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Improving Ventilation and Saving Energy: Laboratory Study in a Modular Classroom Test Bed

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Glossary

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

Acronym	*Definition**
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
CFM	Cubic feet per minute, a measure of ventilation rate per occupant
CO_2	Carbon dioxide
dB(A)	A-weighted decibels, measurement of noise level
DOE	United States Department of Energy
hr^{-1}	Units for air exchange rate
HPAC	Heat pump air conditioner
HVAC	Heating, ventilation, and air conditioning system
IEQ	Indoor air and environmental quality
IHPAC	Improved heat pump air conditioner
IVSE	Classroom HVAC: Improving Ventilation and Saving Energy
L	Liters
LBNL	Lawrence Berkeley National Laboratory
PHPS	Performance of the Heat Pump System
RC	Relocatable, or portable or modular, classroom
RH	Relative humidity, measured as percentage
RMS	Root Mean Square
SEER	Seasonal energy efficiency rating

ABSTRACT

The primary goals of this research effort were to develop, evaluate, and demonstrate a practical HVAC system for classrooms that consistently provides classrooms with the quantity of ventilation in current minimum standards, while saving energy, and reducing HVAC-related noise levels. This research was motivated by several factors, including the public benefits of energy efficiency, evidence that many classrooms are under-ventilated, and public concerns about indoor environmental quality in classrooms. This project involved the installation and verification of the performance of an Improved Heat Pump Air Conditioning (IHPAC) system, and its comparison, a standard HVAC system having an efficiency of 10 SEER. The project included the verification of the physical characteristics suitable for direct replacement of existing 10 SEER systems, quantitative demonstration of improved energy efficiency, reduced acoustic noise levels, quantitative demonstration of improved ventilation control, and verification that the system would meet temperature control demands necessary for the thermal comfort of the occupants. Results showed that the IHPAC met these goals. The IHPAC was found to be a direct bolt-on replacement for the 10 SEER system. Calculated energy efficiency improvements based on many days of classroom cooling or heating showed that the IHPAC system is about 44% more efficient during cooling and 38% more efficient during heating than the 10 SEER system. Noise reduction was dramatic, with measured A-weighed sound level for fan only operation conditions of 34.3 dB(A), a reduction of 19 dB(A) compared to the 10 SEER system. Similarly, the IHPAC stage-1 and stage-2 compressor plus fan sound levels were 40.8 dB(A) and 42.7 dB(A), reductions of 14 and 13 dB(A), respectively. Thus, the IHPAC is 20 to 35 times quieter than the 10 SEER systems depending upon the operation mode. The IHPAC system met the ventilation requirements and was able to provide consistent outside air supply throughout the study. Indoor CO_2 levels with simulated occupancy were maintained below 1000 ppm. Finally temperature settings were met and controlled accurately. The goals of the laboratory testing phase were met and this system is ready for further study in a field test of occupied classrooms.

INTRODUCTION

The primary goals of the “Improving Ventilation and Saving Energy” (IVSE) project were 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 stimulate increased use of advanced classroom HVAC in the market through interaction with key school facility stakeholders.

The need for an improved classroom ventilation system is based, in part, on the considerable evidence, summarized in Daisey et al. (1998, 2003), indicating that ventilation rates in classrooms often do not meet the current ASHRAE minimum rate of 15 CFM per occupant (ASHRAE, 2004). While relatively few measurements of actual classroom ventilation rates are available, concentrations of CO_2 in classrooms 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 classrooms (also called relocatable classrooms or RCs), CO_2

concentrations exceeded 1000 ppm in about 40% of classrooms and concentrations exceeded 2000 ppm in approximately 10% of classrooms (CARB-DHS 2003). In a survey of 400 classrooms in Washington state and Idaho (Shendell et al. 2004), CO_2 concentrations measured at random times in 45% of classrooms exceeded 1000 ppm, thus, a considerably larger fraction of steady state or peak CO_2 concentrations would have exceeded 1000 ppm.

Further evidence of low classroom 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 are aware that ventilation rates in classrooms are often low because teachers frequently operate classroom 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. We also observe 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 classroom HVAC systems.

Several statutes and standard address the provision of adequate ventilation in California classrooms. Continuous ventilation is required in California Classrooms under both state energy and occupational laws (CA Title 24 2001, CCR 1995) and is a required component of ASHRAE Standard 62.1 (ASHRAE 2004).

The relocatable classroom (RC) HVAC industry has been incrementally addressing the classroom noise levels generated by the wall mount heat pump air conditioner (HPAC) that they produce. For example, in the late 1990s Bard Manufacturing Company developed a 12 SEER "Quiet Climate" model to meet specifications from the Los Angeles Unified School District (LAUSD, 1998). This unit was designed to operate at indoor sound levels ≤50 dB(A) measured at a point 3m (10') from the return grille and 1.5m high. This model is the current state of the art, with a relatively small market penetration in California. Unfortunately, 50 dB(A) is not currently considered an adequate target for classroom sound levels. The Collaborative on High Performance Schools (CHPS) recommends unoccupied classroom levels to be at or below 45 dB(A) (CHPS 2002). Additionally, the Acoustical Society of America (ASA) provide a guideline for classrooms of 35 dB(A) (ASA 2002).

A great deal of energy is used to condition ventilation air in high occupancy spaces such as classrooms. 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 finding 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 CO_2 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 CO_2 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 studies indicate that ventilation rates have important effects on the health of occupants.

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.

LABORATORY STUDY OBJECTIVES

The objectives of this controlled laboratory study were to evaluate the energy, ventilation, and IEQ performance of the advanced HVAC system relative to a standard, widely used, 10 SEER HVAC system. With respect to this laboratory study the specific goals were as follows.

<u>Quantitative Energy Consumption Goal/Expectation</u>
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.

<u>Quantitative Noise Reduction Goal/Expectation</u>
The advanced HVAC system is designed to significantly cut classroom 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.

<u>Physical System Integration Goals/Expectations</u>
HVAC system meets general physical dimension and integration characteristics suitable for mounting on new and existing relocatable classrooms in California. This requirement is extremely important for market transfer.

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

Quantitative Ventilation System Improvement Goals/Expectations
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

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.

HVAC system maintains indoor CO_2 levels below 1000 ppm
Goal - show under simulated classroom occupancy (using CO_2 gas cylinders) that CO_2 levels can be maintained < 1000 ppm 100% of the time given simulated generation from 31 or fewer occupants

HVAC system can provide thermal conditioning at air velocities and temperatures that meet ASHRAE 55 thermal comfort standards (ASHRAE, 2004).
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.

METHODS

HVAC systems and controls, installation, and commissioning

HVAC systems and controls

The 10 SEER unitary vertical wall-mount HPAC system is the most common and frequently installed HVAC system on RCs in California. Although lower efficiency wall-mount systems are to be found on numerous older RCs, those installed in the last ten years are likely to have a 10 SEER rating. As discussed above, at least one manufacturer has put a similar system on the market that achieves as 12 SEER rating in addition to some attempts to improve the acoustic design. The improved HPAC system (IHPAC) developed in this study maintains the same wall-mount configuration and installation form factor while attempting to address perceived design deficits in the areas of energy efficiency, acoustics, ventilation control, thermal control, and refrigerant types. Brief descriptions of the 10 SEER and IHPAC systems are as follows.

10 SEER. The 10 SEER system was designed to meet the then current California state residential energy efficiency standard of 9.7 SEER (CEC 1999). The 10 SEER system installed for this study is Bard Manufacturing Co. packaged unit operating of single-phase 240VAC power. It consists of a single stage reversible heat-pump compressor, with conventional evaporator coil in the supply air stream, and a condenser coil exposed to the outdoor air. The 10 SEER HVAC systems in use operate with standard HCFC refrigerant. The system utilizes two standard fan motors, one for the supply air fan and one for moving air across the condenser coil. The unit includes a classroom ventilator (CRV) with a motor-driven louver situated such that the

supply air fan draws a set percentage of outside air into the RC and rejects an equal amount of return air from the system. The CRV receives a signal from the HVAC control to open when outdoor air is required, and shut when it is not.

The 10 SEER control can range from a weekly programmable setback timer thermostat to a simple single program type mixed heating and air conditioning thermostat. An additional manual setting on the thermostat allows the teacher to turn on the fan independently if desired, allowing for continuous ventilation. A programmable setback timer was used in this study. The key point regarding this control system is that the CRV louver operation and supply air fan operation are tied to the thermostat setpoint. Thus, air recirculation and outside ventilation air are only provided to the classroom during off-setpoint (i.e., heating or cooling) periods. The 10 SEER HVAC systems were installed and operated using the existing standard that requires that the fan be operated continuously to supply outside air during occupied hours.

IHPAC. LBNL worked with Bard Manufacturing Co. to develop a set of design goals to engineer an *improved HPAC* system based upon the project goals discussed above. The manufacturer then engineered, fabricated and tested a number of prototypes in their factory. A final functional prototype meeting the manufacturer's design was then shipped to LBNL and installed for testing. The basic layout of the unit is very similar to the 10 SEER system with the following differences. The compressor is more energy efficient and operates in two-stages and uses an alternative to an HCFC refrigerant in anticipation of the 2010 HCFC refrigerant phase-out (USEPA, 2004). The supply air fan motor is an energy efficient electronically commutated type. The condenser and evaporator coils are re-configured to optimize energy efficiency within the constraints of the package size. The entire system was re-engineered to minimize acoustic noise and mechanical vibration.

The IHPAC was installed with an automatic "smart controller". This controller was developed for the IHPAC by Bard Manufacturing as part of this project. It was 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 control interface is limited to a simple temperature setting adjustment, using up-arrow and down-arrow buttons to provide a locked indoor temperature range (set by a technician in the field to ±4.0ºF (2.5ºC) 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 also includes a pre-occupancy ventilation purge of three air changes (roughly one hour) as required by California Title 24.

LBNL RC Test Bed

A modular, RC, on loan from a major leasing firm, was installed and commissioned at LBNL. Interior and exterior photographic views of the installation and setup may be seen in Figures 1 and 2. The RC consisted of two modular halves, each 3.7m (12') by 12m (40'), with a ceiling

height of 2.7m (9'), to form an 89 m^2 (960 ft^2) floor. The RC modules were mirror images of each other, each set up with a complete HVAC system and independent electrical system. Unlike most RCs, this unit did not have any windows since most RCs are manufactured with the window on one module and the HVAC on the opposite module. The RC ceiling consisted of a 60cm (24") T-bar grid with typical fiberglass acoustic ceiling tiles.

Both RC modules were delivered with a standard 10 SEER Bard HVAC system with a Bard adjustable classroom ventilator louver system installed internally. The return grille (aprox. 46 cm by 76 cm) of each unit was installed at the standard positions on the rear 7.2m long (24') wall, approximately 1.5m (5') above floor level. Each system was equipped with a sheet metal supply plenum connected to three 30cm (12") insulated flexible supply ducts terminating at three supply diffusers located at approximately 3m (10'), 6m (20'), and 9m (30') from the end wall along the ceiling midpoint of each RC module. The 60cm modular supply diffusers transitioned from 30cm duct to a 30cm square configuration sheet metal-finned discharge area.

One of the 10 SEER HVAC systems was removed after delivery and replaced with a new prototype Bard system (IHPAC) designed to meet the targeted improvements described above. This system also incorporates a classroom ventilator. The IHPAC was ducted similarly to the 10 SEER system, with the exception that the supply diffusers were sized with a 45cm (18") square discharge area. The supply diffusers were placed in the same position as those of the 10 SEER units.

Instrumentation

The instrumentation used in this study is shown in Table 1. Real-time data were stored in an APS datalogger at one-minute intervals and downloaded from the APT datalogger. Total RMS power consumption was measured on each sub-system of the HVAC systems using datalogging power meters. Indoor and outdoor temperature, RH, and CO_2 concentrations were measured in the RC continuously. The outdoor monitoring position was under the eves of the RC roof with a radiation shield placed to reduce radiant heating of the temperature sensor. Indoor monitoring was located on a stand placed in the center of the RC at a height of approximately 1.5m (5'). Temperature and RH were also monitored in the mid-room supply diffuser and in the return plenum of each HVAC system. Acoustical noise was measured using a hand-held sound level analyzer, with a protocol described below.

Measurements of air supply, return, and ventilation

Outside air supply flowrates and supply register flowrates were measured using an active flow hood method (Walker et al. 2001). This method consists of coupling a standard hood with a calibrated fan with integral flow meter, and the 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 equals zero between the room air and interior of the hood at the connection with the register. 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 in the measurement system 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) were set to 15 CFM per occupant, or 465 CFM to represent a class of 30

students and one teacher. The three supply registers were be balanced to split the total supply flow equally (about 500 CFM per register).

Air exchange rates were measured using a steady-state method. Two tracers were measured: CO_2 and SF_6. When using CO_2, the air exchange rate was calculated after subtracting the outdoor CO_2 concentration, using the CO_2 source injection rate.

The steady state tracer method involves injection of SF_6 into the classroom at a constant rate using a low-flow pump to supply the pure gas from a multi-layer gas bag and calculating the air exchange rate from the steady state tracer concentration. The SF_6 concentrations were measured with a portable Miran Sapphire infrared gas analyzer (Thermo Electron Corp., Waltham MA) with an internal datalogger and CO2 was measuring using the sensors described in Table 1. With the steady state method, the air exchange rate was calculated using Equation 1.

$$a = S_{tracer} / [(C_{ss} - C_{out})\ V] \qquad (1)$$

Where,

a = the classroom air exchange rate (h^{-1}),
S_{tracer} = the tracer gas (CO_2 or SF_6) source rate ($m^3\ h^{-1}$),
C_{ss} = the measured steady-state concentration of the tracer in the RC,
C_{out} = the measured average outdoor concentration of the tracer at the time of indoor steady-state measurements, and
V = the internal volume of the RC (m^3).

The outside air supply rate ($m^3\ h^{-1}$) measured in this fashion is merely:

$$Q = Va \qquad (2)$$

The source injection rates of CO_2 and SF_6 were set to $0.147 m^3\ h^{-1}$ (2450 ml min^{-1}) and 7.5×10^{-4} $m^3\ h^{-1}$ (12.5 ml min^{-1}), respectively. Due to instrument failure during the March 2005 testing period no usable CO_2 or SF_6 data were collected.

Modeling of HVAC energy efficiency

The mathematical model used in this study to compare the energy efficiency of the IHPAC to the standard 10 SEER HVAC system is as follows. A stream of air with flow rate Q_r (m^3/sec), at T_r (°C) dry-bulb temperature and ϕ_r (% RH), is returned and mixed with a stream of outdoor air with flow rate Q_o (m^3/sec) at T_o (°C) dry-bulb temperature and ϕ_o (% RH). The resulting mixture is then processed through the heat pump and supplied into the indoor. The supply air flow rate Q_s (m^3/sec), is at T_s (°C) dry-bulb temperature and ϕ_s (% RH).

The total amount of cooling (indoor heat withdrawn) and heating (indoor heat addition), performed by the heat pump, can be calculated as shown in equation (3). The required properties (m_i, h_i) come from the measured T_i, ϕ_i, and Q_i (i=o(outdoor), s(supply), r(room)) as shown in equations (4)~(9).

Total performed cooling or heating $= \int m_r \,|\, h_r - h_s \,|\, dt + \int m_o \,|\, h_o - h_s \,|\, dt$ (3)

when $T_r > T_o$ (heating) or $T_r < T_o$ (cooling).

Where

t is the time variable

$m_i = \frac{Q_i}{\nu_i}$ (kg sec-1), (4)

Q_i = volumetric flow rate at the point i (m^3 sec^{-1}, measured property in this study),

ν_i = specific volume of the moist air at point i (m^3 kg^{-1}),

$\nu_i = \frac{Ra T_i}{P}(1 + 1.6078 w_i)$, (5)

R_a = universal gas constant 8.31441 KJ Kg^{-1} mol^{-1} K^{-1},

T_i = absolute temperature at point i (°K, measured property in this study),

P = total pressure (Pa),

W_i = humidity ratio of the moist air at point i (Kg water vapor per Kg dry air),

$w_i = 0.62198 \frac{P_{wi}}{P - P_{wi}}$, (6)

P_{wi} = partial pressure of the vapor at point i (Pa),

$P_{wi} = \phi_i P_{wsi}$ (7)

ϕ_i = relative humidity at point i, (dimensionless, measured property in this study)

P_{wsi} = saturation pressure of water vapor at point i (Pa),

$P_{wsi} = \exp\left(C_8 / T_i + C_9 + C_{10} T_i + C_{11} T_i^2 + C_{12} T_i^3 + C_{13} \ln(T_i)\right)$, and where (8)

$C_8 = -5800.2206$,

$C_9 = 1.3914993$,

$C_{10} = -0.04860239$,

$C_{11} = 0.41764768 \bullet 10^{-4}$,

$C_{12} = -0.14452093 \bullet 10^{-7}$,

$C_{13} = 6.5459673$, and where

$h_i = t_i + w_i (2501 + 1.805 t_i)$, with (9)

h_i = the moist air enthalpy at point i (KJ Kg^{-1} dry air),

t_i = dry-bulb temperature at point i (°C, measured property in this study).

The overall performance of an installed heat pump system can be described by a Performance of the Heat Pump System (PHPS). PHPS is defined as the total amount of cooling and heating divided by the total electricity consumption in operating a heat pump.

$$\text{PHPS} = \frac{\text{total cooling and heating}}{\text{total electricity consumed by the heat pump}} \quad (10)$$

PHPS measures how much cooling or heating is provided for each unit of electricity energy consumed. This metric incorporates the comprehensive results of the heat pump performance,

thermal performance of the building envelope, indoor flow effectiveness, and the controllers' performance.

HVAC testing schedule

In order to test both the 10 SEER system and the IHPAC system in both heating and cooling modes it was necessary to conduct tests in both cooling and heating seasons. The study began with testing of the 10 SEER HVAC system in September 2004. Unfortunately, due to delays, delivery schedules, and weather, only a few days of cooling data were collected for the 10 SEER system prior to installation of the IHPAC. Again, only a few days of cooling data were collected on the IHPAC system prior to a change in weather. The IHPAC was operated on a continual basis from September 27 to November 24. Some days of mixed heating and cooling occurred. In March of 2005 more 10 SEER data were collected with both heating and cooling periods.

HVAC operation modes and simulated occupancy

The 10 SEER system was operated in the recommended operation mode with the outside air ventilation fan on continuously and heat pump compressor operating on demand from the thermostat. The thermostat was scheduled to turn on in the morning at 8:00 AM and off at 3:30 PM. The IHPAC was operated using the Bard automatic controller described above. Thus, the outside air ventilation fan operated based on simulated occupancy as discussed below.

In order to simulate student occupancy, timers were set up to control a number of functions on a pre-set schedule: sensible heat generation, carbon dioxide generation, and occupancy. The classroom had a standard desk layout using two rows of three 76cm (30") by 2.4m (8') tables centered in the middle of the classroom. Thirty 60W light bulbs, connected to a timer, were placed along the length of the tables to simulate the heat load of thirty students. A pipe with sections of porous tubing (1/2" drip irrigation tubing) was run along the table above the light bulbs, connected to a cylinder source of pure CO_2 metered into a mixing chamber through a mass flow controller. On signal from the timer, the air pump mixed the CO_2 with room air and pumped it through the porous tubing. The source rate of CO_2 (2450 ml min^{-1}) was selected to simulate respiration from 30 students. Due to instrument failure during the March 2005 testing period no usable CO_2 data were collected.

The IHPAC control system senses occupancy with an infrared occupancy sensor. To trigger the occupancy sensor at the desired times, a mirror mounted on a motor revolving at about 6 RPM was used to reflect light off of a heat lamp. The motor and lamp were actuated using a timer as well. The controller reliably sensed occupancy conditions when the infrared heat signal from this assembly was turned on.

The timer schedule was set to Monday through Friday from 8:00h to 14:00h. A 45 minute lunch break at noon, and two fifteen minute recess breaks at 10:00 and 13:30h were included when occupancy was set to zero by turning off the timer switch. During these times the IHPAC occupancy sensor reported no occupancy, and the CO_2 injection and light bulbs were turned off. The 10 SEER system was not turned off during these breaks, so its operation was dependent upon the thermal loads in the RC.

Acoustic noise experimental setup and testing

Acoustic noise levels in the RC were measured for both the 10 SEER and IHPAC units under a range of operational modes and conditions. In addition, the 10 SEER HVAC unit was operated and tested using two experimental sound abatement approaches: an on-site fabricated return wall sound plenum, and a Bard prototype sound curb. These are described more fully below.

The sound measurement protocol consisted of measuring the acoustic spectra of sound pressure levels at distance of 3, 6, and 9 meters (10', 20', and 30') from (and perpendicular to) the rear wall of the RC and at a distance of 3 meters at a angle of 45 degrees off of the rear wall, all at a height of 150 cm (5'). The sound pressure spectra were measured at these locations under the following conditions: all devices in the RC turned off, lights on only, the HVAC outdoor air fan on only, the HVAC fans and compressor on, and in the case of the IHPAC, the fans and compressor on in second stage mode. The measurements were conducted both with lights on, and with lights off. A full set of measurements were also collected at a height of 91 cm (3'), but the sound levels were very close to those at 150 cm, so these measurements were discontinued. The sound level measurements that are presented in this paper are from the lights-off conditions for the purpose of inter-comparison between the different systems and modes.

Sound pressure spectra were measured with and without weighting. Noise Criteria (NC) values (ASHRAE, 2005) were calculated from un-weighted measured sound pressures. A-weighted sound pressures (dB(A))were recorded using the B&K sound level meter's internal software. Measured dB(A) and NC levels are both presented in this paper as they are the two most commonly used metrics for assessing indoor noise level conditions in classrooms and other occupied indoor environments.

RESULTS AND DISCUSSION

HVAC Installation

The IHPAC system was installed at the LBNL RC test bed in September 2004. To make room for the IHPAC, one of the two existing 10 SEER systems and the associated supply plenum was removed and stored for future replacement. The IHPAC and its supply plenum were installed on the existing wall with no alterations to the framing, siding, or interior wall. The replacement was an exact fit and the return register did not need to be moved or altered. No power wiring changes were required. New wiring for the smart control system was required, but was not an involved installation.

HVAC Control, Temperature and Humidity

HVAC control

The 10 SEER HVAC control worked as designed. During the daily-simulated occupancy periods with 10 SEER operation, the thermostat was set to manual fan in order to simulate the Title 24 requirement for continuous ventilation during occupancy. No problems in function were observed. The IHPAC system smart controller was somewhat problematic during the entire laboratory study. The basic functions worked as expected: Thermal control, occupancy sensing to control outdoor air supply, and the learned pre-occupancy ventilation purge worked without problems. However, during the heating season the smart controller was observed to switch to cycle heating on during the night when indoor temperatures were not below the setback temperature (55°F). This problem led to frequent heating of the RC during the nighttime. For

this reason, the energy analyses below are provided for both school day and 24-hour time periods. Note that this problem was subsequently traced to the value of a time constant in the smart controller software and has been fully remedied, however this fix did not occur until the field study component of this project was under way.

Measured Temperature and Humidity

Table 2 presents measured temperature data for each study school day (08:00 to 15:00h periods) in the RC for both the 10 SEER and IHPAC HVAC systems. The tables also show whether the HVAC system was operating in cooling, heating, or mixed heating and cooling mode (i.e., heating in AM and cooling in PM). Measurement statistics include average, standard deviation, minimum and maximum values. Across both HVAC systems, the school day average indoor temperatures during cooling days ranged from 71.6 °F to 78.0°F with an average across the study of 75.4 °F. Similarly, for heating, the temperature range was 69.8°F to 75.0°F with an average across the study of 71.8°F. During days with mixed heating and cooling the temperature range was 70.3°F to 75.1°F with an average across the study of 73.1°F. Average school day outdoor temperatures ranged from 58.7°F to 80.1°F, 59.0°F to 65.5°F, and 55.9°F to 71.7°F for cooling, heating and mixed-mode conditioning, respectively. Averaged school day average indoor temperatures during 10 SEER and IHPAC cooling operation days were within 1.5 °F, and a Student's t-test indicated that the temperature distributions were not statistically different ($p<0.05$). During heating mode test days, average school day indoor temperatures were within 0.5 °F but were statistically different ($p>0.05$). Further details may be seen or calculated from complete data in Table 2.

Temperature control appeared to be adequate in both systems, with average temperatures falling close to the set points of 75°F for cooling and 72°F for heating. The differences seen between systems are likely to be due to slight differences in operation and calibration of thermostats. Certainly thermal comfort due to temperature alone would not be different between the two HVAC systems based on the data collected.

Similarly, Table 3 presents measured RH data for each study school day in the RC for both the 10 SEER and IHPAC HVAC systems. Across both HVAC systems, the school day average indoor RH during cooling days ranged from 22.3% to 52.0% with an average across the study of 39%. Similarly, for heating, the RH range was 24.2% to 52% with an average across the study of 44.3%. During days with mixed heating and cooling the RH range was 35.1% to 52.1% with an average across the study of 46%. Average school day outdoor RH ranged from 21.8% to 89.9%, 34.4% to 95.5%, and 45.5% to 86.9% for cooling, heating and mixed-mode conditioning, respectively. Mean school day average RH during 10 SEER (42% RH) and IHPAC (30.5% RH) cooling operation days were different by almost 12% RH, and a Student's t-test indicated that their RH distributions were statistically different ($p>0.05$). During heating mode test days, the average school day RH was much closer (10 SEER= 45.9%; IHPAC = 43.7%), within <3% RH but were still statistically different ($p>0.05$). Further details may be seen or calculated from complete data in Table 3.

That the average indoor RH was so different between HVAC systems during cooling mode periods was due to a greater difference in outdoor RH during the different testing periods. The corresponding average school day outdoor RH was 55.2% and 38.4% for the 10 SEER and

IHPAC, respectively. In contrast, the mean school day average outdoor RH levels were 73.7% and 75.4% during heating mode periods for the 10 SEER and IHPAC, respectively. As would be expected when using a vapor compression system, some water is removed from the conditioned air during cooling, reducing the absolute humidity in the supply air. The reader should bear in mind that during these tests only sensible load, and no latent load, was added during the "occupied" time periods. Thus a real comparison of thermal comfort that includes the humidity component is not addressed here. These comparisons will be available in the field component of this project.

Indoor CO_2

Table 4 summarizes school day statistics for Indoor CO_2 measured at the center of the RC at a height of 1.5 m. With the exception of one day (10/19) the mean school day average CO_2 concentration during IHPAC operation was 493±45 ppm and the minimum and maximum average concentrations were 390 and 560 ppm, respectively. The only 10 SEER measurements captured in this table are for 9/15/04, and the CO_2 concentrations for that day are consistent with those from the IHPAC dates. On three days (10/18, 11/17, & 11/18) the outdoor air supply was turned off during part of the day leading to elevated CO_2 concentrations.

Outdoor Air Supply Rate Measurement

Table 5 summarizes the outdoor, and HVAC supply and return CO_2 concentrations for each study school day period where data were recorded, as well as calculated outside air flow rates calculated using Equation 2. These data are consistent with those in Table 4 in terms of concentration, and have been used primarily for calculation of outside air supply rates for verification of the IHPAC ventilation and for energy analyses. As discussed above, both the 10 SEER and IHPAC systems were adjusted to provide 480 CFM (32 occupants * 15 CFM occupant^{-1}; 224 l sec^{-1} = 806 m^3 h^{-1}), based upon the California Title 24 and ASHRAE 62.1 ventilation standards. The average outside airflow rates (excluding the three dates discussed above) based on these measurements are 492±76 CFM (837±129 m^3 h^{-1}), very close to the rates set using a duct flow hood during installation.

Table 7 provides a summary of measured indoor and outdoor SF_6 tracer gas concentrations. As with the CO_2 tracer, SF_6 was used to measure ventilation rates. Calculated outdoor air supply rates (excluding the 10/18/04 measurements) for the study IHPAC study dates averaged 497±31 CFM (845±53 m^3 h^{-1}), on average within 1% of the rates measured using CO_2 as a tracer.

Energy Efficiency Comparisons

Table 8 lists daily-calculated PHPS values for the 10 SEER and IHPAC systems calculated as discussed above using Equation 10. Table 9 summarizes these data, showing estimated system efficiencies for the 10 SEER and IHPAC units. Study days with zero or minimal conditioning loads were not included in these analyses. Data are presented both for conditioning loads over the school-day hours and for each 24-hour study day. Due to night-time heating conditions on many days the 24-hour conditioning energy loads and consumption were considerably greater than those for the school-day periods. The 10 SEER unit PHPS values were 2.4 and 3.3 for cooling and heating, respectively. The IHPAC system PHPS corresponding values were 4.3 and 5.2, respectively. The ratio of 10 SEER to IHPAC school day PHPS values were 0.56 for cooling and 0.63 for heating, and 0.59 overall. Using this approach the we find that the

efficiency of the IHPAC is about 44% more efficient during cooling and 37% more efficient during heating than the 10 SEER system.

The PHPS ratio calculated across all (heating and cooling) measurements should be interpreted with caution since it is comprised of a mix of heating and cooling data that is not weighted in any way. Since many more days of heating measurements are in the dataset the ratio is skewed towards the heating mode.

Figure 3 is a plot of the amount of heat and cooling provided by the 10 SEER and IHPAC HVAC systems during school day periods calculated as described in Equation 3 above, plotted versus school day measured HVAC electricity consumption. Figure 4 plots a similar set of data for daily 24-hour monitoring periods. The least square regression fits of these data are tabulated in Table 10. The regression data show good-to-excellent fits. The regression line slopes are the best-fit relationship equivalent to PHPS. The ratio of 10 SEER system slopes to IHPAC slopes are compared to their analogous PHPS ratios in the table. Not surprisingly, they are very similar, differing by only a few percent.

The 24 hour energy efficiency calculations are all presented in the tables and figures, but should be interpreted with some caution because the 10 SEER system was never operated during the nighttime while the IHPAC was regularly operated for nighttime heating due to a controller software bug. These data are provided for completeness. It should also be noted that the enthalpy calculation method used in this analysis accounts for the thermal conditions of the RC structure such that the nighttime conditioning of the space is accounted for in the daytime energy balance.

HVAC System Acoustic Noise Comparisons

Table 11 summarizes acoustic noise levels measured during operation of the 10 SEER and IHPAC HVAC systems, as well as the two additional acoustic experiments when the prototype sound wall and prototype sound curb were tested. Octave band sound pressure levels (dB) for the test conditions and measurement position are included. This discussion will focus on the position 3m (10’) from the HVAC return and 1.5m (5’) above the floor. This position is frequently used by the RC industry and school facilities stakeholders as a test reference point for comparison. The 3m x 45 degree, 6m, and 12m measurement locations listed have consistently lower sound levels in these tests as would be expected since they are at a greater distance from the HVAC system.

The measured A-weighed sound level [NC value] for fan only operation conditions for the 10 SEER and IHPAC systems were 53.5 dB(A) [NC-45] and 34.3 dB(A) [NC-25], respectively. Similarly, during the operation of the 10 SEER system compressor plus fan, and the IHPAC stage-1 compressor plus fan, sound levels were 55.2 dB(A) [NC-55] and 40.8 dB(A) [NC-35], respectively. During stage-2 plus fan operation the IHPAC sound level increased to 42.7 dB(A) [NC-40]. Thus, the IHPAC system noise reduction was about 19 dB(A), 14 dB(A), and 13 dB(A) for fan, stage-1, and stage-2, respectively. In terms of sound intensity the IHPAC fan noise is about 35 times quieter than the 10 SEER fan. Likewise the IHPAC compressor first and second stages are about 22 times and 20 times quieter than the 10 SEER system compressor, respectively. The sound wall and sound curb systems substantially reduced the noise levels from the 10 SEER system, but not to the low noise levels of the IHPAC.

Summary and conclusions

The installation and verification of the performance of the Improved HPAC (IHPAC) system, and its comparison the standard 10 SEER HVAC system was fully successful and suggested that the new system meets the goals set out for this project. These goals included the verification of physical characteristics suitable for direct replacement of existing 10 SEER systems, quantitative demonstration of improved energy efficiency, reduced acoustic noise levels, quantitative demonstration of improved ventilation control, and that it meets temperature control demands necessary for the thermal comfort of the occupants.

The results of this extensive testing showed that with the exception of one small, and subsequently corrected problem that the IHPAC met these goals. The IHPAC was found to be a direct bolt-on replacement for the 10 SEER system. Calculated energy efficiency improvements based on many days of testing showed that the IHPAC system is about 44% more efficient during cooling and 38% more efficient during heating than the 10 SEER system. Noise reduction was dramatic, with measured A-weighed sound level for fan only operation conditions of 34.3 dB(A), a reduction of 19 dB(A) compared to the 10 SEER system. Similarly, the IHPAC stage-1 and stage-2 compressor plus fan sound levels were 40.8 dB(A) and 42.7 dB(A), reductions of 14 and 13 dB(A), respectively. Thus, the IHPAC is 20 to 35 times quieter than the 10 SEER systems depending upon the operation mode. The IHPAC system met the ventilation requirements and was able to provide consistent outside air supply throughout the study. Indoor CO_2 levels with simulated occupancy were maintained below 1000 ppm. Finally temperature settings were met and controlled accurately. As discussed above, the only problem to arise was that the IHPAC software was causing the system to heat during unoccupied nighttime periods. This problem was subsequently solved and remedied in the field study. The goals of the laboratory testing phase were met and this system is ready for further testing in a field study of occupied classrooms.

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Tables

Table 1. The field study instrumentation.

Parameters	Instrument	Location	Accuracy	Precision	Range
Power	Optimum Energy Products, ElitePRO	10SEER and IHPAC systems	<1% of reading, exclusive of sensor accuracy	12 bit (1 part in 4,096); 0.1 Volt, 0.01 Amp, 1 Watt, 1 VAR, 1 VA, 0.01 PF	4 channels of current, 0-6000A. 3 channels of voltage, 0-600 V ac or dc.
RH, Temperature	The Energy Conservatory, Automated Performance Testing (APT) System	Ceiling Supply Return Outside	Temperature: +/- 0.25 °C (0 °C to 75 °C), +/- 0.5 °C (< 0 °C, > 75 °C) RH: +/- 5% (0 to 60% RH), +/- 8% RH at 90% RH (@ 25 °C, noncondensing)	0.025 °C @ -40 °C, 0.05 °C @ 21 °C, 1.0 °C @ 100 °C	Temperature: -40 °C to 100 °C RH: 0 to 100% RH
SF6, CO_2	Thermo Electron Corporation, MIRAN SapphIRe	Ceiling Supply Return Outside	CO2: +/- 15% SF6: 10% up to 1.0 ppm, 20% from 1.0 ppm to 4.0 ppm	CO2: 1ppm SF6: 0.01 ppm	CO2: 0 to 1000 ppm SF6: 0 to 4 ppm
CO2	Fuji Electric Co., Infrared CO_2 Controller (Type ZFP9)	Ceiling Supply Return Outside	+/- 1%	10 ppm	0 to 3000 ppm
Sound	Brüel & Kjær, 2260 Observer		+/- 1%	0.1 db	80 dB (10 db to 90 dB)

Table 2. Measured temperature in the LBNL relocatable classroom test bed during HVAC operation days (continued on next page).

Date	T_room (˚F)			T_out (˚F)			T_supply (˚F)			T_return (˚F)			Tin – Tout (˚F)			HVAC mode	HVAC System
	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max		
09/14/04	71.6 (5.2)	62.4	78.3	75.2 (12.2)	57.9	90.8	69.3 (6.0)	56.6	77.6	71.0 (5.1)	62.3	77.1	-3.6 (7.5)	-16.2	6.9	cool	10 SEER
09/15/04	74.7 (2.8)	68.5	78.4	80.1 (11.1)	64.2	93.5	70.6 (6.1)	55.8	78.7	74.0 (2.7)	68.5	77.5	-5.4 (9.1)	-18.3	6.9	cool	10 SEER
09/27/04	72.8 (1.7)	69.1	77.3	61.0 (5.9)	53.8	72.4	68.1 (5.0)	54.3	87.9	72.7 (1.5)	69.6	76.3	11.8 (5.0)	0.6	20.3	mixed	IHPAC
09/28/04	73.5 (1.5)	70.7	76.1	66.0 (5.1)	57.6	74.3	68.5 (2.8)	61.1	88.7	73.4 (1.5)	70.8	76.4	7.5 (4.0)	-0.5	16.9	mixed	IHPAC
09/29/04	72.0 (1.0)	69.9	74.4	61.1 (3.2)	56.7	67.5	67.2 (3.9)	63.7	87.0	71.6 (1.0)	68.0	74.1	10.9 (3.1)	3.5	17.0	mixed	IHPAC
09/30/04	72.2 (1.1)	70.1	75.0	60.8 (3.8)	55.9	69.0	67.4 (3.7)	63.1	86.8	71.8 (1.2)	68.3	74.3	11.4 (3.5)	3.0	18.0	heat	IHPAC
10/02/04	73.2 (1.7)	69.9	77.5	63.7 (6.9)	54.0	74.2	68.0 (4.4)	54.6	91.7	72.6 (1.4)	69.7	75.7	9.5 (5.7)	-0.2	19.9	mixed	IHPAC
10/03/04	72.5 (1.4)	69.8	75.8	60.6 (6.4)	52.9	72.8	67.6 (5.1)	62.0	90.6	72.0 (1.3)	67.7	75.0	11.9 (5.8)	1.5	21.4	heat	IHPAC
10/04/04	71.9 (1.0)	69.7	75.0	60.9 (4.0)	56.1	75.2	67.2 (4.0)	63.7	89.8	71.6 (1.1)	67.9	75.0	11.0 (3.8)	-3.4	18.0	heat	IHPAC
10/05/04	72.3 (1.3)	69.7	75.5	63.0 (7.2)	54.6	77.3	67.6 (4.5)	63.1	91.8	72.0 (1.1)	69.5	75.5	9.3 (6.5)	-4.7	19.2	heat	IHPAC
10/06/04	73.9 (2.2)	69.8	78.7	71.7 (10.8)	56.3	88.4	69.3 (5.0)	54.3	91.5	73.4 (1.7)	70.3	77.2	2.2 (9.0)	-12.9	17.3	mixed	IHPAC
10/07/04	73.5 (1.9)	70.5	78.0	68.5 (7.9)	58.1	82.9	68.1 (3.4)	55.0	78.7	73.0 (1.5)	71.0	76.3	5.0 (6.3)	-6.9	12.9	cool	IHPAC
10/08/04	73.7 (2.0)	70.1	78.2	69.2 (9.4)	56.7	86.3	68.8 (4.3)	55.8	91.4	73.1 (1.6)	70.6	76.5	4.5 (7.8)	-10.2	17.3	mixed	IHPAC
10/09/04	73.3 (1.9)	69.8	77.3	64.9 (8.4)	54.7	81.9	68.5 (3.8)	54.6	87.2	72.9 (1.5)	70.4	76.0	8.4 (6.8)	-6.2	19.0	mixed	IHPAC
10/10/04	73.7 (2.1)	69.8	77.8	68.7 (10.1)	55.2	85.5	69.3 (4.5)	54.7	90.5	73.2 (1.6)	70.2	76.3	05.0 (8.5)	-9.8	18.7	mixed	IHPAC
10/11/04	75.2 (1.8)	71.5	79.5	76.6 (9.5)	61.8	90.6	70.3 (5.7)	52.7	80.5	74.6 (1.5)	71.9	79.2	-01.4 (8.5)	-15.0	9.9	cool	IHPAC
10/12/04	75.6 (1.3)	72.7	79.8	79.9 (9.9)	67.5	96.7	68.3 (6.9)	51.2	79.7	75.0 (1.1)	72.2	78.8	-04.3 (9.4)	-20.5	9.0	cool	IHPAC
10/13/04	75.7 (1.5)	72.7	80.0	78.7 (10.6)	65.6	94.7	69.0 (6.9)	49.3	80.4	75.1 (1.2)	72.1	80.0	-3.0 (10.3)	-19.0	13.1	cool	IHPAC
10/14/04	75.5 (1.3)	72.0	79.5	75.8 (8.7)	62.0	89.2	68.8 (6.3)	50.6	80.5	74.9 (0.9)	71.9	78.1	-00.2 (8.5)	-14.1	13.9	cool	IHPAC
10/15/04	73.9 (1.7)	71.5	77.7	66.4 (7.9)	55.1	84.0	67.8 (3.6)	53.6	78.0	73.4 (1.2)	70.4	76.4	07.5 (6.7)	-8.3	17.3	mixed	IHPAC
10/16/04	72.5 (1.2)	70.1	74.9	62.9 (3.2)	57.8	68.6	67.7 (3.1)	64.1	88.6	72.1 (1.3)	68.9	74.6	09.6 (2.5)	3.3	15.9	heat	IHPAC
10/17/04	73.5 (0.9)	71.0	75.4	62.8 (1.7)	59.8	67.4	68.3 (2.0)	65.9	74.8	73.0 (1.4)	68.5	74.7	10.7 (1.7)	6.1	13.4	none	IHPAC
10/18/04	72.3 (1.2)	70.1	75.0	63.3 (5.6)	54.7	73.3	67.5 (4.8)	62.8	89.6	71.7 (1.2)	67.7	74.4	08.9 (5.2)	-1.5	19.0	heat	IHPAC
10/19/04	75.0 (3.0)	68.8	79.6	57.1 (3.4)	52.8	62.9	73.1 (3.2)	64.5	78.8	71.5 (3.6)	65.1	77.2	17.9 (3.4)	9.2	22.8	heat	IHPAC
10/20/04	72.0 (1.2)	69.7	75.0	57.5 (6.0)	49.4	69.4	68.0 (6.8)	60.2	90.8	71.3 (1.3)	67.1	75.0	14.5 (6.0)	2.4	24.3	heat	IHPAC
10/21/04	72.3 (1.6)	69.3	76.8	55.7 (6.3)	48.9	71.2	70.0 (7.6)	59.4	90.8	71.0 (1.8)	65.2	75.1	16.7 (5.9)	1.7	25.2	heat	IHPAC

Table 2 (continued) Measured temperature in the LBNL relocatable classroom test bed during HVAC operation days.

Date	T_room (˚F)			T_out (˚F)			T_supply (˚F)			T_return (˚F)			Tin – Tout (˚F)			HVAC mode	HVAC System
	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max		
10/22/04	72.2 (1.1)	69.9	74.9	61.0 (4.5)	54.2	72.5	67.5 (5.0)	62.3	90.8	71.6 (1.1)	68.5	76.0	11.3 (4.3)	1.1	19.3	heat	IHPAC
10/23/04	71.7 (1.1)	69.6	75.1	56.5 (1.0)	55.0	59.3	67.6 (5.8)	62.8	91.7	71.5 (1.1)	70.0	75.6	15.2 (1.5)	10.7	19.5	heat	IHPAC
10/24/04	72.0 (1.1)	69.7	74.9	60.7 (4.5)	53.7	69.4	67.9 (5.2)	62.5	92.9	71.8 (1.0)	69.9	75.7	11.3 (4.7)	2.9	20.8	heat	IHPAC
10/25/04	71.9 (1.2)	69.2	74.9	59.2 (5.6)	51.5	69.6	68.0 (6.5)	61.2	92.6	71.6 (1.1)	69.4	76.4	12.7 (5.6)	3.3	22.5	heat	IHPAC
10/26/04	72.0 (1.3)	69.2	75.3	55.9 (5.5)	49.6	67.6	68.4 (7.6)	59.3	92.2	71.6 (1.3)	69.4	75.8	16.1 (5.8)	3.6	25.0	heat	IHPAC
10/27/04	71.9 (1.4)	68.6	75.0	52.1 (4.2)	47.0	60.4	69.2 (8.3)	58.6	92.2	71.6 (1.3)	69.0	75.8	19.9 (4.5)	10.5	27.3	heat	IHPAC
10/28/04	71.9 (1.3)	68.8	75.2	56.0 (4.7)	48.5	62.9	68.5 (7.4)	59.6	93.8	71.7 (1.3)	68.9	76.1	15.9 (4.9)	8.1	25.5	heat	IHPAC
10/29/04	72.6 (2.9)	66.2	88.2	59.5 (4.6)	52.1	68.6	68.8 (9.2)	43.9	107.9	72.1 (3.1)	66.0	90.1	13.1 (4.8)	3.1	22.4	mixed	IHPAC
10/30/04	69.9 (1.3)	67.2	73.6	56.7 (4.2)	50.1	65.2	65.9 (6.5)	60.6	93.1	69.7 (1.4)	67.4	75.9	13.2 (4.5)	4.2	22.8	heat	IHPAC
10/31/04	70.3 (1.2)	67.7	74.4	58.0 (6.1)	50.2	68.9	66.8 (5.5)	59.8	90.9	70.1 (1.2)	67.7	74.2	12.3 (5.8)	3.1	23.3	heat	IHPAC
11/01/04	71.1 (1.4)	67.9	74.0	60.4 (6.1)	51.5	72.6	67.7 (5.0)	60.6	91.6	70.7 (1.4)	67.5	74.3	51.2 (9.4)	33.4	69.6	heat	IHPAC
11/02/04	71.4 (1.6)	68.2	74.9	60.9 (5.9)	51.1	70.9	66.8 (4.6)	48.3	89.1	70.8 (1.5)	68.3	73.5	51.0 (8.8)	33.1	68.7	mixed.	IHPAC
11/03/04	69.8 (1.4)	65.7	74.0	54.2 (2.8)	48.6	59.9	65.0 (5.7)	58.0	89.6	69.5 (1.3)	66.2	74.7	60.3 (5.2)	47.4	71.5	heat	IHPAC
11/04/04	70.0 (1.5)	66.9	74.4	52.4 (3.0)	46.7	57.0	66.4 (8.0)	57.4	90.4	69.0 (2.2)	62.1	74.1	63.6 (5.9)	52.5	77.9	heat	IHPAC
11/05/04	70.1 (1.4)	67.0	73.8	56.6 (4.6)	48.3	64.1	66.2 (6.1)	59.7	91.4	69.7 (1.4)	66.2	74.7	56.2 (8.1)	44.0	75.9	heat	IHPAC
11/06/04	70.3 (1.3)	67.2	74.1	55.9 (4.3)	48.6	65.1	66.1 (6.4)	59.5	93.0	69.6 (1.5)	66.8	75.8	57.8 (8.0)	39.2	76.6	mixed.	IHPAC
11/07/04	70.2 (1.2)	67.4	73.9	56.0 (2.8)	50.9	61.2	65.4 (5.7)	60.2	92.1	69.5 (1.6)	65.2	75.9	57.4 (5.6)	45.3	72.6	heat	IHPAC
03/01/05	71.9 (1.7)	67.1	74.1	59.9 (5.6)	50.1	67.7	67.8 (7.3)	59.9	90.9	72.0 (1.9)	66.9	74.5	12.0 (5.9)	2.2	22.0	heat	10 SEER
03/02/05	71.0 (1.4)	67.3	72.7	57.8 (4.3)	51.3	65.2	67.8 (7.4)	60.6	92.0	72.0 (2.0)	66.8	74.2	13.2 (4.6)	3.5	19.4	heat	10 SEER
03/03/05	71.9 (1.6)	66.2	74.5	59.3 (5.6)	47.9	69.8	68.2 (7.4)	57.7	90.7	72.1 (1.8)	66.3	74.5	12.7 (5.8)	0.0	24.5	heat	10 SEER
03/04/05	71.9 (1.8)	67.1	74.6	54.3 (3.4)	50.5	62.4	67.9 (8.0)	60.4	91.4	72.1 (2.0)	66.9	74.7	17.6 (4.7)	6.2	23.2	heat	10 SEER
03/05/05	72.2 (1.3)	68.8	74.2	61.6 (8.3)	48.3	73.3	67.9 (6.4)	58.6	90.0	72.3 (1.5)	69.0	74.3	10.6 (8.2)	-1.4	23.8	heat	10 SEER
03/06/05	72.9 (1.0)	69.9	75.3	64.7 (8.7)	51.4	76.3	68.7 (5.8)	60.8	91.1	73.0 (1.2)	70.0	75.8	08.2 (8.3)	-3.5	21.5	heat	10 SEER
03/07/05	72.6 (1.1)	70.1	75.0	63.5 (7.0)	51.9	73.6	68.1 (6.0)	61.4	92.4	72.7 (1.3)	70.0	75.0	3.9 (15.0)	-32.4	34.4	heat	10 SEER
03/08/05	72.5 (1.0)	66.2	74.4	65.3 (8.7)	52.0	76.9	70.0 (6.8)	58.9	92.3	72.4 (0.9)	66.2	74.1	4.0 (17.5)	-23.3	37.4	heat	10 SEER
03/09/05	75.1 (3.2)	67.0	80.4	67.2 (10.1)	52.6	80.7	71.8 (5.6)	57.5	90.2	74.7 (2.9)	67.0	79.4	2.6 (20.9)	-29.9	30.0	mixed	10 SEER
03/10/05	76.9 (2.6)	71.5	81.9	73.6 (10.2)	57.6	86.7	71.2 (6.1)	58.1	83.8	76.5 (2.5)	71.1	81.3	-25.9 (16.2)	-49.5	8.1	Cool	10 SEER
03/11/05	78.0 (2.2)	74.2	83.1	76.5 (10.4)	60.2	88.6	72.2 (7.0)	56.3	86.5	77.3 (2.1)	74.1	82.6	-32.3 (20.9)	-62.0	8.9	Cool	10 SEER
03/12/05	76.4 (1.4)	73.2	78.6	58.7 (2.1)	55.3	61.4	69.7 (5.3)	55.0	76.1	76.0 (1.3)	73.0	77.9	20.2 (7.8)	7.9	40.0	Cool	10 SEER
03/13/05	76.5 (2.6)	70.2	79.4	63.7 (6.3)	54.5	73.2	70.6 (6.2)	54.8	82.7	75.9 (2.5)	70.0	79.0	-2.8 (18.6)	-35.5	26.2	Cool	10 SEER

Table 3. Measured relative humidities in the LBNL relocatable classroom test bed during HVAC operation days (continued on next page).

Date	RH_room			RH_out			RHsupply			HVAC mode	HVAC Type
	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max		
09/14/04	51.0 (8.0)	39.5	64.4	49.6 (21.2)	25.1	82.4	59.1 (10.6)	40.1	79.7	cool	10 SEER
09/15/04	42.6 (1.9)	39.0	46.9	38.7 (11.0)	24.0	54.4	53.9 (12.1)	38.9	88.2	cool	10 SEER
09/27/04	49.0 (1.8)	44.1	53.0	79.6 (14.2)	54.9	97.7	63.1 (8.8)	34.7	98.2	mixed	IHPAC
09/28/04	49.4 (3.6)	43.9	55.6	69.7 (15.6)	47.4	94.9	63.2 (6.5)	35.3	74.3	mixed	IHPAC
09/29/04	49.5 (1.5)	46.5	53.1	79.2 (7.0)	64.7	88.8	63.7 (6.6)	38.3	69.3	mixed	IHPAC
09/30/04	47.4 (1.5)	44.2	50.8	74.0 (11.8)	51.2	89.3	60.5 (5.9)	34.7	68.8	heat	IHPAC
10/02/04	46.9 (1.7)	42.7	51.0	70.4 (18.0)	47.7	96.3	61.2 (7.5)	30.7	88.9	mixed	IHPAC
10/03/04	48.0 (1.6)	45.0	52.0	80.4 (16.6)	53.6	99.6	62.3 (8.3)	31.7	71.2	heat	IHPAC
10/04/04	51.3 (1.3)	48.1	54.8	83.6 (10.5)	53.4	95.6	66.3 (7.2)	33.3	73.5	heat	IHPAC
10/05/04	51.0 (1.5)	47.8	54.8	80.2 (18.3)	49.4	100.5	65.5 (7.7)	34.0	74.5	heat	IHPAC
10/06/04	48.3 (1.8)	44.0	52.6	59.8 (16.9)	35.8	83.1	62.2 (10.2)	30.6	99.3	mixed	IHPAC
10/07/04	52.0 (3.3)	45.8	57.7	71.1 (20.7)	40.6	100.2	68.1 (7.0)	48.8	96.1	cool	IHPAC
10/08/04	51.0 (2.1)	45.1	56.0	68.9 (19.2)	37.8	94.1	66.4 (8.5)	32.1	98.6	mixed	IHPAC
10/09/04	43.2 (5.0)	37.0	53.5	63.2 (21.3)	33.6	94.9	54.3 (7.6)	34.2	70.3	mixed	IHPAC
10/10/04	35.1 (1.9)	30.9	38.8	45.5 (13.4)	25.3	64.8	43.5 (5.7)	23.5	63.0	mixed	IHPAC
10/11/04	22.3 (3.1)	19.3	30.8	21.8 (6.5)	13.3	34.3	26.6 (4.2)	19.9	40.4	cool	IHPAC
10/12/04	29.9 (2.2)	25.7	34.3	27.9 (8.0)	16.9	42.5	41.6 (9.6)	26.3	76.7	cool	IHPAC
10/13/04	29.8 (3.1)	23.7	37.4	28.8 (6.8)	17.7	41.1	40.8 (10.9)	27.8	79.6	cool	IHPAC
10/14/04	39.3 (4.3)	29.6	47.0	42.7 (8.8)	29.6	63.6	55.4 (13.7)	35.4	100.9	cool	IHPAC
10/15/04	46.7 (1.7)	43.0	51.1	70.3 (17.4)	37.6	94.9	63.3 (7.9)	46.6	94.7	mixed	IHPAC
10/16/04	47.1 (1.4)	44.7	50.6	74.0 (6.3)	63.0	84.0	60.7 (5.0)	32.5	66.0	heat	IHPAC
10/17/04	52.1 (2.9)	45.5	58.6	86.9 (5.8)	76.7	95.0	68.8 (7.3)	47.3	76.2	none	IHPAC
10/18/04	48.0 (2.7)	42.8	54.1	74.5 (18.1)	47.6	98.2	61.5 (8.8)	34.9	74.1	heat	IHPAC
10/19/04	44.1 (4.9)	37.5	56.4	95.5 (2.6)	87.8	99.6	51.5 (9.2)	41.8	78.2	heat	IHPAC
10/20/04	43.8 (1.6)	40.9	47.5	79.4 (19.3)	43.7	99.9	55.1 (10.0)	30.0	69.8	heat	IHPAC
10/21/04	38.1 (1.2)	35.5	41.3	73.0 (14.0)	43.0	86.5	45.5 (9.1)	25.2	60.1	heat	IHPAC

Table 3 (continued). Measured relative humidities in the LBNL relocatable classroom test bed during HVAC operation days

Date	RH_room			RH_out			RHsupply			HVAC mode	HVAC
	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max		Type
10/22/04	45.9 (1.4)	42.6	49.3	74.0 (12.6)	48.4	91.6	59.4 (7.7)	29.8	69.1	heat	IHPAC
10/23/04	49.8 (3.4)	42.6	58.4	90.9 (4.5)	82.0	97.7	63.6 (10.2)	31.5	77.9	heat	IHPAC
10/24/04	48.1 (1.8)	44.3	52.7	78.1 (13.7)	55.4	98.1	60.6 (8.1)	31.8	72.4	heat	IHPAC
10/25/04	44.2 (1.5)	41.1	48.1	73.7 (14.3)	48.3	94.9	55.1 (8.9)	27.1	66.2	heat	IHPAC
10/26/04	41.5 (2.8)	36.6	49.4	78.1 (18.3)	46.8	101.8	50.5 (9.8)	27.9	69.1	heat	IHPAC
10/27/04	36.6 (1.8)	33.6	42.3	77.2 (13.0)	54.8	95.6	43.5 (8.9)	24.7	59.7	heat	IHPAC
10/28/04	41.6 (1.6)	38.2	45.4	78.8 (11.2)	63.5	97.5	51.3 (9.8)	24.4	63.9	heat	IHPAC
10/29/04	41.7 (3.2)	28.0	46.6	70.3 (15.4)	46.3	91.7	52.4 (12.1)	16.2	102.4	mixed	IHPAC
10/30/04	48.5 (2.7)	40.3	53.2	85.0 (10.1)	64.3	97.4	61.9 (11.1)	24.4	72.0	heat	IHPAC
10/31/04	38.3 (7.0)	27.2	51.6	61.1 (24.8)	25.6	98.3	45.5 (11.6)	25.8	69.5	heat	IHPAC
11/01/04	24.2 (1.1)	21.6	26.3	34.4 (5.8)	23.0	46.1	28.1 (3.2)	15.9	33.9	heat	IHPAC
11/02/04	36.3 (3.7)	29.3	45.2	56.7 (5.3)	43.9	64.5	46.7 (8.5)	20.9	97.2	mixed	IHPAC
11/03/04	40.3 (3.5)	35.3	50.0	71.7 (8.4)	56.8	91.6	51.0 (7.0)	26.2	62.3	heat	IHPAC
11/04/04	40.1 (1.6)	36.0	44.4	79.0 (7.0)	67.3	94.0	50.0 (10.8)	25.1	65.3	heat	IHPAC
11/05/04	39.6 (1.7)	36.0	42.7	67.6(10.6)	51.4	85.7	49.3 (7.8)	23.1	59.3	heat	IHPAC
11/06/04	46.4 (3.2)	37.7	52.4	84.0 (9.6)	61.6	97.6	59.7 (11.1)	23.4	70.6	mixed	IHPAC
11/07/04	46.0 (1.7)	41.5	50.5	80.1 (6.6)	66.6	92.5	59.1 (8.7)	27.1	66.8	heat	IHPAC
03/01/05	41.6 (1.0)	38.4	43.9	66.5 (14.9)	45.4	90.1	50.7 (8.6)	25.1	62.6	heat	10 SEER
03/02/05	43.7 (2.6)	39.8	49.1	74.1 (15.4)	51.8	99.6	51.8 (9.2)	27.6	68.0	heat	10 SEER
03/03/05	41.8 (1.8)	38.5	47.4	68.8(12.8)	48.6	92.7	50.6 (9.3)	24.3	62.4	heat	10 SEER
03/04/05	46.9 (2.7)	43.5	54.6	91.5 (8.6)	69.3	99.5	57.7 (11.7)	27.4	71.5	heat	10 SEER
03/05/05	46.7 (2.8)	41.5	53.5	75.2 (18.1)	47.1	100.2	58.3 (10.1)	26.6	69.0	heat	10 SEER
03/06/05	46.3 (2.4)	41.6	50.4	68.0 (19.4)	42.7	94.6	57.0 (9.6)	27.4	69.7	heat	10 SEER
03/07/05	48.2 (2.6)	44.9	55.1	72.0 (15.0)	50.5	96.5	60.1 (9.6)	28.0	69.0	heat	10 SEER
03/08/05	52.0 (3.4)	45.7	57.7	74.1 (17.2)	52.2	97.4	61.4 (11.1)	26.7	71.3	heat	10 SEER
03/09/05	48.2 (1.1)	45.1	52.3	74.4 (20.8)	48.8	101.8	65.1 (19.0)	30.3	100.5	mixed	10 SEER
03/10/05	41.0 (3.8)	36.5	49.1	45.3 (14.0)	28.6	70.9	54.1 (9.6)	36.3	76.2	Cool	10 SEER
03/11/05	36.5 (4.7)	30.9	44.2	39.9 (18.0)	22.4	71.3	47.6 (11.0)	29.3	77.3	Cool	10 SEER
03/12/05	42.9 (1.6)	38.7	46.3	89.9 (5.3)	82.0	97.8	67.1 (15.3)	43.4	95.1	Cool	10 SEER
03/13/05	41.6 (2.7)	38.5	48.2	67.8 (16.4)	44.7	93.9	59.8 (13.4)	32.8	87.0	Cool	10 SEER

Table 4. School day CO_2 concentrations measured in the center of the RC.

Date	CO_2 Concentration (ppm)			HVAC Mode	HVAC Type
	Avg (Stdev)	Min	Max		
9/15/05	499 (63)	390	579	cool	10 SEER
9/28/04	486 (71)	390	595	mixed	IHPAC
9/27/04	527 (89)	390	727	mixed	IHPAC
9/29/04	493 (73)	390	607	mixed	IHPAC
9/30/04	481 (69)	377	578	heat	IHPAC
10/2/04	483 (69)	378	586	mixed	IHPAC
10/3/04	484 (66)	381	583	heat	IHPAC
10/4/04	488 (69)	393	593	heat	IHPAC
10/5/04	491 (67)	390	594	heat	IHPAC
10/6/04	505 (76)	389	606	mixed	IHPAC
10/7/04	490 (71)	380	595	cool	IHPAC
10/8/04	493 (73)	393	609	mixed	IHPAC
10/9/04	477 (67)	379	577	mixed	IHPAC
10/10/04	480 (69)	378	577	mixed	IHPAC
10/11/04	391 (19)	347	456	cool	IHPAC
10/12/04	429 (35)	375	538	cool	IHPAC
10/13/04	426 (26)	374	508	cool	IHPAC
10/14/04	485 (64)	421	625	cool	IHPAC
10/15/04	505 (62)	397	600	mixed	IHPAC
10/16/04	478 (66)	382	572	heat	IHPAC
10/17/04	478 (66)	381	566	none	IHPAC
10/18/04	493 (67)	387	599	heat	IHPAC
10/19/04	1060 (468)	393	2177	heat	IHPAC
10/20/04	488 (61)	388	588	heat	IHPAC
10/21/04	542 (99)	408	909	heat	IHPAC
10/22/04	546 (75)	432	698	heat	IHPAC
10/23/04	527 (66)	429	623	heat	IHPAC
10/24/04	538 (69)	433	651	heat	IHPAC
10/25/04	545 (78)	432	708	heat	IHPAC
10/26/04	536 (69)	430	678	heat	IHPAC
10/27/04	516 (68)	407	710	heat	IHPAC
10/28/04	510 (64)	406	617	heat	IHPAC
10/29/04	560 (94)	416	834	mixed	IHPAC
10/30/04	500 (64)	402	600	heat	IHPAC
10/31/04	471 (77)	386	617	heat	IHPAC
11/1/04	424 (22)	368	484	heat	IHPAC
11/2/04	454 (26)	419	524	mixed	IHPAC
11/3/04	499 (65)	394	615	heat	IHPAC
11/4/04	476 (62)	389	599	heat	IHPAC
11/5/04	527 (73)	418	645	heat	IHPAC
11/6/04	504 (70)	396	619	mixed	IHPAC
11/7/04	497 (66)	395	584	heat	IHPAC

Table 5. Measured indoor and outdoor carbon dioxide (CO_2) concentrations and outside air ventilation supply rates in the LBNL RC Test Bed. Ventilation rates were calculated from indoor-minus outdoor steady-state CO_2 concentrations. The indoor CO_2 source injection rate was approximately 2450 mL min^{-1}. Note that on 10/19 and 11/17-18 the outside air damper was closed for part of the day.

Test	Outside			Supply			Return			OA Flow		HVAC	HVAC
Date	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	$m^3 h^{-1}$	CFM	Mode	Type
9/15/04	406 (20)	372	455	464 (35)	394	525	521 (58)	394	629	881	519	cool	10 SEER
10/16/04	378 (7)	364	408	463 (63)	370	539	418 (31)	364	459	968	570	heat	IHPAC
10/17/04	377 (8)	364	392	461 (63)	370	539	417 (32)	364	459	1006	592	None	IHPAC
10/18/04	383 (12)	364	408	477 (65)	377	572	429 (34)	370	477	937	552	heat	IHPAC
10/19/04	411 (25)	377	469	1040 (457)	385	1924	1016 (485)	385	1977	NA	NA	heat	IHPAC
10/20/04	391 (8)	377	408	477 (60)	377	560	432 (32)	377	477	924	544	heat	IHPAC
10/21/04	407 (19)	377	459	511 (103)	377	853	481 (114)	377	950	550	324	heat	IHPAC
10/22/04	394 (8)	377	416	487 (68)	377	583	438 (36)	377	497	826	486	heat	IHPAC
10/23/04	387 (5)	377	399	469 (60)	377	550	427 (32)	377	477	941	554	heat	IHPAC
10/24/04	398 (8)	377	416	483 (62)	385	560	438 (34)	385	487	976	575	heat	IHPAC
10/25/04	390 (7)	377	399	494 (73)	385	695	440 (38)	377	517	633	373	heat	IHPAC
10/26/04	387 (9)	370	408	480 (62)	385	572	432 (33)	385	497	830	488	heat	IHPAC
10/27/04	386 (6)	377	399	485 (67)	377	657	433 (33)	385	517	579	341	heat	IHPAC
10/28/04	394 (8)	375	413	494 (63)	390	581	447 (34)	390	495	851	501	heat	IHPAC
10/30/04	403 (9)	383	422	492 (64)	390	569	444 (33)	390	495	990	583	heat	IHPAC
10/31/04	389 (13)	375	430	454 (79)	375	581	423 (46)	375	505	882	519	heat	IHPAC
11/1/04	388 (11)	375	413	410 (18)	383	448	401 (13)	375	430	NA	NA	heat	IHPAC
11/2/04	420 (17)	397	457	437 (29)	405	629	429 (18)	405	475	NA	NA	mixed	IHPAC
11/3/04	387 (4)	375	397	486 (64)	383	581	440 (34)	383	515	818	481	heat	IHPAC
11/4/04	390 (6)	375	397	473 (67)	383	581	433 (34)	383	495	947	558	heat	IHPAC
11/5/04	414 (17)	390	466	517 (73)	405	655	469 (44)	405	536	862	507	heat	IHPAC
11/6/04	403 (12)	383	422	491 (69)	390	581	448 (39)	383	505	816	480	mixed	IHPAC
11/7/04	399 (8)	383	413	485 (65)	390	569	442 (36)	383	495	871	513	heat	IHPAC
11/8/04	399 (12)	383	430	494 (66)	390	593	446 (36)	397	515	892	525	heat	IHPAC
11/9/04	388 (7)	375	397	476 (64)	383	558	430 (33)	383	475	917	540	heat	IHPAC
11/10/04	391 (5)	375	405	497 (73)	390	629	441 (35)	390	495	705	415	heat	IHPAC
11/11/04	389 (5)	375	397	510 (71)	383	604	452 (38)	383	547	659	388	heat	IHPAC
11/12/04	398 (10)	383	422	510 (80)	397	655	452 (41)	390	525	842	496	heat	IHPAC
11/13/04	397 (10)	383	413	484 (66)	390	581	441 (34)	390	495	938	552	heat	IHPAC
11/14/04	404 (17)	383	438	494 (76)	390	593	450 (45)	383	525	903	531	heat	IHPAC
11/15/04	422 (15)	390	448	526 (78)	397	629	476 (41)	397	536	700	412	heat	IHPAC
11/16/04	443 (30)	390	485	548 (96)	397	666	499 (62)	390	581	662	390	heat	IHPAC
11/17/04	430 (49)	375	547	607 (226)	390	1206	563 (212)	383	1091	NA	NA	heat	IHPAC
11/18/04	465 (51)	390	569	656 (223)	438	1186	602 (200)	422	1073	561	330	heat	IHPAC

Table 7. Measured indoor and outdoor sulfur hexafluoride (SF_6) tracer gas concentrations and SF_6–determined outside air ventilation supply rates in the LBNL RC Test Bed. Ventilation rates were calculated from indoor-minus outdoor steady-state SF_6 concentrations. The indoor SF_6 source injection rate was approximately 12.5 mL min^{-1}.

Test	Outside SF_6 (ppb)			Supply SF_6 (ppb)			Return SF_6 (ppb)			OA Flow		HVAC	HVAC
Date	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	$m^3 h^{-1}$	CFM	Mode	Type
9/16/05	140 (9)	13	59	740 (169)	194	825	504 (130)	124	589	826	486	cool	10 SEER
10/16/04	90 (53)	21	297	743 (433)	21	1801	670 (396)	21	1188	896	528	heat	IHPAC
10/17/04	81 (45)	20	240	713 (427)	27	1889	643 (364)	26	1097	972	572	none	IHPAC
10/18/04	70 (36)	11	190	648 (377)	11	1468	578 (344)	9	993	1003	590	heat	IHPAC
10/19/04	248 (144)	12	482	3360 (1914)	16	8589	2441 (1728)	15	5719	837	493	heat	IHPAC
10/20/04	82 (44)	17	247	728 (423)	17	1675	653 (396)	15	1179	680	400	heat	IHPAC
10/21/04	168 (550)	9	6368	737 (1188)	6	9096	442 (477)	6	1694	826	486	heat	IHPAC
10/22/04	76 (52)	-1	273	996 (1180)	0	10123	772 (366)	-2	1170	822	484	heat	IHPAC
10/23/04	63 (36)	1	125	720 (415)	1	1320	682 (440)	-1	1528	839	493	heat	IHPAC
10/24/04	60 (35)	-5	125	720 (414)	-5	1394	661 (430)	-8	1454	849	499	heat	IHPAC
10/25/04	70 (44)	-5	348	809 (368)	-3	1386	773 (379)	-7	1432	880	518	heat	IHPAC
10/26/04	60 (33)	-3	121	665 (396)	-5	1256	663 (418)	-7	1575	872	513	heat	IHPAC
10/27/04	58 (34)	-2	128	698 (386)	-2	1292	653 (407)	-4	1550	859	505	heat	IHPAC
10/28/04	59 (43)	-8	370	687 (423)	-9	1290	691 (437)	-11	1618	821	483	heat	IHPAC
11/2/04	938 (301)	142	1646	123 (191)	54	973	984 (180)	429	1250	805	474	mixed	IHPAC
11/3/04	648 (444)	-22	1592	46 (41)	-21	106	680 (425)	-19	1200	871	512	heat	IHPAC
11/4/04	608 (416)	-23	1702	35 (37)	-23	107	863 (1232)	-20	8009	901	530	heat	IHPAC
11/5/04	655 (452)	-23	2662	35 (38)	-23	112	934 (1413)	-20	9620	878	517	heat	IHPAC
11/6/04	669 (421)	-23	1126	40 (48)	-21	277	838 (1078)	-18	9487	816	480	mixed	IHPAC
11/7/04	658 (418)	-30	1131	37 (49)	-29	234	822 (926)	-28	8348	818	482	heat	IHPAC
11/8/04	685 (423)	-35	1190	35 (56)	-34	303	697 (468)	-30	1511	838	493	heat	IHPAC
11/9/04	661 (423)	-35	1160	37 (52)	-35	231	703 (475)	-32	1669	831	489	heat	IHPAC
11/10/04	662 (420)	-35	1154	36 (61)	-36	293	686 (465)	-33	1604	837	493	heat	IHPAC
11/11/04	673 (432)	-39	1184	34 (65)	-41	329	709 (473)	-37	1604	839	494	heat	IHPAC

Table 8. Performance of the heat pump system (PHPS) by date, on test dates shown. PHPS is the ratio of total enthalpy change of airstreams to energy consumed by the HVAC systems. Data are shown for heating, cooling, and mixed conditioning days for both 10 SEER and IHPAC systems for both school hours and 24 hour periods.

Study Date	PHPS (school)	PHPS (24h)	HVAC	Mode
09/14/2004	3.55	2.61	10 SEER	Cool
09/15/2004	2.83	2.51	10 SEER	Cool
09/27/2004	4.76	7.01	IHPAC	mixed
09/28/2004	1.94	4.65	IHPAC	mixed
09/29/2004	7.30	4.81	IHPAC	mixed
09/30/2004	5.95	6.83	IHPAC	heat
10/02/2004	3.68	4.92	IHPAC	mixed
10/03/2004	3.88	5.34	IHPAC	heat
10/04/2004	2.59	3.75	IHPAC	heat
10/05/2004	4.01	5.48	IHPAC	heat
10/06/2004	5.36	5.68	IHPAC	mixed
10/07/2004	4.25	4.61	IHPAC	cool
10/08/2004	5.26	6.64	IHPAC	mixed
10/09/2004	4.41	5.97	IHPAC	mixed
10/10/2004	4.86	7.20	IHPAC	mixed
10/11/2004	5.10	5.92	IHPAC	cool
10/12/2004	4.32	3.90	IHPAC	cool
10/13/2004	4.11	4.11	IHPAC	cool
10/14/2004	3.92	3.88	IHPAC	cool
10/15/2004	3.60	4.59	IHPAC	mixed
10/16/2004	1.55	3.09	IHPAC	heat
10/17/2004	1.29	1.56	IHPAC	none
10/18/2004	3.32	4.79	IHPAC	heat
10/19/2004	6.80	7.77	IHPAC	heat
10/20/2004	4.35	6.92	IHPAC	heat
10/21/2004	4.60	8.86	IHPAC	heat
10/22/2004	3.60	7.40	IHPAC	heat
10/23/2004	5.97	7.70	IHPAC	heat
10/24/2004	3.40	7.79	IHPAC	heat
10/25/2004	3.97	7.12	IHPAC	heat
10/26/2004	4.93	7.73	IHPAC	heat
10/27/2004	5.27	8.11	IHPAC	heat
10/28/2004	4.61	7.81	IHPAC	heat
10/29/2004	4.00	8.54	IHPAC	mixed
10/30/2004	4.81	7.51	IHPAC	heat
10/31/2004	6.39	9.38	IHPAC	heat
11/01/2004	5.41	9.42	IHPAC	heat
11/02/2004	4.10	8.55	IHPAC	mixed
11/03/2004	6.91	8.27	IHPAC	heat
11/04/2004	5.35	6.40	IHPAC	heat
11/05/2004	5.29	6.82	IHPAC	heat
11/06/2004	4.44	5.58	IHPAC	mixed
11/07/2004	4.80	6.08	IHPAC	heat
11/08/2004	5.99	7.07	IHPAC	heat
11/09/2004	6.73	7.57	IHPAC	heat
11/10/2004	7.80	7.38	IHPAC	heat
11/11/2004	9.21	8.41	IHPAC	heat
11/12/2004	6.39	6.67	IHPAC	heat
11/19/2004	5.09	5.76	IHPAC	heat
11/22/2004	5.36	6.88	IHPAC	heat
11/23/2004	4.81	5.66	IHPAC	heat
11/24/2004	4.37	5.09	IHPAC	heat
03/01/2005	2.69	3.64	10 SEER	heat
03/02/2005	2.81	3.47	10 SEER	heat
03/03/2005	2.98	3.67	10 SEER	heat
03/04/2005	3.80	3.71	10 SEER	heat
03/05/2005	3.49	3.56	10 SEER	heat
03/06/2005	3.59	3.42	10 SEER	heat
03/07/2005	3.00	3.14	10 SEER	heat
03/08/2005	3.62	3.37	10 SEER	heat
03/09/2005	2.78	2.84	10 SEER	mixed
03/10/2005	2.25	2.30	10 SEER	cool
03/11/2005	1.88	1.87	10 SEER	cool
03/12/2005	2.17	2.15	10 SEER	cool
03/13/2005	1.95	2.08	10 SEER	cool

Table 9. Average and standard deviation of PHPS by HVAC type and by conditioning mode.

HVAC	Avg (Stdev)
10 SEER cool	2.44 (0.64)
10 SEER heat	3.25 (0.24)
10 SEER mixed	2.78 (-----)
IHPAC cool only	4.34 (0.45)
IHPAC heat	5.17 (1.4)
IHPAC mixed (mostly heat)	4.31 (1.5)
10SEER all	2.89 (0.63)
IHPAC all	4.88 (1.4)
Ratios	
School Day	
10 SEER/IHPAC (cool)	**0.56**
10 SEER/IHPAC (heat)	**0.63**
10 SEER/IHPAC (all meas.)	**0.59**
24-hours	
10 SEER/IHPAC (cool)	**0.52**
10 SEER/IHPAC (heat)	**0.50**
10 SEER/IHPAC (all meas.)	**0.46**

Table 10. Least Square regression fits between HVAC heating and cooling and HVAC Energy Consumption for both the 10 SEER and IHPAC and for aggregated heating and cooling data and separate space conditioning conditions. Statistics are presented for both school day and daily 24-hour data. PHPS ratios are also included for comparison purposes

HVAC System	Conditioning Mode	Slope (kW/kW)	Fit (R^2)	Regression Ratio	PHPS Ratio
		School-Day Data			
10 SEER	cool	2.64	0.83		
	heat	3.23	0.57		
	All	3.03	0.81		
IHPAC	cool	4.30	0.90		
	heat	5.10	0.61		
	All Meas.	4.77	0.67		
Ratio	cool			0.61	0.56
	heat			0.63	0.63
	All Meas.			0.63	0.59
		Daily 24 hour Data			
10 SEER	heat	3.50	0.93		
	cool	2.50	0.99		
	All Meas.	3.43	0.97		
IHPAC	cool	4.32	0.47		
	heat	7.42	0.90		
	All Meas.	7.04	0.83		
Ratio	cool			0.58	0.52
	heat			0.47	0.50
	All Meas.			0.49	0.46

Table 11. Acoustic measurements in unoccupied LBNL RC Test Bed. Data include sound levels from the IHPAC, and a 10 SEER HVAC system under three different acoustic installation conditions. Measurements were made at four locations and with fan only, and compressor on. The IHPAC was operated in both Stage 1 and Stage 2 compressor modes. The 10 SEER compressor data are compared with both stages of the IHPAC system. These measurements were made with the RC lighting turned off. Background sound levels in the RC during these measurements, with all equipment off averaged 28±3.2 dB(A), meeting an NC-25 level.

Meas. Position	HVAC System/Configuration	Sound Pressure dB(linear)								Sound Rating	
Dist. x Ht. x ∠		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	NC Value	dB(A)
FAN 10 x 5	IHPAC	44.2	39.1	26.6	26.0	21.4	16.8	17.0	19.1	NC-25	34.3
	10 SEER	49.2	50.9	48.4	43.6	44.4	41.2	36.9	29.4	NC-45	53.5
	10 SEER Sound Wall	50.7	45.6	40.5	31.6	30.5	18.2	14.4	13.0	NC-30	41.2
	10 SEER Sound Curb	47.9	43.3	36.7	32.4	26.4	19.3	16.3	20.1	NC-30	41.5
FAN 10 x 5 x 45°	10 SEER	45.9	38.9	24.5	22.6	15.8	13.4	9.4	20.1	NC-25	32.8
	10 SEER	50.6	49.4	43.4	39.5	39.4	35.1	31.4	26.0	NC-40	48.8
	10 SEER Sound Wall	46.2	50.2	41.0	32.2	31.1	18.9	14.8	12.9	NC-35	42.5
	10 SEER Sound Curb	44.3	45.4	36.4	28.7	25.8	21.4	18.3	12.1	NC-30	41.2
FAN 20 x 5	IHPAC	43.8	35.1	26.8	21.2	21.3	16.9	15.0	20.1	NC-25	32.0
	10 SEER	47.0	44.4	40.2	37.9	36.1	33.7	29.1	24.4	NC-40	47.0
	10 SEER Sound Wall	50.0	45.6	37.8	29.6	32.3	16.7	11.7	20.1	NC-35	39.9
	10 SEER Sound Curb	43.2	41.0	37.7	31.4	26.8	19.4	13.6	20.1	NC-30	38.7
FAN 30 x 5	IHPAC	38.5	32.8	23.0	19.3	19.7	13.3	11.1	20.1	NC-25	29.2
	10 SEER	45.2	40.5	38.6	37.0	34.1	30.9	26.1	23.2	NC-35	44.8
	10 SEER Sound Wall	51.0	46.9	32.9	29.0	33.8	16.5	10.4	20.1	NC-35	40.5
	10 SEER Sound Curb	45.1	39.9	34.4	29.0	23.1	15.6	11.1	20.1	NC-25	36.9
STAGE1 10 x 5	IHPAC	61.0	48.5	34.1	33.1	21.5	16.5	14.3	13.9	NC-40	40.8
	10 SEER	66.8	55.5	57.5	44.6	43.3	39.9	36.8	31.5	NC-50	55.2
	10 SEER Sound Wall	72.3	48.9	50.0	34.5	26.5	23.0	20.6	17.3	NC-55	49.1
	10 SEER Sound Curb	66.7	50.6	39.4	35.2	32.9	25.7	23.8	19.9	NC-45	47.3
STAGE1 10 x 5 x 45°	IHPAC	55.5	51.5	31.5	33.0	19.1	13.3	10.8	20.1	NC-35	39.9
	10 SEER	71.4	58.5	53.9	42.8	40.2	36.7	33.1	28.1	NC-55	54.4
	10 SEER Sound Wall	62.2	51.2	43.6	35.3	28.7	21.7	18.6	16.3	NC-40	45.2
	10 SEER Sound Curb	59.2	49.5	40.0	33.7	29.7	23.0	20.0	16.9	NC-35	45.1
STAGE1 20 x 5	IHPAC	54.3	43.3	30.7	26.1	18.0	12.0	18.0	20.1	NC-30	36.1
	10 SEER	61.9	54.4	47.9	41.0	37.2	34.1	31.6	26.3	NC-40	50.5
	10 SEER Sound Wall	70.1	52.0	45.6	32.2	25.5	17.0	14.3	12.3	NC-50	46.4
	10 SEER Sound Curb	63.5	42.9	37.5	33.3	29.6	21.1	19.6	16.2	NC-40	41.9
STAGE1 30 x 5	IHPAC	49.9	45.5	29.5	28.1	14.8	10.2	18.0	20.1	NC-30	34.6
	10 SEER	60.9	48.3	44.7	40.1	35.0	32.3	29.0	24.7	NC-40	47.8
	10 SEER Sound Wall	61.8	49.0	38.2	31.9	24.1	15.0	12.8	20.1	NC-40	41.9
	10 SEER Sound Curb	65.8	43.3	33.8	32.6	26.0	18.9	16.6	13.9	NC-45	42.5
STAGE2 10 x 5	IHPAC	60.8	52.1	36.3	33.0	30.1	24.2	16.6	12.1	NC-40	42.7
	10 SEER	66.8	55.5	57.5	44.6	43.3	39.9	36.8	31.5	NC-50	55.2
	10 SEER Sound Wall	72.3	48.9	50.0	34.5	26.5	23.0	20.6	17.3	NC-55	49.1
	10 SEER Sound Curb	66.7	50.6	39.4	35.2	32.9	25.7	23.8	19.9	NC-45	47.3
STAGE2 10 x 5 x 45°	IHPAC	57.5	49.8	33.8	32.6	24.7	21.7	15.7	11.9	NC-35	40.6
	10 SEER	71.4	58.5	53.9	42.8	40.2	36.7	33.1	28.1	NC-55	54.4
	10 SEER Sound Wall	62.2	51.2	43.6	35.3	28.7	21.7	18.6	16.3	NC-40	45.2
	10 SEER Sound Curb	59.2	49.5	40.0	33.7	29.7	23.0	20.0	16.9	NC-35	45.1
STAGE2 20 x 5	IHPAC	54.5	47.4	35.4	27.2	25.7	20.3	13.0	20.1	NC-30	38.8
	10 SEER	61.9	54.4	47.9	41.0	37.2	34.1	31.6	26.3	NC-40	50.5
	10 SEER Sound Wall	70.1	52.0	45.6	32.2	25.5	17.0	14.3	12.3	NC-50	46.4
	10 SEER Sound Curb	63.5	42.9	37.5	33.3	29.6	21.1	19.6	16.2	NC-40	41.9
STAGE2 30 x 5	IHPAC	50.0	43.0	31.1	28.7	21.0	19.0	14.0	20.1	NC-25	35.9
	10 SEER	60.9	48.3	44.7	40.1	35.0	32.3	29.0	24.7	NC-40	47.8
	10 SEER Sound Wall	61.8	49.0	38.2	31.9	24.1	15.0	12.8	20.1	NC-40	41.9
	10 SEER Sound Curb	65.8	43.3	33.8	32.6	26.0	18.9	16.6	13.9	NC-45	42.5

Figures

Figure 1. Photograph of interior of LBNL RC Test Bed depicting the occupant simulation system including 60W light bulbs (50% on in this case). Also note dual HVAC systems. The system on the left is the IHPAC and on the right is the 10SEER unit (sealed during IHPAC operation). The room monitoring sensors are located on the stand in the center. Duct and return sensor cables may be seen on the IHPAC side as well. Data from these sensors are logged using the APT datalogger seen on the left above the computer stand.

Figure 2. External wall of LBNL RC Test Bed showing the 10 SEER (left) and prototype IHPAC (right) wall-mount units. Batt insulation seen above the IHPAC was used prior to completion of an insulated top discharge duct. The third HVAC system on the far left was the original system on this RC.

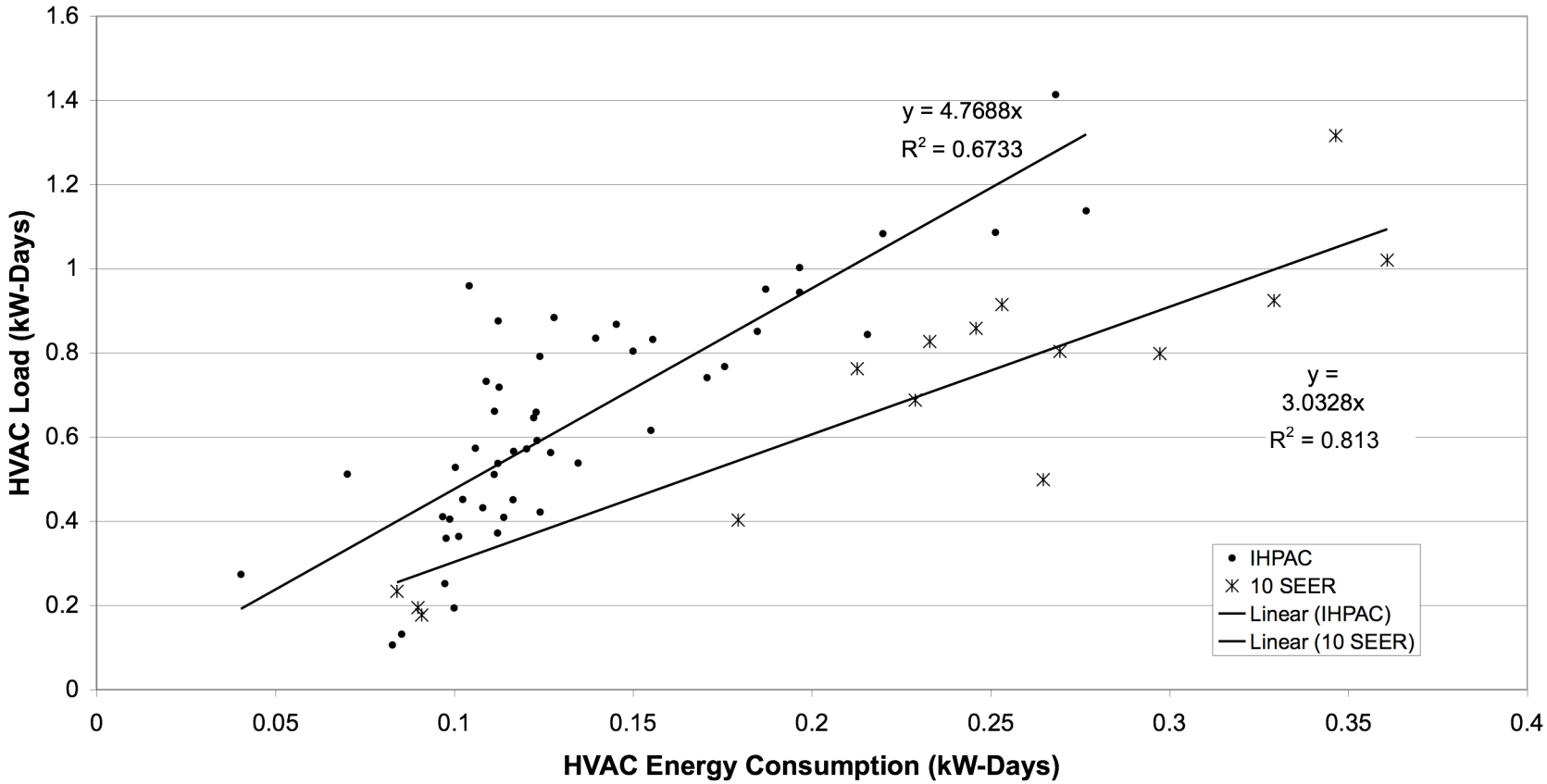

Figure 3. HVAC heating and cooling versus HVAC Energy Consumption in both heating and cooling modes during school day periods (08:00 to 14:30 Monday – Friday).

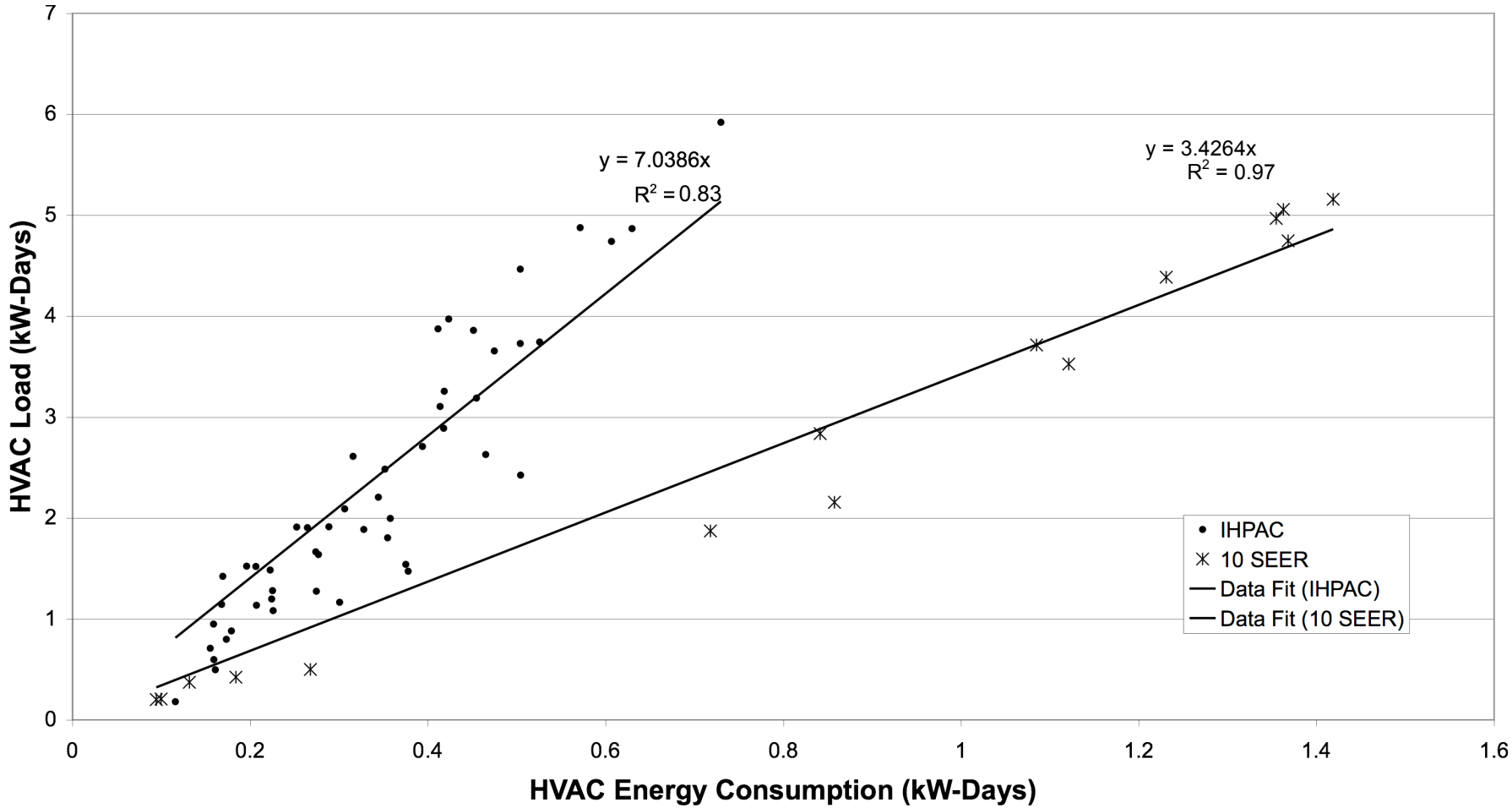

Figure 4. HVAC heating and cooling versus HVAC Energy Consumption in both heating and cooling modes during daily 24 hour periods).