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REVIEW PAPER

Elements of Clean-room Technology and Contamination Control

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ABSTRACT

The heart of the clean room is the high efficiency particualte air (HEPA)/ultra-low penetration air (ULPA) filter, which provides the highest level of air cleaning ever achieved by a single-process step. Filter technology has seen tremendous growth in terms of ultimate performance and air handling capacity. Mere installation of ULPA filters of 99.99995 per cent efficiency for 0.2 μm aerosol is not sufficient for achieving the desired performance of a clean room. Other design aspects like flow fields, face velocity, number of air changes, make-up air fractions and precise control of other environmental parameters (temperature, humidity, airflow, noise, vibrations, electrostatic discharge, etc.) are equally important.

Keywords: Clean-room technology, clean-room design, contamination mapping, super clean rooms, clean rooms, filters, high efficiency particulate air filters, ultra-low penetration air filters

1. INTRODUCTION

Rapid advances in semiconductor and thin-film technology, tremendous growth in microelectronics, shrinking of physical geometry of electronic components and increasing density of components on a single chip during the last two decades have offered stiff challenges to clean-room designers and contamination mapping technologies. Apart from semiconductor and electronics industries, there are various other applications like microbiotechnology, pharmaceuticals, high precision manufacturing and assembly of electromechanical and optical components, nuclear energy and nuclear weapon assembly, and high purity material processing, which require high-level control of particulate levels and ambient conditions.

The semiconductor industry always leads the high-tech world with its efforts to establish highly controlled manufacturing environment that comply with the clean room/super clean room standards. These contamination control efforts serve to increase factory output by increasing wafer throughput, wafer yield and die yield. Material purity has always been a primary requirement for high quality products. Challenges of 0.13 μm line width with aspect ratios up to 8:1, the capability for three to six metal layers, shrinking layering thickness and the development of the 300 nm wafers continue to push the control levels to higher limits. Development of electronic modules with increased circuitry density, the expansion of interconnecting layers and the addition of sealed devices mounted directly onto the circuit boards require immense control of surrounding environment.

Although there are numerous processes, materials, and chemicals that require specific environment with a high degree control of particulate level and other parameters like temperature, humidity, airflow,

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noise, vibrations, electrostatic discharge, etc.; the primary goal of the controlled/clean-room environment remains the quality, reliability, and consistency of the production yield. Ultra-clean environment in semiconductor and many other industries has become a necessity for enhancing profitable results and improving product yield by lowering the rejection rate.

2. GENERAL REQUIREMENTS OF THE CLEAN ROOM

The complexity of the clean room needed to provide satisfactory working conditions for personnel and contamination-free environment for processing and assembly depends on the nature of the contaminants to be removed (eg, radioactivity, toxicity, corrosivity, particle size and size distribution, particle shape, and viscidity, etc.); on temperature, humidity, and other conditions of the environment to be controlled; on the probability of an upset or accident; and on the extent of hazard in the event of such an upset.

The design of the clean room takes into account the following requirements:

(a) Prevention of contamination due to the entry or exit of personnel, material, processes, and circulating air.

(b) Elimination of built-in traps, ledges, and unnecessary horizontal surfaces (where contamination can accumulate), and ensuring that all parts of the room are accessible for cleaning.

(c) Ensuring removal of contamination generated inside the clean room.

(d) Provision of facilities for airconditioning and filtration.

(e) Provision of fail-safe continuous clean air supply; even during planned and unplanned outages.

2.1 Airborne Particulates & Gases

Although removal of process-generated particulate matter is the primary reason for installing particulate-control equipment and ultra clean-up filters in the clean room, there are other major sources as well for airborne particles. For example, a person at rest exudates more than 2.5 million particles (through the skin, hair, etc) and moisture droplets per minute, in the size range 0.3 μm to 1.0 μm. Process-generated aerosols fall into two classes depending on their size range. Those produced by machining, grinding, polishing, and other mechanical operations are generally large, probably ranging from 1 μm to several hundred micron, according to the nature of the process, and can be removed effectively using common air filters or through other conventional air cleaning techniques.

The other class includes those produced by evaporation/condensation, and other chemical operations, which generate condensational aerosols and droplets that are often in the submicron size range. These aerosols are more difficult to remove from the air or gases, and recourse must be made to collectors, such as high efficiency particulate air (HEPA) and other higher grades of filters. Other process-generated contaminants may include chemical vapours, gases, fumes (eg, organic solvents, etching agents, acids, etc.) in a semiconductor industry or radioactive halogens and noble gases in a nuclear installation. Noble gases are separated by cryogenic fractionation, activated charcoal adsorption and are stored/delayed until a significant degree of radioactive decay take place. The halogen gases, essentially elemental iodine and organic iodides, constitute the most significant fraction of the gaseous effluent and are captured by adsorption on modified activated carbon or on certain synthetic zeolites.

2.2 Space & Airconditioning

The air circulation and the airconditioning within the clean room should fulfil the following requirements:

(a) Maintain laminar airflow with desired direction and velocity; free from eddies and vortices throughout the clean room.

(b) Carry away particles generated, or vapours released during processing within the clean room.

(c) Maintain the clean room at a small positive pressure relative to the outside air so that in

leakages of outside to the workplace is avioded completely.

(d) Control temperature and humidity of the clean room as per the process requirement and personnel comfort. [Relative humidity level (< 30 %) can give rise to static electricity problems and which may trouble the operators' skin and throat. High relative humidity (> 60 %) can cause condensation on surfaces leading to rusting and surface contamination].

(e) Reduce the particulate contamination level of make-up air entering the clean room.

(f) Provide adequate number of air-changes to continuously maintain clean room conditions.

In addition, noise and vibration are the other important factors required to be controlled in a clean room. Apart from this, discomfort to personnel, excessive vibration or pulsation can result in eventual mechanical damage to the system components. Vibration produces noise that can range from unpleasant to intolerable. An important stage in the prevention of excessive vibration and noise is the initial stage of planning and building layout and adopting design for good aerodynamics of ductwork, fan connection and fan mounting[1,2].

3. ELEMENTS OF THE CLEAN ROOM

3.1 Air Filtration & Circulation

Air filtration is the key to the current clean-room technology. Clean room cleanliness is measured by determining the number of particles of a given size (0.5 μm or more) per cubic feet of air, and is termed as the class of the clean room, eg, a typical office environment might be rated class 500,000 if the air contains 500,000 or fewer microscopic particles per cubic feet. On extreme end of this scale is the clean room of a modern semiconductor manufacturing facility which is rated Class 1, having, at the most, one particle of 0.5 μm in any cubic feet of air and also meeting concentration standard of very fine particles, i.e., 0.12 μm.

In a conventional clean room, the air enters the clean room through a filter bank situated either on the ceiling or on the one of the walls of the clean room; and flows across the clean room to outlet filter bank located opposite to the inlet filters bank, providing a streamlined airflow pattern across the clean room. It is important to adjust the flow rate for achieving a condition as close to the 100 per cent laminar air flow, since, more the air flow approaches laminarity, better will be the control of particulate contamination, temperature, and humidity throughout the clean room.

An efficient air filtration system generally consists of a series of filter banks, which progressively remove larger-to-sub-micron particles. The pre-filter system, upstream of the final high efficiency filter bank, generally consists of two high-capacity pleated panel filter stages, one rated at 30 per cent efficiency, and one extended-surface rigid air filter with an ASHRAE efficiency rating at 80-86 per cent for 0.5 μm particles. These filters provide maximum protection to the final filter while offering low air flow resistance, thus optimising system operating costs. The final filter stage comprises HEPA filters rated at 99.97 per cent on 0.3 μm or a ultra-low penetration air (ULPA) filters rated at 99.999 per cent on 0.3 μm (Table 1). Overall clean-room conditions achieved in a facility are based, to a large extent, on the number, grade, and quality of HEPA/ULPA stages of the air filteration system.

Table 1. Performance of filters by grade of media

Medium	Efficiency
HEPA	99.97000 % on 0.3 μm
ULPA	99.99900 % on 0.3 μm
VLSI	99.99950 % on 0.12 μm
VLSI II	99.99999 % on 0.12 μm

3.1.1 *High Efficiency Particulate Air Filters*

HEPA filters are made of micro glass fibre paper of 0.50-0.70 μm diameter, which is pleated to maximise the filtration area of the filter paper packed in the filter. Normally, HEPA filters use pleated aluminium separators, tape, glue, strips or strings to separate adjacent pleats of the media to

facilitate uniform air flow through the cross section of the filter, but completely separatorless filter elements, which are very efficient for clean-room applications, are also available. Both, these types of filters have their advantages and disadvantages.

Most commonly used HEPA and ULPA filters remove particles from the air stream using two basic particle removal mechanisms, i.e., Brownian diffusion and direct interception as inertial impaction is not an effective mechanism for particle size of interest at low velocity regimes, these filters operate; since bigger size particles are removed by pre-filters. Construction of the filter media pack also plays an important role in maintaining the cleanliness as well as airflow laminarity in a clean room. These factors–uniform resistance of the filter media and a large number of properly shaped parallel pleats–are very important characteristics of the filter for overall clean room's performance.

High quality laminar flow-grade filters are scan-tested, and effeciencies measured on a generalised most penetrating particle size using parameters typical of of the facility where such filters are to be used. Mostly, penetrating particle size is dependent on many factors, including particle density, air velocity, thickness of the medium, and size and distribution of fibres, hence, for ultimate high performance, these factors must be considered.

3.1.2 *Effect of Underrating/Overrating*

Usage of the filtration system can be extended and system pressure drop from a given level of dust loading can be reduced by underrating, that is, by installing filter of slightly more capacity than is required, based on system design airflow needs. Figure 1 shows the effect on the filter life obtained by underrating; but design optimisation should consider the initial installation costs with the operating and replacement costs in the facility.

Operation of the system at airflow greater than the installed airflow capacity should be avoided at all costs since when air flow rates exceed rated air flow capacity of HEPA filters, not only the filter's life decreases more rapidly than the equivalent

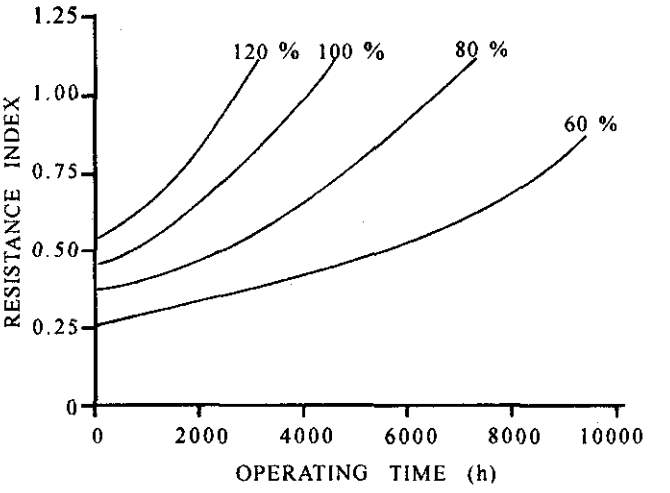

Figure 1. Effect of underrating on service life of extended medium filters, based on percentage of manufacturer's rated air flow capacity.

increase in flow rate, as can be seen from the 120 per cent curve in Fig. 1, but operating costs also shoot up.

3.1.3 *Uniformity of Airflow*

In large air cleaning systems, because of the improper design of the system components, specially inlet plenum and outlet transitions, filters at the centre of a filter bank may receive higher airflow than those at the periphery of the bank. This not only results in non-uniform dirt loading of filters, but may result in excessive penetration of those HEPA filters closer to the air intake if the degree of airflow uniformity is high.

Figure 2 shows that the penetration of HEPA filters by sub-micron particles is directly velocity-dependent and increases significantly at high flow rates, and it is a very important factor in higher cleanliness clean rooms. If some filters are operating at very high airflow and some at very low airflow, as could happen in poorly designed housing and filter bank, it is possible that significant penetration could occur even though the filters are in good condition. Therefore, operation at low airflow rates than the rated airflow rates, and well-designed duct-to-housing transitions increase the efficiency of the air cleaning systems.

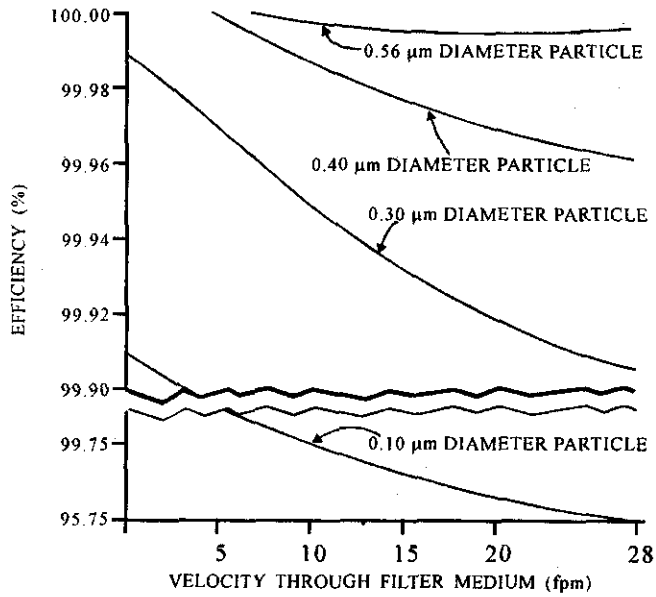

Figure 2. Penetration of HEPA filter medium by sub-micron particles as function of flow rate through medium.

3.1.4 *Airflow Laminarity*

Another closely associated major factor of clean-room performance is the degree of laminarity for airflow in the facility. Straight, parallel streamlines throughout the clean room guarantee that air is replaced at the design air changes in the total volume of the facility, and that particles generated due to the manufacturing process in the clean room do not become trapped in vortices, where these may accumulate and cause contamination at the workplace surfaces.

Laminar airflow may be either vertical or horizontal. Although vertical airflow is generally more expensive, it produces the cleaner working conditions, because any contamination is carried immediately downwards, out of the room and away from other workplace positions. Therefore, appropriate air velocity in a clean room is adjusted to ensure that contamination generated is removed from the clean room before it has time to settle under gravity.

Air supply needs to be monitored constantly to ensure that the required airflow is being maintained, and any reduction due to flockage in a filter or defect in the air supply system need to be compensated by providing feedback to the flow-control device.

Clean room is maintained at a low positive pressure relative to the outside air (>1.5 mm of water gauge (WG) so that in-leakage of contaminated air is prevented. In a multi-zone clean-room design, leakage, if any, should take place from the cleanest to the less cleaner zone, and hence, pressure gradients are accordingly balanced.

3.2 Chemical Contamination Control

A wide variety of industrial and commercial applications require to control odours, corrosive gases, and airborne hazardous chemicals. Recently, chemical-grade products, such as chemical absorbents, granular activated substrate adsorbers and deep-bed adsorber systems have become available and can be used effectively, depending upon the contaminants to be controlled. Catalytic combustion systems are highly effective in eliminating hard-to- recycle noxious voc emissions as well as solvent gases from the paint, printing, chemical, electrical wiring, and rubber industries. It can also be effectively used for post-treatment of gases after processing by gas-adsorption equipment.

Operations which generate dirt and vapour should not be carried out inside the clean room, eg, soldering, removal of small amounts of material during fitting and assembly by scraping, filling, or grinding, or the use of solvents or processes involving the generation of vapours by chemical reactions. Where it is not possible to separate out such operations, proper installation of vacuum duct or vapour extraction arrangements or separate laminar air flow enclosures should be provided.

4. DESIGN FEATURES OF AIR HANDLING & CIRCULATION SYSTEM

It is important to understand the complex nature of the total air handling system for a really good design to evolve as the system is not only large, i.e., handling well over a million cubic feet of air an hour, but control of temperature and humidity in several independent areas, and maintaining all velocities at the design level is a highly difficult technical problem. Therefore, fan system with

inlet-outlet plenum/ducts and dampers should be thoughtfully designed, constructed, and tested.

4.1 Ductwork or Plenum System

The sizing and layout of ductwork to provide desired air distribution, ventilation rate, transport velocities and other functional requirements of an air cleaning system are covered by ASHRAE handbooks, ACGIH Industrial Ventilation, and ANSI Z9.2 code. The physical layout of ductwork in a building is often compromised to conform to the confines of a building structure or design. This may be unavoidable when installing new ducts in an existing building. In a new construction, however, consideration should be given to providing adequate space and optimising configuration for duct layout, in the earliest phases of building layout, long before the building design has been finalised. Easy access to filter housings, fans, dampers, and other components is vital to maintainability and testability, and hence, to reliability of the system. The allowance of adequate space for well-designed elbows, size transitions, and fan inlets and outlets is vital to least-cost operation.

4.2 Dampers

By definition, a damper is any device that controls pressure, direction, or volume of airflow in a ventilation system; including those items normally classed as valves used in piping systems. Clear, concise specifications must be established for mechanical strength, for leakage rate at maximum operating conditions, and for the ability to perform under required operational conditions.

4.3 Fan System

Fan and motor with inlet and outlet transitions, and fan control are the heart of the clean-room system. These must have sufficient capacity to deliver the design airflow at the maximum differential pressure, to which the system will operate under maximum load, just prior to the change. Consideration must, therefore, be given not only to the installed capacity required to operate at the higher pressure drop, but also to the fact that the fan operates at a penalty for much of the time to provide the required airflow over the wide span of pressure drop between installation and replacement of filters.

Fan horsepower can be estimated from the following equation:

$$h_{pf} = \frac{Q\Delta p}{6356 E_f} \quad (1)$$

where h_{pf} is the fan horsepower and Q is the system airflow, cfm. Δp is the maximum pressure drop across air cleaning system at the time of filter replacement in inches of WG and E_f is the fractional efficiency of fan, (usually assumed = 0.60 for estimating).

Motor horsepower can be estimated from the Eqn (1) as

$$h_{pm} = \frac{h_{pf}}{E_m} \quad (2)$$

where h_{pm} is the motor horsepower, h_{pf} is the fan horsepower, and E_m is the fractional motor efficiency (usually assumed = 0.90 for 20 hp motor and larger).

4.3.1 *Fan Performance vs System Performance*

The increase in resistance across the filter is usually the major factor influencing the pressure flow relationship (represented by the numbered curves in Fig. 3) of high efficiency air cleaning system. Fan performance (airflow versus pressure capability) and system resistance versus airflow are represented by characteristic curves[3], such as curve A, (1 and 2) of the Fig. 3.

The volume of air that can be delivered by the fan is determined by the intersection of the fan and system characteristic curves (Fig. 4). The airflow represented by this point of intersection is the only airflow that can be delivered by the fan under the given operating conditions. In most cases, a fan with a steeply rising characteristic (curve A, Fig. 4) is desirable to maintain reasonably constant airflow in the system over the entire life of the HEPA filters. Pressure equalising device (damper)

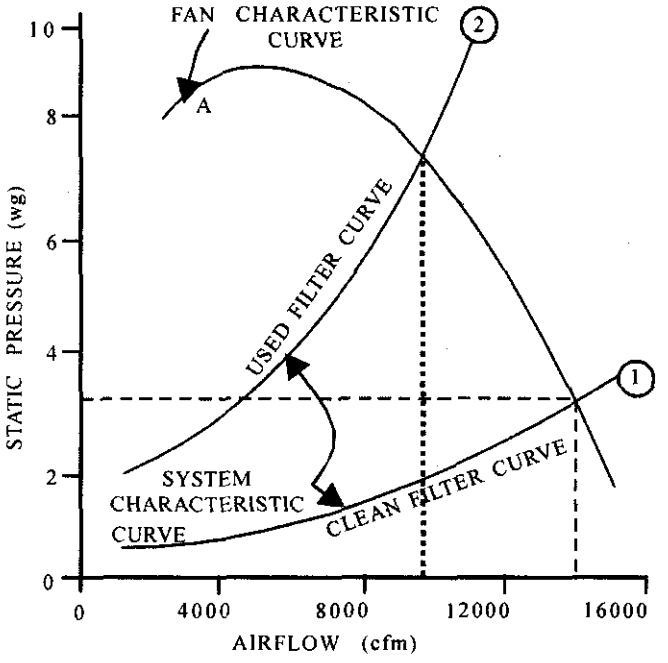

Figure 3. Fan and system characteristic curves showing relationships between airflow delivery and resistance.

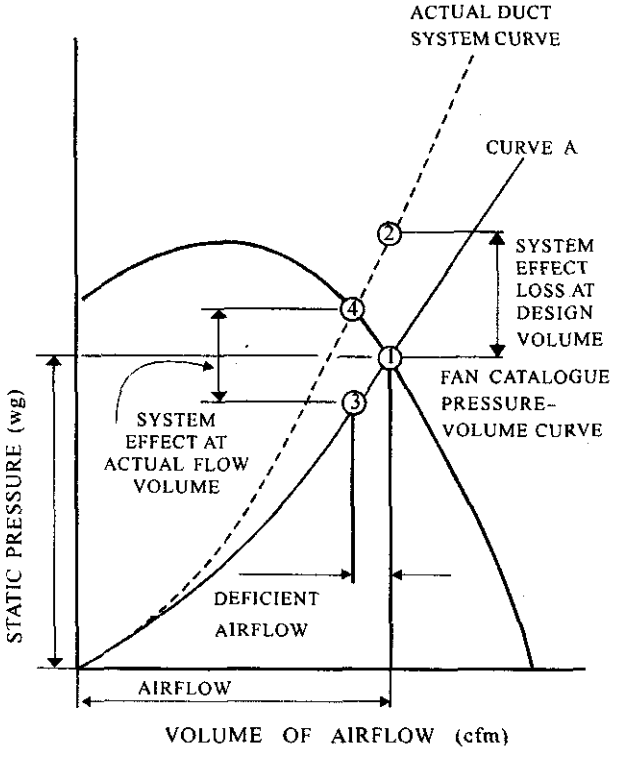

Figure 4. Result of selecting a fan on the basis of manufacturer's ratings. Curve A shows calculated duct system curve with no allowance for system effect.

is usually installed to balance system pressure against filter pressure drop to maintain a constant pressure airflow relationship in the system but at higher operating power cost.

The inability of fans to perform in the field in accordance with the published ratings has long troubled the industries. The problem arises partly because the ratings are based on idealised laboratory conditions, and partly because of design and field compromises made to accommodate the field conditions. Many of the problems of fan operations stem from poorly designed connections to the duct, cross-coupling, too short transitions between unmatched (in size) duct and fan inlets, square-to-round transitions. Poorly designed inlet boxes create a vortical or eccentric flow into the fan impeller and result in noise, and reduced efficiency*.

4.3.2 *Fan Reliability*

Air moving devices in any clean room facility must provide trouble-free reliable services, often for long periods of time and with minimum maintenance. Recent years of successful operation have proven that carefully chosen in-line centrifugal and vane-axial fans are capable of providing such services. These fans require less volume and space for a given volume-pressure duty, and their installed weight is generally less than other conventional air moving devices. In addition, because of the straight through design, these can withstand shock waves in the duct system better than the conventional centrifugal fans, and these can tolerate high humidity and temperatures without failure or loss of efficiency[4].

4.3.3 *Fan Installation & Location*

Proper mounting of the fan minimises noise and vibration and also reduces maintenance costs. Noise is undesirable in supply and exhaust systems and is often difficult to eliminate after the system goes into service and also costly. Vibration and pulsation that may be detrimental to filters, adsorbers, and other components often accompany excessive noise in exhaust and air clean-up systems. Flutter or reeding of filter separators can cause bypass between frame and filter medium, and vibration of activated carbon adsorbers can cause settling and

*AMCA-201 "Fan Application Manual" provides guidelines for the designer to predict the system effects for various system configurations and to determine the actual fan required to produce the designed operating characteristics.

crushing of the granules and eventually, carbon loss leading to bypassing of contaminated air.

When practicable, mounting of the fan and motor on a common base, designed for isolation of vibration is recommended and careful balancing of the fan shaft and impeller minimises vibrations. Fan and filter housings also should be designed for minimum resonance. Fan location has a direct bearing on ventilation and air cleaning system performance and must be selected very carefully, taking into consideration the maintenance requirements.

4.3.4 *Airflow Control*

Control of airflow and air pressure are two important parameters in an air cleaning system. These can be achieved by: (i) control dampers, (ii) variable inlet vanes on the fan, (iii) variable speed fan, or a combination of these. A comparison of fan and system operating characteristics with different methods of airflow control is shown in Fig. 5 and should be chosen based on the specific needs of the system.

5. SERVICEABILITY & MAINTAINABILITY OF SYSTEM COMPONENTS

Maintenance and serviceability are two operational factors whose cost can be minimised by good initial design and layout of ventilation and air cleaning facilities. Two elements that largely influence the costs of these functions are the accessibility of components requiring periodic test, and service and the frequency of filter and adsorber replacements.

The location of filters, fans, other contamination-control components and working space adjacent to these play a major role in system accessibility for maintenance and testing. Failure to provide adequate space in and around housings and mechanical equipment (fans, dampers, etc.) results in high maintenance and testing costs, inhibits proper care and attention, and creates hazards.

Use of good quality supply air filters and pre-filters, operation of HEPA filters to high pressure

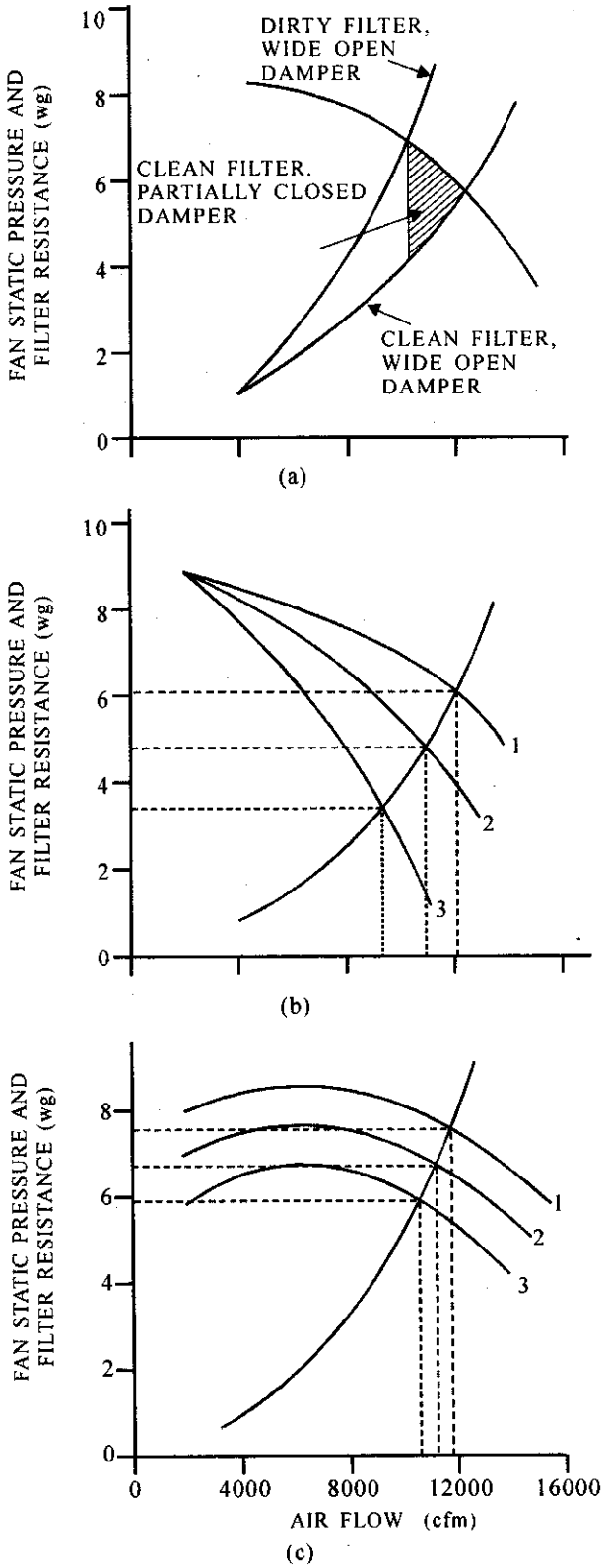

Figure 5. Comparison of fan and system operating characteristics with different methods of airflow control: (a) damper control (b) inlet vane control, and (c) variable speed control.

drop, and underrating serve to extend the component life and reduce the frequency and cost of service. HEPA filter and adsorber installations must be tested after each component change; therefore, any extension of service life directly reduces testing costs.

6. CLEAN-ROOM TESTING & CERTIFICATION

Clean-room facilities are required to be tested for compliance with the relevant specifications. Stringent testing is necessary to achieve and maintain the high performance levels required for a clean room. Verification of air cleanliness shall be accomplished by measuring the concentrations of ultra-fine airborne particulates under specified operating conditions.

The status of the clean-room or clean zone during verification/testing shall be reported as as-built, at-rest, operational, or as otherwise specified in the design specifications. For higher clean-room classes, U-descriptors (number of ultra-fine particles) should be specified besides the class and should be complied with[1**].

Measurements and observations of applicable environmental factors related to the clean room or clean zone should be recorded. Such factors include air velocity, air volume change rate, room pressurisation, make-up air volume, unidirectional airflow parallelism, air turbulence, air temperature, humidity or dew point, noise level, and room vibration. Transfer and presence of equipment and personnel activity should also be monitored and controlled; and documented[1,5-7].

7. CONCLUSION

Dedicated and clean room/super clean room facilities with stringent, state-of-the-art control measures for temperature, humidity, electrostatic discharge, noise, and vibration are required for efficient and quality production. Flexible arrangements and the requirements for rapid adjustments to changing and demanding market and technology conditions promote the use of modular design in a state-of-the-art clean-room facility. Whatever be the design of a clean room, regular maintenance and testing of the facility for compliance with the standards and other relevant specifications is very essential. Good initial design and layout of ventilation and air cleaning facility; and proper selection of various clean-room system components can minimise maintenance and the testing costs.

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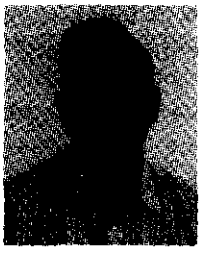
** For a detailed procedure and techniques for clean room testing, Fed Std 209E can be referred to.

Contributors



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