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# Air Handling Considerations for Cleanrooms

by

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As industries and markets grow more competitive- and as the unarguable edict of energy conservation becomes widely accepted in all industries- it is necessary to re-evaluate existing methods of airflow design. Airflow rate in a cleanroom is the biggest factors affecting both the initial and operating costs of cleanrooms.

The basis of cleanroom airflow design has not changed much over the past twenty years. In designing new facilities or upgrading existing ones, most cleanroom companies simply use design charts [1] (see **Table 1**) showing different air exchange rates and average room velocity for various classes of cleanrooms. These charts are often based on nothing more than mere opinions or on the simple fact that this is how rooms were designed in the past. Another design approach is to simply fix the filter velocity at 90 fpm[1] and then specify different ceiling coverage percentages for different classification levels.

Experience has demonstrated that these methods are not efficient and, in many cases, result in over design or in problem installations. Further, these methods were "formulated" when most HEPA filters had a rated filtration efficiency of 99.97% at 0.3 Um. Most terminal HEPA filters in use today have a filtration efficiency of 99.99% at 0.3 Um. This is not an insignificant difference. A 99.97% efficient filter has a fractional penetration of 0.0003, while a 99.99% filter's fractional penetration is 0.001. This means that a 99.99% filter is *three times more efficient* in removing 0.3 Um particles! Thus, when considering the use of ULPA and better than ULPA filtration systems, such charts become even less useful.

Table I Typical Airflow Design Chart [1]

| **Cleanroom Class** | **Airflow Type** | **Av. Airflow Velocity, fpm** | **Air changes/hr** |
|---|---|---|---|
| 1 | Unidirectional | 60-100 | 360-540 |
| 10 | Unidirectional | 50-90 | 300-540 |
| 100 | Unidirectional | 40-80 | 240-480 |
| 1,000 | Mixed | 25-40 | 150-240 |
| 10,000 | Mixed | 10-15 | 60-90 |
| 100,000 | Mixed | 5-10 [corrected] | 5-48 |

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[1] It is interesting to note that 90 fpm was simply the coincidental velocity achieved by the use of an available fan with a HEPA filter at the Department of Energy laboratory at Los Alamos, NM.

To make matters worse, many regulatory agencies and technical societies propagate these charts through their guidelines and standards. The FDA, for example, uses 90 fpm filter velocity as a recommended filter velocity in its GMP documents. Although such guidelines provide the non-expert end user with some useful information, after a few years of publication such guidelines become unreasonable edicts, especially when considering the fact that they apply to secondary parameters. After all, the primary performance criteria are that:

- the cleanroom maintain required particle and bio burden cleanliness levels.
- the desired effect on the product or process be attained as determined by QC/QA testing.

*All other design parameters are, in reality, secondary.* Guidelines should leave room for innovation in achieving the above primary performance objectives in an energy efficient and cost effective manner. Unfortunately, most agencies base their "standards" on current methods, without questioning the basis and validity of such methods and certainly without considering the impact of their "standards" on innovation. This paper examines airflow design methods by using a simplified, rational model for airflow design. Air handling systems are also considered.

## Airflow design

The primary purpose of air handling units (AHUs) in a cleanroom is to provide clean air (adequate for the cleanroom classification) that can efficiently ***dilute*** and carry away or ***transport*** contaminants generated within the room. Since the cleanroom classification- whether FS209E or ISO 14644-1 and/or ISO 14644-2- is affected to a larger extent by higher contamination areas or zones within the cleanroom, it is important to design the airflow for these dirtier areas. Consider each of these fundamental aspects separately.

## Clean Air Dilution

The dilution effect is determined by the cleanliness of the filtered air and the airflow rate. To understand how airflow dilutes contaminants, a simplified model is presented (see **Figure 1**).

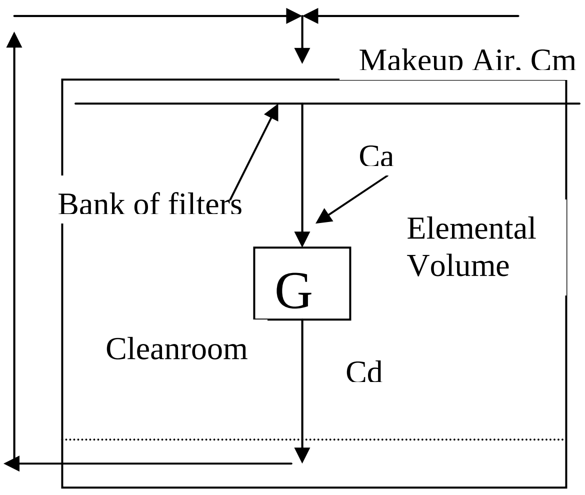
1) Consider a small volume of air, V, about the same size as the sampled volume (during classification). This is an important stipulation.
2) Consider steady state conditions for simplicity.
3) Assume that there is no transport of particles into this small volume from surrounding space, since we are considering only the dilution effect of the cleanroom air here.
4) Assume also that above and below this packet of air there is no generation of contaminants. Hence, the concentration of particles entering this small volume is equal to Ca, the steady state concentration of particles leaving the filter.

Then the diluted concentration, Cd, is then given by:

Cd=Ca+G/Q **(1)**

where G is the contaminant generation rate (e.g., #/min.), Ca is the concentration of particles in the air entering the elemental volume, and Q is the airflow rate.

Figure 1 – Flow Schematic-Elemental Volume



If there is no generation of particles above the elemental volume (and no influx from surrounding areas), then Ca is also the concentration of particles in the air coming out of the filter. If the cross section of the elemental volume is unity (say 1ft$^2$), then Q is also the flow velocity.

If designing without any safety or other factors, then Cd should be less than the maximum concentration allowed for that cleanroom class. If, for example, the target room concentration is to be 1/5 of the maximum allowed concentration, then for a Class 10 cleanroom, Cd should be less than 2 (0.5 Um particles). Note that the volume, V, enters into play only via Q.

If there were no additional generation of particles below this packet of space (keep in mind that this is a simplified use of this model, aimed at understanding how airflow affects cleanroom performance), then the return air will also have a concentration equal to Cd. If Cm is the concentration of particles in the make-up air, then Ca is given by:

Ca = (1-E) [f Cm + (1-f) Cd] **(2)**

where E is the fractional filtration efficiency of the filter system for the room classification particle size and f is the fraction of the make-up airflow rate to the total filtration flow rate. Thus, by combining equations 1 and 2,

Cd = [f (1-E) Cm+ G/Q]/[1 - (1-f)(1-E)] **(3)**

In the absence of turbulence (and considering the other assumptions regarding particle generation), Equation 3 illustrates how the filtration flow rate and efficiency affect cleanroom performance, with make-up air concentration and flow rate and internal particle generation as parameters.

If the cleanroom space was broken down into a grid of such elemental packets, and if the output from each packet is taken as input for each successive packet, then the model could be accurately applied to the whole room. If the elemental volume considered is small enough, this model should accurately describe the dilution effect of the airflow in the cleanroom.

## Dilution Model Calculations/Results

In the following calculations the make-up air conditions are fixed: 3% make-up air (as a percent of total airflow circulation), with make-up air concentration, Cm, fixed at 500,000/ $ft^3$. The results from Equation 3 can be presented in many different ways in order to illustrate the interaction of velocity, filter efficiency and contamination generation for fixed make up air conditions.. It should be kept in mind, that this model is being applied with many assumptions, simply to illustrate the effect of the cleanroom airflow variables. For example the model in not used in a more rigorous manner by using a successive grid of elemental volumes as suggested above. Nor has transport of particles from surrounding volumes been taken into account. **Figures 2-10** are utilized for this illustrative purpose and are based on Equation 3. Below each Figure is an observation regarding the effect of the cleanroom airflow design variables.

Four 0.3 Um efficiencies are considered: a) 99.9%, b) 99.97%, c) 99.99% and d) 99.999999%. The last one is an extremely high efficiency filtration system such as achievable at reasonable pressure drop using Electrically Enhanced Filtration (e.g. Technovation Systems, Inc. [2]) as a primary HEPA in series with a terminal HEPA filter. The mid efficiencies, 99.97% and 99.99%, are common HEPA efficiencies. The 99.9% efficiency filter is used to consider a lower HEPA efficiency filter that will have a significantly lower pressure drop.

Other observations that can be made from the dilution model are listed below.

1. The dilution model properly illustrates the effects of internal particle generation rates, flow velocity, filter efficiency, make up air flow rate and concentration. Design charts such as **Table 1** do not show such dependencies and the use of these charts can lead to either over design or poorly functioning cleanrooms.
2. It is clear that for low energy consumption in cleanrooms, both high filtration efficiency filters operating at lower flow rates and lower efficiency filters operating at higher flow rates

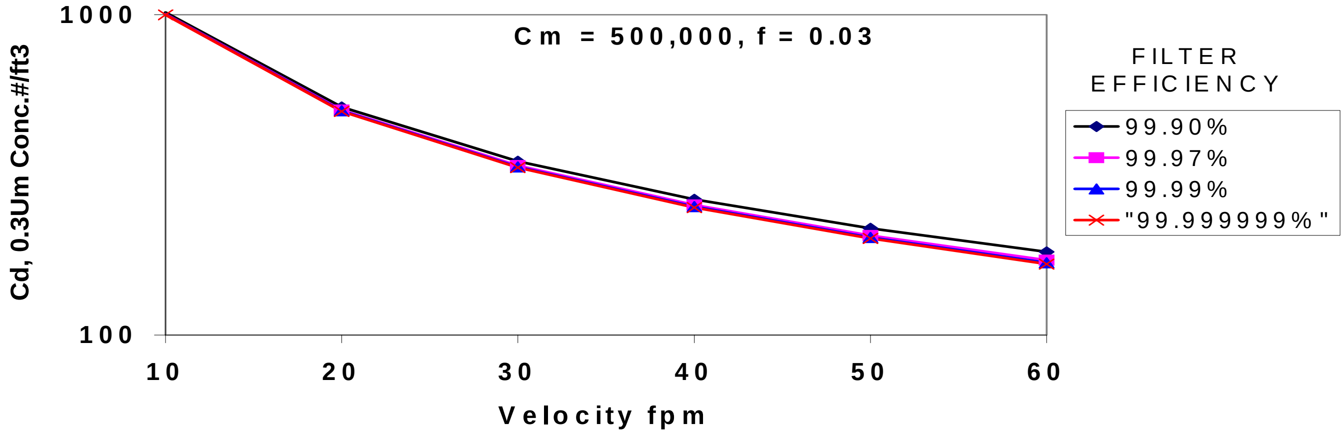


Fig 2 - Effect of Velocity, G=10,000

For less clean environments (e.g. Class 10K or 100K) 99.9% filters may be used for energy savings. High efficiency filters are not necessary! Higher filter efficiency at this high contamination level does not improve room performance. Instead it simply adds to the pressure drop and energy consumption.

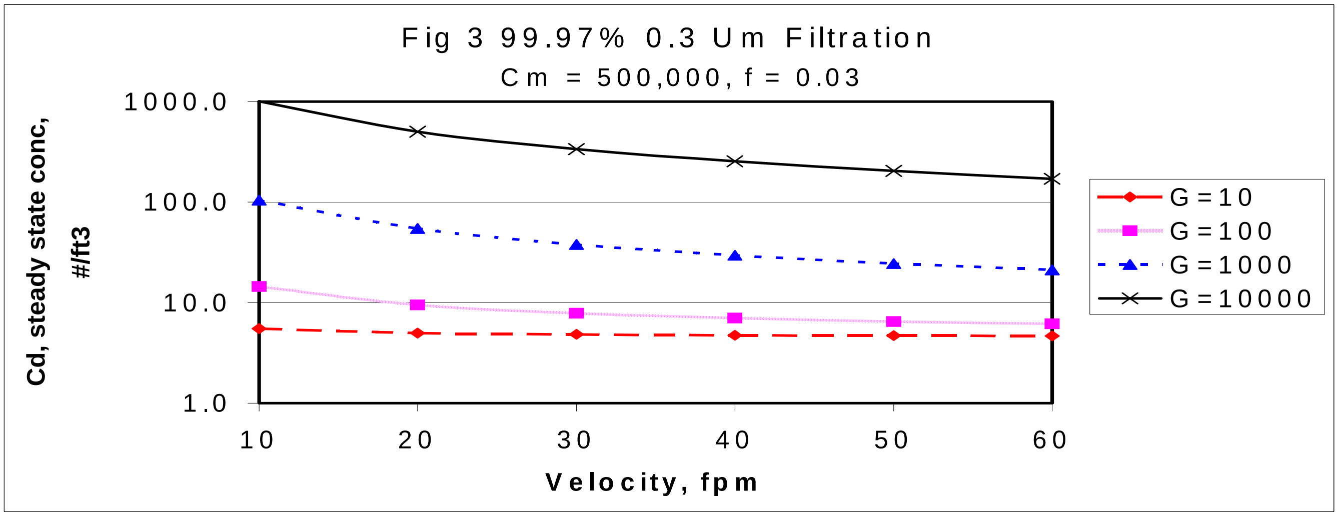


Fig 3 99.97% 0.3 Um Filtration

Beyond 60 fpm there is no concentration reduction. Velocity has a smaller impact on Cd when G is lower.

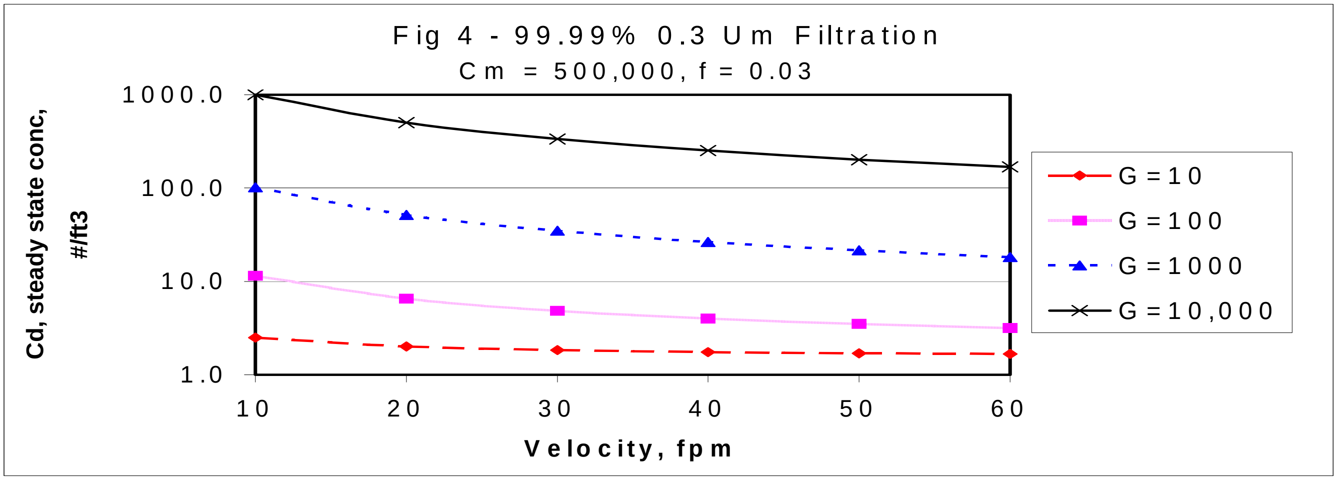
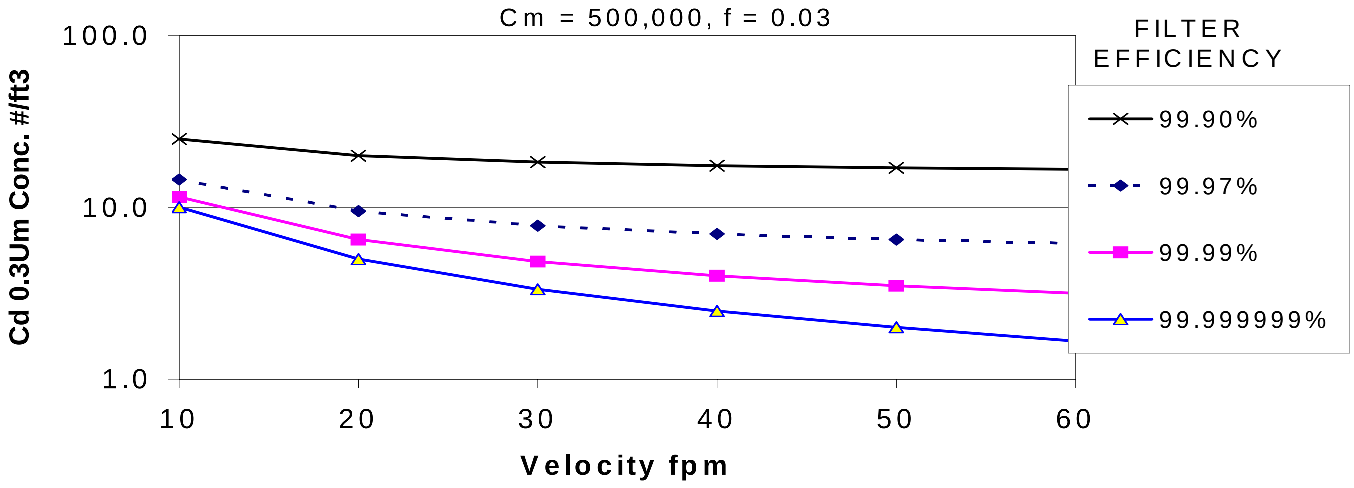


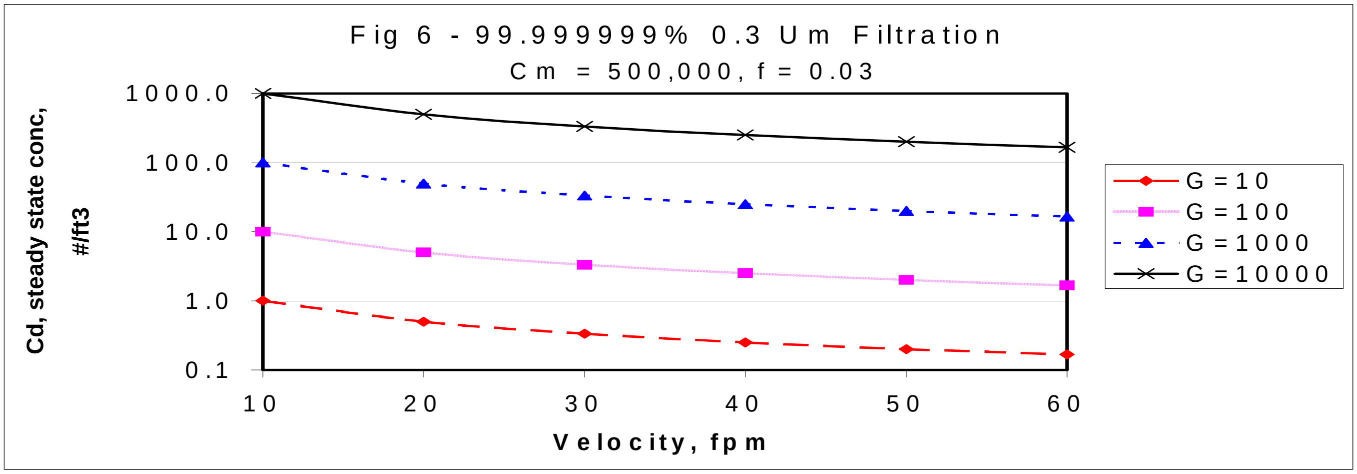
Fig 4 - 99.99% 0.3 Um Filtration
Cm = 500,000, f = 0.03

The achievable cleanliness with any filter is limited by the value of G - even at high velocity.

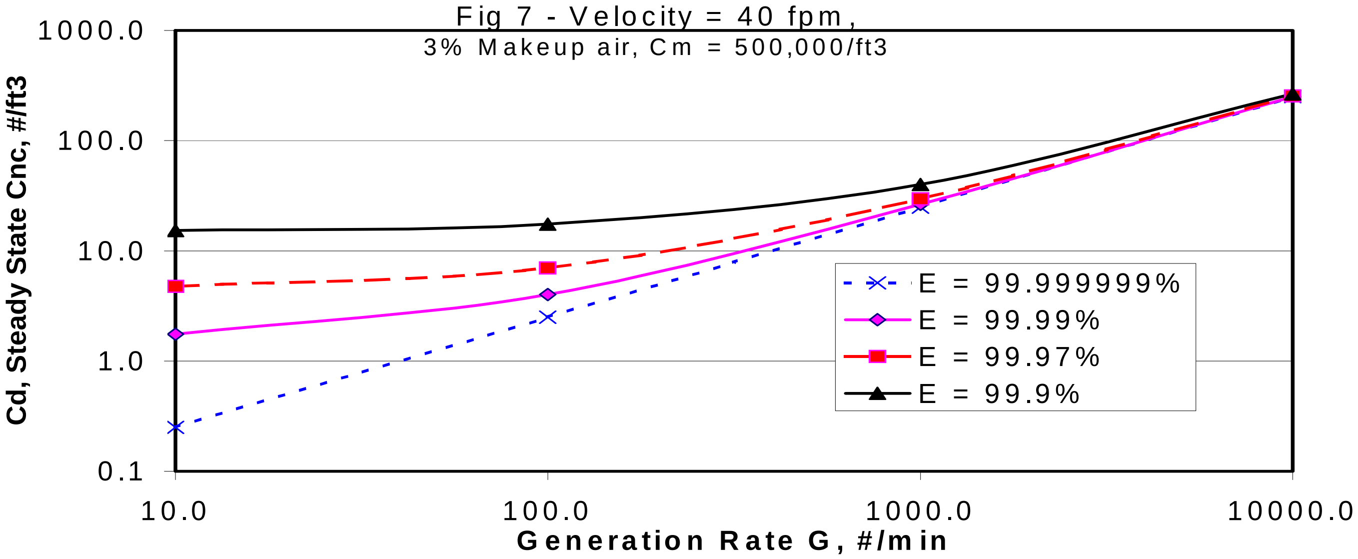
Fig 5 - Effect of Flow Rate G=100


Cm = 500,000, f = 0.03

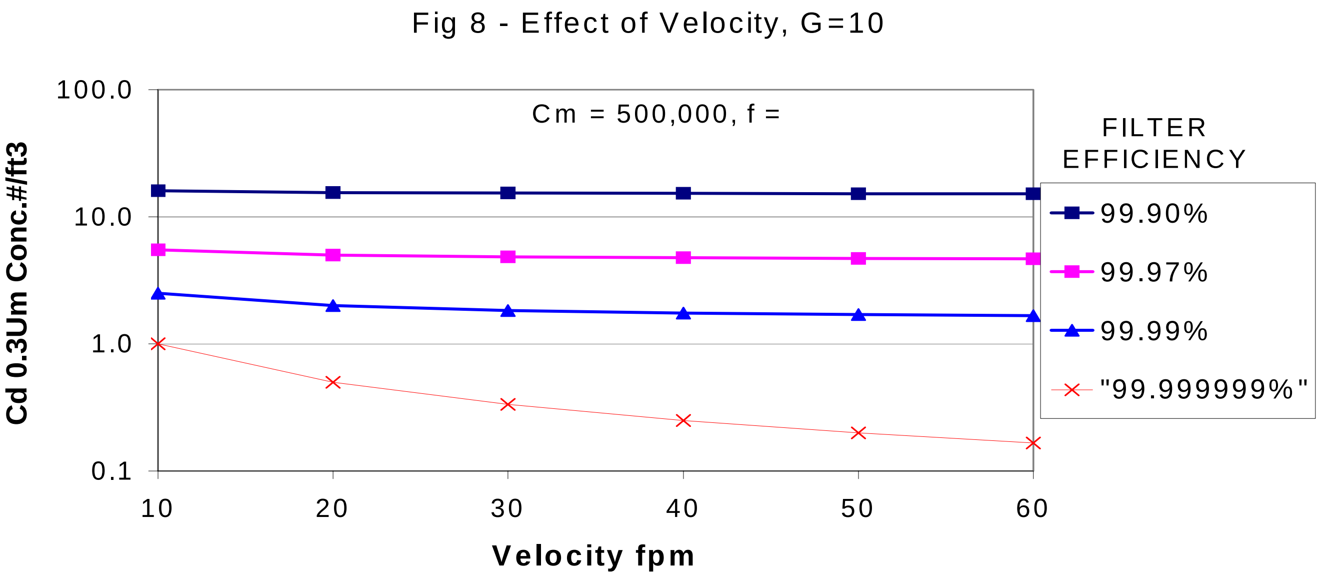
Higher efficiency filters can be utilized to achieve the desired cleanroom classification at lower airflow rates- for the same internal particle generation rates.



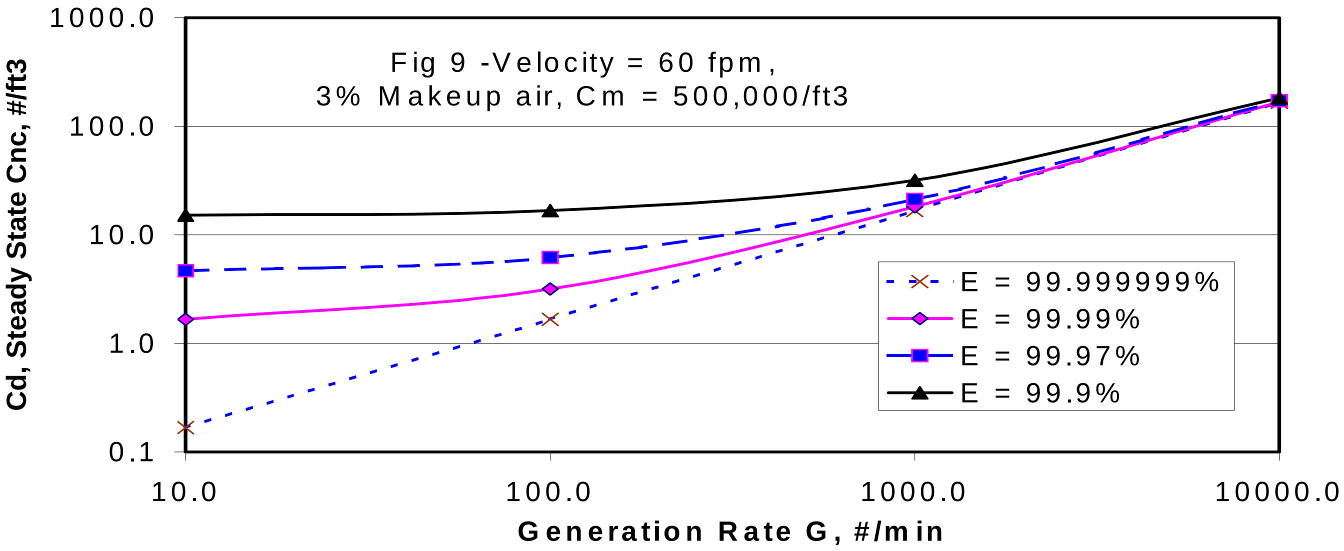
Double HEPA filters can be used to achieve lower (cleaner)class at lower velocity. This is due to the higher filtration efficiency - 99.999999% @ 0.3 Um! Lower airflow rates are sufficient at lower internal generation rates.



Higher efficiency filtration results in cleaner rooms at lower velocity. Thus if the higher filtration efficiency can be obtained at a reasonable pressure drop (as with Electrical Enhanced Filtration) then significant savings in energy consumption can be realized.



Low Gs are synonymous with ultra clean environments. Under these conditions ultra high filtration (e.g. Double HEPA filtration) is a must!



Ultra clean rooms can only be achieved by using better filtration efficiency & clean processes! Note also how Cd converges for different filters - around G=5000 @ 60 fpm.

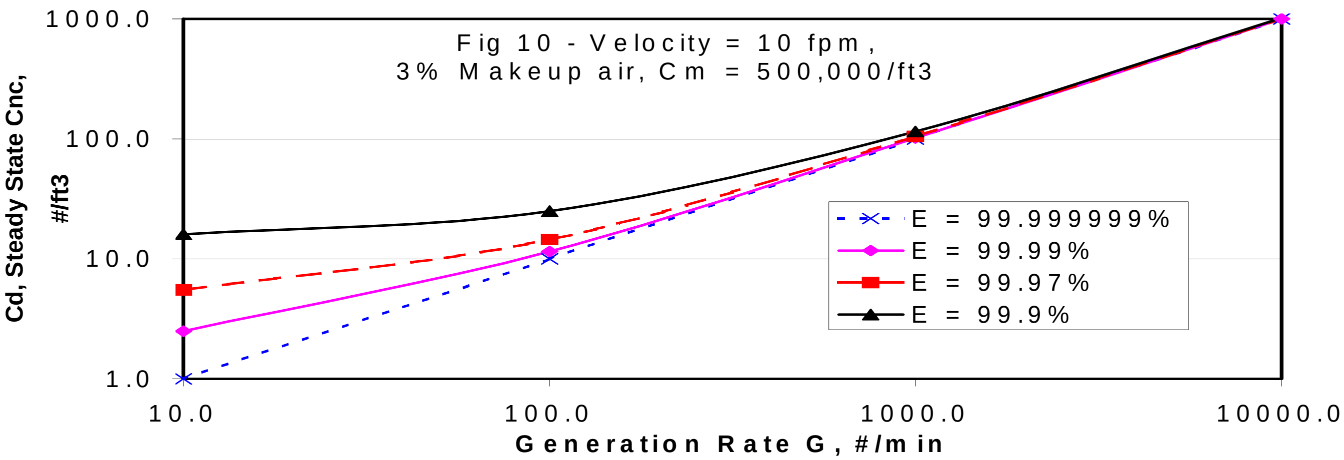


Fig 10 - Velocity = 10 fpm,
3% Makeup air, Cm = 500,000/ft3

Convergence for various efficiency filters takes place at lower values of G as the velocity is reduced. For example at 10 fpm the convergence takes place G=1000.

should be considered. The low energy consumption selection depends on both the flow rate and the pressure drop values.

3. Clearly for Class 0.1 to 10 performance, an ultra high filtration efficiency, with a reasonable pressure drop (such as a double HEPA system with Electrically Enhanced Filtration), has tremendous advantages in terms of energy consumption.
4. Keep in mind, of course, that other factors such as particle re-entrainment due to turbulence and other factors have not been considered here. This author's experience, however, has been that the higher efficiency filter system is capable of comfortably achieving Class 1 performance at flow velocities as low as 40 fpm!

## Transport of Particles - Process Considerations

In the absence of re-entrainment, with proper airflow distribution, even low airflow velocity (e.g., 10-20 fpm) can easily sweep off or transport generated particles out of the room. The mobility of submicron particles due to diffusion mechanisms is still much lower than the convection mobility at such low flow rates. Up to about 65 fpm, higher velocities will have faster convection transport of such particles- but these differences may not always be significant in the time frame of the cleanroom processes. The residence time, Tr, in the above elemental volume is given by:

Tr= Volume/Flow Rate = 1/Q **(4)**

Thus, at 20 fpm the residence time will be 3 sec.: at 40 fpm, it will be 1.5 sec., and at 60 fpm, it will be ~ 1 sec. What needs to be determined is the probability of whether the existence of the particle for this time frame, within this volume, will have a detrimental effect on the product. This should be one of the primary reasons for increasing airflow velocity. The answer can only be obtained via statistical analysis of QCA data.

Recent studies [3-5] show that due to turbulent re-entrainment and eddy formation, there is no gain in cleanroom performance at velocities higher than about 65 fpm.

### Turbulent Re-entrainment, Diffusion, and Convection

Re-entrainment can be due to turbulence and convection -due to gradients in room pressure. These gradients are typically a result of poor distribution of airflow through the ceiling. At flow rates typically used in cleanrooms it is unlikely that particle diffusion plays a role in the re-entrainment process, except in zones of very low velocity.

Many cleanroom standards or guidelines call for 90 fpm velocity through ceiling HEPA filters. There is simply no basis for this. Recent work conducted at Sematech [3] and MIT [4] and related work at Asyst [5] has shown that 90 fpm flow velocity is too high and can, in fact, lead to turbulent re-entrainment. Most of these researchers have recommended that the maximum velocity for a well-distributed ceiling discharge should not exceed about 65 fpm. Note also that from a strictly dilution point of view, the dilution model also shows that there is no improvement in room concentration above about 60 fpm velocity.

To precisely design for minimal turbulence and re-entrainment, finite element or finite difference analysis methods are typically used to solve the Navier-Stokes fluid mechanics equations. It is beyond the scope of this article to describe those methods here. It should be sufficient to state here, however, that such methods typically require personnel with significant training and experience in numerical fluid mechanics (computational fluid dynamics) to produce accurate results.

### Airflow distribution

As discussed above, one of the main reasons for particle entrainment and turbulence is poor airflow distribution. Airflow distribution is probably the most important aspect of airflow design in cleanrooms. Unfortunately, not enough attention has been paid to this matter, and instead a great deal of emphasis has been placed on invalid criteria such as 90 fpm filter velocity.

With better distribution, less total airflow is needed resulting in higher performance and lower energy costs. A cleanroom with 100% ceiling coverage of filters will outperform a cleanroom with lower ceiling coverage even if the lower coverage system has significantly higher airflow rate. Thus airflow distribution itself is a major variable that can affect cleanroom performance and energy costs.

## Air Handling

Air handling systems are also a factor in cleanroom performance and cost, since different types of air handling systems have different characteristics in terms of practical filtration efficiency and airflow distribution. An ideal air handling system should have the following characteristics:

a) Independence of flow rate and filter velocity (in the room). This characteristic allows for controlling air flow distribution in a cost effective manner
b) Allow for higher filtration efficiency, including the use of double HEPA filtration. As we have seen above, double HEPA filtration can enable highly efficient filtration systems that can use lower airflow rates. While ULPA and better than ULPA filters have significantly higher efficiency than HEPA filters, one of the main advantages of double HEPA filters is that the secondary or terminal HEPA filter should normally not require any servicing. All filter servicing is done outside the room thus eliminating cleanroom contamination and reducing downtime during filter servicing.
c) Enable use of energy efficient and durable electric motors. The system should be highly reliable.
d) Have low noise radiation into the room.
e) Provide for cost effective air cooling/heating/humidification/dehumidification.

There are three main types of air handling systems:

1. The centralized air handling system
2. The ceiling distributed system - based on Fan Filter Units (FFU) with or without booster fans.
3. A new hybrid system - we will simply call this the "distributed air handling system". This system does not use any air movers in the cleanroom ceiling.

### 1. <u>The Central Air Handling System</u>

The traditional central air handler includes typically custom rooftop air handlers used with some level of pre-filtration. The air is supplied to the room via terminal HEPAs using "spider leg" ducting. Some older cleanrooms designs used a pressurized plenum to distribute the air into the terminal HEPAs. However, this practice is now frowned upon, especially for Class 1000 and better cleanrooms, due the high probability of leakage of unfiltered air into the cleanroom.

This system meets the above requirements in terms of airflow distribution, filtration efficiency (including double HEPA filtration), reliable motors and low noise radiation. The main disadvantage with this system this system requires customized units, since often non standard coils and velocities are required. Standard air conditioning systems (not for dehumidification) cost about $350 to $400 per ton, while customized units can cost anywhere from $1200 to $2000 per ton. Additionally, customized rooftop units can be significantly heavier than standard units. Thus, in some cases roof structural reinforcement becomes necessary. Obviously, this adds to the cost of the project.

## 1. The FFU System - Ceiling Distributed Air Handling

Typically, FFUs are used in a ceiling with a negative pressure plenum. The air handling units simply feed air into this "negative" pressure plenum. Since FFUs do not develop the pressure head required to overcome ducting flow resistance, either custom air conditioning systems or booster fans are often required in conjunction with the FFUs. The main advantage of this is simplicity. However, this system has the following drawbacks:

1. The plenum can often have zones of positive pressure depending on the ceiling coverage of the FFUs. This can cause leaks into the room.
2. The FFU, puts out a quantum amount of flow in a 2'x4' ceiling space. *Flow rate and velocity are not independent variables* - this does not lend itself to *efficient* design for proper airflow distribution. It is not possible, with the FFUs, to use the energy consumption advantages of 100% or high (ceiling coverage) airflow distribution along with lower supply velocity, in a cost effective manner.
3. The system does not lend it self to double HEPA filtration.
4. Although, FFU motors have become more efficient with the use of energy efficient DC fan motor, the energy consumption values can be misleading. One must consider the energy cost of AC to DC conversion.
5. Although individual FFUs can be very quiet, the use of multiple fans (in some cases hundreds of them) can result in significant noise level being radiated into the room.
6. When many FFUs are used, it is essential to have a monitoring system to check the status of each motor for assured proper operation of the cleanrooms.

## 3. The Hybrid Distributed Air Handling System

**Figure 11** shows the airflow schematic of the distributed air handling system.

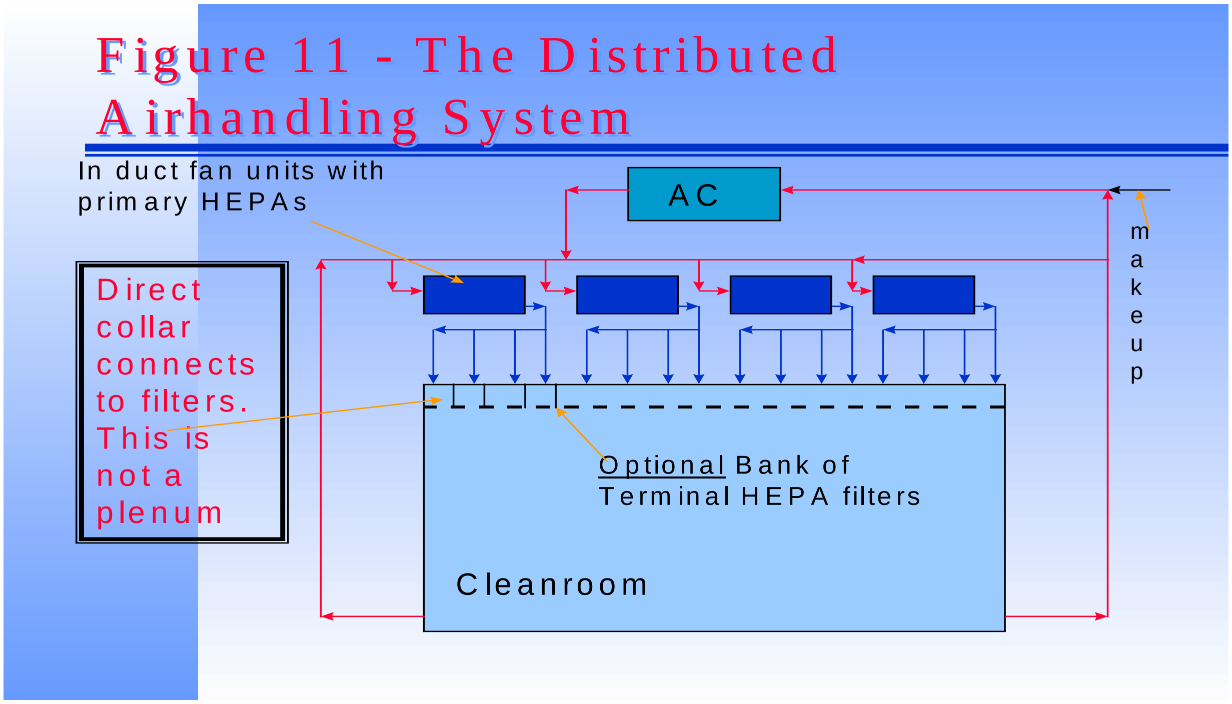


Figure 11 - The Distributed Airhandling System

Basically, the system uses distributed IN-DUCT filters with fans, each capable of about 4 times the flow rate of a FFU. Part of the return air is processed through conventional AC units and this temperature and RH conditioned air is combined with the rest of the return air in the in-duct filters. The in-duct filters thus also act as a mixing box. The main advantages of this system are as follows:

A. Airflow rate and filter velocity are independent…100% or less ceiling coverage/airflow distribution is easily facilitated, without affecting total airflow rate.
B. Double HEPA filtration, with all its advantages, is conveniently and cost effectively accomplished for Class 1-100 rooms.
C. There is no need for terminal filters for Class 1000 and higher cleanrooms.
D. Inexpensive standard AC units can be used - rather than expensive custom units for centralized and FFU systems.
E. No leaky plenums – this results in savings in initial costs.
F. Less noise inside the cleanroom.
G. High quality, energy efficient 3 phase motors can be used.
H. Filter change-out is done away from the room. Thus there is no need to service terminal filters in or over the room. This leads to less downtime and avoids room contamination.

This hybrid system also readily lends itself to the use of Electrically Enhanced Filters (EEF) as the first stage HEPAs in a double HEPA filtration system. The EEF filter has two primary advantages:

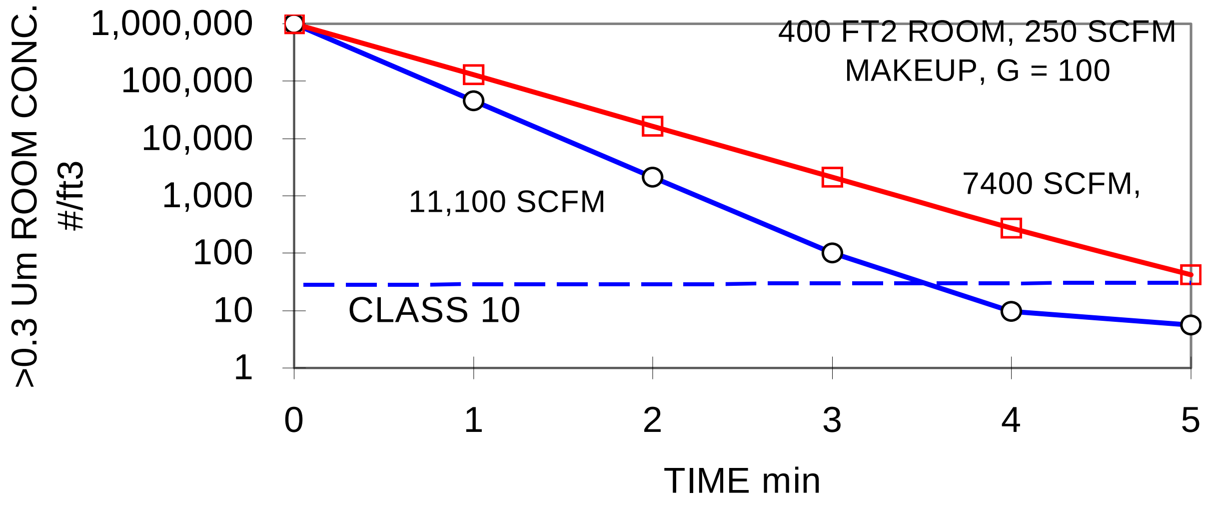
a) It has been shown to be bactericidal and results in lower bio burden in cleanrooms [2,7].
b) The EEF has lower pressure drop than conventional HEPA filters at the same flow rates[2].

## Summary

This paper has discussed the methods used in cleanroom design and impact of various factors affecting cleanroom performance and energy consumption. Clearly, cleanroom airflow design is too complex to use the design charts. On the other hand the dilution model presented above does not take into account transport phenomena. A different approach is to use assume well-distributed airflow and to use the solution to the particle material balance differential equation [2] to the dirtiest zone in the cleanroom. This solution enables the transient calculation of the room concentration after the room has been contaminated as shown in **Figure 12**. The proper airflow is chosen based on how fast the room cleans up. A cleaner environment is expected to cleanup faster. This model has been successfully applied by Technovation in over 50 cleanrooms. It is beyond the scope of this paper to present details of this approach.

FIG 12 TRANSIENT RESPONSE CALCULATION

EEF HEPA FILTERS - DOUBLE HEPA SYSTEM



The following are the main conclusions from this work:

A. The current design charts are not adequate for efficient design.
B. The dilution model properly takes into account filter efficiency, particle generation and airflow rates. Transport is not described.
C. A hybrid distributed air handling system, with or without double HEPAs, can reduce airflow and energy consumption, especially if low pressure drop primary (EEF) filters are used.

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