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Summary

The factory-built relocatable classroom (RC) is a dominant force in the school facility construction industry in the United States (U.S.) and elsewhere. It is estimated that there are approximately 650,000 RCs currently occupied in the U.S., housing about 16 million students. RCs receive public attention due to complaints about poor indoor environmental quality (IEQ). Both measured data and anecdotal evidence in California have suggested excessive acoustical noise from heating, ventilation, and air conditioning (HVAC) equipment as a central factor leading to degraded IEQ. In the U.S., RCs are typically equipped with unitary exterior wall-mount HVAC systems, and interior acoustical noise due to structural and airborne transmission can reach levels of about 58dB(A) with compressor cycling, under unoccupied conditions. Due to these noise levels teachers often simply choose to turn off the HVAC, leading to inadequate ventilation, as well as poor thermal conditioning, and thus to poor indoor air quality. Elevated levels of carbon dioxide and volatile organic compounds including formaldehyde are common. We discuss the acoustic component of our efforts to develop and test energy efficient HVAC systems that address the ventilation, controls, and acoustic requirements necessary to ensure high quality indoor environments in RCs.

1. Introduction

Energy efficiency and indoor environmental quality (IEQ) are key building design issues, but they are often considered to conflict when design, construction, and operation decisions are made. Designs achieving good IEQ can be expected to have beneficial effects with respect to occupant health, work performance and attendance, therefore promoting their implementation is of benefit to society. Indoor acoustical conditions including sound levels can strongly affect the habitability and suitability of a building for its occupants. When HVAC is the source of the noise, ventilation and thermal comfort can be impacted. This issue is no more clearly evident than in the classroom. Instruction relies upon the audibility of the teacher, and concentration relies on minimization of distracting or excessive noise. Nonetheless, considerable information both qualitative and quantitative, indicate that unoccupied baseline classroom noise levels, the noise in the room due to the building acoustics, mechanical systems and surroundings, are often excessively high. This being so, the additional sound energy input from student and teacher occupants, often competing against the baseline, can become untenable.

A number of existing guidelines have been promulgated for noise levels in school environments with exposures ranging from a time-weighted average sound level, or sound exposure (L_{eq}), of 35 to 65 A-weighed decibels (dB(A)), with a high of short intervals at levels as high as 115 dB(A) in vocational and music areas (Table 1). Children, in their formative years of academic development, require better acoustic quality than adults in classrooms, especially given good speech recognition is necessary for optimal comprehension and learning during the processes of language and reading acquisition (WHO, 2001a-b). Children with hearing impairments and learning disorders are especially susceptible to noise. Auditory processing for clear discrimination of speech requires a speech signal of about 10 dB above baseline levels. With normal teaching voice levels of about 55 dB(A), classroom baseline noise levels should therefore be ≤ 45 dB(A) (ASA 2002).

This paper reports on the acoustical investigation elements from two studies of IEQ in relocatable classrooms (RCs). Study of RCs has value from both scientific and societal perspectives. RCs are modular factory-built structures that have become increasingly prevalent in the U.S. They are a cost competitive means of providing flexible, movable, school housing in areas where school enrollment and community populations are in flux, or where government mandates changes in classroom occupancy limits. California has more than 85,000 RCs in its public school systems while U.S.-wide an estimated 650,000 RCs are in use. California's occupied RC stock is growing at a rate of 3000 to 10,000 a year (CARB/CDHS 2003, Sarich 2001), depending upon demands such as new class size reduction initiatives. Due to their relative low-cost and perceived low-value, RCs probably suffer more than their share of neglect by school maintenance and operation budgets. Thus, 16 million students and teachers are at risk from IEQ-related problems on a daily basis. From the building science perspective, the RC is an ideal structure in which to investigate implications of design, maintenance, and operation on IEQ conditions as well as occupant health, productivity, and performance. The reasons for this include their abundance, relative ease of access, and their parametric simplicity; that is, a single building operator, a consistent occupancy pattern, and identical structures are frequently located side-by side for controls.

We know ventilation rates in RCs are often low (Shendell *et al.* 2004a, 2004b) because teachers frequently operate their HVAC systems in the mode where the ventilation shuts off except when heating or cooling is required. We also know anecdotally that teachers operate the HVAC system this way to avoid HVAC system-related noise. These reports are supported by the findings from the CARB-CDHS survey where teachers in 60% of surveyed RCs reported that they sometimes turned off HVAC systems to reduce noise levels (CARB-CDHS 2003). If true, the acoustics of these HVAC systems contribute to further degradation of the classroom IEQ by causing ventilation to be avoided. Continuous ventilation is required in California Classrooms under two state laws (CA Title 24 2001, CCR 1995) and is a required component of ASHRAE Standard 62.1 (ASHRAE 2004).

Table 1. Existing noise guidelines for school environments at local, state and international levels

Specific Microenvironment	Leq, dB(A)	Time	Reference
School classrooms and pre-schools, indoors	35	During school hours	WHO, 1999; WHO, 2001a-b
School, playground, outdoors	55	Recess/Physical Ed.	WHO, 2001a
School classrooms, unoccupied, indoors[1]	45 (35 goal)	During school hours	CHPS, 2002
School classrooms, unoccupied, indoors[1]	35[2]	During school hours	ASA, 2002; Wakefield, 2002

[1] 0.6 second max. unoccupied reverberation time also included
[2] Specified in Americans with Disabilities Act, 2003

We report acoustic measurement results from a yearlong study comparing energy and IEQ benefits from a standard heat pump air conditioner (HPAC) and an energy efficient Advanced Hybrid (AH) Indirect/Direct evaporative cooler with gas-fired hydronic forced air heating (Apte et al. 2004, 2005a). The systems were compared in four RCs in Northern California. Based on the results from this study we have embarked on a collaborative project with Bard Manufacturing (Bryan, OH), a major manufacturer of wall mount HVAC systems, to develop an Improved HPAC (IHPAC) system that addresses the key energy efficiency and IEQ problems identified in the first study. A major goal of this project has been to significantly reduce the acoustic noise levels during HVAC operation. A prototype IHPAC system was intensively tested in an RC under simulated occupancy conditions.

2. Methods

2.1 High Performance Commercial Buildings RC Study (HPCBS)

Pertinent methods from this study are summarized below and provided in more detail by Shendell et al. (2002). Four newly manufactured and installed High Performance RCs were studied in side-by-side pairs at two school districts (SDA and SDB) in two distinct CA climate regions. One RC installed in each SD was manufactured with alternative interior materials (type A) while the second was constructed in the manufacturer's standard manner (type B). The details of the RC construction, much of which is not particularly relevant to this paper, can be found elsewhere (Apte et al. 2004, 2005a). We refer to classrooms of type "*A*" and "*B*" located in *SDA* and *SDB* as SDA-A, SDA-B, SDB-A, and SDB-B.

The high performance RC design used in this study combines available energy efficient construction materials and methods. Each of the four study RCs were equipped with two HVAC systems: a standard 1 0 SEER heat-pump air conditioning system (HPAC), and an AH energy-efficient indirect/direct evaporative cooler (IDEC) which is suitable for use where outdoor summertime humidities are moderate to low. Additionally, compared to the standard heat-pump system, it consumes about 70% less cooling energy. It has no compressor and a quiet fan. Incorporated into the IDEC is an 85% efficient (annual fuel utilization efficiency) gas-fired hydronic space heating system. Both HVAC systems were adjusted to supply ventilation at ≥7.5 L s^{-1} (15 CFM) $person^{-1}$ and require that the system be turned on to provide the required ventilation. The IDEC component of the AH system provides continuous outside air, while in the heat pump system this action is tied to the temperature set point, such that outside air is only supplied when heating or cooling is needed. The IDEC supply consisted of three 61 cm (2 foot) square ceiling diffusers evenly spaced across the length of the RC, while the HPAC had only two.

Detailed monitoring included energy consumption, indoor and outdoor temperature and relative humidity, and carbon dioxide, particles, volatile organic compound and aldehyde concentrations. Acoustics noise levels were monitored continuously and stored as 6-minute average values over a period of one year using Extech 407736 Sound Level Meters (SLM; Davis-Inotek Instruments, Baltimore, MD) positioned at the center of the teaching space of each RC.

2.2 Improving Ventilation and Saving Energy: Classroom HVAC Study (IVSE)

Working in collaboration with Bard Manufacturing Company (Bard, Bryan OH) and Geary Pacific Supply (GP, Orange, CA), major manufacturers and distributors of the wall-mounted HVAC systems predominantly installed on RCs, we have developed a prototype improved heat pump air conditioner (IHPAC). The HVAC system was designed to meet the following goals: 1) improve the energy efficiency to at rated Seasonal Energy Efficiency Ratio (SEER) of 13; 2) improve ventilation controls by separating ventilation from thermal conditioning and providing for a CA code required pre-occupancy ventilation purge of three air exchanges (CA Title 24 2001, CCR 1995); 3) lower noise levels under standard test conditions to, or below 45 dB(A) under the loudest operation mode; 4) design for a simple replacement procedure for existing systems being replaced or upgraded.

An RC from a lease fleet was installed at LBNL and instrumented with continuous energy and ventilation monitoring equipment (Apte *et al.* 2005b). The RC, a standard 7.3 x 12.2 m (24'x40') structure was atypical in that it was assembled from two opposite module halves each equipped with an RC HVAC system. This enabled the installation of a new IHPAC on one side while leaving a SEER 10 system on the other as a control, allowing for direct performance comparisons between the two systems while using the same building. A new supply plenum is used with the IHPAC, allowing for three supply ducts rather than the two often used in RCs; three ceiling supply registers replace the two existing. Both HVAC systems were adjusted to provide 230 l s^{-1} (480 CFM) based on an expected occupancy of 32. Energy and ventilation measurements were conducted continuously during many days of operation using the SEER 10 system followed by several weeks using the IHPAC. The systems were each operated under both heating and cooling conditions depending on changing weather during the fall of 2004.

Indoor noise levels were conducted using a Brüel and Kjær (Nærum, Denmark) model 2260 sound spectrum analyzer. Half octave band sound level spectra (6Hz – 20 kHz) were characterized at two heights (1.1 and 1.5 meters) and at four standard locations as described in the results section. The measurements were taken on the module half in which the HVAC was being operated. Sound levels at these locations were measured with the fluorescent room lighting both on and off. Background noise levels in the room were measured just before the studies began for several minutes.

3. Results

3.1 High Performance Commercial Buildings RC Study (HPCBS)

Table 2 summarizes measured noise levels as Leq, or time-weighted average exposure. The measured school day L_{eq} (Time period (T.P.) 1-4) across RCs and seasons in SDA was slightly higher during AH system operation weeks than during HPAC operation weeks. In SDB-A, however, the school day L_{eq} across seasons was similar across HVAC systems, and in SDB-B the school day L_{eq} across seasons was slightly higher during HPAC operation weeks than during AH system operation weeks.

Cooling demand during the cooling season was assumed to be greater in the afternoon (T.P. 4). Across SDs and RCs, the school day afternoon L_{eq} in the cooling season was slightly higher during HPAC operation weeks than during AH system operation weeks; the difference in SDB was 1.5 dB(A). Likewise, heating demand during heating season was assumed to be greater in the mornings (T.P. 1 and 2), and greatest in T.P. 1. Across SDs and RCs, the school day AM L_{eq} in the heating season was slightly higher during HPAC operation weeks than during AH system operation weeks. In both seasons these data suggest that occupants were the dominant source of noise, and that the AH system was slightly quieter for conditioning than the HPAC system.

Measurements in SDA-B when the HPAC was operated outside school hours by a teacher working alone in the evening or on a weekend, contributed up to 15 dB(A) above the background noise level. The range observed during the study was approximately 8-15 dB(A). When the HPAC operated in the adjacent RC (SDA-A), the noise level apparently increased about 1-1.5 dB(A); the RC door and windows were closed. During periods when the AH system started up automatically overnight when the thermostat dropped below 55ºF, noise levels appeared to increase approximately 4-7dB(A), about 4-8 dB(A) lower than the noise contributed by the HPAC above background during unoccupied hours. Anecdotally, the teachers all stated that the AH system was quieter in operation that the HPAC, making it easier to teach. For more details on these data see Apte et al., (2004, 2005a). Clearly, the levels of noise observed in these classrooms are in excess of acceptable limits for educational environments, however the HVAC systems were only partial contributors.

Table 2. AM, PM and day-long summary of occupied classroom HPCBS study average noise levels (dB(A)).

		RC A				RC B			
	HVAC system operational:	HPAC		Advanced Hybrid		HPAC		Advanced Hybrid	
SD	Statistic/time period[2]	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
A	school day L_{eq}[1] (T.P.1-4)	58.4	58.6	59.1	59.6	53.7	55.3	54.3	55.9
	school day AM L_{eq} (T.P.1-2)	58.9	59.7	59.6	59.2	53.2	55.3	53.7	55.0
	school day PM L_{eq} (T.P.4)	60.5	57.9	60.0	61.4	57.5	57.1	57.5	58.7
B	school day Leq (T.P.1-4)	53.5	54.4	53.7	54.3	56.3	55.5	55.9	53.9
	school day AM Leq (T.P.1-2)	53.8	55.6	55.3	55.1	56	56.7	56.4	54.6
	school day PM Leq (T.P.4)	55.2	54.7	53.7	55.2	58.2	56	56.9	54.9

[1] L_{eq} = time-weighted average sound level, or sound exposure.
[2] T.P. 1=AM before recess; T.P. 2. = AM before lunch; T.P.4 = post lunch until end of school day

3.2 Improving Ventilation and Saving Energy: Classroom HVAC Study (IVSE)

Table 3 presents a comparison of sound exposure levels measured at four distinct indoor locations during operation of the prototype IHPAC and 10 SEER (Control) HVAC systems in the unoccupied IVSE test RC. These measurements provide an accurate assessment of the difference in indoor sound levels generated by the prototype IHPAC and a standard system. Location 1 at a height of 1.5m is considered the standard HVAC acoustic measurement point by the modular classroom industry, and is the worst-case measurement location. The difference between the sound levels generated by the two systems is clear, and is statistically significant ($p<0.005$, Students t-test). Location 1 L_{eq} was reduced from 53.7 to 39.2 dB(A).

Note the interesting effect of the fluorescent room lighting on sound levels. Lights with no HVAC added from 1 to 2.5 dB(A) to the room noise depending upon the location (data not shown). The data suggest that the T8 fluorescent lighting and HVAC noise contributions are not strictly additive and can combine to create a slightly lower or higher overall sound level. Although the differences may be small, it is important to consider the effects of lighting noise when measuring HVAC sound levels.

Table 3. Comparison of IVSE Study sound exposure levels (Leq) of 10 SEER and IHPAC in a furnished RC during loudest operation mode and fan-only modes with fluorescent room lighting on and off.

		Fan & Compressor on Full dB(A)				Fan Only dB(A)			
		Lights On		Lights Off		Lights On		Lights Off	
Height[1]	Loc[2]	10 SEER	IHPAC	10 SEER	IHPAC	10 SEER	IHPAC	10 SEER	IHPAC
1.1m	1	53.4	44.2	53.7	44.7	51.2	33.1	51.3	33.0
	2	53.4	41.8	53.1	41.7	49.8	33.0	49.0	33.4
	3	50.2	40.2	50.0	41.2	46.9	33.8	46.8	31.1
	4	47.9	39.2	47.8	39.4	44.8	32.0	44.7	29.5
1.5m	1	55.3	39.2	55.2	43.0	52.7	31.8	53.5	31.5
	2	54.3	41.8	54.4	40.7	49.5	32.0	48.8	32.1
	3	50.7	39.6	50.5	40.0	47.0	32.0	47.0	32.1
	4	47.7	38.1	47.8	38.3	45.1	30.1	44.8	29.9

[1] Height = measurement distance from floor.
[2] Loc = location: On RC module side with the system under investigation (1) 3 meters from and perpendicular to return grille; (2) 3 meters from and 45º to return grille; (3) center of the module (6m to back wall and 1.5m to outside wall); (4) far end of the module (1.5 meters to front wall and 1.5 meters to side wall).

Figures 1 and 2 depict half-octave sound level spectra for the 10 SEER and IHPAC systems, respectively. The relative contributions of fan and compressor are clearly seen in these figures. The 10 SEER fan appears to dominate the mid and high frequency sound output while the compressor adds a large power boost in the lower frequencies. In the case of the IHPAC, the fan noise is almost non-detectable while the compressor adds to the lower octaves. The IHPAC is clearly much quieter and the noise that it generates occurs intermittently when the compressor cycles on.

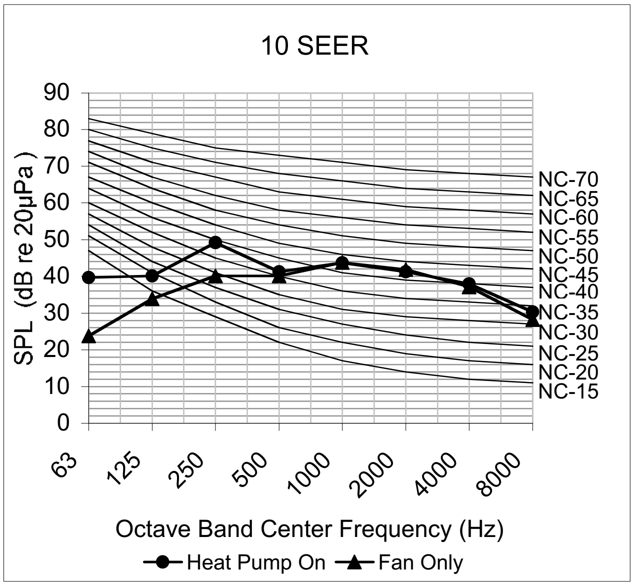

Figure 1 IVSE Study half octave-band sound power level (SPL) spectra of 10 SEER control HVAC system with fan only and both fan and compressor on. Fluorescent lighting in RC was on.

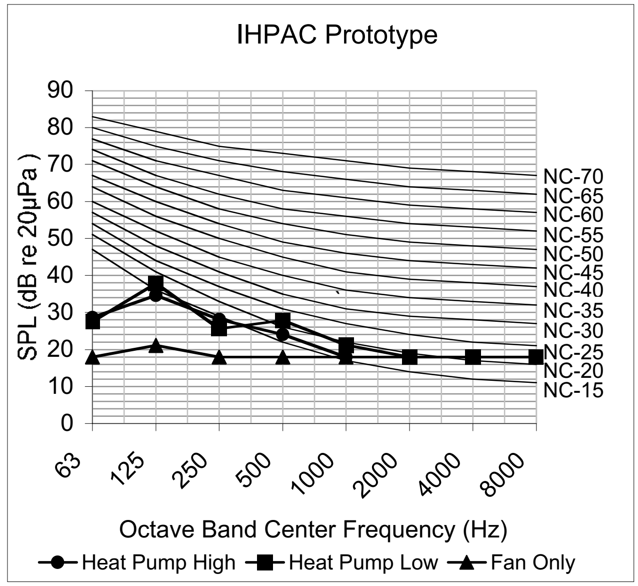

Figure 2 IVSE study half octave-band sound power level (SPL) spectra of prototype Improved HVAC system (IHPAC) with fan only and both fan and compressor on low and high settings. Fluorescent lighting in RC was on.

The noise level in a space is often described with a single-number rating called the noise criteria (NC). The NC rating is the measured sound pressure level at each measured frequency compared against a set of standard NC curves. By plotting measured levels superimposed on the NC curves a rating is derived. The lowest NC curve not exceeded by the plotted noise spectrum is the NC rating (ASA 2002). Indoor noise levels are assessed according to an Acoustical Society of America (ASA) guideline that indoor NC levels should not exceed NC-25 to NC-30. The ASA also provide a guideline of 35 dB(A) (ASA 2002).

Based upon the data shown in the Figures the NC ratings within a standard RC, using the 10 SEER and IHPAC systems are about NC45 and NC25, respectively. These measurements will be replicated in the ongoing field study during four seasonal measurement cycles in the upcoming year.

4. Discussion

During the year long monitoring of the four HPCBS RCs sound levels using both the 10 SEER and AH systems noise levels were high, consistent with those reported by others (i.e., CARB/CDHS 2003). Unfortunately no octave band measurements were taken during he HPCBS study, but the AH system has only a fan and no compressor, so it is safe to assume that the majority of the system noise was contributed by the IDEC fan. The occupied room noise levels were not as low as expected during the AH operation, although the non-occupied levels were 4-8 db(A) lower when it was operating. It is probable that the supply plenum, duct, and diffuser arrangements would benefit from an acoustic analysis that could reduce the AH system noise further.

The IHPAC showed major reductions in RC noise levels under unoccupied conditions. It is anticipated that these reductions will lead to improvements in occupied RC noise levels. However, this is very dependent upon the occupants themselves. The octave-band sound spectrum analyses point to fan and air supply noise as a key cause of excessive noise in the RC. The requirements for continuous supply of outside air for ventilation expect a properly operated classroom to have the fan on all of the time. Thus, it is essential that ventilation supply is acceptably quiet, and the IHPAC appears to have these characteristics. Field results should indicate whether the laboratory-based measurements translate to quieter classrooms

5. Acknowledgements

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