Arnold Schwarzenegger
Governor

High-Performance High-Tech Buildings

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By: William Tschudi
Lawrence Berkeley National Laboratory

March, 2008
CEC-500-02-004

Prepared By:
Lawrence Berkeley National Laboratory
William Tschudi
Berkeley, CA 94720
Commission Contract No.: UC Research Agreement,
Contract #500-02-004;
Commission Work Authorization No: MR-016

Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Paul Roggensack
Contract Manager

Pramod Kulkarni
Program Area Lead
Industrial, Water, and Agriculture

Darryl Mills
Office Manager
Energy Efficiency Research Office

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B.B. Blevins
Executive Director

Acknowledgements

Special thanks are extended to the Industry Partners and project participants for their support of this project.

- **Principal LBNL Investigator:**
  - Bill Tschudi
- **Additional LBNL Investigators:**
  - Dale Sartor
  - Tengfang Xu
  - Evan Mills
  - David Faulkner
  - Geoffrey Bell
  - Steve Greenberg
  - Bruce Nordman
- **Sub-contractors**
  - Peter Rumsey, Kim Traber, and Larry Chu, Rumsey Engineers, Inc.
  - Jay Madden and Michael Tatoyan, EYP Mission Critical Facilities
  - My Ton and Chris Calwell, Ecos Consulting
  - Arshad Mansoor and Brian Fortenbury, EPRI
  - Tom Smith, Exposure Control Technologies

- **Industry Partners and Other Collaborators**
  - 365 Main
  - Rockwell International
  - Abgenix
  - Johnson & Johnson
  - Hewlett Packard
  - Cisco
  - Jazz Semiconductor
  - Balazs Analytical Services
  - Equinix
  - International Sematech
  - Earthlink
  - Cornell University
  - State University of New York at Binghamton
  - Georgia Institute of Technology
  - IBM
  - Pacific Gas and Electric Company
  - Intel Corporation
  - Sun Microsystems
  - Additional firms acknowledged in DC Power Demonstration Report
  - Critical Facilities Roundtable

Citation

LBNL. 2008. *High Performance High Tech Buildings.* California Energy Commission, PIER. 500-02-004

Preface

The PIER Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER program, managed by the Commission, conducts public interest Research, Development, and Demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. **The Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.**

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings Energy Efficiency End Use
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration.

What follows is the Final Report for the **Lawrence Berkeley National Laboratory,** UC Research Agreement, Contract #500-02-04; Work Authorization #: **MR-016** conducted by the **Lawrence Berkeley National Laboratory and it sub-contractors.**. The report is entitled **High-Performance High- Tech Buildings.** This project contributes to the **PIER Industrial, Water, and Agriculture** program.

For more information on the PIER Program, please visit the Commission's Web Site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at (916) 654-5200.

Table of Contents

List of Figures

Abstract

This report summarizes research, demonstration, and market transformation activities directed at the High-tech buildings market. Included are elements focused on laboratory, cleanroom, and data center facilities. This work spans 2003 through 2007and generally supports the PIER research roadmaps for these building types. This report is organized with stand-alone appendices which provide more detail for specific topics included in this phase of the work. Many industry partners and industry associations acknowledged herein participated in this project through in-kind support, collaboration, and through project advisory committees.

Executive Summary

Prior research and investigations by Lawrence Berkeley National Laboratory (LBNL) focused on energy intensive buildings that contain laboratories, cleanrooms, and data centers. LBNL studies and data provided by the California Energy Commission, and California pubic utilities concluded that energy use in the industries and institutions that rely on these facilities represented a large and growing portion of the state's energy consumption. These facilities are characterized as having large, continuous electrical demand as well as significant gas demand in many cases, and far higher energy intensities (e.g. energy per unit of floor area) than conventional buildings.

Preliminary investigations into energy efficiency improvement opportunities conducted within this project involved multiple sponsoring organizations[1] and industry partners, which led to a better understanding of how they presently operate, and identified research that would be needed to achieve greater efficiency in the future. The PIER "energy research roadmaps" for these building types highlighted numerous areas ripe for public interest research support, where dramatic energy efficiency gains were possible. The research activities that ultimately were included in this project were prioritized by industry leaders through workshops and public utility hosted meetings. This project was designed to address specific high-priority opportunities identified in the roadmaps for each of the building types. A variety of research, development, demonstration, and deployment activities were included.

Two project advisory committees - one focused on laboratories and cleanrooms and the other on data centers - were assembled and provided valuable project review and input. These committees consisted of industry leaders representing various stakeholders: public utilities, facility operators, design firms, manufacturers, industry associations, and other public interest organizations.

[1] Previous sponsoring organizations included CIEE, CEC-PIER, PG&E, SDG&E, Northwest Energy Efficiency Alliance, NYSERDA, DOE, and EPA

The results of this project include many high-value findings that are described within this report. Highlights include:

- Benchmarking of laboratories, cleanrooms, and data centers provided insight into opportunities for efficiency improvement. Many efficiency recommendations were relayed to the participating industry partners and presented at industry meetings. Best practices revealed through the case studies were summarized and posted on LBNL's high-tech buildings website along with case study reports and benchmark summaries. In addition, a self-benchmarking protocol for data centers was developed to assist industry in obtaining their own benchmark data. A similar resource for laboratory buildings is available through the EPA/DOE Laboratories for the 21st Century website.

- A standard method of testing and reporting performance of fan-filter units (commonly used in cleanrooms and mini-environments) was developed and reviewed by industry experts. This procedure enables end users to compare energy use when making purchasing decisions. Use of the procedure was demonstrated in the testing of 17 units. The results illustrated the wide range of performance that exists and they can be used to establish baselines for use in utility incentive programs. Extensive targeted print and electronic publications, as well as in-person presentations have made industry aware of this resource.

- A technology that controls cleanroom airflow based upon real-time monitoring of particles (contamination levels) in the room was developed and demonstrated in a pilot study and in two operating industrial cleanrooms. This technology enables cleanroom operators to reduce air flow based upon actual cleanliness conditions, resulting in large energy savings. This task successfully demonstrated the viability and cost-effectiveness of this technology.

- Energy implications for the use of mini-environments (self-contained clean spaces) were studied. Two case studies provided insight into the efficiency of the mini-environments themselves as well as the energy impact of their use within cleanrooms. Findings suggest opportunity for large energy savings in both areas.

- The high performance Berkeley Fume Hood which exhausts 50% as much conditioned air as a conventional fume hood was evaluated in side-by-side testing with a conventional fume hood. To accomplish this, industry consensus was obtained to define new static and dynamic tracer gas tests to verify containment capability. The testing successfully demonstrated that the Berkeley hood containment performance equaled or exceeded that of a conventional hood while providing large energy savings. The results of this testing were successfully used as technical justification in Cal/OSHA variance hearings wherein Cal/OSHA accepted the use of the hoods with minimal supplemental requirements. Unfortunately, Cal/OSHA would not revise their mandated face -velocity requirement so this variance procedure would have to be followed for any installation of the hood. As a result PIER management decided to terminate the planned industrial demonstrations and further work on this technology. The rational for terminating further work was that unless the California standard was changed there would not be widespread adoption and there are alternative technologies available to achieve savings.

- Uninterruptible power supplies (UPS), used extensively in data centers, cleanrooms, and hospitals, account for a constant energy loss due to conversions between alternating current and direct current. A test protocol was developed and used to test the major commercially available UPS systems. Test results showed a wide variation in energy loss among these competing systems suggesting that use of the more efficient systems in data centers could save up to 20% of the electricity powering IT equipment plus approximately equal savings due to the reduction in HVAC energy use for not having to remove the heat generated in the power conversions. In addition, since UPS systems are often deployed in redundant configurations, the losses can be magnified. Various redundancy schemes were studied to determine the relative efficiency of commonly used configurations. This information can be utilized to establish utility incentives to encourage use of more efficient UPS units and their deployment in redundant system configurations. Finally, a draft labeling criteria was developed which could be used in California or Energy Star programs to provide information for those that specify and purchase these systems.

- Energy required to keep standby generation systems ready to function was measured. This data reveals that standby generation consumes more energy than it will ever generate and that State-wide, these losses could be significant.

- Various industry experts were consulted to begin developing consensus on metrics that could be used to evaluate computing performance and associated energy use. These types of metrics will be useful in evaluating energy use together with computing capability. An EPA sponsored conference in January, 2006 attended by over 250 data center professionals recommended that the industry focus on developing a consensus for such metrics. Subsequently, a performance metric procedure that considers computational performance and energy performance was developed for one of the common computational benchmarks.

- Electrical power conversions within IT equipment accounts for a large percentage of its power consumption. A calculator was developed and posted on LBNL's website to quantify energy savings that could result if more efficient components were used. The energy performance of the majority of the most popular class of AC-DC power supplies used in servers was measured. Similar to UPS systems, a wide variation in performance was observed, suggesting that encouraging use of highly efficient power supplies could immediately save an additional 15% or more at the equipment level coupled with a similar saving for facility energy use. This work helped to raise awareness of the inefficiencies in power supplies and over the life of this contract, significant improvement in power supply efficiency became evident.

- Potential demonstration projects were evaluated and proposed. Five of these were selected to highlight the savings opportunity for industry:

- Direct DC powering of a rack of computers
    - DC powering at the facility level
    - Alternative cooling (subsequently cancelled)
    - Fan-Filter testing
    - Demand controlled filtration
    - Data Center design process

- Numerous outlets were employed to transfer technology and findings from this project to industry stakeholders. Highlights of this activity include:
    - Over 100 meetings with industry and other stakeholders
    - Extensive web-based publishing of results and data (http://hightech.lbl.gov)
    - Video documentary of the DC Powering demonstration
    - Articles in 33 trade publications, 10 professional journals, and best-practice guides produced by project researchers
    - Dozens of interviews and references to the project by reporters in the trade media plus coverage in 14 mainstream "popular" media outlets
    - Periodic newsletters entitled *News from The Hood* and *High-Tech News* (each distributed to about 400 people)
    - Active participation in 21 industry Technical Committees or standard-setting groups
    - Provided numerous professional training sessions and curriculum development through the California utilities, community colleges, etc.
    - Collaboration with Industry Associations:
        - ASHRAE
        - 7x24 Exchange
        - Sematech
        - Uptime Institute
        - Silicon Valley Leadership Group
        - Critical Facilities Roundtable
        - Labs 21
        - Green Grid

1.0 Introduction

1.1 Background and Overview

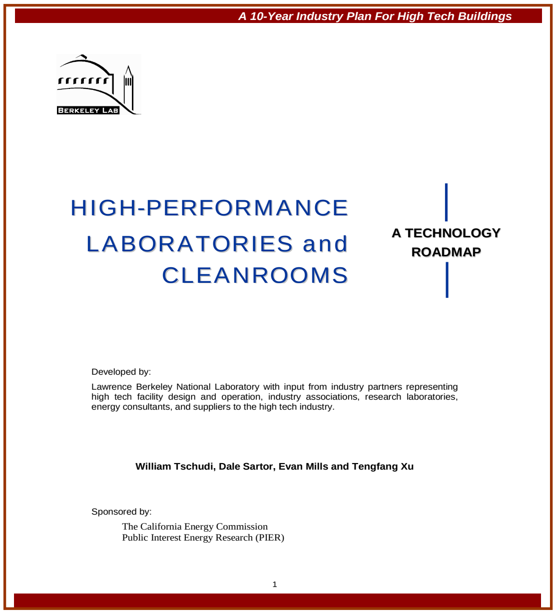
California has long been known for its innovative and robust high-tech industries as well as a research focus which spawned growth in the industries and institutions that rely on laboratory and cleanroom facilities. In addition, California's businesses and institutions operate numerous computing facilities - data centers - with seemingly endless growth in size, complexity, and energy intensity. The PIER Industrial program, recognizing the importance of California's high-tech industries and institutions, and the increasing reliance on computing systems, previously developed "research roadmaps" which were meant to guide and prioritize public interest research related to high-tech buildings. These were developed by LBNL utilizing industry input, and they provide a comprehensive summary of research needs relating to laboratories, cleanrooms, and data centers. Prior LBNL research confirmed that the high-tech building "market" was characterized as large and growing in terms of total size of market and in energy intensity. Further research and case studies confirmed that energy efficiency measures, if developed, could readily be applied resulting in 40% or more in energy savings. Since high-tech buildings typically operate continuously with high energy intensity, energy reduction often translates into very impressive life cycle cost savings while lowering utility peak demand. This project was designed to advance the research agenda for high-tech buildings by focusing on high-priority research on selected topics (as determined by industry feedback) in each of the three facility types. To help guide the current research activities, two project advisory committees (PACs) were formed. One focused on cleanrooms and laboratories and the other on data centers. These PACs were made up of many leading firms, public interest organizations, and industry experts. In addition, a comprehensive tech-transfer and market transformation activity was included to enable the results to reach the targeted industries and other stakeholders.

This report is organized so that each task is addressed in summary fashion in the body of the report. Detailed stand alone reports and supplemental materials were prepared and are attached as appendices to this overall project report. These collectively constitute the deliverables for the project.

2.0 Project Objectives

This project included objectives in the following areas:

2.1 Cleanrooms and Laboratories



The objective of this task was to improve energy efficiency of cleanroom and laboratory facilities by executing selected high priority activities from the PIER high-tech buildings roadmap as described below:

Benchmark laboratory and cleanroom facilities and document best practices.

The objective of this task was to solicit industry partners who operate laboratory or cleanroom facilities to participate in in-depth case studies of their facilities. This involved measurement of the energy performance of building systems in order to develop a more robust set of benchmark data building upon previous benchmark results. This also was to include, for the first time, performance information on standby generation - a typical feature of most high-tech buildings. Site reports were to be developed for each facility and were to include benchmark data along with observations of areas for potential efficiency improvement. Using this data combined with prior benchmark data, the technologies or techniques that contributed to better performance were to be identified in "best practice" summaries. This information along with the benchmark data was to be used to begin market transformation through interaction with industry professionals.

In particular, cleanroom energy intensive air systems (recirculation, make-up, and/or exhaust) were targeted. The findings were to be reviewed against current industry accepted practices such as use of air-change ranges recommended by the Institute of Environmental Sciences and Technology (IEST). The objective was to provide insight into whether the existing practices established by rule-of-thumb were appropriate and whether lower airflow –with resulting energy savings - could be used to achieve acceptable production.

This task was notable in that it entailed a far more detailed level of benchmarking than is common, which, in turn enabled more precise opportunity identification.

- **Advance energy efficient filtration**

  This task's objective was to develop a standard method of testing and reporting performance of fan-filter units commonly used in cleanrooms and other enclosures by collaborating with the Industrial Technology Research Institute (ITRI) of Taiwan, and the Air Movement and Control Association (AMCA- the U.S. fan manufacturer's association) or other industry organizations.

- **Investigate Improvements in Efficiency of Heating, Ventilating, and Air-Conditioning in High-Tech Buildings.**

  The objective of this task was to research promising technologies that could contribute to efficiency savings in cleanroom HVAC systems. Investigations into energy efficiency opportunities using demand-controlled filtration - use of real-time particle monitoring to control airflow in cleanrooms - and in the use of minievironments commonly used in many high-tech industries were conducted.

2.2 Berkeley Fume Hood Development

The objective of this task was to continue the development of the Berkeley Fume Hood by overcoming institutional barriers, and demonstrating energy savings by using the fume hood in industrial settings. This was to be accomplished through the following tasks:

- **Overcoming institutional barriers**

  This task's objective was to devise and provide technical justification acceptable to CAL/OSHA to support granting of variances authorizing the use of the Berkeley Hood in industrial settings.

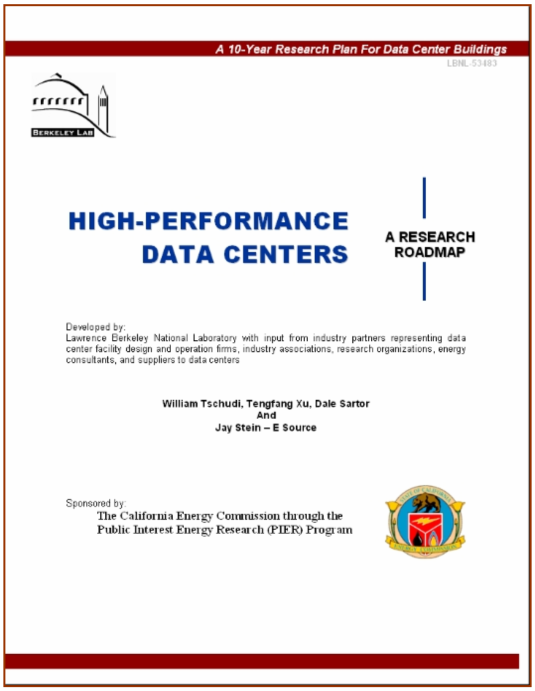
- **Conduct Side-by-side tests with conventional hoods.**

  In this task, the objective was to demonstrate that the Berkeley Hood's safety and energy performance was equivalent to or exceeded that of a conventional fume hood when subject to identical static and dynamic tests.

- **Perform industrial field demonstrations.**

  The industrial demonstrations task primary objective was to demonstrate that the Berkeley Hood performed safely in real-life industrial settings while achieving significant energy savings.

2.3 Data Centers


A 10-Year Research Plan For Data Center Buildings

LBNL-53483

BERKELEY LAB

HIGH-PERFORMANCE DATA CENTERS

A RESEARCH ROADMAP

Developed by:
Lawrence Berkeley National Laboratory with input from industry partners representing data center facility design and operation firms, industry associations, research organizations, energy consultants, and suppliers to data centers

William Tschudi, Tengfang Xu, Dale Sartor
And
Jay Stein – E Source

Sponsored by:
The California Energy Commission through the
Public Interest Energy Research (PIER) Program

Similar to the cleanrooms and laboratories tasks, the objective of the data center tasks was to perform high priority research as identified in the PIER "Data Center Energy Research Roadmap" to develop solutions that could lead to 40% or more energy efficiency improvement. The activities selected are detailed below:

- **Investigate data center efficiency opportunities and perform energy benchmarking**

The objective of this task was to solicit industry partners to participate in case studies and to measure energy performance of data center and associated standby generation systems. Detailed energy benchmark data for data centers was to be collected in order to develop a more robust set of benchmark data when combined with prior benchmark results. For standby generation, the goal was to obtain initial assessments. Site reports were to be developed for each facility and were to include benchmark data along with observations of areas for potential efficiency improvement. A further objective was to review this data along with prior benchmark data to determine the technologies or techniques that contributed to better performance. These "best practices" were to be summarized for use in market transformation activities. In addition, a self-benchmarking protocol was to be developed with the objective of encouraging data center professionals to obtain their own benchmarks. Ultimately the objective of these activities was to identify energy efficiency measures, encourage industry action, and reduce energy consumption in data centers by 10-20%.

- **Improve Uninterruptible Power Supplies (UPS)**

This task's objective was to research and test energy performance of existing UPS systems commonly used in data center environments with a possible longer-term objective of establishing labeling criteria. Possible labeling options were to be explored. In addition, various redundancy strategies were to be investigated with the objective of determining their relative energy efficiencies.

- **Performance metrics**

  The objective of this task was to investigate metrics that could be used to evaluate computing performance along with energy consumption. This task replaced a task to monitor and evaluate new or emerging rack systems used in data centers.

- **Energy Efficient Power Supplies**

  The objective of this task was to investigate the energy performance of selected power supplies currently used in servers and investigate the energy efficiency opportunity to improving their performance.

2.4 Demonstration Projects

The objective of this task was to first identify demonstration projects for consideration. Once the candidate demonstration projects were selected by PIER's Industrial Program, the objective was to organize and perform the demonstrations in conjunction with industry partners. New or underutilized technologies and practices were selected to be demonstrated in commercial settings. The demonstrations were authorized in a second phase of the project. Demonstrations were expected to highlight promising products, technologies, or approaches; or better application of existing technologies. The objective of the demonstrations was to encourage wider adoption of these technologies to a broad audience of high-tech building design and operations professionals. As a result, a substantial technology transfer component was included to disseminate the benefits of the demonstrations to larger targeted audiences.

2.5 Technology Transfer

The objective of the technology transfer activities was to convey the knowledge gained, the experimental results, and the lessons learned to key decision-makers in the various industries and institutions involved with high-tech buildings. Targeted audiences included facility designers and operators, manufacturers and suppliers, and policy makers and public interest organizations.

3.0 Project Approach

3.1 Cleanrooms and Laboratories

- **Benchmark laboratory and cleanroom facilities and document best practices.**

The approach for the energy benchmarking portion of this task involved soliciting benchmarking sites through contacts within individual companies, industry associations, California public utilities and project advisors. Initial contacts focused on Southern California since previous benchmarking efforts were focused on Northern California facilities. At each site, typically, one or more meetings were held to explain the benchmarking process and its benefits to the host site. Once an industry partner agreed to participate, a meeting was held along with our subcontractor; Rumsey Engineers, to describe the system's evaluation and monitoring that would take place, and request a limited amount of design information that would be used to help determine monitoring points. Utility customer representatives for the sites were invited to participate in both the kick-off meeting and the final meeting where results were presented and discussed. The subcontractor then arranged to be on site for several days to collect measurements and obtain existing information from building management systems. Since cleanroom facilities' energy use is typically not dominated by weather conditions, a relatively short monitoring period was planned - usually 3-4 days. Then, over a period of several weeks, the team analysed the data and developed a site-specific report with measured results and energy efficiency recommendations which were based upon observations while on site. In a final meeting with the host site, the report was reviewed and explained. The host site was given the opportunity to correct any factual errors in the report and then the anonymous reports were posted on LBNL's website: http://hightech.lbl.gov/cr-benchmarking-results.html

The benchmarking focused mainly on cleanroom air systems and standby generation systems; however other data were obtained if readily available. All benchmark results were entered into the ACCESS ™ data base developed through a prior PIER project. Summary graphs were then prepared in order to focus on the energy performance for selected systems or components. Results were compared to typical industry practice for various parameters. By reviewing all of the benchmark data and recommendations from the current case studies combined with information contained in case studies obtained from various sources, many areas where better energy performance was achieved became evident. From these, a series of best practice summaries were prepared.

In all, eleven separate cleanrooms at four sites were benchmarked. Two of the sites were in Southern California and two were in the San Francisco Bay Area. In addition, a laboratory facility in Southern California was benchmarked.

- **Advance energy efficient filtration - Standard testing for fan-filter units**

This task involved development of a standard method of testing and reporting performance of fan-filter units (FFUs), which are very common ventilation system components in cleanrooms. In current practice, there is a lack of consistent measurement and reporting of FFU energy performance making it difficult for those specifying them to make informed choices among manufacturer's products. Initially, there was interest within the fan manufacturers association, the Air Movement and Control Association (AMCA), to work with LBNL to develop a standard test method. However, for their continued involvement, a large number of FFU manufacturers (members) were needed and they would need to agree to pay for testing. Since there were not enough manufacturers that were AMCA members, AMCA consequently decided to reduce their involvement in the procedure development yet maintained high interest in collaborating in its development. With LBNL's urging, IEST then agreed to take the lead as the "standards body" by developing an IEST "Recommended Practice" (RP) which would include the test procedure. The IEST RP also plans to address other non-energy considerations such as noise and vibration.

During the project, LBNL developed several drafts of the FFU testing procedure and collaborated with numerous industry professionals who provided input to the draft procedures. LBNL also collaborated with the Industrial Technology Research Institute (ITRI) in Taiwan. In this collaboration, ITRI sponsored a trial application of the test procedure in their AMCA certified test facility. LBNL participated in the test and gained additional insight that was useful in the development of the test procedure. For this test, a FFU was donated by a manufacturer and its energy performance was obtained through use of the draft test procedure.

Discussions with PG&E also led to interest in performing a trial application of the fan-filter test procedure at the PG&E test facility in San Ramon, CA. Consequently, PG&E sponsored a test at this facility where performance of the same unit that was tested in Taiwan was again tested. This test arrangement used a somewhat different configuration. PG&E in collaboration with LBNL performed the testing and obtained a second set of test data.

- **Investigate Improvements in Efficiency of Heating, Ventilating, and Air-Conditioning in High-Tech Buildings - Demand Controlled Filtration and use of Mini-environments.**

Demand Controlled Filtration - The approach for the demand controlled filtration task was to first perform a pilot study in an operating LBNL cleanroom. In this study, the technology of sensing particles in the room and directly controlling cleanroom airflow based upon particle concentrations was attempted using various particle counters. The study focused on determining variations in particle size and quantities that could be used for controlling the airflow and achieving desired cleanliness levels. Based upon the pilot study, a demonstration of the technology in an operating industrial cleanroom was proposed and implemented in the second phase.

Minienvironments - The approach to investigating energy efficiency issues when minienvironments are utilized was to locate and work with an industry partner who manufactures minienvironments. The manufacturer provided access to a minienvironment for assessment of its performance. Airflow and electrical fan energy were measured throughout its full operating range. Although beyond the original scope of this task, an additional study or "macro" study was able to be accomplished. This involved working with one of the benchmarking site partners to study the aggregate effects of using many minienvironments within a larger cleanroom.

3.2 Berkeley Fume Hood Development

The approach in the continuing development of the Berkeley Fume Hood involved actions designed to overcome the institutional barrier impeding its acceptance in California, performing side-by side testing with a conventional fume hood in order to document the relative performance of each, and demonstrating containment (safety) and energy performance by using the fume hood in industrial settings.

- **Overcoming institutional barriers**

The primary institutional barrier to acceptance of the Berkeley Hood was the CAL/OSHA requirement to maintain 100 ft/min. of airflow through the face of the hood opening. The Berkeley Hood provides containment through a different approach so a variance to the requirement was necessary since face velocities were, by design, far lower than the CAL/OSHA threshold. The approach to overcoming this barrier was to negotiate acceptance criteria with the regulatory body, CAL/OSHA, and then obtain and provide that information through variance requests. Numerous meetings and communications with CAL/OSHA attempted to define technical criteria that would provide assurance that the Berkeley Hood would provide containment that was as safe (or safer) than a conventional fume hood. Standard ASHRAE tests, along with non-standard tracer gas tests, were proposed and although CAL/OSHA would not agree to formal acceptance criteria, the variance procedure provided the best opportunity for eventual acceptance.

- **Conduct Side-by-side tests with conventional hoods.**

To support the variance process, test protocols for static and dynamic side-by-side testing of the Berkeley hood compared to a conventional hood were prepared and a series of tests were then conducted. A highly respected third-party industry expert, Tom Smith of Exposure Control Technologies, performed and/or witnessed the tests and provided an independent assessment of the results. The test results were provided to CAL/OSHA through the variance process to enable demonstration of the hood in industrial settings.

- **Perform industrial field demonstrations.**

Industry partners interested in demonstrating the Berkeley Hood were solicited and a California fume hood manufacturer, Genie Scientific, was selected to manufacture the Berkeley Hoods. Variance applications were prepared for two of the industry partners, the National Food Service Laboratory and Chevron Texaco. Several hearings were held with Cal/OSHA in order to attempt to develop mutually agreeable criteria that would allow them to issue variances for this technology.

3.3 Data Centers

Similar to the cleanrooms and laboratories tasks, the approach for the data center tasks involved performing high priority research as identified in the PIER "Data Center Energy Research Roadmap". The approach to each task is detailed below:

- **Investigate data center efficiency opportunities and perform energy benchmarking**

The approach for the energy benchmarking portion of this task involved soliciting data center sites for benchmarking through contacts within individual companies, industry associations, CA public utilities, and project advisors. The initial focus was on obtaining benchmarking partners from Southern California since previous data center benchmarking was primarily conducted in Northern California. Typically, one or more meetings were held to explain the benchmarking process and its benefits to the host site. Once an industry partner agreed to participate, a meeting was held with the host site and our subcontractor, EYP Mission Critical Facilities, where the systems that would be monitored were described along with how the monitoring would take place. A limited amount of design information that would be used to help determine monitoring points was requested. The subcontractor then arranged to be on site for several days to collect measurements and/or obtain existing information from building management systems. Since data center energy use is typically not dominated by weather conditions unless outside air economizers are used, a relatively short monitoring period was used - usually 3-4 days. Then over a several week period, the team analysed the data and developed site specific reports. These reports provided the data collected by measurement or other means along with energy efficiency recommendations based upon observations while on site. Finally, the report was reviewed and explained with the host site. The host site was given the opportunity to correct any facts in the report and then the anonymous reports were posted on LBNL's website:
http://hightech.lbl.gov/benchmarking_dc.html

Utility representatives were invited to attend meetings where benchmark summary results were presented.

The benchmarking determined energy intensity and end use within the center, and focused on the efficiency of key systems and standby generation. All benchmark results were entered into spreadsheets and summary graphs including prior benchmarks were prepared in order to focus on the energy performance for selected systems and components.

In a synergistic effort, PG&E began developing data center design guides during this project. The LBNL team collaborated with PG&E's contractor, Rumsey Engineers, in the development of "best practice" Design Guides. By reviewing all of the benchmark data and recommendations from the current case studies combined with the information contained in case studies from a prior PIER project and various other sources, the team identified key areas where improved design and operation led to better energy performance (best practice). Due to the timing of this effort, the team simply developed the design guides rather than preparing separate summary documents.

In all, seven data center spaces at five sites were benchmarked during this phase. Two of the sites were in Southern California and three were in the San Francisco Bay area.

Finally, a self-benchmarking protocol was developed based upon the metrics and methods used in the PIER benchmarking task. This protocol was submitted to a number of industry partners for review and comment. Comments were incorporated and the protocol was posted on LBNL's website for use by data center professionals.

- **Improve Uninterruptible Power Supplies (UPS)**

Ecos Consulting and Electric Power Research Institute (EPRI) were selected as subcontractors to investigate UPS system efficiency. In order to determine the energy performance of existing systems, first a testing protocol was developed. Then all of the major manufacturers of larger UPS systems used in data centers were surveyed and test data for individual systems was obtained. The test results were then plotted for comparison purposes. Redundancy strategies (e.g. 2N, N+1, 2N+1, etc.) have an effect on overall energy consumption and the more common configurations were studied to determine their relative efficiency.

A draft labeling criteria was developed based upon a similar labeling criteria produced in Switzerland. The labeling criteria could be used in programs such as Energy Star or utility incentive programs.

- **Performance metrics**

This investigation sought to identify metrics that could be used to compare the computing and energy performance of like kinds of IT equipment - i.e. comparisons during different operational states. To accomplish this, various manufacturers were contacted and available benchmark metrics were evaluated. During the project, EPA's Energy Star program became interested in developing a metric and convened an industry workshop to seek agreement on applicable approaches. Also, the US

Environmental Protection Agency has endorsed the concept of developing performance metrics and is planning to develop criteria for Energy Star rating of servers and will utilize a performance metrics approach.

- **Energy Efficient Power Supplies**

  In this task LBNL worked with subcontractors, Ecos Consulting, and EPRI, to investigate the market for power supplies commonly used in servers. The most prevalent "form factor" (typically used in low-end servers) was selected for more detailed energy performance evaluations. A testing protocol was developed and many individual power supplies were tested to determine their relative performance. Energy performance over a full range of loading was measured to see how energy efficiency varied as the power supply was loaded. This information was summarized graphically to readily determine the range of efficiencies in the market.

3.4 Demonstration Projects

This task focused on identifying possible technologies or strategies that would be appropriate to demonstrate to industry through public interest support. Initially selection criteria were developed that included the following key criteria:

- Use of new or underutilized technologies, strategies, and/or concepts applicable to any of the target building types. The demonstrations were to focus on technologies that were ready to be implemented, i.e., no research will be involved.
- Industry participation in demonstrations ideally involving key industry leaders in California and reaching a large number of California companies involving a cross-section of the state. Typical cost sharing of 25 to 75% was expected.
- Technologies that have the potential for significant energy savings if implemented on a wide scale.
- Additional benefits such as cross-cutting applicability in other building types, or other non-energy benefits such as improved worker safety.
- Technologies that industry would not otherwise undertake or readily adopt.
- A reasonable probability of success.
- Co-funded demonstrations receiving higher priority.
- Priority to those demonstrations involving multiple facets of the industry (e.g. building owners, designers, equipment suppliers, etc.)

Dozens of potential demonstrations were suggested by project advisors, industry partners, or other researchers. Of these, fifteen were presented as possible demonstrations and PIER selected the following five demonstrations to be included in the project:

- DC powering a rack of servers
- Alternative cooling of a rack of servers (subsequently cancelled)
- Demand controlled filtration in an industrial cleanroom

- Fan-filter testing of 15 or more units
- Data Center design process

3.5 Technology Transfer

The approach to technology transfer activities was to utilize as many channels of communication as possible, with efforts tailored for distinct target audiences, in order to reach the largest number of stakeholders. This included:

- An extensive website where detailed technical information was presented and continuously updated and maintained
- Periodic newsletters distributed to large audiences
- Trade publications
- Video documentaries
- TV interviews
- Journal articles
- Workshops with industry
- Collaboration with industry associations and professional societies
- Interim reports of findings
- Best Practice summaries
- Utility workshops/training
- Individual requests for information
- Interaction with PIER
- Industry press releases

4.0 Project Outcomes

Project findings for each task are summarized below and detailed task reports are provided as appendices to the report.

4.1 Cleanrooms and Laboratories

o **Benchmark laboratory and cleanroom facilities and document best practices.**

The project successfully arranged for laboratory and cleanroom facilities to be studied. In total, eleven (11) cleanrooms at four sites, and one laboratory were benchmarked. Individual case study reports for each facility are attached as Appendix I. For each site, energy benchmarks were obtained through direct measurement or from building management systems where direct measurement was not practical. In some cases design information was used in lieu of direct measurement - for example, if entry into the cleanroom to obtain airflow measurement was not allowed, then design or test and balance were obtained. The case studies each contain recommendations of potential energy efficiency improvement areas that were observed during the course of the benchmarking. Key findings from these case studies include:

- Two of the cleanroom sites were reducing airflow in their cleanrooms at night and weekends when no, or fewer, workers were in the rooms. In one case, 70% energy reduction was evident. See figure 1.

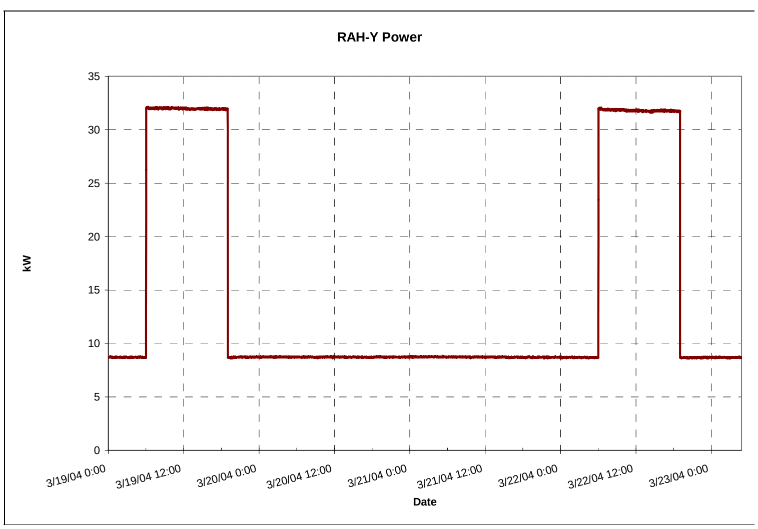


Figure 1. Recirculation fan energy savings during setback at facility 1.

In the other case, set-back was not occurring as planned due to a controls problem. This highlights the need for continuous commissioning. Once the controls problem was identified and corrected, this site showed a similar large energy reduction of approximately 75% as illustrated in

Figure 2 , resulting in estimated yearly savings of approximately $138,000.

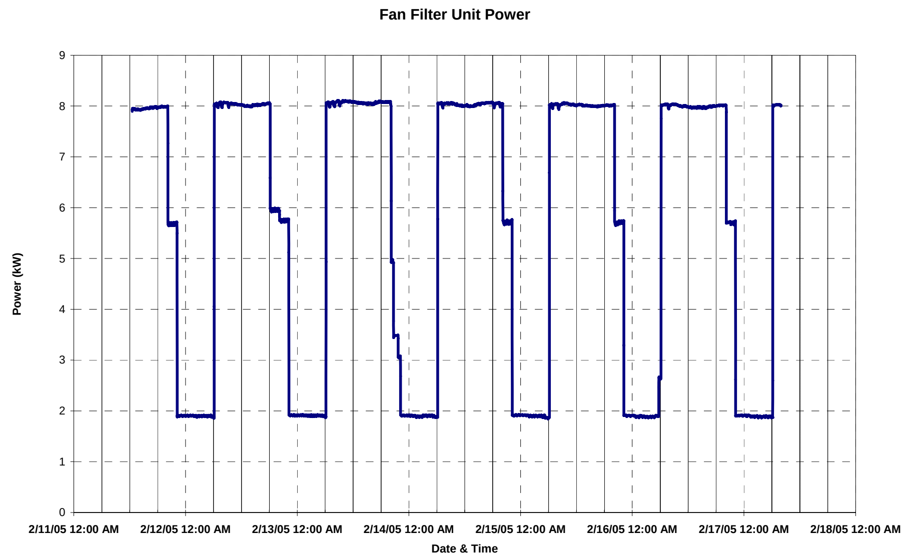


Figure 2. Recirculation fan energy savings during setback at facility K.

- As an indicator of the energy efficiency opportunity for these building types, many observations of efficiency opportunity were presented for each of the sites. Recommendations included no/low cost measures as well as more capital intensive improvements. Recommendations suggested that lower air-change rates (recirculation) in cleanrooms should be possible.
- It was found that many systems could benefit from better humidity control.

Benchmark results were recorded in the Access™ Database developed during the prior PIER benchmarking project. Summary graphs of various metrics were prepared and posted on LBNL's website: http://hightech.lbl and are also included in Appendix I.

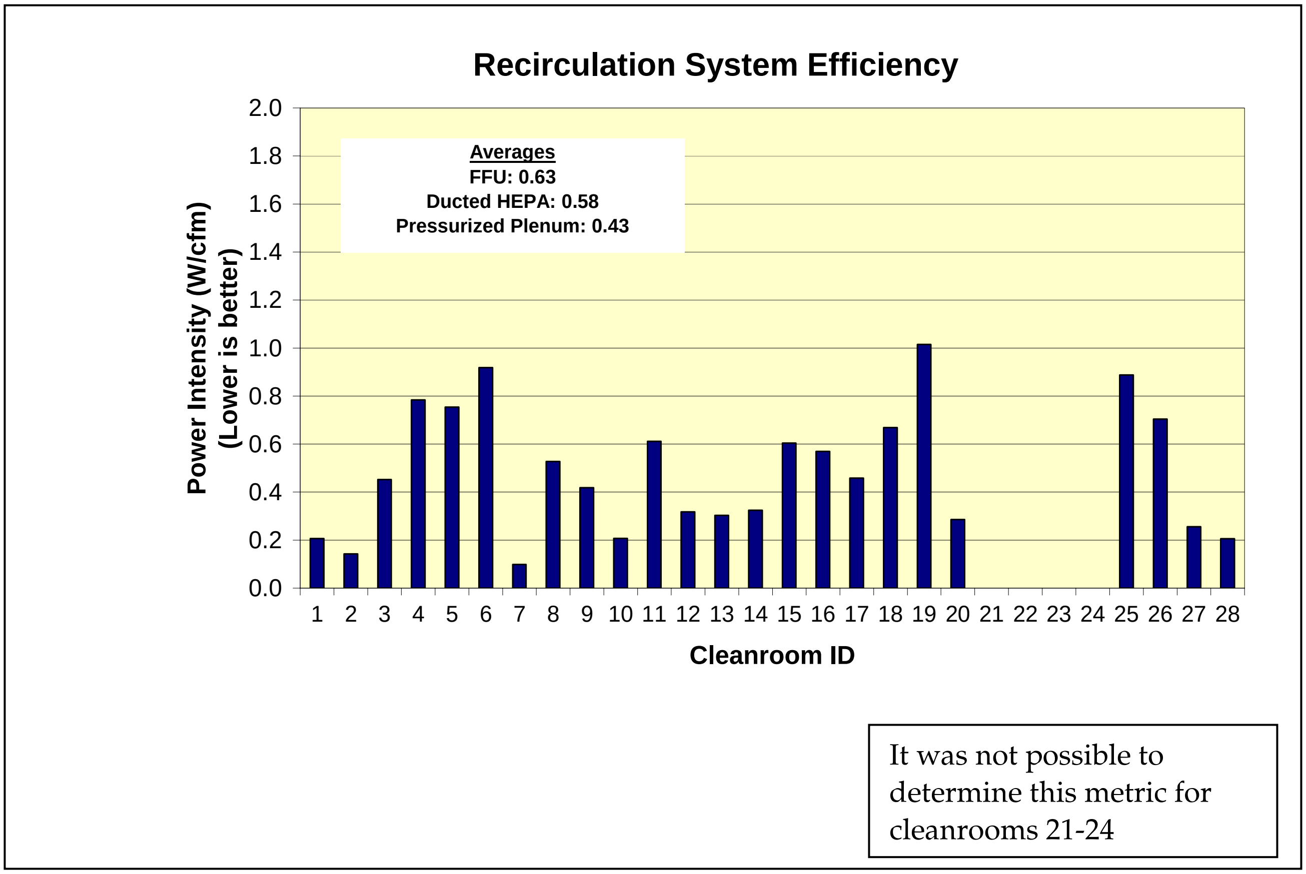


Figure 3. Cleanroom recirculation air system efficiency

A review of current and prior case studies was performed in order to identify the "best practices" which helped in achieving higher energy efficiency in cleanrooms. Based upon this review, best practice topics were identified and summaries were prepared which focused on the following measures:

- Low pressure drop design
- Recirculation air-change rate optimization
- Demand controlled filtration
- Fan-filter efficiency
- Use of minienvironments
- Exhaust optimization
- "Right-sizing" systems
- Process systems vacuum pump optimization
- Variable speed pumping
- Variable speed chillers
- Use of free cooling
- Dual temperature cooling loops

- Cooling tower and condenser water optimization
- Control of chilled water systems
- Air-recirculation system type
- Exhaust systems

Through collaboration with PG&E, the best practice summaries were used to develop design guides and were finalized by Rumsey Engineers for PG&E. LBNL provided review and input to the design guides. The best practice summaries are available here: http://hightech.lbl.gov/cleanrooms_bpg.html and contained in Appendix I of this report.

- **Advance energy efficient filtration - Standard testing for fan-filter units**

Fan-filter units are commonly used in cleanrooms for both new construction and retrofits of existing spaces in virtually all types of industries and institutions that utilize cleanrooms. Lower capital cost, ease of construction, and flexibility are frequently cited reasons for their selection. Prior to this however, an owner or designer wishing to compare competing units based upon their energy performance had no common basis for comparison. In this task, first a standard test method was developed in collaboration with the Industrial Technology Research Institute (ITRI) in Taiwan, members of the Institute of Environmental Sciences and Technology (IEST), and other interested industry partners. IEST is developing a "Recommended Practice" for fan-filter units which will address many facets of its design other than energy use, and has committed to including the test procedure in the recommended practice document.

The proposed standard test procedure is attached in Appendix II.

A trial run of the procedure was performed in conjunction with ITRI at their AMCA certified test facility in Taiwan. A second test was performed in conjunction with PG&E at their San Ramon, CA test facility. The two test configurations were significantly different, as was the electrical power supply. As a result, the tests were not able to obtain repeatable results. Further testing in a controlled test set-up was recommended and subsequently a task to demonstrate testing of multiple units was included in the second phase of the project (see demonstrations).

A report of the fan-filter test procedure development and its use in the initial two tests (LBNL Report: LBNL-57727) is attached in Appendix II.

- **Improvements in Efficiency of Heating, Ventilating, and Air-Conditioning in High-Tech Buildings - Demand Controlled Filtration and use of Mini-environments.**

Demand Controlled Filtration

The pilot study conducted in LBNL's cleanroom demonstrated the technology of sensing particles in the room and directly controlling cleanroom airflow based upon particle concentrations. Various particle counters were used in order to study the impact of particle sizes and concentrations. This study concluded that the technology to control airflow based upon real time particle counts is viable, however additional study is needed to examine the relationships between air change rates and particle counts. Figure 4 illustrates typical data that was collected and analysed during the pilot study. This data provides insight into the relationship between contamination (particle counts) and air change rates. Also, a better understanding is needed concerning the ability to control by counting various sizes of particles.

A report of the pilot study is provided in Appendix III.

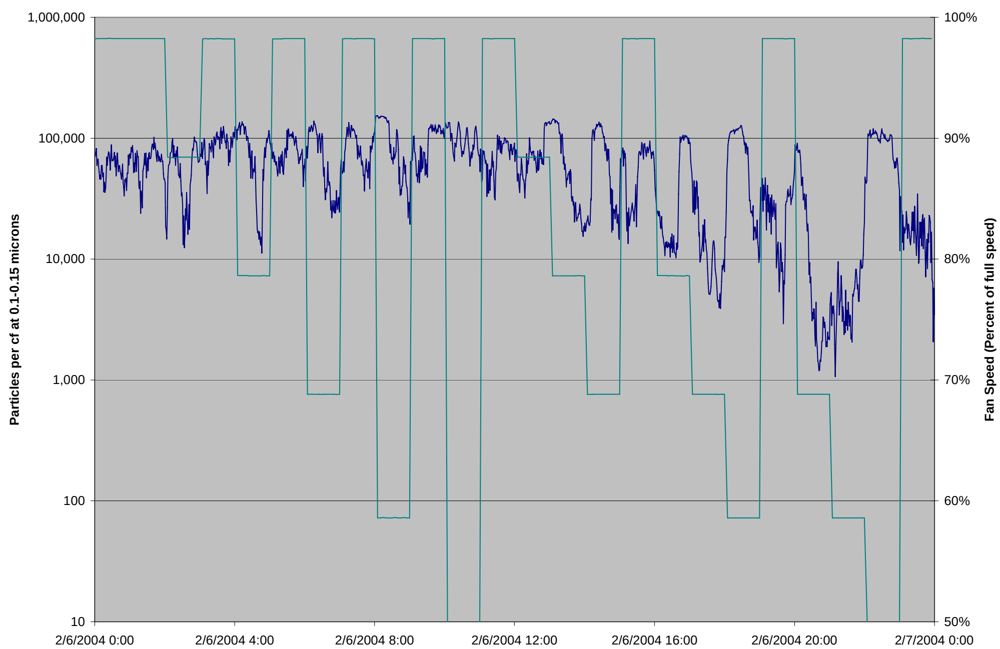


Figure 4. Particle counts and fan speed

Based upon the pilot study, a demonstration of the technology in an operating industrial cleanroom was proposed and subsequently added to the project. See Demonstrations for a description of the demonstration activities.

Minienvironments

The minienvironment study included investigation into the energy efficiency opportunity of minienvironment devices (micro level) and an investigation into the energy implications when minienvironments are deployed throughout cleanrooms (macro level). The micro level investigation evaluated the energy performance of the fan-filter unit which is used to provide filtration through HEPA filters. Considerations such as leakage from the minienvironment, exhaust opening, fan speed control, air change rates, etc were evaluated in the study.

The study investigating energy efficiency issues in minienvironments was performed with an industry partner who manufactures minienvironments. The manufacturer provided access to a minienvironment for assessment of its performance. Airflow and electrical fan energy were measured throughout its full operating range. Although beyond the original scope of this task, an additional study or "macro" study was able to be accomplished. This involved working with one of the benchmarking sites to study the aggregate effects of using many minienvironments within a larger cleanroom. Reports of both studies are included in Attachment IV.

4.2 Berkeley Fume Hood Development

This task was designed to overcome the institutional barrier presented by the requirement of 100 ft./min face velocity mandated by CAL/OSHA. This work led to a better understanding of the Berkeley Fume Hood performance.

- **Overcoming institutional barriers**

The primary institutional barrier to acceptance of the Berkeley Hood was the CAL/OSHA requirement to maintain 100 ft/min. of airflow through the face of the hood opening. Evaluation criteria were negotiated with Cal/OSHA through a number of meetings and information exchanges. While we attempted to get agreement on acceptance criteria, there was no agreed upon level of performance that would satisfy Cal/OSHA either before or after the performance tests. Side by side tests were agreed upon in order to compare the performance of the Berkeley hood with a standard hood. Although the results of the side by side testing provided sufficient justification for Cal/OSHA to issue a variance, it became evident that the only way that Cal/OSHA would accept use of the Berkeley Hood would be through individual variances rather than a blanket acceptance. At this point, PIER management and LBNL decided to terminate further work in this area.

- **Conduct Side-by-side tests with conventional hoods.**

A series of tests were conducted utilizing the protocols for static and dynamic tests for both a conventional fume hood and the Berkeley Hood. These tests involved standard industry tests but also included more rigorous dynamic tests that aren't typically performed for standard hoods. The testing was observed/conducted by a third party fume hood expert, Tom Smith of Exposure Control Technologies, who provided an independent assessment of the results. The test results showed that the Berkeley Hood performed as well or better than a standard fume hood and these results were acceptable to Cal/OSHA to grant a variance for use of the hood in one location.

- **Perform industrial field demonstrations.**

Industry partners interested in demonstrating the Berkeley Hood were identified. The National Food Service Laboratory, Dublin, CA; Chevron Texaco, Richmond, CA; and Genentech expressed interest in participating in the demonstrations. A California fume hood manufacturer, Genie Scientific, was selected to manufacture the Berkeley Hoods and LBNL procured three hoods for demonstration - although actual manufacture was deferred pending variance approvals. Variance applications were prepared for the National Food Service Laboratory and Chevron Texaco. Several hearings were held with Cal/OSHA and a variance was granted for the first installation at the National Food Service Laboratory.

However, since it became evident that Cal/OSHA would not grant a blanket variance for this technology, the fume hood work was terminated by PIER, so consequently the demonstrations were cancelled.

4.3 Data Centers

- **Investigate data center efficiency opportunities and perform energy benchmarking**

  Data centers were identified for benchmarking through interaction with industry associations (e.g. Critical Facilities Roundtable), subcontractors, and public utilities. Initially we focused on obtaining benchmark sites in Southern California since previous benchmarking primarily involved Northern California. As a result of these efforts two Southern California companies were identified having three distinct data center spaces. In addition two firms in Northern California were recruited accounting for an additional three data center spaces. The centers included web hosting, internet service provider, and network equipment manufacturers.

  For each site, energy use was determined through direct measurement, use of building management data, or other available means. Case study reports were prepared to summarize the energy end-use breakdown in the centers and to provide recommendations based upon observations. The case studies were anonymous reports to protect the confidentiality of the host site. These reports are included in Appendix VI and available through LBNL website: http://hightech.lbl.gov/benchmarking_dc.html.

The case study findings from this study and prior benchmarking revealed a large variation in performance in virtually every aspect of data center operation. The observed differences suggested that applying better design and operational practices could lead to greatly improved efficiency. Figure 5 illustrates the wide range of performance exhibited by all of the centers benchmarked by LBNL to date. This metric is the ratio of IT power to the total power delivered to the data center and its supporting systems. It gives an indication of the amount of electrical power that is actually powering the IT equipment.

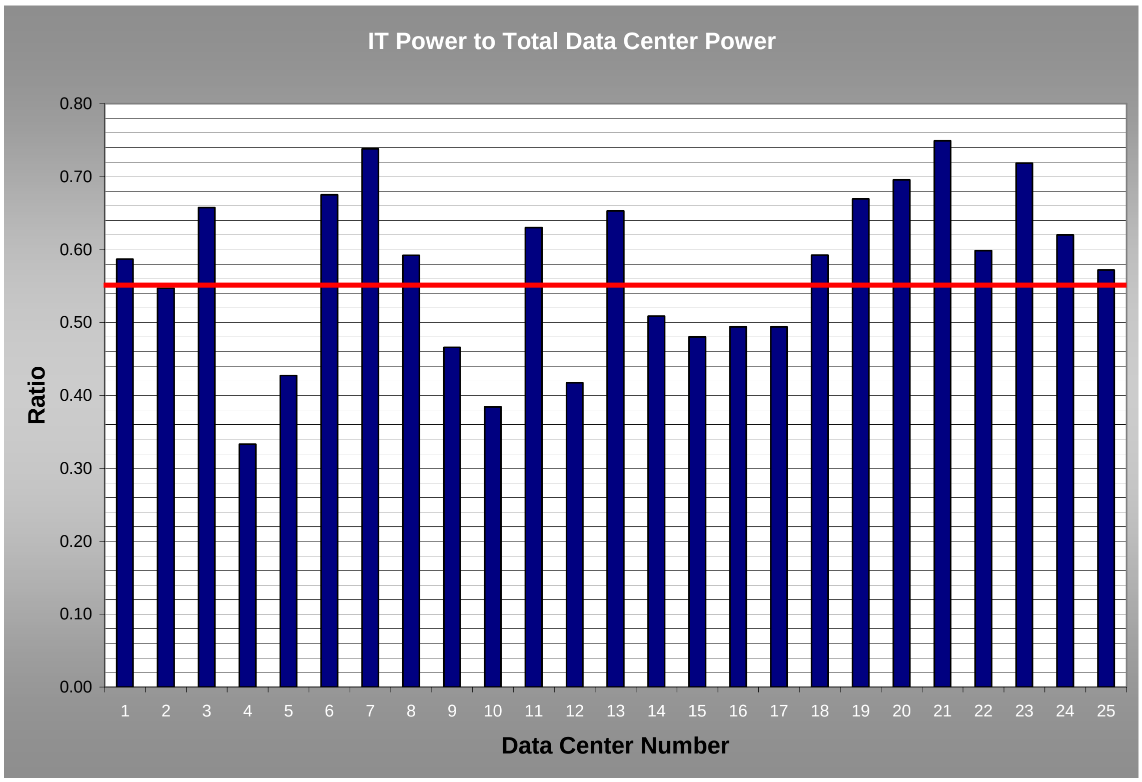


Figure 5. Ratio of IT power to total data center power

By examining the design of key systems in centers that had higher ratios, best practices were identified. In collaboration with PG&E and Rumsey engineers, design guidelines for selected systems were developed. The guidelines include the following topics:

1. Air Management (guidelines for improving air flow)
2. Air Economizers
3. Centralized Air handling

4. Cooling Plant Optimization
5. Direct liquid cooling
6. Free cooling via water-side economizers
7. Humidification controls alternatives
8. Power supplies
9. Self Generation
10. Uninterruptible power supply systems

A self-benchmarking protocol was developed to provide guidance for end-users to obtain the same benchmark data for their data centers. This protocol outlines metrics and the procedure to obtain benchmarks similar to the data collected by LBNL. Use of this protocol will enable comparison of like metrics amongst the benchmarked facilities. The protocol is included in Appendix VI and is available through the LBNL website: http://hightech.lbl.gov/datacenters

- **Improve Uninterruptible Power Supplies (UPS)**

Ecos Consulting and EPRI measured UPS system performance throughout the operating range for essentially all commercially available UPS systems. The results revealed that there is a large variation in performance as shown in Figure 6. A 30% variance in performance was found at low utilization levels and a 10% variance for fully-loaded equipment.

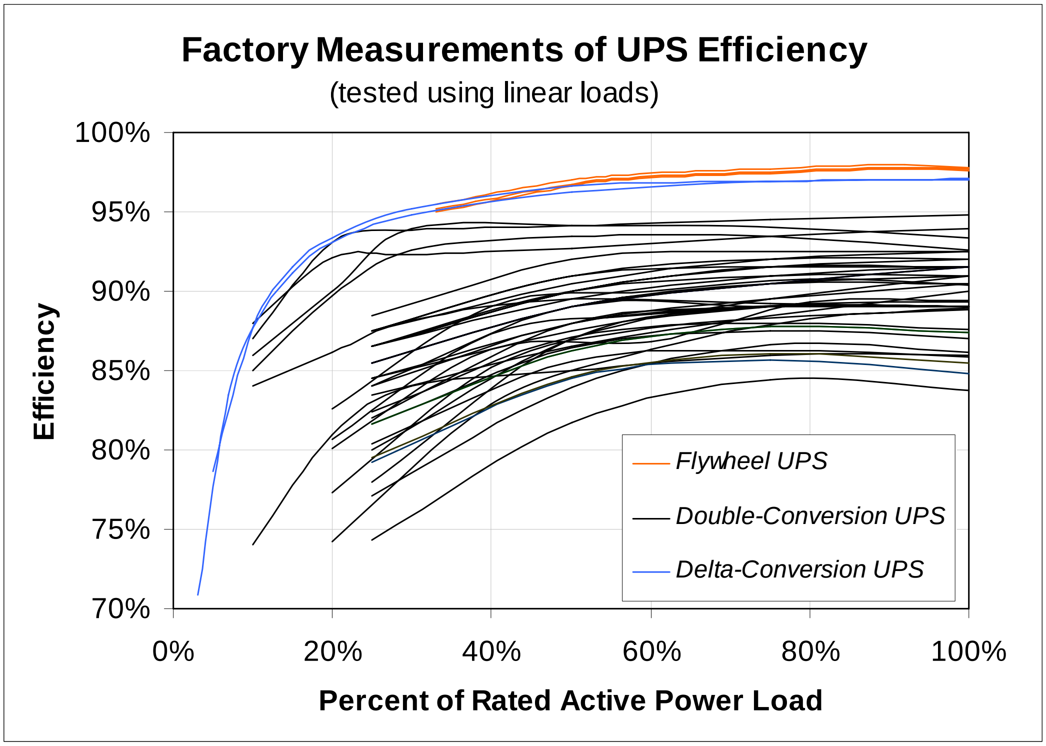


Figure 6. UPS system efficiencies

Redundancy configurations also influenced the ultimate efficiency of the electrical distribution systems.

A draft labeling criteria was developed that could be used in programs such as Energy Star or utility incentive programs.

The full report of the UPS task is in Appendix VII.

- **Performance metrics**

In this task, the concept of coupling computational work with energy used to produce it was advanced. By working with various industry groups, the metrics appropriate to various computational workloads began to be identified. Different computational work loads, require different metrics to evaluate performance. For example, scientific computing has a much different metric than say web hosting. We collaborated with the Standard Performance Evaluation Corporation (SPEC) to develop the first performance metric protocol. We continued collaboration with the Energy Star program as it sought to develop performance metrics for a broader range of applications. The work in this task is further discussed in Appendix VIII.

- **Energy Efficient Power Supplies**

In this task subcontractors, Ecos Consulting, and EPRI, investigated the market for power supplies used in low-end servers. Measurements of the most prevalent "form factor" were performed. A testing protocol was developed and then used to evaluate many individual power supplies to determine their relative performance. Energy performance over a full range of loading was measured to see how energy efficiency varied as the power supply was loaded. This information showed that, similar to UPS systems, there was a wide range of performance as shown in Figure 7. A factor-of-two variance in performance was found at low utilization levels and a 30% variance for fully-loaded equipment.

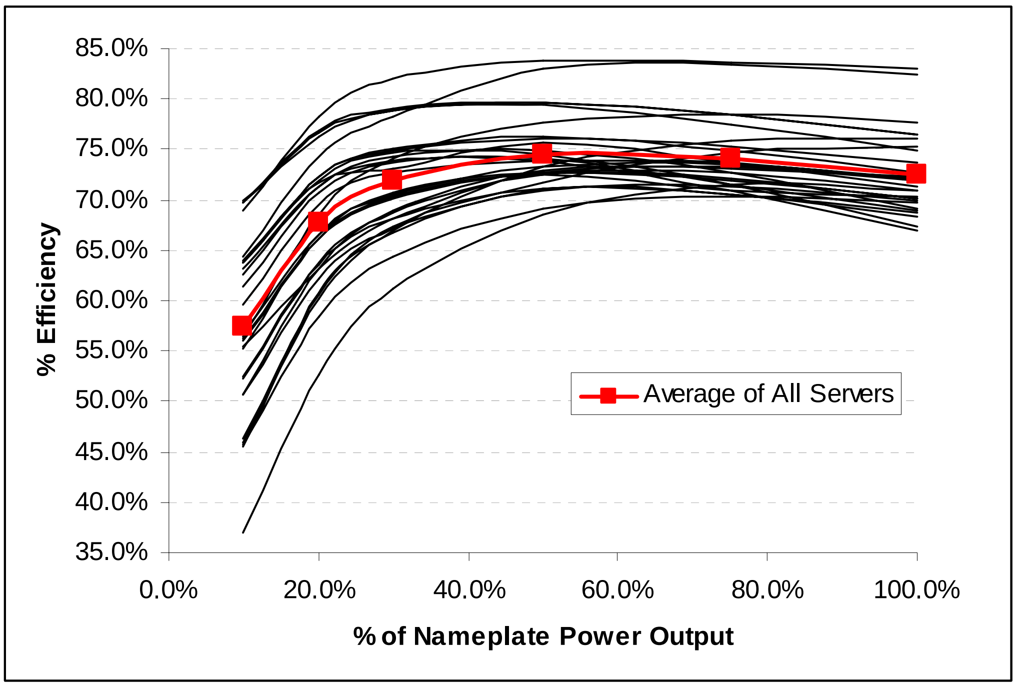


Figure 7. Performance of power supplies

The report of this task is included in Appendix IX.

4.4 Demonstration Projects

The following demonstrations were conducted:

- Demand controlled filtration - see Appendix XI
- Fan-filter testing - see Appendix XII.
- DC powering of servers - see Appendix XIII
- Data center design process - see Appendix XIV

In each demonstration, industry partners participated by providing equipment, services, and/or use of their facility for the demonstration. Highlights from the demonstrations are:

- Demand Controlled filtration - We discovered that the host facility thought that cleanroom airflow was being controlled by a timer but in actuality no setback of airflow was occurring. Having this corrected saved the host facility considerable energy. Use of the demand controlled strategy was also shown to be effective in controlling cleanroom airflow.

- Fan Filter Testing - The test procedure developed in an earlier phase of the project was successfully used to test seventeen fan-filter units donated by manufacturers. A wide range of performance was observed.

- DC powering of servers - Over 25 firms collaborated on this demonstration by donating equipment, services, and a demonstration site. Intel and Sun Microsystems modified servers to directly accept 380 V. DC. This side by side demonstration illustrated that commercially available equipment is available today for a DC system. Energy savings of over 25% compared with typical systems is possible.

- Data Center design process - The design process for the design of a new supercomputer facility illustrated the differences in understanding between IT and facility professionals. Through an understanding of the different focus of these organizations, it is possible to bridge the gaps and develop energy efficient solutions.

4.5 Technology Transfer

Appendix X includes a summary of the extensive technology transfer activities included in this task. The technology transfer activities enabled the project results to be provided to a large number of California, National, and International stakeholders. The PIER program is recognized as leading efficiency efforts in the high-tech sector as evidenced by the synergistic activities begun by NYSERDA, US EPA, US DOE, and public utilities since this project began. Reporters from the professional as well as popular press routinely seek information from members of the project team. Technology transfer activities were critical to informing the industry and other public goods efforts concerning the research and demonstrations undertaken through the PIER project.

5.0 Conclusions and Recommendations

5.1 Conclusions

The following conclusions can be drawn from this project:

- Benchmarking of laboratories, cleanrooms, and data centers provides insight into areas for efficiency improvement, and motivates end-users to take action. Benchmarking helped to identify best practices and areas where further efforts should be targeted. A wide variation in performance illustrates that some facilities can achieve energy efficient operation while supporting the critical nature of the operation.

- The self-benchmarking protocol developed for data centers can assist industry in obtaining their own benchmark data. A similar resource for laboratory buildings is available through the EPA/DOE Laboratories for the 21st Century website. Obtaining similar benchmark data will enable comparison to others and comparison of similar facilities within corporations.

- The standard method of testing and reporting performance of fan-filter units developed in this project will enable "apples to apples" comparison of their energy performance, where before there was no consistent method. This procedure will enable end users to compare energy use when making purchasing decisions. This procedure could also be used in incentive programs.

- Demand controlled filtration is a viable technology to control cleanroom airflow through real-time monitoring of contamination levels linked to air-flow controls. This technology will enable cleanroom operators to reduce air flow based upon actual cleanroom cleanliness conditions, resulting in large energy savings.

- Energy efficiency improvement opportunities are suggested for minienvironments. In addition, use of minienvironments within cleanrooms can reduce the energy required for the room itself, resulting in large energy savings.

- Side-by-side testing of the high-performance Berkeley Fume Hood compared to a conventional hood illustrated equivalent or better containment with 50% less airflow The institutional barrier introduced by the Cal/OSHA requirement of 100 ft. per minute face velocity however would require individual variances for each installation. Midway through the project it appeared that Cal/OSHA would not provide a blanket approval of the Berkeley Hood for use in California. At this point, PIER and LBNL decided to terminate further demonstrations of the technology. The Berkeley Hood has since been licensed and will be marketed outside of California.

- Uninterruptible power supplies (UPSs), test results showed a wide variation in energy loss suggesting that, use of the more efficient systems in data centers could save 20% or more of the electricity powering IT equipment plus savings due to the reduction in HVAC energy use. Benchmarking results indicate that approximately an equal amount of HVAC energy would be saved In addition, awareness of the energy implications of various redundancy configurations can lead to improved overall system efficiency. This information can be utilized to establish utility incentives to encourage use of more efficient UPS units and provide incentives for more efficient redundancy configurations. The draft labeling criteria developed in this project could also be used in California or Energy Star programs to provide information for those that specify and purchase these systems.

- Standby generation consumes more energy than it will ever generate. Further study of options to current standby generation schemes (e.g. use of on-site generation with utility back-up) may lead to improved efficiency in this area. Efficiency opportunities also exist within the current standby generator systems.

- Performance metrics considering computational ability coupled with energy performance can be effective metrics to compare performance of IT equipment. Different metrics would need to be developed for use with various applications. For example, web hosting performance would be quite different than scientific computing.

- Power supplies within IT equipment account for a large percentage of the IT equipment power consumption. Similar to UPS systems, a wide variation in performance was observed, suggesting that encouraging use of highly efficient power supplies could immediately save a significant amount of energy both for the direct loss and for the cooling required to remove the heat produced.

- The demonstration of Direct DC powering of IT equipment illustrated that 10-20% energy savings are possible if DC power is distributed directly into IT equipment. The demonstration showed that 380V. DC power can be distributed using UL-rated equipment which is commercially available today. Sun Microsystems and Intel Corporation demonstrated that power supplies in IT equipment can be easily modified to accept 380V. DC. Over 25 firms participated in the demonstration and this was observed by several hundred industry professionals. The industry is interested in this technology, however further efforts are needed to standardize distribution voltages and connectors, to address safety concerns, and generally overcome current paradigms. Through very wide coverage in industry and mainstream media, this demonstration has already had an impact in raising awareness of the efficiency of the power conversion processes and will likely lead to improvements in AC distribution schemes as well.

- The fan-filter test procedure developed in this project demonstrated comparative data can be obtained for various manufacturers units. This procedure will enable “apples to apples” comparisons to aid in the selection of energy efficient units. This will enable purchasers to make informed decisions and will provide a basis for incentives to encourage use of more efficient units.

- The demonstration of the fan-filter test procedure validated the procedure and illustrated that repeatable results can be obtained. Further experimentation also suggested that the procedure is applicable to “push” or “pull” configurations and that the test rig could be shortened in order to make its implementation more attractive to the industry. An analysis of the results of the testing led to a method to graphically show the interrelation of pressure, flow, and energy use.

- The demonstration of demand controlled filtration illustrated how this control strategy can be deployed in industry cleanrooms using existing commercially available equipment. Cleanroom airflow was directly controlled through use of particle counters communicating with cleanroom fan systems. Alternative airflow reduction strategies such as use of occupancy sensors were also shown to be effective.

- The demonstration of the data center design process showed a process where industry experts could interact as a group to brainstorm energy efficiency solutions. The "charrette" process enabled a group of industry experts to explore best practice and cutting edge solutions without the constraints of a typical compartmentalized design process. The charrette identified energy efficiency strategies and concepts that could be explored in more detail later in the design process.

- Technology Transfer activities enabled the project to reach large numbers of stakeholders through various channels for each of the high-tech facility types. Frequent outreach activities were successful in informing a large component of California's high-tech industries and the industries around the world. California is viewed as leading in developing high–tech energy efficiency solutions. PIER is now recognized as the first and leading supporter of research in this domain.

5.2 Recommendations

Research opportunities identified in prior PIER research roadmaps should be reviewed and updated to reflect the rapid pace of innovation in this field. Important opportunities should be pursued. Our Recommendations from this project are in line with the original roadmaps' recommendations, and include:

- Existing benchmarking data should be made more readily available to industry stakeholders, e.g. through a action-oriented interactive web-based tool and such as that currently being developed by the PIER Buildings program.

- Additional benchmarking of high-tech buildings should be performed to assist in:
    - Motivating industry to take action
    - Comparing like facilities
    - Benchmarking performance over time
    - Identifying trends in industry
    - Recognizing/labeling to encourage high performance
    - Defining incentive program baselines
    - Identifying Best Practices

- The standard method of testing and reporting performance of fan-filter units developed in this project should be adopted by standards organizations. Currently IEST is planning to include the procedure in a "Recommended Practice" (RP). The PIER program should consider continuing interaction with IEST to ensure that the provisions of the procedure are adopted. Adoption by other organizations such as AMCA should also be encouraged.
- Market transformation activities to promote use of demand controlled filtration should be pursued for the various sectors that operate cleanrooms (e.g. biotech). This technology should also be explored for use in healthcare facilities.
- Best practices should be publicized through demonstrations and case studies for training and in order to promote wider adoption.
- New and emerging data center cooling solutions should be evaluated in order to determine their energy implications. Strategies such as demonstrations or incentives should be explored in order to encourage use of solutions that offer the most efficient operation.
- The same efficiency issues identified through the evaluation of UPS and standby generation systems in data centers exist in a large number of other facilities that provide for backup power (e.g. hospitals). Outreach targeting a broader cross section of other market sectors would expand the energy savings potential.
- Performance metrics for servers to enable energy and computational comparisons should continue to be developed with collaboration with industry.
- Power supply efficiency improvements should be encouraged through programs similar to the 80+ program.
- Power distribution efficiency within data centers and other high-tech facilities should continue to be a major focus for research, best practice identification, and outreach. Efficiencies of various power distribution designs utilizing AC or DC power should be studied. Collaborations with industry organizations such as Green Grid, IEEE, and others should be established to help identify energy efficient schemes and evaluate performance of their power conversion devices. Specific activities related to overcoming barriers identified in the demonstration of the use of 380V DC power are 1) gaining consensus on distribution voltage, 2) gaining consensus and standardizing design of connectors, and 3) developing pilot installations in order to accelerate adoption.

5.3 Benefits to California

High-tech industries are extremely important to the California economy. Many High-tech firms are headquartered in California and represent most major sectors of the economy including biotech, semiconductor, aerospace, healthcare, etc. Energy use and intensity is large in these industries and continues to grow as these companies flourish. This project has provided insight into the energy efficiency opportunity in cleanrooms, laboratories and data center facilities. The various technologies explored show that there is potential for large energy savings using solutions available today. Energy savings of 20-40% have been shown to be possible. This project has also helped to raise the awareness of industry and has garnered the interest of other public interest programs. California is now seen as leading efficiency efforts in the high-tech sectors.

6.0 References

Publications produced under this project are as follows:

1. RMI. 2003. Final Report on Energy Efficient Data Centers - A Rocky Mountain Institute Design Charrette. Hayes Mansion Conference Center, San Jose, California.
2. "High-Performance Data Centers – a Research Roadmap", Lawrence Berkeley National Laboratory Report No. 53483
3. Mills, E. 2007. "Eco-Solutions." *Forbes.* April 23.
4. Tschudi, W. 2007. "DC Power for Data Centres." *Zerodowntime*. March 21
5. Shamshoian, G., M. Blazek, P. Naughton, R. Seese, E. Mills, and W. Tschudi. 2005. "High-Tech Means High-Efficiency." *Forbes*. November 18.
6. Tschudi, W., P. Rumsey, E. Mills, T. Xu. 2005. "Measuring and Managing Energy Use in Cleanrooms." *HPAC Engineering*, LBNL/PUB-946.
7. Faulkner, D., D. DiBartolomeo, and D. Wang. 2007. "Demand Controlled Filtration in an Industrial Cleanroom." Lawrence Berkeley National Laboratory Report No. 63420
8. US EPA. 2007. Report to Congress on Server and Data Center Energy Efficiency : Public Law 109-431. Washington, DC: U.S. Environmental Protection Agency, ENERGY STAR Program. August 2
9. Xu, T. 2007. "Characterization of Minienvironments in a Clean Room: Design Characteristics and Environmental Performance." *Building and Environment*, 42:2993–3000
10. Xu, T., C-H. Lan, and M-S. Jeng. 2007. "Performance of Large Fan-filter Units for Cleanroom Applications." *Building and Environment*, 42: 2299–2304.
11. Greenberg, S., W. Tschudi, and J. Weale. 2006. LBNL "Self-Benchmarking Guide for Data Center Energy Performance (Version 1.0)
12. Rumsey Engineers and Lawrence Berkeley National Laboratory. 2006. "High Performance Cleanrooms: A Design Guideline Sourcebook." Part of *Energy Design Resources* collection
13. Rumsey Engineers and Lawrence Berkeley National Laboratory. 2006. "High Performance Data Centers: A Design Guideline Sourcebook." Part of the *Energy Design Resources* collection.
14. Greenberg, S., E. Mills, B. Tschudi, P. Rumsey, and B. Myatt. 2006. "Best Practices for Data Centers: Results from Benchmarking 22 Data Centers." *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings*
15. Exposure Control Technologies, Inc. 2005. "'Side by Side' Fume Hood Tests Using ASHRAE 110 and 'Human As Mannequin' (HAM) Test Methodology to Compare Performance of a

Jamestown Conventional Fume Hood and a LBNL High Performance Hood." Final Report (March 21)

16. Ecos Consulting and EPRI Solutions. 2005. "High Performance Buildings: Data Centers -- Uninterruptible Power Supplies (UPS)."
17. Ecos Consulting and EPRI Solutions. 2005. "High-Performance Buildings: Data Centers -- Server Power Supplies."
18. Shamshoian, G., M. Blazek, P. Naughton, R.S. Seese, E. Mills, and W. Tschudi. 2005. "High-Tech Means High-Efficiency: The Business Case for Energy Management in High-Tech Industries." Lawrence Berkeley National Laboratory Report.
19. Tschudi, W.T., D. Faulkner, and A. Hebert. 2005. "Energy Efficiency Strategies for Cleanrooms without Compromising Environmental Conditions." *ASHRAE Transactions*, DE-05-9-1 10pp.
20. Koomey, G.K., O.Sezgen, and R. Steinmetz. 2005. "Estimating Total Power Used by Data Centers in California."
21. Mills, E. and D. Sartor. 2005. "Energy Use and Savings Potential for Laboratory Fume Hoods." LBNL-55400. *Energy* 30:1859-1864.
22. Bell, G. and D. Sartor. 2004. "Side-by-Side Fume Hood Testing: ASHRAE 110 Containment Report -- Comparison of a Conventional and a Berkeley Fume Hood." LBID-2560
23. Bell, G. and D. Sartor. 2004. "Side-by-Side Fume Hood Testing: Human-as-Mannequin Report -- Comparison of a Conventional and a Berkeley Fume Hood." LBID-2561
24. Jeng, Ming-Shan, T. Xu, and Chao-Ho Lan. 2004. "Toward Green Systems for Cleanrooms: Energy Efficient Fan FIlter Units." *Proceedings of SEMI Technology Symposium: Innovations in Semiconductor Manufacturing*, SEMICON West 2004. San Francisco (July) pp 73-77. LBNL-55039.
25. Tschudi,W.F. and P. Rumsey. 2004. "Using Benchmarking to Identify Energy Efficiency Opportunities in Cleanrooms: The Labs21 Approach" *ASHRAE Symposium*.
26. Tschudi, W.F., P. Sreedharan, T. Xu, D. Coup, and P. Roggensack. 2003. "Data Centers and Energy Use - Let's Look at the Data." ACEEE Conference Paper
27. Mills, E., G. Bell, D. Sartor, A. Chen, D. Avery, M. Siminovitch, S. Greenberg, G. Marton, A. de Almeida, and L.E. Lock. 1996. "Energy Efficiency in California Laboratory-Type Facilities." Prepared for the California Institute for Energy Efficiency. LBNL-39061.

7.0 Glossary

Specific terms and acronyms used throughout this work statement are defined as follows:

AMCA	Air Movement and Control Association (fan manufacturers association)
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BTU	British Thermal Unit
CAL/OSHA	California Occupational Safety and Health Authority
Cfm	cubic feet per minute, a measure of ventilation rate
Commission	California Energy Commission
CPR	Critical Program Review
DOE	United States Department of Energy
GW	Gigawatt (1x10^9 Watt)
HEPA	High Efficiency Particulate Air
HVAC	Heating, ventilation, and air conditioning system
IEST	Institute of Environmental Standards and Technology
IT	Information Technology
ITRI	Industrial Technology Research Institute, Taiwan
KW	Kilowatt (1000 Watts)
LBNL	Lawrence Berkeley National Laboratory
MW	Megawatt (1x10^6 Watt)
PAC	Project Advisory Committee
PIER	Public Interest Energy Research program (Commission)
RD&D	Research, Development and Demonstration
RP	Recommended Practice
T	Temperature, measured in degrees Celsius or Fahrenheit
TC	Technical Committee
TWh	Terrawatt hour (1x10^9 kWh)
UPS	Uninterruptible Power Supply

Appendices

Appendix Number	Task Number	Task Description	Deliverable Description
I	2.1	Cleanroom/laboratory benchmarking	Case study reports Summary benchmark graphs Best practices
II	2.2	Development of fan-filter test procedure	Fan-filter test procedure
III	2.3.1	Investigate demand controlled ventilation	Demand controlled ventilation case study
IV	2.3.2	Investigate mini-environments	Mini-environment case study
V	3.2	Side-by-side fume hood testing	Summary of side-by-side testing
VI	4.1	Data center benchmarking	Case study reports Best practices (Design Guidelines) Self-benchmarking protocol
VII	4.2	Improve Uninterruptible Power Supplies	UPS report
VIII	4.3	Investigate computer performance metrics	Performance metrics report
IX	4.4	Energy efficient power supplies	Power Supply report
X	6.0 and 12.0	Technology transfer activities	Technology transfer report
XI	7.0	Demonstrate demand controlled ventilation	Demand controlled ventilation report
XII	8.0	Demonstrate standardized testing	Fan-filter testing report

		of fan-filter units	
XIII	9.0	Demonstrate DC powering of IT equipment	DC power demonstration report
XIV	11.0	Energy efficient scientific computing	Scientific computing summary report