CLEANROOM ENERGY OPTIMIZATION METHODS

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ABSTRACT

The design and operation of semiconductor cleanrooms play an important role in the advancement of many of today's technology needs as the use of microelectronic products become engrained in our society. Cleanroom construction has averaged double-digit growth through the 1990's and into early 2000. Advances in factory technology have placed demands on all aspects of cleanroom design, construction, materials, and so on. Much of this growth has been centered in hot climate of the sunbelt.

Energy efficiency has not been a high priority for the semiconductor industry in the past, since costs related to this issue have historically represented a relatively small percentage of overall operating costs. From a Semiconductor Industry website in October 2001: "Slashing energy consumption has become an unquestioned semiconductor industry goal." Semiconductor Industry Association's International Technology Roadmap for Semiconductors has energy goals on the roadmap for power per unit of silicon processed; the World Semiconductor Council has policies for energy reduction, numerous publications, workshops, and seminars touting need for energy reduction. There is no longer any question that cutting energy usage makes good business sense, especially given rate increases being experienced in many parts of the country. This paper will present some of the methods being used by a multi-national semiconductor company to change the way they design and build cleanrooms with a focus on resource conservation, energy conservation methods, and cost of ownership. Various clean air and energy management scenarios will be compared with their potential for energy savings.

Semiconductor Industry

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Semiconductor Cleanroom Energy

Based upon surveys the Semiconductor industry has over 12,800,000 ft^2 (1,190,000 m^2) of cleanroom space in the United States varying in cleanliness from Class M1 (ISO Class 3) to Class M6 (ISO Class 9). These cleanrooms have recirculation air handlers moving millions of cubic feet (cubic meters) of air to transport contamination out of the cleanroom and maintain the room's cleanliness. Whereas, many in the semiconductor industry are implementing energy conservation policies this is relatively new philosophy for many companies.

Even the most aggressive of energy efficient semiconductor factories may use over 450 kWh of energy for every 200 mm wafer processed and the typical semiconductor factory uses enough electricity to serve over 7500 homes and will spend over $1,000,000 per month for electricity during peak usage periods of the summer. Yet, electrical costs still represent less than 5% of the total operating cost for today's 200 and 300 mm factories hindering investments in capital projects to improve energy efficiency.

Semiconductor Factory Characteristics

Semiconductor factories, referred to as wafer fabs or just fabs, employ several types of cleanrooms, clean support spaces, and non clean spaces. The specifics of semiconductor fabrication are beyond the scope of this paper; a good description of the process can be found at: http://sematech.org/corporate/news/mfgproc/mfgproc.htm#steps1_2.

In order for the cleanroom designer to begin an optimization of the cleanroom they must understand energy use, energy flow and appropriate design of HVAC systems for the industry they have targeted. The characteristics of semiconductor cleanrooms are different from cleanrooms used in other industries such as pharmaceutical, aerospace, and biotechnology. These differences lead to having unique considerations when designing the cleanroom layout and the HVAC systems. The following list includes some of the characteristics of semiconductor manufacturing cleanrooms:

1. Within the semiconductor industry, the factory cleanroom air cleanliness requirements, as defined by Federal standard 209E, "Federal Standard Clean Room and Work Station Requirements, Controlled Environment[1]," including cleanliness classes M1 to M6. This document is to be replaced by the new ISO 14644 documents. To achieve the desired cleanliness level, unidirectional airflow cleanrooms with average air velocity ranges of 40 fpm (0.20 m/s) to 100 fpm (0.51 m/s) are typically used, with 70-80 fpm (0.35-0.41 m/s) as the most common design velocity. Vertical unidirectional airflow air management concepts are the design of choice for the majority of semiconductor manufacturing facilities. The ramifications for choosing an air management concept will be discussed later.

2. Within the cleanroom component load analysis, room sensible heat ratios of 0.99 or higher are normal due to large concentrations of manufacturing equipment. High sensible internal heat loads approaching 200 W/ft^2 (2152 W/m^2) are common, while 50-75 W/ft^2 (602-807 W/m^2) is a typical design criteria for many merchant, high volume, semiconductor factories. The HVAC parameters restrict the cleanroom design's flexibility of heat transfer options. Representative environmental control tolerances in many facilities today are ±0.2°F (±0.11°C) to ±0.5°F (±0.28°C) and ±1% RH to ±2.5% RH for many process areas. These arduous tolerances are required throughout a specific process area and present difficult control methodology requirements as the size of the process area increases.

3. The typical metal oxide semiconductor (MOS), bi-polar, Silicon-Germanium, or gallium arsenide facility requires large quantities of conditioned fresh air to replace process exhaust and to provide for cleanroom pressurization. Process exhaust requirements of up to 10 cfm/ft^2 (51 L/s• m^2) may be required for some processes areas, while typical industry averages are 2 to 3 CFM per ft^2 (10.2-15.3 L/s•m^2). This fact also limits the degree of energy reduction associated with cleanroom make-up and its interaction with the cleanroom air management concept.

4. In addition to controlling the cleanroom air cleanliness level, control of cleanroom temperature and relative humidity is crucial for a semiconductor factory to operate successfully. Temperature and humidity control within the cleanroom will have a direct influence on the quality of the products manufactured to the point that without proper environmental control, many products will fail minimum functional tests and thus cannot be sold or used. Providing the correct temperature and humidity control as part of the air management concept must be fully understood when optimizing energy consumption.

Opportunities for Cleanroom Energy Optimization

There are numerous areas in a fab where implementing energy efficiency options can result in significant resource and cost savings. Annual savings of millions of kWh are possible with many energy efficiency projects. The cleanroom designer must balance the need to meet critical environmental factors, cleanroom specifications set by the operator/owner, and maintain reasonable installation and operating costs; while at the same time providing an efficient, functional, and flexible cleanroom. The cleanroom designer must understand the aforementioned characteristics and their interactive nature to begin an analysis of the energy components that will achieve the given scope. With the proper analysis, the cleanroom designer can optimize the performance of individual components and systems to produce an effective and energy efficient total design. The final performance of the cleanroom is judged

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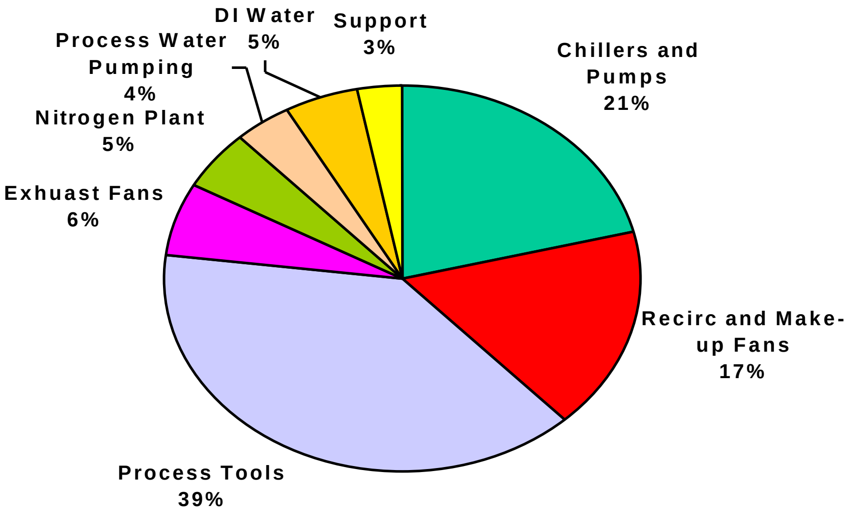
[1] As of November 2001 the US General Services Administration cancelled Federal Cleanroom Standard, 209E, but the actual application of the standard does exist in many industries. The use of the new ISO 14644 standards is slowly gaining acceptance in the US and around the world.

by the quality of control of the critical environmental factors.

Energy Usage in a Semiconductor Factory

For the semiconductor industry in the U.S., cleanroom electricity demand is estimated at 3500 megawatts and consumption at over 15,000 gigawatt-hours per year about 1.5 percent of total industrial electricity use, for all industry sectors in 1998. For many plants, electricity costs are the single greatest facility operating cost, greater than both labor and materials. In fact, for large fabs, it is not uncommon to have electric bills that are greater than $1 million per month. According to several studies energy use within semiconductor cleanrooms can be divided into several large components (See figure 1). Maintaining fab cleanliness, providing fresh air to replace process exhaust, and removing the heat of process tools are the primary reasons for the large energy usages of the HVAC system. The largest energy use within the factory is the manufacturing tools. These large energy components may be divided into direct and indirect with respect to the manufacturing process. Direct energy needs are the actual energy consumed by the manufacturing tools. Indirect energy components are exhaust and water utilities consumed by the tools.

FIGURE 1

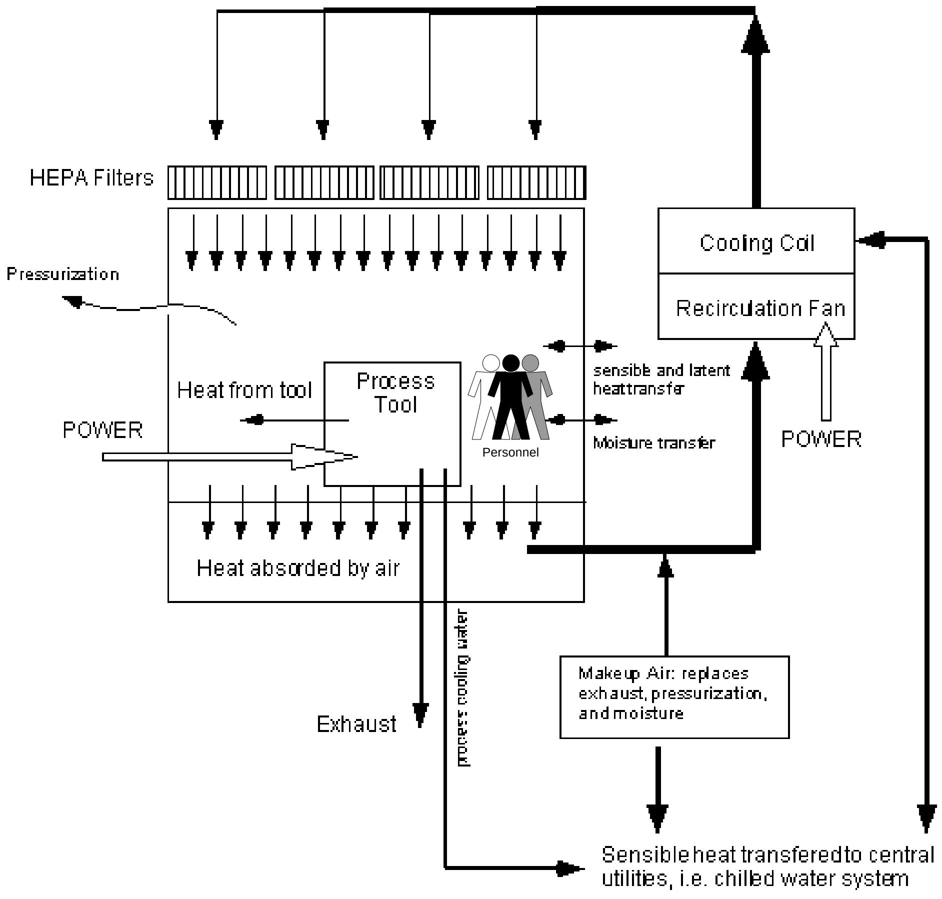


FACTORS EFFECTING FAB CLEANROOM ENERGY USE

We have presented which systems consume energy within a typical semiconductor fab. Of the systems shown in figure 1 the cleanroom design will directly affect the energy consumption of the recirculation and make-up air system and some of the support system (this is where cleanroom lighting consumption is located) and indirectly affect the chiller and pumps.

Energy associated with air movement, cleanroom pressurization (exhaust and make-up air balance) and how heat (sensible and latent) is removed from the cleanroom are the primary opportunities for optimization (see figure 2). For example, the ability to separate sensible heat transfer from latent heat transfer provides significant savings due to the high sensible heat ratios and the large amount of make-up air needed to offset process exhaust and maintain positive room pressurization. There are also heat transfer efficiency opportunities between internal loads and the chiller plant. Efficiency gains are available during the equipment selection process, but some are beyond the cleanroom designer’s scope (e.g. process equipment heat transfer to process cooling water is designed by the process equipment supplier).

Figure 2: Fab energy flow



Airborne Cleanliness

Controlling airborne cleanliness is a fundamental requirement of a cleanroom. Maintaining cleanliness requires the removal of internally generated contaminants, the filtration of external contaminants from the fresh air introduced to the cleanroom, and the prevention of external contaminants by means of positive pressurization. To accomplish these goals, large air change rates of 300 to 600 air changes per hour for air cleanliness classes of class M1 (ISO Class 2) or better will be necessary, (Table 1). The control of internally generated particles is a function of the cleanroom protocol established by the owner's contamination control specialist, while the need for sufficient airflow to quickly remove the contaminants from the workspace is a function of the cleanroom design. The ability to maintain room cleanliness is proportional to the volume of recirculation air. The challenge facing cleanroom designers is to provide the minimum amount of recirculation air needed to maintain room cleanliness. The cleanroom designer must design an air management concept to meet the cleanroom owners requirements.

Temperature and Humidity Control Zones

The method of temperature and humidity control can produce one of the largest variations in energy consumption. During the past years a thorough understanding the heat transfer dynamics in semiconductor cleanrooms has resulted in several methods for temperature and humidity control. The air management concept will also impact the available choices for control, especially humidity control. Temperature and humidity control can be one of the largest users of energy over which the designer has the most amount of influence.

Table 1. Cleanroom Classifications

ISO 14644-1 compared to FED-STD-209E

			Particles limits					Traditional
ISO Classificatic	Limit at 0.1 µm		Limit at 0.5 µm		Limit at 5 µm		FED-STD-209E Cla	Cleanliness Class
	(m^3)	(ft^3)	(m^3)	(ft^3)	(m^3)	(ft^3)		
ISO Class 1	10	0.28						
ISO Class 2	100	2.83	4	0.11				
ISO Class 3	1000	28	35	1			M1.5	
ISO Class 4	10,000	283	352	10			M2.5	Class 10
ISO Class 5	100,000	2832	3520	100	29	1	M3.5	Class 100
ISO Class 6	1,000,000	28321	35,200	997	293	8	M4.5	Class 1,000
ISO Class 7			352,000	9969	2,930	83	M5.5	Class 10,000
ISO Class 8			3,520,000	99688	29,300	830	M6.5	Class 100,000
ISO Class 9			35,200,000	996885	293,000	8298		

Maximum concentration limits (particles per cubic meter of air) for particles equal to and larger than the considered sizes shown.
Concentration limits are calculated in accordance with Cn=10^N x (0.1/D)^2.08
Concentration limits per cubic foot are not recognized by ISO standards, they are given for comparison purposes only and should not be used for application of the ISO 14644 family of standards.

Process Exhaust

While process exhaust does not have a direct impact on cleanroom energy consumption the method of exhaust replacement or makeup air does. How the makeup air is configured into the overall air management concept can have significant impact on overall cleanroom energy consumption. Depending upon local climatic conditions, the treatment of makeup air is also a significant user of energy in maintaining the cleanroom environment

Humidity Control Method

The control of relative and absolute humidity is of extreme importance to the cleanroom designer. Many processes require precise humidity control to insure product quality; and the control of humidity is also important for the control of electro-static discharge. Corrosion of thin films during metal deposition and etch processes may occur, depending on the process. Humidity within the cleanroom is best controlled by control the make-up moisture content. Make-up with the correct moisture content is mixed with the cleanroom recirculation air. Due to the high sensible heat ratios of semiconductor cleanrooms, humidity excursions are typically caused by localized wet processes or moisture migration from adjacent spaces. Therefore, precise make-up control can provide consistent cleanroom control. Energy consumption can be minimized with the make-air treatment process. Attempts to control humidity with a dehumidification/reheat process of the recirculation air will result in extremely high operating costs.

Pressurization Control

Good pressure control is needed for many reasons in today's cleanrooms. Pressure control of the clean spaces can have an impact on atmospheric processes such as film deposition. Pressure control is used to provide barriers to contamination. Positive cleanroom pressure is maintained to keep external contamination (particles and moisture) out of the cleanroom, and negative pressurization is used when trying to contain hazardous materials inside the cleanroom from exiting (metal ions like gold, boron, potassium, etc. must be carefully contained). Similar to the benefits of humidity control the method of pressure control will have an impact on the makeup air quantity and quality, and the method that makeup is introduced into the air management concept will also impact the total energy consumption.

Recirculation Fan Evaluation

The cleanroom recirculation fans are used to provide a uniform airflow of ultra-clean air over the product workspace. In a large semiconductor cleanroom with 100,000 ft^2 (9290 m^2) of ISO 2-3 cleanliness (class M1) work space (i.e., less than 10 particles per cubic foot of particles less than 0.1µm in size), airflow rates of 6,000,000 to 9,000,000 CFM (2,832,000 to 4,248,000 L/s) may be involved. Large amounts of energy are used to transport the cleanroom air and remove the fan heat. Many significant energy savings are possible when high-efficiency components are used for large quantities of air circulation.

Improving fan system efficiencies will reduce the recirculation air handler brake horsepower requirements. Changes in fan system efficiencies are achieved through:

- -- Fan Drive efficiency
- -- Fan mechanical efficiency
- -- Motor efficiency

Proper selection of cleanroom fans involves evaluating fan types, drive mechanisms, maintenance requirements, sound power levels, etc. Concepts 1 and 2 may use several fan options: open and closed scroll centrifugal fans, either forward curve, backward inclined, or airfoil centrifugal fans, or vane and tube axial fans. When vane-axial fans are selected, the higher fan sound power levels may require additional sound attenuation with correspondingly higher pressure drops, while some centrifugal fans have lower efficiencies but operate at lower sound power levels. The lower static pressure system combined with low speed large diameter vane-axial fans will have substantial reduction to sound power thus reducing the need for some sound attenuation. An analysis of the factors effecting total power can be show by the following:

$$\mathbf{Bhp} = \frac{\text{Airflow x Static Pressure}}{6356 \text{ x } \eta_m \text{ x } \eta_f} \qquad (1)$$

Rearranging terms and solving for static pressure

$$\frac{\text{Airflow x Static Pressure(v)}}{6356 \text{ x } \eta_m \text{ x } \eta_v} = \frac{\text{Airflow x Static Pressure(c)}}{6356 \text{ x } \eta_m \text{ x } \eta_c} \qquad (2)$$

Combining similar terms

$$\frac{\text{Static Pressure(v)}}{\eta_v} = \frac{\text{Static Pressure(c)}}{\eta_c} \qquad (3)$$

Solving for centrifugal fan efficiency

$$\text{Static Pressure(v)} = \frac{\text{Static Pressure(c) x } \eta_v}{\eta_c} \qquad (4)$$

Where:

Airflow is in ft^3 per minute
Static pressure is in inches WC
6356 is a conversion factor
η_m is motor efficiency
η_f is fan efficiency
η_c is centrifugal fan efficiency
η_v is vane-axial fan efficiency

Using Equations 1 through 4, one can see that the change in fan efficiencies results in a linear offset in static pressure. Thus, when comparing an 75% efficient (total efficiency) vane-axial fan with a 65% efficient (total efficiency) centrifugal fan, the ratio of 75/65 (1.154) times the static pressure of the centrifugal fan will allow a 15.4% higher static pressure for the vane-axial fan for equal brake horsepower requirements. When high-efficiency fans are selected, considerable energy savings will result.

The trend toward smaller local fans for cleanroom recirculation should be evaluated against the use of larger, more efficient central fans. Localized FFUs provide for greater flexibility in the cleanroom configuration and localized cleanliness zones can be achieved in the midst of less clean spaces. FFUs typically have lower static pressure requirements since sensible and latent cooling is done within other heat transfer blocks. When localized fan filter units (FFU) are used to reduce the system's static pressure, there is a trade-off between decreasing efficiency and static pressure decreases. FFUs cannot develop significant static pressure so the cleanroom designer must be careful in designing the cleanroom air path. Careful selection of very low velocity, low pressure cooling coils is needed. After air passes through any internal sound attenuators and the discharge HEPA filters, there is comparatively little pressure left to offset external static pressure losses. For many older small FFUs with motor sizes less than 1 horsepower (0.75 kW) and in-line centrifugal forward-curved fans, the total efficiency drops to 25% to 50% due to poor motor and fan efficiencies. An 85% mechanically efficient, direct-drive vane-axial fan has a motor efficiency of 94% and total efficiency of (0.85 x 0.94) x 100% = 79.9%. Compare this with an FFU operating at 1.5 in. WC (373.5 Pa) of static pressure, 55% mechanical efficiency, 70% motor efficiency (3 phase motors), and total efficiency of (0.55 x 0.70) x 100% = 38.5%. Using single phase shaded pole motors the total efficiency can drop to 25%. FFUs designs are now available with the fan, the motor and the motor controller optimized for efficiency. These designs include a brushless, electronically commutated dc motor with an external rotor. The fan impeller is fitted directly onto the rotor. Either embedded microprocessors or remote microprocessor control is used to adjust the motor voltage to match the torque requirement of the fan, thereby minimizing inefficiencies due to slip. Overall, the resultant motor efficiency is 75% to 80%, compared to less than 40% for phased split capacitor or shaded pole motor designs. With this improved efficiency also comes the byproduct of quieter operation. New backward inclined versus forward curve centrifugal fans are used with a mechanical efficiency of 60%, this allows for a potential total efficiency of (0.6 x 0.8) x 100% = 48%, still significantly less than the 80% achieved by direct drive vane-axial fan systems.

Good fan selection provides an optimum mechanical design; the choice of drive mechanism and motor type will also yield considerable energy-savings potential. Additional energy savings of 2-5 W/ft^2 of cleanroom space (21.6-54 W/m^2) may be achieved with the substitution of high-efficiency motors for standard efficiency motors. The choice to use fans with motors outside the primary air stream will save 1.0-1.5 W/ft^2 (10.7-16.15 W/m^2) due to motor inefficiency, but removal of the motor from the airstream by using belt-driven fans with lower mechanical efficiencies will reduce the energy savings. High-efficiency motors have an inefficiency of 6-8%, whereas belt drive systems have inefficiencies of 4-6%. The use of special direct-drive fans with motors outside the airstream (bifurcated fan housings) may result in higher system effects and lower total efficiency.

To summarize cleanroom fan energy: the energy associated with the cleanroom fan is a function of the type of fan used, the fan arrangement (i.e. direct drive, belt driven), motor type, and the total pressure (static pressure + velocity pressure = total pressure) of the fan system. As seen in equations 1-4, static pressure is also a contributor to energy consumption. Significant air-side saving can be achieved by lowering the system static pressure: 1) Reduce the cleanroom airflow static path pressure losses. 2) Reduce the cleanroom airflow in all areas or in selected areas with mixed cleanroom HEPA filter velocities. Many manufacturers use cleanroom unidirectional velocities of less than the historical average of 90 fpm (0.457 m/s). The potential air-side energy savings for cleanroom velocity reductions only are summarized in Figure 3.

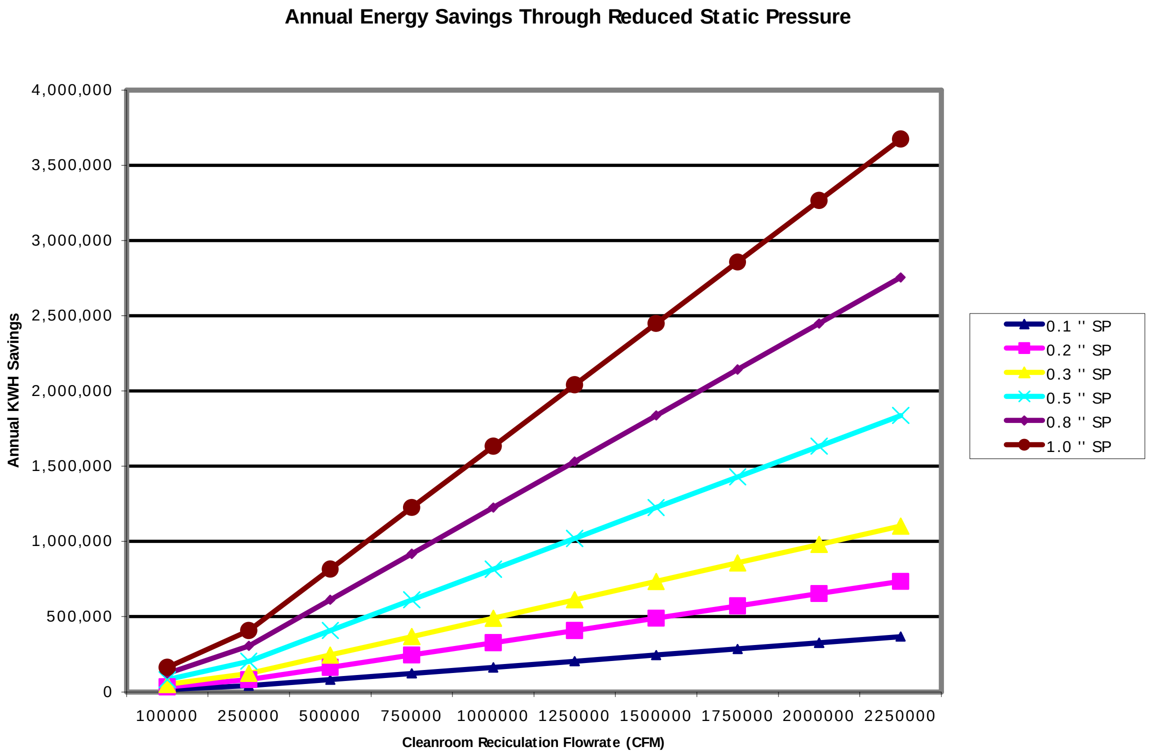


FIGURE 3

Airflow Path Evaluation

The primary source of energy saving's potential is from reduced air-side static pressure losses, using efficient ductwork fittings, lower coil and filter face velocities, etc. The following air-side components typically are used within the standard cleanroom air supply and return system:

-- Air-moving apparatus

-- Cooling/heating apparatus

-- Air filters

-- Sound attenuators

-- HEPA/ULPA filter plenums or supply ducts

-- Air balance devices

-- Supply/return ductwork and fittings

-- Fire and smoke protection devices

-- Cleanroom components including raised flooring, ionization grids, etc.

The design and selection of each component are interrelated, and the cleanroom designer must balance the energy use of each component with its impact on cleanroom performance. This interrelationship must be considered in order to assess the operating cost benefits of one device vs. the first cost of another. When the optimized system requires a threefold increase in capital cost with a ten-year simple payback, the cleanroom owner may decide to distribute the investment dollars to other systems.

Most of the economical static pressure reductions can be accomplished with lower coil, damper, and/or filter face velocities and efficient ductwork design. Removing or redesigning air filtration and cleanroom components must be balanced against the primary goals of the cleanroom, such as the desired air cleanliness level.

When hundreds of thousands of CFM are involved, the reduction in fan static pressure of just 0.1 in. WC (24.9 Pa) can result in $7200 per year of savings for a 10,000 ft^2 (929 m^2) cleanroom (see Figure 7). In addition to fan horsepower savings, each 0.1 in. WC (24.9 Pa) will also produce 3.9 tons (13.7 kW) of air conditioning savings due to the reduced fan heat load [10]

Lowering the air-side pressure drop associated with heat transfer coils and filters is a readily available energy-saving option for designers. While the use of air filters is the primary means to achieve the desired air cleanliness level, the quantity and quality of filtration are normally established by the cleanroom owner's contamination control specialist. Many semiconductor cleanrooms use only minor amounts of prefiltration, typically one set of 30% efficient prefilters. Other semiconductor firms use two stages of prefiltration, a 30% and a 90% efficient filter in series. The removal of pre-filters after a cleanroom is operating is also quite common. The owner normally makes the choice of one-stage filtration, two-stage filtration, or no prefiltration. Therefore, the extra operating costs associated with the 0.75 in. WC (186.8 Pa) to 1.0 in. WC (249 Pa) pressure drop required for prefiltration must outweigh the shorter HEPA filter life expectancy. (Prefilter operating costs will vary from $5.00 to $8.00 per year per square foot verse the HEPA filter cost of $12.00 to $15.00 per square foot.) The expected life of the HEPA/ULPA filters is not the only issue. The potential down-time required to replace the HEPA filters are typically an overriding factor in the decision.

A good HEPA filter ceiling system design can prevent external contaminants from entering the cleanroom and provide the proper unidirectional airflow to remove the internal contaminants. The cleanroom designer has many choices available for potential energy savings within the HEPA filter system. The quality of HEPA filter removal efficiency and the pressure drop of the HEPA filter must be discussed during project planning. HEPA filters with 99.97% removal efficiency of all particles 0.3µm or larger are available, as well as HEPA filters with removal efficiencies of 99.99999% for particles 0.12µm or larger. The pressure drop associated with many HEPA filters will depend on the type of filter media used and the quantity of media per square foot of filter face area. Today, HEPA filter pressure drops vary from 0.2 in.WC (49.8 Pa) to 1.0 in. WC (249 Pa). Normally, the lower the pressure drop, the higher the cost of the filter, but with higher dust holding capacity and lower operating costs. The choice of which filter to use must be input from the cleanroom owner.

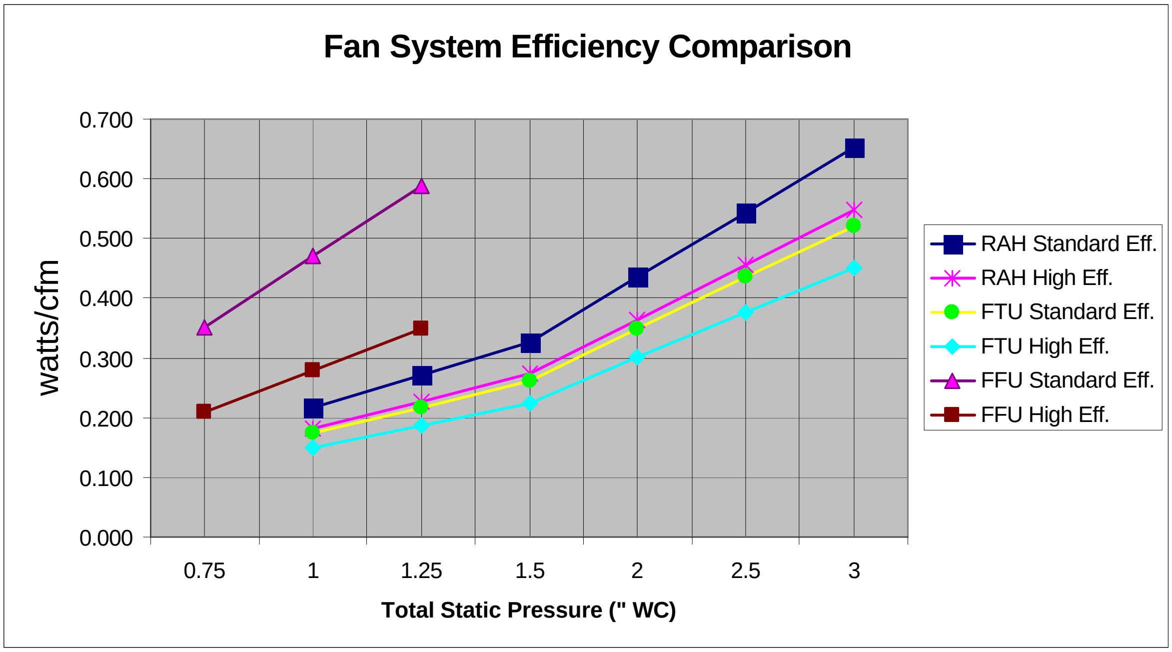
Another method of reducing the system's static pressure is to use a low-velocity duct design. Low-velocity systems occupy more facility space and have higher capital costs. Therefore, alternative designs must be used that compensate for higher velocity distribution system pressure losses. A common design to solve this predicament is the use of a pressurized plenum for air supply to the HEPA/ULPA filter ceiling.

Pressurized plenum designs may reduce system static requirements up to 1.0 in. WC (249 Pa) when compared to ducted HEPA filter systems. The primary benefit of ducted HEPA filters is the precise balance of the cleanroom unidirectional velocity profile or parallelism. Precise balance also provides the flexibility to have mixed cleanroom velocities. For example, the cleanroom airflow velocity may provide 90 fpm (0.457 m/s) over the production equipment and the remainder of the cleanroom may operate at 60 fpm (0.305 m/s) which results in a lower overall cleanroom velocity proportional to the ratio of mixed velocity areas. Most of the latest Semiconductor factories are using *minienvironments* are based upon this principle.

For cleanrooms using FFUs, the ability to reduce the air path static losses is quite limited. The cleanroom air path for FFUs is limited to the cleanroom itself and this may seem to indicate a significant benefit to the FFU concept it also one of the drawbacks. FFU arrangements cannot make changes to the air path without impacting the manufacturing environment or manufacturing equipment arrangement. Therefore, the range of system static pressure is small. For the latest factories with reduced cleanroom coverage, the use of FFUs is become a *de facto* standard. FFU manufacturers are responding to request for higher efficient units.

Figure 4 shows the static pressure range for each the common fan types used. Also, indicated is typical power consumption per unit of airflow. Figure 8 also presents the ranges for high efficiency fan systems and typical system efficiencies are also shown.

Figure 4. Static Pressure Range for Fan Types



The individual system components discussed so far can greatly impact the total system operating costs. Within the total semiconductor cleanroom system, smaller subsystems may also be optimized for improved total system operation. Methods to improve energy efficiency within the direct cleanroom air management system have been presented. The HVAC process also includes another large energy user, the make-up air treatment system. One of the largest subsystem energy users is the make-up air-handling system when both its fan energy and the chiller operating costs are considered. The heat transfer load of the makeup is a very large portion (typically greater than 25%) of the total heat transfer.

Make-up Air Treatment Evaluation

As previously mentioned, the treatment of the cleanroom make-up air is a significant user of energy. Although the make-up treatment is not within the cleanroom envelop per se' its airflow is filtered using HEPA filters and the control of the temperature and moisture content (dewpoint control) is very critical. Also, the volume of make-up air is proportional to cleanroom integrity (leak mitigation) and the quantity of exhaust volume from the space. This HVAC process affords the cleanroom designer several opportunities to optimize the energy consumption.

The water temperatures selected for chilled/glycol water dehumidification systems will directly affect the conditioned make-up air leaving temperature as well as the operating costs. Assuming a typical semiconductor cleanroom space condition of 68°F (20°C) at 40%RH and the resultant 42.8°F (6°C) dewpoint, a chilled/glycol water temperature of 35°F (1.7°C) to 37°F (2.8°C) normally would be used. A minimum heat exchanger approach of 5°F to 7°F (2.8°C-3.9°C) is recommended for good controllability. The cost of generating the chilled water is a large portion of the total operating costs of the make-up air conditioning system. Selecting chillers with low kilowatt per ton (kW/ton) ratios will prove cost-effective for many large semiconductor facilities. The designer should evaluate the chilled-water temperature differential design to minimize the kW/Ton ratio.

When traditional chilled water dehumidification is used for conditioning make-up air, the operating costs may be reduced with a number of innovative approaches, including pre-cooling the make-up air with heat recovery modules, using evaporative cooling, using closed-circuit cooling tower water, and using less expensive (i.e. lower kW/ton) chillers. The use of evaporative cooling is not very feasible in humid climates. Closed-circuit cooling towers may function in humid climates, but the additional capital costs may prove this method unattractive. Using dual water temperature systems is an effective and economical means of reducing operating costs. Further discussion of the HVAC process is beyond the scope of this paper, but the possible range of energy consumption and operating cost can vary by 70% is some cases and several times higher in extreme cases.

In summary, when the chilled-water system and the cleanroom air-management system are examined, the professional designer should not underestimate any potential energy savings with semiconductor cleanrooms.

Total System Dynamics

Several optimization methods have been reviewed. When the entire cleanroom energy flow is considered and the interactions of air flow and heat transfer are optimized as a total system this can be referred to as optimization of the total system dynamics. The potential savings of the complete system dynamics are sometimes difficult to envision. It is obvious to most design engineers that the use of high efficiency motors, fans, pumps, etc., will provide for higher total system efficiency. The key is to foresee the interaction of the individual components with the whole system, as demonstrated when comparing reduced system static pressure vs. high fan efficiency. By using identical high-efficiency equipment, many different psychometric processes can be analyzed.

After the consideration of air management concept is made, the system dynamics are considered when designing the temperature and humidity control system. Within each air management concept the factors affecting cleanroom energy are different. When a total system dynamics analysis is performed the cleanroom designer can begin an HVAC optimization process. This HVAC optimization process involves a thorough knowledge of all heat transfer and particle transfer mechanisms occurring. It is beyond the scope of this paper to derive or expand the concepts involved in a detailed optimization or case study, but there are several sources available to those wishing to explore this topic in more detail.

CASE HISTORIES:

Energy Savings Project Methodology:

Although some metered energy usage data was available where multiple projects were successfully implemented, the majority of the systems were not monitored or recorded by the Facilities Management Control System (FMCS). Simplified energy modeling (which can take many forms) can be completed to model or simulate a building or system's energy usage when monitoring is lacking. The modeling can be completed to take into account specific types of energy-using systems and their operating schedules; thus providing a more accurate estimate of energy consumption.

The following approach was used to estimate baseline year energy consumption for various system's energy distribution: 1) analyze available measured and recorded system operating data; 2) model and simulate the system's energy usage for all conditions; and, 3) benchmark the energy model with other measured data to ensure the model's accuracy.

One important system modeled was the 100% outside air handling system to a major semiconductor manufacturing plant. The OA system was modeled using a Bin Method Spreadsheet based upon the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) "Simplified Energy Analysis Using the Modified Bin Method". After the "Base Case" model was completed, measured and monitored field data was used as a benchmark by which the model was compared. Once complete the "Base Case" model was then modified to represent various changes in the systems' operation and to determine possible energy cost savings. The savings and implementation costs were then used to determine associated simple paybacks in order to recommend project retrofits.

Process Exhaust Reductions

The purpose of this project was to reduce excess exhaust amounts to all Gas Cabinets (GCs), Valve Manifold Boxes (VMBs), and Chemical Dispense Units (CDUs) in HPM rooms and Subfab areas within the fab facility. This not only had an immediate impact on exhaust fan power, but on the energy required to condition makeup air used to supplant the exhaust quantities. This overall project effort resulted in the rebalance, or new install balance, of approximately 240 GCs, 180 VMBs, and 38 CDUs.

The project, actually implemented over a period of about two years, did not decrease the availability of the exhaust system and maintained all NFPA, local Fire Department and ESIH Standards. It was actually anticipated to assist in Toxic Gas Monitoring (TGM) at all localized points. Additionally, since airflow was reduced in some areas (primarily at VMBs) to a level below which the installed pressure gases can reliably read, those existing gauges were removed and made available for other tool install requirements.

Gas Cabinet Exhaust Reductions.

The optimization of exhaust for the fab's gas cabinets resulted in a total estimated savings of approximately 41,000 cfm of exhaust and associated makeup air. This was determined to provide annualized savings of about: 928,000 kWhs ($41,700), 570,000 lbs steam ($2,700), and 1.5 million Ton-hrs chilled water ($68,900) for a total cost savings of $113,300. This equates to an approximate savings of about $2.77 per CFM. Previous studies had indicated costs in $/CFM in the range from $2.80 to as high as $4.50 for the treatment of Makeup Air (MUA).

VMB Exhaust Reductions.

The optimization of exhaust for the fab's VMBs resulted in an estimated savings of approximately 5,400 cfm of exhaust and associated MUA. This was estimated to provide similar annualized savings of: 122,950 kWhs ($5,500), 75,000 lbs steam ($350), and 201,000 Ton-hrs chilled water ($9,100) for a total cost savings of $15,000. This project also provided a one time savings of about $9,100 for the avoided costs of the relocated magnehelics.

CDU Exhaust Reductions.

The optimization of exhaust for the fab's CDUs and associated VMBs resulted in estimated savings of about 6,700 cfm of exhaust and MUA; and annualized savings of: 151,500 kWhs ($6,800), 93,000 lbs steam ($450), and 247,750 Ton-hrs chilled water ($11,250) for a total cost savings of $18,500.

Recirculation Air Reductions

The purpose of this project was to reduce excess recirculation CFMs within the fab's Recirculation Air Handling Units (RAHUs) without compromising airborne cleanliness. Prior to implementation of this project the maximum, minimum and average air change rates for the cleanroom areas were 443, 269, and 338 ACHs, respectively. After implementation, the maximum, minimum and average ACHs were 337, 139, and 252 ACHs. However, this data is somewhat misleading in that not all areas (particularly Photolithography) were reduced due to manufacturing risk aversion. Another way to review this data is that the maximum reduction was about 34% from pre- to post laminar flows, while the minimum was 9% and the average was 22%, respectively.

All post-data indices indicated no significant change to any environmental or contamination control issues (AMCs, particles, pressurization, parallelism, and/or temperatures and humidities). Every significant area of concern was trended, checked, measured, and verified and all remained within required specification levels after the airflow reductions.

HEPA Velocity/Laminar Flow Reductions.

The optimization of recirculation airflows resulted in a total estimated savings of approximately 2.55 million cfm of recirculation airflows. This was determined to provide annualized savings of about 13.61 million kWhs (1,585 kW demand) for the direct airflows, and another 3.48 million kWhs for central plant refrigeration savings (about 451 Tons, 406 kW demand). Total yearly dollar savings was estimated to be between $769,100 to 923,000 dependent upon the energy rate used.

MUA System Evaluation

The MUA system consists of multiple, 100% outside air units that function to provide a constant dewpoint temperature (DPT) and static pressure control to the fab ductwork. The DPT is approximately 46º F because the clean space specifications are 68º F +/- 2º F, and 45% RH +/- 3%. Thus, the initial sensible and practically all latent cooling and humidification requirements are met by these units. The fab MAHUs have both a 42° F pre-cooling coil (PCC) and a secondary cooling coil (SCC) which begin the primary cooling of the outside air. Final dehumidification cooling uses a 32° F CHW coil (GCC) generated from glycol chillers. The fan is a variable volume (speed) plug fan, whose speed is regulated by duct static pressure in the MUA header ducts.

In the direction of airflow, the MUA system was broken into six main blocks. The first four blocks are within the MAHUs themselves, while the remaining two blocks are the ductwork sections. The first block or Inlet Section consists of an outside air damper, 30/30 pre-filters, a hot water pre-heating coil (PHC), a set of chemical/carabon filters, and a set of 95% intermediate filters.

The second block, the Cooling Section, is comprised of two 42º F chilled water coils (PCC and CC), and the final 32º F glycol coil (GCC). The third block is the Fan Section with the plenum fan as the only mechanical component. The fourth block is the Outlet Section and consists of the reheat coil with a recirculation pump (RHC and RHCP), final ULPA filters, a steam grid humidifier (SH), and a discharge damper.

All the MUA entering the complex is mixed with the return air from the fab and is controlled to maintain the fab temperature, humidity and pressurization requirements.

Each of the MAHUs separate coils should be controlled as well as possible so there is no extraneous heating and cooling, but in fact actual operation of the MAHUs resulted in some unnecessary heating and cooling. This was primarily due to some institutionalized reasoning for risk mitigation to the fab, but also because of normal issues regarding mechanical system components such as valves, and controllers.

Through some specialized maintenance increases, manual setpoint changes and optimization programming of controls algorithms, this project was completed to provide additional assistance in control of the units for energy savings.

MUA Control Treatment Adjustments.

The baseline estimate of the energy use of the MUA system was as follows: 9.94 million kWhs, 8,030 lbs steam, and 17.62 million ton-hrs chilled water for a total cost of $1.29 million annually. The optimization of the MAHU final air delivery to meet fab specifications consisted of correcting valve leakages and adjusting and controlling setpoints on all the heating (Preheat, Reheat), cooling (Precool, Secondary cool, and final glycol cool), and steam humidifier coils. The resulting total estimated savings from these efforts were approximately 12,350 lbs steam, and 2.56 million ton-hrs of chilled water for a total savings of $185,200 annually. Of this savings, approximately $10,700 dollars is savings from high quality water used in the clean steam humidifiers.

MUA Leakage Reduction.

In the process of the overall system review, it was determined that increased maintenance in replacing door seal gaskets in the hundreds of existing RAHUs would result in savings to MUA. Once completed, this project added additional estimated savings of: 986,700 kWhs, 1,500 lbs steam, and 276,450 ton-hrs chilled water for a total savings of $65,000 annually.

SUMMARY

This paper presented some of the methods being used by multi-national semiconductor companies to change the way cleanrooms are being designed and operated. Considering resource conservation, energy conservation methods, and cost of ownership, allows for unique opportunities for employing innovative designs to reduce system operating costs and help the customer compete in a world economy. Various clean air and energy management optimization methods were presented along with their potential for energy savings. This paper also introduced a holistic design approach, total system dynamics, to evaluate the energy efficiency of cleanroom designs. The benefits of individual system component efficiency and the optimization of the total system dynamics will result in cost and energy savings for the operator and for the customer. Implementation of these principles will produce better designs for the client and a rewarding satisfaction for the designer.

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