LBNL-50219
HT-479

Presented at the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) conference, Honolulu, Hawaii on June 22-26, 2002 and published in the proceedings.

Cleanroom Energy Benchmarking Results

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September 2001

The research reported here was funded, in part, by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technology Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Abstract

A utility market transformation project studied energy use and identified energy efficiency opportunities in cleanroom HVAC design and operation for fourteen cleanrooms. This paper presents the results of this work and relevant observations. Cleanroom owners and operators know that cleanrooms are energy intensive but have little information to compare their cleanroom's performance over time, or to others. Direct comparison of energy performance by traditional means, such as watts/ft^2, is not a good indicator with the wide range of industrial processes and cleanliness levels occurring in cleanrooms.

In this project, metrics allow direct comparison of the efficiency of HVAC systems and components. Energy and flow measurements were taken to determine actual HVAC system energy efficiency. The results confirm a wide variation in operating efficiency and they identify other non-energy operating problems. Improvement opportunities were identified at each of the benchmarked facilities. Analysis of the best performing systems and components is summarized, as are areas for additional investigation.

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.). A representative breakdown of cleanroom floor areas in the industries that use cleanrooms in California is shown in **Figure 1**. Similar diverse uses of cleanrooms occur throughout the United States and around the world.

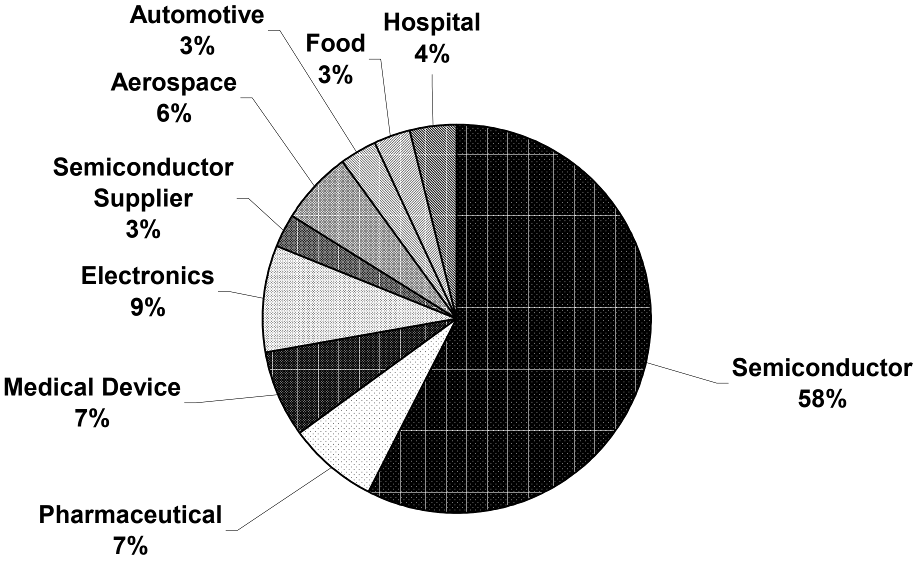

Figure 1. Cleanroom floor area used by California industries (Total =4.2M ft^2).

Although energy costs are high, owners and operators of cleanrooms 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 the design of new systems. To evaluate energy efficiency of HVAC systems, simple comparisons of energy use per square foot are of little value since process related energy (heat load for the HVAC systems) varies greatly from cleanroom to cleanroom. Some industries use production metrics relating energy use (in watts) to number of units of produced. The semiconductor industry, for example, considers watts/cm^2 of silicon wafer. These types of metrics focus on overall production efficiency but overlook, or mask, the efficiency (and opportunities for improvement) of energy intensive HVAC systems and other facility systems. It is therefore possible to have seemingly efficient manufacturing and/or continuous improvement through manufacturing process improvements, while continuing to operate inefficient HVAC systems.

This paper presents the results of a study to benchmark measured energy performance in cleanrooms. The project developed a benchmarking strategy to obtain the energy end use breakdown for the various industries represented in the study, and to enable direct performance comparison between cleanrooms regardless of the process. The metrics used allow comparison of energy performance of key systems and components. This paper describes the metrics used in this study and discusses some of the results obtained during the course of this work. It also provides summary benchmarks for the HVAC systems for all of the participating cleanrooms. Preliminary results were previously reported at the ACEEE Summer Study on Industrial Energy Efficiency (Tschudi et al. 2001).

Background

HVAC systems serving cleanroom facilities are typically energy intensive. They include large central plant heating and cooling, huge 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, safety, and/or process requirements. Prior research and industry studies have documented representative energy intensity and some of the opportunities for efficiency improvement (Mills et al. 1996). Representative breakdowns of total energy use in a cleanroom highlight the need to focus on the HVAC systems for energy efficiency improvement.

Recirculation airflows vary considerably based upon cleanliness class, air change rates recommended by the Institute of Environmental Sciences and Technology (IEST), and individual operating preferences. Exhaust, and corresponding make-up air requirements, are primarily governed by building and fire codes, and/or insurance requirements. Within these recommendations and requirements, there is considerable flexibility for the cleanroom designer and operator to choose air change rates, overall system configuration, and layout that will affect the HVAC systems' energy performance. We observed a wide variability in performance.

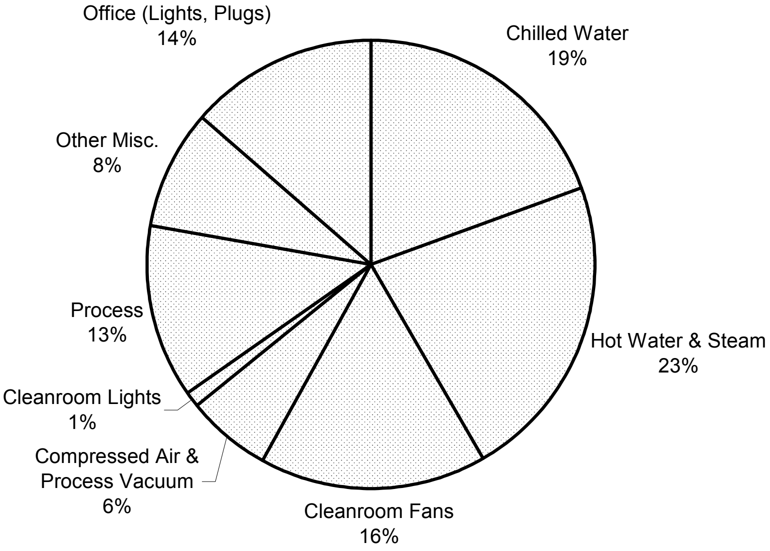

Figure 2. Energy end-use in production cleanroom.

Although activities performed in cleanrooms, and the related contamination control requirements vary greatly, cleanroom HVAC systems typically utilize a large percentage of total building energy (up to 50%). **Figure 2** shows the representative breakdown for a production cleanroom in the electronics industry. (Sartor, et al. 1999)

Energy intensity varies with the cleanliness level (IEST ESO Standard 14644-1, 1999) and use of the cleanroom. Since cleanrooms are 10 to 100 times as energy intensive as office buildings (typically 6 watts/ft^2, (CBECS), they are attractive candidates for energy savings. Efficiency opportunities for the HVAC systems are prevalent and crosscut all cleanroom applications in all industries.

Project Description

The metrics developed for this project allow comparison of widely varying HVAC systems regardless of the design configuration, 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 using metrics compiled from design or measured data. These metrics readily illustrate how efficiently the systems are designed and operating. Performance as demonstrated by metrics such as cfm per kW was based upon direct measurement. In some cases where direct measurement was not possible due to operational concerns, balance reports, EMCS readings, or design data was used. Even though wide variations in process load, HVAC system and component design, cleanliness requirements, and other operating parameters make standard comparisons impossible (such as kW/ft^2); it is possible to directly compare energy performance of systems and components by use of these metrics.

A hierarchical approach was used for this project, beginning with whole building energy use and progressing to selected system level measurements, and then to key component measurements. Site measurement plans were tailored to each individual cleanroom 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 systems as possible for each site in approximately a two-week period. A representative sample of the metrics and priorities for obtaining the data are shown in **Table 1**.

Table 1. Cleanroom/Central Plant Metrics

Description	Units	Description	Units
Recirculation Air Handler Efficiency	cfm/kW	Chiller Efficiency	kW/ton
Make-up Air Handler Efficiency	cfm/kW	Tower Efficiency	kW/ton
Annual Energy Cost per Cleanroom Square Foot	\$/ft^2	Condenser Water Pumps Efficiency	kW/ton
Annual Fuel Usage	MBtu/ft^2/yr	Chilled Water Pumps Efficiency	kW/ton
Annual Electricity Usage	kWh/ft^2/yr	Total Chilled Water Plant Efficiency	kW/ton

To guide the data collection and to inform the host site staff of how the information would be obtained, plans were prepared detailing the methodology, metrics, and data measurement tools to be used. A General Plan was used to help explain the study. Then site-specific, measurement plans were prepared. The plans identified the specific systems and components to be measured. The site-specific plans described how and where the information would be obtained. Where systems contained multiple identical components such as similar chillers, pumps, air handlers, etc. a representative sample was measured. This assumes that similar units will have similar operating efficiency and will provide a general indication of overall system efficiency. The most energy intensive systems were selected as the highest priority as determined in prior investigations (Mills, et al., 1996). In addition, lower priority systems and components were targeted if data could be readily obtained in the time allotted. In this way, some data on other less energy intensive systems was collected as time permitted. Benchmark data for cleanrooms of different cleanliness classes were 1000 obtained. These included five Class-10 (ISO Class-4) cleanrooms, seven Class-100 (ISO Class-5) cleanrooms, one Class-100/1000 (ISO Class-5/6) cleanroom, and one Class-10000 (ISO Class-7) cleanroom.

Even though process systems were not always 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 typically ignored.

Data collected from the site was organized into a database to allow eventual comparison to other similar class cleanrooms. The database was structured specifically to document measured facility data and calculate the cleanroom related metrics. Graphical representation of the Data was then automatically provided to allow easy comparison. Results were analyzed to understand the relative ranges of operating parameters and to determine the reasons for the better performing systems and components.

The current population of cleanrooms is limited. To develop a more robust data set, many additional cleanrooms will need to be measured and entered into the database. The current information provides a level of comparison however, once additional cleanroom are benchmarked and made available, building designers, facility managers, and process engineers will be better able to gauge the relative performance of the cleanroom system's and component's performance.

During the project, the team on-site noted potential efficiency opportunities through visual observation and analysis of the data. These improvement opportunities were provided to the building representatives in a final report. The observations were not meant to be all encompassing but captured any obvious efficiency opportunities and areas to target for more in depth study. These areas typically required additional evaluation by the owner but could result in efficiency improvement.

The goal of this project was to develop the benchmarking protocol and collect data so that operators and owners could compare the performance of their cleanrooms. In the future, a mechanism for self-evaluation could be developed to allow cleanroom owner/operators to compare performance to a sampling of similar class cleanrooms. The database should be large enough to capture the full range of operating performance. As owners and operators see the comparison to best practices, they will naturally demand that their systems operate at higher efficiencies. The results may also pinpoint areas needing new or improved technologies or strategies to allow improvements to be made.

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 includes provision for recording critical facility information, operating parameters, environmental conditions, measured energy use, design values, utility billing data, notes, and other narrative descriptions. By recording the benchmark data in a standard, structured format and using graphical representation of the results, direct comparisons between HVAC systems and components is possible.

Discussion

For each of the cleanrooms, energy end use was determined. From the data it was readily apparent that the electrical loads serving 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. As expected, the relative percentages for each end use varied based on the type of process and due to variations in the HVAC system design. HVAC energy use as measured in the individual cleanrooms accounts for 36–67% of the total facility energy. While the relative percentages vary due primarily to the magnitude of the process systems energy consumption, and the cleanliness class of the room, the HVAC systems clearly are the dominant contributor to the energy intensity in cleanrooms.

Recirculation Systems

By focusing on the recirculation air systems and their components, the benchmark data reveals that energy use for the same amount of delivered air can vary by factors of 5 or more, for systems that serving cleanrooms of the same cleanliness class. For example, **Figure 3** illustrates the relative efficiency of the measured recirculation systems. To facilitate comparisons of air systems, cfm/kW is a useful metric. This provides a direct comparison of the efficiency of moving air. One would expect that the energy intensity should generally increase for higher cleanliness levels with higher airflows, but system design and component selection also plays a significant role. Some systems used for higher cleanliness levels can be more efficient in terms of cfm/kW than lower cleanliness levels. The results demonstrate that there can be a wide range of energy performance depending upon the design and the operating strategy (i.e., air changes per hour).

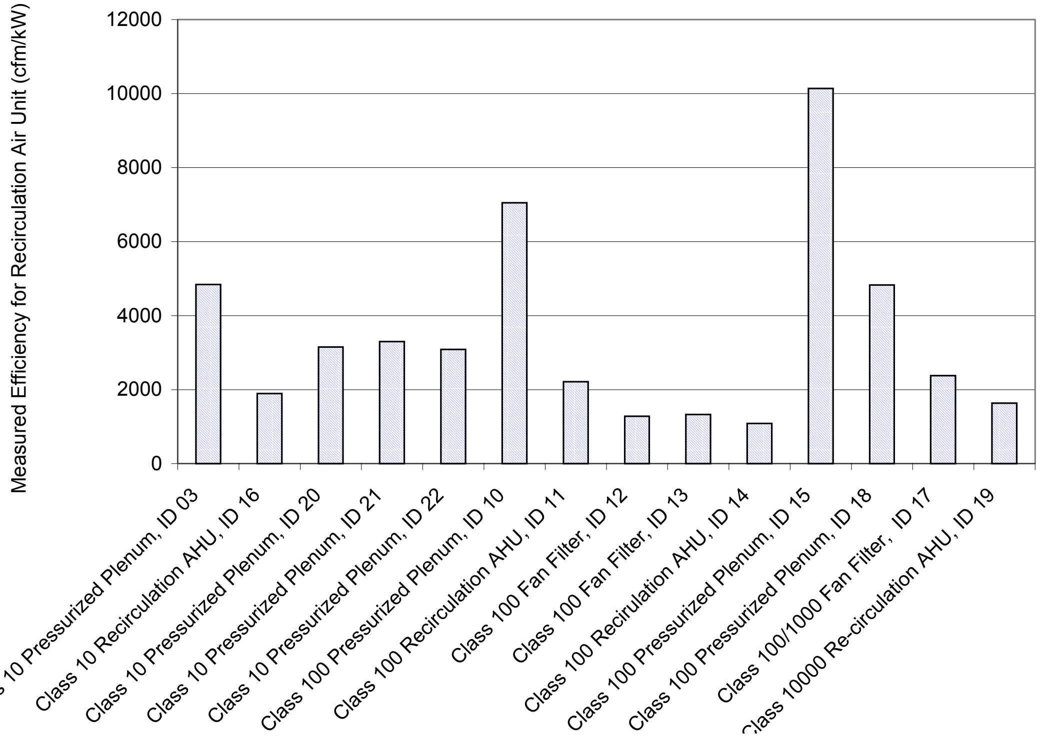

Figure 3. Cleanroom recirculation air system efficiency.

Figure 3 shows a comparison of data for three system configurations—two using larger recirculation units with ducting leading to HEPA filters or pressurized plenums and the balance using fan-filter units. Focusing on the class 100 systems, re-circulation system efficiency varied by greater than a factor of five. The obvious conclusion with this information is that there is wide variation in energy performance for systems achieving the same contamination control objectives. Obviously, some systems perform extremely well compared to others. This wide variation underscores the need to understand the features and principles of the more efficient systems as well as individual components. Decision makers will tend to implement more efficient systems once the energy performance is known and given equal weight with other design considerations. In addition, the influence of construction practices (such as system tightness) and operational practices (such as cleanroom air velocity) will be evident.

As an example, this benchmarking highlights that systems where the return air path has low pressure drop are more efficient in terms of cfm/kW. One way to accomplish this is through use of an adequately sized pressurized plenum providing air to the cleanroom ceiling filters. From the plenum, the recirculated air can then be supplied directly to the cleanroom HEPA filters, or through individual ductwork to each filter. Ducting adds additional pressure drop, although there are other non-energy considerations such as ease of balancing that enter into the final selection.

Although there are advantages and disadvantages to each configuration, the benchmark results confirm that open plenum systems are generally more efficient than ducted systems. The low-pressure drop criteria should also be applied to the rest of the recirculation path including filters, floor systems, return chases, cooling coils, etc.

Another useful observation is that the airflow through a given class of cleanroom can vary significantly and still achieve the desired cleanliness rating. IEST provides a range of recommended air change rates (and resulting range of air velocities) which, when followed usually achieve the desired cleanliness rating. **Figure 4** illustrates the variation in air change rates for the measured cleanrooms as determined through the benchmark measurements.

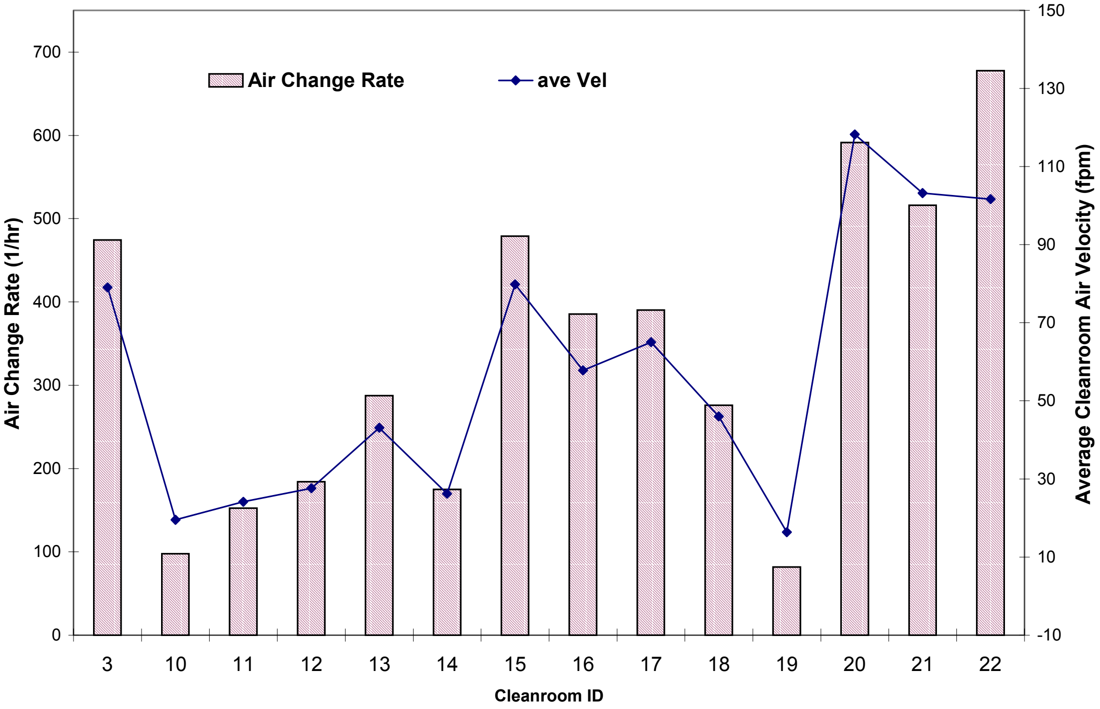

Figure 4. Cleanroom air change rates and average velocities.

This graph shows how air change rates can vary significantly, yet all cleanrooms met contamination control requirements and were certified. Process engineers and cleanroom operators are likely to lower airflow for their facility if presented with data demonstrating that other cleanrooms are functioning well with lower flows. In addition other scientific justification should be developed to provide further basis for lowering air flows. Since fan power in theory is approximately proportional to the cube of airflow, a small reduction in airflow could result in large reductions in fan energy.

Chilled Water Systems.

Similar large variations in energy performance of chilled water systems were observed. **Figure 5** illustrates that the chiller efficiencies in this study vary from 0.4 kW/ton to over 1.6 kW/ton and the efficiency of other system components similarly vary significantly. Water-cooled chillers are generally more efficient, but pumping and part load operation can play a significant role in total system energy use.

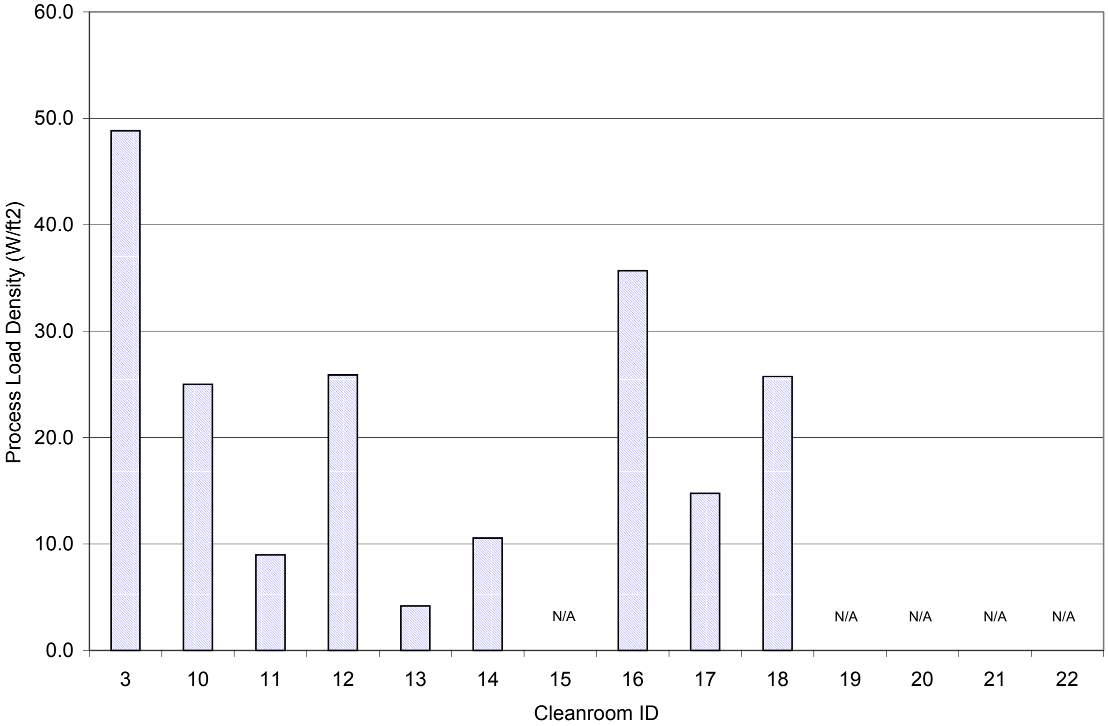

Figure 5. Chiller performance comparison process loads.

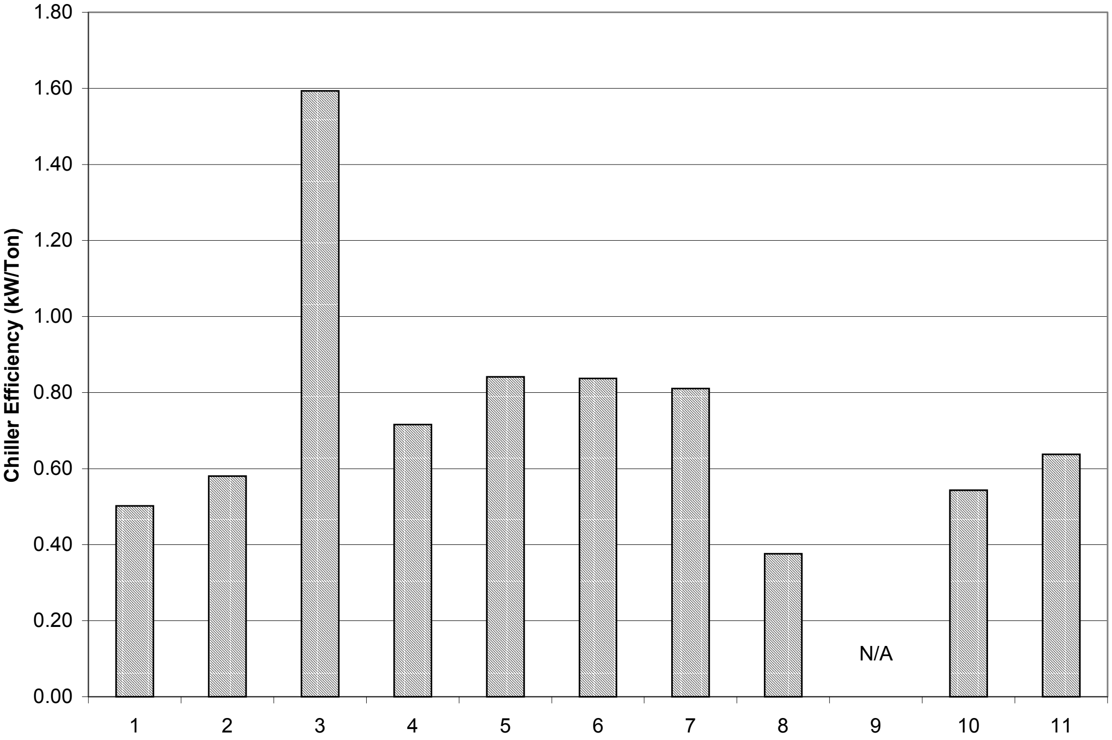

Figure 6. Process power intensity.

Process Loads.

The process electrical load has a major influence on the design and operation of the cooling system. Most process electrical loads convert directly into heat load for removal by the HVAC air or process cooling systems. The amount of process load can vary significantly from cleanroom to cleanroom. 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 6)**.

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 often are more efficient when operated near the full design load. In addition, however, cleanrooms often are designed for unrealistic loads—cleanroom HVAC 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 conservatism. The figure shows that the process load intensities ranged from 4 to 26 W/ft^2 among ISO Class-5 cleanrooms, and from 36 to 49 W/ft^2 among ISO Class-4 cleanrooms. 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.

Efficiency Recommendations.

Based upon the data collected and site observations, a number of efficiency recommendations to achieve better efficiency are emerging for the benchmarked facilities. Representative recommendations include:

Install free cooling system using cooling tower water for sensible and process cooling loads.

Install separate high temperature chillers for process cooling.

Improve cooling tower efficiency by operating multiple 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.

Reduce recirculated airflow.

Recirculation airflow setback at non-production or unoccupied times.

Reduce or eliminate pre-filters.

Remedy cycling equipment identified through monitoring

Energy costs associated with cleanroom operation are high. It is not uncommon to have electricity cost exceed $500,000–$1,000,000 for a production cleanroom. Owners and operators can use the benchmark results to determine areas for significant energy and cost savings.

Conclusions

Energy benchmarking is an effective tool to aid in visualizing energy end use in complex cleanroom facilities. HVAC systems, being the most energy intensive cleanroom building systems, have widely varying energy performance. System configuration, components, operational parameters, and sizing all significantly impact energy performance. For a cleanroom owner/operator there are a number of high value benefits to benchmarking these systems. The benefits include:

- Providing a mechanism to establish a baseline and then track energy performance over time.
- Prioritizing where resources need to be applied to achieve improvements in energy efficiency.
- Identifying best practices by comparison to other systems and components.
- Identifying maintenance or control problems.
- Significant potential for operating cost savings

The metrics developed for this project can be used for system or component comparison between different types of cleanrooms. This comparison is possible even though the system design and configuration may be completely different. By analyzing the variation in the data, more efficient 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 costly 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 measured benchmarks and incorporation of existing 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, compare performance over time, or compare energy performance to others.

Acknowledgements

The research reported here was funded, in part, by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technology Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Special thanks are extended to the California Institute for Energy Efficiency (CIEE) and Pacific Gas and Electric Company for their support of this project.

Special appreciation is given to the project team:

PG&E

Kathleen Benschine
Pat Eilert
Stephen Fok
Keith Rothenberg (consultant)
Charlie Middleton
Ken Gillespie

Lawrence Berkeley National Laboratory

Dale Sartor (Principal Investigator)
Bill Tschudi
Don Aumann
Mary Ann Piette
Geoffery Bell
Tengfang Xu

Supersymmetry

Peter Rumsey
Leslie Hummel
Joe Regester
John Weale
Larry Chu
Peter Stevens

CIEE

Karl Brown
Ed Vine

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