Cleanroom Energy Benchmarking in High-Tech and Biotech Industries

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ABSTRACT

Cleanrooms, critical to a wide range of industries, universities, and government facilities, are extremely energy intensive. Consequently, energy represents a significant operating cost for these facilities. Improving energy efficiency in cleanrooms will yield dramatic productivity improvement. But more importantly to the industries which rely on cleanrooms, base load reduction will also improve reliability. The number of cleanrooms in the US is growing and the cleanroom environmental systems' energy use is increasing due to increases in total square footage and trends toward more energy intensive, higher cleanliness applications. In California, many industries important to the State's economy utilize cleanrooms (Figure 1, (McIlvaine)).

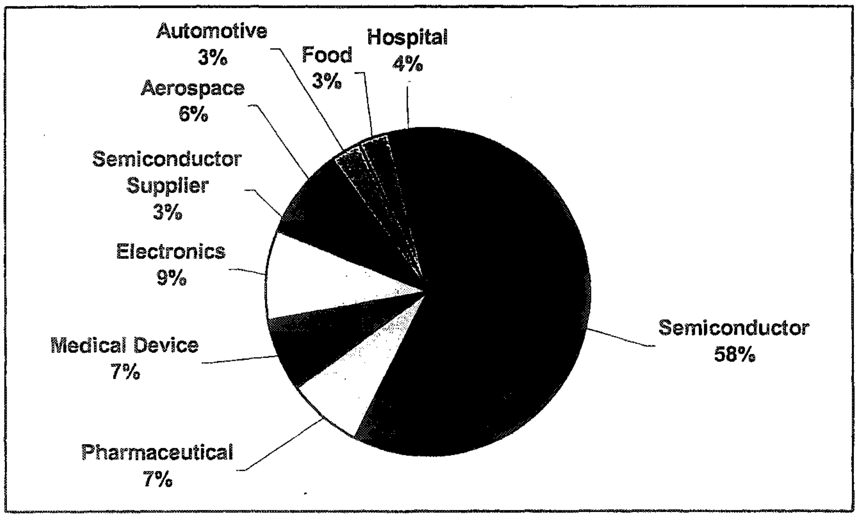

Figure 1. California Industries Utilizing Cleanrooms

In California these industries utilize over 150 cleanrooms with a total of 4.2 million sq. ft. (McIlvaine).

Energy intensive high tech buildings offer an attractive incentive for large base load energy reduction. Opportunities for energy efficiency improvement exist in virtually all operating cleanrooms as well as in new designs.

To understand the opportunities and their potential impact, Pacific Gas and Electric Company sponsored a project to benchmark energy use in cleanrooms in the electronics (high-tech) and biotechnology industries. Both of these industries are heavily dependent intensive cleanroom environments for research and manufacturing. In California these two industries account for approximately 3.6 million sq. ft. of cleanroom (McIlvaine, 1996) and

4349 GWh/yr. (Sartor et al. 1999). Little comparative energy information on cleanroom environmental systems was previously available. Benchmarking energy use allows direct comparisons leading to identification of best practices, efficiency innovations, and highlighting previously masked design or operational problems.

Introduction

Cleanrooms are common in universities, government labs, hospitals, and in many industries. Industries relying on cleanrooms include automotive, aerospace, biotechnology, pharmaceutical, and electronics (disc drive, semiconductor, flat panels, telecommunications, etc.). Although energy costs are high, owners and operators currently have little information concerning where to place their resources to improve their efficiency. Also, there is little information available to highlight best practices for design of new systems. Simple comparisons of energy per square foot are of little value since process related energy (conditioned by the same environmental systems) varies greatly. Some industries use production metrics such as watts per unit of product. These focus on overall production efficiency but overlook the efficiency (and opportunities for improvement) of energy intensive environmental or process systems.

This project developed a benchmarking strategy for use in cleanrooms to obtain energy end use breakdown and to allow energy use comparison of key systems and components. This paper describes the metrics used in this study and some of the observations and conclusions that the project team has identified to date.

Background

Buildings with cleanrooms typically include energy intensive HVAC systems consisting of large central plant heating and cooling, large amounts of air recirculation, and make-up and exhaust ventilation. They frequently have demanding environmental considerations with tightly controlled temperature and humidity for worker comfort and/or process requirements. Prior research documents the energy intensity and some of the opportunities for efficiency improvement (Mills et al. 1996).

Although activities performed in cleanrooms vary greatly, the environmental systems (primarily HVAC) typically utilize a large percentage of total building energy (up to 50%). Energy intensity varies with the cleanliness level (IEST-ISO std. 14644-1, 2000) and use of the cleanroom. Cleanroom "classes" are defined based upon the number and size of particles allowed to be present. Class 1 is cleaner than Class 10, Class 10 cleaner than Class 100, etc. Cleanrooms are 10 to 100 times as energy intensive as office buildings (typically 6 watts/sq.ft.)(CBECS). Efficiency opportunities for the environmental systems are prevalent and crosscut all cleanroom applications. Also, the research or manufacturing process occurring in the cleanroom is often very energy intensive and has its own efficiency opportunities. However, this project focused only on the environmental systems and components common to most cleanrooms.

Project Description

This project developed a measurement methodology and metrics most useful for comparing these systems. The selected metrics allow comparison of widely varying environmental systems regardless of the design, cleanliness class, or the process occurring in the cleanroom. This methodology differs from use of production metrics in that it facilitates direct comparison of energy intensive systems and components by calculating metrics from design or measured data. These metrics readily illustrate how efficiently they are designed and operating. Quantities such as flow per KW are calculated based upon direct measurement. Even though wide variations in process load, system and component design, cleanliness requirements, and other operating parameters make standard comparisons impossible (such as KW/sq. ft.), it is possible to directly compare performance with use of these metrics.

A hierarchical approach was used beginning with whole building energy use and progressing to selected system level measurements, and then to key component measurements. Site plans were tailored to each individual cleanroom facility with the objective of collecting data to as great a detail as practical within a short period of time. To accomplish this, the systems and level of detail, were prioritized. In some cases data was collected where it was opportunistically feasible, and ignored where it wasn't readily obtainable. The goal at each site was to measure as many of the targeted systems as possible in approximately a two-week period. A representative sample of the metrics and priorities developed for the project are shown in Table 1.

Table 1. Cleanroom/Central Plant Metrics

Cleanroom Metrics			**Central Plant Metrics**		
Description	**Units**	**Priority**	**Description**	**Units**	**Priority**
Recirc AHU Efficiency	cfm/kW	1	Chiller Efficiency	kW/ton	2
MUAH Efficiency	cfm/kW	1	Tower Efficiency	kW/ton	2
Annual Energy Cost per Cleanroom Square Foot	$/sf	1	Condenser Water Pumps Efficiency	kW/ton	2
Annual Fuel Usage	MBtu/sf/yr	1	Chilled Water Pumps Efficiency	kW/ton	2
Annual Electricity Usage	kWh/sf/yr	1	Total Chilled Water Plant Efficiency	kW/ton	2
Annual Energy Usage	MBtu/sf/yr	1	Plant Efficiency While Free Cooling	kW/ton	2
Make-Up Air	cfm/sf	1	Hot Water Pumping Efficiency	kW/M Btu	4
Recirculation Air	cfm/sf	1			

Cleanroom Metrics Con't		
Recirculation Air	ACH/hr	1
Cooling Load Density	sf/ton	2
Lighting Power Density	W/sf	2
Exhaust System Efficiency	cfm/kW	3

Actual facility data is available through the LBNL website (PG&E project website).

General, and then site-specific, measurement plans were prepared. Various types of cleanrooms (cleanliness classes) in the targeted industries (electronics and biotech) were selected. The plans identified specific systems and components to be measured. Where systems contained multiple equipment such as similar chillers, pumps, air handlers, etc. a representative sample was measured. The most energy intensive environmental systems were selected as the highest priority (as determined in prior investigations (Mills, et al., 1996)). Additional, lower priority systems and components were targeted if data could be readily obtained. In this way some data on other less energy intensive systems was collected as time permitted.

Even though process systems were not individually benchmarked, the total process load was determined in order to develop a total energy breakdown for the facility. Systems and components that accounted for less than 5% of the facility energy use were ignored, with the exception of lighting systems which were included since they could be readily obtained and they were expected to have obvious efficiency opportunities even though the relative magnitude of energy use is low (1-2% of total energy).

Once the on-site measurements were completed, they were entered into a database for comparison to other similar class cleanrooms. The database was structured specifically for the cleanroom metrics and measured facility data. Data was then analyzed to determine best practices and to understand the relative ranges of operating parameters. To develop a more robust data set, many additional cleanrooms will need to be measured and entered into the database. Once this information is available, building operators will be able to gauge the relative performance of their building as well as individual system and component performance.

During the project, the on-site team noted potential efficiency opportunities through visual observation and analysis of the data. These opportunities were provided to the customer in a final report. The observations were not meant to be all encompassing. Based upon the site team's prior experience and limited observed conditions, recommendations were made for further investigation. These areas typically required additional evaluation by the owner but could result in short or long-term efficiency improvement.

The underlying objective of this project was to develop a tool that operators and owners could use to understand the performance of their cleanroom. For this project, 10-12 cleanrooms will be studied. In the future, a mechanism for self-evaluation will be developed allowing a cleanroom owner/operator to compare his cleanroom's performance to a large sampling of similar class cleanrooms. This will then lead to identifying best practices and new energy-saving opportunities.

Database Structure

An Access™ database was designed specifically to record the measured data and calculated metrics of interest for the cleanroom energy benchmarking. The structure of the database allows recording critical facility information, operating parameters, environmental conditions, measured energy use, design values, utility billing data, and other narrative descriptions. By recording the benchmarking data in a standard, structured format direct comparisons between systems, components, and between facilities will be possible. The database structure is shown in Figure 2. Each of the categories in the database is structured specifically for the design values, measurements, and the calculated metrics of interest.

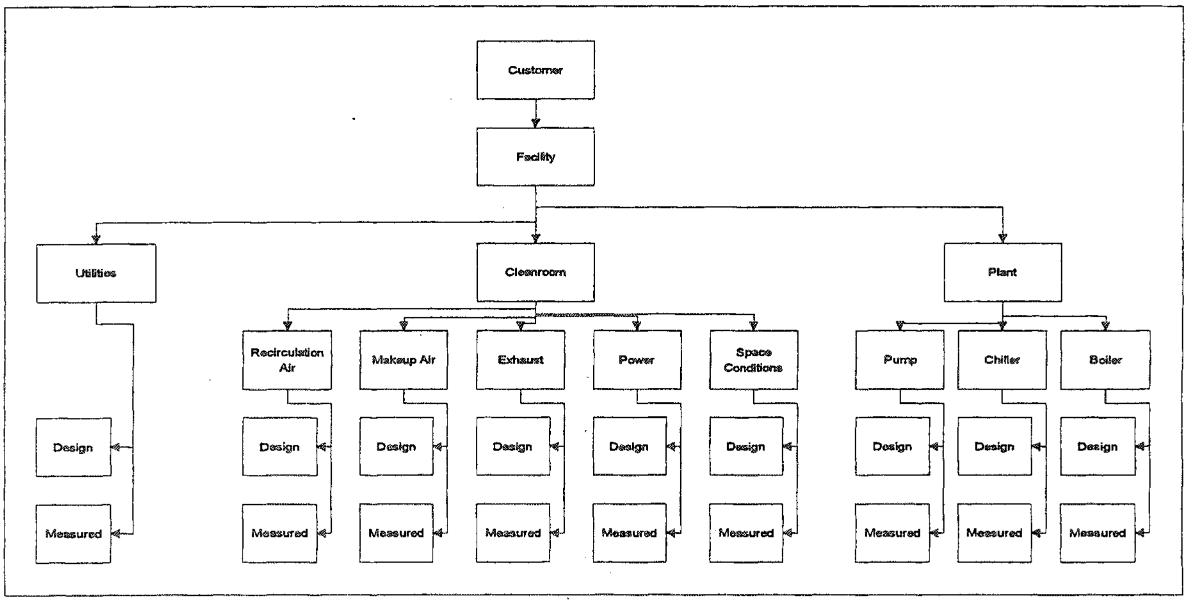

Figure 2. Cleanroom Energy Benchmarking Database Structure

Observations

End use energy breakdowns were obtained for the benchmarked cleanrooms. Table 2 presents the energy use breakdown for three of the benchmarked facilities. From this data it is readily apparent that the electrical loads of the HVAC system (chilled water, hot water, steam, and cleanroom fans), and the process systems account for the majority of the energy use in a cleanroom facility. Measured HVAC energy use has accounted for 36-67% of the total facility energy in the facilities monitored to date. While the relative percentages vary based upon the magnitude of the process systems energy consumption, and the cleanliness class of the room, the environmental, i.e. HVAC, systems clearly are the dominant contributor to the energy intensity in cleanrooms.

Table 2. Cleanroom Energy Use Breakdown

End Use	Facility A (%)	Facility B (%)	Facility C (%)
Total Chilled Water	18	19	20
Hot Water and Steam	7	22	17
Cleanroom Fans	11	16	26
Process Utilities (Compressed Air, DI Water, etc.)	17	6	7
Cleanrooom Lights	1	1	1
Process	35	13	9
Other Misc.	6	9	11
Office (Lights, Plugs)	5	14	9

Recirculation Systems

By focusing on the various HVAC systems and their components, the benchmark data reveals that energy use can vary by factors of 5 or more for systems that serve essentially the same purpose. For example, Figure 3 illustrates the efficiency of systems used to recirculate clean, conditioned air through a cleanroom. In this figure, the metric is the flow rate (in cubic feet per minute) per unit of electrical energy (in Kilowatts). The limited data collected to date is useful in several ways. There are three distinct classes of cleanrooms (cleanliness levels termed class 1,10,100) on this chart. The results indicate that the energy intensity generally increases for higher cleanliness levels, but system design also plays a significant role and some higher cleanliness levels may actually be more efficient than lower levels. This shows the importance of specifying only the cleanliness that is needed for a specific process, and once the cleanliness level is specified, there is a wide range of energy performance depending upon the design selected.

For this study, data from several facilities was obtained for various system types or classifications. Figure 3 shows a comparison of data for three system configurations for eight of the individual cleanrooms measured in this study. Each produced a class 100 cleanliness rating, but efficiency varied by greater than a factor of five. The bars on figure 3 represent individual measured values for eight of the benchmarked cleanrooms. The descriptions below the bars show the cleanliness class and the type of system. The lower the class number, the higher the cleanliness. That is, class 10 is cleaner than class 100 and so forth. The main purpose in showing this information is to highlight that there is wide variation and the type of design does matter. This wide variation underscores the need to understand the features and principles of the more efficient systems. This will lead to best practices in design and construction of these systems.

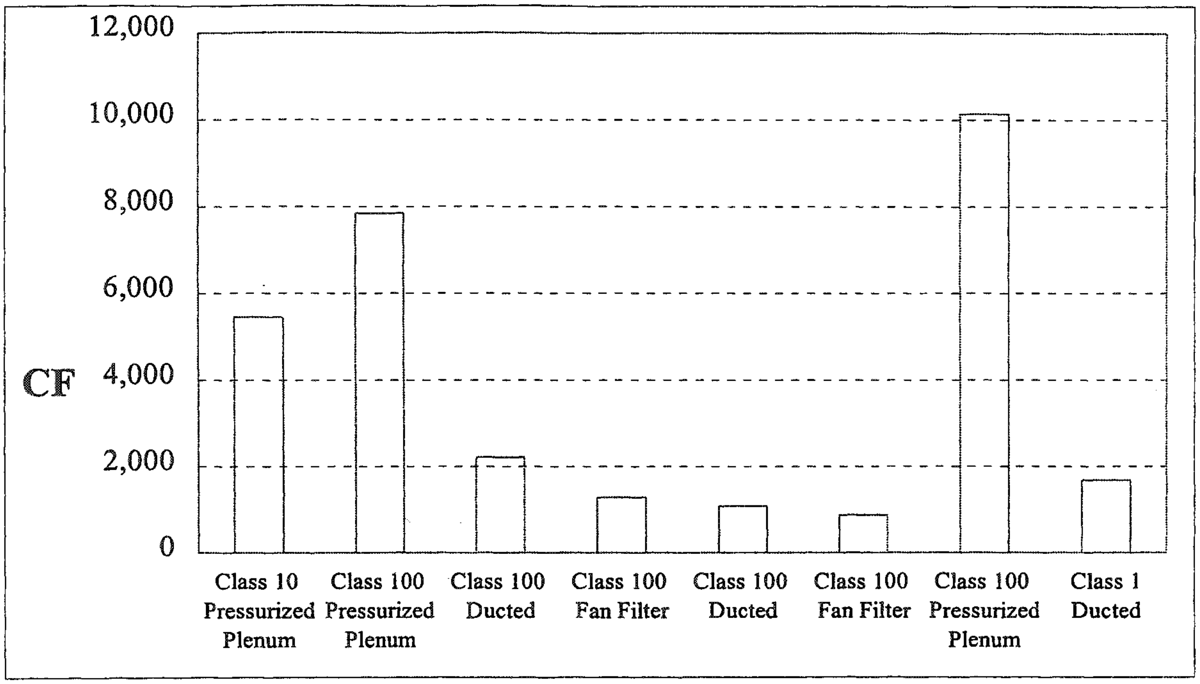

Figure 3. Cleanroom Air Recirculation System Efficiency

For example, it is evident that systems with low return air pressure drop are more efficient in terms of CFM/KW. One way to accomplish this is through use of a pressurized plenum that provides air to the cleanroom ceiling filters. This design option provides separate ductwork to each of the ceiling filters. The two configurations are illustrated in figures 4 and 5. Although there are advantages and disadvantages to each configuration, the benchmark results confirm that open plenum systems are more efficient than ducted systems.

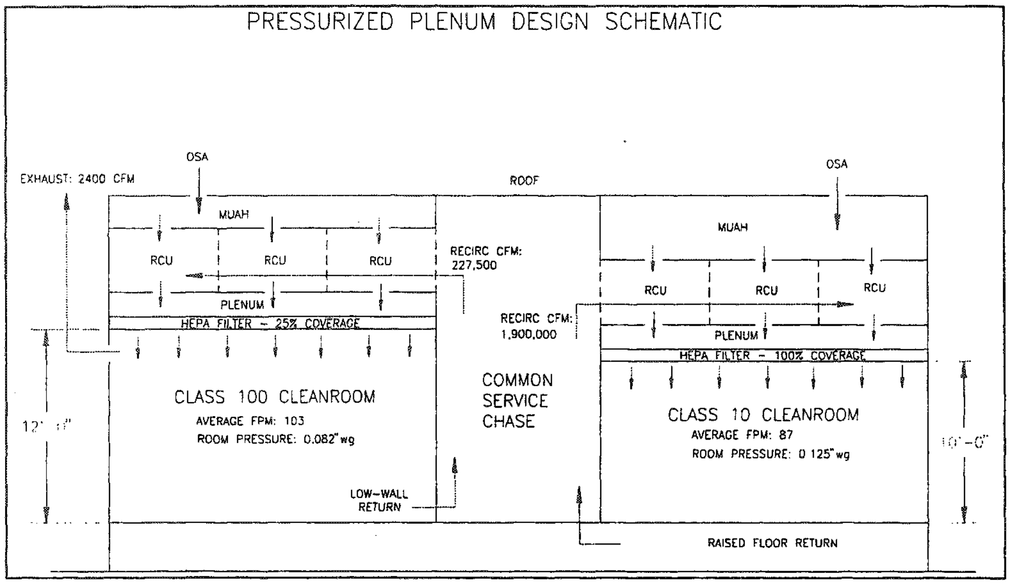

Figure 4. Plennum Recirculation System

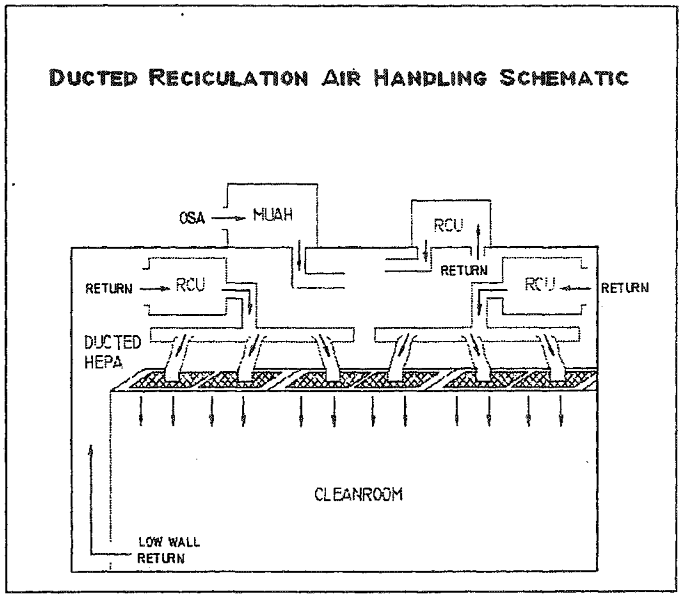

Figure 5. Ducted Recirculation System

Another useful observation is that the air-flow through a given class of cleanroom can vary significantly and achieve the desired cleanliness rating. IEST recommends a range of air changes (and resulting range of air velocities) which, when followed usually achieves the desired rating. Figure 6 illustrates the variation in air change rate for the measured cleanrooms as determined through the benchmark measurements. This graph shows how air change strategies can vary significantly from facility to facility. Cleanroom operators may choose to lower airflow for their facility if presented with data demonstrating that other cleanrooms are functioning well with lower flows. Since fan power is proportional to the cube of airflow, a ten percent reduction in airflow could result in approximately a thirty percent reduction in fan energy.

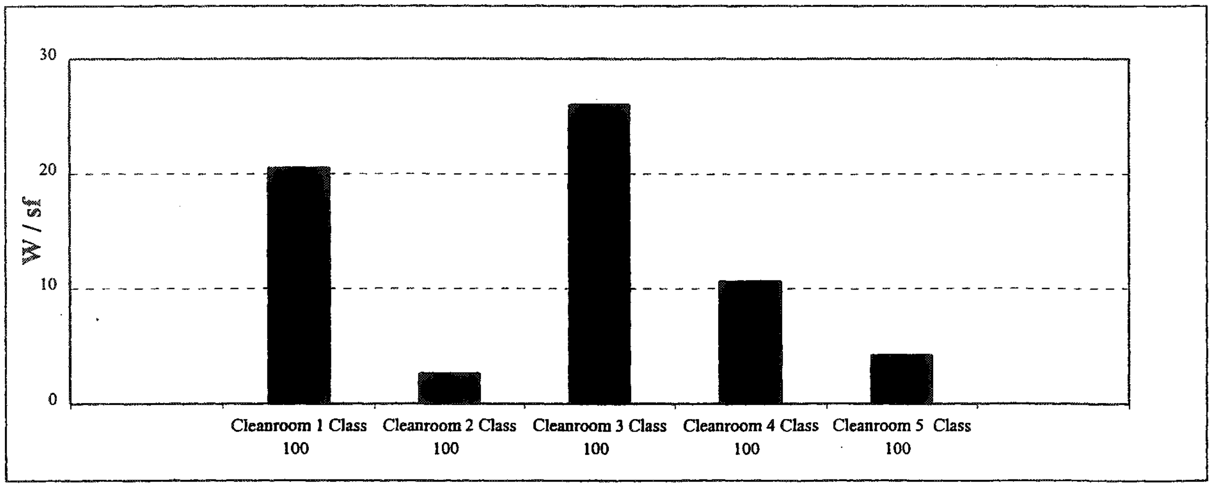

Figure 6. Cleanroom Air Changes per Hour

Chilled Water Systems. Similarly for chilled water systems, Figure 7 illustrates that the chiller efficiencies in this study vary from 0.5 kW/ton to over 0.8 kW/ton and the efficiency of other system components similarly vary significantly. Water-cooled chillers are generally more efficient, but pumping can play a significant role in total system energy use.

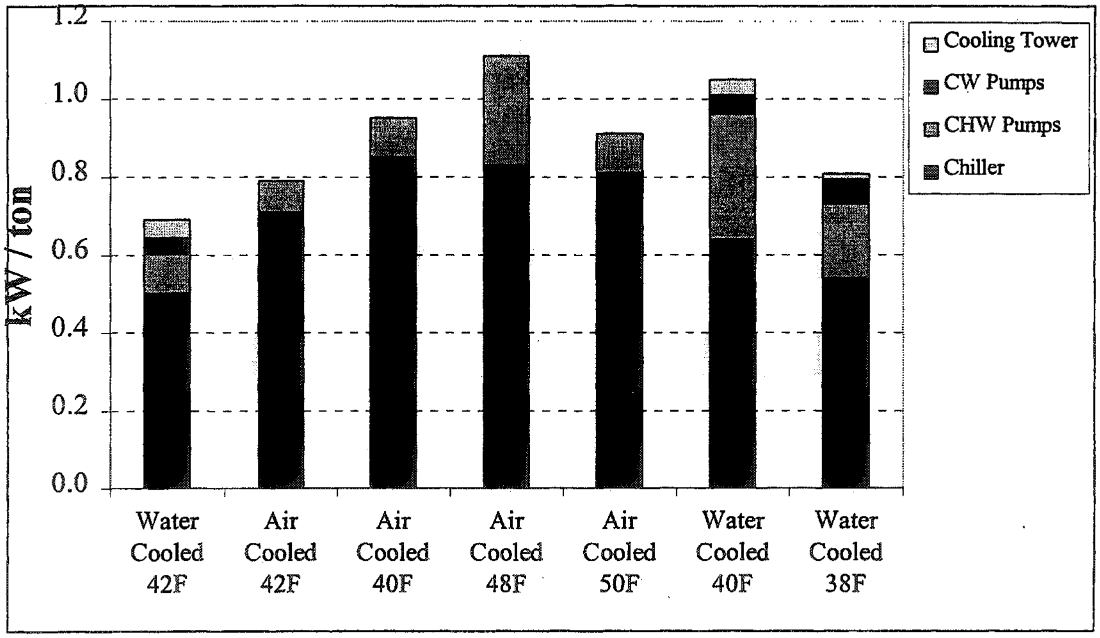

Figure 7. Chilled Water System Comparison

Process Loads. The process electrical load has a major influence on the design and operation of the cooling system. Process electrical loads convert directly into heat load for removal by the HVAC systems. The amount of process load can vary significantly from cleanroom to cleanroom and uncertainties in predicting process load often make sizing the HVAC system a challenge. Measured energy intensity is quite different depending upon the process occurring in the cleanroom (figure 8). While the load is dependent on the type of manufacturing or research in the cleanroom, measured data from facilities with similar processes will help "right-size" the cooling equipment. Cooling systems are more efficient when operated near the full design load. Often, however, cleanrooms are designed for unrealistic loads – design loads between 75 and 125 Watts/sf are common. Over-sizing is common due to uncertainties in the process load, provision for future expansion, and engineering tendencies to add conservatisms. The Benchmarking Project found process loads at all facilities below 30 Watts/sf. Use of benchmark data can lead to better prediction of design loads and better build-out strategies. Designing systems and components in closer alignment with the actual operating loads will also lead to more efficient operation.

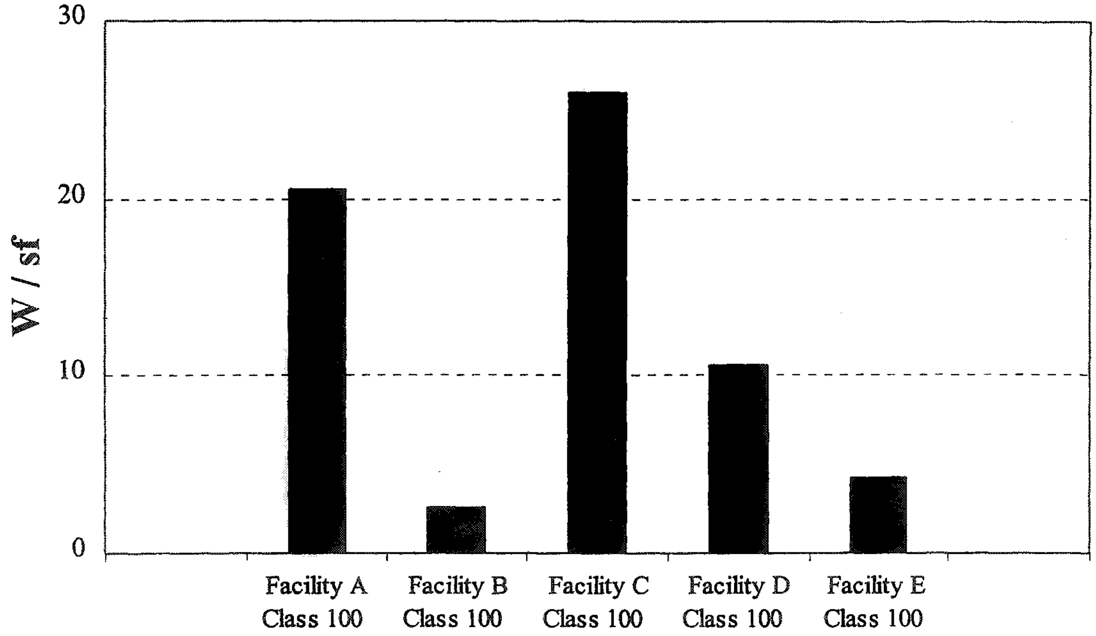

Figure 8. Class 100 Cleanroom Intensity Variation

Best Practices

Based upon the data collected and site observations, a number of efficiency recommendations are emerging as best practices for the facilities monitored in Northern California. Representative recommendations include:

- Install free cooling system using cooling tower water for sensible and process cooling loads.
- Install a separate high temperature chiller for process cooling.
- Improve cooling tower efficiency by operating all cooling towers at reduced fan speed rather than operating fewer towers at full speed.
- Improve chiller efficiency by lowering condenser water temperature.
- Reduce pumping - increase chiller temperature difference.
- Recirculation airflow setback at non-production or unoccupied times.
- Remedy cycling equipment identified through monitoring

Conclusion

Energy benchmarking is an effective tool to aid in visualizing the energy end uses in complex cleanroom facilities. For a cleanroom owner/operator there are a number of high value benefits. Measured energy use determined by a benchmarking program can provide a baseline for tracking energy performance over time. Benchmarking can also be used to prioritize where resources need to be applied to achieve improvements in energy efficiency.

Use of the metrics developed for this project provides a mechanism of system and component comparison to other cleanrooms. This comparison is possible even though the system design and configuration may be completely different. By analyzing the variation in the data, best practices can be identified. The strategies and configurations resulting in the most efficient operation can then be applied to new designs or retrofit into existing facilities. Large apparent variations in the energy use of systems or components may signify design, installation, operational, or maintenance problems. Finding the root cause of the discrepancy could solve on going operational or maintenance problems or correct problems originally built into the facility. For cleanroom designers, access to actual comparison data will highlight best practices and lead to new creative energy efficient designs. Energy efficiency for industries that rely on cleanroom technology will create productivity gains resulting in immediate and on-going bottom line savings.

Future activity should be directed at developing a more robust database through additional benchmarking and collection of existing measured data. As an alternate to collecting physical measurements, it would also be useful to build a database of design-based values. This would provide some needed guidance to designers and owners in deciding on various design options. Finally, a self-benchmarking tool is needed to allow building operators to perform their own assessments and then compare performance over time or compare to others.

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