

THE PREDICTION OF PARTICLE CONCENTRATION IN AIR SUPPLIED TO CLEANROOMS.



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Summary

The design of the air supply system for a cleanroom and the choice of high efficiency air filters is often based on experience and rarely on calculation. This paper describes two methods that can be used to estimate the airborne standard of a cleanroom in the 'as built' condition. The accuracy of these models was verified.

Design Requirements.

The cleanroom to be built was a vertical unidirectional airflow type. The air circuit, with the air filters shown, is shown in figure 1. These filters are numbered as follows:

- 1 a prefilter in the fresh air supply;
- 2 a HEPA filter, also in the fresh air supply;
- 3 a recirculation filter, and
- 4 the final filters in the ceiling.

The meaning and actual values of the symbols given in figure 1 are as follows:

- n_c number of air changes per hour for the total airflow; with a vertical velocity 0.45 m/s and a ceiling height of 3 metres the value is 540 h^{-1} ;
- n_o number of air changes per hour of fresh air to maintain the overpressure and to compensate for the exhausted process air; in this example 35 h^{-1} ;
- C_o number of particles $\geq 0.1 \mu\text{m}$ per m^3 of fresh air, assumed as to be 10^{11} ;
- C_s number of particles $\geq 0.1 \mu\text{m}$ per m^3 of supplied air through the ceiling; the unknown;
- G number of particles $\geq 0.1 \mu\text{m}$ per m^3 of supplied air, generated by the people in the cleanroom and the production process, assumed as to be $2 \cdot 10^6$;
- R number of particles $\geq 0.1 \mu\text{m}$ per m^3 of supplied air, generated by the air ducts, fans, noise dampers, etc, assumed as to be $2.2 \cdot 10^7$.

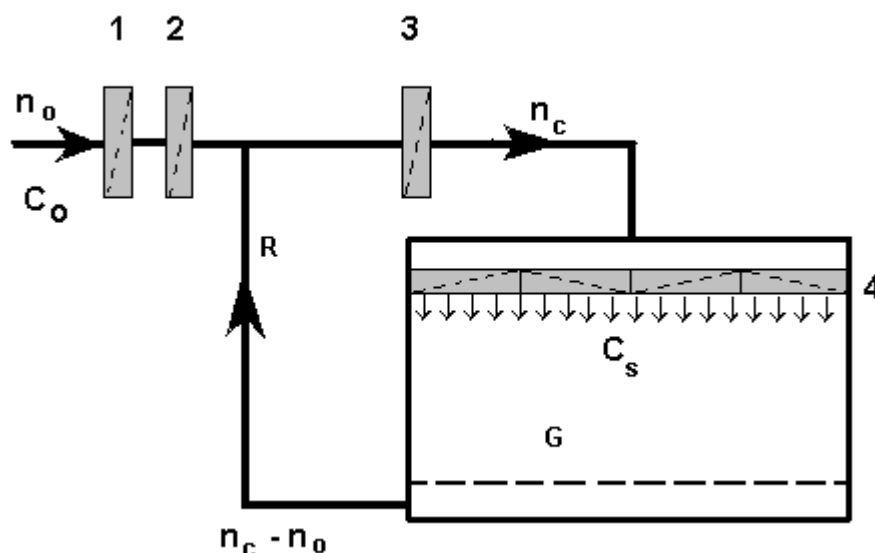


Figure 1 Air circuit and air filters used in the cleanroom.

The design specification required that the supplied air should contain no more than 3 particles with a size of $0.1 \mu\text{m}$ or larger per cubic foot and not more as 0.1 particles with a size of $0.5 \mu\text{m}$ or larger per cubic foot. This corresponded to Federal Standard Class 0.1. In metric terms, this is equivalent to ISO Class 2. Shown in figure2 are the better classes of ISO 14644-1 and the required design specification.

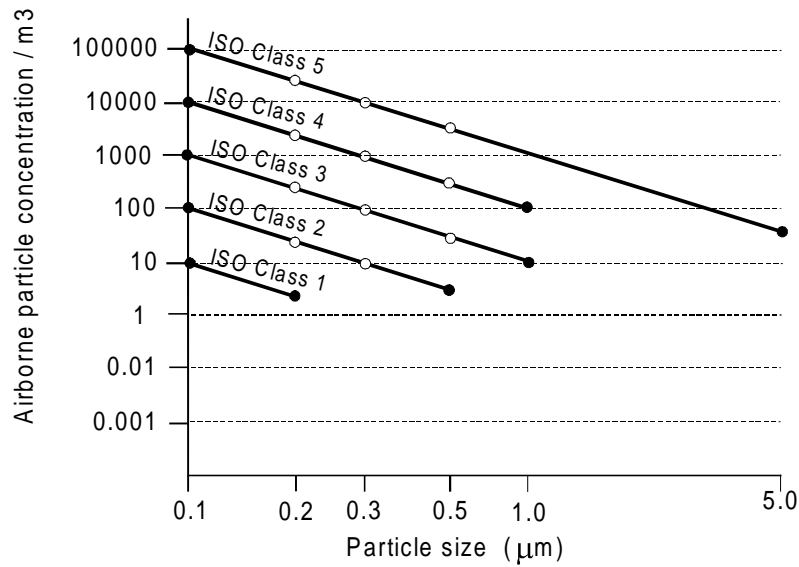


Figure 2 ISO 14644-1 classes along with: **A**-the design specification (ISO Class 2). **B**-design point calculated from simple model. **C**-design point calculated from size distribution. **D**-size distribution calculated from air filter penetrations. **E**-actual measured values in 'as built' conditions.

Different combinations of air filters were studied to achieve these requirements. The final choice, with the assumed efficiencies for dust particles $\geq 0.1 \mu\text{m}$, is given in table 1.

Table 1. Installed air filters.

No.	Filter type	Assumed efficiency (η) for particles $\geq 0.1\mu\text{m}$
1	Pre-filter, 85 % discoloration test (type EU 7)	0.50
2	HEPA-filter, 99.97 % DOP (type S)	0.995
3	Recirculating filter, 95% discoloration test (type EU 9)	0.75
4	Final filters in the ceiling (type ULPA)	0.99995

Simple Model Using Single Size of Particles

The number of particles $\geq 0.1 \mu\text{m}$ per m^3 in the air supplied (C_s) through the filters in the ceiling can be assumed to come from three sources:

$$C_s = C_a + C_b + C_c \quad (1)$$

where C_a is the particle concentration derived from the fresh air

C_b is the particle concentration derived from the air ducts fans etc.

C_c is the particle concentration derived from personnel and machinery and η_n the efficiency of the numbered filters in figure 1

$$C_a = n_o/n_c \cdot (1-\eta_1)(1-\eta_2)(1-\eta_3)(1-\eta_4)C_o \quad (2)$$

$$C_b = (1-\eta_3)(1-\eta_4)R \quad (3)$$

$$C_c = (1-n_o/n_c)(1-\eta_3)(1-\eta_4)G \quad (4)$$

Using the values given in table 1 and in the list of symbols for figure 1 it can be calculated that:

$$C_s = 5$$

This design value is shown as point B in figure 2.

Model Using a Size Distribution of Particles

Airborne particles size distribution

Federal Standard 209 E gives a series of class limits for cleanrooms that relate the particle count (equal to and larger sizes) to the concentration in the air. The allowed number of dust particles, N per m^3 air, from a given size δ can be described by

$$N = N_{cl} \cdot (0.5/\delta)^\beta \quad (5)c$$

Where N_{cl} - cleanroom classification with as reference value of $0.5 \mu m$;

δ - particle size in μm ;

β - an exponent with the value 2.209.

Particles/ m^3 (cumulative value)

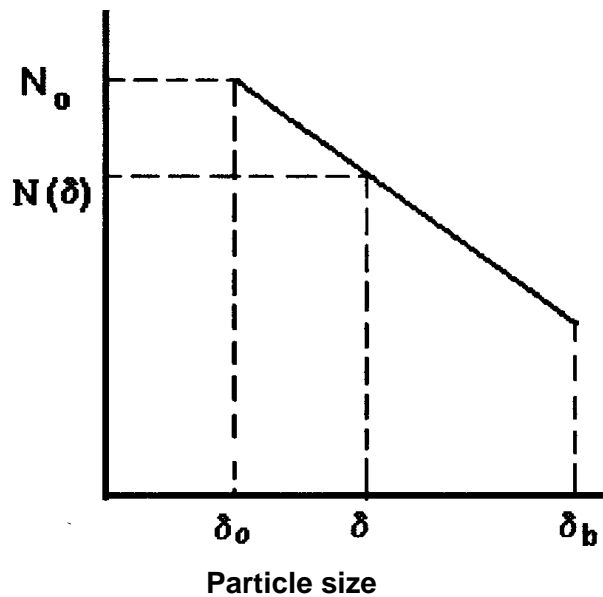


Figure 3. Dust size distribution (logarithmic scale)

Analogous to this, the number of particles $N(\delta)$ per m^3 with a size equal or larger than a value δ can be described by (see figure 2)

$$N(\delta) = N_o \cdot (\delta_o/\delta)^\beta \quad (6)$$

where N_o is the number of particles per m^3 with a size equal or larger than the lower value δ_o .

The number of particles per m^3 with a size δ equals, in that case

$$n(\delta) = - \frac{dN(\delta)}{d\delta} = \beta \cdot N_o \cdot \delta_o^\beta \cdot \delta^{-(\beta+1)} \quad (7)$$

It is assumed here that dust in the fresh air and generated by dust sources will show a similar size distribution.

Dust particle size distribution after the air filters

The efficiency of the air filter efficiency depends in the size of particles in the airflow. Experiments by the Philips Building Design and Engineering Department belonging to Cleanroom Laboratory (now belonging to DHV-AIB, a Dutch consulting engineering group) showed that the efficiency $\eta(\delta)$ for particles with a size $\delta \geq 0.1 \mu m$ grows linearly with increasing values of δ . As an "engineering approach" it is possible to use within certain limits the following equation:

$$\eta(\delta) = 1 - A \cdot e^{-B \cdot \delta} \quad (8)$$

where A and B are filter type constants

The penetration $p(\delta)$ of a filter for particles with a size δ is defined as $1-\eta(\delta)$, resulting in

$$p(\delta) = A \cdot e^{-B \cdot \delta} \quad (9)$$

With formula (9) the number of particles $N(\delta)$ per m^3 with dimensions $\geq \delta$ which passes through the filter can be calculated

$$N(\delta) = \int_{\delta}^{\delta_b} n(\delta) \cdot p(\delta) \cdot d\delta = \beta \cdot N_o \cdot \delta_o^{\beta} \cdot A \cdot \int_{\delta}^{\delta_b} e^{-B \cdot \delta} \cdot \delta^{-(\beta+1)} \cdot d\delta \quad (10)$$

Keeping the upper value limited to δ_b and n sufficient large the integral can be solved numerically as follows with $\Delta\delta = (\delta_b - \delta)/n$:

$$\int_{\delta}^{\delta_b} e^{-B \cdot \delta} \cdot \delta^{-(\beta+1)} \cdot d\delta \cong \sum_{i=1}^n [e^{-B \cdot \{\delta + (2i-1) \cdot \Delta\delta/2\}} \cdot \{\delta + (2i-1) \cdot \Delta\delta/2\}^{-(\beta+1)} \cdot \Delta\delta] \quad (11)$$

Series connection of air filters.

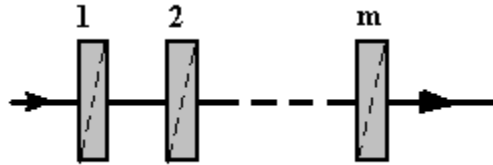


Figure 4. Series connection of air filters.

When the air passes m filters (see figure 4) with, respectively, a particle size dependent efficiencies of $\eta_1(\delta)$, $\eta_2(\delta)$, ..., $\eta_m(\delta)$ the penetrations corresponding to formula (9) are as follows:

$$\begin{aligned} p_1(\delta) &= A_1 \cdot e^{-B_1 \cdot \delta} \\ p_2(\delta) &= A_2 \cdot e^{-B_2 \cdot \delta} \\ &\dots\dots\dots \\ p_m(\delta) &= A_m \cdot e^{-B_m \cdot \delta} \end{aligned} \quad (12)$$

then we get for the total penetration an analogous expression:

$$p_t(\delta) = p_1(\delta) \cdot p_2(\delta) \cdot \dots \cdot p_m(\delta) = A_t \cdot e^{-B_t \cdot \delta} \quad (13)$$

with

$$A_t = A_1 \cdot A_2 \cdot \dots \cdot A_m = \prod_{i=1}^m A_i \quad (14)$$

and

$$B_t = B_1 + B_2 + \dots + B_m = \sum_{i=1}^m B_i \quad (15)$$

From the measurements of the Dust Control Laboratory mentioned above the value of A and B of the installed filters are determined and are given in table 2. With these corrected values of the efficiencies for dust particles of $0.1 \mu m$ substituted in the formulas (1) up to and including (4) the concentration in the supplied air can be calculated. This was found to be $C_s = 1.13$. This is shown as point C in figure 2.

Table 2. Calculated values of A and B and the efficiency for 0.1µm particles.

No.	Filter type	A _i	B _i	Efficiency for 0,1µm particles
1	EU 7	1.044	0.48	0
2	S	0.00232	12.792	0.9994
3	EU 9	0.1676	2.117	0.864
4	U	0.393*10 ⁻⁶	2.253	0.9999997

Up till now, no account has been taken of the fact that not all of the particles have a size of 0.1 µm. To include the influence of the size distribution, it is necessary to use as a starting point formula (10) and substitute in formula (1) the sum of the formulas (16) up to and including (18). This is instead of using the sum of the formulas (2) up to and inclusive (4) being used to calculate the number of dust-particles per m³ of supplied air that are equal or larger than a given size δ.

$$C_a = n_o/n_c \cdot \beta \cdot C_o \cdot \delta_o^\beta \cdot A_a \cdot \int_{\delta}^{\delta_b} e^{-B_a \cdot \delta} \cdot \delta^{-(\beta+1)} \cdot d\delta \quad (16)$$

$$C_b = \beta \cdot R \cdot \delta_o \cdot A_b \cdot \int_{\delta}^{\delta_b} e^{-B_b \cdot \delta} \cdot \delta^{-(\beta+1)} \cdot d\delta \quad (17)$$

$$C_c = (1-n_o/n_c) \cdot \beta \cdot G \cdot \delta_o^\beta \cdot A_c \cdot \int_{\delta}^{\delta_b} e^{-B_c \cdot \delta} \cdot \delta^{-(\beta+1)} \cdot d\delta \quad (18)$$

In this is: $A_a = \prod_{i=1}^4 A_i = 1.61 \cdot 10^{-10}$; $B_a = \sum_{i=1}^4 B_i = 17.64$

$$A_b = A_c = A_3 \cdot A_4 = 6.59 \cdot 10^{-8}; \quad B_b = B_c = B_3 + B_4 = 4.37$$

With δ_o = 0.1 µm and the numerical values, as given before, it is now possible to calculate for 0.1 ≤ δ ≤ 0.5 µm the cumulative value of the number of particles equal or larger than a size δ. The results are given by the curve E in figure 2. As can be seen from this curve, the value for δ = 0.1 µm is only a factor 1.5 smaller than point C.

Actual measurements in ‘as built’ condition.

Curve D shows some measured values in the cleanroom that had been designed using the method outlined above. It was measured in the "as built" state. This showed good correlation between the calculations using the methods outlined in this paper and the actual results.