Project Report: Thermal, Energy, and IAQ Testing on a Small Prefabricated Structure

Sponsored by the Mike Rock Co. of Arizona

Principal Investigator Benjamin L. Ruddell
Co-Principal Investigator Larry Olson (air quality)
Graduate Research Assistant Chao Yan (data collection and modeling)

Arizona State University (ASU) at the Polytechnic Campus
College of Technology and Innovation

25 March 2013 (v4 13 May 2013)

Executive Summary

There is a growing need for field-deployable, logistically favorable, and energy-independent shelter systems for applications in disaster relief, remote field stations, border patrol, energy exploration, and military uses. This system is manufactured and shipped using an ISO 22’ x 8’ standard shipping container that can be easily transported by ship, truck, train, plane, or helicopter to remote or difficult locations. It can be installed in less than a day, does not require extensive foundation work, and can provide its own energy and sanitation services. When a water supply is provided, the system is a complete and immediately useable housing system adequate for a small family or a group of workers. Development of innovative structural insulated panel using a ceramic like coating is improving the energy performance and environmental footprint of this system.

A small prefabricated structure prototype was deployed at ASU’s Sustainable Technologies Testbed facility at the Polytechnic campus for field testing and scientific validation of its thermal, energy, and indoor air quality performance. Models of energy performance are developed and then validated using observational data measuring the structure’s actual energy use and thermal properties; these models allow the estimation of energy performance of the structure for any climate in the world. Indoor air quality tests against the TO-11A, TO-15, and other standards are performed to determine whether the air quality in the structure is safe for habitation both immediately after installation and over the long term, according to government standards.

Indoor Air Quality (IAQ) samples taken the day construction was completed indicate that the Aldehyde concentrations are well below “acute” (or brief-exposure) Arizona standards. Samples taken months after construction was completed indicate concentrations of all three Aldehydes slightly in excess of “chronic” (or 24-hour 365-day constant exposure) standards, but similar to background outdoor air quality samples which also exceed chronic IAQ standards in this location. Because the samples were taken while the structure was fully sealed for a 24 hour period in the absence of any ventilation, and because indoor results resemble the outdoor background results, these chronic results are not likely to be of concern when ventilation is provided.

Energy testing indicates that the structure uses approximately 31% less energy for Heating Ventilation and Air Conditioning (HVAC) purposes as compared with a “baseline” standard code residence in the Southern Arizona climate, measured on a per-square-foot basis. The provided 3000-Watt solar photovoltaic system with batteries provided more than adequate energy for HVAC purposes during the testing period, and the 1-ton heat pump unit was more than adequate to heat and cool the structure. The provided heat pump is relatively efficient, and the building envelope is well insulated, reflective of thermal energy, and unusually well-sealed, which accounts for the superior performance of the system relative to the baseline residence reported in Southern Arizona. Because of the relatively high performance of the building envelope and HVAC system, the main source of energy losses is the windows, and air exchange, and the building’s energy use will therefore be dominated by human occupancy factors rather than HVAC energy uses. To further optimize the energy performance of this structure in the field, we recommend that the highest quality windows be fitted, that the ventilation fans be operated on an occupancy basis, and that efforts be made to manage occupant-caused energy loads that are not HVAC loads. This test does not consider occupancy energy loads.

Finally, HVAC energy use estimates are provided for a variety of U.S. climates, to be used as a basis for sizing HVAC and power systems for field deployments of this structure. The structure will use more energy in cold climates during the winter than in warm climates during the summer. Solar systems should therefore be designed with respect to the larger winter loads and lower solar availability in the winter.

Given the energy, thermal, and IAQ performance demonstrated, this structure will be suitable for FEMA temporary housing, remote housing such as for border security, natural resource exploration, USDA land management, emergency command center, tribal lands housing, mother-in-law suites, military FOB deployments, or any other remote housing needs where standard construction is logistically impossible or too slow, but where standard shipping logistics are available.

Table of Contents

1 Introduction

There is a growing need for field-deployable, logistically favorable, and energy-independent shelter systems for applications in disaster relief, remote field stations, border patrol, energy exploration, and military uses. This system is manufactured and shipped using an ISO 22' x 8' standard shipping container that can be easily transported by ship, truck, train, plane, or helicopter to remote or difficult locations. It can be installed in less than a day, does not require extensive foundation work, and can provide its own energy and sanitation services. When a water supply is provided, the system is a complete and immediately useable housing system adequate for a small family or a group of workers. Development of innovative structural insulated panel using a ceramic like coating is improving the energy performance and environmental footprint of this system.

The objective of this study is to measure, validate, and/or model the energy and indoor air quality performance of this structure. A small prefabricated structure prototype was deployed at ASU's Sustainable Technologies Testbed facility at the Polytechnic campus for field testing and scientific validation of its thermal, energy, and indoor air quality performance. Models of energy performance are developed and then validated using observational data measuring the structure's actual energy use and thermal properties; these models allow the estimation of energy performance of the structure for any climate in the world. A "Simple Matlab Energy Model" (SMEM) is developed for thermal diagnostics of the structure. The industry-standard eQuest building energy modeling software is also applied. These energy models are applied to estimate HVAC energy requirements in a selection of extreme U.S. climates. Recommendations are made for the additional improvement of energy performance. Indoor air quality tests against the TO-11A, TO-15, and other standards are performed to determine whether the air quality in the structure is safe for habitation both immediately after installation and over the long term, according to government standards, and air quality recommendations are made.

2 Methods

The methods are divided into the following sections:

(2.1) Field Site and Installation
(2.2) Field Instrumentation
(2.3) Indoor Air Quality Methods
(2.4) Simple Matlab Energy Model
(2.5) eQuest Model

2.1 Field Site, Experimental Design, and Installation

The structure was installed in August 2012 in the research yard of the Photovoltaic Research Lab at Arizona State University's Polytechnic campus, near the Mesa Williams Gateway airport. It is situated with the door and windows facing south, in a weathered asphalt parking lot (Figure 2.1.1). The site has a low chain link fence immediately to the west, and a collection of automobiles and solar panels surrounding the structure to the north, east, and south, within 100 meters; no significant direct shading of the structure occurs except during late afternoon near sunset. Temporary power was installed for construction but then removed when the Photovoltaic power system was installed on the roof and activated. The size of the structure is approximately 22 feet wide by 18 feet long. The structure has two bedrooms on the "east" side, a large kitchen/living room on the "west" side, and a small bathroom where plumbing and electrical service connects to the structure in the center of the "north" side. The Photovoltaic system's batteries are housed in a temporary shed on the north side of the structure, and the inverter is located inside the structure for thermal protection. A small exhaust fan in the northeast bedroom creates negative pressure differences within the conditioned space, and is calibrated to exchange 30% of the structure's air per hour.

The experimental design calls for a "clean" solstice-to-solstice testing run with hourly data sampling of all variables; no attempt is made to simulate the role of occupants, indoor electronic or kitchen energy use, varying climate control setting, opening of doors and windows, shading of windows, etc. The interior heating temperature is set at a constant 70 F degrees. The only internal heat load is the Photovoltaic inverter that is attached to the inside wall of the kitchen space in order to thermally protect the inverter; because this inverter will generally be placed inside the structure, this makes the HVAC loads more realistic.

Key dates of the experiment are as follows:

- Structure Installed and Sealed: 24 June 2012
- Acute Indoor Air Quality Tests: 25 June 2012
- Photovoltaics Activated: 19 December 2012
- Modeled and Observed Wintertime Period: First week of January 2013
- Chronic Indoor Air Quality Tests: 23 January 2013
- Observed Summertime Period: end of April 2013
- Structure Removed from Site: May 2013

Figure 2.1.1: The completed prototype from the SE, in The PRL yard at ASU Polytechnic, January 2013.

2.2 Field Instrumentation

A Campbell Scientific CR1000 datalogger was programmed to compute hourly averages of the following measurements. The logger program is given in Appendix J.

- Solar Radiation, W/m2, CS300 Pyranometer (Figure 2.2.2)
- Wind Speed and Direction, m/s and degrees, 03002 Wind Sentry Set (Figure 2.2.2)
- Precipitation, mm, TE525 Tipping Bucket Rain Gauge (Figure 2.2.2)
- Outdoor Air Temperature, C, 108 Temperature Probe (Figure 2.2.2)
- South Wall Indoor and Outdoor Surface Temperature, C, SI-111 IR Temperature Sensor (Figure 2.2.3)
- (2x) South Wall Core Temperature at 2.25" center depth, C, 108 Probe (Figure 2.2.3)
- HVAC Heat Pump Total Current (fan and pump), Amperes, CS10 Current Transformer (Figure 2.2.4)
- (4x) Indoor Air Temperature near floor and ceiling, near fan and vent, C, 108 Probe (Figure 2.2.4)

Figure 2.2.2: 2 meter tower installation for Solar Radiation, Wind Speed and Direction, Precipitation, and Outdoor Air Temperature, approximately five meters southwest of the structure. Prevailing winds are from the west during the day and the east at night.

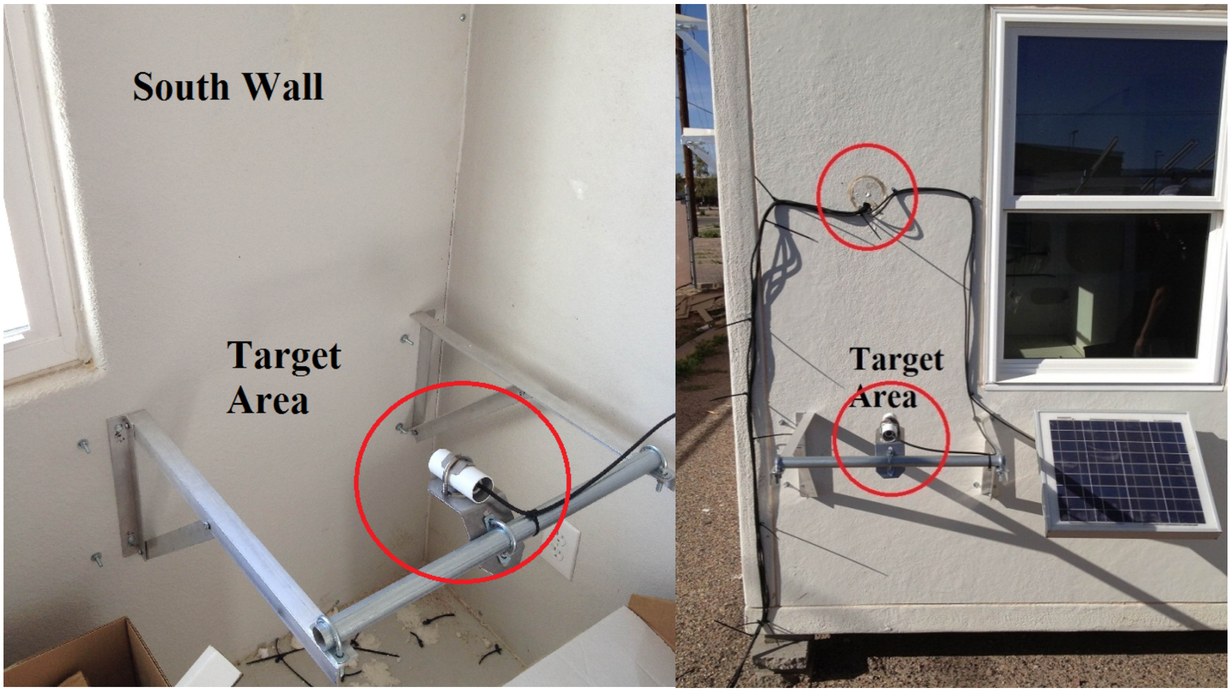


Figure 2.2.3: South Wall Indoor IR Surface Temperature, Outdoor IR Surface Temperature, and Wall Core Temperature.

Figure 2.2.4: Ramsond SEER-13 one-ton ductless heating and cooling heat pump; AC power 120 volt current meters installed on main power line driving both fan and heat pump functions.

Figure 2.2.5: Indoor Air Temperature probes suspended roughly one foot from the floor and ceiling in the northwest corner of the structure. Paper shrouds are to shield the probes from window-source direct solar radiation in the late afternoon. A duplicate installation exists in the northeast corner of the structure.

2.3 Simple Matlab-based Energy Model (SMEM)

During preliminary modeling exercises for the project it was observed that industry-standard energy models, including eQuest, generally over-estimated observed energy use by a wide margin, unless unrealistic parameterizations were introduced to calibrate the model. Therefore the ASU team developed an idealized "Simple Matlab-based Energy Model" (SMEM) for the purpose of providing an independent and thermodynamically simple and well-understood model to help triangulate realistic estimates of HVAC energy requirements.

Experimentation with SMEM shows that its idealized assumptions yield much better fidelity of model and observed results for January 2013 data as compared with eQuest, especially with respect to peak-hour energy use rates. However, SMEM exhibits a tendency to underestimate total energy use on daily to annual timescales, especially in heating months, and SMEM fails to accurately replicate the more subtle dynamics of a building system, including energy storage, and especially the effects of occupancy. As a result, SMEM results should be used with care, and in association with other model results (e.g. eQuest) and rules-of-thumb, if energy use estimates are desired.

2.3.1 SMEM Assumptions and Parameterizations

The structure is well insulated with 3.5 inches of Styrofoam insulation (R value of 5 per inch) between half-inch sheets of OSB. The footprint of the structure is 18x22 ft and the space is 8ft tall. The structure is coated with a reflective ceramic coating which will reduce solar insolation absorption. A ductless mini split heat pump and air conditioner with a high efficiency of SEER-13 is installed. Four double-pane standard efficiency windows are installed; these windows are approximately 3.5ft tall and 2.5ft wide.

Steady state climate control and operating usage conditions are assumed. During wintertime runs the indoor temperature is fixed at 70 °F, matching the heat pump's experimental setting. Zero occupancy and zero lighting and indoor appliance use is assumed, to match the experimental observation design.

It is complicated to calculate the variable solar intensities striking the structure's walls at different times of day and year. SMEM assumes that during the day time, the floor and one of the total five walls will be fully shaded. SMEM assumes that the surface temperature of the floor and the shaded wall will be equal to the outside air temperature. SMEM assumes that no solar insolation enters through the window of shaded walls; this neglects scattered indirect insolation.

Validation of SMEM assumptions from observational data is provided in Appendix K.

2.3.2 SMEM Energy Balance Calculations

During cooling conditions, energy flows into the system can be divided into heat conduction through walls and windows, solar radiation absorbed by sunlit walls, the roof, and windows, energy gained from the exchange of outdoor air, the resident's body heat, and equipment heat, plus heating inputs by HVAC (during heating conditions only). There are two types of energy flow out the system: heat removed by HVAC and radiation emissions.

Based on the energy balance of the system, a governing equation is established as[1]:

$$E_{conductionwall} + E_{conductionwindow} + E_{absorptionwall} + E_{absorptionwindow} + E_{airexchange} + E_{bodyheat} + E_{equipmentheat} + E_{AC} = 0 \quad (1)$$

Where energy flows into the system are positive, and energy flows out of the system are negative.

2.3.3 Heat conduction through walls and windows

Heat conduction is the most important part of energy flow into the system, especially through walls. To quantify this type of energy, we add convection factor into traditional heat conduction equation to simulate the process[2]:

$$E_{conduction} = A \times \frac{T_{out} - T_{in}}{\frac{1}{h} + \frac{l_{coating}}{\lambda_{coating}} + \frac{l_{wood}}{\lambda_{wood}} + \frac{l_{\text{styrofoam}}}{\lambda_{\text{styrofoam}}} + \frac{l_{wood}}{\lambda_{wood}} + \frac{l_{coating}}{\lambda_{coating}} + \frac{1}{h}} \quad (2)$$

Where A is the area of heat transfer (m^2), T is temperature (℃), h is convection factor of air ($W/(m^2 \cdot °C)$), l is the length of material in heat conduction direction (m), and λ is the conductivity of the material ($w/(m \cdot °C)$).

[1] Cengel, Yunus A., and Michael A. Boles. *Thermodynamics: an engineering approach*. McGraw-Hill Higher Education.

[2] Kays, William Morrow, Michael E. Crawford, and Bernhard Weigand. "Convective heat and mass transfer." (1993).

2.3.4 Solar radiation absorbed by walls and windows

When we are considering absorbed radiation, energy transfer processes in walls and windows are treated differently. In the case of wall absorption, most solar radiation is absorbed by the surface layer creating an extra temperature gradient which will enhance the heat conduction process. We assume a fixed boundary layer where radiation energy transforms into thermal energy in the indoor air.

The absorbed radiation is[3]:

$$E_{raditaion} = A \times \partial \times I \tag{3}$$

Where ∂ is the absorptivity and I is the solar radiation intensity (W/m^2). The temperature increase of the internal wall is calculated by setting the surface layer thickness to be 1x10^{-5} m:

$$\Delta T = \frac{E_{radiation}}{C \times m} = \frac{E_{radiation}}{C \times \rho \times l \times A} \tag{4}$$

Where C is specific heat capacity of the coating (J/(kg·℃)), ρ is density, l is thickness of the boundary layer. Therefore, the energy absorption is:

$$E_{absorbwall} = A \times \frac{\Delta T}{\frac{l_{coating}}{\lambda_{coating}} + \frac{l_{wood}}{\lambda_{wood}} + \frac{l_{\text{styrofoam}}}{\lambda_{\text{styrofoam}}} + \frac{l_{wood}}{\lambda_{wood}} + \frac{l_{coating}}{\lambda_{coating}}} \tag{5}$$

In the case of windows, direct transmission of solar radiation is possible. This part of energy can be calculated by:

$$E_{absorbwindow} = A \times \beta \times I \tag{6}$$

Where β is transmittance[1].

2.3.5 Air Exchange

The system is exchanging air with the environment at the minimum recommended rate of 10% of volume per hour, which will dilute conditioned indoor air using outdoor air:

$$E_{air} = C_{air} \times \dot{m}_{air} \times (T_{out} - T_{in}) = C_{air} \times \rho_{air} \times rate \times V \times (T_{out} - T_{in}) \tag{7}$$

Where V is the total volume of the system (m^3).

2.3.6 Resident Body Heat

The radiative heat exchange from humans (with clothing) with the building internal surface can be calculated by[4]:

---

[3] Siegel, Robert, and John R. Howell. "Thermal radiation heat transfer." *NASA STI/Recon Technical Report A* 93 (1992): 17522.

$$E_{body} = n_p \times A_p \times \varepsilon_p \times f_{cl} \times f_{eff} \times \sigma \times (T_{in}^4 - T_{skin}^4) \quad (8)$$

Where n_p is the average number of the residents, A is the area of human skin (m^2), ε_p is the emissivity of human skin (1), f_{cl} is cloth area factor (1), f_{eff} is effective radiation area factor of human (1), σ is Stefan-Boltzmann constant (5.67×10^{-8}W/(m^2·k^4)). Body Heat is neglected in the current SMEM because the experiment has no occupants.

2.3.7 Equipment Heat Load

Under normal conditions, internal equipment will add additional heat as:

$$E_{equipmentheat} = U * I \quad (9)$$

Where U is overall voltage of the system (V), I is overall current of the system (A). Equipment heat loads are neglected in the current SMEM because the experiment has no equipment other than the inverter, which will be present in all structures.

2.3.8 Heat removed by A/C

The governing equation of SMEM solves for heat removed by A/C, so the electricity consumption (cooling load) can be calculated using the SEER rating of the unit as:

$$E_{coolingload} = \frac{E_{AC}}{SEER} \quad (10)$$

Where SEER is the seasonal energy efficiency (Btu/Wh).

2.4 eQuest Model

The eQuest software version used is 3.64. The hourly model framework is utilized. Most settings are based on exact properties of the structure, with notable approximations detailed as follows.

2.4.1 Envelope Structure

The envelope structure is 4.5" thick, symmetrical, with ceramic coatings (white) on both sides, ½" OSB sheathing, and 3.5" of expanded styrofoam insulation at the core, as detailed in the table below.

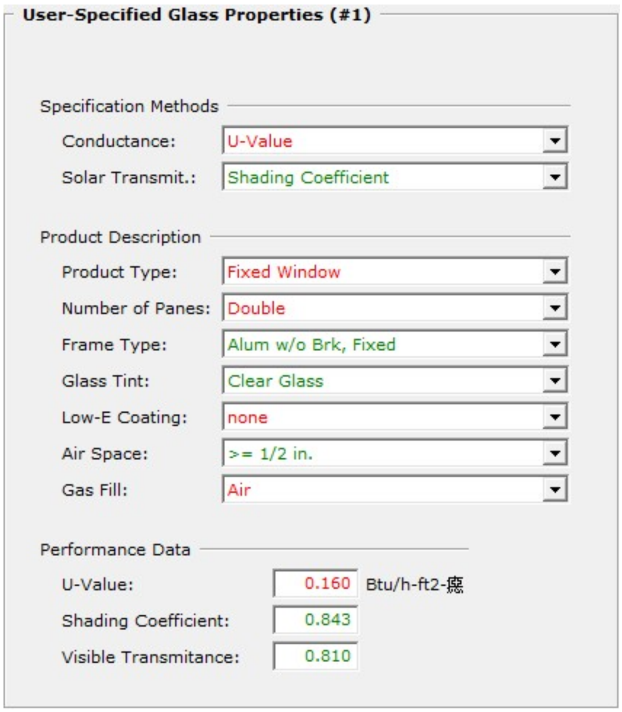
	Spec Method	Category	Material	R-Value (h-ft2-瘧/Btu)	Thickness (ft)	Conductivity (Btu/h-ft-瘧)	Density (lb/ft3)	Spec. Heat (Btu/lb-瘧)
1	Library Entry	Finish	Finish (HF-A6)		0.033	0.2400	78.00	0.260
2	Library Entry	Wood	Wood, 1 Inch (HF-B7)		0.083	0.0700	37.00	0.600
3	Library Entry	Polystyrene	Polystyrene, Expanded, 4 Ir		0.302	0.0200	1.80	0.290
4	Library Entry	Wood	Wood, 1 Inch (HF-B7)		0.083	0.0700	37.00	0.600
5	Library Entry	Finish	Finish (HF-A6)		0.033	0.2400	78.00	0.260
6	- select mater							

[4] Gagge, A. Pharo, and Yasunobu Nishi. "Heat exchange between human skin surface and thermal environment." *Comprehensive Physiology* (1977).

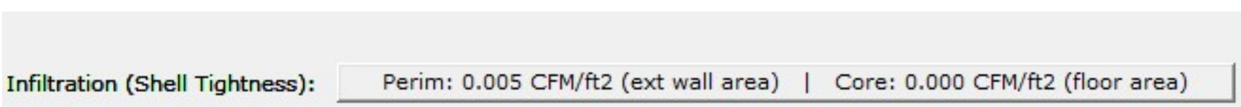
The ceramic coating is approximated with the HF-A6 finish. This is a conservative assumption; the real structure should have a higher energy efficiency and consume less energy especially in hot climates (cooling weather) as compared with HF-A6.

2.4.2 Windows

Clear double pane windows are used with visible transmittance of 0.81, with details below.



2.4.3 Infiltration



Based on our air exchange assumption that there is 10% air which is exchanged to the outside environment, we can calculate the Infiltration.

In eQuest, the volume change rate of air should be (22x18x8.3)x10%/60=5.5cfm.

and we are using parameter infiltration, so 5.5cfm should divided by parameter area, which is celing and four wall's area.

So parameter area will be 1060 ft^2 (22ft*18ft+22ft*8.3ft*2+18ft*8.3ft*2)

And Infiltration will be 5.5cfm/1060ft^2=0.005 cfm/ft^2

2.5 Indoor Air Quality Methods

Air sampling was conducted on June 25, 2012, shortly after the structure was erected and on January 23, 2013 after all of the components of the structure had been completely cured. On both occasions, all of the doors and windows of the structure were closed during the sampling period. There was no electrical power and thus no forced air movement through the structure during the sampling period.

Two types of air samples were collected. Volatile Organic Compounds (VOCs) were determined in accordance with EPA Method TO-15 from the Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Second Edition (EPA/625/R-96/010b), January 1999. A clean, evacuated 6.0 L stainless steel summa canister was supplied by Columbia Analytical Services (CAS) in Simi Valley, California. The canister was filled using a pre-calibrated flow controller supplied by CAS and shipped overnight under chain of custody procedures to the CAS Laboratory in Simi Valley, California. Analysis of the VOCs contained in the ambient air sample was performed with a gas chromatograph/mass spectrometry (GC/MS) system. A target list of 75 volatile organic compounds, commonly found in ambient air, was utilized.

A second type of air sample was designed to detect various aldehydes, including formaldehyde, which can be emitted from building materials. These compounds are reactive and are not part of the TO-15 analysis described above. Aldehyde samples were collected on DNPH silica gel tubes supplied by Columbia Analytical Services. Ambient air was pulled through the tubes using calibrated personal sampling pumps for a specified period. The DNPH tubes were then shipped on ice via overnight express delivery back to the CAS Laboratory in Simi Valley, California using chain of custody procedures. Analysis for a target list of 12 aldehydes was conducted using high performance liquid chromatography (HPLC) according to EPA Method TO-11A. The flow rate of the sampling pumps was determined with a soap bubble calibration before and after the sampling period. The average rate was used to determine the total volume of air pulled through the sampling tube.

During both the 6/25/12 and 1/23/13 sampling periods, a background sample of ambient air outside of the prefabricated structure was collected for both the TO-15 and TO-11A analysis. The location for the background sample was approximately 10 yards north of the prefabricated structure, inside the fence surrounding the location of the building. There were no obvious sources of air pollutants near this site except for two lightly travelled streets on the ASU Poly campus.

3 Results

The Results are divided into the following sections:

- (3.1) Model and Observations for January 2013
- (3.2) Comparison with the Baseline Phoenix Home
- (3.3) Model Estimates for Various U.S. Climates
- (3.4) Diagnostics of Structure Thermal Performance
- (3.5) Indoor Air Quality Results

3.1 Model and Observations for January 2013

The SMEM and eQuest model results are compared with observed HVAC electrical current in units of average kW in a given hour (or kWh, equivalently) for the first week in January 2013, during which time clean observational data is available for clear meteorological conditions and during which time the Photovoltaic system is powering the heat pump. This comparison represents heating conditions during the coldest time of the year, during which freezing temperatures are typical at night and daytime highs are in the 50's F in Mesa, Arizona. Results are shown in Figure 3.1.1 below.

eQuest provides monthly average usage rates, which average to an hourly rate of 0.16 kW, or 0.16 kWh during the simulation period. This rate is roughly three times higher than the hourly-average peak observed rate of roughly 0.06 kW during the middle of the night, and roughly five times higher than the hourly-average rate of 0.03 kW observed during this week.

SMEM provides hourly estimates. After the HVAC standby energy use rate is added, SMEM estimates an hourly-average rate of 0.015 kW during the week, which is roughly half of the observed average rate. SMEM is skilled at estimating peak energy use rates, closely matching peak rates observed. However, SMEM underestimates the duration of the heating peak; this accounts for the underestimation of overall average rates.

The total HVAC energy used on a daily average rate during this January 2013 period is observed to be slightly under 1 kWh, as compared with model results of just under 4 kWh (eQuest) and less than 0.5 kWh (SMEM).

If these model results are typical for other climates and seasons, it is reasonable to estimate realistic HVAC energy use as some value between the SMEM and eQuest estimates. eQuest may provide a more conservative total energy use estimate, and SMEM may do a better job with peak-rate calculations required for HVAC system sizing.

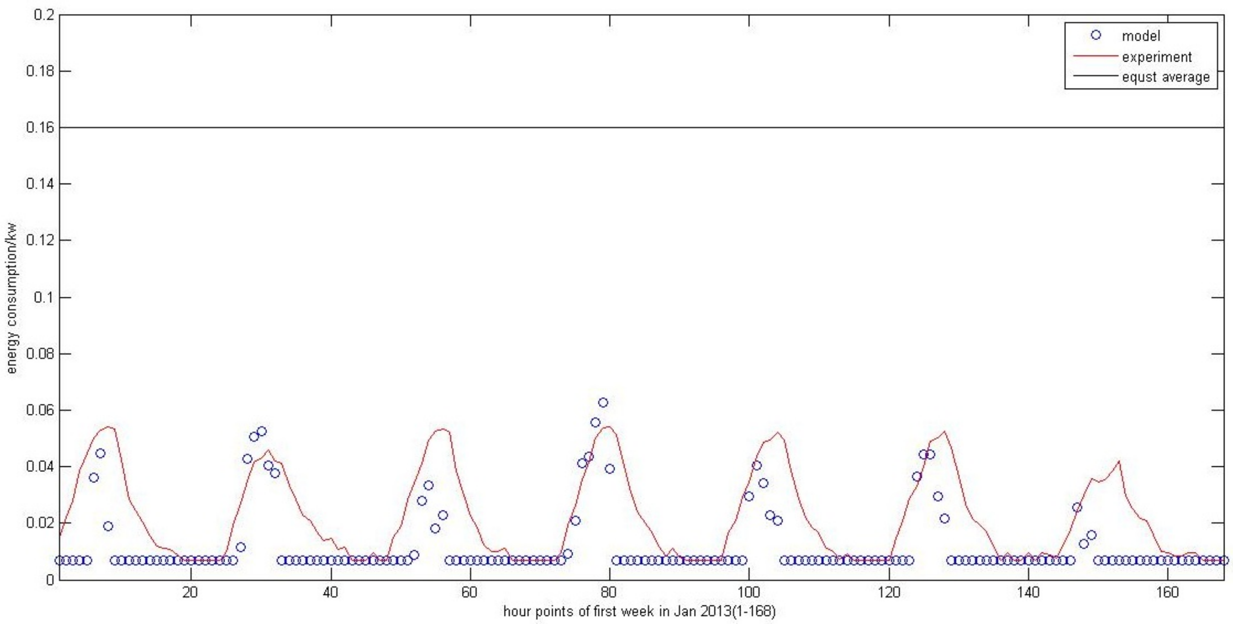


Figure 3.1.1: Comparison of SMEM "model", eQuest "equest average", and observed HVAC electrical power usage "experiment" in kW, on an hourly interval, for seven days in the beginning of January 2013.

3.2 Comparison with the Baseline Phoenix Home

Comparison of this prototype structure with other residential building systems is challenging for the reason that it is not built to the same prescriptive code standards that are specified by the International Building Code (IBC), the Energy Star™ standards, or typical home energy use ratings systems such as the HERS index score. Additionally, the structure is very small and intended for emergency and field applications, and therefore has a different fundamental ratio of HVAC energy use to other energy uses than the typical residence (emergency uses will tend to depress non-HVAC energy use vs. a standard residence, whereas the high number of residents per square foot will tend to increase non-HVAC energy use). The only possible comparison is on the basis of HVAC-only energy use, which accounts for typically less than half of the average residence's energy use[5]. With these qualifications understood, a comparison will be made in relative terms on the basis of HVAC-only energy use in units of annual kWh per ft^2, a metric similar to the Btu/ft^2/year numbers commonly used[6]. This comparison is based on the structure's observational data from January 2013 and on reported HVAC-only energy use from residences in the Phoenix, Arizona metropolitan area.

Annual HVAC energy use for the structure in Phoenix, Arizona is estimated by the industry-standard eQuest software at 2174 kWh per year. Based on observations of actual energy use from January 2013, the eQuest number of 119 kWh in January is approximately 400% too large during these heating climate conditions (recall Figure 3.1.1, and that the indoor air temperature was a very high 80 F during this test, exaggerating observed energy use). Based on observations from the end of April and beginning of May 2013, which included some unseasonable 100-degree weather, the observed monthly total of 130 kWh is roughly 45% overestimated by the eQuest modeled value of 188 kWh for May. It appears that the eQuest model is more accurate for the conditions where energy use is higher.

Because energy use is dramatically over-estimated by the eQuest model in low-energy-use winter conditions and slightly over-estimated by the same model during early summer high-energy-use conditions, the model probably overestimates energy used by this structure during the year as a whole. The model is better during the high-energy-use cooling season. Also, human occupancy will increase cooling loads in a cooling climate. Therefore, the model overestimation error factor is probably closer to 45% than 400%. Let us assume within that range an approximate baseline for our comparisons of 1000 kWh per year for Phoenix, Arizona HVAC-only energy loads, which is 2.5 kWh/ft^2/year; this is half of the eQuest-estimated annual average energy use per square foot in Phoenix Arizona[7].

A large 2005 study of energy efficiency in Phoenix-area residences[7] establishes three categories of residences: "baseline" or code-built standard housing stock, "Energy Star" for EPA-certified housing, and "guaranteed" for homes with builder guarantees of high energy performance. This study establishes 1732 as the average square footage of the study's homes, and 6300 kWh/year combined heating and cooling energy load for "baseline" homes, which yields 3.64 kWh/ft^2/year for HVAC-only energy use.

If the average baseline home in the Phoenix area uses 3.64 kWh/ft^2/year and this structure uses 2.5 kWh/ft^2/year, this structure uses roughly 31% less energy for HVAC purposes compared with a baseline residence. If the more aggressive 500 kWh per year number is assumed, the structure uses 65% less energy for HVAC purposes compared with a baseline residence. It is worth noting that the baseline stock of housing in Phoenix is newer and therefore somewhat more energy efficient than the national average.

3.3 Model Estimates for Various U.S. Climates

Using the SMEM and eQuest models, and the average weather files provided by eQuest for the city climates of New York, Fargo, Miami, Phoenix, and Fairbanks, estimates of peak hourly-average energy use rates and total monthly energy use are provided in Figures 3.3.1 (SMEM peak hourly energy use rate estimates), 3.3.2 (SMEM average monthly energy use totals), 3.3.3 (eQuest average monthly energy use totals), and 3.3.4 (Ensemble of SMEM and eQuest average monthly energy use totals) below.

The greatest hourly-average peak rates are slightly below 2 kW in Fairbanks, Alaska during January, as simulated by SMEM, and total monthly HVAC electrical use is greatest at between 1200 (SMEM) and

---

[5] U.S. Department of Energy (2010), Energy Efficiency Trends in Residential and Commercial Buildings, prepared by McGraw Hill Construction for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, August 2010.

[6] Eldrenkamp, P. (2010), A Simple Approach to Home Energy Rating, *JLC*, 1-6, Feb 2010.

[7] Swanson, C. et al. (2005), Measuring Public Benefit From Energy Efficient Homes, USEPA Project ID XA-83046201 Technical Report from M. Blasnik & Associates and Advanced Energy.

1600 (eQuest) kWh in Farbanks, Alaska during January. Fargo, North Dakota, and New York, New York have proportionately lower estimated heating HVAC energy use during the winter. Summertime cooling energy use is highest in Phoenix, Arizona, during July, estimated at between 302 (SMEM) and 306 (eQuest) kWh; other climates are estimated at between 100 and 270 kWh in July.

It is notable that winter-climate heating loads are estimated to be substantially higher for the structure than summer-climate cooling loads; this is not surprising, given that the same electrically powered heat pump is being used for both climates, and that winter temperatures in harsh northern climates are much farther from room temperature than summer temperatures in even the hottest southern climates. These models probably overestimate winter heating loads because human body heat and equipment will tend to lower heating requirements by providing supplemental heat. These models probably underestimate summertime cooling loads for the same reason, that human and equipment loads are neglected.

A footnote to this HVAC energy use estimation exercise is that the 1-ton heat pump and 3000W Photovoltaic system are more than adequate for the heating and cooling needs of the structure in the Arizona climate, by a factor of roughly two to three, and these same systems are likely to be adequate for any climate in which the structure is placed- with the exception of extreme northern climates (Alaska, and perhaps North Dakota) with extreme low temperatures at night and heavy cloud and snow cover where the Photovoltaic system may struggle to produce and store enough electricity to heat the structure through dark winter nights.

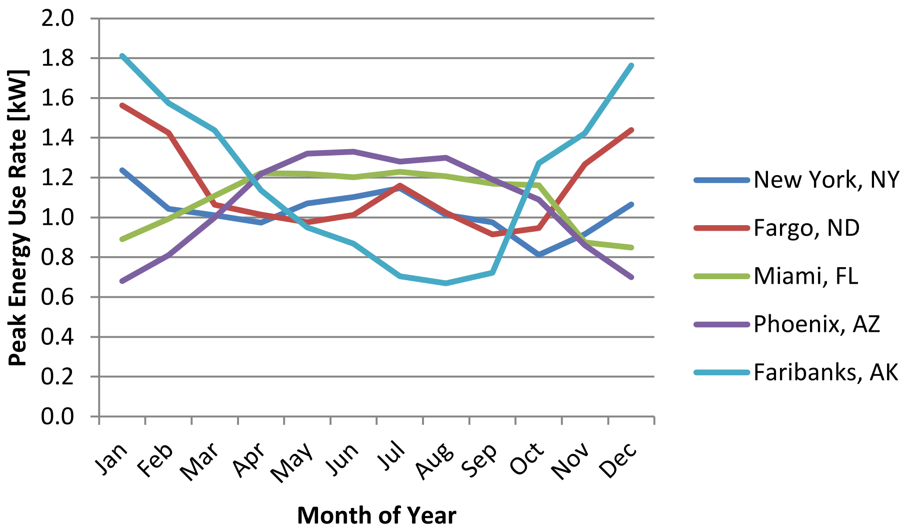


Figure 3.3.1: SMEM simulated hourly-average peak HVAC energy use rates for several U.S. climates.

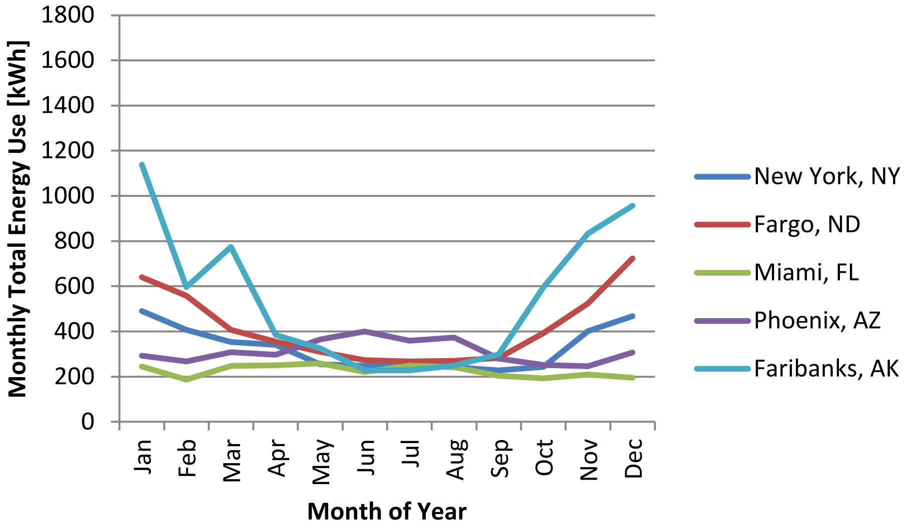


Figure 3.3.2: SMEM simulated monthly total HVAC energy use for several U.S. climates.

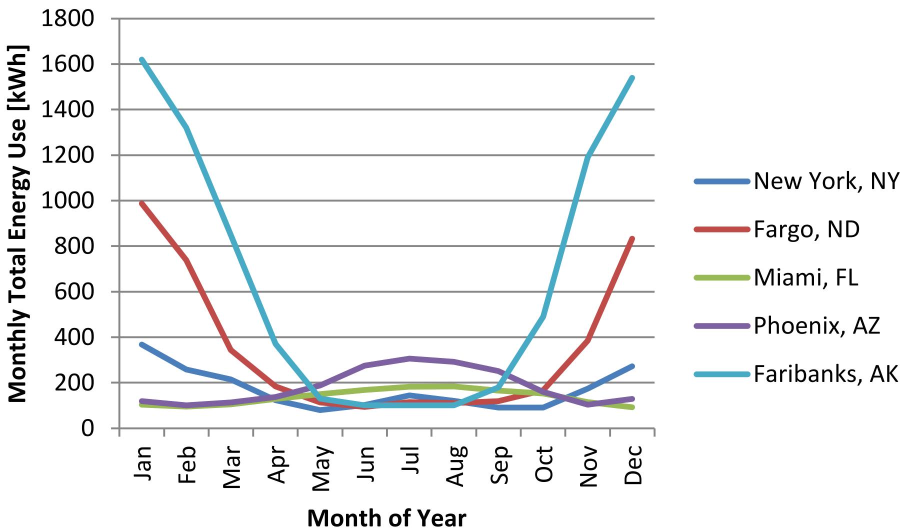


Figure 3.3.3: eQuest simulated monthly total HVAC energy use for several U.S. climates.

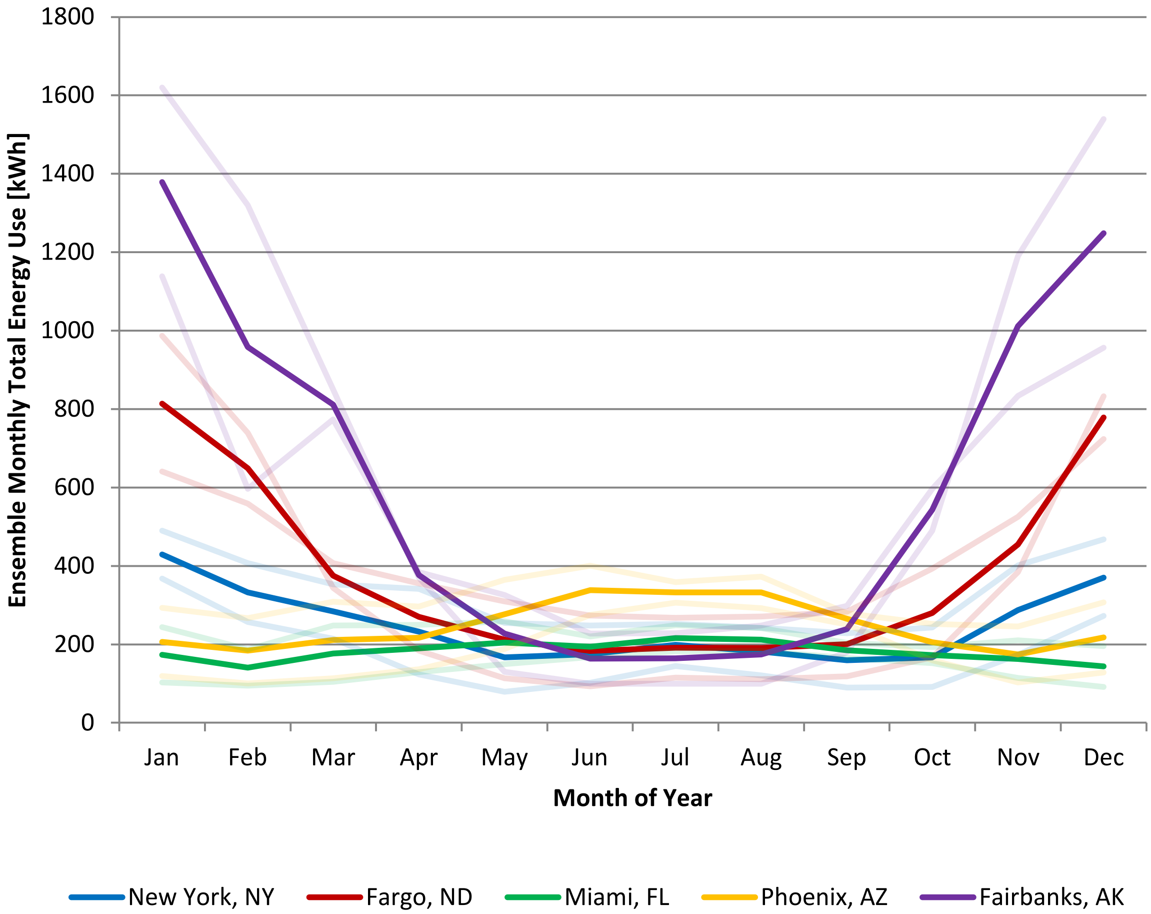


Figure 3.3.4: Ensemble average of eQuest and SMEM models for simulated monthly total HVAC energy use for several U.S. climates. Bold colors represent the average value of the SMEM and eQuest models, and the faded colors represent the estimates of those two models. Faded colors may be interpreted as a range of likely uncertainty in model estimates.

3.4 Diagnostics of Structure Thermal Performance

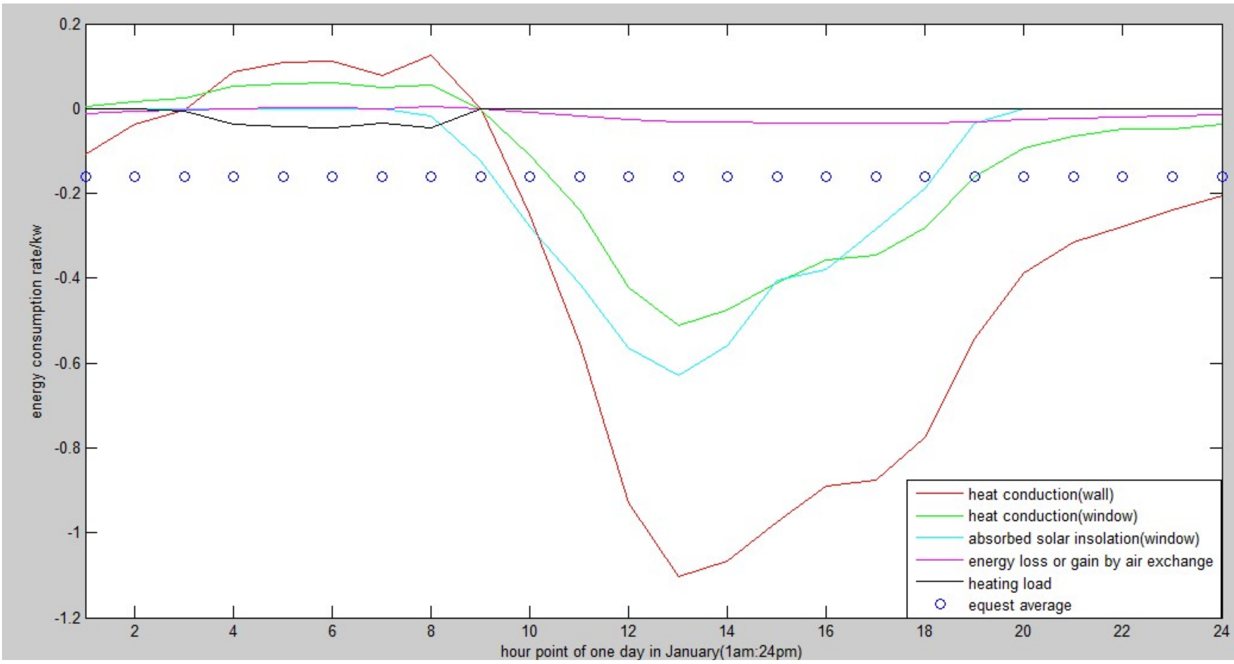


Figure 3.4.1: Hourly modeled components of the SMEM structure energy balance on a day in January, 2013, in Phoenix, Arizona, compared with eQuest average results. Despite covering a very small fraction of the building envelope, the windows are responsible for approximately half of the total energy transfer between the building environment and the outdoor climate. Interior air temperature is 80 F.

During January 2013, the heating load of the structure is concentrated between 3am and 8am, when outdoor temperatures approach freezing and there is no solar insolation. In this climate, even in the coldest and darkest part of winter, solar insolation and thermal conduction provide for most of the structure's heating requirements. Roughly half of the energy transfer is due to conduction through walls, and half due to a combination of conduction and insolation through windows. Because the windows are a small fraction of the surface area of the building envelope, this means that the windows are the main issue that should be addressed to improve energy performance. This will become even more important during the cooling season in Phoenix when solar insolation through windows will be very large and very disadvantageous to the energy performance.

To improve energy performance in hot or cooling climates such as Phoenix, we recommend that the structure be upgraded with windows that have a smaller "visible light transmittance" or Vt, such as those with a "silver 20" window film. To improve energy performance in cold or heating climates such as Alaska, we recommend that the windows have a smaller infrared light transmittance. In all climates, an upgraded R-value and reduced thermal conductance will be very helpful.

3.5 Indoor Air Quality Results

The Indoor Air Quality (IAQ) results cover two main classes of compounds: Aldehydes and Volatile Organic Compounds (VOC's). Summaries are provided in the sections below, and details are provided in Appendix B (Aldehydes) and Appendix C (VOC's).

3.5.1 TO-11A Results (Aldehydes)

Results of the TO-11A analysis are shown in the following table.

Sample #	Date	Location	Sample Volume	Units
MR 2	6/25/12	Background	554 L	$\mu g/m^3$
MR 10	1/23/13	Background	413 L	$\mu g/m^3$
MR 1	6/25/12	Indoors N/W corner, near bathroom	576 L	$\mu g/m^3$
MR 5	6/25/12	Indoors N/E corner	710 L	$\mu g/m^3$
MR 12	1/23/13	Indoors N/W corner, near bathroom	460	$\mu g/m^3$
MR 13	1/23/13	Indoors N/E corner	612 L	$\mu g/m^3$

	MR 2	MR 10	MR 1	MR 5	MR 12	MR 13
Formaldehyde	4.3	2.5	60	44	11	11
Acetaldehyde	1.7	2.1	8.5	2.6	5.7	5.8
Propionaldehyde	ND	0.39	9.2	3.4	1.4	1.4
Crotonaldehyde	ND	ND	0.32	0.46	ND	ND
Butyraldehyde	ND	0.42	20	7.8	1.2	1.2
Benzaldehyde	ND	0.94	160	140	3.8	3.9
Isovaleraldehyde	ND	ND	9.1	7.7	0.47	0.64
Valeraldehyde	ND	ND	49	42	2.4	2.6
m,p-Tolualdehyde	ND	ND	1.5	1.6	ND	ND
n-Hexaldehyde	ND	0.38	140	130	7.8	7.9
2,5-Dimethylbenzaldehyde	0.29	ND	0.52	0.82	ND	ND

There is good agreement between the background Samples MR 2 and MR 10. Both of the outdoor samples are lower in aldehyde concentrations than the indoor air samples.

The indoor air samples taken on 6/25/12 (MR 1 and MR 5) are higher than the samples taken on 1/23/13 (MR 12 and MR 13). This can be attributed to the fact that the first set of samples was taken shortly after building construction, reflecting the off gassing from new building components. Indeed, a detectable odor was present upon entering the building on 6/25/12.

Two indoor samples were taken during each sampling period, differing only in their placement within the building. The final indoor air samples (MR 12 and MR 13) were almost identical. The initial indoor air samples on 6/25/12 (MR 1 and MR 5) were similar, but the sample nearer the bathroom (MR 1) was somewhat higher.

There are no federal or Arizona state indoor air standards. So there are no specific laws regulating the air quality within the structure.

Arizona does have enforceable health based ambient air concentrations for hazardous air pollutants. These are found in Title 18 of the Arizona Revised Statutes, R18-2-1708[8]. The AACs are designed to provide a level of public protection and are divided into acute and chronic values. There are only three applicable standards for those aldehydes detected in TO-11a.

---

[8] Title 18 of the Arizona Revised Statutes, R18-2-1708, http://azsos.gov/public_services/Title_18/18-02.htm

	Acute AAC, mg/m^3	Chronic AAC, mg/m^3
Acetaldehyde	306	8.62 E-04 (0.862 $\mu g/m^3$)
Formaldehyde	17	1.46 E-04 (0.146 $\mu g/m^3$)
Propionaldehyde	403	8.62 E-04 (0.862 $\mu g/m^3$)

None of the indoor air samples (MR 1, MR 12, MR 5 or MR 13) were above the Acute AAC for Arizona. The indoor air concentrations on both sampling dates were higher than the chronic AAC concentrations. However, even the background outdoor concentrations of acetaldehyde and formaldehyde exceeded the chronic AAC limits.

The chronic AAC is derived based on an assumption of breathing air for 24 hours per day, 365 days per year. Obviously, this is not the case for anyone living in these prefabricated structures. Also, the sampling was conducted with no ventilation and all windows and doors closed. This would also not likely be the case if the structure was inhabited. The relatively close agreement with the final indoor air concentration of aldehydes (MR 12 and MR 13) with the background ambient air (MR 10) indicates that this exceedance is likely not an issue of concern.

3.5.2 TO-15 Results (VOC's)

Results of the TO-15 analysis for Volatile Organic Compounds are shown in the following table. The complete laboratory reports are shown in Appendix 2.

Sample #	Date	Location	Units
MR 3	6/25/12	Background	$\mu g/m^3$
MR 11	1/23/13	Background	$\mu g/m^3$
MR 4	6/25/12	Indoor, N/E corner	$\mu g/m^3$
MR 14	1/23/13	Indoor, N/E corner	$\mu g/m^3$

	MR 3	MR 11	MR 4	MR 14
Propene	ND	0.92	ND	1.2
Dichlorofluoromethane, CFC 12	1.9	2.4	ND	2.2
Chloromethane	ND	ND	ND	0.63
Ethanol	ND	7.0	ND	24
Acetonitrile	1.7	29	390	1600
Acetone	12	8.8	740	35
Trichlorofluoroethane	0.99	1.2	ND	1.1
2-Butanone	ND	ND	620	13
Ethylacetate	ND	ND	38	1.8
Toluene	ND	1.4	ND	1.2
1,4-Dioxane	ND	ND	22	ND
n-Butyl Acetate	ND	ND	410	1.1
Ethylbenzene	ND	ND	22	0.82
Styrene	3.0	ND	3000	39
n-Nonane	ND	ND	120	ND
alpha-Pinene	ND	ND	290	17
d-Limonene	ND	ND	19	1.3

There are four applicable AAC standards for VOCs detected in Method TO-15.

	Acute AAC, mg/m^3	Chronic AAC, mg/m^3
Acetonitrile	38	2.79 E-05 (0.0279 µg/m^3)
Toluene	1923	5.21 E+00 (5210 µg/m^3)
Ethylbenzene	250	1.04 E+00 (1040 µg/m^3)
Styrene	554	1.04 E+00 (1040 µg/m^3)

In general, the indoor air samples (MR 4 and MR 14) had larger concentrations of VOCs than the background outdoor samples (MR 3 and MR 11). With one exception, the final VOC indoor concentrations (MR 14) were larger than the initial indoor concentrations (MR 4). The lone exception is acetonitrile, where there was an increase from 390 to 1600 µg/m^3.

None of the indoor air samples exceeded the Acute AACs. Both indoor air samples (MR 4 and MR 14) exceed the Chronic AAC for acetonitrile, but so do both the outside background samples. The styrene Chronic AAC is exceeded by sample MR 4, but the final concentration of styrene after curing was below this standard.

4 Conclusions

Conclusions can be drawn on the basis of this report, regarding the energy and air quality performance of the container-based prefabricated structure that is the subject of the research.

The structure's annual HVAC-only energy use is estimated at approximately 69% of the baseline average of the code-built housing stock (a 31% savings), on the basis of observations and models of performance in the Phoenix metropolitan area. These estimates place the HVAC-only energy use of the structure at approximately 1000 kWh per year, based on a combination of models and observations. This estimate is very rough, and could vary between roughly 500 kWh per year (a 65% savings vs. baseline) and 2000 kWh per year (more energy use vs. baseline) in this climate, based on the full range of model estimates. The lower range of the energy use estimates for the structure is more likely, in our opinion, based on observations from our field tests.

The structure's one-ton heat pump was fully adequate to handle HVAC requirements during both summer 2012 and winter 2013 climate conditions in Phoenix area tests, with more than half of its capacity to spare. Likewise, the 3000W Photovoltaic system and battery bank was more than adequate to power the HVAC system in this climate.

The greatest hourly-average peak rates are slightly below 2 kW in Fairbanks, Alaska during January, as simulated by SMEM, and total monthly HVAC electrical use is greatest at between 1200 (SMEM) and 1600 (eQuest) kWh in Farbanks, Alaska during January. Fargo, North Dakota, and New York, New York have proportionately lower estimated heating HVAC energy use during the winter. Summertime cooling energy use is highest in Phoenix, Arizona, during July, estimated at between 302 (SMEM) and 306 (eQuest) kWh; other climates are estimated at between 100 and 270 kWh in July.

It is notable that winter-climate heating loads are estimated to be substantially higher for the structure than summer-climate cooling loads; this is not surprising, given that the same electrically powered heat pump is being used for both climates, and that winter temperatures in harsh northern climates are much farther from room temperature than summer temperatures in even the hottest southern climates. These models probably overestimate winter heating loads because human body heat and equipment will tend to lower heating requirements by providing supplemental heat. These models probably underestimate summertime cooling loads for the same reasons.

Because the structure's energy performance is so good, and because the structure is so small, total energy loads will tend to be dominated by occupancy, human uses, and electrical equipment in the structure. Extra care should therefore be taken to manage these non-HVAC loads by educating occupants on the effects of window and door leaks, appliance energy use, etc.

The building envelope is very well sealed and well insulated, and the ceramic coating is very reflective of infrared energy. As a consequence, energy losses in the structure are dominated by the windows and by air exchanges. It is therefore recommended that the structure be fitted with the highest quality windows and window shades available, and that the venting system be designed to minimize air exchange per local ordinances, perhaps by triggering vents based on occupancy.

To improve energy performance in hot or cooling climates such as Phoenix, we recommend that the structure be upgraded with windows that have a smaller "visible light transmittance" or Vt, such as those with a "silver 20" window film. To improve energy performance in cold or heating climates such as Alaska, we recommend that the windows have a smaller infrared light transmittance. In all climates, an upgraded R-value and reduced thermal conductance will be very helpful.

For TO-11A standard air quality tests, none of the indoor air samples (MR 1, MR 12, MR 5 or MR 13) were above the Acute AAC for Arizona. The indoor air concentrations on both sampling dates were higher than the chronic AAC concentrations. However, even the background outdoor concentrations of acetaldehyde and formaldehyde exceeded the chronic AAC limits. The chronic AAC is derived based on an assumption of breathing air for 24 hours per day, 365 days per year. Obviously, this is not the case for anyone living in these prefabricated structures. Also, the sampling was conducted with no ventilation and all windows and doors closed. This would also not likely be the case if the structure was inhabited. The relatively close agreement with the final indoor air concentration of aldehydes (MR 12 and MR 13) with the background ambient air (MR 10) indicates that this exceedance is likely not an issue of concern.

For TO-15 standard air quality tests, the indoor air samples (MR 4 and MR 14) had larger concentrations of VOCs than the background outdoor samples (MR 3 and MR 11). With one exception, the final VOC indoor concentrations (MR 14) were larger than the initial indoor concentrations (MR 4). The lone exception is acetonitrile, where there was an increase from 390 to 1600 $\mu g/m^3$. None of the indoor air samples exceeded the Acute AACs. Both indoor air samples (MR 4 and MR 14) exceed the Chronic AAC for acetonitrile, but so do both the outside background samples. The styrene Chronic AAC is exceeded by sample MR 4, but the final concentration of styrene after curing was below this standard.

On the basis of these air quality tests, it is our recommendation that the structure is safe for occupancy based on established standards and best practices. The structure generally has indoor air quality that is comparable with background (i.e. outdoor) samples, over the long term. However, concentrations of Aldehydes and VOC's are higher immediately after construction is completed, while caulks and construction materials are curing. For this reason, ventilation should be maximized during the time period immediately after construction is complete, if the structure is to be immediately occupied. This time period when ventilation is critical is likely much shorter than six months, which was the delay between the Acute and Chronic indoor air quality tests. After the initial period, ventilation is still important for other reasons but low ventilation is not likely to increase Aldehydes or VOC's much above background concentrations.

This structure is relatively efficient and well suited to off-grid and nonstandard housing situations.

Appendices

Appendix A: Indoor Air Quality Report
Appendix B (A-1): Laboratory Report for TO-11A (Aldehydes)
Appendix C (A-2): Laboratory Report for TO-15 (VOCs)
Appendix D: Arizona TO-15 Standards Document
Appendix E: Exhaust Fan Calibration Report
Appendix F: One-page Handout
Appendix G: Model Results Spreadsheet
Appendix H: Raw Structure Monitoring Data Text Files
Appendix I: Wiring Diagram for CR1000 (and index to data text files)
Appendix J: CR1000 program (and index to data text files)
Appendix K: SMEM assumption validation results
Appendix L: eQuest Model Documentation