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ENERGY SAVINGS IN CLEANROOMS FROM DEMAND-CONTROLLED FILTRATION

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Abstract
In cleanrooms, very low particle concentrations are maintained by recirculation of air at a high rate (e.g., 600 room air volumes per hour) through highly efficient air filters. We report results in a Class M3.5 (Class 100) cleanroom with 28 m^2 (300 ft^2) floor area, where significant energy savings were realized by controlling the rate of air recirculation through the filters in response to real-time measurements of particle concentrations. An inexpensive, $2500, optical particle counter was used to measure particle concentrations. The effect of varying the recirculation air flow rate on particle concentrations was investigated. Changes in recirculation fan speeds of 10% or greater did not cause a noticeable particle release from filters or resuspension from indoor surfaces. With new automatic control systems in operation, there were occasional, usually fewer than 10 per day, non-consecutive one-minute episodes in which the particle concentration exceeded Class M3.5 (Class 100) status. Depending upon the choice for baseline energy use, the energy consumption of the recirculating fans was reduced by 60% - 80% and the estimated payback period for a 90 m^2 (1,000 ft^2) Class M3.5 (Class 100) cleanroom is from 1 to 4 years.

Introduction
Cleanrooms are extensively used in the manufacturing of computer equipment (integrated circuits), sub-micrometer size particle sensitive equipment, and in the biological and pharmaceutical industries. To maintain low particle concentrations, for example less than 3,530 particles/m^3 (100 particles/ft^3) at >0.5 micrometers, the air in the room must be filtered. Typically air in a cleanroom is circulated through high efficiency particulate air (HEPA) filters at a very high rate (e.g., 400 - 600 room air volumes per hour) to maintain very low particle concentrations. The combined effect of very high recirculation with a high pressure drop through HEPA filters translates to very high average power costs per unit floor area to operate a cleanroom as compared to the average power costs per unit floor area to ventilate a commercial building.

A current design guideline for cleanrooms is to establish a nearly unidirectional flow of filtered air at 0.3 - 0.5 m/s (60 - 100 ft/min) usually from ceiling to floor. Thus, any particles that are not filtered out of the supply air or that are generated in the room, will be carried through the room via the minimum distance possible and thus have the lowest probability of impacting upon a critical area of a product. Also, if any disturbance in the unidirectional flow occurs in a cleanroom operating at 0.3 - 0.5 m/s (60 - 100 ft/min), the flow pattern is quickly reestablished.

Usually manufacturers who use cleanrooms to mass-produce products attempt to maximize the usage of the facility by using the room 6 or 7 days per week for 2 or 3 shifts per day. Thus, cleanroom fans are typically run 24 hours per day, 7 days per week in order to maintain very low particle concentrations. It is commonly thought that if the cleanroom fans are turned down or off that it may take many hours to have the room back to specifications. Also, it is thought that if the fan speeds are changed by any significant amount, there will be an increase in the airborne particle concentration in the room from particles being disturbed. Finally, manufacturers of semiconductor devices report that the cost of energy to run their cleanrooms is small compared to the cost of manufacturing, thus, they are not willing to jeopardize their products in order to save a small amount in their energy costs.

Other smaller cleanrooms such as the one used for this study, may be used less than 40 hours per week. There may be processes that do not require cleanroom conditions, but are done inside the cleanroom for convenience. Thus, the cleanroom may not always need to be maintained at the same level of cleanliness.

The components of this technology: computer control systems for building heating, ventilation and air conditioning (HVAC) systems, variable frequency drives for fan motors, and particle counters have been developed, refined and reduced in price within the last decade. The use of computer controlled systems and variable frequency drives has become a fairly routine practice in buildings.

Description of Demand Controlled Filtration

Demand-controlled filtration (DCF) is a method of controlling particle concentration in a room by changing the recirculation flow rate based upon real-time measurements of particle concentrations. As measured particle concentrations rise above set limits, recirculation fan speeds are increased. Similarly, as the particle concentrations fall below a set limit, recirculation fan speeds are decreased. By maintaining lower average fan speeds, the energy consumed by fan motors is decreased.

Cleanroom users may have concerns about the use of DCF for the following reasons: (1) they expect a burst of particles when the fan speed is changed significantly; (2) the time to reestablish satisfactory cleanroom conditions after fans have been lowered, is thought to be excessive; and (3) any product exposed to an environment with DCF will result in a lower product quality and yield because the cleanroom environment will be degraded.

Experimental Facilities, Instrumentation and Procedures

Facility

The facility used to evaluate DCF is a Class M3.5 (Class 100)[1] cleanroom with a nearly rectangular floor area of 28 m^2 (300 ft^2) see Figure 1. This cleanroom is used primarily as a laboratory for the fabrication of silicon detectors and is adjacent to and entered from a Class M5.5 (Class 10,000) cleanroom. The Class M3.5 (Class 100) cleanroom is used 2 - 4 times per week for 1 - 4 hours per day. The maximum weekly usage of the cleanroom that was logged during our data collection was 13.5 hours. Usually one person and occasionally as many as three persons used the room at the same time. Occupants use standard cleanroom apparel (hairnet, nose and mouth mask, gloves, booties and body suit).

Outside air is supplied to the Class M3.5 (Class 100) room from the same fan that supplies the Class M5.5 (Class 10,000) room. The outside air is prefiltered before mixing with a much larger quantity of air drawn from the cleanroom. The mixture of outside and recirculation air passes through four parallel recirculating fans and then through HEPA filters that cover the entire ceiling area. Except near two exhaust hoods (see Figure 1), air travels in a unidirectional downward direction and is returned via grilles on all four walls located just above floor level.

Each of the recirculating fans is driven by its own variable frequency drive (VFD) capable of varying each fan from 25% to 100% of full speed. Fan information is listed below.

Control Strategies

Except for the period when one fan was accidentally not operating, all fans were always operated in unison.

The preexisting control strategy, hereafter called "Preexisting," was based upon maintaining a set pressure drop across one bank of HEPA filters. The measured pressure drop was input into a proportional, integral and derivative control routine. Two setpoints were used, one for the day-time period 6:00 - 18:00 and the other for nights. The day-time setpoint was determined at the time the cleanroom was certified Class M3.5 (Class 100). During the day-time period, the fans ran at about 72 - 75% of full speed. At night 18:00 to 6:00, the setpoint was changed to realize some energy savings and the fans ran at about 58 - 67% of full speed. This control strategy was used every day of the week.

For the first DCF control scheme, hereafter called "Ten Percent," the particle concentration was read each second. If the particle concentration in either size range exceeded a high limit then the fan speeds were increased by 10% of the existing speed. As long as the measured particle concentration, in either size range, exceeded the high limit, the fans speeds continued to increase by 10% of the existing speed. If the particle concentrations for both size ranges were below a low limit, the fan speeds were decreased by 0.13% of the existing speed. With this control scheme the fan speeds could increase from 33% to 58% in 6 seconds and decrease from 78% to 33% in 11 min. Thus the rate of decrease was much lower than the rate of increase in fan speeds. The maximum fan speed was set to 78% (slightly above the typical daytime fan speed while using the Preexisting control scheme). The minimum fan speed was initially set to 28% but was subsequently changed (see details below) to 33% early in Phase 1.

The second DCF control scheme, hereafter called "Proportional," was a proportional routine. Every 6 seconds, the particle concentration from both channels was read. If either of the concentrations was above a high limit, the fan speeds were changed in proportion to the magnitude of the difference between the concentration and the high limit. If the particle concentration was slightly greater than the high limit, the fan speeds would increase by about 10% of the existing speed. If the measured particle concentration was much higher than the high limit, the fan speeds could be increased by as much as 70% of the existing speed. With this proportional control, the fan speeds could also be increased from 33% to 58% in 6 seconds. If counts for both size ranges were below a low limit then the fan speeds were decreased by 3% of the existing speed. This rate of decrease corresponded to a speed decrease from 78% to 33% in about 3 minutes. The fan speeds were always set between 33% and 78%.

Table 1. Recirculating fan information.

	Rated flow rate, lps (cfm)	Rated Power, kW (HP)	Measured power @ max. fan speed, kW (HP)
Fan #1	2550 (5400)	2.2 (3)	1.5 (2.0)
Fan #2	2800 (5940)	2.2 (3)	1.8 (2.4)
Fan #3	1720 (3640)	1.5 (2)	1.1 (1.5)
Fan #4	2210 (4680)	2.2 (3)	1.3 (1.8)

With the fans at 70% speed, the velocity of air in the cleanroom was measured using a hot wire anemometer at a height of 1.5 m (5 ft) from the floor and at the return grilles. At the 1.5 m (5 ft) height the velocity ranged from 0.15 - 0.50 m/s (30 to 100 fpm) with the most common reading being 0.30 - 0.36 m/s (60 - 70 fpm). At the return grilles the velocity ranged from 0.28 - 2.5 m/s (55 to 500 fpm) with most readings in the range of 2.2 - 2.3 m/s (440 to 460 fpm). Both exhaust hoods operated constantly with a face velocity of 0.70 - 0.76 m/s (140 - 150 fpm), with an opening of 0.20 m high by 1.50 m wide (8 in high by 59 in wide).

Particle concentration and fan power usage data were collected in three phases. In Phase 1, baseline data were collected on the system as it was run before implementing DCF. In Phase 2, DCF was implemented using a control scheme that increased the fan speeds by 10% of the existing speed whenever the particle concentration was above set limits. Finally in Phase 3, the first particle counter was replaced with a counter that had better resolution. Also in Phase 3 the fans were controlled based upon a proportional control scheme. Details of each particle counter and control scheme are outlined below.

The relationship between fan speed and power consumption was determined twice, using a Dranetz Series 808 power meter before Phase 1and an Angus PMT 1A power meter before Phase 3, both with an estimated accuracy of less than 5%. As expected there was a cubic relationship between fan speed and power. During the second calibration it was found that one fan had been accidentally turned off sometime after the first calibration. During this time period, the energy savings calculated assume this fan was always operating. The fan was switched on and the data collection continued.

Particle Counter

Both particle counters employed in our experiments, use a laser light scattering technique to count and classify particles in two size ranges, greater than 0.3 and greater than 0.5 micrometers. The first counter sampled air at the rate of 2.8 lpm (0.1 cfm) and was programmed to transmit every second the average concentration over the last 10 seconds. Assuming 100% counting efficiency, this produced an effective resolution of 2,100 particles/m^3 (60 particles/ft^3). This particle counter was used in Phases 1 & 2 and performed adequately, but better control of particle concentrations were thought possible with a particle counter that had greater resolution. For Phase 3, a particle counter was used that sampled air at a rate of 28 lpm (1.0 cfm). This particle counter transmitted counts every 6 seconds. The combined flow rate and sampling period gave an effective resolution of approximately 350 particles/m^3 (10 particles/ft^3), therefore, the second counter could detect changes in particle concentrations sooner. The counters were placed on a benchtop near a machine that was frequently used by the cleanroom users.

Data Acquisition and Control System

An existing energy management and control system was used for control of the fans and for data collection. Control was performed with software blocks which could run as often as every second, thus, control of the fan speeds could be updated every second. Recorded data though were one minute average values; therefore, the instantaneous maximum and minimum values of particle concentration and fan speeds during each one minute time interval were not recorded.

Results

Energy Savings

For energy saving calculations, two baseline average power values will be used. The first baseline is based on the average power measured, from 6:00 to 18:00 of 2.6 kW (3.5 HP), while using the Preexisting control routine. This corresponds to the average power used after the cleanroom was certified Class M3.5 (Class 100). The second baseline assumes that the motors have no VFDs or other means for speed control (which is typical) and thus operate constantly at full speed at an average power of 5.9 kW (7.9 HP). Below is a table showing energy savings for various control strategies.

Table 2. Average ± standard deviation of energy savings for different control strategies and two baselines.

CONTROL STRATEGY	**Average Energy Savings Per Day**		**Average Energy Savings During Occupancy**	
	Baseline1*	Baseline2**	Baseline1*	Baseline2**
Preexisting	10% ± 5%	60% ± 2%	0% ± 5%	56% ± 2%
Ten Percent	64% ± 1%	84% ± 1%	63% ± 2%	84% ± 1%
Proportional	64% ± 3%	84% ± 1%	60% ± 6%	83% ± 2%

* Average power for first baseline is 2.6 kW (3.5 HP).

** Average power for second baseline is 5.9 kW (7.9 HP).

The values in Table 2 show that energy savings were being attained while using the Preexisting control strategy by operating the recirculation fans at less than full speed producing a 60% savings of which 10% of the savings were from reducing the fan speeds at night. Greater energy savings, from 60% to 84% dependent upon which baseline is used, were realized by using the two DCF control routines. There was no significant difference in energy savings between the two DCF control routines. The percent energy savings while the cleanroom was occupied was nearly the same as when it was not occupied (and thus equal to the daily energy savings). During occupancy of the cleanroom, the fan speeds sometimes increased for short time periods, hardly affecting the daily average power consumption. Although the data is not shown in the table, there was a slight (less than 5%) reduction in the average power while using the high flow particle counter as compared to the low flow rate particle counter.

Particle Concentrations

We made investigations with the cleanroom unoccupied, manually controlling the fans to see the interaction between the fan speed and particle concentration. The fan speeds were lowered from 75% to 25% of full speed in steps, pausing to measure the particle concentration. A discontinuous response was found. At about 26% fan speed the particle concentration suddenly increased. With the fan speeds set to 25% we entered the chamber and moved the particle counter to different parts of the room. At wall penetrations, such as the telephone and thermostat locations, as well as in front of the return grille and at the junction of the ceiling plane and wall plane, there was a high particle concentration (3,530 - 35,300 particles/m^3 (100 - 1,000 particles/ft^3)). We hypothesized that the reason for these high particle concentrations was that at a fan speed of 25% of full speed and lower, some of the outside air entered the cleanroom backward through return ducts thus through return grilles and the wall penetrations without first passing through the HEPA filters. The wall penetrations provide a pathway from the return duct and the cleanroom. With the fan speeds set to 75% of full speed there were still a few locations, such as in front of some return grilles and at wall penetrations, with particle concentration as high as 10,600 particles/m^3 (300 particles/ft^3).

As the fan speeds neared 26% of full speed it would take from 1 to 50 minutes for the particle concentration to increase. If the particle concentration was high because of low fan speeds, it would typically take less than a minute for the particle concentration to decrease to near zero as the fan speeds were increased above 33% of full speed.

The fan speeds were manually controlled, with the room unoccupied, to see if a sudden increase or decreases (10% or greater) in fan speeds would produce an increase in particle concentration. There was no evidence of this, except, as noted earlier, if the fan speeds were decreased to 26% of full speed or less.

The number of minutes per day that the particle concentration was outside Class M3.5 (Class 100) boundaries (>10,600 particles/m^3 (300 particles/ft^3) for 0.3 micrometers and >3,530 particles/m^3 (100 particles/ft^3) for 0.5 micrometers) are shown in Figures 2 and 3. In general, these were discrete occurrences, and the minutes were not consecutive. The worst instance in which particle concentrations were beyond Class M3.5 (Class 100) status was after three occupants had used the cleanroom simultaneously. The particle concentration was out of bounds for 20, 30 and 23 minutes on three consecutive days including periods without cleanroom use. We suspect that due to some change in cleanroom operation, the minimum fan speed of 28% of full speed was no longer sufficient. After that episode, the minimum fan speed was increased from 28% to 33% of full speed and the high limit for particle concentration for one of the size ranges was lowered. The problem reoccurred once after these measures.

There was no noticeable difference between the low and high flow particle counters, while using the same control scheme, with respect to the number of minutes that the cleanroom was beyond the Class M3.5 (Class 100) boundaries.

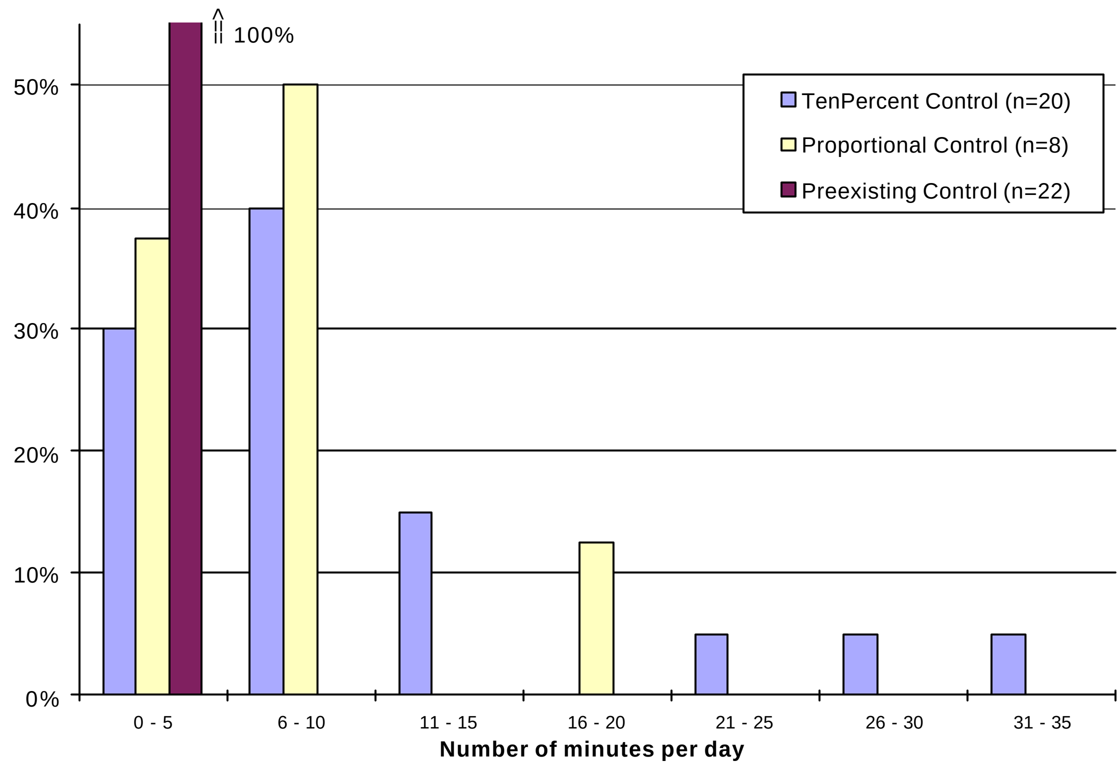

Figure 2. Frequency distribution of the number of minutes per day that the concentration of >0.3 micrometers size particles was outside Class M3.5 (Class 100) boundaries.

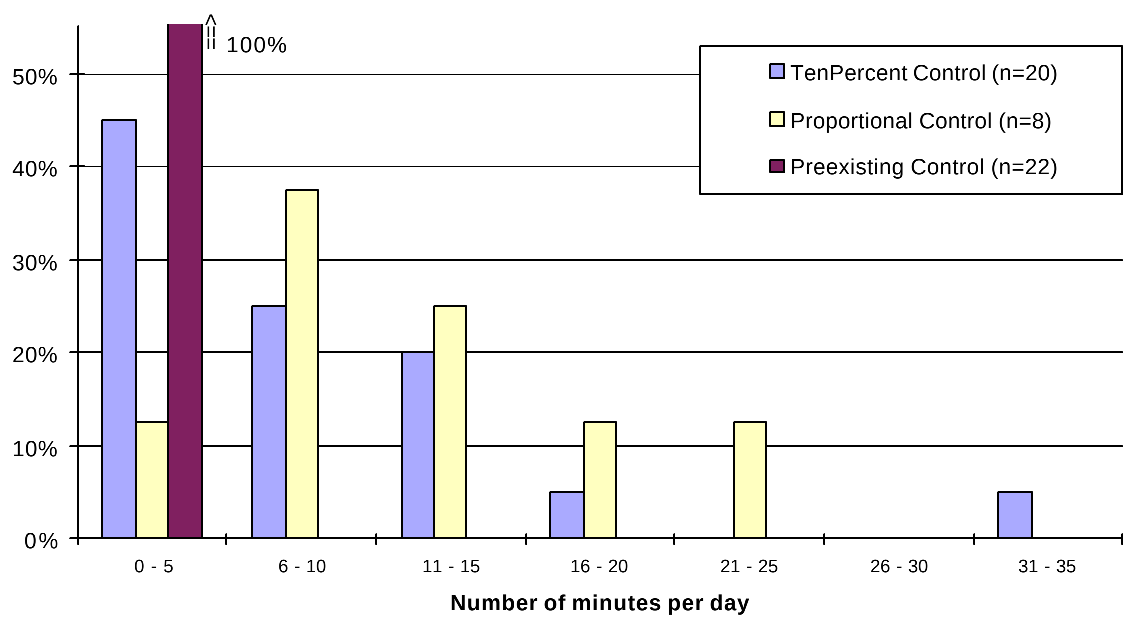

Figure 3. Frequency distribution of the number of minutes per day that the concentration of >0.5 micrometers size particles was outside Class M3.5 (Class 100) boundaries.

The maximum one-minute average particle concentration during occupancy was less than 35,300 particles/m^3 (1,000 particles/ft^3) for both >0.3 and >0.5 micrometer size particles, except in one isolated instance of 71,600 particles/m^3 (2,028 particles/ft^3) for >0.3 micrometer size particles. Since these are one-minute average values the instantaneous maximum values were certainly higher. The Proportional control scheme (median 21,700 particles/m^3 (614 particles/ft^3) for >0.3 micrometers) seemed better than the Ten Percent control scheme (median 30,500 particles/m^3 (863 particles/ft^3) for >0.3 micrometers) in keeping the maximum particle concentration low.

Cost-Benefit Analysis

As in the above discussion of energy savings, two baselines will be considered for the cost-benefit analysis. These two baselines represent the upper and lower bounds for payback times. For the first baseline, 2.6 kW (3.5 HP) is assumed as the average power for our 28 m^2 (300 ft^2) cleanroom. Normalizing to a 90 m^2 (1,000 ft^2) floor area, the annual baseline energy use would be 7.6 x 10^4 kWh costing approximately $6,100. With the energy savings shown above, the annual savings will be approximately $3,700 per 90 m^2 (1,000 ft^2). To implement the technique outlined in this paper, one or more particle counters need to be purchased at $2,500 each. Also if VFDs are not part of the current system, two need to be purchased per 90 m^2 (1,000 ft^2) floor area. VFDs cost about $3,000 each plus another estimated $3,500 for installation and connection to a computer controlled system. We assume that a computer controlled system is available since most new HVAC system have some energy management system connected which controls temperature, humidity and other thermal comfort parameters for a facility. Therefore for a 90 m^2 (1,000 ft^2) Class M3.5 (Class 100) cleanroom to be retrofitted to use this technique, we assume that two particle counters and two VFDs are required. Thus the cost to retrofit would be $14,500 and the payback time approximately 4 years.

For the second baseline, the average power for our 28 m^2 (300 ft^2) cleanroom is 5.9 kW. Normalizing to a 90 m^2 (1,000 ft^2) floor area, the annual baseline energy use would be 1.7 x 10^5 kWh costing approximately $14,000. The energy savings would be approximately $11,000 per 90 m^2 (1,000 ft^2). We assume the same retrofit costs of $14,500. Thus the estimated payback time is approximately 1 year.

Discussion

This investigation has shown that large fan energy savings can be achieved in cleanrooms through the use of demand-controlled filtration. Some degradation in the particle concentrations were evident; however, as can be inferred in Figures 2 and 3, concentrations remained within the Class M3.5 (Class 100) specifications at least 98% of the time. Within the scope of this study, it was not possible to explore a large variety of control strategies for fan speed and select an optimum. It is quite possible that improved control strategies, such as maintaining a slightly higher minimum fan speed, would result in eliminating excursions above the Class M3.5 (Class 100) rating.

We were not able to measure particle concentrations at multiple locations within the cleanroom, thus the uniformity of particle concentrations is unknown. Therefore, the particle counter was placed near a critical location with frequent activity. Further research is necessary to determine the optimal locations and the required number of particle counters in various types of cleanrooms.

DCF seems to hold the most immediate promise for use in small research cleanrooms that are not used continuously and that have one activity underway at a time. Many universities and research institutions and semiconductor manufacturers have such cleanrooms. Another alternative for these cleanrooms would be to install variable frequency drives, manually reduce fan speeds to a low baseline value when the cleanroom is not used, and operate at full fan speed during cleanroom use. Energy savings would be smaller than achieved with DCF. However, in cleanrooms with limited use, the fan energy savings could easily exceed 50% with essentially no adverse effects on indoor particle concentrations.

Implementation of DCF in large cleanrooms used for semiconductor manufacturing would be more complicated. These large cleanrooms usually contain numerous work sites with different activities underway at each site. Products may be transported between sites. The air velocity needs to be maintained relatively uniform through out the entire cleanroom to maintain the desired unidirectional air flow pattern. To implement DCF, a particle counter would need to be installed at each critical location and the air velocities for the entire cleanroom varied upward or downward simultaneously based on the highest (or most critical) particle concentration. Given the very high energy use in these large cleanrooms, this option would seem to be worthy of further consideration; however, semiconductor manufacturers have suggested that potential energy savings are not sufficient to justify implementation of a control system that might have an adverse effect on the manufacturing process.

In the experimental facility, there was no reason to expect that changes in the speed of recirculation fans affected the pressure difference between the cleanroom and the surrounding space (until the recirculation rate approached the rate of outside air supply). Usually, cleanrooms are maintained at a positive pressure with respect to their surroundings. Before implementing DCF in a specific facility, its potential impact on pressure differences should be considered.

Industry Comments

We solicited comments from managers and designers of cleanrooms about the technology presented in this paper. The individuals that made comments represent a wide spectrum of cleanroom users, from large manufacturers of integrated circuits to modest sized university research facilities.

All reviewers thought that the technology presented in this paper is worthwhile and should be investigated further. Most agreed that the technique would most likely be adopted in cleanrooms used for research. One manager at a university is considering implementing this technique in their facility.

Researchers at IBM have estimated savings of $1 million dollars per year by reducing the fan speeds in one of their Class 1 cleanrooms[2]. After measuring particle concentrations at 0.50 m/s (100 fpm) and at 0.25 m/s (50 fpm), it was determined that the increase in particle concentrations at 0.25 m/s (50 fpm) was low relative to particle contamination from sources such as tools and equipment normal to a semiconductor production line.

Some concerns that were brought forward are: 1) particle generation is fairly localized and thus there is a need to be able to detect particles at many different locations within a cleanroom, 2) the recirculated air in the room may be conditioned (temperature and humidity controlled) thus any variation in the rate of the recirculation air may cause problems with maintaining desirable environmental conditions in the room, 3) the continual changing of the fan speed could be an acoustical nuisance to the cleanroom users, 4) the time lag between the detection of a high particle concentration and the increase in fan speed has to be a matter of seconds for this technique to work, thus all components, the particle counter, data acquisition system and VFDs all need to respond in less than a second.

All of the concerns expressed above should be investigated and will most likely be solved with further research. Studies should be done to determine the spatial variability of the particle concentration in cleanrooms at different fan speeds. The variations in temperature and humidity should also be recorded.

Conclusions

With a relatively simple system it has been demonstrated : 1) that reduced air flow in a Class M3.5 (Class 100) cleanroom can be implemented without seriously compromising the cleanliness of the room and 2) that substantial reductions in energy, by 60% or more, use can be achieved employing a particle counter and a modern HVAC control system.

The DCF system maintained particle concentrations in the clean room at or below Class M3.5 (Class 100) specifications at least 98% of the time. However, with the DCF system in operation, there were occasional (usually fewer than 10 per day) non-consecutive one-minute periods in which particle concentrations exceeded the Class M3.5 (Class 100) criteria. It may be possible to reduce these periods with elevated particle concentrations by optimizing the control parameters for DCF.

The estimated payback period, based upon \$0.08 per kWh, for DCF in a 90 m^2 (1,000 ft^2) Class M3.5 (Class 100) cleanroom ranged from 1 to 4 years.

DCF or manual control of the speed of recirculation fans (using variable speed drives) appear most promising for small research cleanrooms that are not used continuously and that are used for one activity at a time. Implementation of DCF in large cleanrooms used for semiconductor manufacturing would be undoubtedly more complicated than the procedure presented here, but the potential energy cost savings may well justify development of a more sophisticated control scheme than used in this study.

Comments from managers and designers of cleanrooms were encouraging and they recommended further research to perfect the technology.

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Figure 1. Floor Plan of CLass M3.5 (Class 100) cleanroom