturing (Lui and Ann, 1987; Wu et al, 1989; Copper et al, 1990; Pui et al 1990). Also, much of the published information on particle deposition in cleanrooms has been theoretical, and the effect of turbulent deposition largely disregarded. This article reviews some of the published information relevant to surface deposition in a variety of cleanrooms, especially from larger particles (≥10µm), and reports on the results of an experimental investigation into the importance of different deposition mechanisms, including turbulent deposition.

Possible mechanisms of surface deposition of particles in cleanrooms

There are a number of mechanisms that cause airborne particles to deposit onto surfaces, although not all are important in cleanrooms. These deposition mechanisms are discussed in detail by Hinds (1999) and Liu (2010) and are: gravitational settling, turbulent deposition, electrostatic attraction, Brownian diffusion, impaction, interception, turbophoresis and thermophoresis.

The transfer of airborne particles to surfaces in cleanrooms can be considered in two stages. Airborne particles are transferred from the general area of a cleanroom to the layer of air next to a surface, and then transferred through the layer to the actual surface. As air passes over a surface, the surface drag slows the air velocity down so that it approaches zero at the surface. However, as the distance from the surface increases, the velocity increases until it reaches that of the general cleanroom area. The area next to the surface is known as the 'boundary layer' and the area outside that layer is known as the 'free flow' area. The thickness of the boundary layer in a ventilated room will be a few centimetres, but this varies. The transfer of particles from the free flow area to the boundary layer is mainly by (a) air movement and turbulence caused by mechanical ventilation, (b) gravity, and (c) Brownian diffusion. In addition, electrostatic forces will attract particles that are relatively close to a surface. When the particles reach the boundary layer they will be deposited onto the surface and retained. The particles can be deposited by one or more of the following mechanisms.

a. An important deposition mechanism is gravitational settling, where particles settle onto surfaces under the influence of gravity. This is less important with small particles, as they sediment slowly e.g. a 0.5µm spherical particle settles at about 0.0008 cm/s. However, deposition velocity increases in proportion to the square of the particle diameter, and with larger particles it is a dominant mechanism e.g. 5µm and 50µm spherical particles have a settling velocity of about 0.08 and 8 cm/s, respectively.

b. Turbulent deposition occurs when air turbulence deposits particles onto a surface and particles greater than about 1µm are deposited by their inertia. The greater the air turbulence, the more particles will deposit onto a surface.

c. Most airborne particles have electrical charges on their surface, and are attracted to oppositely-charged surfaces. This mechanism can be a dominant force in some situations, but cleanrooms are generally designed and constructed to avoid large electrostatic charges on critical surfaces, so as to minimise the attraction of particles. Electrostatic charges are additionally minimised during manufacturing by electrically grounding materials and by the use of ionizers. Electrostatic attraction can be an important deposition mechanism but only in certain circumstances.

d. Small airborne particles below about 0.5µm are bombarded by air molecules and particles and this causes a random movement in the air known as Brownian motion, and the diffusion

of these particles through air allows them to collide with surfaces, where they are retained.

e. Impaction is an important mechanism in the removal of particles by air filters, and occurs when an airstream flows round surfaces, such as fibres in filter media. If the velocity is sufficiently high and the particles are of sufficient size and inertia, the particles will not move with the air stream but are thrown onto the surface, where they are retained.

f. Interception is another important mechanism in the removal of particles in air filters and occurs when airflow brings a particle very close to a surface, such as a filter media fibre, where they are attracted and retained.

g. Thermophoresis occurs when a surface is colder that the surrounding air. This deposition mechanism can be important in particles less than 0.5 µm, but the effect decreases as the particle size increases and there is little deposition of particles over 10µm. Cold surfaces are normally not found in cleanrooms and such a mechanism is unlikely to be important.

h. Turbophoresis occurs when turbulence pushes particles into areas of low turbulence, such as a boundary layer, and there is insufficient turbulence to push the particles out of the area.

Taking account of the air velocities, differential temperatures, and other prevalent conditions in cleanrooms, the conclusions that can be drawn are that the dominant deposition mechanisms in cleanrooms are likely to be a) gravitational deposition, b) turbulent deposition, and c), in certain conditions, electrostatic deposition. If particles are below 0.5µm, Brownian diffusion is also important, but owing to the larger particles studied in this article, this mechanism is not considered in further detail.

The rate of deposition of particles onto a surface is known as the particle deposition rate (PDR) and is calculated by means of Equation 1.

Equation 1

$$\text{PDR (no./dm}^2\text{/h)} = \frac{\text{number of particles deposited/dm}^2}{\text{time of deposition (hours)}}$$

The PDR is calculated as the number of particles that deposit onto a standard surface area in a standard time, and in this article the units are number/dm^2/h as this gives results close to actual counts found on witness plates. The PDR can be determined for discrete (also known as differential) sizes of particles, but as contamination problems in cleanrooms are normally caused by *all* particles over a stated size, it is the cumulative size that is normally measured in cleanrooms, and discussed in this article.

Experimental equipment and methodology

The cleanroom used in these experiments was a non-UDAF type with a floor size of 6m by 4.2m i.e. a floor area of 25m^2. The height of the wall was 2.7m, and the room volume 67.5m^3. HEPA-filtered air was normally supplied by nine fan-filter units in the ceiling, with each supplying 450m^3/h. This gave a total air supply of 4050m^3/h, and an air change of about 60 per hour. The cleanroom air was extracted at five grilles located on the walls at floor level. The differential pressure between the cleanroom and outside areas was maintained at 15 Pa.

To obtain a higher particle concentration than normal during the experiments, and ensure that the PDR was high enough for experiments to be completed in a reasonable time, only two of the fan/filter units were switched on. These gave a total air supply of 900m^3/h and air change rate of about 13 per hour. The air outlets of the fan-filters in the ceiling did not have air diffusers, and to assist the mixing of supply and cleanroom air, the location of the two active fan-filter units was about one third of the way along the length of the cleanroom, with the sampling location about two thirds.

Experiments were also carried out when all fan-filter units were switched off, and this condition was known as the 'unventilated' condition. Unidirectional airflow conditions were also investigated but, to obtain a high particle concentration, unventilated room air was used and directed by a table fan to the sampling location in a unidirectional manner.

To obtain similar types and size distribution to airborne particles normally found in a cleanroom, the cleanroom was occupied during the experiments by three people. To achieve a suitably-high concentration of particles, the people did not wear cleanroom clothing but their ordinary indoor clothing. The exception was the person who manipulated the witness plates, who wore a full set of cleanroom clothing and gloves, but only during the manipulation. The three people mainly sat and talked, worked with their computers, and occasionally walked about the room. They sat at the end of the cleanroom where the filtered air was supplied and the table fan located.

Clean glass witness plates of 12 cm diameter (with a measuring area of 49cm^2) were exposed in the cleanroom for approximately 90 minutes and, after exposure, the particles on the surface were immediately counted and sized. This was carried out automatically by means of a HE850 Particle Deposition Measurement (PDM) instrument (SAC, Netherlands), which used an image recognition method. The instrument counted the number of particles on the witness plates in the following cumulative sizes: ≥10µm; ≥25 µm; ≥40µm; ≥50µm and ≥100µm, with a definition accuracy of +/-5µm.

The area of the top surface of each particle was determined and the equivalent diameter of a spherical particle was calculated by means of the following equation:

Equation 2

$$\text{Equivalent particle diameter} = \sqrt{\frac{4A}{\pi}}$$

Where, A is the area of top surface of the particle.

The number of particles on the surface of the witness plate after exposure was counted, and the background count on the witness plate after cleaning was deducted. The PDR was then calculated as the number of particles deposited per dm^2 per hour.

Experimental investigations of particle deposition

An experiment was carried out in the cleanroom to ascertain the relative importance of the different particle deposition mechanisms by using witness plates orientated in different directions and in dissimilar ventilation conditions. Previous results obtained from a similar experiment carried out with microbe-carrying particles (MCPs) are also reported. Another experiment is reported in which the protective effect of one surface placed above another to reduce particle deposition was investigated.

Witness plate orientation study

Four clean witness plates were inserted into steel holders mounted on a 14 cm polycarbonate box shown in Figure 1. One witness plate was mounted horizontally on the top of the box and faced upwards, the second was on the bottom facing downwards, and the third and fourth were mounted vertically on the front and back of the box. The mounting box was suspended on metal stands and about 1m from the floor.

Three ventilation conditions were studied:

1. Unventilated cleanroom: the air supply to the cleanroom was switched off. However, the air was not completely 'still', as it was stirred when personnel moved, and the air intake and exhaust of the airborne particle counter and membrane sampler were within a metre of the witness plate holder.
2. Non-unidirectional airflow: the air change rate was set at 13 per hour.
3. Unidirectional airflow: the air in the unventilated cleanroom was blown in a unidirectional manner by a table fan at a velocity of 0.75m/s towards the box holder. This velocity was greater than normally found in unidirectional airflow but was necessary to overcome the disturbing effect of the downflow of the supply air from the two fan/filter units in the ceiling. One vertical witness plate directly faced the airflow and the other faced backwards.

The PDR of a range of particle sizes ≥10µm was determined for each ventilation condition, and this information will be given in a future article. However, shown in Figure 2 are the PDR values calculated as an average of the three ventilation conditions. Also given in Figure 2 are the PDR values for each cumulative size as a percentage of the total PDR. The latter graph allows the average size of particles (50% value) in the distribution to be ascertained. This is about 30µm, although it must be understood that this is the average value of the sizes measured above 10µm.

Table 1 shows the PDRs of particles ≥10µm obtained from the four witness plates orientated in different directions in the three ventilation conditions. Each result is the average of two tests.

It can be seen in Table 1 that substantially greater PDRs were obtained on the top plates. It can be assumed that particles on the top plates were deposited by all mechanisms, including gravity, but the other three plates had no gravitational deposition. Therefore, the proportion of non-gravitational deposition on each witness plates (other than the top ones) can be obtained by dividing a plate's PDR by the PDR on the corresponding top plate. These proportions are given in Table 1 as a percentage, and in parentheses. In the bottom row of Table 1, the average PDR and percentage of non-gravitational deposition is given for each ventilation condition. Excluding the unventilated condition, which would never be used in a cleanroom, an overall average percentage of non-gravitational deposition was also calculated. This was 18% and, therefore, the overall percentage of deposition by gravity by particles ≥10µm was 82%.

The witness plates were set up in different orientations not only to ascertain the importance of gravitational deposition but to obtain an indication of the importance of turbulent deposition. It can be seen in Table 1 that the average non-gravitational deposition in the unventilated cleanroom was 11%, with little variation caused by the orientation of the witness plates. Although the air in the unventilated cleanroom was not perfectly still, the particle deposition owing to turbulence must have been low, and any additional non-gravitational deposition found in the 13 air change/hour conditions was likely to have been caused by turbulence. Table 1 shows that the non-gravitational deposition in the non-UDAF ventilation condition was 22%, which was double that in the unventilated condition of 11%.

In UDAF conditions, the magnitude of the non-gravitation deposition was dependent on the orientation of the plate to the unidirectional airflow. When unidirectional airflow passes the cube holding the witness plates, the air flow and turbulence change. Figure 3 shows a CFD simulation of air flowing passing a cube of the same size and at the same velocity as that used during the experiments. The CFD simulation was obtained by use of ANSYS Fluent solver, assuming transient airflow

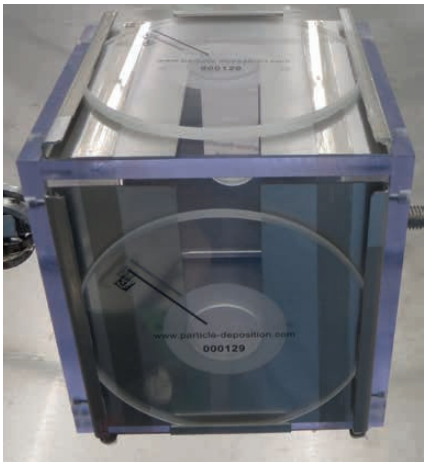

Figure 1: Box holder with witness plates as seen from the front

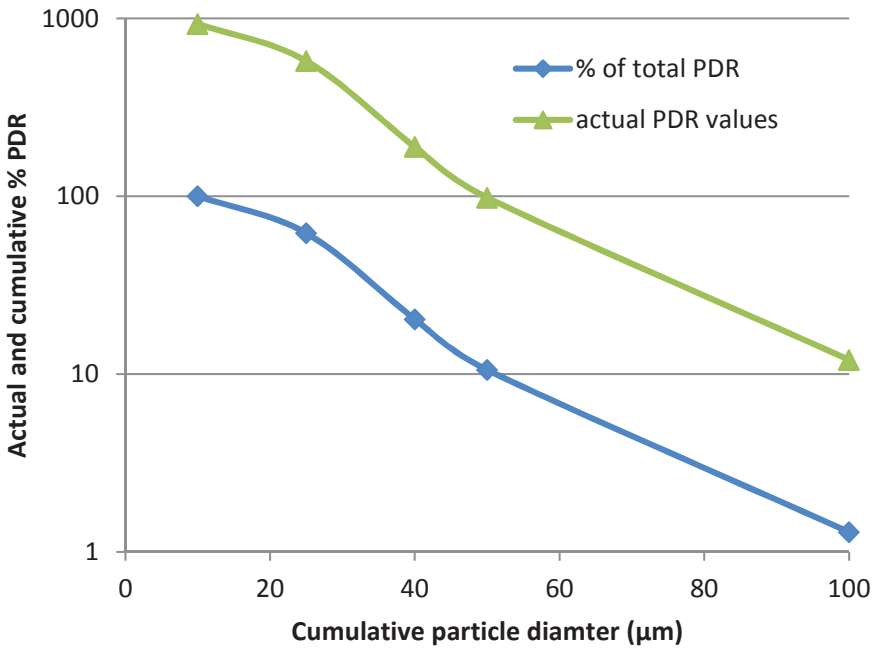

Figure 2: Distribution of actual values of the PDRs and percentages of the total PDR

Table 1: PDR (no./dm²/h) of particles ≥10 µm during different ventilation conditions

Orientation of plate	Ventilation condition		
	13 AC/h	unventilated	unidirectional
Top	612	874	1305
Bottom	168 (27%)	89 (11%)	108 (8%)
Front	106 (17%)	86 (10%)	166 (13%)
Back	132 (22%)	126 (14%)	263 (20%)
Average of non-gravitational deposition	135 (22%)	100 (11%)	179 (14%)

AC/h = air changes per hour

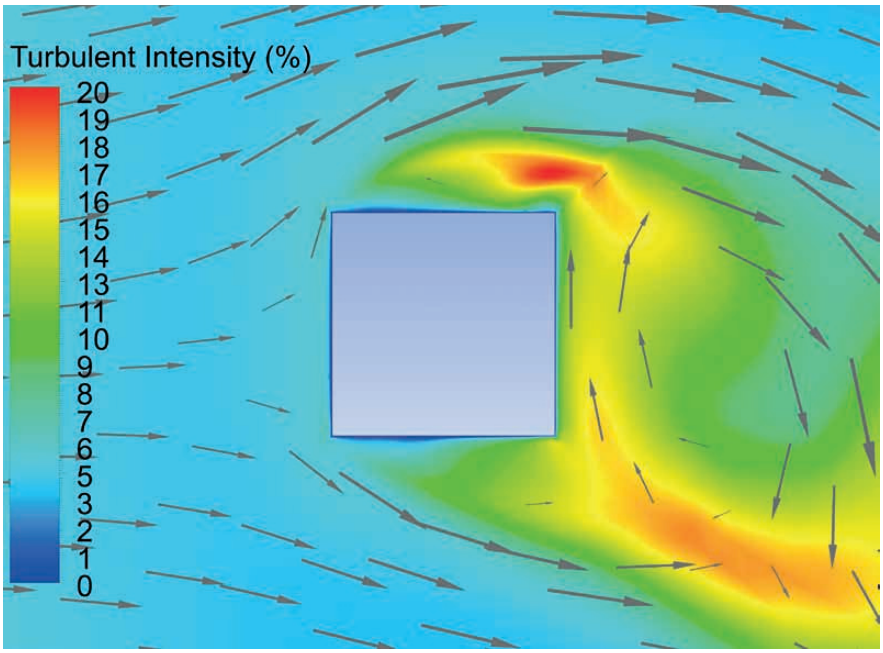

Figure 3: CFD simulation of airflow around cube

and using a SST k-ω turbulence model. The turbulent intensity of the air approaching the cube was set at 5%, and the intensity round the cube calculated and shown in Figure 3. It can be seen that the greatest turbulent intensity was in the rear of the cube, with lesser intensities at the side and front. These results can largely explain the differences in particle deposition around the cube that are given in Table 1, where it can be seen that the highest non-gravitational deposition was at the back of the cube (20%), less in the front (13%), and the least at the cube's sides (8%).

The results given in this section can be summarised, with respect to non-gravitational deposition, as follows: (a) there was a doubling of non-gravitational deposition in the 13 air changes per hour condition compared to the unventilated condition and, (b) a near-doubling in UDAF conditions in the area with the greatest turbulence at the rear of the cube. These results suggest that turbulent deposition may account for at least half of the non-gravitational deposition. The remaining deposition could also have been caused by turbulent deposition, or it could have been caused by other non-gravitational mechanisms, such as electrostatic attraction, and this possibility is now discussed.

Electrostatic deposition on the witness plates

The witness plates used in these experiments were made from glass. They were inserted into metal holders fitted with Teflon tape to avoid the glass coming into contact with the metal and being scratched. The metal holders were attached to a box made from polycarbonate plastic. Because of the electrical insulating properties of these materials, any electrostatic change on the witness plates would not be easily dissipated from the surface. Before being exposed to particle deposition, the plates were cleaned with a cleanroom wipe, which would produce an electrostatic surface charge. However, the handling of a witness plate during its mounting into the holder and the exposure to air might cause changes. Measurements were therefore made of the static field charge to ascertain the likely charge that would be present during the experiments.

The field voltage was measured by an Elektrofeldmeter EFM 022 at a distance of 20mm from the plate surface. The witness plates were wiped with a cleanroom wipe and inserted into the box holder and the field voltage measured. The charge varied, with a field voltage of between -300v and +500v.

Previous experiments on the deposition of airborne microbe-carrying particles

Similar experiments to those described in the previous section have been carried out on airborne microbe-carrying particles (MCPs) by Whyte (1986). Petri dishes of 140mm diameter containing nutrient agar were inserted into a holder and orientated in the same way as described in the previous section. They were then exposed to ventilation conditions similar to those previously described, namely, (a) still air, (b) air changes equivalent to 30 per hour, and (c) unidirectional airflow of 1.0 m/s. The Petri dishes were exposed to deposition from naturally-occurring MCPs dispersed by a person active in the room for several hours and, after incubation, the resulting microbial colonies were counted. The results were analysed in the same way as discussed in the previous section, and given in Table 2.

An important difference from the experiments with particles ≥10µm reported in the previous section was that MCPs were deposited onto nutrient agar, and not onto glass witness plates. Nutrient agar contains about 95% water, and would be expected to have no electrostatic charge. The charge was measured and the assumption shown to be correct.

The overall non-gravitational deposition on the Petri dishes was found to be 6%, i.e. 94% of the MCPs came from gravitational deposition. It can be seen in Table 2 that the average non-gravitational deposition in still

air, and in the 30 air changes per hour, was the same i.e. 5%. In the UDAF condition, the backward-facing plate had the greatest amount of deposition (15%), the forward-facing plates less (5%), and the downward-facing plates, the least (2%), showing the same trend as the experiments carried out with particles ≥10µm. These results showed that in these conditions, when electrostatic attraction is not present, the overall percentage of gravitational settling is greater (94%), and that most of the remaining deposition (6%) is likely to be accounted for by turbulent deposition. However, the size distribution of MCPs is smaller than the particles ≥10µm and this may account for a lesser amount of turbulent deposition. The sizes of the airborne MCPs were not measured, but it has been well established that MCPs in occupied and ventilated rooms are dispersed by people on skin and clothing particles. These MCPs have an average aerodynamic particle diameter of about 12 µm (Noble, Lidwell and Kingston, 1963), and Whyte et al (2012) have reported that the size distribution ranges from about <1 µm (with an occurrence of 1%) to >50 µm (with an occurrence of 5%). This MCP size distribution is smaller than of particles ≥10 µm, which are shown in Figure 2 to average about 30µm. However, the equivalent particle size as measured by the PDM instrument is based on a measurement of the surface area of the top of the particle and does not take account of the thinness of the flake-like skin particles. In addition, the size distributions of MCPs are measured as aerodynamic diameters, which will be affected by the flake-like shape of the particle and have slower deposition velocities, and therefore appear smaller than the size measured by the PDM. These two reasons will therefore account for at least part of the difference between the size distributions, although it is not clear if this explains the full difference.

Parallel witness plate study

Shown in Figure 4 is a photograph of the two metal holders used to hold two witness plates parallel to each other. The two witness plates were 10 cm apart and about 1 metre from the floor, with one plate placed exactly above the other. Tests were carried out with plates exposed for about 90 minutes in each of the three air movement conditions. In the case of unidirectional airflow, the air velocity passing between the plates was 0.5m/s.

The PDR of particles ≥10µm was measured on each plate in the three ventilation conditions and calculated as a percentage of the total PDR from both plates. These percentages, which are given in Table 3, are all similar and close to 50%.

Discussions and conclusions

The mechanisms of airborne deposition of particles onto surfaces have been reported in the scientific literature and reviewed in the introduction to this article. It was concluded that in cleanrooms the most important mechanisms were gravitational settling, turbulent deposition and, in certain circumstances, electrostatic attraction. Brownian diffusion was also important, but only for particles of a size less than about 0.5µm. Measurements of the PDR on witness plates orientated in different directions and in three air movement conditions were carried out to help to resolve the question of the relative importance of these deposition mechanisms.

The particle deposition rates (PDRs) of particles ≥10µm were measured on witness plates exposed in four different directions in a cleanroom. Most of the deposition occurred on the upward-facing plates, and gravitational deposition account for 82% of the overall deposition. The deposition mechanisms of the remaining 18% of particles deposited by non-gravitational means were likely to be turbulent deposition or electrostatic attraction, and these possibilities were investigated.

Experiments carried out into the deposition of particles ≥10µm onto witness plates orientated in different directions and airflow conditions suggested that at least half of the 18% of the non-gravitational deposition was caused by turbulent deposition. This finding was supported by previously-reported experiments carried out on microbe-carrying particles using nutrient agar plates, and therefore depositing onto surfaces free of electrostatic charge. In that situation only 6% was non-gravitational but differences in the size distribution could be a contributing cause.

The electrostatic field charge on the glass witness plates used in the particle

Table 2: Number of MCPs deposited on nutrient agar plates

Orientation of plate	Ventilation conditions		
	30AC/h	unventilated	unidirectional
Top	229	150	158
Bottom	5 (2%)	9 (6%)	3 (2%)
Front	14 (6%)	9 (6%)	8 (5%)
Back	12 (5%)	6 (4%)	24 (15%)
Average of non gravitational deposition	5%	5%	7%

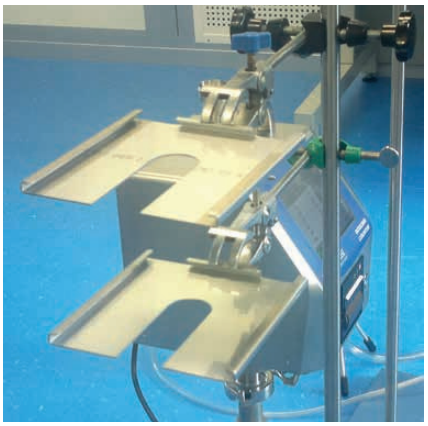

Figure 4: Two parallel witness plate holders with an airborne particle counter in the background

Table 3: Percentage of particles ≥ 10µm deposited on the lower or upper plates

Cumulative particle size ≥10 µm	Ventilation condition					
	13 AC/h		No ventilation		Unidirectional	
	Lower	Upper	Lower	Upper	Lower	Upper
	51.9%	48.1%	49.5%	50.5%	51.3%	48.7%

experiments was measured at 20mm from the surface and found to range from -300v to +500v. This charge would attract particles and could account for some of the non-gravitational deposition, although the exact proportion was uncertain.

Experiments carried out on the deposition of particles on parallel plates gave an additional insight into particle deposition in cleanrooms. As gravitational deposition was the dominant mechanism in these experiments, it might be expected that a plate located directly above another plate, and 10cm apart, would protect the lower plate from particle deposition. This method of protection is used in cleanrooms to minimise surface contamination but it is clear that it cannot be relied upon. The result was a little surprising but can be explained. Air turbulence above the top and bottom plates should be similar and give a similar amount of turbulent deposition. Any electrostatic deposition should also be the same. Cleanroom air passing between the two plates will have a turbulent movement in which the particles will move up and down but these movements should balance each other out, and the downward gravitational sedimentation of particles should largely determine the PDR. It should, therefore, be expected that the two parallel plates will have similar PDRs. It can be anticipated that in cleanroom areas where deposition might not be thought to occur but room air can flow in and out, deposition will occur and the PDR will be similar to that found in the general cleanroom area.

Further investigations into the PDR in a cleanroom will be reported in a further article, along with the relationship between the PDR and airborne particle concentration. Methods that can be used to calculate airborne particle contamination of products, and the cleanliness class of cleanroom required for an acceptable amount of product contamination, will also be discussed.

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Koos Agricola is an Applied Physicist and has worked in R & D at Océ Technologies, a Canon Company, since 1986. His responsibilities include contamination control in cleanrooms for the manufacture of critical parts. In his spare time, Koos assists Technology of Sense b.v. as a Contamination Control Specialist. Koos is secretary of the VCCN (Dutch Contamination Control Society), ICCCS (International Confederation of Contamination Control Societies) and ICEB (International Cleanroom Education Board) and a technical expert on ISO/TC 209 Working Groups 1, 3, 4, 11, 12 and 13 and CEN/TC243 Working Group 5. Koos is treasurer of the CTCB-I (Cleanroom Testing and Certification Board – International) and regularly teaches various cleanroom technology subjects.

Martin Derks is a skilled electronics engineer and has worked as calibration engineer and contamination control equipment expert for Philips Semiconductor where his role included responsibilities for cleanrooms, contamination control equipment for cleanrooms, maintenance and service. After 10 years as sales engineer for a manufacturer of particle counters, Martin became managing director for the European Headquarters of Lighthouse Worldwide Solutions. This company supplies contamination monitors for various cleanroom industries, like pharma, medical and semiconductor.