Preliminary Evaluation of Performance Enhanced Relocatable Classrooms in Three Climates

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ABSTRACT

A research project has monitored a specifically modified energy efficient portable classroom compared with a standard unit, in side-by-side installations in three states (NY, NC and FL). Energy performance data is summarized in this paper.

Introduction

Increasingly, portable relocatable classrooms are used to accommodate growing school populations. An estimated 36% of the nation's schools use portable classrooms (Lewis, et al., 2000). They also are large energy users and are often blamed for indoor air quality problems. Although recent research contradicts conventional wisdom, portables are perceived to provide a sub-standard quality of learning environment as typically they are constructed to the minimum codes (Heshong Mahone Group, 2003). Whereas many school districts intend them as temporary, units are seldom removed – temporary classrooms are often permanent.

Several studies have evaluated potential improvements to portable classrooms. Washington State University and the Oregon Office of Energy conducted a study, which examined the cost effectiveness of energy improvements to PNW relocatable classrooms (Brown et al., 1997). They concluded that energy efficiency opportunities were favorable, with on-site commissioning during set up being particularly cost effective (Klure et al., 2001). Other research conducted by Lawrence Berkeley National Laboratory examined modifications to save energy but also evaluated the volatile organic compound (VOC) emissions from typical interior finish materials used in the manufactured modular industry (Apte et al., 2002).

A much-discussed study done for the *Pacific Gas & Electric Company*, suggested a correlation between classroom daylight levels and improved student academic performance and attendance levels (Heschong et al., 2002). However, a more recent study shows weaker association, with window views and the acoustic environment being more important than daylighting itself (Heschong Mahone Group, 2003).

In previous work, Florida Solar Energy Center (FSEC) studied retrofits in two existing portable classrooms in Central Florida demonstrating measured energy use reduction of 40% (Callahan et. al., 1999). In a separate simulation analysis, FSEC evaluated potential improvements to new portable classrooms across U.S. climates (Parker et al., 2001).

Specifications for Experimental Classrooms

Within our project, Performance Enhanced Relocatable Classrooms (PERC) are factory constructed modular classrooms designed to use less energy, potentially improve indoor air quality and provide enhanced levels of natural lighting. Most relocatable classrooms around the

United States are 24′ x 40′ or 24′ x 36′ units with a conditioned floor area of 860 - 960 ft^2. However, regional and local building codes create different specifications.

To meet our research objectives, we located matched pair units in three very different climates. Thus, one pair of classrooms is located in Cornwall, NY (cold climate), Chapel Hill, NC (mixed climate) and Orlando, FL (hot-humid). The standard classroom was typical for each location. In contrast, the experimental PERC unit used the research strategies mapped out from the previous analysis (Parker and Fairey, 2001). The New York and Florida portables were of elementary classrooms, while high school students occupied those in North Carolina. Tables 1 - 3 list the key differences:

Table 1. New York Standard and PERC Specifications

Characteristic	Standard Relocatable	PERC
Floor Insulation	R-11, standard	R-13 Formaldehyde Free
Wall Insulation	R-11, standard	R-19 Formaldehyde Free insulation w/ ½" polystyrene board
Ceiling Insulation	R-19, standard	R-30 @ roof deck, w/ airspace between rafters for maintaining cold roof*
Windows	Season Shield, Double Glazed	Low-E Thermopane by Atrium (U= 0.24, SHGC = 0.38)
Lighting	14 fixtures @ (4) T12 34W lamps plus 1 fixture with (2) T12 each; 15 ballasts; Other: bathroom (2) 60 incandescent bulb plus (4) outdoor lights @ 60W; Connected Lighting Load = 2,264W	12 fixtures @ (3) T8 32W lamps plus 1 fixture with (2) T8 each; 25 ballasts; Other: (2) 15W CPL for bathroom, (4) 60W outdoor; Connected Light Load = 1,422W
Skylights	None	12 SunOptics skylights w/ site modified skylight wells
Interior Floor Finish	26 oz. rolled carpet	Non-permeable backing, Interface carpet tile, low VOC glue
Heating System	10 kW Electric Resistance Heat	Bard QTec Heat Pump, HSPF 7.5 with 10 kW auxiliary strip heat
Cooling System	Bard 3-ton Air Conditioner SEER 10, WA381A15	Bard QTec 3-ton Heat Pump with ERV SEER 12, SH381A1
Ventilation System	Fixed CFM during occupancy	CO^2 control for ventilation with 3-step fan speed and energy recovery ventilator Bard CS2000 Energy Monitor
Bathroom Exhaust Fan	Broan, 4 sone	Broan Ultra Silent Fan, 1.0 sone
HVAC through Wall Install	Standard gasket provided with unit-rough opening not addressed	On site - sealed rough opening at HVAC wall connection with mastic and fiber tape
Duct Joints	Industry Standard	Sealed with Mastic (on site)
Duct Leakage	CFM25out = 458	CFM25out = 271
Building Leakage	ACH50 = 16.37	ACH50 = 16.66
* The intended airspace between air barrier and the roof deck was not constructed as intended.		

Table 2. North Carolina Standard and PERC Specifications

Characteristic	Standard Relocatable	PERC
Floor Insulation	R-11, standard	R-15 Formaldehyde Free
Wall Insulation	R-11, standard	R- 15 Formaldehyde Free insulation w/ R-7 isocyanurate sheathing, Tyvek house wrap
Exterior Door	Honeycomb core R= 1.626	Polystyrene core R= 4.8
Ceiling Insulation	R- 19 batt insulation	R-38 blown
Roof	Dark colored asphalt shingle	Light colored asphalt shingle w/ Techshield radiant barrier decking by Louisiana Pacific
Windows	Single pane, aluminum frame (U= 1.10, SHGC= 0.86, Vt=0.90)	Low-E Argon gas filled, vinyl framed by Reynolds 200 Series (U=0.35, SHGC = 0.38, Vt=0.58)
Lighting	16 fixtures @ (2) T12 34W; 16 ballasts; Other: Bathroom (1) 60W incandescent bulb plus (2) outdoor lights @ 60W; Connected Lighting Load = 1,268W	10 fixtures @ (3) T8 32W lamps plus 3 fixtures with (1) T8 each; 20 ballasts; Other: Bathroom (1) 13W CFL plus (2) outdoor lights @ 13W CFL; Connected Lighting Load = 1,065W
Light Controls	Manual	Sensor switch photosensor controls continuous dimming ballast with manual override
Outdoor Light	Manually controlled	Photosensor controlled
Skylights	None	(6) SunOptics Skylights
Interior Floor Finish	Roll carpeting	Non-permeable backing, Interface Cubic carpet tile, low VOC glue
Interior Wall Finish	Vinyl covered gypsum	Harmony Low Odor Latex Paint
Heating System	10 kW electric resistance heat strip	Bard SH Series Heat Pump, HSPF 7.5, 5 kW auxiliary heat strip
Cooling System	Bard WA423A1D Air Conditioner 3.5 ton, SEER 10	3 ton Bard SH Series Heat Pump with ERV SEER 12, SH381-A1DR
Ventilation System	Fixed CFM during occupancy	CO^2 control for ventilation with 3-step fan speed with ERV
HVAC controls	Manual t-stat	Bard CS2000 Energy Monitor
Bathroom Exhaust Fan	Broan, 4 sone, 100 CFM	Broan Ultrasilent model #S80LU, 0.3 sone, 50 CFM
Duct Leakage	CFM25out = 197	CFM25out = 182
Building Leakage	ACH50 = 9.08	ACH50 = 4.83

Table 3. Florida Standard and PERC Specifications

Characteristic	Standard Relocatable	PERC
Floor Insulation	R-14 unfaced	R-14 unfaced Formaldehyde Free
Wall Insulation	R-11 faced	R-14 unfaced Formaldehyde Free insulation w/ 1/2" Dens Glas with ¾" polyisocyanurate foam insulation board
Exterior Door	Honeycomb core R = 1.5	polystyrene core R = 4.8
Ceiling Insulation	R-19 faced	R-30 Icynene spray foam insulation @ roof deck
Roof	Standard dark roof; 0.45 mm black EPDM over ½" Densdeck	Reflective roof; 0.45 mm white EPDM over 5/8" Densdeck
Windows	1/8" non-tempered bronze tint glass (U=1.03, SHGC=0.84, Vt=0.77)	Low-E Argon gas filled, vinyl framed by Ellison with Solarban 60 glass (U= 0.28, SHGC = 0.39, Vt = 0.71)
Lighting	14 fixtures @ (2) T12 34W lamps plus 3 fixtures with (1) T12 each; 17 ballasts; Other: Bathroom (1) 60W incandescent bulb plus (2) outdoor lights @ 60W; Connected Lighting Load = 1,234W	8 fixtures @ (3) T8 32W lamps plus 3 fixtures with (1) T8 each; 20 ballasts; Other: (3) 15 W CPL, photosensor controlled; Connected Lighting Load = 915W
Outdoor Light	60W incandescent manually controlled	15 Watt CPL, photosensor controlled
Skylights	None	(6) 21" dia. Solatube Skylights
Interior Floor Finish	26 oz. rolled carpet	Non-permeable backing, Interface 'Sabi' carpet tile, low VOC glue
Heating System	Strip Electric Heat 10kW heat strip	Bard QTec Heat Pump, HSPF 7.5, 5 kW strip heat
Cooling System	Bard Central AC 3.5 ton with ERV, SEER 10, WA422D-41D	Bard QTec Heat Pump with ERV, SEER 12, SH381A15
Ventilation System	Fixed CFM during occupancy	CO^2 control for ventilation with 3-step fan speed and energy recovery ventilator, Bard CS2000 Energy Monitor
Bathroom Exhaust Fan	Broan, 4 sone, 100 CFM	Panasonic Whisperlite Fan, 1.3 sone, 190 CFM
Duct Leakage	CFM25out Supply = 426	CFM25out = 274
Building Leakage	ACH50 = 23.2 ACH	ACH50 = 9.6 ACH
SF_6 Tracer Gas decay Est. Infiltration	Air handler on: 2.60 ach Air handler off: 0.27 ach	Air handler on - 0.66 ach Air handler off - 0.05 ach

Monitoring Results

Beginning in the fall of 2002, two side-by-side classrooms in each of three climate locations were constructed, sited, and monitored for performance. Detailed 15-minute data were obtained on end-use energy use, meteorological conditions and interior classroom conditions for temperatures, humidity, CO_2 concentrations and light levels. All of the classrooms were all-electric with measured end-uses including total electrical demand, lighting loads, air conditioner, strip heat and bathroom heaters where applicable. Miscellaneous electricity used for plug loads were obtained by differencing the total recorded site electrical use from the recorded energy use of the various sub-metered major appliances.

Table 4 shows the measured energy consumption averaged in kWh/day for the experimental classrooms compared with the standard unit as well as interior conditions prevailing over the measurement period. The monitoring was from November 17, 2002 to June 20, 2003 for the NY units and from November 1, 2003 through May 12, 2004 for the North Carolina and Florida units.

Table 4. Measured Long-Term Performance of Portable Classrooms

Parameter	NY Control	NY Exp	NC Control	NC Exp	FL Control	FL Exp
Total (kWh/Day)	134.3	88.6	51.1	27.3	55.5	10.4
HVAC (kWh/Day)	118.8	71.9	45.0	19.9	49.6	8.5
Lighting (kWh/Day)	14.9	13.6	3.9	1.3	4.2	1.3
DHW (kWh/Day)	0.2	0.4	1.0	0.9	---	---
Other (kWh/Day)	0.4	2.7	1.2	5.2	1.7	0.6
Savings (kWh/Day)	---	45.7	---	23.8	---	45.1
Interior CO_2 (ppm)*	777	788	746	628	531	744
Interior Temp. (ºF)*	71.3º	70.4º	68.9º	67.5º	70.7º	70.7º
Interior R. Humidity (%)*	32%	30%	42%	38%	50%	49%

* Weekdays, 8AM-3PM

New York Experiment

Plots below summarize the measured energy performance of the control and experimental NY classrooms over the school year from 2002 – 2003. The portables are located side-by-side at Willow Avenue Middle School in Cornwall, New York, about 50 miles north of New York City. The NY units consist of two classrooms each (24'x34") attached end-to-end. Thus, both the control and experimental portables are 24'x68' with 1,632 ft^2 of conditioned floor area. Cornwall, New York is a heating dominated climate with 30-year normals showing 6,848 heating degree-days and 507 cooling degree-days.

Energy savings. Figure 1 shows the average electrical load shape describing the energy savings for the entire school year over a 24-hour cycle from November 2002 - June 20th of 2003. The measured overall energy savings of the PERC was 46 kWh/day or 34%. Most of the savings were concentrated in the evening and early morning hours when the heating system was operating at its maximum. Note that the average peak electrical demand of the experimental unit at 8 AM is 2 kW (20%) lower than the control. The slightly greater demand around 4 PM is due to a difference in the lighting controls systems as documented below.

HVAC. Figure 2 shows how the heating, energy savings varied over the winter months. Savings from November - March averaged 79 kWh or 47% even with a problem with the control thermostat in the PERC portable. A controls problem, the heating system would refuse to turn during unoccupied periods and would maintain abnormally high temperatures. Other difficulties were experienced with the control of auxiliary strip heat, which was always activated with the heat pump. Trial and error procedures isolated the problem as a thermostat compatibility issue with the automated control system. This was only resolved near the end of the project; savings would likely have been higher in a second year of monitoring (the units were vacant in 2003 - 2004). As seen in Table 4, we could discern no significant drop in CO_2 levels from operation of the enthalpy recovery ventilation (ERV) in the experimental unit although this may have to do with relative occupancy levels.

Figure 1. Electric Demand Profile November 16, 2002 – June 20, 2003, Cornwall, NY

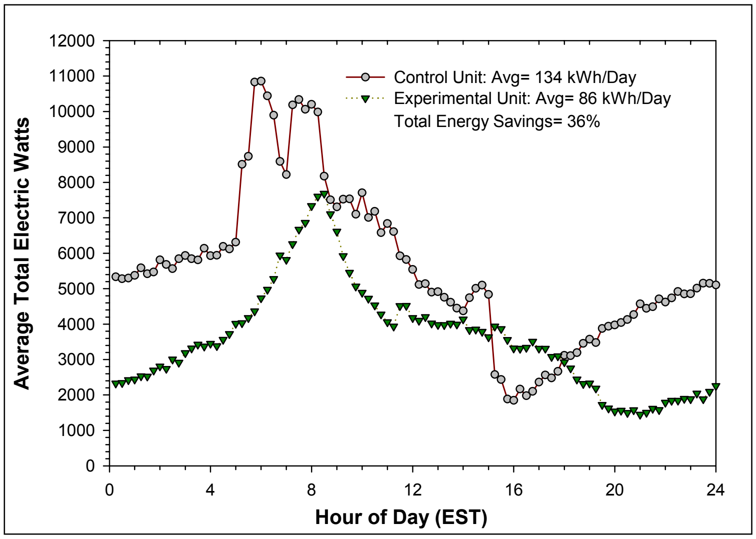
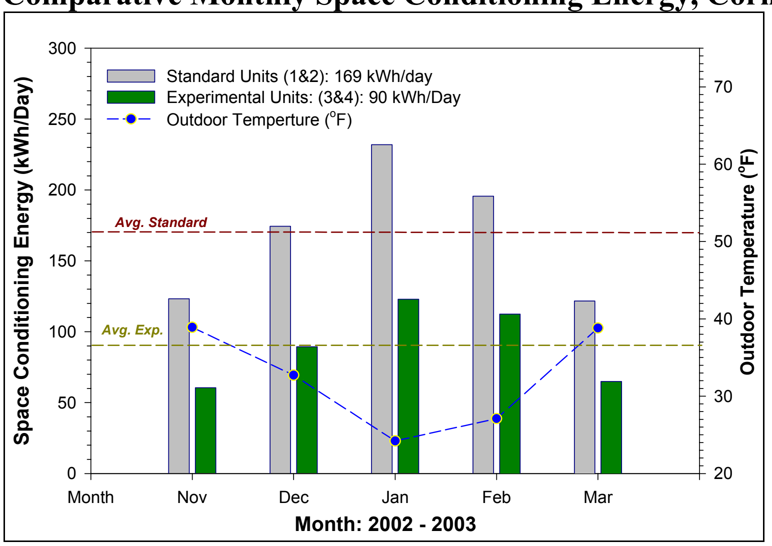


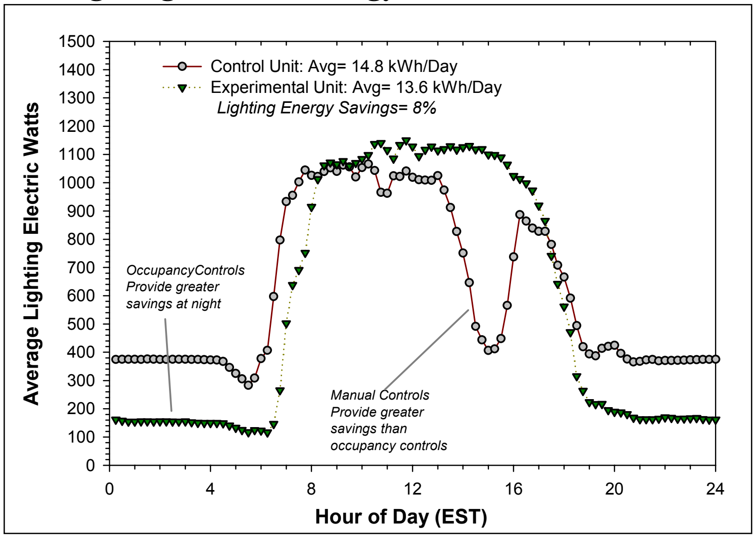
Figure 2. Comparative Monthly Space Conditioning Energy, Cornwall, NY



Lighting. Figure 3 shows the lighting demand profile evaluated over the year. Performance was disappointing as the experimental unit had a lower installed connected lighting load, as well as the daylighting system, which was aimed to reduce lighting energy use. What was not expected, however, was that the teacher in the control classroom would often only turn on half of their lighting for use with an overhead projector. Also, due to hardware troubles, we never achieved satisfactory daylighting-responsive controls in the experimental unit.

Even so, we showed about an 8% lower average daily lighting use (1.2 kWh/day) in the PERC unit– largely due to lower lighting during evening hours from the occupancy controls. On the other hand, the occupancy controls actually increase lighting use around 3-4 PM after school is out. This seemingly contradictory result comes from the janitorial staff activating the lighting due to occupancy sensing in the experimental unit, whereas the lights are manually turned off in the control. Our trouble with the daylight dimming system emphasized the need to ensure that such controls operate from the outset as seen previous projects (Floyd, 1995).

Figure 3. Lighting Electric Energy Demand Profile, Cornwall, NY



Subjectively, however, the interior lighting quality in the PERC was significantly improved. This is visually apparent in Figures 4 and 5, comparing daytime interior illumination in the two units with lights off. Although labor intensive, daylight distribution was improved by retrofitting a reflective enclosure around the skylight's wells. This increased desktop light levels by 10-15% after the retrofit.

Figure 4. Control Unit With Lighting Off

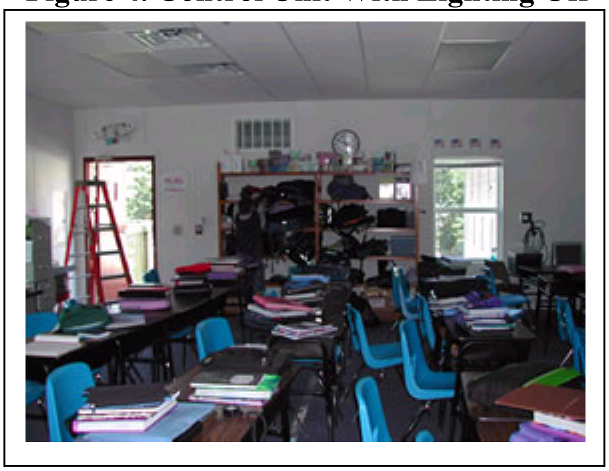


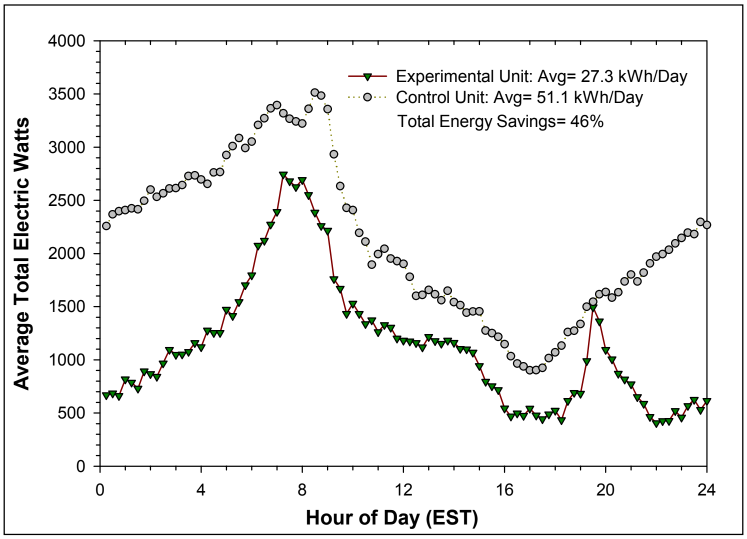
Figure 5. PERC With Lighting Off

North Carolina Experiment

The North Carolina matched pair portable classrooms are located in Chapel Hill, which has a mixed heating and cooling climate. The 30-year normals show 3,733 heating degree-days and 1,294 cooling degree-days. Each are 24'x36' units with 864 ft^2 of conditioned floor area. The typical classroom used in this school district is a wood-framed structure with gypsum ceiling, unlike the FL and NY typical classrooms, which used acoustic tile t-grid ceilings.

Energy savings. Over the school year from November 1, 2003 through May 12, 2004 data showed that the modified classroom achieved an overall energy savings of 46%. Total electricity use averaged 51.1 kWh/day in the control against 27.3 kWh in the PERC (Figure 5).

Figure 5. Electric Demand Profile November 1, 2003 – May 12, 2004, Chapel Hill, NC



The relative proportions of the daily energy end uses in the conventional control are shown in the pie chart in Figure 6, illustrating that space heating and cooling dominates portable classroom energy use – as seen in each of the portables in each location. Also, we did see somewhat lower CO_2 levels in the NC experimental unit, which is likely due to operation of the ERV (Figure 7).

Figure 6. Measured Electricity End-Uses in Control Portable, Chapel Hill, NC

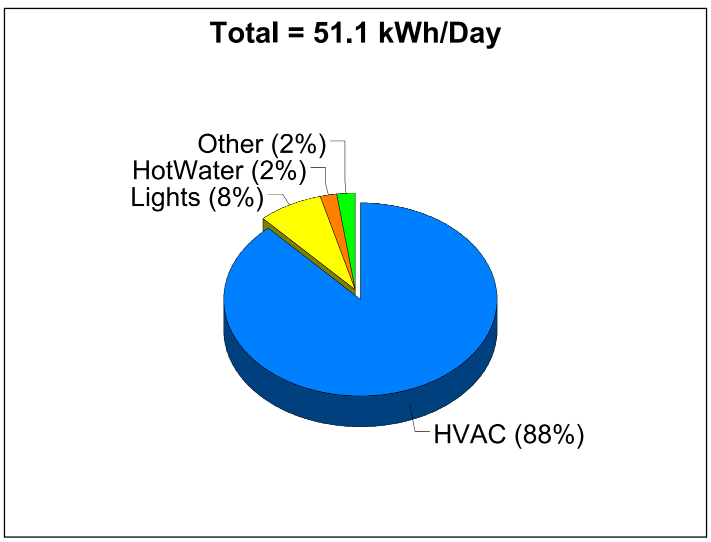
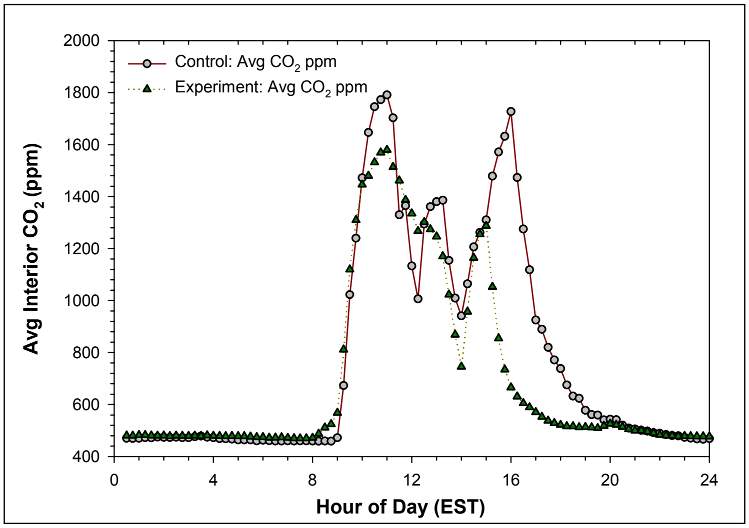
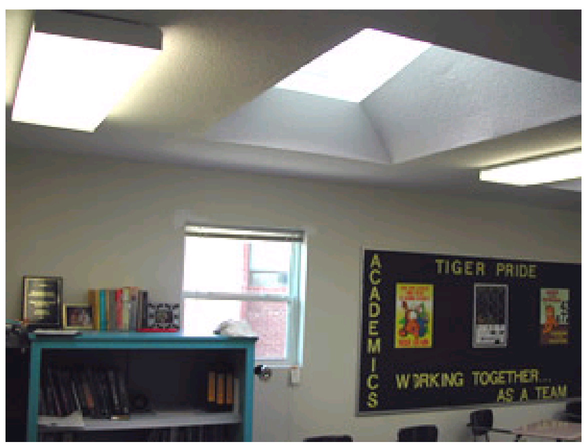


Figure 7. Average Weekday Interior CO_2 Concentrations, Chapel Hill, NC



Lighting. Figure 8 shows the improved aesthetic quality of the PERC with the flared skylight wells. Not surprisingly, the teachers at the school preferred the lighting quality and appearance of the daylit classroom. The lighting system with its controls was also very successful, reducing lighting energy by 67% (2.61 kWh/day) relative to the control.

Figure 8. Daylighting from Overhead Skylights Inside Nc Experimental Classroom

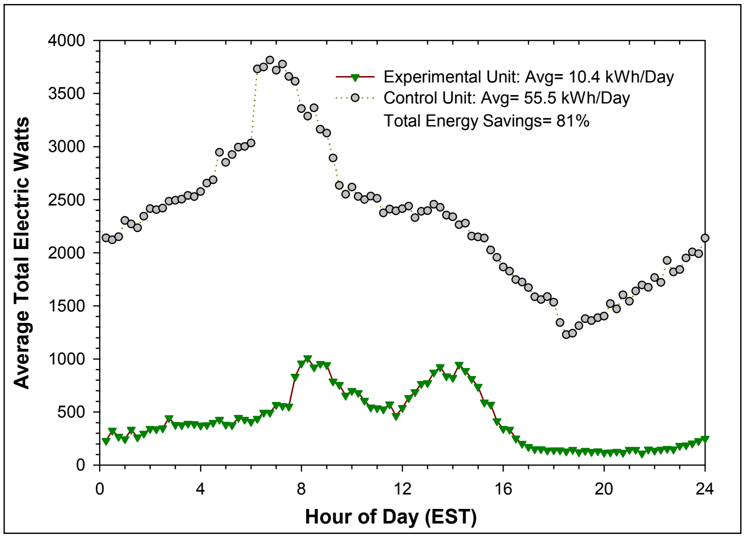


Florida Experiment

The Florida PERC experiment was located in hot and humid Orlando, which has 580 heating degree-days and 2,428 cooling degree-days. Specifications were based on experiences with the NY experiment and for climatic differences. For instance, rather than greater insulation levels, reflective surfaces were specified for the roof. A major difference between the Florida PERC and those in New York and NC was the insulation of the roof deck rather than the ceiling. This has the advantage of reducing plenum heat gain and bringing the duct system inside.

Energy savings. Measured data from November 2003 – May of 2004 showed an overall savings of about 81% or 45 kWh/day (Figure 9). The higher savings experienced in this project appeared related to the insulated roof deck system with the white roof which reduced cooling loads by reducing heat gain to the duct system and greatly lower building air infiltration.

Figure 9. Average Electric Energy Demand Profile, Orlando, FL



Lighting. From the NY experiment we learned the difficulty of integrating skylights into classrooms with acoustical ceiling tiles. The gypsum ceiling solution used in the North Carolina was effective, but expensive to fabricate. Therefore in Orlando, we implemented round 21" diameter *Solatube* skylights to simplify installation and reduce labor costs. We also simplified the lighting controls. The *Solatube* system has continuously dimming ballasts with photocell sensors to harvest daylighting savings. Figure 10 shows the 69% lighting energy savings achieved by using more efficient fixtures, with occupancy controls and daylight integration. Figure 11 illustrates the increases desktop illuminance levels produced by the skylights: more than twice that in the control unit between 9 AM and 3 PM.

Figure 10. Lighting Electric Energy Demand Profile, Orlando, FL

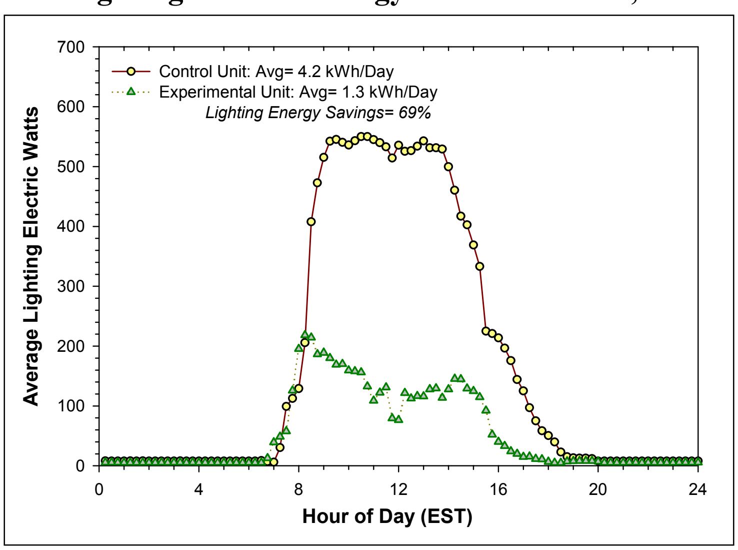
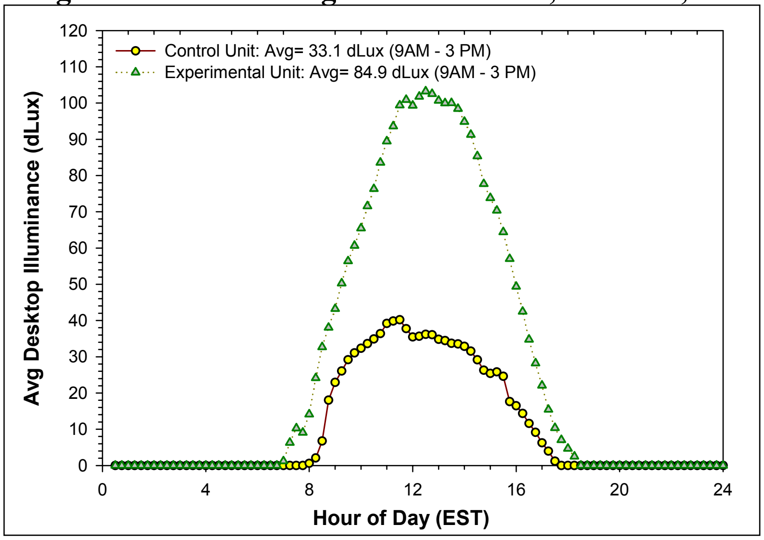


Figure 11. Interior Light Level Profile, Orlando, FL



Reducing building and duct leakage. The FL PERC had a white reflective roof against the black single-ply membrane in the control, helping to lower roof/ceiling heat gains. The experimental unit also had Icynene foam insulation applied to the roof deck to bring the duct system within the insulated envelope and lower air infiltration. Unlike the other sites, the attic or plenum space in the Florida portable are sealed rather than ventilated. Blower door and tracer gas decay testing suggested this is a significant factor in reducing building and duct system leakage in the experimental model. The blower door test showed 23.2 ACH at a 50 Pa pressure for the control against only 9.6 ACH for the experimental unit. Similarly SF_6 tracer gas tests showed 2.60 ACH with the air handler operating in the control vs. only 0.66 ACH for the PERC unit. We also know from previous projects that moving the duct system inside the conditioned zone will have large benefits to HVAC system efficiency by lowering duct heat gains – a fact reinforced by the excellent comparative performance observed in the Florida PERC.

Both the Florida control and experimental units have ERVs , but the experimental unit had substantially elevated CO_2 levels, almost certainly due to the lower measured air infiltration.

Preliminary Economics

The experimental PERC classrooms had higher incremental costs associated with increased insulation, high performance windows, skylight integration, automated controls, higher efficiency HVAC systems and improved interior finishes. These costs are likely much higher than what could be actually realized in mass manufacture due to the experimental nature of our project. With these caveats understood, Table 5 shows the incremental costs, energy savings and payback periods for each classroom. Note that savings per unit floor area were similar between the NC and NY units, although the Florida PERC clearly shows the best overall electric savings performance.

Table 5. Preliminary Economics

	Incremental Cost ($)	Incremental Cost ($/ft^2)	Electric Rate ($)	Energy Savings (kWh/ day)	Energy Savings (Wh/Day/ ft^2)	Annual Savings ($)	Payback Period
NY PERC	$23,160	$14.20	$0.11/kWh	46 kWh	28.2	$1,850	12.5 years
NC PERC	$12,300	$14.20	$0.08/kWh	24 kWh	27.8	$700	17.6 years
FL PERC	$24,400	$28.20	$0.09/kWh	45 kWh	52.1	$1,480	16.5 years

Lessons Learned

Based on our experiences, we provide the following "lessons learned":

1. Skylights: Careful integration is necessary to incorporate skylights into the lighting plan. Consider tubular skylights to simplify integration.
2. Daylighting Controls: Select daylight dimming controls that can be verified by the vendor to operate as indicated. We had best results with continuously dimming ballasts with a pull timer to temporarily close off skylighting. Require controls be commissioned.
3. HVAC: Downsize auxiliary strip heat on heat pumps to prevent excessive morning use of inefficient resistance heating. This also helps avoid thermostat "overshoot" during morning temperature recovery. Warn HVAC contractors of the exact specification.
4. Controls Integration: Verify that the thermostats are compatible with occupancy controls. Also verify compressor operation in heating mode and termination of auxiliary strip heat after temperature recovery. Commission occupancy controls for lighting and HVAC.
5. Roof/Plenum Insulation: Evidence from the New York project suggests that acoustic ceiling tiles with a ventilated plenum leads to very leaky buildings with excessive heating and cooling. Prefer either sheetrock ceiling or sealed attic/plenum construction with an insulated roof deck. The Florida PERC with an insulated foam roof deck – and sealed plenum was significantly tighter than the other portables. It also had the duct system within the insulated envelope under a reflective roof, leading to much lower heating and cooling energy use relative to the other types.

Conclusions

In the Performance Enhanced Relocatable Classrooms (PERC) project, we conducted experiments with very energy efficient units compared with standard ones in three locations of varied climate: Cornwall, NY, Chapel Hill, NC and Orlando Florida. An assessment compared various climate specific energy efficiency improvements in each experimental portable with a conventional side-by-side twin. In each location we found that annual portable energy requirements were dominated by heating and cooling end-use – with lighting only about 10-15% of total. The monitored long-term measured energy savings of the PERC models were 34% in New York, 46% in North Carolina and 81% in Florida. Superior interior lighting with integrated skylights in the experimental model was demonstrated at each site. "Lessons learned" should allow integration of identified technologies in a more cost effective fashion. For instance in Florida, the combination of tubular skylights integrated into a sealed attic plenum with an insulated roof deck covered by a reflective roof showed superior performance at potentially lower cost.

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