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ADVANCED HVAC SYSTEMS FOR IMPROVING THE INDOOR ENVIRONMENTAL QUALITY AND ENERGY PERFORMANCE OF CALIFORNIA K-12 SCHOOLS

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Preface

The Public Interest Energy Research (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 California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California.

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

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

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

Advanced HVAC Systems For Improving the Indoor Environmental Quality and Energy Performance Of California K-12 Schools is the final report for the Indoor Environmental Quality K-12 project, (contract number 500-03-303), conducted by Architectural Energy Corporation. The information from this project contributes to PIER's Building End-Use Energy Efficiency program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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Abstract

The three projects described in this report were designed to evaluate advanced equipment for cooling, heating, and ventilating California's K-12 schools that improve indoor air quality, save energy, reduce peak demand, and reduce pollution. The program investigated the ability of thermal displacement ventilation technology to increase economizer use, improve ventilation effectiveness, reduce fan energy use, enhance pollutant removal, and reduce noise. The study also examined the potential of ultraviolet light in the "C" spectrum to improve coil cleanliness, enhance equipment service life, remove microorganisms, and reduce odor. In addition, the program conducted market connection activities to improve the market focus of the technologies and thereby increase the public benefits.

The results this program indicated that displacement ventilation can enable 10 to 40 percent energy savings in California K-12 schools, depending on climate. The primary data for the ultraviolet project showed substantial surface disinfection, but no statistically significant reduction in heating, ventilation, and air conditioning coil energy use or absentee rates. Market connection efforts were successfully conducted by developing access to existing information dissemination channels through e-mail efforts, telephone conversations, articles and publications, and presentations and meetings with influential market participants and organizations.

Keywords: Displacement ventilation, DV, heating, ventilation, and air conditioning, ultraviolet light, UVC, K-12 schools, energy savings, indoor environmental quality, IEQ

Executive Summary

Introduction

Schools use more than 3 percent of California’s electricity each year, and 27 percent of that electricity powers heating, cooling, and ventilation. The way that schools are ventilated and the quantity of the ventilation used directly affects the quality of the school environment, which has implications for student health and overall learning performance. This program addresses three of the four indoor environmental quality (IEQ) target areas identified by the California Energy Commission (Energy Commission).



Purpose

The goal of the *Advanced HVAC Systems For Improving Indoor Environmental Quality and Energy Performance Of California K-12 Schools Program* (IEQ-K12) was to develop and demonstrate advanced heating, ventilation, and air conditioning (HVAC) equipment for school classrooms. Such equipment would improve indoor environmental quality, save energy, reduce peak demand, and, ultimately, reduce pollution for the citizens of California.

Meeting this goal yields the following benefits:

- The next generation of California K-12 classrooms will be more comfortable, energy efficient, and healthier because of the improvements mandated by Proposition 47 (State of California 2002) and local bond funding.
- Teachers will have more control over the IEQ and thermal comfort of their classrooms.
- Students and teachers will be sick less often and more comfortable, and thus perform better.
- School districts will spend less money on energy and so are able to spend proportionally more on books, computers and other equipment, and teachers’ salaries.

The IEQ-K12 Projects

The IEQ-K12 program, headed by Donald Frey and Vernon Smith of Architectural Energy Corporation (AEC), included the following projects:

- Thermal Displacement Ventilation (DV) in Schools (Project 2), led by Charles Eley and John Arent of AEC
- Effectiveness of UVC [ultraviolet light in the “C” band, 200-280 nanometers] Technology for Improving School Performance (Project 3), led by Roger Wright and Stacia Okura of RLW Analytics, Inc.
- Program Market Connection (Project 4), led by Morton Blatt of Morton H. Blatt, Energy Utilization Consultancy

Each of these three projects had different objectives, approaches and results. These elements are summarized by project below.

Thermal Displacement Ventilation in Schools (Project 2)

Poor environments in schools adversely affect the health, performance, and attendance of students. Many existing school air conditioning systems using conventional mixed ventilation systems fail to provide the indoor air quality, appropriate acoustic environment, and comfort level that produces optimal student and teacher performance. DV is a cost-effective means of providing an optimal environment by delivering a cool air supply directly to the occupants of the space. The air enters the room at about 65°F (18.3°C) – approximately 10 degrees warmer than with a conventional air conditioning system. The fresh air, supplied near the floor at a very low velocity, falls towards the floor and spreads across the room until it encounters heat sources. Then this air slowly rises as it picks up heat from occupants and equipment. The warmed air also picks up contaminants as it rises towards the ceiling, where it is exhausted from the space. This vertical airflow pattern near each occupant, often referred to as a thermal plume, decreases the likelihood that germs will spread between occupants. This air distribution system provides for effective ventilation, since the fresh supply air is delivered directly to each occupant. All this can be provided at an initial cost comparable to that of many less effective conventional mixed-ventilation systems that rely on creating fully mixed air in the room.

The overall goal of this project was to gain wide acceptance of DV in both newly constructed and renovated K-12 schools.

DV Project Outcomes

Key information products developed for this project are listed in the Attachments section of this report and may be found at

www.archenergy.com/ieq-k12/thermal_displacement/thermal_displace.htm.

Specifically, the following outcomes were achieved:

- Coordination with related Public Interest Energy Research (PIER) natural ventilation and DV research yielded new information and showed that computational fluid dynamics (CFD) simulation and testing can validate existing or mandate new DV design guidelines for best thermal comfort and air quality. The CFD analyses of different DV classroom configurations showed specific conclusions:
 - Nine foot (ft) ceilings are sufficient if not optimal.
 - Two diffusers providing 65°F supply air are sufficient.
 - Double-pane windows substantially diminished the need for perimeter heat.
 - Lights contribute less heat than equipment or occupants.
 - Comfort levels vary with proximity to diffusers.
 - DV lowers CO₂ levels and “age” of air in a space.
- The Barriers Study identified cost and the lack of demonstration classrooms as key hurdles to acceptance. Even though most respondents identified the energy and indoor air quality (IAQ) benefits, most erroneously thought DV had a higher initial cost than conventional systems.

- Three DV system design options for California K-12 classrooms were evaluated for cost-effectiveness and performance. Single-classroom rooftop units won as the most probable near-term solution for widespread implementation.
- Two demonstration DV systems were installed, commissioned, and monitored in two classrooms. Results of the DV demonstration showed that DV can provide up to 20 percent energy savings and improve IAQ and acoustic comfort while providing acceptable humidity levels.
- Technical documents and marketing collateral were developed presenting the results of this project and technology transfer activities were conducted. Papers and articles on DV design have been presented or published in professional venues throughout the DV development period from 2002 to present.

Conclusions and Recommendations

Project 2 resulted in the following conclusions:

- DV provides good thermal comfort for classrooms with normal ceiling heights (9 ft).
- A supply of 1100 cubic feet per minute (cfm) of 65°F air is sufficient for most classrooms in California climates.
- The use of a tuned variable air volume (VAV) control strategy will optimize energy savings.
- DV can be achieved today using a variety of HVAC system designs.
- DV provides many compelling benefits, including energy savings.

Recommendations from Project 2 include the following:

- Adopt load calculation procedures for Title 24 Standards.
- Offset cost premiums with incentives for high performance designs.
- Increase education and numbers of demonstrations for wider acceptance and implementation of DV in California schools.
- Make DV technology available as off-the-shelf equipment.
- Improve design options for heating with displacement diffusers to further increase efficiency.
- Initiate additional design research into potential DV use in other space types such as libraries, gymnasiums, and auditoriums.
- Continue IAQ research, such as in particle motion studies.

Effectiveness of UVC Technology for Improving School Performance (Project 3)

This project attempted to quantify the impact of ultraviolet irradiation in the “C” band (UVC) of evaporator coils for disinfection and IEQ of California K-12 schools. UV is a line-of-sight technology; when produced by a lamp it can only provide effective disinfection on components with exposure to direct or reflected ultraviolet radiation.



The goal of the study was to determine if UVC is effective in reducing mold and mildew in HVAC systems, improving IEQ, and saving energy.

This study was originally funded as a purely analytical study that would quantify the benefits of the UVC disinfection systems using existing data. A recommendation endorsed by the Project Advisory Committee (PAC) and the Energy Commission changed the direction of the project from an analytical model to a field study.

Outcomes

Key information products developed for this project are listed in the Attachments section of this report and may be found at

www.archenergy.com/ieq-k12/uvc_technology/uvc_technology.htm.

Specifically, the following outcomes were noted:

- Microbial analysis showed the reduction of growth on the evaporator coils, as expected. Total fungal and bacterial colonies were reduced by 65–100 percent with the use of UVC.
- Airflow and efficiency analyses showed a positive trend. More tests are needed to ascertain statistical significance.
- Attendance data analysis was inconclusive. More attendance data collection is needed along with a larger sample size of UVC field tests.
- Teacher and classroom surveys indicated positive feedback on some issues of health and attendance. More research, larger sample populations, and longer test periods are needed to draw more scientifically valid conclusions.
- Some of the HVAC housings created challenges for proper installation. The success of the technology is also dependent on the quality of the installation, which can also depend upon the available unit configuration.
- Additional adverse environmental factors were determined, including standing water, dirty rooftops, toxic substances in the classroom, and dirty floors.

Conclusions and Recommendations

- The research team could not conclusively determine if there were statistically valid improvements in some areas. These include air flow and efficiency of the air conditioning units with UVC disinfection systems.
- UVC technology effectively reduced surface microbial levels on cooling coils. This finding is not in question.
- The potential impact of this technology on IEQ in California schools is in question. It will be proportional to the pervasiveness of microbial growth on cooling coils and the relationship between surface microbial growth and IEQ.
- The success of the technology is dependent upon the quality of the installation. Review and inspection of installation will help assure quality.
- The primary recommendation is to increase sample sizes and allow for repetition of sampling within the study. The limitations can be overcome with additional funding to allow a research team to develop a comprehensive study methodology.

- Both laboratory and field work are required to adequately answer research questions. A discussion of questions and opportunities is provided in the main body of this report.
- Labeling and testing procedures must be standardized. Currently, each manufacturer uses only its own discretion on printed information in marketing material.
- Existing measures and processes could predictably contribute to improved HVAC system performance and IEQ. The main factors that can contribute to improved IEQ are good ventilation and filtration, which also depend upon proper inspection and maintenance.

Market Connection (Project 4)

The Market Connection Project was concerned with disseminating the results of the two previously defined technology projects, DV and UVC, each designed to improve energy use and indoor air quality in K-12 schools in California. The goal of this project was to improve the market focus of the entire program's activities, thereby increasing the ultimate viability and public benefit of the resulting technology products. The information products are designed to overcome market barriers, influence market participants, and produce desired market effects.

Outcomes

Key information products developed for the Market Connection project are listed in the Attachments section of this report and may be found at

www.archenergy.com/ieq-k12/market_connection/market_connection_reports.htm.

Specifically, the project achieved the following outcomes:

- Input was gained from influential market participants and the PAC. This helps ensure that the needs of these influential market participants are met through their involvement and that their feedback is utilized.
- A Technology Transfer Plan was prepared and expert guidance provided. Market barriers at all levels of implementation from finance to infrastructure can thus be more easily overcome.
- Key organizations have been identified. Useful organizations were identified and tabulated according to their missions, publications, and meetings.
- Fact sheets addressing issues of both DV and UVC were developed. The fact sheets were distributed at various presentations and conferences.
- Journal articles have been and continue to be published. Information on these articles for *Engineering Systems* is provided in the Project 4 section of this report.
- Presentations, forums, and training sessions were conducted. Among these are venues at American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE) meetings 2004-2006; the annual CASH conference; and the American Council for an Energy Efficient Economy (ACEEE).
- Guidelines for the Collaborative for High Performance Schools (CHPS) *Best Practices Manual* were developed and training material was created. Training material for both DV and UVC technologies was utilized.

- Educational Specifications (EdSpecs) were produced. Model EdSpecs for siting and construction were prepared; reference information is provided under Project 4 and in the Attachments section of this report.
- Application guidelines were developed. Separate guidelines for DV and UVC were provided to meet school and equipment provider needs.
- Key meetings were conducted and numerous communication activities occurred. These included information exchanges with Carrier and Commissions Codes and Standards personnel.
- Code Action Plans and White Papers were developed and outreach efforts begun. The focus was on identifying and assessing issues, influences, and needs that affect implementation of DV and UVC technology in the schools.

Conclusions and Recommendations

- Key market barriers for the DV and UVC technologies must be addressed.
- Continued action is needed to address codes and standard issues that impede the specification and installation of DV and UVC.
- Results are encouraging but inconclusive. Additional testing is recommended.
- Extending market connection activities for future PIER programs beyond the study period for these technical projects should be considered.
- Statewide energy impacts should be revisited after data from field tests is analyzed.

Benefits to California

Project 1: Administration

Project 1 comprised all and only administrative tasks, is not detailed in this final report, and has no associated energy impacts.

Project 2: Thermal DV in Schools

The results of this project indicate that DV technology may reduce classroom cooling energy use from 10 to 40 percent depending upon the climate. Non-energy benefits include improved ventilation effectiveness and acoustics, which are both compelling findings.

Project 3: Effectiveness of UVC Technology for Improving School Performance

Statewide energy impacts from this technology could not be calculated due to small sample size and inconclusive results. The UVC impact on system airflow, though not statistically significant for this study, produced a positive trend, 1 to 2 percent improvement. The study also concluded that the UVC technology is effective in reducing microbial growth on air conditioning cooling coils, a non-energy benefit.

Project 4: Program Market Connection

Statewide energy impacts are not directly applicable to the market connection activities under the PIER Indoor Air Quality (IEQ) program.

1.0 Introduction

1.1. Background and Overview

The goal of the *Advanced HVAC Systems for Improving Indoor Environmental Quality and Energy Performance of California K-12 Schools Program* (IEQ-K12) was to evaluate advanced equipment for heating ventilating, and cooling school classrooms, with an emphasis on the latter two. This equipment improves indoor environmental quality, saves energy, reduces peak demand, and, ultimately, reduces pollution for the citizens of California. Schools use more than 3% of California's electricity each year, and 27% of that electricity powers heating, cooling, and ventilation. The way in which schools are ventilated and the quality of the ventilation directly affects the quality of the school environment, which has implications for student health and overall learning performance. This program addresses three of the four IEQ target areas identified by the Commission:

- The next generation of California K-12 classrooms, resulting from Proposition 47 (State of California 2002) and local bond funding, are more comfortable and energy efficient, as well as healthier.
- Teachers have better control over the IEQ and thermal comfort of their classrooms.
- Students and teachers are sick less often, are more comfortable, and perform better.
- School districts spend less on energy and so are able to spend proportionately more of their budgets on books, computers, and salaries.

Under the projects in this program, the project team worked with major manufacturers to investigate innovative systems that potentially have energy and IEQ advantages over conventional systems, to demonstrate the energy performance and cost advantages of these systems, and to develop and distribute design tools and related information to decision makers and school design professionals.

The IEQ-K12 program consisted of two technical projects and a market connection project. (Information about Project 1, Program Administration, led by Donald Frey and Vernon Smith of AEC, is not included in this report.) The three projects are as follows:

- Thermal DV in Schools (Project 2), led by Charles Eley and John Arent of AEC
- Effectiveness of UVC [ultraviolet light in the "C" band] Technology for Improving School Performance (Project 3), led by Roger Wright and Stacia Okura of RLW Analytics, Inc.
- Program Market Connection (Project 4), led by Morton Blatt of Morton H. Blatt Energy Utilization Consulting

1.2. The Project Team

The IEQ-K12 program was overseen by Program Manager Vernon Smith and Principal-in-Charge Donald Frey, both of AEC. Vernon Smith provided administrative, financial, and technical guidance to the project team.

Thermal Displacement Ventilation (DV) in Schools (Project 2) was led by Charles Eley and John Arent of AEC. John Arent provided the technical expertise and was responsible for the field demonstrations at the two school districts.

Effectiveness of UVC Technology for Improving School Performance (Project 3) was led by Roger Wright and Stacia Okura of RLW Analytics, Inc. Stacia Okura provided the technical expertise and was responsible for the field demonstrations at the school districts.

Program Market Connection (Project 4) was led by Morton Blatt of Morton H. Blatt Energy Utilization Consulting. Morton Blatt provided his expertise regarding market and code issues related to the two technologies.

The PAC representatives, named in the Acknowledgements section of this report, offered invaluable input and helped guide the project team on numerous issues.

School district personnel provided access and feedback for the field demonstrations at Coyote Ridge Elementary School in Roseville, northern California, and Kinoshita Elementary School in San Juan Capistrano, southern California.

Representatives from heating, ventilation, and air conditioning (HVAC) and UVC manufacturers supplied information about the technologies along with equipment and support.

California Energy Commission staff reviewed and provided input into the research at critical points throughout the IEQ Program.

1.3. Report Organization

Under each project in this study, researchers investigated, or advanced the understanding of an area of concern related to, the IEQ of K-12 classrooms. Project 1 focused on the administrative tasks of orchestrating monthly reports, deliverables, and invoices and is not discussed in this report. Accordingly, this report is organized into three distinct sections, one for each of the remaining projects 2, 3, and 4. These sections discuss the objectives, outcomes, conclusions, and recommendations for each project.

2.0 Thermal Displacement Ventilation in Schools (Project 2)

2.1. Introduction

Poor environments in schools influence the health, performance, and attendance of students. Many existing school space conditioning systems that use conventional mixed ventilation systems fail to provide the indoor air quality, acoustic acceptability, and comfort that can produce optimal student and teacher performance. DV is a cost-effective means of providing an optimal indoor environment by delivering cool supply air directly to the occupants in a space. The air enters the room at about 65°F (18.3°C), about 10 degrees warmer than with a conventional air conditioning system. The fresh air, supplied near the floor at a very low velocity, falls towards the floor, and spreads across the room until it comes into contact with heat sources. The supply air slowly rises as it picks up heat from occupants and equipment. The warmed air picks up particulates as it rises towards the ceiling, where it is exhausted from the space. This vertical airflow pattern near each occupant is often referred to as a *thermal plume*; this thermal plume makes it less likely that germs will spread between occupants. This air distribution system provides for effective ventilation, since the fresh supply air is delivered directly to each occupant. All this can be provided at an initial cost comparable to that of less effective conventional mixed-ventilation systems that rely upon creating fully mixed air in the room to achieve their ends.

The overall goal of this DV project was to gain wide acceptance of DV in both newly-constructed and renovated K-12 schools. Specifically, the project team worked toward four goals:

- Create a DV HVAC system that uses less energy; that is, only 50% of the fan energy and 33% of the cooling energy of conventional HVAC systems.
- Achieve a target 20% market penetration in the new construction and retrofit/renovation market for schools.
- Reduce the peak demand for electrical energy in California by 224 megawatts (MW) at the 20% level of market penetration.
- Reduce annual energy consumption in California by 380 gigawatt-hours (GWh) at the 20% level of market penetration.

2.2. Project Objectives

The objectives for Project 2 follow:

- Coordinate with other natural ventilation and under-floor air distribution Public Interest Energy Research (PIER) research projects to inform the DV project regarding relevant recent research results
- Develop definitive guidelines based on computational fluid dynamics (CFD) analyses of eight classroom configurations for the quantity and conditions of air that must be delivered in order to maintain thermal comfort in a variety of classroom configurations
- Validate the CFD results with a full-scale mockup of one classroom designed so that it could be reconfigured to allow study of various thermal conditions

- Contact approximately 40 individuals involved in the design, construction, and operation of California schools in order to gain an understanding of concerns about implementing DV in new schools and in major modernizations
- Develop at least two detailed engineering solutions for applying DV in K-12 California classrooms including specific equipment specifications, system schematics, control sequences, and other information
- Construct two demonstration DV classrooms, one in northern California and one in southern California
- Monitor the performance of the demonstration classrooms for a period of at least 6 months
- Work with manufacturers to develop new products that meet DV-related marketplace needs
- Develop a series of fact sheets for school decision makers and an engineering guide for design professionals and work with the Collaborative for High Performance Schools (CHPS) representatives to integrate these materials into the CHPS Best Practices Manual for 2006
- Develop a one-day training curriculum on DV for design professionals and present the training program to technical audiences in a variety of California locations
- Prepare and submit for publication at least two articles on the application of DV in California schools in professional trade journals or technical conference proceedings

2.3. Project Approach

Key tasks and approaches by the project team are summarized below.

2.3.1. Coordination with ongoing related PIER natural ventilation and DV research (Task 2.1)

The objective of this task was to review, coordinate, and leverage the content of work under this project with two other Commission-sponsored research projects.

The two projects and the objectives of the review were to:

- Review research, conducted at University of California (UC) San Diego and at Lawrence Berkeley National Laboratory (LBNL), on natural ventilation modeling and algorithms developed for EnergyPlus (PIER Contract Number 400-99-012, Element 4, Task 2.8)
- Review current under-floor air distribution research by UC Berkeley, UC San Diego, LBNL, and York International (PIER Contract Number 500-01-035)

Other work under this task included a literature search on other DV research.

2.3.2. CFD analysis of thermal comfort and ventilation effectiveness (Task 2.2)

The project team first built a CFD model of a typical California classroom, designed to comply with the current or proposed California energy efficiency standards and validated this model through full-scale testing (see Figure 1). The team then studied variations from the baseline case to understand how the design parameters (such as air flow) would change with variables in ceiling height, internal heat gains, and building envelope loads.

For the baseline case classroom, a series of CFD simulations were performed to determine the supply rate of 65°F (18.3°C) air needed to maintain acceptable thermal conditions. A supply air temperature (SAT) of 65°F was selected based on prior applications of DV in other locations. Warmer air provides inadequate cooling, and colder air carries a greater risk of causing cold feet for those sitting near the diffusers.

Through parametric CFD simulations, air volume was gradually increased in order to achieve satisfactory thermal conditions; that is, until the average temperature at the top of the occupied zone (60 inches [in] above the floor) was no greater than 75°F (74+1°F) (23.8°C) and the temperature difference from the top to the bottom of the occupied zone was no greater than 5.4°F (12° C) – the recommendations of American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE) Standard 55.

For the other simulation cases, the volume of air was scaled up or down from the baseline case with thermal loads. The same diffuser area was used in all cases.

The project team determined the volume of air, the delivery velocity, the number and configuration of delivery points, and the temperature and humidity needed to maintain thermal comfort and IEQ for a variety of K-12 classrooms. The researchers examined the thermal needs of typical California classrooms and related these to air temperature and volume requirements for DV systems. This study resulted in recommended supply-air temperature and air volume levels for the various classrooms analyzed by the team. Three-dimensional visualization techniques were used to illustrate temperature, air quality, and movement. Under the direction of the Architectural Energy Corporation (AEC), Halton Company performed the CFD simulation studies for this project.

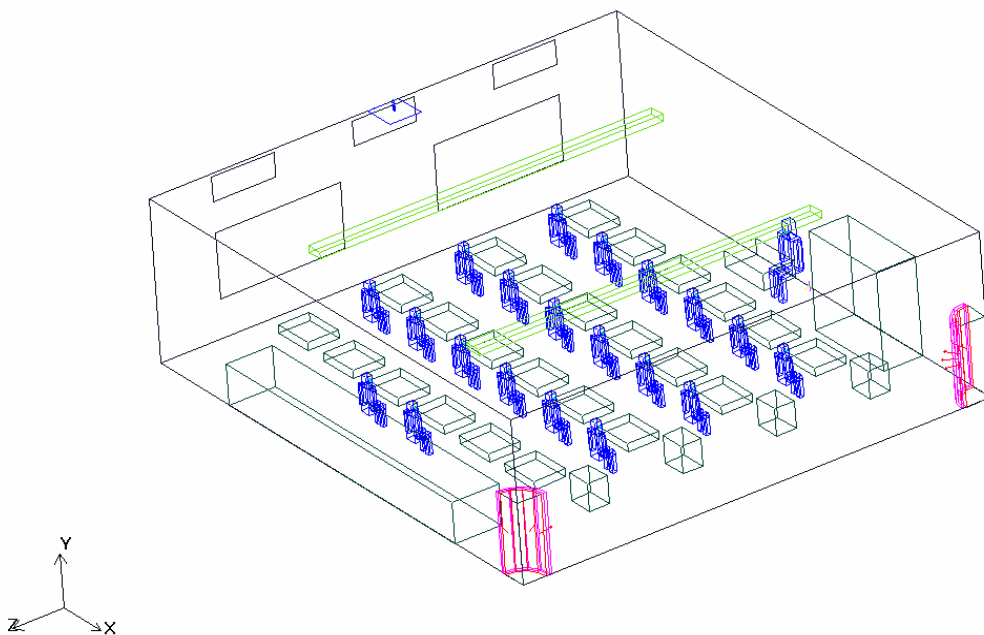


Figure 1. 3-D layout of CFD classroom model

2.3.3. CFD validation with full-scale mockup (Task 2.3)

The objective of this task was to validate the results of the CFD analysis using a full-scale mockup of a classroom at a key industry partner's laboratory. A CFD model was developed as a classroom representative of current California classrooms meeting Title 24 standards. The CFD simulation of the classroom provided detailed information on the temperature distribution and air velocities in the room. A comparison of predicted air temperatures and air velocities with CFD simulation predictions served to validate the CFD model. Once the model is validated, parametric CFD runs can be performed to determine supply-air requirements for different cooling load conditions.

A full-scale mockup of one-half of a typical classroom (32 ft x 16 ft x 10 ft height) was constructed at the Halton test facility. The heat load in the classroom consisted of overhead fluorescent lighting, 2 computers, 10 60-watt (W) light bulbs inside of steel cylinders to represent students, and 3 heat tapes used to simulate solar radiation, conduction, and lighting loads.

Air temperature and air velocity measurements were made at six different heights for each of eight locations in the test room. The space temperatures and air velocities measured at various locations in the room were collected using eight thermal anemometers (air velocity detectors). These devices have a velocity accuracy of 3.94 feet per minute (fpm) (0.02 meters per second [m/s]) $\pm 1\%$ of reading within 1–200 fpm (0.05–1 m/s), a temperature accuracy that is $\pm 0.4^\circ\text{F}$ (0.2°C). Supply-air flow was measured using a laminar flow element (LFE) with an accuracy of $\pm 0.7\%$ of the reading. Two cases were validated and both demonstrated good agreement between the CFD simulations and the measurements. This allows researchers to conclude that the CFD software package (Airpak 2.1.10 from Fluent Inc.) can be used as a reliable tool to simulate thermal DV systems for a classroom environment.

2.3.4. Barriers study (Task 2.4)

The objective of this task was to perform a market research study to identify both the perceived and encountered barriers that restrict the implementation of DV systems in the design of new and retrofitted K–12 classrooms. Perceived and real barriers were identified through an in-depth study that included structured interviews among leading designers, engineers, manufacturers, decision makers, and users.

In-depth interviews – 30- to 45-minute detailed telephone interviews – were held with 35 professionals in the field (see Table 1). The focus was on general knowledge, attitudes (past, present, and future), experience, and perceived or actual problems with thermal DV in classrooms. A mix of closed and open-ended questions was used. On occasion, some participants were asked subsequent questions via e-mail and telephone for clarification. All interviews were recorded for further reference.

All participants in this study had previous experience working with schools and school districts. Those participating in the in-depth interviews derived more than 60% (and usually more than 70%) of their business from service to schools. The participants' experience also reflected a variety of school and school project sizes that ranged from 15 to more than 75 classrooms.

The interview script was designed to uncover and determine participants’ level of knowledge of and attitudes about of DV as compared to HVAC systems currently in use in California schools. To gain the most useful insights, respondents were stratified across the following responsibilities and experience levels. Market researchers working for SDV/ACCI contributed significantly to this market barriers study.

Table 1. DV interviews: participant stratifications

Segment	With TDV Experience	Without TDV Experience
A. HVAC Mechanical Engineers	6	3
B. School Architects / Designers	3	3
C. School District Facilities		3
D. Maintenance and Operations personnel		3
E. Construction/Contractors	1	3
F. Manufacturers	2	2
G. Division of the State Architect Plan Examiners		2
H. Users (Teachers)		4
Total	12	23

2.3.5. System design options (Task 2.5)

To fulfill this task, the project team evaluated and developed practical and cost-effective engineering solutions for supplying neutral DV air to K-12 classrooms. Conventional HVAC designs and equipment used for typical schools are not well configured for DV, which requires higher air delivery temperatures and different load assumptions than conventional HVAC solutions with overhead air delivery. This task involved developing load calculations for a representative classroom building in each of two California climates in order to determine required system cooling capacity.

The approach for this task was first to gather leading design engineers and architects for K-12 schools at a design charrette to develop conceptual design options and discuss practical design considerations. Results from the charrette were applied to detailed design solutions developed for the project. AEC worked with CTG Energetics to develop three design solutions, using available HVAC technology and the standard design of a typical modern classroom building in a California coastal climate. Researchers then evaluated the options considering energy savings, comfort, and simplicity.

An eight-classroom building was chosen as a prototype building, meeting Title 24 prescriptive requirements, to determine typical loads. EnergyPro was used to determine design cooling

loads, assuming year-round operation in an 8:00 am–5:00 pm operating schedule. For the southern California coastal climate of Capistrano in climate zone 6, the classroom has a design cooling load of 28,400 British thermal units per hour (Btu/h), comprising a 22,800 Btu/h sensible load and a 5600 Btu/h latent load. Adding the combined sensible and latent ventilation load from 600 cubic feet per minute (cfm) of outside air, at design conditions of 85°F (29.4°C) dry bulb and 67°F (19.4°C) wet bulb, the total system cooling load is 40,300 Btu/h (3.3 tons). A similar load analysis for a Sacramento building, meeting current Title 24 prescriptive envelope requirements, shows a design room cooling load of 28,600 Btu/h and a system cooling load of 40,900 Btu/h (3.4 tons). Thus, while the sensible cooling load is significantly higher for the Sacramento classroom, the total (sensible plus latent) system cooling load is only marginally higher.

DV systems require different load calculation procedures than conventional systems. A procedure must account for the portion of heat gains that affect the occupied portion of the space in order to determine required airflow. The return air temperature can then be determined in order to calculate the required system capacity. The required DV system capacity depends greatly on the supply air temperature (SAT) when leaving the cooling coil. Systems that can provide 65°F (18.3°C) supply air without reheat will have a much lower cooling requirement, since the latent load is reduced or eliminated. For the representative Capistrano classroom building, a 3-ton nominal cooling capacity per classroom was chosen, as this is the smallest available size that provides the required sensible cooling capacity.

The final step of this task was to address detailed design considerations that are unique to DV. The unique design considerations addressed were diffuser selection and layout, load calculation procedures and energy modeling, and HVAC control sequences. Several existing load calculation procedures, documented in prior research, were reviewed for applicability to DV applications in classrooms. Energy modeling procedures using both DOE-2 and EnergyPlus were evaluated through simulation studies of typical California classrooms built to Title 24 standards. Control strategies were developed by first working with HVAC manufacturing partners and refined by practical results of the two demonstration projects. The detailed design results were packaged in the *Displacement Ventilation Design Guide* developed under of this project (referenced in the Attachments section of this report).

2.3.6. Construct demonstration classroom (Task 2.6)

This task was designed to demonstrate the viability of DV in two classrooms, one in northern California and one in southern California. Researchers developed a list of selection criteria. School district representatives were contacted to gather data and qualitative information and to identify candidate classrooms. Finally, a list of specific sites was recommended and presented to district representatives. The sites selected had to meet the following key criteria:

- The classroom should have a minimum ceiling height of 9 ft to allow for adequate stratification. (A ceiling height of 12 ft is desirable, if possible).
- The building envelope should meet the Title 24 standards.
- Internal heat gains should be minimized to control the cooling load of the classroom.
- If HVAC equipment is mounted on the roof, space will be required to drop the ducts so air can be delivered near the floor.

- The classroom should have the ability to conveniently locate the diffusers near the floor and to provide for exhaust near the ceiling.
- For existing classrooms, the classroom must be easily retrofitted and not have excessive envelope loads.
- The interior floor surface should be chosen to promote indoor air quality. (One criticism of distribution systems that deliver supply-air at floor level, such as DV, is that pollutants residing at floor levels may be brought up to the students' breathing space from rising air plumes.)

Schools meeting the CHPS selection criteria and that meet the conditions above will have many of the desirable characteristics for DV.

Two schools were selected, and DV systems installed and commissioned. Instrumentation was installed inside the classrooms and connected to a data collection system, and the data was transferred to a computer sitting outside the classroom. Researchers installed the monitoring equipment at each site, performed short-term monitoring of IAQ, and verified equipment operation and upload data.

For the first demonstration, AEC worked with the Trane Company to design an HVAC system specifically to meet DV requirements. The most important design requirement was tight control of the supply-air temperature. The design selected used a heat pump with a refrigerant-water heat exchanger that could provide chilled water for cooling and heated water for heating. The system also included a custom outdoor air handler, with an economizer and variable-speed drive for VAV control. The system was integrated with the school's existing Alerton controls network for diagnostics and analysis.

The first construction project came in well over budget, leaving very little budget for the second demonstration. The factors contributing to the high costs were system complexity, the requirement for a new electrical panel, and a significant cost for custom Alerton controls for programming and graphics. For this reason, AEC held a Critical Project Review meeting with the California Energy Commission to revise plans for the second demonstration. The Commission desired a packaged equipment solution for DV that was not yet available from manufacturers. This accelerated the product development tasks of the project: to design and develop a new packaged rooftop product for DV that could be used in the Capistrano demonstration. AEC obtained match funding from San Diego Gas & Electric's Emerging Technologies Program to help fund the installation and monitoring costs for the second demonstration.

2.3.7. Monitor performance of demonstration classrooms (Task 2.7)

For this task, the project team collected detailed data for approximately nine months on the temperature and IEQ conditions of the demonstration classrooms at the two school campuses. For each DV classroom, a similar classroom using a conventional overhead air mixing system for climate control was also instrumented and monitored as the control for the test.

There were two key components: monitoring of the equipment operation via the system controller, and monitoring thermal comfort and indoor air quality inside the classroom. The primary objectives were to:

- Determine if the DV system provides thermal comfort and IEQ as well as or better than an overhead ventilation system
- Confirm what supply-air volume is required to cool the space

Prior research indicates that fewer cfm are required to cool the space with DV systems, even though the air is supplied at a higher temperature. One objective of the study was to determine whether or not this claim is true. The Halton CFD analysis predicted a slightly higher supply-air flow than a conventional mixing system would provide.

Measurements were taken of temperature, relative humidity, and carbon dioxide. Data on supply- and return-air temperature and supply-air flow (determined from fan speed) were collected via the system controller and building energy management system and reviewed periodically. Temperature measurements, taken at four different heights for each of three locations in each classroom, were used to evaluate thermal comfort. Temperature levels at different heights were compared to verify that stratification levels comply with ASHRAE 55-2004 requirements.

In addition, the team assessed the IAQ and energy use of the DV system. To evaluate IAQ, carbon dioxide sensors were installed in the occupied zone, at the exhaust sites of each classroom, and outside. The CO₂ sensors had an accuracy of ± 30 parts per million (ppm) + 2% of the reading. These measurements were used to evaluate ventilation effectiveness. ASHRAE 62.1-2004 states that DV systems have higher ventilation effectiveness, indicating a higher outside air ventilation rate in the breathing zone than with mixing systems. This is the principal documented IAQ benefit of DV systems. Since natural ventilation sources will also affect IAQ, door status was monitored with magnetic contact switches. Data on HVAC electricity use was recorded to compare the heating and cooling energy used by the DV classroom to that of the conventional classroom. HVAC electricity use was monitored with WattNode pulse counters and Magnelab 5A current transducers.

Data was collected at one-minute intervals and routinely uploaded for review. The data was reviewed to detect any sensor malfunctions or collection issues. Teachers, students, and maintenance personnel were contacted to verify that the system was operating correctly and that thermal comfort was being maintained.

Match funding from San Diego Gas & Electric enabled the research team to proceed with the monitoring activities and data analyses for the southern California Capistrano Kinoshita Elementary School site. Although the primary expected energy benefit of DV was electricity savings, HVAC heating energy was also monitored at Kinoshita with gas meters.

2.3.8. Product development (Task 2.8)

The objective of this task was to develop new products for DV systems in classrooms. Although chillers with hydronic coils may be configured for DV applications, packaged direct-expansion (DX) equipment is generally not capable of producing neutral air from 100% outside air (OA) conditions.

New product requirements have been identified as a result of the market barriers study, the DV design charette, work on system design options, and preliminary results of the first demonstration classroom. New technologies for capacity modulation may be applied to new

products for DV. These products are described in more detail in the Commercialization Potential section of the report for this project.

The outline specifications for the packaged DX unit for displacement ventilation were provided to multiple manufacturers. The second demonstration at Kinoshita was delayed in order to allow time for the development of a custom unit meeting these requirements.

2.3.9. Fact sheets and guidelines (Task 2.9)

Under this task, the project team developed promotional materials that highlight the benefits of DV in classroom applications for school district personnel and an engineering guide for design professionals and contractors. The fact sheets and guidelines developed in this task summarize the findings of the previous tasks. The information is packaged for effective distribution to industry and distributed to groups that make school-related decisions. The collateral was developed jointly under this task and under the Program Market Connection (Project 4) activities. Several of the documents are referenced in the Attachment section of this report.

2.3.10. Information dissemination (Task 2.10)

The objective of this task was to introduce the informational products to the target audiences of school districts, school architects, engineers, construction managers, and contractors. In California, a large share of school HVAC system design is carried out by a handful of mechanical engineering firms. The project team worked with various organizations to unveil the tools that emerged from this project and to help designers become more comfortable with the DV concept.

Each school district has a set of Educational Specifications (EdSpecs) that describe, often in detail, typical design and system concepts to be considered for each school facility. The EdSpecs often restrict the type of HVAC system that is permitted and specify requirements for controls, design temperatures, and other aspects. The project team developed model EdSpec language focusing on DV for HVAC systems.

Another major focus of this task was to develop training material to be delivered at the state energy centers. Training sessions were delivered at the Sacramento Municipal Utility District (SMUD) facility and at the Southern California Edison (SCE) Customer Technologies Application Center (CTAC). The seminars included an overview of the technology, a discussion of architectural design issues and air delivery options, guidelines for diffuser specifications, load calculation and energy modeling procedures, and performance monitoring results.

Due in part to scheduling difficulties, some of the planned seminars were not provided. In lieu of additional seminars, AEC provided several outreach activities to school designers. These included a design charette for the Los Angeles Unified School District (LAUSD) in May 2005, an ASHRAE presentation at the 2005 Winter Meeting, a CASH presentation in February 2006, and several publications.

Again, the work under this task was completed in parallel with the Program Market Connection (Project 4) activities. More detailed information about information dissemination may be found in the Program Market Connection section of this report.

2.3.11. Technology transfer activities (Task 2.11)

Under this task, the project team helped researchers under Project 4 develop a plan for key decision makers that presents the experimental results, knowledge gained, and lessons learned during the DV study. The plan provided a time-phased tabulation and description of documents to be published and distributed to disseminate the results and increase the market penetration of the DV technology being studied. The plan addressed market barriers that often impede the adoption of new technologies and analyzed the roles of influential market participants in the funding, specification, installation, and operation of the technology. Potential advantages and disadvantages were tabulated. Information dissemination channels were outlined for each set of market participants, including publications, periodicals, web sites, and upcoming meetings.

The general approach to the development of the technology transfer deliverables for the different dissemination channels was to provide varying levels of technical materials. One level included materials of general interest such as fact sheets that have been distributed to a broad set of market participants. Another category of deliverables were those produced specifically for a group of market participants, such as detailed design guidelines for engineers and architects. Other materials included technical papers, journal articles, and tailored presentations.

Again, the work under this task was completed in parallel with the Program Market Connection (Project 4) activities. More detailed information about the technology transfer activities may be found in the Program Market Connection section of this report.

2.3.12. Production readiness plan (Task 2.12)

For this task, the researchers provided the project results to the manufacturing partner and other interested organizations such as CHPS to further develop the design specifications and equipment tested under this project. The research team will continue to promote the results of this project and provide market and technical information on request.

2.4. Project Outcomes

A summary of the project outcomes follows. Key information products developed for this project are listed in the Attachments section of this report and may be found at www.archenergy.com/ieq-k12/thermal_displacement/thermal_displace.htm.

- Coordination with related PIER natural ventilation and DV research yielded information of interest.

Researchers reviewed a thermal plume model based on UC San Diego research designed to help professionals understand the fundamental driving forces of displacement flow. This analytical plume model predicts the airflow of a single thermal plume for a given supply velocity and heat gain. The model is applicable when thermal plumes generated by internal heat gains are the driving force of the flow. For well-insulated classrooms, internal heat gains from occupants make a large contribution to the cooling load. Experiment results from the DV mockup tests can be compared with predictions from this model.

EnergyPlus offers a more accurate estimate of DV than other energy simulation programs such as DOE-2. The CFD simulation data and mockup test data from the PIER DV project can be used to validate the EnergyPlus model. The CFD and mockup tests provide a more accurate estimate of the temperature profile for design cooling conditions. The CFD and mockup tests are used primarily to estimate an appropriate size for the system. The value of EnergyPlus is in estimating annual energy costs of the DV system. EnergyPlus can estimate the annual savings in cooling costs of a DV system over a conventional system. Modeling rules for DV can be incorporated into the Title 24 performance compliance procedure so that users receive proper credit for use of DV systems.

Researchers also reviewed PIER research on under floor air distribution (UFAD) systems to determine its applicability to DV. It was determined that due to differences between the test setup and load patterns for the UFAD and DV systems, the UFAD test data cannot be applied to DV in classrooms.

Existing design guidelines published by ASHRAE and the European Federation of Heating and Air-Conditioning Associations offer procedures for designing DV systems for thermal comfort and air quality. The CFD simulation results and mockup test results can validate the applicability of these guidelines to California classrooms or serve as the basis for new design guidelines.

CFD simulation results and field test data obtained in later phases of this project showed that while a pattern of thermal stratification is maintained, it is lower than that predicted by the ASHRAE model. The results of this research suggest that the model introduced in the *Energy Design Resources Simulation Guidebook* provides a fair estimate of the performance of DV systems in classrooms.

- The CFD analyses of different classroom configurations provided the following outcomes:

In all cases, sufficient cooling and thermal comfort can be provided through two displacement diffusers, providing 65°F (18.3°C) supply air. A supply-air flow rate of 1000 cfm to 1500 cfm of 65°F air is sufficient for most classroom cooling conditions.

A 9-ft ceiling is sufficient for thermal DV. Benefits of stratification are seen with higher (12-ft) ceilings; as a result, less air is required to maintain the same room set-point for the same design cooling loads.

For all cases, marginal comfort is maintained at locations close to the diffusers. The temperatures at floor level are cool (67–68°F or 19.4–20°C) and the temperature stratification slightly exceeds ASHRAE 55 recommendations. Adding additional diffusers would improve comfort at locations near the corners of the room. Seated students should be situated at a distance of at least 4 ft from the corner diffusers to stay comfortable.

As expected, lighting loads contribute less heat to the occupied zone than occupant or equipment loads.

DV shows improvements in ventilation effectiveness, as evidenced by lower CO₂ levels and a lower mean age of air in the occupied zone.

For classrooms with double-pane windows, perimeter heat is not required for coastal and valley California climates. Perimeter heat is required in mountain climates where the winter design dry-bulb is 10°F (-12°C) or less. Perimeter heat losses through the slab cause the most comfort issues during heating conditions.

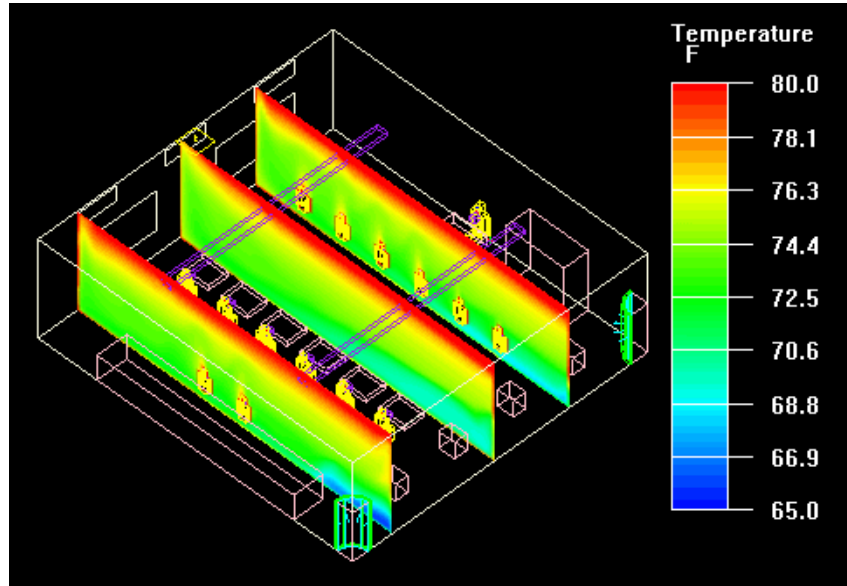


Figure 2. CFD modeling - base case - vertical slice

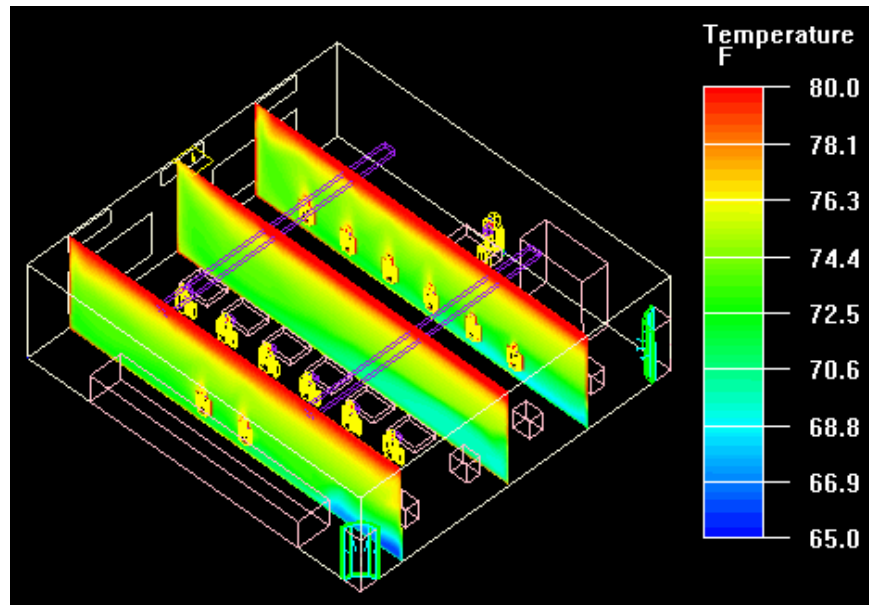


Figure 3. CFD modeling - DV case 9 ft ceiling - vertical slice

Figures 2 and 3 show vertical temperature profiles at different locations in the space. At a height of 4 in above the floor, there is a temperature gradient between the interior of the space (near the diffusers) and exterior of the space. However, at head level of seated students (40 in) the temperature is uniform throughout the space.

- The market barriers study identified initial cost and the lack of demonstration classrooms as key hurdles to acceptance.

The study showed that many respondents thought DV to have a higher first cost than do conventional systems. Most participants readily identified the energy and IAQ benefits. Other groups not experienced with DV were less convinced of the benefits. Also, all outside air systems may not make sense in some climates; respondents in southern California in particular were concerned about using all outside air. Many thought that incentive programs could offset the perceived higher first cost and greater risk if using DV systems.

- Three DV-system design options for California K–12 classrooms were evaluated for cost effectiveness and performance.

Three general schematic design solutions were evaluated for DV in classroom applications, using available HVAC technology and the standard design of a typical modern classroom building in a California coastal climate.

The first option is to use a packaged air-cooled chiller and central boiler with individual fan coil units for each classroom. With typical classroom buildings, the air handlers would likely have to be mounted on the roof. This option provides the greatest degree of supply-air temperature control with high system efficiency and good thermal comfort at part-load conditions. However, this option has the highest actual first cost for equipment and installation.

The second option is a VAV packaged rooftop unit serving multiple classrooms, with VAV terminal units for each classroom. This option provides fan energy savings at part-load conditions and requires relatively low maintenance. A single 25-ton unit allows for multiple stages of cooling, providing good energy efficiency at part-load conditions. However, this option requires more sophisticated controls and, while less expensive than an air-cooled chiller, is more expensive than single-zone packaged units.

The third option is a separate 3-ton packaged gas-electric rooftop unit for each classroom. This option has a substantially lower first cost than either a single packaged VAV rooftop or a central chiller. A unit with two-stage cooling, multiple speed fan, and two-stage gas heat is the best currently available unit in terms of energy efficiency and supply-air temperature control at part-load conditions. This system would require some control modifications to ensure that the discharge air temperature meets DV system requirements. However, this option is likely to have higher operating costs and maintenance costs than the other two options.

Based upon a comparison of energy performance, thermal comfort, practicality, and first cost, researchers felt that option 3, individual-package rooftop units serving each classroom, is the most practical application for near-term implementation in California classrooms.

- Two demonstration DV systems were installed, commissioned, and monitored in two classrooms; one in northern and one in southern California:

For northern California, Coyote Ridge Elementary in the Dry Creek Joint School District of Roseville, Sacramento County, was selected. This school has a high open ceiling in the center of the classrooms with a skylight and a 9 ft ceiling around the perimeter of the classroom. Eight new classrooms were completed in June 2004. The Coyote Ridge classrooms are served by individually packaged HVAC rooftop units.

For southern California, Kinoshita Elementary in the Capistrano Unified School District of San Juan Capistrano, Orange County was selected. The school is on a site approximately 2 miles inland in southern Orange County, with a temperate climate. The school has 6' x 6' skylights in the center of each classroom. The perimeter of the classroom has a suspended ceiling at a height of 9 ft. The large 14 ft x 14 ft skylight well provides additional space for temperature stratification. The Kinoshita classrooms are served by individually packaged HVAC rooftop units.

The research team collaborated with the manufacturer on the two installations. The first system at Coyote Ridge Elementary was a custom system designed for the retrofit of a single existing classroom. The air handler unit was modified to adapt to the existing roof curb for the packaged unit. The system was specifically designed for tight control of the supply-air temperature. The system was installed for a single classroom, and was tested and commissioned prior to monitoring.

The DV system for the second installation at Kinoshita Elementary features Copeland Digital Scroll™ compressor technology and allows for a reduction in cooling output to as low as 10% of full capacity. This virtually eliminates the on-off cycling that commonly occurs with small packaged systems. The unit also incorporates a variable-speed drive for the supply fan in order to provide fan energy savings at part-load conditions. This unit was developed as a prototype for a future product.

Commissioning activities were provided by the project team and started during the construction phase. Activities included equipment startup, calibration of controls, testing, adjusting and balancing, and functional testing. The commissioning activities for the demonstration classrooms focused on ensuring the proper function of the equipment after installation and on proper operation during the school year.

- Results of the DV demonstration classrooms showed that significant energy savings are possible.

HVAC electricity use was monitored at the control classroom and the DV classroom at Kinoshita during the fall 2005 and spring 2006 semesters. Initially, energy monitoring results did not show a reduction in HVAC electricity use in the DV classroom. However, an investigation of the data showed that the DV classroom was being maintained at a cooler average temperature. Moreover, the HVAC system's economizer settings were not optimally set for DV. After configuration changes were made to the DV unit, the energy monitoring results showed energy savings of 20% over the length of the monitored time periods (see Table 2).

Table 2. HVAC electricity comparison, Kinoshita Elementary

Period	Control Unit kilowatt-hours (kWh)		DV Unit kWh	
	Total	Daily Average	Total	Daily Average
8/22/05–9/30/05	392.0 kWh	19.6 kWh/day	448.0 kWh	22.4 kWh/day
10/31/05–12/14/05	330.8 kWh	10.7 kWh/day	197.9 kWh	6.4 kWh/day
2/23/06–4/18/06	128.4 kWh	2.9 kWh/day*	239.0 kWh	5.4 kWh/day
4/19/06–5/23/06	611.3 kWh	17.0 kWh/day	266.9 kWh	7.41 kWh/day
Entire Monitoring Period	1462.5 kWh		1151.8 kWh	

** During this period the supply fan was often set to "auto" during school hours. Supply fans are typically required to be "on" during occupied hours.*

It also is important to note that a direct comparison of the monitoring results of the two Kinoshita Elementary classrooms was made difficult because the teacher in the control classroom often set the fan to "auto" rather than the "on" position. This setting caused the fan to operate only intermittently between February and April 2006, resulting in lower electricity use in the control classroom but at the expense of the IAQ. Typically, supply fans are required to be set to "on" during occupied hours. .

The DV demonstration also shows that teachers are less likely to turn off HVAC fans due to noise, which positively affects both comfort and air quality. This is an important finding.

The DV design allows the cooling capacity to vary continuously to meet the space load. As a result, the supply-air temperature is controlled closely to the set point. This allows for good space temperature control with the DV system.

The primary IAQ benefit of the DV system is improved ventilation effectiveness. In the DV classroom, the CO₂ concentration is consistently lower in the occupied zone than in the return (see Figure 4). As a result, the outside air is delivered more effectively to the occupants. This result was consistently shown in monitored data from both northern and southern sites. It should be noted that this benefit prevails only when cool-to-neutral air is supplied to the classroom.

With the use of a higher supply-air temperature, some engineers have been concerned that DV may not provide sufficient dehumidification in some cases. The results from this demonstration indicate that the relative humidity is maintained to acceptable levels in the DV classroom (see Figure 5). While the conventional unit provides additional

dehumidification, DV classrooms showed improved IAQ and acoustics with acceptable humidity levels.

Another noticeable benefit of DV is an improvement in acoustic comfort. Spot measurements of background noise levels showed a typical range of 40–44 decibels for the DV classroom (with the fan at maximum speed) and 48–50 decibels for the control classroom. As a result, teachers are less likely to turn off the DV fan.

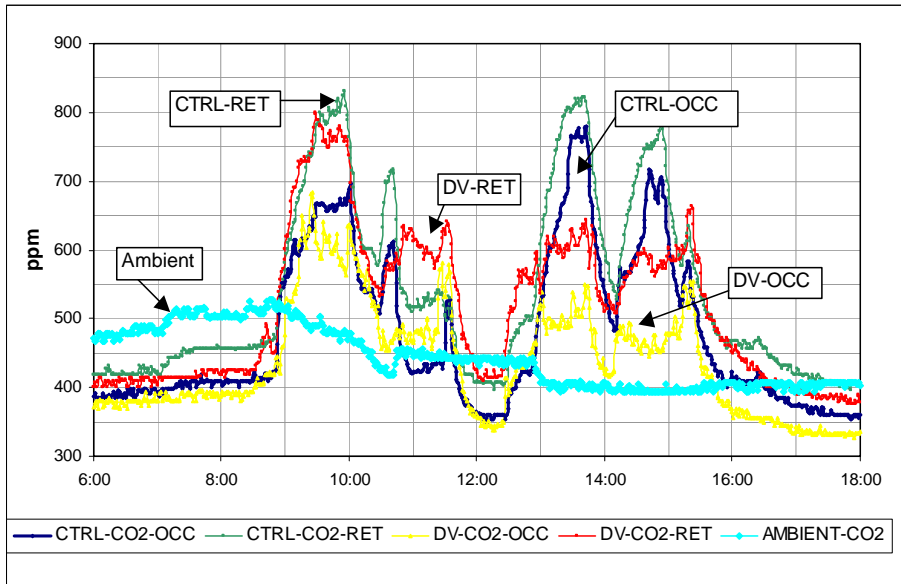


Figure 4. The CO₂ concentration in the occupied zone of the DV classroom is consistently lower than the concentration at the return, a sign of good ventilation effectiveness.

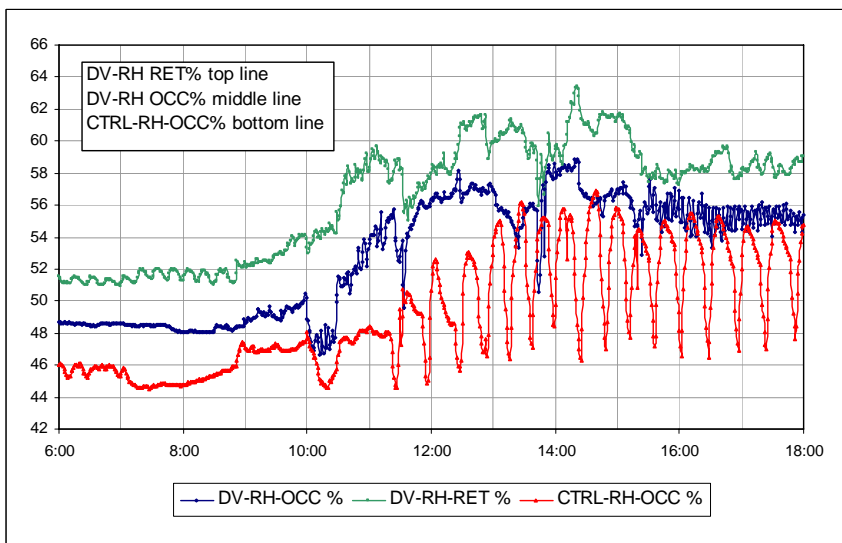


Figure 5. Relative humidity, September 15, 2005. While the RH in the DV classroom is slightly higher than the RH in control classroom, it remains within acceptable limits.

Teacher feedback has been positive in the DV classroom. The teachers in both the DV and the conventional classrooms were given surveys on the acoustics, indoor air quality, and thermal comfort they experienced in their classrooms. The teachers in the displacement ventilation classrooms gave the DV system higher marks for both acoustics and thermal comfort compared with the conventional classrooms.

- Various technical documents and marketing collateral have been developed that present the results of this project.

Fact sheets, guidelines, case studies, presentations, and technical articles were developed. The information has been distributed as part of the CHPS program to the CASH, the Energy Design Resources Program, ASHRAE, and other groups that make school-related decisions. The project team developed model EdSpec language, which focuses on DV for HVAC systems. A detailed DV Design Guide has been developed that provides practical design information to engineers and architects.

The collateral was developed jointly under this task and under the Program Market Connection (Project 4) activities. Several of the documents are referenced in the Attachment section of this report.

Technology transfer activities were conducted, including the following:

- Presentations given at the DV School design charette, ASHRAE meeting, CASH conference and CASH representatives, American Council for an Energy Efficient Economy (ACEEE) 2004 and 2006 Summer Study
- Article published in *Engineered Systems* magazine (April 2006)
- Training sessions held at SMUD and CTAC

Again, the work under this task was completed in parallel with the Program Market Connection (Project 4) activities. More detailed information about information dissemination may be found in the Program Market Connection section of this report.

The research team will continue to promote the results of this project and provide market and technical information upon request.

2.5. Conclusions and Recommendations

2.5.1. Conclusions

- The demonstration classrooms confirmed that DV provides good thermal comfort for classrooms with normal ceiling heights (9 ft).

The DV system did not create problems with cold drafts at floor level. The system provides a consistent thermal stratification in the space and good ventilation effectiveness. The effects of occupant activity and the opening of doors and windows did limit the amount of (desirable) stratification achieved in practice.

- The DV system provides a remarkable improvement in acoustics.
- A supply of 1100 cfm of 65°F air is sufficient for most classrooms in California climates. Both the CFD simulation results and monitored data show that design cooling conditions can be met by a DV system without increases in system cooling capacity or

airflow. While simulation studies indicate that up to 20% more supply air is needed with DV, a system supply-air flow rate of 1100 cfm is less than what is typically supplied to California classrooms in actual practice.

- The use of a tuned VAV control strategy will optimize energy savings.

The expected energy savings potential for this demonstration were not realized during the initial phase of the project. Control setting modifications and tuning dramatically improved system performance. With VAV systems, in which air volume is the primary means of space temperature control, compressor operation is not directly tied to space temperature (and cooling requirements). Under such a VAV control strategy, tuning and verification are critical to ensuring system performance.

- DV can be achieved today using a variety of HVAC system designs.

Large, off-the-shelf HVAC units that have multiple cooling stages are compatible with current DV system design requirements. The principal design requirement is a steady supply of 65°F air. The customized HVAC unit used at Kinoshita Elementary proved to be effective in meeting the design requirements, and is unique in its ability to provide single-zone, VAV control for a single classroom. Further development of additional innovative HVAC design options for DV will most likely afford increased opportunities for energy savings.

- DV provides many compelling benefits.

DV has shown to provide effective ventilation and excellent thermal comfort for California classrooms. Acoustic benefits alone are a sufficiently compelling reason to use DV. Energy savings are significant, especially when the HVAC system includes variable-speed drive and VAV control for fan energy savings.

2.5.2. Commercialization potential

New product requirements have been identified as a result of the market barriers study, the DV design charette work on system design options, and preliminary results of the first demonstration classroom study. New technologies for capacity modulation may be applied to new products for DV. These products are described below.

- Packaged DX unit with improved discharge air temperature control and capacity modulation

The results of the design charette made clear the need for a new packaged DX rooftop unit, by far the most common HVAC system in use in California K-12 classrooms. This new product would be designed to provide the relatively constant 65°F supply air required for thermal DV, over a range of outdoor temperatures and part-load conditions. Existing packaged products of capacities of 5 tons or lower do not have the capacity to provide 65°F supply air under varying outdoor conditions and load conditions. Additionally, packaged rooftop units are typically constant-volume units. The product should have capacity modulation in both heating and cooling modes.

Variable capacity compressors have great potential to provide a much tighter supply-air temperature control and energy savings during part-load conditions. The Copeland Digital Scroll™ compressor has a capacity modulation down to 10%, and has been used

in air-conditioning systems in Korea. One possible product solution is to incorporate a variable-capacity scroll compressor in a gas-electric rooftop or a heat pump configuration. The prototype unit installed for the Kinoshita demonstration verified the potential for this product. The technology is a good match for displacement ventilation and offers benefits of improved space temperature control, improved humidity control, and high efficiency.

- Diffuser integrated with teaching wall

Another idea that arose from the design charrette is a diffuser that could be integrated into the casework. The diffusers could be integrated into the side of the teaching wall, or a long, linear slot diffuser could be positioned underneath the casework. Displacement diffuser manufacturers do not currently offer a diffuser that would work under a casement. Perhaps the cabinet base becomes 8 in or 10 in tall instead of the typical 6 in, providing space for low velocity air distribution. At the design charrette, participants commented on the desire for more architectural options for diffusers. As DV technology gains acceptance, more options should become available. A long, low diffuser has the advantage of delivering air directly to low heights, and it takes up less wall space that would otherwise be used by the teacher. Potentially, the casework and diffusers could be installed by the same contractor, with a mechanical contractor simply making the duct connections.

- Variable aperture displacement diffuser for heating

Low-velocity diffusers are well suited for cooling with DV. However, the air distribution is less effective in heating mode. Previous studies caution the use of low-velocity diffusers for heating. For California classrooms, perimeter heating is only required in mountain climates where the winter design dry-bulb is 10–15°F (-12 to -9°C) or less. Therefore, the diffusion performance of displacement diffusers in heating mode is an important design consideration.

In heating, the goal of the air delivery system is to achieve a thermally well-mixed airspace. The idea with this product is to vary the opening area of the diffuser in heating mode to increase the air velocity. Using low-velocity displacement diffusers for heating can cause short-circuiting of the supply air if the warmer supply air moves toward the return grille before it diffuses throughout the space. A higher air velocity will promote mixing when the diffuser is used for heating, thereby improving diffuser performance.

2.5.3. Recommendations

- Adopt load calculation procedure for Title 24 Standards.

To provide an accurate estimate of energy use of DV systems, the Title 24 Standards and Alternate Calculation Method (ACM) must be revised to include a procedure for modeling DV systems. A procedure has been recommended for modeling the stratification and predicting the supply-air flow requirements for DV systems. While this procedure would require an independent review, the model outputs are consistent with CFD simulation results and field data from this study. Additional monitored data from other DV installations would most likely strengthen the case for inclusion of the model.

- Incentives for high performance designs will help offset cost premiums.
While DV has the potential to be competitive with traditional systems, it does carry a slight cost premium because the HVAC designs for displacement ventilation require more sophisticated control strategies. Programs such as Southern California Gas and Electric's Savings By Design could offer incentives. However, load calculation and energy modeling procedures that can provide an accurate estimate of energy savings must be adopted.
- More demonstrations and education are needed.
Gaining acceptance for DV in California schools will require more examples of successful applications and a significant education campaign. The research from this project suggests that familiarity with DV is low among all professionals involved in the classroom design process. While many of the architects and engineers without DV experience were familiar with the theory of DV and its benefits, most had little working knowledge of it and questioned the specifics of how the system might be implemented. The education of engineers represents the crucial front line of acceptance. Architects, contractors, construction managers, maintenance personnel, and facilities managers also are looking for more than just information on material costs and specifications. They are looking for experiences and success stories of DV used in similar situations and climates.
- DV technology must become available as off-the-shelf equipment.
A significant desire and need exists for low-maintenance HVAC system options for California K-12 classrooms. Although other HVAC system designs can be readily designed to meet DV requirements, school districts strongly prefer to use packaged rooftop units for each classroom. The DV prototype unit developed for the Kinoshita demonstration is unique in its ability to meet requirements for DV in a packaged unit. A sustained educational outreach to market participants is recommended to further the development of packaged unit solutions for displacement ventilation.
- Improved design options are needed for heating with displacement diffusers.
It is well known that low-velocity displacement diffusers are not designed for heating. Although adequate comfort in the heating season was maintained in the two demonstration classrooms, the air distribution pattern was not ideal. The supply of very warm air at a very low velocity through displacement diffusers will cause some of the warm supply air to rise to the ceiling before it reaches the occupants. European manufacturers have addressed this concern by developing products that increase discharge air velocity to improve heating performance. The availability of these products in the United States market would make DV a more compelling solution in applications with greater heating needs.
- Additional design guidance is needed for other space types.
This PIER project showed that DV design is relatively straightforward for simple space types such as classrooms. DV has also been successfully used in libraries and gymnasiums. However, the design of DV for spaces with higher ceilings is not as simple. Many design professionals recommend the use of CFD analysis when using DV for these space types. While CFD is a good design tool, it will increase project soft costs and

could be a deterrent to the widespread application of DV. Additional research is needed to determine thermal stratification patterns and optimal diffuser layouts for school gymnasiums, libraries, and auditoriums without the use of time-consuming simulation studies.

- Additional IAQ research is needed.

This project focused on the air quality benefit of improved ventilation effectiveness. Some researchers have questioned whether or not the air patterns from DV would cause particles to be drawn upwards from carpet and into the breathing zone. Particle count studies were not feasible within the monitoring budget of this project. Additional field studies would clarify whether respirable particle counts are higher or lower in the breathing zone.

2.5.4. **Benefits to California**

The results of this project indicate that DV technology may reduce classroom cooling energy use 10–40% depending on the climate. Non-energy-cost benefits include improved ventilation effectiveness and improved acoustic quality, which are both compelling findings.

3.0 Effectiveness of UVC Technology for Improving School Performance (Project 3)

3.1. Introduction

This project quantified the impact of ultraviolet irradiation in the “C” band on evaporator coil disinfection and IEQ of California K-12 schools. The goal of the study was to determine if UVC is effective in reducing mold and mildew in HVAC systems, improving IEQ, and saving energy.

UV is a line-of-sight technology; when produced by a lamp it can only provide effective disinfection on components with direct or reflected exposure to ultraviolet irradiation. For this study, the project team, RLW Analytics, focused on surface disinfection systems that manufacturers claim kill mold and bacteria growing on cooling coil, drain pan, and other surfaces in the supply-air stream. The UVC lamps in these systems are mounted in the HVAC system supply duct, usually right above the evaporator coil. Because microbial colonies act as insulating agents, removing the microbial buildup should result in increased air flow and energy efficiency of the HVAC unit. In addition, the removal of these microbes can improve the IEQ by eliminating the cause of potential contamination of the air passing by the dirty coils and drain pan.

In the past 12 years, some manufacturers have begun to produce UVC systems designed specifically for HVAC systems. Manufacturers have re-engineered their main line of UVC products to work in HVAC systems because the non-HVAC-specific lamps suffered drastic output losses, specifically a loss in “killing power” when exposed to cold or moving air. According to some manufacturers, not all of the products on the market have these adjustments.

Since the application of UVC disinfection technology in HVAC systems is relatively new, there are currently no codes or performance standards for the industry, making product comparisons difficult. The International Ultraviolet Association is currently working to establish performance standards. ASHRAE is forming a standards committee to address this issue as well. Output levels at specific temperatures and safety features for each disinfection system should be tested by an independent laboratory and clearly stated in the marketing material to allow for comparisons between products. Equally important is the total application of UVC lamps within the geometry of the system. The number of lamps and the spacing between rows of lamps is critical to the actual distribution of UVC energy over a given surface.

The UVC disinfection system consists of an assembly whose primary components serve similar functions to those of a standard fluorescent fixture. This includes the UVC lamp, lamp socket, ballast, associated wiring, and enclosure. Mercury vapor is the gas used in the lamps, which produces UVC irradiation. Inert gases are used to illuminate the lamps. UVC bulbs are made of quartz or soda barium glass, which transmits UVC, rather than common “soft” glass, used in fluorescent lamps, which largely absorbs UVC. The mounting arrangements vary depending on the configuration and physical constraints of the equipment upon which it is installed, and have been designed with flexibility in mind in order to be adaptable to a variety of field conditions. The enclosures, ballasts, and related components can be installed internally in or externally on the equipment that it serves. Some examples of typical UVC disinfection systems are pictured in Figure 6.



Figure 6. Example UVC disinfection systems

Within the HVAC industry, UVC technology is applied to packaged, unitary, and built-up (site constructed) air-conditioning equipment, on both direct-expansion and chilled-water cooling systems. The irradiation process can be applied to the cooling coil, condensate pan, AC unit internal surfaces, and air distribution systems.

As mentioned previously, this study investigated the use of UVC to provide surface disinfection of the cooling coil and condensate drain pan. The reduction in buildup on the coils could result in an increased system capacity by increasing air flow across the coils and improving coil-to-air heat transfer, resulting in energy savings due to the resulting increase in efficiency. A recent study showed that the reduced air flows that result from coil fouling cause typical efficiency and capacity degradations of less than 5%. However, the losses can be much greater for marginal systems or in extreme conditions. (Seigel) The disinfection systems also may reduce fungal-related odors and alleviate air quality concerns in the indoor environment, and also reduce the need for costly chemical or pressure washing treatments of the cooling coil.

3.2. Project Objectives

The primary purposes of the study were as follows:

- Understand whether or not UVC surface disinfection systems reduce the energy consumption of AC units and, if so, to quantify the reduction
- Quantify any changes in average daily attendance (ADA) as a result of the decrease in the microbial levels after the UVC disinfection systems are installed
- Understand whether or not UVC surface disinfection systems reduce the microbial growth on air-conditioning (AC) cooling coil surfaces and, if so, to quantify the amount, which might be used to explain improvements in IEQ and, potentially, ADA

3.3. Project Approach

This study was originally funded as a purely analytical study that would quantify the benefits of the UVC disinfection systems using existing data. Through the course of the project, several factors changed the direction of the project from an analytical model to a field study. The team originally planned to work with a single manufacturer to identify the existing UVC systems in California K-12 schools and to obtain utility billing and attendance data from these schools in order to determine if there were any significant decreases in kWh usage and increases in ADA when comparing the pre- and post-UVC periods. As a result of some initial research into the

number of installed systems in California K-12 schools, it was determined that there were not sufficient numbers of systems installed in classrooms where students were in the rooms for the majority of the school day, providing inadequate data to complete the ADA analysis.

The researchers recommended that a comparative field study be performed in place of the analytical study in order to provide some research into the field effectiveness of the UVC disinfection systems. With concurrence from the PAC members and the Energy Commission, the research team reassessed the study budget and goals and transformed the project into a field study. While the field study was designed to provide exploratory research into measuring UVC efficiency and ADA changes, the budget was not sufficient to provide the large sample sizes, comprehensive testing, and customized instrumentation needed to provide more robust and definitive results.

At the outset of this project, the research team spoke with 12 manufacturers of UVC disinfection systems for HVAC systems to discuss current UVC products and technologies, market barriers, product availability, customer demand, markets served, and available research.

Two manufacturers of UVC disinfection systems were included in this study. Both manufacturers produce surface- and air-treatment disinfection systems. The two manufacturers donated equipment, technical support, and installation services to the study. The research team is appreciative of their generosity and support. This study was designed to be a technology, rather than a product, assessment. Therefore, no manufacturer names are disclosed. The disinfection systems are analyzed separately in this report and will be referred to as system, treatment, or group 'A' and 'B' in subsequent sections.

The disinfection systems were installed downstream of and adjacent to the cooling coil and provided irradiation to both surfaces, except for a few units in which the systems were installed upstream due to downstream internal space limitations. This approach is widely employed by installers because on small air conditioning units just one or two lamps provide effective coverage of the surfaces that are most likely to have microbial growth

The UVC technology was applied to both packaged rooftop and wall-mounted AC units. Rooftop units are the most common type of air conditioning units for conventional permanent school buildings. The wall-mounted style is often referred to as a "Bard" (heat pump style) unit after the manufacturer that originally developed the configuration and currently dominates the market for California portable classroom HVAC units. These units are installed on an exterior wall of portable classrooms. Both types of cooling systems, rooftop and wall-mounted, employ conventional direct expansion/refrigerant vapor compression systems with a direct expansion coil providing the cooling in the air stream. All UVC disinfection systems provided in this study were standard production units. The UVC systems that were chosen for this study can be generally characterized as shown in Table 3. Figure 7 shows example installations.

Table 3. UVC systems studied

Units	Treatment A	Treatment B
One Lamp Units	30 Watts	36 Watts
Two Lamp Units	30 and 20 Watts	21 Watts

The two lamp fixtures were typically used in units with space constraints. The smaller wattage lamps were typically used for drain pan irradiation.

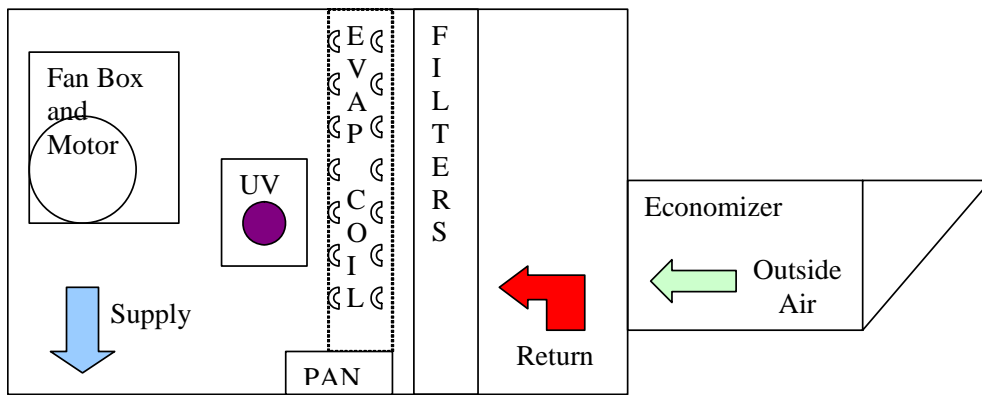


Figure 7. Example of a rooftop air conditioning unit in UVC study (top), schematic of a typical unit (middle), and example of a wall-mounted air conditioning unit in UVC study (bottom)

The most common installation approach was to mount the UVC ballast and wiring externally on the casing of the cooling equipment with only the lamp or tube penetrating into the system while the power supply remains external. All disinfection systems used in this study were rated for outside installations and, with one exception, were mounted on either the side or the top of the AC units. The UVC disinfection systems can be wired either so that they are in operation continuously or only when the AC is on. The UVC disinfection systems in this study were powered on continuously, so they were in operation regardless of a call for cooling.

The team investigated the study goals by performing a side-by-side comparison of two treatment groups receiving UVC disinfection systems to a control group receiving no UVC treatment. Measurements were taken before and after turning on the UVC disinfection systems in order to compare changes in AC efficiency, microbial contamination, and ADA between the treatment and control groups. The study period commenced in August 2005 and lasted approximately six weeks.

A total of 54 AC units at nine schools within three school districts across California were included in the study. Of the 54 AC units, 36 received UVC treatments. A total of 18 AC units were included in each of the three study groups, one control group, and treatment groups A and B. Identical AC units serving similar grade-level classrooms comprised each of the three study groups. Both packaged rooftop and wall-mount-type units were included in the study. The study goal was to determine the impact of DV technology on typical AC systems in California schools; therefore, the study did not specifically target fouled coils. However, the team did exclude units that were less than four years old to ensure that newer coils were not in the study.

The three districts that were included in the study were located in cooling climates and had year-round school schedules. Districts with year-round schedules were targeted in order to ensure that the units in the study were running throughout the summer with the exception of two-to three-week breaks between sessions. The level of coil fouling was approximately that expected during a normal cooling season. Elementary grade levels were selected to ensure that students were in the same classrooms all day for full school days to enable adequate pre- and post-ADA analysis.

3.4. Primary Data Collection

The research team performed a variety of primary data collection tasks consisting of survey, microbial, and engineering information. There were five primary sources for data gathered and analyzed for this study, which are categorized and described as follows:

3.4.1. Manufacturer Interviews and Literature Review

The research team began the study by contacting the major manufacturers across the country in order to better understand current UVC disinfection products and technologies, market barriers, product availability, customer demand, markets served, and existing research. This background research was used to inform the selection of the surface disinfection technology to be included in the study, and to provide background information about the technology.

3.4.2. Microbial data

The research team collected microbial samples from the surface of cooling coils prior to and after the installation of the UVC disinfection systems. A single swab sample was taken from the cooling coil fin edge and fin face from each AC unit over one square inch using an absorption spear. The on-site team followed the sample handling techniques as directed by the microbiology lab that performed the testing. These surface samples were analyzed for culturable fungi and bacteria. The laboratory provided the research team with estimates of the number of colony-forming units (CFUs) per area sampled per coil. These lab results were used to analyze the reduction in CFUs on treated units relative to the control group units. This analysis was performed in order to determine improvements in IEQ and, potentially, ADA.

3.4.3. Engineering data

The research team collected data to support the evaluation of in-situ air conditioner efficiency. The team first qualified each unit to ensure that the units were in proper working order by measuring operating pressures and temperatures and determining diagnosis-level refrigerant charge, air flow, coil condition, and the state of various other malfunction indicators. Incorrect condenser fan speed, or incorrect evaporator fan speed, and were excluded from the study. The selected units were then subjected to extensive measurements to evaluate system efficiency. Careful measurements were taken using high-quality calibrated instruments during steady-state operation of the system in order to evaluate the field-operating efficiency and capacity of the systems. These measurements quantified pressure drop across the evaporator coil, cooling capacity, and efficiency readings. On/off event motor loggers were installed for the duration of the study period in order to quantify run-time of the units in cooling mode (fan plus compressor). At the end of the study, field staff returned to retest the operating efficiency and capacity of the units. The units underwent the same set of measurements as were taken during the first visit. The resulting data were used to quantify UVC-related impacts on energy efficiency.

3.4.4. Teacher and Classroom Surveys

To supplement the analysis of the changes in biological contamination on the cooling coil, other field observations were collected that are typically used in the assessment of indoor air quality. The observations account for the condition of the area or building in question. The teachers in the studied classrooms were also surveyed during the pre-installation site visits. They provided information to the research team about the thermostat controls, the ventilation in the rooms, and any other IEQ observations. Fifteen of the teachers participated in a follow-up survey to determine what, if any, changes they noticed as a result of the UVC disinfection systems.

3.4.5. Attendance Data

Average daily attendance data were collected from each school district for each classroom in the study. Attention was paid to ensure that the same students were in the classrooms during the study period. The study period began approximately three weeks after the beginning of the school year. Any changes in ADA were analyzed and summarized.

3.5. Project Outcomes

A summary of the UVC project outcomes follows. Key information products developed for this project are listed in the Attachments section of this report and may be found at www.archenergy.com/ieq-k12/uvc_technology/uvc_technology.htm.

- Microbial analysis showed the reduction of growth on the evaporator coils, as expected. Microbial samples were taken from the surface of the cooling coils for each of the units prior to and after the installation of the UVC disinfection systems. The samples were taken on the leading coil fin edge and fin face using sterile swabs. Each sample was sent to a microbiology lab for quantitative fungal and bacterial testing. The results of the microbial analysis indicate that the two treatments *notably* reduce levels of microbial growth on the evaporator coils. Total fungal and gram-positive bacteria reductions were 65–100% of colony forming units.
- Air flow and efficiency analyses showed a positive trend. The UVC impact on system air flow, though not statistically significant for this study, produced a positive trend, 1–2% improvement. This suggests that further laboratory tests or field tests over a longer period may produce more statistically significant results. There were no statistically significant impacts on efficiency and no distinguishable trend such as the trend identified in the air flow analysis other than a mild positive trend as noted. In future research, true energy impacts must be studied in terms of a systems air flow and efficiency degradation over time and the impact of disinfection systems on preventing this decline. As previously mentioned, one study showed that air flow restrictions that result from coil fouling can cause typical efficiency and capacity degradations of less than 5%; however, the degradations can be much greater for marginally functional systems or extreme conditions. Fouled coils were not targeted for inclusion in this study and were in fact systematically excluded from this study, and the on-site team did not observe much fouling of the coils; therefore, it is not surprising that air flow and efficiency impacts were inconclusive.
- Attendance data results were inconclusive. Average daily attendance data were collected from each school district for each classroom in the study. Attention was paid to ensure that the same students were in the classrooms during the study period. The study period began approximately three weeks after the beginning of the school year. After analyzing data, researcher did not find a strong correlation between the reduction of microbial growth and student attendance. More attendance data is needed along with a larger sample size of UVC field tests in order to draw conclusions that are more scientific.
- Teacher and classroom surveys indicated positive feedback for some issues. In the survey, 13 of the 15 teachers stated that the room did cool more quickly. One teacher stated, “It feels like the air cools quicker; in a matter of seconds it gets cold in here.” In addition, 13 respondents (87%) said that the room seemed to be less stuffy.
- Concerning attendance, the responses were not as clear. When asked, 47% of respondents said attendance had improved; 33% said it had not improved; and 20% said they did not know if there was a change. None of the teachers were able to confirm a correlation between the units and attendance. In fact, many teachers had new groups of students by the time the post-installation surveys were administered, which made it difficult to see changes in student health. Teachers in one district said they were in the middle of a “district-wide push on attendance.” However,

in comparing the responses from teachers in the UVC group to those in the control group, researchers found that the teachers in UVC-treated rooms reported an improvement in attendance (5 out of 7) while those in the control group stated that their attendance had not improved (4 out of 6).

Sixty percent of the teachers asked about the prevalence of air quality issues stated that there were fewer air-quality-related illnesses than before the study period began. One teacher made the statement “Students who have air quality related illnesses seem to be less affected by them,” while another said “There are fewer kids with asthma than in last year’s class.” Twenty-seven percent of teachers said that there was no improvement. Thirteen percent of the teachers said they could not tell any difference in the amount or severity of air-quality illness. When asked if illnesses had decreased, there was an even split of yes and no responses. Seven teachers said yes, seven said no, and one responded don’t know. The majority of the *yes* responses came from UVC teachers, while only one teacher in the control group noted a decrease in illness. The majority of the control group teachers did not find a decrease in illnesses.

The responses to questions about using the AC less and opening doors and windows more often than in the two months prior to the study period were split: 7 yes, 7 no, and 1 don’t know. The responses were evenly split among UVC and control groups. Four of the teachers commented that it was district policy to keep doors and windows closed, possibly to conserve energy. None of the teachers reported any new staining or mold growth. One teacher stated she had smelled moldy smells in the past but that they were gone now. She was in the UVC test group, but the information can only be treated as anecdotal due to the small sample size.

- Some of the HVAC housings created challenges for proper installation.
The effectiveness of UVC can be limited by the AC unit configurations. In pursuit of economy, rooftop and wall-mounted units employ very compact designs. It is common to find the evaporator fan housing within 2 in of the cooling coil on one side and the same distance for the air filter on the other side. For example, fan housings may obscure access to coils. These types of configurations result in less-than-ideal lamp locations. The greatest irradiation area per lamp is afforded when the lamps are installed perpendicular to the coil fins. In some instances for this study, the technicians were forced to install the lamps parallel to the coil fins, a less advantageous position for irradiation. The success of the technology is also dependent on the quality of the installation. Installers often rely on their own judgment to compensate for challenges in the field. The field staff for this project made some observations of installations performed in space-constrained systems. For example, an inspection of one installation shows that the lamp was installed with the intention of irradiating the condensate pan; however, it was placed on the upstream side of the coil on the opposite side of the pan due to space constraints. In another instance, the lamp lens was in contact with the fan housing, which may contribute to premature lamp failure. Review of installers’ approaches and inspection of their work are useful in assuring quality installation.
- Environmental issues were found.

The research team made a number of environmental observations at the schools while performing engineering measurements. These observations indicate that there are additional areas where attention could be paid to potential sources of IEQ problems and energy-saving opportunities in California K-12 schools such as dirty rooftop surfaces, standing water near classroom and outdoor air intake areas, cleaning supplies in classrooms, and lack of door mats at the entry to each classroom that may contribute to the level of contaminants transferred to interior floors.

3.6. Conclusions and Recommendations

3.6.1. Conclusions

- The research team could not conclusively determine if there were any improvements in air flow or efficiency of the air conditioning units with UVC disinfection systems.

With the small sample size, large error bounds, and study limitations discussed earlier, the analysis did not determine with statistical significance that the technology significantly affected airflow or efficiency. The trend for the six-week study was a small increase in air flow in units with either of the two manufacturers' disinfection systems and inconclusive impacts on efficiency. True energy impacts must be studied not only as an improvement in efficiency or air flow, but in terms of the degradation of a system's air flow and efficiency over time and the disinfection system's impact on slowing the decline of unit performance. Coils that are fouled may be the best application for this technology, in order to produce greater energy savings through coil disinfection.

- The microbial sampling, which was undertaken primarily to explain the results from the energy analysis and the ADA analysis, did provide notable findings.

The study did find that the UVC technology is effective in reducing surface microbial levels on cooling coils. The research team did not find high concentrations of fungi or bacteria on the cooling coils in the study. This could be due to the fact that California's climate is relatively dry compared to the rest of the country, which equates to a smaller latent load. Since microbial activity is correlated with the amount of moisture present, the more humid the climate, the more applicable this technology. Additionally, this technology is probably more applicable in regions with high annual cooling hours or in more inland climate zones where the potential for mold growth may be greater.

- This study concludes that UVC technology is effective in reducing microbial growth on air conditioning cooling coils.

However, the impact of this technology on IEQ in California schools would be directly proportional to the pervasiveness of microbial growth on cooling coils and the relationship between surface microbial growth and IEQ. The presence and magnitude of microbial activity on the population of existing classroom cooling coils is uncharacterized at present. The UVC technology may be best suited for application in AC units in classrooms with pre-existing or substantial microbial growth, or classrooms with IEQ problems.

- The success of the technology is dependent on the quality of the installation.

Installers often rely on their own judgment to compensate for challenges in the field. Review of installers' approaches and inspection of their work are useful in assuring quality installation.

3.6.2. **Commercialization Potential**

Customers purchase the UVC disinfection systems to improve indoor air quality. The manufacturers contacted at the beginning of this study agree that very few buildings in the country have UVC disinfection systems installed in their HVAC systems. Most thought the percentage of buildings with UVC was below 5%, with more installations occurring in the South and on the East Coast since these regions are characterized by longer cooling seasons and high humidity. Most installations currently occur in retrofit applications when the end users have reacted to mold and moisture problems.

A fundamental barrier to the adoption of UVC for AC systems is that potentially interested people are not aware of the benefits of the technology. Many have misconceptions that UVC technology will produce ozone or will damage eyesight. More information needs to be disseminated that states the benefits of the technology in simple terms that are easy for people to understand. Consumers need to be shown the cost payback of the technology in terms of lessened chemical cleaning costs and possible energy savings. Once the information barrier is overcome, the sale is relatively easy.

Many manufacturers claim that the lamps have low penetrating ability and that UVC light is nearly completely absorbed by the outer, dead layer of skin. They say that the light can reach the most superficial layer of the eye, if exposed, where overexposure can cause reddening and painful but temporary irritation, but claim it cannot penetrate to the lens of the eye and cannot cause cataracts. Regardless of the effects, the UVC disinfection systems that were included in this study were all safely enclosed within the HVAC systems and were not in direct view of humans. As a further safety option, door safety interlocks can be wired into the circuitry of AC units, preventing accidental exposure to UVC light by interrupting power to the UVC lamp when specific access doors and or panels are opened.

It is important for any individual who installs and maintains these systems to be completely familiar with any hazards posed, and potential damage that can be caused by, UVC radiation. In addition to human safety, there are other issues that could potentially arise from the equipment components and wiring being directly exposed to UVC radiation. There is no clear consensus on whether such items as unit wiring, air filter materials, and fan drive belts are subject to deterioration due to UVC exposure. Originally, Underwriters Laboratory (UL) required that lamp wiring be shielded with metal, but they have since removed that requirement.

Until there are federal standards for the industry that address this issue, the end user should carefully read and understand the manufacturer's installation and safety data prior to selection, installation, and maintenance of these disinfection systems. In many instances, manufacturers can provide information on and references for local contractors familiar with the technology. It was the research team's experience that the technical support from each manufacturer was invaluable in the proper and safe application of the UVC disinfection systems. For market commercialization, manufacturers must continue to address these issues and provide customer support.

3.6.3. Recommendations

The primary recommendation is to increase sample sizes and allow for repetition of sampling within the study. Throughout this PIER project, researchers have documented the limitations in terms of the numbers of AC units in the study, the number of microbial samples taken, the engineering data that were logged, etc. The limitations can be overcome with additional funding (estimated by researchers to be in the \$2 million range). This funding would allow a research team to develop a comprehensive study methodology that allows for primary data collection in order to directly answer all possible research questions. Both laboratory and field work are required to answer these research questions.

Some of the outstanding research questions and study opportunities are as follows:

- What is the irradiation efficacy and microbial disinfection effectiveness near to and distant from UVC lamps?

An important factor to study is the irradiation efficacy directly under, and at specified distances from, the UVC lamp. A number of research studies have been written that describe output measurement procedures and some suggest required documentation of the process (Sagges and Robinson 2005). A common metric measurement such as microwatts per square centimeter, at specified distances, should be addressed by a standard. This would also assist the standards committee in setting regulations as to how much distance can be placed between the lamps when installed to provide sufficiently effective irradiation. To test the overall efficacy factor, microbial samples would have to be taken at prespecified distances from the lamp, with ideally at least five samples being taken at each distance on each coil.

- Does the UVC irradiation cause deterioration of non-metal HVAC equipment?

There is no clear consensus on whether or not such items as unit wiring, air filter materials, packaged unit case insulation, and fan drive belts are subject to deterioration due to UVC exposure. Originally, Underwriters Laboratory required that system wiring be shielded with metal, but they have since removed that requirement. Teflon, used to shield outdoor wiring, is resistant to all bandwidths of UV and so is a possible defense for wiring exposed to UVC. An independent laboratory needs to perform tests to determine what type of materials and parts should be shielded and with what material. A standard should be established to address this issue.

- Are the UVC disinfection systems designed to work properly in the cooling environment?

According to some manufacturers, not all of the UVC for HVAC products on the market have been adjusted properly to work inside the units. At such low temperatures, the lamps may not be performing optimally once installed in the HVAC systems since some lamps are tested at room temperature. Laboratory testing under HVAC conditions of all of the products being offered on the market is needed to confirm or disprove this assertion. Laboratory testing is also needed to test output in general. As mentioned above, a number of research studies have been written that describe output measurement procedures and some suggested required documentation of the process.

- What would the recommended repetition of cooling-coil surface sample quantities and locations reveal?

The microbial reduction findings would be optimized with a robust sampling plan. When looking at any particular cooling coil, the degree of microbial growth varies from spot to spot. If one were to inspect multiple locations on a coil, some areas would have more colonies, others fewer. In order to characterize the entire coil, additional sampling points for each coil are necessary to calculate an average level of contamination for each coil. It is now recommended that a minimum of five samples be taken per coil (i.e., five repetitions per sample). It is also logical to ask the upstream and downstream sides of the coil experienced different microbial growth. For instance, the coil fin edge on the upstream side would see impingement of debris and airborne spores, whereas the downstream side would see a greater accumulation of condensate. To gain a comprehensive picture of microbial activity on cooling coils, it would be best to collect up to 10 samples on both the upstream and downstream sides of the cooling coil for culturable and non-culturable fungi and bacteria.

- Can UVC be used effectively as a preventative measure to inactivate destructive bio-agents?

UVC might be effectively used for cleaning building ventilation air in order to prevent contamination by chemical agents that would otherwise be used for this purpose. The Environmental Protection Agency (EPA) and the Research Triangle Institute are currently investigating this research question through the EPA's Technology Testing and Evaluation Program. This study is currently outlining the laboratory test parameters that could be used to develop standardized testing procedures for all products on the market.

- What is the probable UVC output degradation over time?

The UVC products currently on the market are rated for varying hours of useful life. In order to test the life of the products, a study should be performed over a 12-month period. This will allow for at least three testing intervals within the year. Those treatments that degrade over time will have less disinfection effectiveness at the end of the study. Such a study might also show a reduction in more resilient strands of mold in a longer test period. In addition, a school attendance analysis would be strengthened by having at least one year of pre- and post-data.

- What is the ability of UVC to penetrate into the cooling coil fins?

There are currently no thorough research studies on how long it takes UVC to penetrate into the coil fins. This is the subject of one proposed research project request being prepared by ASHRAE TG 2.UVAS. It is widely accepted that a one-to-two month study period will show high levels of microbial reduction on the irradiated surfaces. However, tests should be performed to determine the optimal length of time needed for the UVC irradiation to penetrate deep into the coil. UV levels can be quite low deep in the narrow spots between fins. As the fins clear, more UVC is able to get in and reflect deeper into the coil. A minimum depth to test would be a depth similar to that reached by the research team with the swab sampling technique.

- What might be the relative contribution of AC system, classroom, and outdoor contaminants to air in conditioned space?

Many sources contribute to the air quality characteristics in the HVAC system air stream. Some of the more significant factors are the seasonal and incidental conditions that affect the airborne count of mold spores, quantity of outdoor (ventilation) air being brought in to the conditioned space, seasonal weather conditions that affect the latent load on the system, AC unit air filter efficiency, air filter bypass conditions, and classroom contaminants. It is important to understand the source of contamination to determine the most appropriate mitigation method.

When trying to determine what types of microbial sampling to perform, the research team realized that a study is needed to quantify the correlation between surface fungal colonies and air stream spore counts. In addition, this study should quantify the relationship between outdoor contamination and seasonal weather conditions on indoor air quality in order to control for these effects using filtration or other methods. The season affects the amount of latent load on the AC. Latent load should be correlated with effects on system performance and the amount of fungal proliferation during different seasons. The presence of mold in the building structure, along with elevated levels of volatile organic compounds (VOCs), formaldehyde, and many other contaminants may compromise the indoor air quality. Supplies customarily provided for children's activities in classrooms (paints, markers, glues, paper, and clay) as well as the activities themselves (cutting, filing, scraping of wood) can also have an impact. In addition, classroom occupants, particularly students, introduce contaminants from their home environments and through exposure to other students and the outdoors at lunch and recess. Children living in less desirable environments may introduce agents outside the control of school districts and teachers. A study could address the effects of wiping off shoes on floor mats and of washing hands before entering the classroom, AC air stream testing for culturable bacteria, and other practices to detect and prevent contaminants from entering the classroom via its occupants.

- Detection in particular might entail the following considerations:

There are many potential locations for airborne microbial tests such as on air duct surfaces; in the AC air stream (upstream and downstream from the cooling coil); and elsewhere in the outdoor, return, and classroom air. To bring greater clarity to the influence of these many factors, desirable tests would include those for fungi and a spore trap analysis.

Microbiological testing of classroom air could use interval data for endotoxins, microbial antigenic proteins, culturable bacteria and fungi, volatile organic compounds, formaldehyde, carbon dioxide and monoxide, and other particulates.

- What is the quantifiable amount of outdoor air being supplied to classrooms and what are its true effects on indoor air quality?

It is a widely supported conjecture that there is an important relationship between the amount of ventilation air and the concentration of airborne contaminants, or measurable IEQ. Numerous studies imply that an increase in ventilation air supply into classrooms could affect and improve academic performance. The U.S. General Accounting Office in

1995 conducted a study that found that nearly one third of all schools surveyed reported unsatisfactory ventilation in the classrooms. That same survey indicated that nearly two thirds of the U.S. student population receives its education in buildings that, due to deterioration of the facility, warrant major repairs or renovations.

Additionally, there is energy savings potential when utilizing outdoor air for space cooling needs, referred to as the economizer cycle. Minimum or enhanced levels of ventilation air can also be introduced independent of the heating or cooling modes in an HVAC system. Special attention should be placed on portable classrooms, where units may not be providing outside air when not in cooling mode, and also heating mode. Particular focus and analysis of the effects of insufficient versus minimum or enhanced levels of ventilation air would be fortuitous.

- What are the best sampling techniques to determine UVC-related impacts?

A six-month planning period would enable the research team to determine the most appropriate sampling techniques and tools to use for surface and air samples. As mentioned previously, there is no broad consensus on appropriate air sampling techniques for this type of study. Therefore, thorough secondary research and in-depth discussions with a team made up of IAQ experts, researchers, and UVC disinfection system manufacturers must take place before any air sampling is attempted. To allow for comparison between air sampling results, a set of standard testing protocols could also be developed based on future research.

- Standardize labeling and testing procedures.

One critical factor that would assist with the widespread adoption of UVC disinfection systems for HVAC systems is the development of standardized labeling and testing procedures for the products on the market. Currently, there are no such standards; each manufacturer uses its own discretion on selecting the type of information offered on marketing material. There are no standardized industry tests for the products offered, allowing too much room for products that do not provide the disinfection that higher quality products do. Consumers currently rely on manufacturers to provide reliable information about their products. It would be a great improvement if the information came from a standardized laboratory facility that could verify the manufacturers' claims and allow for comparisons between suppliers, eliminating uncertainty for the consumer.

UVC technology can and will contribute more to IEQ in California schools by reducing microbial growth on cooling coils. However, while awaiting the future widespread deployment of UVC technology, much can be done in the way of proper maintenance now to ensure better IEQ with existing equipment, including the following:

- Increase air filter efficiency: The use of air filters that have a minimum efficiency reporting value (MERV) rating of 8 or greater would provide a significant improvement in the prevention of the passage of airborne allergens including pollen, mold spores, and coarser particulate matter. Numerous manufacturers have available filters in the typical 1-in and 2-in depths.
- Increase air filter replacement frequency: Appropriate change-out frequency will prevent excessive dirt loading of air filters and the resulting degradation of air flow and

performance. It is apparent that increased frequency of replacement would benefit numerous units.

- Check for air filter bypass: Filter bypass is due primarily to poor construction of the filter rack assembly, which allows wide tolerances between the filter and its mating surface. This, along with substandard installation of replacement filters, results in appreciable debris buildup on the evaporator coil and therefore a decrease in air flow and AC unit efficiency. Correcting bypass conditions through appropriate alterations to filter racks, as well as stipulating better filter replacement methods, would produce beneficial results to AC performance and IEQ.
- Verify/increase ventilation air: This involves the retrofitting to code of existing outdoor air dampers, controls, and associated components to achieve the minimum requirements for ventilation air as noted in the California Energy Code and ASHRAE standard 62.
- Improve areas near air intakes: Areas near packaged HVAC units where outside air supplies are drawn are often overlooked in routine maintenance. These area within the classroom and outdoor activity areas commonly receive little attention from school district maintenance crews. To improve IEQ, condensation, rainwater, and other liquids should drain away from the air intake side of a unit. Routine cleaning crews should report visibly poor conditions to maintenance, and roofs should be regularly inspected for evidence of mold, mildew, standing water, etc.
- Mitigate contaminants introduced by occupants: Many contaminants could be reduced by the introduction of door mats and hand washing.
- Encourage use of door mats: Many indoor contaminants and particulates are transported from outdoors via shoes. Dirt, mold, plant matter, pesticides, and lead are routinely brought into the classroom on the soles of shoes. Track-off mats are essentially long door mats and provide a very effective and passive means of extracting debris from shoes. Use of the mats at the exterior entry to each classroom or classroom building would be beneficial.
- Encourage hand washing: Many contaminants introduced into the classroom by students and teachers are transported via their hands. Interaction with other students, the outdoors, and home environments could lead to the introduction of microbial species into the classroom. The use of this strategy, hand washing, along with track-off mats limits potential sources of IEQ problems to those under the control of school districts.
- Clean coils: Some of the evaporator coils had slight-to-heavy accumulations of particulate debris. In many instances, a one-time vacuuming or washing of evaporator and condenser coils effected a notable improvement in performance.
- Test and adjust refrigerant charge: It is common to find AC units that are under- or over-charged with refrigerant. Correcting this condition often brings about a notable reduction in energy costs and premature equipment failure and improves performance.
- Retire the oldest units: It is common for units to remain in service well beyond typical replacement time limits, especially in monetarily constrained school districts. The new Department of Energy Air Conditioning Standard (Department of Energy) sets the minimum efficiency of small units (<5.5 ton cooling capacity) to seasonal energy

efficiency ratio (SEER) 13, and prices should drop as these become base models for manufacturers. Replacing units more than 20 years old with these new SEER 13-certified units could result in significant energy savings, and falling prices would yield shorter payback periods.

- Reduce diesel exhaust emissions: Diesel exhaust is a prevalent source of air pollution at many school sites and is often produced by school buses and traffic on major nearby roadways. When inspecting used air filters at several different school sites, there was evidence of this problem. The presence of black particulate matter on the filters indicates pollution from combustion engines and other equipment. Implementing a program to reduce diesel exhaust emissions can have a positive impact on air quality and the incidence of asthma and other respiratory issues. Similar pollution sources in the school's proximity, such as airports and manufacturing facilities, should be mitigated to ensure optimal IEQ.
- Clean cool roofs: White, cool roofs are meant to reflect solar radiation from roof surfaces, thereby reducing heat transfer during the warmer months. The research team observed many cool roofs that had a buildup of dirt and debris, resulting in a darker roof and thereby reducing reflection benefits.

3.6.4. Benefits to California

The UVC impact on system air flow, though not statistically significant for this study, produced a positive trend, a 1–2% improvement. This suggests that further laboratory or field tests over a longer time period may produce statistically significant results. Statewide energy impacts from this technology could not be ascertained due to the small sample size and inconclusive results.

This study concludes that the UVC technology is effective in reducing microbial growth on air conditioning cooling coils. However, the impact of this technology on IEQ in California schools would be proportional to the pervasiveness of microbial growth on cooling coils and the relationship between surface microbial growth and IEQ. The presence and magnitude of microbial activity on the population of existing classroom cooling coils is uncharacterized at present. The UVC technology may be best suited for application in AC units in classrooms with pre-existing microbial growth or IAQ problems.

4.0 Program Market Connection (Project 4)

4.1. Introduction

The market connection project was concerned with disseminating the results of two technology projects designed to improve energy use and indoor air quality in K-12 schools in California. One of the technology projects examined the use of DV for delivering fresh air more effectively to students and teachers; the other tested UVC for cleaning air-handling units and improving their cooling performance.

The goal of this project was to improve the market focus of the program's activities, thereby increasing the ultimate viability and public benefits of the technology products resulting from the program. Specifically, the market connections effort was intended to result in the production of a number of information products designed to overcome market barriers, influence market participants, and produce desired market effects.

4.2. Project Objectives

The objectives of this project follow:

- Involve influential market participants at all stages of program planning and execution to make sure that the design, conduct, and documentation of the program achieves results with maximum market penetration and benefits. This level of involvement ensures that the needs of influential market participants are met.
- Draw on the expertise of the PAC market participants and other important players, as well as use existing information channels, meetings, and publications, to ensure that information about the project's technology enhancements is disseminated to those who can influence school facility construction and operations.
- Provide specific expert guidance to the program, and project participants as well as technology developers on technology transfer approaches, formats, and content requirements needed to meet infrastructure and design specifier needs in order to maximize market success.
- Disseminate consistent and appropriate information in effective forms of communication to relevant market actors and consumers to enable understanding and further acceptance of all program products. These materials should be designed to convince those concerned that the new technologies work; that the risks of adopting these technologies are minimal; and that the corresponding energy and cost savings, along with environmental benefits, are considerable.
- Understand the basis for codes and standards that affect the adoption of the proposed technology enhancements, identify individuals who could influence the acceptance of desired changes in codes and standards, and identify the results needed to affect the changes.

4.3. Project Approach

The project was executed by completing key activities and creating products within four main task areas: Project Administration, Program Wide Market Connection System, Program Technology Transfer, and Indoor Air Quality Codes Assessment. Key aspects of these main tasks are summarized below.

4.3.1. Project Administration

The objective of this task was to verify that satisfactory progress was made toward achieving the market connections objectives of this program. This task provided the format for continuous updates between IEQ team members and involvement with the PAC members. The task consisted of these elements: a program kick-off meeting, bi-weekly phone calls, monthly progress reports, Program Advisory Committee meetings, and a Project Final Report.

4.3.2. Program-Wide Market Connection System

The objectives of this task were to develop a plan to identify market barriers impeding the market penetration of DV and UVC technologies in California schools and to determine what actions and products are needed to overcome those barriers. This task consisted of preparing a Technology Transfer Plan.

4.3.3. Program Technology Transfer Plan

The objective of this task was to execute the Technology Transfer Plan by developing and delivering the products needed to maximize the benefits of this PIER research and the appropriate use of DV and UVC technologies in K-12 schools in California. The following products were developed as part of this task:

- Promotional fact sheets and brochures
- Articles in trade publications and engineering journals
- Presentations and forums for DV and UVC
- CHPS training session information and materials for incorporation into CHPS Best Practices Manual
- EdSpec Models for DV and UVC applications
- Communication conduits for disseminating information
- Applications guides for off-the-shelf DV and UVC equipment for schools

4.3.4. Indoor Air Quality Codes Assessments

The objective of this task was to identify codes and standards that might need to be modified to facilitate adoption of project results, define information needs that must be supplied to affect changes to applicable codes and standards, and present that information in a format that can be used by codes and standards- and guideline-setting bodies.

4.4. Project Outcomes

A summary of the project outcomes follows. Key information products developed for the market connection project are listed in the Attachments section of this report and may be found at www.archenergy.com/ieq-k12/market_connection/market_connection_reports.htm.

- Input was solicited and gained from influential market participants and the PAC. Influential market participants were involved at all stages of the IEQ Program planning and execution to assure that the projects were designed, conducted and documented in a manner that achieved results that maximized market penetration and benefits. This also assured that the needs of these influential market participants were met through their involvement and that their influence was utilized.

Four meetings were conducted with the PAC participants during the program. Input was gained and integrated into the projects. A highlight of the meetings was a walk-through tour of the DV technology installations at Coyote Ridge Elementary School in Roseville, California, and Kinoshita Elementary School in San Juan Capistrano, California.

- A Technology Transfer Plan was prepared and expert guidance was provided.

A detailed Technology Transfer Plan was prepared with the objective of overcoming market barriers affecting market participants involved in specification, financing, installation, operation, maintenance, and use of DV and UVC technologies in K-12 schools in California (Blatt 2004).

Specific expert guidance was provided on the approaches, format, and content requirements needed to meet infrastructure and specifier needs to maximize market success. This information consisted of cost assessments and benchmarks for the two technologies, technical assessments of coil fouling, and an assessment of the potential benefits of UVC for coil cleaning. Market connection and market potential information from a manufacturer's point of view was gained in the course of influencing a participating HVAC manufacturer to provide a single-package, direct-expansion HVAC unit that met the needs of the DV project. In addition, influential parties suggested obtaining additional cooling test data for the Capistrano classroom demonstration in order to provide a more compelling case for code changes.

- Key organizations were identified.

Organizations providing outreach and technology information dissemination for specific market participants as well as organizations dealing with schools were identified and tabulated according to their missions, key publications and periodicals, and key meetings. The following list comprises these organizations as well as some of the products and meetings that served as information dissemination vehicles:

- Alliance to Save Energy: *Green Schools Update*, e-newsletter
- California's CASH: Annual conference in February
- *DesignShare*: The International Forum for Innovative Schools, e-newsletter
- Healthy Schools Network: Guidebooks
- Savings By Design: Case studies and design briefs as part of the Energy Design Resources Program; training sessions at utility energy centers
- Sustainable Buildings Industry Council: *High Performance Schools Buildings Resource and Strategy Guide*, workshops
- CHPS: Best practices manuals, training sessions
- United States Green Building Council: Standards for government buildings
- Whole Building Design: *Whole Building Design Guide*

- Fact sheets were developed.

Fact sheets were produced for both DV and UVC to address issues and market barriers impeding the acceptance of these technologies in California. The fact sheets were distributed at various presentations and conferences.

The DV fact sheet contained information on and answers to the following frequently asked questions:

- What are the system benefits?
- How does this technology fit in with Leadership in Energy and Environmental Design (LEED™), CHPS, and Savings By Design?
- How can the technology increase neighborhood property values?
- What are the building requirements?
- What is the applicability to retrofit situations and relocatables?
- What kinds of HVAC systems can be used?
- What are the best ways to handle heating, humidity, field experience, and cost?

The UVC fact sheet provided information on and answers to the following frequently asked questions:

- What are the technology benefits?
- How does it fit into sustainable building practices?
- What are the types of systems available?
- What about sizing and operation?
- What are the safety issues?
- What has been the field experience so far?
- What is the probable cost?
- What are the variables affecting the cost-effectiveness of UVC technology for coil cleaning?

- Journal articles have been published.

Material from the fact sheets was supplemented with secondary research on field experience with the DV and UVC technologies to produce articles for *Engineered Systems*, a magazine focused on “practical applications for innovative HVACR mechanical systems engineers.” The article in the March 2006 issue, “Ultraviolet Light for Coil Cleaning in Schools,” (Engineered Systems 2006A) was followed by an article in the April 2006 issue, “The Right Place for Displacement” (Engineered Systems 2006B). Electronic versions of these articles were obtained from the editor of *Engineered Systems* and distributed to a wide audience, as delineated in the Technology Transfer Plan.

- Presentations, forums, and training sessions were conducted.

Presentations were conducted throughout the course of the Program for the purposes of informing market participants, eliciting involvement from influential participants, and

using participant involvement to both shape the results of and disseminate the information about the technical projects.

Technical presentations, forums, and training sessions occurred at several venues. Several ASHRAE and other venues typified the range of these informational events:

- Informal presentations were made to ASHRAE technical committees at the Winter meeting in Anaheim in January 2004. These included a presentation to the mechanical subcommittee of ASHRAE 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings.
- Forums were held at the ASHRAE Chicago (January 2004) and Nashville (June 2004) meetings on issues relating to work that needed to be done in order to apply UVC systems to commercial buildings and on research and programs needed to better inform the HVAC community about UVC technology.
- Seminars were held at the ASHRAE meeting in Chicago on field experience with DV and UVC technologies.
- Forums also occurred at the ASHRAE Denver (June 2005) meeting and the ASHRAE Quebec meeting (June 2006).
- A presentation on Computational Fluid Dynamic Modeling was made at the American Council for an Energy Efficient Economy Summer Study Conference on Buildings (held in August 2004 at the Asilomar Conference Center in Pacific Grove, California).
- The proposal prepared for a session at the CASH conference held in February 2006 in Sacramento was accepted; presentations were prepared and given. The CASH DV presentation (Eley 2006) and UVC surface disinfection (Okura 2006) presentation may be found on the Program web site.
- Training presentations were made at utility energy centers. These presentations were made at the SMUD facility in Sacramento on April 27, 2006, and at the SCE Customer Training and Assistance Center in Irwindale on May 2, 2006. The DV and UVC presentations were appended with explanatory notes that could be used by a trainer or trainee in utilizing these materials as training tools for a training session or for self-study.
- Guidelines for CHPS *Best Practices Manual* were developed.

The CHPS organization has developed a series of best practices manuals for *Planning* (Volume I) and *Design Guidelines* (Volume II), as well as four other volumes on criteria, maintenance and operations, commissioning, and relocatable schools. The results of the research conducted under this IEQ Program were used to update the DV guidelines and to create new guidelines for UVC. The revised-draft guidelines for DV (Collaborative for High Performance Schools A) contain updated information on applicability, codes and standards, cost effectiveness, advantages, disadvantages, design tools, design details, air distribution requirements, and references. The new draft guidelines for UVC (Collaborative for High Performance Schools B) contains recommendations, description, variations and options, applicability, applicable codes, integrated design implications, cost effectiveness, attributes, benefits, disadvantages, design tools, design information, operation and maintenance issues, commissioning, and references. These guidelines

have been transmitted to CHPS personnel and will be used as starting points for these technologies in the next version of Volume II of the CHPS *Best Practices Manual*.

- CHPS training material was created.

Training material for both DV and UVC technologies was created and will be used by CHPS representatives to provide future training to various audiences including architects, school and utility representatives, and consulting engineers.

- Educational Specifications were produced.

Educational Specifications, often known as EdSpecs, are used as guidelines for the siting and construction of school facilities to provide comfortable, healthy, productive learning environments. Model EdSpecs were prepared for UVC (Blatt 2006A) and for DV (Blatt 2006B) were reviewed by Tom Rayburn of Capistrano Unified School District. A number of examples are provided in each model EdSpec. For example, for the model DV EdSpec, the examples ranged between a simple statement of facility objectives; building HVAC needs; suggestions for HVAC options to be considered in the facility planning; and the most detailed specifications. This last example, the most detailed specifications, consisted of an overview of facility requirements; acoustic requirements; HVAC System requirements; and climate-related issues. Similarly, for the UVC system, the most detailed specifications provided information on climate and environmental issues, maintenance and operational issues, HVAC/UVC system requirements, and safety issues.

- Application guidelines were developed.

Guidelines were developed to assist school facility decision makers, equipment specifiers, and manufacturers in assessing whether DV and UVC for coil cleaning could meet their needs, and to provide them with information to help them select appropriate system configurations and components. Separate guidelines are provided for each technology: Application Guidelines for Off-the-Shelf DV Equipment (Blatt 2006C) and Applications Guidelines for Ultraviolet Lighting Equipment for Coil Cleaning (Blatt 2006D).

- Key meetings were conducted and numerous communication activities occurred.

A presentation on market issues was given to Carrier Corporation personnel at a meeting of the California Energy Commission on August 13, 2004. The meeting was designed to provide Carrier with an overview of PIER research that might be of interest with a specific focus on DV.

A presentation on Title 24 Issues was prepared for delivery to California Energy Commission Codes and Standards personnel and was transmitted to them along with a detailed e-mail message in fall 2004. The presentation dealt with the benefits of UVC; the limitations of Title 24 in assuming system performance in the as-built condition; and the actions needed to address field degradation with consideration to issues such as inspection, commissioning, retro-commissioning, and performance measurement. DV benefits were outlined and the need for handling the differences in mixed-ventilation systems and DV were described along with modeling suggestions on how to best facilitate these changes.

- Other communication activities consisted in part of “word of mouth” efforts to involve influential market participants.

One focus of these efforts was involvement with the activities of ASHRAE, an organization influential in reaching specifiers, users, and manufacturers, to organize forums that encourage discussion of the attributes of DV and UVC and the issues surrounding each technology’s use. Efforts were fruitful: ASHRAE forums and presentations were approved that afforded dissemination of Market Program results.

In the course of developing the Technology Transfer Plan and Code Action Plans, as well as gathering general information on market connections activities needed to encourage the adoption of these and other new technologies in schools, numerous telephone conversations and e-mail exchanges occurred. These connections with individuals who are involved in maintaining information channels with influential market participants and with code- and guideline-setting bodies has helped to ascertain the issues involved in handling DV and UVC technologies for such codes and guidelines. The results of these contacts and communications were incorporated into the Technology Transfer Plan and Code Action Plan.

Existing information channels, meetings, and publications were utilized to deliver accurate and timely information regarding DV and UVC technologies to those who can influence school facility construction and operations.

- Code Action Plans and White Papers were developed and outreach efforts begun.

Code action plans and white papers were developed. They provided assessments of the codes and standards issues affecting the adoption of DV and UVC technologies, identified individuals and organizations that could influence the acceptance of desired changes in codes and standards, and identified the changes needed to properly account for the attributes of DV and UVC systems in schools.

This information, which included the secondary research on DV and UVC benefits and the results obtained from this IEQ Program, were included in the Code Action White Papers. Information regarding the issues impeding the acceptance of these technologies has already been disseminated to influential code-, standard-, and guideline-setting bodies in the course of developing these plans and white papers. Some actions have already been taken to include the recommended changes in existing codes, standards, and guidelines, in part as a result of these interactions. The Code Action White Papers have been transmitted to numerous interested individuals and organizations.

4.5. Conclusions and Recommendations

4.5.1. Conclusions

- Key market barriers for DV and UVC technologies must be addressed.

Influential market participants and their market roles have been identified. Barriers that inhibit market penetration of new technologies for each of these market participants have been determined and actions needed to overcome these barriers described. Barriers such as performance uncertainties, hidden costs, and product availability were identified. These barriers must be properly addressed through incentives, documented

case studies, guidelines, and other actions needed for both technologies to succeed. Table 4 below summarizes these barriers along with the action recommended for addressing the each issue.

Table 4. Information/actions needed to overcome selected market barriers

Information/Actions Needed to Overcome Selected Market Barriers	
Market Barrier	Information/Action Needed
Costs of identifying efficient equipment	Product directory showing characteristics and performance
Performance uncertainties	Case studies documenting performance with testimonials
Acquisition costs	Guidelines for specifying and purchasing
Financing	Benefits information, sources of funding
Hidden costs	Installation, operation, and maintenance guidelines
High purchase price	Rebates or other financial incentives
Codes and standards	Documented performance
Product availability	Publicity and other actions in this table

- Continued action is needed to address codes and standard issues that impede the specification and installation of DV and UVC systems.

The main codes and standards issues with DV revolve around the differences between conventional mixed-ventilation systems and stratified DV systems. These differences occur in the areas of room air flow patterns, sizing, room air temperature distribution, ventilation effectiveness, thermal loads and indoor pollutants, supply-air quantity and temperature, control strategies, and economizer operation. Existing standards need to be modified to assure that DV is handled fairly. These standards are principally the Energy Code provisions (Part 6) of the State of California Building Code (Title 24) and the ASHRAE 90.1 standards. Other corollary programs, based in part on the California Energy Code (Title 24, Part 6) and ASHRAE standards, are the CHPS, LEED™®, and Savings By Design programs.

With UVC systems, a comprehensive UVC standard is needed to assure that acceptable practice is defined for UVC system design (sizing), installation, field performance, maintenance, lamp replacement, and safety. An emerging effort with these goals in mind is being led by the International Ultraviolet Association. Title 24, ASHRAE, CHPS, LEED™®, and Savings by Design standards and programs need to be modified to assure that efficiency improvements associated with the use of UVC lamps are incorporated. The general problem with receiving credit for UVC systems is that building codes and standards and the corollary programs based on these standards assume that the coils are

clean and do not account for the degradation in performance that naturally occurs over time.

- Results are encouraging but inconclusive.

The results of the IEQ Program indicate that DV reduces energy use and improves indoor air quality in K-12 schools in California. The primary data for DV showed savings during the month of November 2005 of $\geq 39\%$ with most of the savings due to increased economizer use and some savings due to reduced cooling loads. Energy savings of 10-40% are expected, depending on the climate.

The results for UVC technology in coil cleaning showed substantial surface disinfection but no statistically significant reduction in HVAC coil energy use or student absentee rates. These preliminary findings, while different from what was originally expected, should not be considered surprising once the influence of coil fouling on system performance degradation is better understood.

4.5.2. Commercialization Potential

Specific commercialization information for the DV and UVC technologies is provided under the respective sections for Project 2 and Project 3 of this report.

Market connection efforts for these two technologies need to continue with influential market participants and organizations for the California K-12 schools market. Consistent and relevant information needs to be delivered in effective media forms to relevant market actors, consumers, and codes-and-standards governing bodies in order to enable understanding and acceptance of the new DV and UVC products. Market barriers and issues of concern must be overcome by promoting understanding and by continuing research activities for both technologies.

4.5.3. Recommendations

- Additional testing is recommended.

With DV systems, more data is needed from the Capistrano test classroom in order to corroborate the findings that the system provides cooling energy savings and indoor air quality improvement. If possible, additional data should be obtained in order to perform validation of the "load partitioning" being considered by Title 24 personnel as a means for enabling the use of programs such as DOE-2.1 or DOE-2.2 to model displacement systems. If this data and corresponding correlations were made available, the case for implementing code changes to accommodate the use of these technologies would be stronger. A much larger sample of air-handling units and UVC light systems should be evaluated, with some of these test UVC units placed in situations that would include moist, microbial-rich conditions that encourage coil fouling and loss of performance.

- Market connection activities for future PIER programs should be extended beyond the period of performance for the technical projects.

This action would enable the more effective distribution and dissemination of the research results to key market participants, and to be able to adequately follow up questions and requests with answers, additional information, published articles, as well

as with presentations in meetings and other venues critical to reaching and influencing key market participants.

- Statewide energy impacts should be revisited after data from field tests is analyzed.

It is recommended that the estimates of energy impact and market penetration for both the DV and the UVC technologies be revisited after better data is available on performance improvements. Market penetration estimates can be made based on life-cycle cost calculations, payback periods, and market research (that includes interviews with key infrastructure participants).

4.5.4. Benefits to California

Statewide energy impacts are not directly applicable to the Program Market Connection (Project 4) activities conducted under the PIER IEQ program.

5.0 References

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6.0 Glossary

Specific terms and acronyms used throughout this report are defined as follows.

Acronym	Definition
AC	air conditioning
ACEEE	American Council for an Energy Efficient Economy
ACM	alternate calculation method
AEC	Architectural Energy Corporation
ADA	average daily attendance
ASHRAE	American Society of Heating, Ventilating, and Air Conditioning Engineers
Bioaerosols	Airborne products that include microorganisms, their fragments and spores, metabolic gases, and other toxins and waste products
Btu	British thermal unit
CASBO	California Association of School Business Officials
CASH	Coalition of Adequate School Housing
CFD	computational fluid dynamics
cfm	cubic feet per minute
CFU	Colony-forming unit
CHPS	Collaborative for High Performance Schools
CSBA	California School Board Association
CTAC	Customer Technologies Application Center
DOE-2	An hourly building energy simulation software package
DV	displacement ventilation
DX	Direct expansion (refers to the thermodynamic process where the refrigerant in an air-conditioning or heat pump system expands directly in the cooling coil or evaporator). Technology is commonly used in packaged and split system equipment.
EdSpec	Educational Specification (the document that sets forth the requirements that design professionals must follow when they design new schools or modernize existing schools)
EnergyPlus	A subhourly building energy simulation software package
EPA	U.S. Environmental Protection Agency

Acronym	Definition
ft	foot
GWh	gigawatt-hour
HVAC	Heating, ventilation, and air-conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
in	inch
K-12	Kindergarten through high school
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LEED™	Leadership in Energy and Environmental Design™
MEV	minimum efficiency reporting value
Modernization	A set of extensive improvements to an existing school that often includes air conditioning for spaces that were previously only heated. The scope of a modernization project may also include new lighting systems, controls, and finishes, among others.
MW	megawatt
Neutral air	Conditioned air delivered through DV systems, which is at a temperature between about 63°F and 68°F and with a maximum humidity of about 60%.
OA	outside air
PAC	Program Advisory Committee (or Project Advisory Committee)
PG&E	Pacifica Gas and Electric Company
PIER	Public Interest Energy Research
ppm	parts per million
RD&D	research, development and demonstration
SAT	supply air temperature
SCE	Southern California Edison Company
SDG&E	San Diego Gas and Electric Company
SEER	seasonal energy efficiency ratio
SMUD	Sacramento Municipal Utility District

Acronym	Definition
UC	University of California
UFAD	under-floor air distribution
UL	Underwriters Laboratory
UVC	ultraviolet in the "C" band
VAV	variable air volume
VOC	Volatile organic compound
W	watt

7.0 Appendices

This section lists the appendices to the final report of the *Advanced HVAC Systems for Improving Indoor Environmental Quality and Energy Performance of California K-12 Schools Program*, Contract Number 500-03-003, conducted by Architectural Energy Corporation (AEC).

The final report and these appendices are intended to provide a complete record of the program's objectives, methods, findings, and accomplishments. Architects, school designers and specifiers, contractors, school district owners and operators, manufacturers, researchers, and the energy efficiency community should find the report and the attachments highly applicable to their interests. Table 5 summarizes information about each attachment, including the Energy Commission's publication number, the title of the report or the type of publication, and a short description. To obtain copies of these a or other reports produced within this contract, or for more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Energy Commission's Publications Unit at (916) 654-5200. All research products are also available through AEC at www.archenergy.com/ieq-k12/.

Table 5. Summary attachments

Publication Number	Title	Short Description
CEC-500-2003-XXXA	Thermal Displacement Ventilation (DV) in Schools Final Report	Final report provided overview of project results
CEC-500-2003-XXXB	Thermal Displacement Ventilation (DV) in Schools Research Report	Research report detailing technical results
CEC-500-2003-XXXC	Thermal Displacement Ventilation (DV) Design Guide	Design guide for design teams and school facility personnel
CEC-500-2003-XXXD	Effectiveness Of UVC Technology For Improving School Performance Final Report	Final report provided overview of project results
CEC-500-2003-XXXE	Program Market Connection Final Report	Final report provided overview of project results
CEC-500-2003-XXXF	DV and UVC Fact Sheets	Promotional material
CEC-500-2003-XXXG	DV and UVC Training Presentations	Promotional material
CEC-500-2003-XXXH	EdSpec Models for DV HVAC Applications and UVC Applications	Sample Inputs for Educational Specifications

CEC-500-2003-XXX	Application Guides for Compatible Off-the-Shelf Equipment for Use in DV and UVC Applications in Schools	Application Guidelines
CEC-500-2003-XXX	Code Action White Papers and Brochures for DV and UVC Technologies	Code action documents