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ABSTRACT

Relocatable classrooms (RCs) are commonly utilized by school districts with changing demographics and enrollment sizes. Four energy-efficient RCs were designed and constructed for this study to demonstrate technologies that simultaneously attempt to improve energy efficiency and indoor environmental quality (IEQ). Two were installed at each of two school districts, and energy use and IEQ parameters were monitored during occupancy. Two (one per school) were finished with materials selected for reduced emissions of toxic and odorous volatile organic compounds (VOCs). Each RC had two HVAC systems, alternated weekly, consisting of a standard heat-pump system and an indirect-direct evaporative cooling (IDEC) system with gas-fired hydronic heating. The hypothesized advantages of the IDEC include continuous outside air ventilation at $\geq 7.5 \text{ L s}^{-1}$ per person, $\sim 70\%$ less cooling energy and efficient particle filtration. Measurements include: carbon dioxide, particles, VOCs, temperature, humidity, thermal comfort, noise, meteorology, and energy use. Preliminary IEQ monitoring results are reported.

INDEX TERMS

energy, indoor pollutants, ventilation, thermal comfort, schools

INTRODUCTION

Energy efficiency in buildings is a key design consideration regulated by governmental agencies. Buildings also can be designed to explicitly improve indoor environmental quality (IEQ). Designs that achieve good IEQ can be expected to have beneficial effects with respect to occupant health, work performance and absenteeism (Fisk, 2000). This study is being conducted with the goal of quantifying and demonstrating technologies that simultaneously attempt to improve energy efficiency and IEQ using new relocatable (modular or portable) classrooms as the exemplary buildings. Relocatable classrooms (RCs) are particularly well suited for this demonstration because they are self-contained structures with dedicated HVAC systems and well-defined occupancies. In addition, a large number of these units are being constructed in California (CA). Here, we present the design, status and preliminary results for a field study of four new high-performance (HP) RCs that have been constructed and located at two schools. This study is a collaboration among Lawrence Berkeley National Laboratory (LBNL), Davis Energy Group (DEG), a RC manufacturer, and two CA school districts.

The use of RCs in California schools has increased dramatically in recent years due to an increasing student population and to state and federal mandates for class size reduction. An estimated 75,000 RCs are currently in place in California schools, and the numbers are

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increasing at a rate of at least 10,000 per year (EdSource, 2002, Waldman, 2001). The most common RC configuration is the two module 7.2-m x 12-m, 86-m² (960-ft²) classroom, although a number of other styles, including a three module and two-story designs exist.

The HVAC system is a critical component of RC design from both energy and IEQ perspectives. Operating costs, electric demand, and other constraints influence HVAC design decisions such as equipment configuration, energy efficiency, and fuel source. The system also must be capable of providing adequate outdoor air ventilation since natural ventilation is often unfeasible and may be inadequate. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62-1999 (ASHRAE, 1999), as well as the State of CA Building Standards and Occupational Safety and Health Codes (CCR, 1995; CCR, Title 8) specify a minimum ventilation rate of 7.5 L s⁻¹ per person in nonresidential buildings. Ventilation delivered at this rate will typically maintain indoor occupant-generated carbon dioxide (CO₂) at less than 1000 parts-per-million (ppm).

Standard CA RCs typically provide a ducted supply-air all-electric 10 SEER (Seasonal Energy Efficiency Ratio) compressor-based wall-mounted HVAC system with a direct return through the wall. These units are equipped with a movable damper that can be set to provide up to 25% of the delivered supply from outside air, providing ventilation sufficient to supply 7.5 L s⁻¹ per person to about 30 occupants. In practice, the amount of outside air delivered to a classroom can be less due to fan on/off cycling or improper setup of the system. Additional HVAC characteristics affecting IEQ are mechanical noise and the efficacy of supply air filtration. Loud compressor and fan cycling noise is reported as disruptive to learning and results in reduced ventilation system usage. Air filtration, often minimal (10-20% ASHRAE dust spot efficiency) in many RC HVAC systems, is necessary to ensure low particulate matter (PM) concentrations indoors, especially in regions with elevated outdoor levels.

Considerable concern also has been generated regarding indoor levels of toxic and odorous volatile organic compounds (VOCs), including formaldehyde in classrooms, with special scrutiny placed on RCs. Careful selection of construction materials in combination with adequate ventilation can reduce baseline VOC concentrations and resultant occupant exposures to these chemicals.

METHODS

The field study phases include: school district and RC manufacturer recruitment; RC design specification and construction; RC installation at schools and instrumentation; field measurement and data collection during cooling and heating seasons; and data analysis. A concurrent energy simulation effort will enable extrapolation of collected energy data to predict energy savings by climatic zone and to conduct cost benefit analyses.

School districts and a RC manufacturer were simultaneously recruited for participation in the study. In order to test the RC designs in diverse climates, we wanted the schools to be located in two distinct regions: the CA Central Valley (extreme climate) and the San Francisco Bay Area (moderate climate). Several independent manufacturers in the CA modular classroom industry were approached. American Modular Systems (AMS, Manteca, CA) was willing to participate and had pending orders for numerous RCs from school districts in both of the desired regions. Through AMS, we secured agreements for placement of two HP RCs each at an elementary school in Modesto (MCS, Central Valley) and Cupertino (CUSD, SF Bay Area).

The HP RC design used in this study utilizes available energy efficient construction materials and methods including additional wall, floor, and ceiling insulation; ceiling vapor barrier, “Cool Roof” reflective roof coating, low-emissivity window glazing, and efficient (T8) fluorescent lighting (DEG, 2000). Each of the four study RCs are equipped with two HVAC systems: a standard 10 SEER heat-pump system, and an energy-efficient indirect/direct evaporative cooler (IDEC). The IDEC supplies continuous ventilation at $\geq 7.5 \text{ L s}^{-1}$ per person even when heating or cooling is not required. Additionally, compared to the standard heat-pump system, it consumes about 70% less cooling energy, and as it has no compressor and a very quiet fan, the noise output from the system is much lower. Incorporated into the IDEC is an 85% efficient (AFUE) gas-fired hydronic space heating system and an inlet filter system with 65% ASHRAE dust spot efficiency (Apte et al., 2001). Both the IDEC and the heat pump system controls, as currently designed, require that the system be turned on in order to provide the required ventilation. In the case of the heat pump system, this action is tied to the temperature set point, such that outside air is only supplied when heat or cooling is needed.

In order to study VOC source reduction potential, one RC at each school received alternative low-VOC emitting wall panels, carpet, and ceiling panels (Hodgson et al., 2001 and 2002). Otherwise, all four RCs were constructed identically.

Table 1. IEQ and energy monitoring instrumentation in study relocatable classrooms.

<i>Parameter</i>	<i>Method¹</i>	<i>Mfr. / Model</i>	<i>Location²</i>
<i>Continuous:</i>			
Carbon Dioxide	NDIR	Fuji / ZFP-9	I, O
Particle size, count	Laser counter	Met One / 237B	I,O
Relative Humidity	Capacitance	General Eastern/MRH	I, O,HPD, ID, TC, C
Temperature	Thermistor	YSI/44018 and 44303	I, O,HPD, ID, TC, C,
Air Velocity	Thermo-anemometer	Sensor Elect. & Meas. Equip. / HT412-2	TC
Sound Level	dB, A-wtd., Leq	Extech/407736.	C
Door open	Door sensor	LBNL	Door
Window position	LDP	JK Controls/LDP-500	
Wind speed, dir.	Anemometer	Davis/Industrial #7914	O
Electricity	Current transducer	CCS/Wattnode	HVAC, Lights, Total
Natural Gas	Gas meter	Equimeter/pulse output	IDEC Heating
<i>Time-averaged:</i>			
VOC	Multisorb GC/MS	LBNL ³	I, O
Formaldehyde, acetaldehyde	DNPH HPLC UV detector	LBNL ³ /Waters	I, O
Thermal Comfort	ASHRAE 55-1992	LBNL ⁴	I (0.1m, 0.5m, 1.1m)

¹NDIR=non-dispersive infrared; multisorb=multisorbent tubes GCMS=gas chromatography/mass spectrometry; HPLC=high performance liquid chromatography, LDP = linear displacement potentiometer; A-wtd=A-weighted, Leq = equivalent noise level

²I=Indoors, O=Outdoors, HPD=Heat pump system diffuser, ID=IDEC Diffuser, TC=thermal comfort cart, C=Indoors@ 2.5m, center of RC, m=meters above floor

³See Hodgson *et al.*, 2001 ⁴See ASHRAE, 1992

Two HP RCs were sited side-by-side at each of the schools prior to the fall 2001 semester. They were occupied and used by 3rd and 4th grade classes consisting of 20-25 students and one teacher. During nine weeks of the 2001 summer/fall cooling season (August-October 2001)

and currently during nine weeks of the heating season (January-March 2002) the two RCs at each school were simultaneously operated with either the standard heat pump or the IDEC unit, switching weekly. Each RC is instrumented to measure a range of IEQ and energy parameters (Table 1). Indoor and outdoor CO₂ concentrations are measured continuously. The particle counters measure particle number concentrations in six size ranges from 0.3 to 10 micrometers. Real-time data are stored as 6-minute averages to a central data acquisition system (CDAQS) operated continuously. During the study period, all four RCs are visited once a week (typically Tuesday or Thursday). Data stored on the CDAQS is retrieved. Integrated, 8-hour indoor and outdoor VOC and aldehyde samples are collected and later analyzed. A thermal comfort cart, designed and constructed at LBNL based upon ASHRAE 55-1992 thermal comfort standard (ASHRAE, 1992), is operated in three locations representative of occupant placement in each classroom during break periods. Observational information on HVAC usage, teacher and student clothing levels, and an inventory of cleaning and classroom supplies is collected. At the end of the school day, the system operation is switched from the standard HVAC to the IDEC, or visa-versa.

RESULTS AND DISCUSSION

As of this writing, data analysis is in progress and only preliminary results from the IEQ monitoring are available. Thus, the results are observational rather than quantitative. The RCs were sited and commissioned at the beginning of the 2001 school year. The participating teachers and school custodians received training on the operation of the two HVAC systems and were briefed on field visit procedures and the schedule of weekly system switching. They were instructed to turn the HVAC system control on at the beginning of each school day. In order not to bias the teachers' behavior, we avoided discussing IEQ issues with the teachers and simply described the project as a study to test a new energy-efficient, quiet HVAC system.

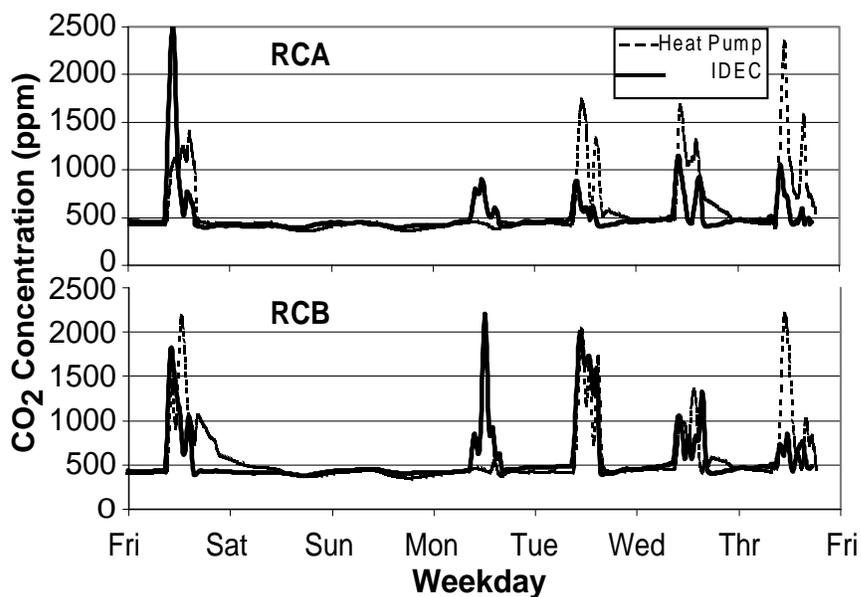


Figure 1. Indoor carbon dioxide concentrations in Cupertino study classrooms (RCA and RCB) during two consecutive weeklong cooling periods. The IDEC was operated during one week and the heat pump system was operated during the other.

Figure 1 displays weeklong indoor CO₂ concentrations in the two CUSD RCs for consecutive standard heat pump and IDEC weeks during the cooling season. No occupancy or HVAC

operation occurred during Saturdays or Sundays. The CO₂ data support a pattern verified by the energy and HVAC control data. The teachers' operation of the HVAC systems was not solely based upon cooling demand, and they did not always turn the IDEC on in the morning as instructed. During periods when the teachers did not provide ventilation, the CO₂ concentrations in the classrooms were elevated well above 1000 ppm, with peaks reaching about 2000 ppm, irrespective of the HVAC system. Note that during Monday of the IDEC week there was a field trip and both RCs were vacant. On Thursday of the IDEC week, our field staff was onsite and reminded the teachers to operate their systems the entire day. Indoor CO₂ concentrations on that day were well below 1000 ppm. Likewise, the CO₂ levels in RCA (but not RCB) reflect operation of the IDEC as instructed on Wednesday.

Table 2. Average (standard deviation) daytime indoor/outdoor particle-count concentration ratios in Cupertino study classrooms RCA and RCB during consecutive heat pump and IDEC weeks.

	Fri	Sat	Sun	Mon	Tues	Wed	Thr
	RCA						
IDEC	0.9 (0.2)	0.6 (0.0)	0.5 (0.0)	0.5 (0.1)	0.6 (0.1)	0.5 (0.0)	0.5 (0.1)
Heat Pump	1.0 (0.2)	0.7 (0.1)	0.6 (0.1)	0.7 (0.1)	0.7 (0.1)	0.6 (0.1)	0.6 (0.1)
	RCB						
IDEC	0.6 (0.1)	0.5 (0.1)	0.2 (0.1)	0.3 (0.1)	0.5 (0.1)	0.3 (0.0)	0.3 (0.0)
Heat Pump	0.8 (0.3)	0.4 (0.0)	0.3 (0.0)	0.4 (0.1)	0.5 (0.1)	0.6 (0.1)	0.4 (0.1)

Average (\pm standard deviation) daytime indoor particle number concentrations in the same classrooms during the same weeks were $64 \pm 55 \times 10^6$ and $47 \pm 45 \times 10^6$ particles m^{-3} for RCA and RCB, respectively. The simultaneous outdoor particle concentrations were $98 \pm 87 \times 10^6$ particles m^{-3} . The large standard deviations of particle concentrations reflect the variability of daytime particle concentrations. Table 2 presents daytime (8:00-15:00) indoor to outdoor (I/O) cumulative particle count ratios (sum of all size bins). The I/O ratio was highest on both Fridays. This is consistent with the elevated CO₂ levels (Figure 1) and is most likely due to the combination of low ventilation and re-suspension of particles by the occupants. During Monday through Thursday on both IDEC and standard heat pump weeks, the I/O ratios were well below unity, but consistently lower during IDEC operation. On Thursday during proper IDEC operation, the ratio was about 0.5 in RCA and 0.3 in RCB. Overall it appears that particle infiltration from outdoors or indoor particle re-suspension was less in RCB.

Preliminary findings from the VOC measurements made in the RCs when they were operating with the IDEC system are presented elsewhere (Hodgson et al., 2002).

As discussed above, the teachers' patterns for operation of their HVAC systems directly influenced classroom IEQ parameters during the school day. As noted, both systems, as currently designed, must be turned on in order to provide the required ventilation. The heat pump thermostat does provide a "Fan Only" setting, but the teachers may prefer not to use it due to fan noise. The IDEC control requirement is only that it be on during occupancy since its fan provides continuous 100% outside air when it is turned on. In some cases the decision to not turn the systems on is based upon a desire to save energy. For example, to save energy one teacher in the study regularly opened the RC windows during the morning instead of running the HVAC. The resulting indoor CO₂ levels often rose above 1000 ppm indicating that windows alone may not have provided adequate ventilation for the 21 occupants.

Data analyses will include multivariate regressions measuring operational parameters against the IEQ metrics, in order to identify the effectiveness of the IDEC system. Thermal comfort data will be analyzed to identify the extent to which the IDEC system is able to provide a thermally acceptable environment. Energy analyses will provide a basis for estimating the cost effectiveness of this HP RC package including the IDEC system as an alternative to the standard RC designs currently in use.

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