

Classroom HVAC: Improving Ventilation and Saving Energy

Field Study Plan

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Glossary

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

| <i>Acronym</i> | <i>Definition*</i> |
|------------------|--|
| ASHRAE | American Society of Heating, Refrigeration, and Air Conditioning Engineers |
| Bard/GP | Bard Manufacturing and Geary Pacific Corporation |
| CDHS | California Department of Health Services |
| CEC | California Energy Commission |
| CFM | Cubic feet per minute, a measure of ventilation rate per occupant |
| CO ₂ | Carbon dioxide |
| CR | Classroom |
| dB(A) | A-weighted decibels, measurement of noise level |
| DOE | United States Department of Energy |
| hr ⁻¹ | Units for air exchange rate |
| HVAC | Heating, ventilation, and air conditioning system |
| IEQ | Indoor air and environmental quality |
| IVSE | Classroom HVAC: Improving Ventilation and Saving Energy |
| L | Liters |
| LBNL | Lawrence Berkeley National Laboratory |
| NIST | National Institute of Standards and Technology |
| OPC | Optical Particle Counter |
| RC | Relocatable, or portable or modular, classroom |
| RH | Relative humidity, measured as percentage |
| RMS | Root Mean Square |
| SEER | Seasonal energy efficiency rating |
| T | Temperature, measured in degrees Celsius or Fahrenheit |
| VOC | Volatile Organic Compounds |

Abstract

The primary goals of this research effort are to develop, evaluate, and demonstrate a very practical HVAC system for classrooms that consistently provides classrooms (CRs) with the quantity of ventilation in current minimum standards, while saving energy, and reducing HVAC-related noise levels. This research is motivated by the public benefits of energy efficiency, evidence that many CRs are under-ventilated, and public concerns about indoor environmental quality in CRs. This document provides a summary of the detailed plans developed for the field study that will take place in 2005 to evaluate the energy and IAQ performance of a new classroom HVAC technology. The field study will include measurements of HVAC energy use, ventilation rates, and IEQ conditions in 10 classrooms with the new HVAC technology and in six control classrooms with a standard HVAC system. Energy use and many IEQ parameters will be monitored continuously, while other IEQ measurements will be performed seasonally. Continuously monitored data will be remotely accessed via a LonWorks network. Instrument calibration plans that vary with the type of instrumentation used are established. Statistical tests will be employed to compare energy use and IEQ conditions with the new and standard HVAC systems. Strengths of this study plan include the collection of real time data for a full school year, the use of high quality instrumentation, the incorporation of many quality control measures, and the extensive collaborations with industry that limit costs to the sponsors.

Introduction

The primary goals of the “Improving Ventilation and Saving Energy” (IVSE) project are to develop, evaluate, and demonstrate a very practical HVAC system for relocatable classrooms (RCs) that consistently provides them with the quantity of ventilation in current minimum standards, while saving energy, and reducing HVAC-related noise levels. The ultimate goal is to provide the specification of this system to the public domain, and promote its acceptance into the market through interaction with key school facilities stakeholders.

The need for an improved classroom (CR) ventilation system is based, in part, on the considerable evidence, summarized in Daisey et al. (1998, 2003), indicating that ventilation rates in CRs often do not meet the current ASHRAE minimum rate of 15 CFM per occupant. While relatively few measurements of actual CR ventilation rates are available, concentrations of CO₂ in CRs often substantially exceeded 1000 ppm; implying ventilation rates less than 15 CFM per occupant, with several studies reporting peak concentrations exceeding 1500 ppm, and some concentrations exceeding 3000 ppm. In a recent survey of California portable CRs (also called relocatable classrooms or RCs), CO₂ concentrations exceeded 1000 ppm in about 40% of CRs and concentrations exceeded 2000 ppm in approximately 10% of CRs (CARB-DHS 2003). In a survey of 400 CRs in Washington state and Idaho (Shendell et al. 2004), CO₂ concentrations measured at random times in 45% of classrooms exceeded 1000 ppm, thus, a considerably larger fraction of steady state or peak CO₂ concentrations would have exceeded 1000 ppm.

Further evidence of low CR ventilation rates was obtained in a study in 14 California schools (Lagus Applied Technologies 1995). The measured mean minimum air exchange rate was 2.4 h⁻¹, with a range of 1.2 to 2.9 h⁻¹, while the air exchange rate corresponding to the current standard was estimated to be 3 h⁻¹.

Anecdotally, we know ventilation rates in CRs are often low because teachers frequently operate CR HVAC systems in the mode where the supply fan shuts off except when heating or cooling is required. Thus, outside air is supplied mechanically only during periods of heating or cooling and the time average rate of supply is below standards. Anecdotally, we also know that teachers use this mode of HVAC system operation to avoid HVAC system-related noise. These anecdotal reports are supported by the findings from the recently completed survey of California RCs. Teachers in 60% of RCs reported that they sometimes turned off HVAC systems to reduce noise levels (CARB-CDHS 2003). Consequently, the available evidence indicates the importance of reducing HVAC noise in the development of improved CR HVAC systems.

We also know that ventilation is a particularly important cause of energy use in high occupancy spaces, such as CRs. Mudarri et al. (1996) used an energy simulation model and estimated that increasing school building ventilation rates by 10 CFM, from 5 to 15 CFM per occupant, would increase annual HVAC energy use by 15%, 31%, and 32% in Miami, Washington, DC, and Seattle, respectively. From these predictions, we can estimate that the energy to provide 15 CFM per student of ventilation is approximately 22%, 45%, and 45% of total classroom HVAC energy in these three climates, respectively. This indicates the existence of a clear energy and financial penalty from increasing ventilation to meet existing standards if improved energy efficiency is not applied to offset the increased demand.

A number of studies (e.g., Seppanen et al. 1999, Wargocki et al. 2002; Erdmann et al. 2002) have investigated the relationship of ventilation rates to health outcomes (sick building syndrome symptoms, respiratory illnesses), absence rates, and perceived air quality; however, most studies have been performed in office buildings. Some studies have used indoor CO₂ concentrations as a surrogate for ventilation rate per occupant. A large majority of these studies have found a worsening of some health, absence, or perceived air quality outcomes at lower ventilation rates or higher CO₂ concentrations. Detrimental effects have been particularly clear when ventilation rates are reduced below 20 CFM per occupant and several studies have found benefits of increasing ventilation rates above 20 CFM per occupant. These study results indicate that ventilation rates have important effects on people.

When we consider these factors together – the important effects of ventilation on people, the energy used for ventilation, and the evidence of ventilation deficiencies in classrooms, it is very clear that we need to develop and promote use of highly energy efficient systems for providing classroom ventilation.

The purpose of this document is to describe the IVSE Project field study including: a) how intervention and control CRs are matched; b) parameters measured; c) measurement methods, periods, and frequencies; d) calibration procedures; e) how data will be processed and analyzed.

Overall goals for the IVSE project

The goals for the IVSE project are as follows:

1. Quantitative Energy Efficiency Goal/Expectation

The advanced HVAC system will have an increase in energy efficiency of 10% or more compared against the current state-of-the-art 12 SEER 3 to 5 ton wall mount products.

- a. Demonstrate the reduced energy consumption of the advanced HVAC system in a laboratory setting.

Goal –Quantitatively show in the laboratory that energy consumption reductions are at least 30% lower than the 10 SEER system or by inference a 10% improvement compared to the 12 SEER system.

- b. Demonstrate the energy and IEQ capabilities of the advanced HVAC system in a set of occupied CRs in two distinct climate zones in CA.

Goal –Quantitatively show that energy consumption reductions and IEQ improvements under real conditions match those intended by design and those observed in laboratory tests. This is at least a statistically significant 30% decrease relative to the 10 SEER system or by inference a 10% decrease compared to the 12 SEER system.

2. Quantitative Noise Reduction Goal/Expectation

The advanced HVAC system is designed to significantly cut CR noise levels relative to the Low-Noise 12 SEER system, a major reduction relative to the baseline 10 SEER system.

Goal – The acoustic specification for the 12 SEER HVAC is that it operate in an unoccupied room at <50 dB(A) at a distance of 10 feet from the air return, measured five feet above the floor. The advanced system will be conservatively expected to operate at <45 dB(A) at the same location in its noisiest operating condition. This is a reduction in sound power of more than 50%. This will be shown quantitatively in laboratory and verified in the field.

3. Quantitative Ventilation System Improvement Goals/Expectations

HVAC system meets general physical dimension and integration characteristics suitable for mounting on new and existing relocatable classrooms in CA. This is extremely important for market transfer.

Goal – show dimensionally that advanced unit fits on and can be integrated into new and existing relocatable classrooms.

- a. HVAC system provides sufficient outside air ventilation flow for up to 31 occupants (ASHRAE standard 62: 465 CFM), continuously

Goal - show quantitatively that system meets 100% of ASHRAE 62 Standard outside air supply flow and can provide it continuously

- b. HVAC system controls provide signals to air handler to constantly and continuously ventilate during occupancy irrespective of thermal demand

Goal - show that controls react upon occupancy to provide ventilation. Monitoring will verify that HVAC system ventilation activates upon occupancy demand.

- c. HVAC system maintains indoor CO₂ levels below 1000 ppm

Goal - show under simulated classroom occupancy (using CO₂ gas cylinders) that levels can be maintained < 1000 ppm 100% of the time given simulated generation from 31 or fewer occupants

- d. HVAC system can provide thermal conditioning at air velocities and temperatures that meet ASHRAE 55 thermal comfort standards

Goal – Show that air velocities and supply temperatures lead to acceptable thermal comfort based upon ASHRAE 55. Note that acceptable relative humidity per ASHRAE 55 may not always be met depending upon ambient humidity conditions.

- e. Demonstrate the energy and IEQ capabilities of the advanced HVAC system in a set of occupied CRs in two distinct climate zones in CA.

Goal – Quantitatively show that IEQ improvements under real conditions match those intended by design and those observed in laboratory tests. This will be accomplished by showing that the system is capable of continuously maintaining indoor CO₂ concentrations lower than 1000 ppm for averaging times of 5-minutes or more. Indoor particle, VOC, and formaldehyde concentrations are expected to be significantly lower under these conditions, but the absolute concentrations will vary across classrooms due to variability of their emission factors from class to class. The distribution of the concentrations of these indoor contaminants will be presented quantitatively and statistical comparisons will be presented.

- f. Demonstrate that the Title 24 pre-occupancy ventilation requirement is met by the advanced system.

Goal – Present data from field monitoring that prove regular reliable (>90% of scheduled school days) automatic CR ventilation startup at least 1 hour prior to scheduled occupancy, and average ventilation rate data to indicate that at least 3 air exchanges occur prior to occupancy. Also demonstrate that this system reliably does not initiate pre-occupancy ventilation on weekends and other scheduled non-school days.

Field study objectives

The objectives of this task are to evaluate the energy, ventilation, and IEQ performance of the advanced HVAC system when deployed in occupied classrooms and to perform a highly visible demonstration of the system.

The advanced HVAC system will be installed in approximately six relocatable classrooms, called intervention classrooms. Six matched control classrooms will be selected. To the degree possible, control classrooms will be matched with intervention classrooms by location (school), grade level, classroom size and manufacturer, and classroom age. In addition to the six CR pairs, an additional four CRs equipped with an advanced HVAC system will be studied less intensively at the same school sites. Instrumentation systems will be installed in each intervention and control classroom and HVAC energy performance and IEQ will be monitored over a school year. Energy monitoring and limited IEQ monitoring will be conducted in the additional four advanced HVAC systems. The benefits of the advanced HVAC system will be quantified by comparing the measured data from the intervention and control classrooms, using statistical models to adjust for imperfect matching to the degree possible.

The field study will measure some parameters in real time (continuously or every 1 to 30 minutes) and make periodic measurements (once per season) of other parameters. Parameters measured in real time will include indoor and outdoor temperature and humidity, HVAC power, and indoor and outdoor carbon dioxide concentrations. Parameters measured periodically will include concentrations of formaldehyde and other volatile organic compounds, particle concentrations, noise levels, and ozone concentrations.

The objectives of the data evaluation will be to quantify how the advanced HVAC system influences: a) HVAC operation periods; b) HVAC energy use; c) ventilation rates; d) noise levels; e) pollutant concentrations and f) thermal comfort.

Field Study Plan

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School Recruitment

Criteria for school selection were based upon climate, and geography. Northern and Southern California locations were selected for broader representation of the state. The San Joaquin Valley was selected for cold winter and hot summers, and the San Bernardino Valley was selected for the high cooling demand and long cooling season. Schools were selected and recruited for this study in early 2004. Recruitment of participant schools was accomplished through two mechanisms. In the case of the Modesto City Schools in Northern California, we contacted the Facilities Manager directly as LBNL had previously conducted research in the district and had a working relationship with them. In the case of San Bernardino, Geary Pacific Corp., the California Distributor of Bard HVAC equipment provided a list of potential school districts in the Southern CA region to LBNL. Contact letters were sent to a number of school district facilities managers in the region and site visits were conducted to those districts that expressed interest in participating. The Fontana Unified School District was found to meet the needs of the study and was therefore selected. Principals from two schools in each district were contacted with the assistance of their facilities managers, and were found to be willing to host the research in their schools.

RCs in each school were assessed for their potential to be studied as a set where some would be used as controls and some would receive the HVAC system upgrade with the advanced systems. Each school had to have a group of RCs, preferably sited in a row, equipped with 10 SEER Bard HVAC systems, and in at least pairs with the same year of manufacture. It was preferred that the RCs were at most 10 years old. Additionally if they had a known or suspected IAQ problem they would not be acceptable.

Advanced HVAC system installation and RC HVAC commissioning

The ten advanced HVAC systems will be shipped from Bard Corporation's factory to Northern and Southern CA branches of Geary Pacific Corp. GP is to install, with the assistance of local HVAC contractors, the HVAC systems and associated ducting, registers, and controls in all ten study RCs. GP will also commission the advanced systems and re-commission the existing HVAC systems in the matched control RCs. Commissioning will include setting of the outdoor air supply rates at 15 CFM per occupant, replacing air filters, balancing of supply registers, and verifying proper functioning of controls. In addition, any mechanical problems with the control RC HVAC systems will be remedied to meet school district standards.

HVAC Control Systems

The HVAC systems in the Control RCs will be operated using the existing standard thermostat coupled with an existing standard twist-type four-hour shutoff timer. The operation of this thermostat is entirely under the control of the teachers, and sometimes the school custodians at the beginning or end of the day. The thermostat has an automatic mode where it heats or cools according to setpoint, providing ventilation and air circulation only when thermal conditioning is required. An additional manual setting on the thermostat allows the teacher to turn on the fan independently if desired, allowing for continuous ventilation. However, as discussed above, this option is seldom used consistently due to the additional noise produced when the air supply fan is operating. The expectation is that the thermostats in the Control RCs will be used in the typical fashion during the study, and the teachers will be advised that they should follow their school district policy for HVAC operation.

In the RCs equipped with the advanced HVAC systems, an automatic "smart controller" will be provided. This controller has been developed for the Advanced system by Bard Corporation as part of this project. It is designed to relieve the responsibility of the teachers of the majority of HVAC operation tasks. Additionally, it decouples the ventilation and thermal aspects of control through the use of an internal infrared motion-detector-type occupancy sensor that triggers ventilation whenever occupants are detected. The teacher's control interface is limited to a simple temperature setting adjustment, using up-arrow and down-arrow buttons to provide a locked indoor temperature range (field settable by a technician, and set to $\pm 4.0^{\circ}\text{F}$ (2.5°C) in this study) in order to accommodate individual comfort differences. The occupancy sensor logic is set to wait 30 minutes after the last observed motion in the RC before setting back the temperature and shutting down the ventilation. It is also desensitized to very short (i.e., one-minute) detection of motion to avoid unneeded operation, but triggers HVAC operation as soon as a valid occupancy is detected. Finally, the system is designed to learn the classroom occupancy schedule over a moving two-week period, and then start anticipating occupancy by pre-conditioning the RC to the settings learned from the teacher's temperature control use patterns. Pre-conditioning will also include a pre-occupancy ventilation purge of three air changes (roughly one hour) as required by California Title 24. An additional benefit of this control system is that it has a digital electronic interface configured to operate on a LonWorks (www.echelon.com) network, allowing remote access for monitoring and control of all of the thermostat and HVAC functions.

Instrumentation specification

The instrumentation to be used in the field study is shown in Table 1. Real-time data will be stored as 6-minute averages or totals. Total RMS power consumption will be measured on each HVAC system using WattNode™ (Continental Control Systems, Bolder CO, www.wattnode.com) power meters. Indoor and outdoor temperature, RH, and CO₂ concentrations will be measured for each RC continuously. Indoor and outdoor particle, aldehydes, VOCs, and ozone concentrations in the RCs will be monitored once a season during site visits. Classroom acoustic noise during occupied and unoccupied periods with the HVAC operating will be measured during the seasonal site visits in each RC.

Indoor and outdoor temperature and RH will be monitored primarily using the sensors in the PureChoice Nose™ (PureChoice Inc., Lakeview, MN). This device will be connected to the i.Lon 100 network (see below), and will be accessible on the internet by the researchers 24 hours a day. Additionally, a selected subset of these sensors will have a Hobo® temperature or temperature and RH sensor co-located with data stored for downloading during each seasonal site visit.

CO₂ will be measured using two different systems; the Fuji ZPF-9 has been used by LBNL for many years as a standard method in buildings. In this study we will also be using the PureChoice Nose™ CO₂ sensor in each RC. The sensors differ in stated accuracy, and the Fuji unit samples with a pump, while the PureChoice sensor samples using gas diffusion. The PureChoice sensor is factory-calibrated and expected to maintain accuracy specifications for five years. The Fuji units will be calibrated at least once a season during site visits. Both systems will be connected to the i.Lon 100 network and will be accessible on the internet by the researchers 24 hours a day.

Site visits to the schools will occur at least once per season in order to check and calibrate instrumentation, download Hobo® (Onset Corp., Bourne, MA) logger data, to characterize indoor and outdoor concentrations of particles, VOCs, aldehydes, and ozone, and to conduct acoustical measurements. Classroom ventilation rates will be measured during unoccupied periods using SF₆ and/or CO₂ decays. Real-time data from the particle, sound level meter, and ventilation tracer gas analyzers will be downloaded onto a laptop computer for subsequent analysis. Similarly, the VOC, aldehyde, and ozone sampling media will be transported to LBNL for subsequent laboratory analysis.

Thermal Comfort Assessment with LBNL Schools Cart

A measurement system based on ASHRAE Standard 55 (2004) was developed (Shendell et al., 2002) to quantitatively assess of teacher and student thermal comfort (TC) that is more accurate than estimates using room air temperature and RH alone. Standard 55 incorporates air temperature, mean radiant (globe) temperature, RH and air velocity measurements. Three prescribed measurement heights in Standard 55, designed relative to the seated adult worker, are likely relevant to a child 5-10 years old. The lowest height, 0.1 m, represents occupant feet and ankles. The middle height, 0.6 m, represents the adult midsection and likely child torso and head while seated. The 1.1 m height represented a teacher's upper torso and head while seated, and likely a child's torso and head while standing. In a school classroom and especially smaller RCs, occupants are fairly sedentary for lessons and supervised activities, with recess and lunch outside.

Calibration and measurements.

Temperature sensors used in the study have National Institute of Standards and Technology (NIST) traceable factory calibration. All temperature sensors (Hobo® and PureChoice Nose™) will have a multipoint linearity check against precision RTD sensors in the laboratory. Any sensors with significant deviation from calibrated standards will be adjusted or replaced. Similarly, all RH sensors have NIST traceable factory calibrations that will be confirmed in the laboratory against multiple RH levels created using a range of salt solutions. The long-term stability of the sensors precludes the need for subsequent calibration checks during the field study.

Both Fuji and PureChoice Nose™ carbon dioxide sensors will have multipoint calibration curves developed in the laboratory prior to deployment in the field. These curves will be used as a baseline. The PureChoice sensors will not have calibration checks again until the end of the study. The Fuji sensors will have new calibration curves developed using calibration standards in the field, at least once per season during the scheduled school site visits. The calibrated Fuji sensors will be co-located with the Nose™ sensors, and will be used as a standard to which the Nose™ sensors can be compared.

Both the optical particle counters (OPCs), and sound level meter, are factory calibrated from NIST traceable standards. The particle counters will have no further calibration provided with the exception of a flowrate adjustment to the specified setting of 2.73 L Min⁻¹. The sound level meter will undergo a secondary sound level span at 94.0 dB(A) at 1kHz prior to each day in the field. VOC and aldehyde sampling pump flowrates will be measured using a BIOS DryCal flow meter and recorded before and after each sample collection.

VOC and aldehyde analyses

Multi-point internal standard calibrations will be created using pure compounds and 1-bromo-4-fluorobenzene as the reference compound. The relative precision of the sampling and analysis method for VOCs has been determined to be about ±10% for most compounds (Hodgson, 2000). The lower limit of quantitation for a 3-L sample is about 0.5 µg m⁻³ for many compounds.

The aldehyde samples will be extracted with acetonitrile, and the extracts will be analyzed by high performance liquid chromatography with UV detection generally following U.S. EPA Method TO-11. Multi-point calibrations will be prepared for formaldehyde and acetaldehyde using their respective hydrazone derivatives. Relative precision is better than ±10%. The lower limit of quantitation for a 30-L sample is about 1 µg m⁻³.

Continuous data collection method

The continuously collected real-time data in the RCs will all have LonWorks (www.echelon.com) networking functionality. LonWorks is a flexible network communication protocol well suited to the interoperability needs of this project. The sensors will be connected via a twisted-pair open-topology network to a central i.Lon 100 network server. The i.Lon 100 (Echelon Corp., San Jose, CA. www.echelon.com) is an Internet interface to the LonWorks network, providing World Wide Web and e-mail servers as well as acting as a datalogger. The i.Lon 100 allows for two-way communication with equipment that can enable control as well as data retrieval. Using this method the data will be available for retrieval at any time from any

web browser. The bulk of the data collected will be protected with a password, but a subset will likely be made available to the public on the Internet in order to bring attention to the project for market connection purposes. Data collected in this manner will include indoor and outdoor temperature, RH, and CO₂; instantaneous true RMS HVAC power consumption and total energy consumed.

Measurements of air supply and ventilation

Outside air supply flowrates and supply register flowrates will be measured using an active flow hood method (Walker et al. 2001) developed at LBNL. This method consists of coupling a standard hood with a calibrated fan with integral flow meter, and use of a differential pressure sensor to measure the pressure at the register. With the flow hood in place, the fan is adjusted until the differential pressure between the room air and the register is zero. The calibrated flow measured by the fan is then equal to the supply flow rate. The same process is applied to measure the outside air intake flow and the return flow, although the fan is reversed to supply a positive air pressure rather than a negative pressure. Outside air supply rates (outside air is about 30% of the total supply air in this recirculating system) will be set to 15 CFM per occupant, or 465 CFM for a class of 30 students and one teacher. The three supply registers will be balanced to split the total supply flow equally (about 500 CFM per register).

RC air exchange rates will also be measured using a tracer decay method. Two tracers will be measured: CO₂ and SF₆. CO₂ decays will be measured with the installed CO₂ sensors, and the air exchange rate will be calculated after subtracting the outdoor CO₂ concentration. On many days CO₂ decays will be available in the control RCs when the HVAC system is left running after the class is vacated, a common practice in RCs that operate on a manual timer that is activated in the afternoon. In the intervention RCs, the HVAC control system will be remotely accessible through the LonWorks system, allowing the technicians to remotely activate the ventilation fan as the RC is vacated at the end of the day, allowing an assessment of CO₂ decays during this period. These decays will not be conducted more than once a week. During seasonal site visits, additional CO₂ decays with the HVAC system ventilation fans on will be conducted by injecting CO₂ from a cylinder into the unoccupied rooms until the concentration reaches approximately 2000 ppm, and then allowing it to decay to background levels.

The second tracer method is roughly equivalent, but involves injection of SF₆ into the RC, and will be used during the four seasonal site visits. One advantage is that the concentration of SF₆ outdoors can be assumed to be zero relative to the ppm-level peak concentration of injected tracer. SF₆ will be injected into the unoccupied RCs with the ventilation fans on. The tracer concentration will be measured with a portable Miran Sapphire infrared gas analyzer (Thermo Electron Corp., Waltham MA) with an internal datalogger.

Air exchange rate is calculated as the negative slope of the logarithm of the indoor minus outdoor tracer concentration during the tracer decay.

Thermal Comfort Carts

Calibration of the TC Carts is conducted periodically. Their thermistor-based temperature sensors are compared against a standard precision thermometer in a temperature controlled water bath. Thermistors are typically very stable unless they are damaged, so they are replaced if found to be out of specification. The RH sensors are operated in a well-mixed humidity-

controlled chamber and a multipoint calibration check is conducted against a chilled mirror hygrometer. Minor deviations of 5 percent or less in the calibration settings are adjusted by post processing. RH sensors out of specification are replaced if they exceed these limits. The air velocity sensors are factory calibrated in a wind tunnel against an array of NIST traceable air velocity sensors.

Installation of instrumentation and data collection

Sampling sites

Power monitoring sensors will be located inside the HVAC systems with their current transducers connected to the WattNode™ modules. Outdoor temperature, RH, and CO₂ sensing will be shielded from direct sunlight and the elements by placing them in an inverted enclosure under the eaves of the RCs. One co-located PureChoice Nose™, temperature and RH Hobo® datalogger will be placed outdoors at each school. The outdoor Nose™ will be connected to the LonWorks network. The primary indoor sampling location will be the center of the RC where a mobile-like hangar will be suspended from the ceiling such that sampling probes can be placed at a height of about 2 m. Other sampling sites will include the middle HVAC system supply register and the HVAC return duct.

Continuously collected data.

All instrumentation for continuous data collection will be installed in all of the study RCs prior to installation of advanced HVAC systems in study classrooms or re-commissioning of existing HVAC systems in control classrooms. The PureChoice Indoor temperature, RH, and CO₂ sensors, Fuji CO₂ sampling inlet, and Hobo® dataloggers will be placed on the central mobile hangar. Additional Hobo® temperature dataloggers will be placed in the HVAC supply and return sampling points.

One RC at each school will house the i.Lon 100 server and will provide a connection to Internet port. This will be the common twisted pair endpoint for the LonWorks network. A run of twisted pair data wire will connect to all of the LonWorks sensors in all of the classes. As the RCs will be in a row, wiring will be fairly simple. It will be run along the back of the classrooms at roofline and first connect through the HVAC systems externally and then through the wall into each RC.

Six study RCs and six control RCs will be equipped with Fuji CO₂ sensors. The Fuji's 4-20 mA current loop output will connect to a LonPoint 16 Bit analog to digital converter (Echelon Model AI-10) that will be collected to the LonWorks network. One Fuji sensor at each school will have a digitally controlled valve connected to the LonWorks network via a digital output port on the i.Lon 100. This valve will be actuated to switch between two sampling points; one indoors at the central sampling point of the RC and the other outdoors at the outdoor sampling point. The i.Lon 100 will be programmed to switch to outdoors once an hour for a period of five minutes to collect outdoor CO₂ concentrations.

Seasonally collected data.

In the six study RCs and six control RCs, instrumentation to be used once a season will be installed in the RCs for one school day of study. This sampling will occur once per season in

each RC during a pre-scheduled school day. The dates of this sampling will be set to avoid school holiday and testing schedules.

Seasonally collected data include indoor and outdoor VOC, aldehyde, and ozone samples, one-day time-resolved particle concentration and size distribution measurements, morning and afternoon time-resolved classroom thermal comfort measurements, spot measurements of acoustic noise level spectra under HVAC fan-only and compressor operation modes, during both occupied and unoccupied periods. Sulfur hexafluoride or CO₂ tracer gas ventilation data will be collected in each classroom with the HVAC system on during an unoccupied period.

The ozone samplers will be co-located with the other monitoring devices at the central monitoring point in the RCs. Just prior to the start of the school day they will be uncapped and secured with the other sensors. Date, start time, location, and sampler numbers will be recorded in the study log. At the end of the school day they will be removed, capped, and sample end times will be recorded on an ozone data log sheet. Similarly VOC and aldehyde samples will be collected in each RC for an entire school day using quiet active sampling pumps. Samples will be collected at a representative place in each classroom, with the location depending upon the layout of the space. Sample times, flowrates, and sampling locations will be recorded on VOC sampling log sheets. All samplers will be sealed in leak proof containers and cold-stored until analysis.

Acoustical noise in A-weighted decibels, at 1/3 octave bands, will be characterized at a point 5.0 ft (150 cm) high and 10.0 ft (300 cm) from the center of the HVAC return grille and parallel to the module center line of the RC. Noise will be measured with the RC unoccupied HVAC system off, ventilation fan on only, and in ventilation fan plus compressor on modes. Ambient noise outside will also be characterized just prior to the indoor measurements. A detailed acoustic map of each of the 12 full study RCs, measured at 10 additional points throughout the class, at 3.0 ft (90 cm) from the floor will be made at the beginning of the field study.

Reverberation time measurements for the full study RCs will also be collected at this time. Noise-producing monitoring equipment utilizing pumps, such as the OPC and Fuji CO₂ sensors will be either operated in the attic space above the acoustic ceiling tiles, or turned off for these measurements.

Particle concentration and size distributions will be measured using an OPC in each RC at a representative location for 30 minutes during the morning and afternoon. Using a separate OPC, ambient particle concentrations will be measured continuously at a single outdoor site at each school for each day for which indoor particle monitoring is conducted.

Thermal Comfort in each RC will be assessed at three locations for ten minutes each in both the morning after the first half hour of class time, and in the afternoon. The locations will be in the center of the room under the middle supply register, near the teacher's desk, and at a location near the RC window within the range of direct insolation.

Field study data handling and analysis

The goal of analyzing the field study data from intervention and control RCs is to determine: a) HVAC energy savings; b) indoor class-time thermal conditions; c) benefits, if any, from the advanced HVAC system in terms of, ventilation rates, reduction in indoor pollutant concentrations, and reduction in noise in intervention relative to the control RC systems; d)

potential increase in ozone concentrations in intervention RCs. Models will be developed and used when possible, to adjust for imperfect matching between intervention and control classrooms.

The online data collection via the LonWorks network will provide flat files containing real-time data averaged at 6-minute intervals, 24 hours a day, for the one-year duration of the study. These files will be imported into MS Excel spreadsheets and data files for a statistical analysis package. The seasonally collected data in real-time formats (e.g., thermal comfort, particle size and concentration data, acoustics data) will be collected on computer and transferred into MS Excel spreadsheets.

Data will be checked for consistency and completeness prior to analyses. Field logs and school schedules will be consulted to verify unexpected data patterns. Data outliers clearly due to instrumental problems or systematic errors will be censored from the dataset.

Teacher assessment of HVAC system

A questionnaire is to be developed prior to the field study to address teacher's experiences with using the HVAC controls and their satisfaction with different aspects of the HVAC system. It will be administered voluntarily to all sixteen willing teachers in the intervention and control RCs. This survey instrument will include their impressions on ease of use and perceptions regarding noise, thermal comfort, quality of the indoor air, and overall adequacy of the system to provide HVAC suited for a public school environment. The questionnaire will not be used ask any personal information about the teachers or the students, but only as a means to provide information on the adequacy of the HVAC systems.

Energy performance data analyses

Daily energy use totals will be plotted against daily average outdoor air temperature. Separate regression relationships for the intervention and control RCs will be developed using daily average outdoor air temperature and indoor air temperature as the independent variables. The regression relationships for each HVAC system type will then be used for comparing the monitored energy of the matched RC pairs, eliminating any weather effects.

Using measured temperature and humidity data as inputs, combined with standardized regional climate data, measured occupancy data, measured ventilation data, and calibrated RC Energy Plus or DOE-2 models (Rainer et al., 2003), classroom energy loads will be calculated and evaluated against measured energy consumption to estimate annual SEER values for each intervention and control HVAC system.

Classroom ventilation data analyses

Data from tracer gas decays during unoccupied classroom periods with the ventilation systems on will be used to estimate ventilation rate. The air exchange rate data from available daily ventilation-on post-occupancy CO₂ decays will be compared with the seasonal site visit CO₂ and SF₆ data. Hourly outside air fan operation time will be derived from the HVAC power consumption data enabling a calculation of total volume of outside ventilation air on a daily occupancy basis. This value will be compared between intervention and control RCs to assess the relative amount of ventilation each RC type receives. The commissioned outside airflow rates and hourly ventilation air fan use will be used to calculate the same quantities. The air-exchange rate and ventilation supply methods will be compared.

IEQ data analyses

Using monitored daily indoor minus outdoor CO₂ concentrations, peak and average daily values will be calculated for each RC. The seasonal and annual distributions of these statistics for each classroom pair will be compared using parametric (i.e., Students T) and non-parametric (i.e., Kolmogorov Smirnov) tests (SAS, 1999) to assess the difference in indoor CO₂ levels between the intervention and control RCs. This measure will establish the primary differences in IEQ based on per-person ventilation rate.

VOC measurements will be used to establish potential differences between IEQ conditions due to fixed structural sources (i.e., building materials, furniture), activities (i.e., art projects, cleaning) in the intervention and control RCs. Study-aggregate average concentrations across all matched pairs of RCs, for a number of material-related VOCs, for each season and annually, will be compared using the parametric and non-parametric methods mentioned above. The same analyses will be applied to formaldehyde and acetaldehyde data.

Unlike the VOCs and aldehydes, the only expected source of ozone in the RCs is outdoor air. Although most ozone entrained into a building is thought to react with interior surfaces of the HVAC system and room, it is possible that some remains in the air to expose occupants. It is possible that in a classroom that supplies more outside air may have higher indoor ozone concentrations. Thus, a comparison of the difference in indoor levels of ozone in between the intervention and control RCs will be of interest. These differences will be explored using the same parametric and non-parametric tests. It is anticipated that there will be seasonal and regional differences in the outdoor ozone concentrations at the schools.

Acoustical data will be assembled and three-dimensional sound level surfaces will be calculated. Area-weighted, A-weighted decibel calculations will be made for each full-study RC. These data, for the matched RC pairs, will be compared as above in order to statistically discern the differences in noise levels between the Intervention and Control RCs for the different modes of operation. Additionally, it will be possible, by calculating the number of hours per day in each operational mode, to calculate an estimated daily noise exposure for occupants of RCs with each HVAC type.

Particle measurement data will be downloaded from the OPCs after each day in the field. The data will be parsed into a different set for each RC and time period. Total, and cumulative size counts for both number and mass concentration will be calculated assuming a particle density of 1 gm cm⁻³. For particle mass calculations, OPC particle diameters will be skewed toward an estimated geometric mean for each size bin rather than the arithmetic mean, as the number concentration tends to increase non-linearly as the size diminishes. Estimated average indoor and outdoor respirable particle mass concentrations (particle diameter $\leq 2.5 \mu\text{m}$) and inhalable particles (particle diameter $\leq 10 \mu\text{m}$) for each RC and time period will be calculated. A comparison of the difference in indoor levels of respirable and inhalable particles between the intervention and control RCs will be conducted. These differences will be explored using the same parametric and non-parametric tests discussed above. It is anticipated that there will be seasonal and regional differences in the outdoor particle concentrations at the schools.

Thermal comfort data will be downloaded from the TC Carts after each day in the field. The data will be parsed into a different set for each RC and time period, and indoor location. Data analyses will be conducted using ASHRAE Standard 55-2004 to calculate acceptable thermal

comfort. The complex details of these analyses will be provided in subsequent reports. The primary thermal comfort index will be whether the conditions at each measurement point meets the ASHRAE 55 10% satisfaction definition of Acceptable Range of Operative Temperature and RH, accounting for allowable offsets at higher air movement rates. Once again, the differences between measured TC parameters in intervention and control RCs will be explored using the above parametric tests.

The benefits of the new controls for the advanced HVAC system will be assessed by inspecting the real-time usage information from the monitored HVAC power data. Evidence of consistent use of the outside air supply fan during occupied hours will indicate whether the goal of ensuring continuous ventilation through control strategies has been met. The number of daily hours of fan use in the intervention and control RCs will be compared for statistical differences. These data will be borne out by CO₂ and other IEQ parameters as well. The power data will be assessed to determine whether the Title 24 classroom pre-purge requirement has been met in the Intervention RCs.

Overall, the above analyses are expected to accurately address the goals of assessing the energy and IEQ benefits of the Advanced HVAC system.

Summary

This document has provided a summary of the detailed plans developed for the field study that will take place in 2005 to evaluate the energy and IAQ performance of a new classroom HVAC technology. The field study will include measurements of HVAC energy use, ventilation rates, and IEQ conditions in 10 classrooms with the new HVAC technology and in six control classrooms with a standard HVAC system. Energy use and many IEQ parameters will be monitored continuously, while other IEQ measurements will be performed seasonally. Continuously monitored data will be remotely accessed via a LonWorks network. Instrument calibration plans that vary with the type of instrumentation used have been established. Statistical tests will be employed to compare energy use and IEQ conditions with the new and standard HVAC systems. Strengths of this study plan include the collection of real time data for a full school year, the use of high quality instrumentation, the incorporation of many quality control measures, and the extensive collaborations with industry that limit costs to the sponsors.

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Tables

Table 1. The field study instrumentation.

| Parameters Measured | Instrument | Calibration method | Data collection rate/acquisition method |
|---|--|---|---|
| Air temperature | Onset Instrument, HOBO-Pro Series Temp Ext © loggers with a resolution of 0.02 °C and rated accuracy of ± 0.2 °C | NIST-traceable RTD system with 0.02 °C rated accuracy | Real-time, internal data logger – download monthly |
| Relative humidity | Onset Instrument HOBO® Temperature, RH © with rated accuracy of $\pm 3\%$ RH | Use of salt solutions to produce air with various reference values of humidity | Real-time, internal data logger – download monthly |
| Carbon dioxide concentration | California Analytical Instruments infrared analyzer, ZPF-9, 0-3000 ppm range | Cylinders of primary standard calibration gases | Real-time – data logged to i.Lon 100 web server, acquired continuously |
| Air Temperature, Relative Humidity, Carbon Dioxide (CO ₂) | PureChoice Nose™. Temperature (resolution 0.1 °C, rated accuracy ± 0.5 °C), RH (resolution 1% RH, rated accuracy larger of $\pm 10\%$ or $\pm 5\%$ RH), CO ₂ range 0-5000 ppm (resolution 10 ppm, accuracy greater of $\pm 5\%$ or 100 ppm). | NIST-traceable calibrations | Real-time – data logged to i.Lon 100 web server, acquired continuously |
| Ventilation rate | Tracer gas decay during unoccupied time using sulfur hexafluoride (SF ₆), or carbon dioxide tracer gas. Tracers monitored using infrared analyzers | Cylinders of primary standard calibration gases | Measured once a season per RC during site visits. Real-time data collected on laptop computer |
| Particle concentration, size distribution | Particle Measuring systems LASAIR Aerosol Particle Counter or equivalent multi-channel counter that detects particles as small as 0.2 micrometer | Factory calibration, and intercomparison with other aerosol instrumentation at LBNL | Measured once a season per RC during site visits. Real-time data collected on laptop computer |
| Aldehyde concentrations | 7-hour aldehyde samples collected onto treated silica-gel cartridges (WAT047205, Waters Corp.) with sample flow rate of 0.15 L/min. Analysis by high performance liquid chromatography with UV detection following ASTM standard method D-5197-97 (ASTM, 1997b). | Sorbent tubes spiked with known quantity of aldehydes | Samples collected once a season per RC during site visits. Analyzed at LBNL post sampling. |
| VOC concentrations | 7-hour VOC gas samples collected onto Tenax-TA™ sorbent tubes (CP-16251; Varian Inc.) modified by substituting a 15-mm section of Carbosieve S-III 60/80 mesh (10184, Supelco Inc.) at the outlet end. Sample flow rate will be 0.005 l/min. VOC samples analyzed by thermal desorption-gas chromatography/mass spectrometry generally following U.S. EPA Method TO-1 (U.S. EPA, 1984) | Sorbent tubes spiked with known quantity of VOCs | Samples collected once a season per RC during site visits. Analyzed at LBNL post sampling. |
| Ozone concentrations | 7-hour indoor and outdoor ozone passive samplers (Ogawa 3300) with Ion Chromatography (IC) analysis by IML Inc., Sheridan WY. | Nitrite to nitrate chemistry. Nitrate standards used to calibrate IC. | Samples collected once a season per RC during site visits. Analyzed at IML post sampling. |
| Sound levels | Sound spectrum meter for ~6 to 20 Hz spectrum such as the Bruel and Kjaer model 2260 | Factory calibration | Measured once a season/RC during site visits, collected on laptop computer |
| Power Monitoring | WattNode™ datalogging line power monitor measures true RMS power and energy consumption– logged continuously. Current measured with inductive current transducers simultaneously with line voltage. Accuracy of the WattNode™ is $\pm 0.5\%$ of reading over operating range. | Factory Calibration | Real-time – data logged to i.Lon 100 web server, acquired continuously |
| Thermal Comfort | LBNL Thermal Comfort Cart. ASHRAE Standard 55-2004. Measures air temperature, mean radiant temperature, relative humidity, and air velocity. | Factory Calibration and Calibration checks using NIST-traceable methods | Integrated datalogger downloaded after collection |