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Equations for predicting airborne cleanliness in non-unidirectional airflow cleanrooms

W Whyte[1], N Lenegan[2] and T Eaton[3]*
[1] *School of Engineering, University of Glasgow, Glasgow G12 8QQ*
[2] *Energy and Carbon Reduction Solutions, Ashton-Under-Lyne, Lancashire, OL5 0RF*
[3] *AstraZeneca, Macclesfield, Cheshire, SK10 2NA*

Equations are derived in this paper for predicting the airborne concentration of particles and microbe-carrying particles in non-unidirectional airflow cleanrooms during manufacturing. The equations are obtained for a variety of ventilation systems with different configurations for mixing fresh and recirculated air, air filter placements, and number and efficiency of air filters. The variables in the equations are air supply rate, airborne dispersion rate of contamination from machinery and people, surface deposition of particles from air, particle concentration in fresh make-up air, proportion of make-up air, and air filter efficiencies. The equations are amenable to relatively simple modification for the study of different cleanroom ventilation systems. The use of these equations to investigate the effect of different configurations of ventilation systems and the relative importance of the equation variables on airborne concentrations will be reported in a further paper.

Key words: Equations, airborne cleanliness, particles, microbe-carrying particles, non-unidirectional airflow cleanrooms.

Introduction

When designing a cleanroom to achieve a required airborne cleanliness class or grade, such as specified in the International Organization for Standardization (ISO) 14644-1[1], or the European Union Guidelines to Good Manufacturing Practice (EU GGMP)[2], designers have a problem in deciding how much filtered air should be supplied to the cleanroom. Currently, this is not normally calculated but based on experience or some rule of thumb, and the consequence of this is that designers are over-cautious, and many cleanrooms have excessive air supply that is associated with high capital and running costs, and energy waste. Conversely, a low air supply may result in too high a concentration of airborne contamination, and major remedial work to rectify the problem. There is, therefore, a need for a method to calculate the air volume supply rate for a required concentration of airborne contamination, and information on such a method has been previously published by the authors[3]. The airborne cleanliness of a cleanroom is directly related to the amount of filtered air supplied to a cleanroom, and equations derived to calculate airborne cleanliness can be rewritten so that the amount of air required is determined for a specified airborne cleanliness condition. These equations do not consider air mixing and distribution in the cleanroom and this is discussed elsewhere[4].

A number of equations have been derived to calculate the airborne concentration in a cleanroom[5–9]. These equations have been mainly derived for a single type of ventilation system and are not applicable to all design configurations, and an investigation is required to determine whether changes in the design of ventilation systems through filter placement, numbers of filters, and methods of mixing fresh and recirculated air within the ventilation plant, will cause differences to the airborne concentrations in the cleanroom. Also, the previously-derived equations have either not considered the effect of surface deposition of particles, or not done so in an analytical way. In addition, some of the previously reported equations have been derived by assuming a transient state, and, therefore, the mathematics is relatively complicated, and it would be useful if the derivation method was simplified.

This paper derives equations for a variety of ventilation plants. These equations provide a means of investigating (a) the influence of different designs of ventilation plants, (b) the importance of the different variables that influence the airborne concentration, (c) the possibility of simplification of the equations, and (d) the usefulness of the method suggested by Whyte, Whyte, Eaton and Lenegan[3] for calculating the air supply rate for a specified airborne concentration in non-

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***Corresponding author:** Tim Eaton, Sterile Manufacturing Specialist, AstraZeneca, UK Operations, Silk Road Business Park, Macclesfield, Cheshire, SK10 2NA; Email: tim.eaton@astrazeneca.com; Tel: +44(0)1625 514916.

unidirectional airflow (non-UDAF) cleanrooms. These will be investigated in a further paper.

Derivation of equations to calculate airborne cleanliness in a cleanroom

At the start of activity in a cleanroom, personnel will enter an empty cleanroom with a low airborne concentration of particles and microbe-carrying particles (MCPs). For a manufacturing operation, equipment will be set-up, and machinery switched on, and this activity causes a build-up of airborne contamination. When manufacturing starts and the activity of personnel settles down, the airborne contamination will be reduced a little to a fairly constant 'steady-state' condition, i.e. the operational condition. Equations are derived in this section for calculating the concentration of particles in a non-UDAF cleanroom in the steady-state condition, such as found during manufacturing. However, they should not be used in UDAF systems, as air cleanliness is not dependent on the air supply rate but on its displacement by UDAF.

The symbols used in the equations are as follows:

C = Concentration of airborne particles or MCPs in a cleanroom (no./m^3)

C_F = Concentration of airborne contamination in fresh make-up air (no./m^3)

C_R = Concentration of airborne contamination in recirculated air (no./m^3)

C_E = Concentration of airborne contamination in excess or extracted air (no./m^3)

Q_s = Total air volume supply rate to cleanroom (m^3/s)

Q_F = Air volume supply rate of fresh make-up air (m^3/s)

Q_R = Air volume recirculated from cleanroom (m^3/s)

η_P = Removal efficiency of primary air filter

η_S = Removal efficiency of secondary air filter

η_T = Removal efficiency of terminal air filter

D_M = Average dispersal rate of airborne contamination from machinery (no./s)

D_P = Average dispersal rate of airborne contamination from personnel (no./s)

A = Area of deposition (m^2) of particles

V_D = Deposition velocity of particles of a size D (μm) falling through air (m/s)

Cleanrooms are typically maintained at a positive pressure with respect to adjacent areas, in order to minimise the entry of airborne contamination. In cases where the prevention of the entry of contamination is important, or the contamination challenge is substantial, air locks can be used. It can, therefore, be assumed that an insignificant amount of contamination enters the cleanroom from adjacent areas. In addition, it has been shown that in a typical cleanroom, the dispersion of contamination from a floor during walking contributes a small amount to the airborne concentration[10] and, therefore, need not be included in the following calculations. Therefore, the particle balance in a cleanroom is given by **Equation 1**.

Equation 1

Rate of airborne contamination entering the room + rate of airborne contamination generated within the room

=

Rate of contamination exiting the room through recirculated and exhaust air + particle deposition rate onto room surfaces

Whyte, Agricola and Derks[11,12] have investigated the deposition mechanisms of particles in cleanrooms. Their investigation has shown that the following **Equation 2** can be used for calculating the deposition rate of particles onto a given surface area.

Equation 2

$$\text{Surface particle deposition rate} = C*V_D*A$$

Where, C is the airborne particle concentration in a cleanroom, and V_D is the deposition velocity of particles falling through air onto a surface. A is the surface area onto which the particles deposit, and if the loss of particles by deposition in the whole cleanroom is considered, the surface area can be assumed to be equivalent to the floor area.

In cleanrooms, cumulative particle sizes are counted, which includes all particles over a threshold size, and the deposition velocities of a range of cumulative particle sizes in different ventilation conditions have been obtained by Whyte, Agricola and Derks[11]. The deposition velocities of MCPs are reported by Whyte and Eaton[13].

Air filters are normally considered by their removal efficiency, which is usually given as a percentage. In this article, the proportion of airborne contamination that penetrates through filters is also used. These quantities are related as follows:

$$\text{Penetration proportion} = 1 - \{\text{removal efficiency } (\%)/100\}$$

A typical cleanroom ventilation system will recirculate air from the cleanroom, add fresh air, modify the temperature and humidity, filter the air, and supply it to the cleanroom. The airborne concentration in a cleanroom is influenced by the contamination in the air supply, which may differ according to the design of the air ventilation system. The importance of this was investigated by consideration of the following different configurations of ventilation systems.

1. **Type 1:** Standard recirculation loop, where fresh air is introduced into the recirculated air before any filtration occurs.
2. **Type 2:** The fresh air is filtered before being introduced into the recirculated air.
3. **Type 3:** Part of the recirculated air by-passes the air conditioning plant.

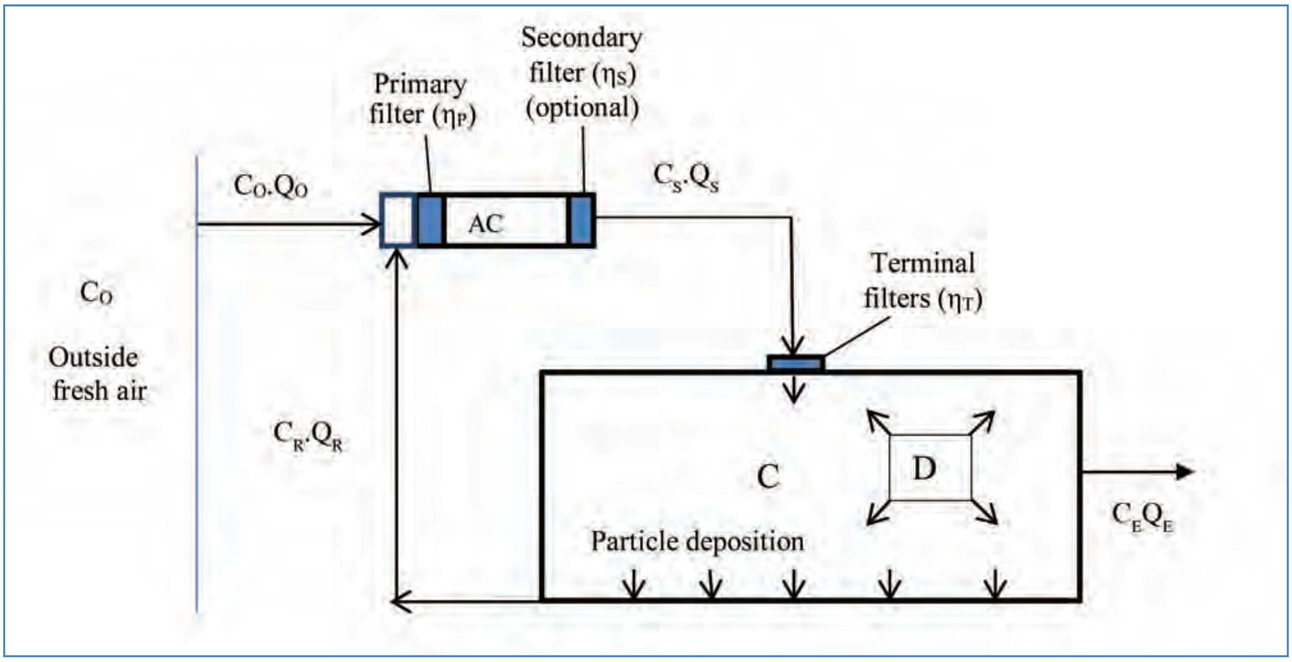


Figure 1. Type 1: Standard recirculation loop. AC = air conditioning plant, D = dispersion from machinery and personnel, air filters = 🟦.

These three types of ventilation systems were investigated when they had a primary, secondary and terminal filter or, alternatively, a primary and terminal filter.

Type 1: Standard recirculation loop

Shown in **Figure 1** is, possibly, the most common ventilation system arrangement found in cleanrooms, where air is recirculated from the cleanroom, mixed with fresh make-up air, and filtered by a primary filter prior to the air conditioning plant. After conditioning, the air can be filtered by a secondary filter, which is used to extend the life of the terminal filter, and reduce the contamination risk to products should a leak occur in the terminal filter. The air is finally filtered by a terminal filter in the cleanroom ceiling.

The rate that particles enter a cleanroom (no./s) is the product of the air supply rate (m^3/s) and the associated particle concentration (no./m^3). The rate of outdoor fresh air supplied to the cleanroom is $C_O.Q_O$, and the recirculated air rate is $C_R.Q_R$. The mixed air passes through primary, secondary (when installed), and terminal filters that have particle penetrations of 1-η_P, 1-η_S and 1-η_T, respectively. The rate that particle contamination enters the cleanroom in the supply air is therefore:

$$(C_O Q_O + C_R Q_R)(1-\eta_P)(1-\eta_S)(1-\eta_T)$$

The filtered supply air enters the cleanroom and mixes with contaminants dispersed from people at a rate of D_P, and from machines at a rate of D_M. Therefore, particles are added to the cleanroom air at the following rate:

$$(C_O.Q_O + C_R.Q_R)(1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M$$

The rate that airborne contamination exits a cleanroom and is recirculated to the air conditioning plant is C_RQ_R. The surplus air that pressurises a cleanroom can be exhausted by means of an extract fan to the outside, or passes through the room's fabric, doorways, air dampers or grilles, at a rate of $C_E.Q_E$. There is also a loss of particles within the cleanroom by surface deposition, and the previously discussed **Equation 2** can be used to calculate the rate that they are lost. The total loss of airborne contamination from the cleanroom is, therefore:

$$C_RQ_R + C_EQ_E + C.V_D.A$$

In the steady-state condition, the particle balance shown in **Equation 1** can be expressed mathematically as follows:

$$(C_O.Q_O + C_R.Q_R)(1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M = C_RQ_R + C_EQ_E + C.V_D.A$$

The particle concentration in both the recirculated (C_R) and exhaust air (C_E) can be assumed to be the same as in the cleanroom (C) and, to retain the air volume balance, the fresh air supply is equal to that exhausted i.e. $Q_E = Q_O$. Therefore, the equation can be rewritten as follows:

$$(C_O.Q_O + CQ_R)(1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M = CQ_R + CQ_O + C.V_D.A$$

Rearranging and solving for C, which is the required airborne concentration in the cleanroom, and assuming the volume of air supplied to the cleanroom is equal to the sum of the recirculated and fresh air supply rate, i.e. $Q = Q_R + Q_O$, the following equation is obtained:

Equation 3

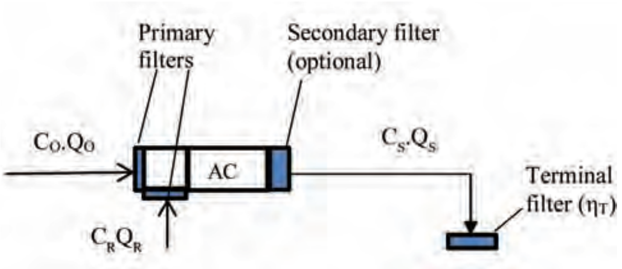
$$C = \frac{C_O Q_O (1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M}{Q_S + V_D.A - Q_R (1-\eta_P)(1-\eta_S)(1-\eta_T)}$$

If a secondary filter is not installed, the following equation is obtained:

Equation 4

$$C = \frac{C_O Q_O (1-\eta_P)(1-\eta_T) + D_P + D_M}{Q_S + V_D.A - Q_R (1-\eta_P)(1-\eta_T)}$$

Shown in figure below is a variation of the layout of the Type 1 ventilation system, in which fresh and recirculated air are filtered before they mix. If the primary filters have the same removal efficiency, then **Equations 3** and **4** can be used.



Type 2: Fresh air filtered before mixing with recirculated air

Shown in **Figure 2** is another ventilation arrangement used in cleanrooms, where fresh make-up air is filtered by a primary filter, and passed through an air conditioning plant before being mixed with recirculated air. The mixed air is then drawn through a secondary filter (where installed) and directed to the terminal filter in the cleanroom ceiling. If the particle-balance **Equation 1** is again used, and the same assumptions made as in the previous section, the following equation is obtained.

Equation 5

$$C = \frac{C_O Q_O (1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M}{Q_S + V_D A - Q_R (1-\eta_S)(1-\eta_T)}$$

If a secondary filter is not installed, the following equation applies:

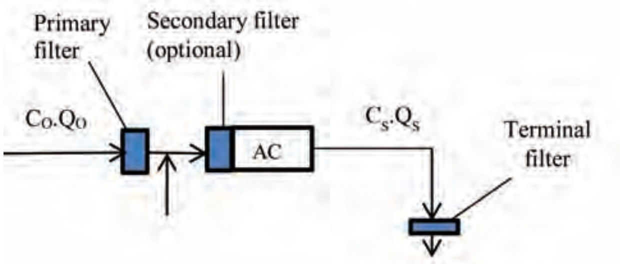
Equation 6

$$C = \frac{C_O Q_O (1-\eta_P)(1-\eta_T) + D_P + D_M}{Q_S + V_D A - Q_R (1-\eta_T)}$$

Or, alternatively, the equation previously reported by Whyte *et al.*[10]:

$$C = \frac{C_O Q_O (1-\eta_P)(1-\eta_T) + D_P + D_M}{Q_S + V_D A + Q_R \eta_T}$$

A variation on the Type 2 ventilation system is shown in the figure below. Although the air conditioning plant is in a different location, it draws the same mixture of filtered air through the secondary filter, and **Equations 5** and **6** are applicable.



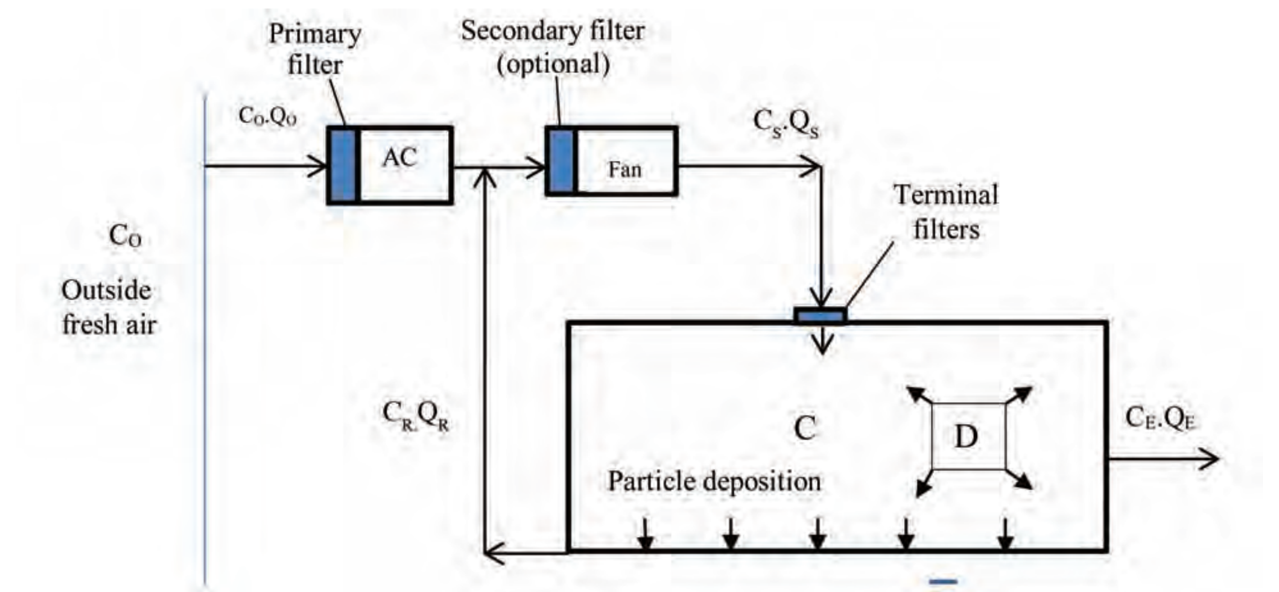


Figure 2. Conditioned fresh air system. AC = air conditioning plant, filters = ■.

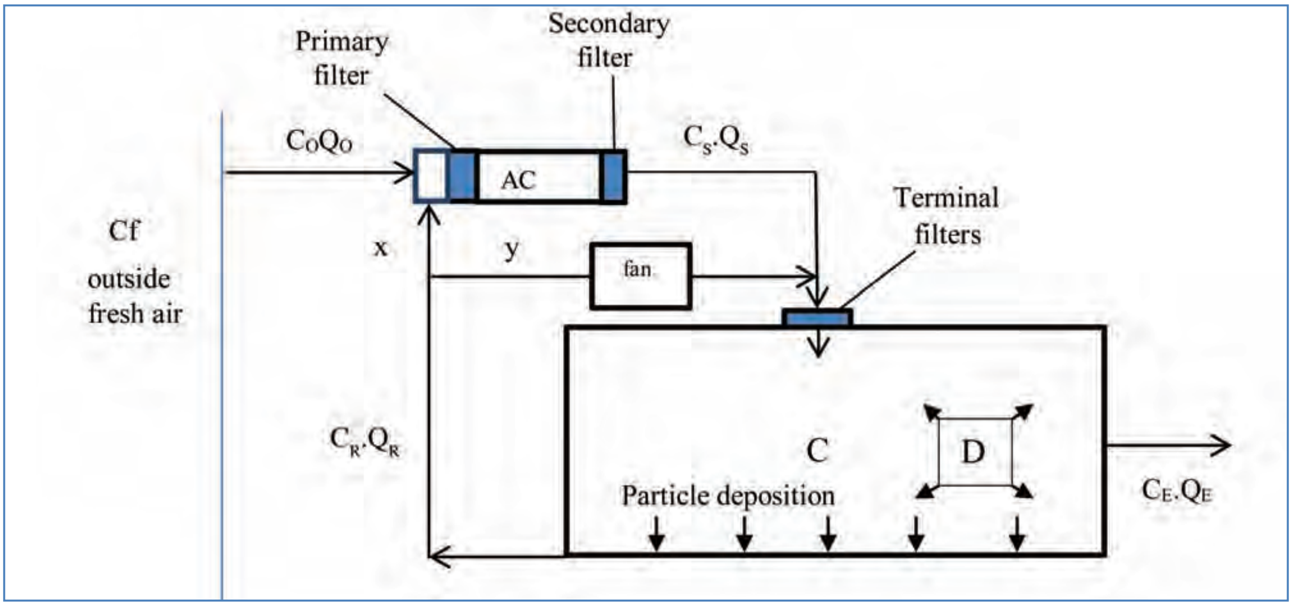


Figure 3. Recirculated air by-pass, AC = air conditioning plant, filters = 🟦.

Type 3: Recirculated air by-pass

In some cleanrooms, where there is a large demand for clean air but where the air conditioning requirement is relatively small, a proportion of the recirculated air is designed to by-pass the air conditioning plant and flow directly to the terminal filter. Such an arrangement is shown in **Figure 3**.

Using the same particle-balance **Equation 1**, and assumptions used in the previous two sections, the following equation is obtained.

Equation 7

$$C = \frac{C_O Q_O\,(1-\eta_P)(1-\eta_S)(1-\eta_T) + D_P + D_M}{Q_S + V_D.A - Q_R.x\,(1-\eta_P)(1-\eta_S)(1-\eta_T) - Q_R.y\,(1-\eta_T)}$$

Where, x is the proportion of the recirculated air that goes through the air conditioning plant, and y is the proportion that enters directly into the supply air duct.

If a secondary filter is not installed, the following equation is applicable:

Equation 8

$$C = \frac{C_O.Q_O(1-\eta_P)(1-\eta_T) + D_P + D_M}{Q_S + V_D.A - Q_R x\,(1-\eta_P)(1-\eta_T) - Q_R.y(1-\eta_T)}$$

Simple dilution equations

If the air filters installed in the ventilation system have a sufficiently high removal efficiency to ensure that the airborne contamination in the filtered air supplied to the cleanroom has no practical significance, i.e. the removal efficiency (η) is 1, **Equations 3** to **8** can all be reduced to the following 'dilution and deposition' equation.

Equation 9

$$C = \frac{D_P + D_M}{Q + V_D.A}$$

If surface deposition is unimportant, then the following **Equation 10**, which is known as the 'simple dilution' equation, can be used.

Equation 10

$$C = \frac{D_P + D_M}{Q}$$

Discussion

Equations have been derived in this article to calculate the airborne concentration of particles or MCPs in cleanrooms during the operational state. These equations are applicable to non-UDAF cleanrooms and assume a steady-state condition brought about by a balance between particles introduced into the cleanroom and those removed. Similar equations have been previously derived by research workers but usually apply to a single design of ventilation systems, which may differ from other systems in the way fresh air is introduced into the recirculated air, and in the placement and number of air filters. This article derives equations for three configurations of ventilation systems, where a secondary filter is, or is not, installed. The variables in these equations include air supply rate, airborne dispersion rate of contamination from machinery and people, surface deposition of particles from the air, particle concentration in the fresh air, proportion of fresh air, and air filter efficiencies. It is considered that these equations are a useful advance over previously derived equations, and have been obtained in a way that allows the simple derivation of similar equations for other ventilation system.

Actual values for dispersion and deposition rates, and for particle concentrations in make-up air, are provided in a paper to be published, and these values will be used with the derived equations to more accurately calculate the airborne concentration in non-UDAF cleanrooms. An investigation into the importance of the variables in the equations, and the effect of different efficiencies and placement of air filters in the different ventilation systems is also carried out. In addition, by considering the importance of the various equation variables, the derived equations are simplified.

Rearranging the equations derived in this paper will allow the calculation of the air supply needed to obtain a specified airborne concentration of contamination in non-UDAF cleanrooms. The information gathered in the next article will also enable the validity of the approach suggested by Whyte, Whyte, Eaton and Lenegan[3] for calculating the air supply rates for non-UDAF cleanrooms to be investigated.

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