BUILDING AMERICA FIELD TEST REPORT
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NREL / Wonderland Development
Wonderland Near-Zero Energy Row Houses – Boulder, CO

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Introduction

Wonderland Development has constructed a new "near zero energy" row home design in North Boulder consisting of 9 units: one 5-plex and two duplexes. NREL has performed short-term tests and installed long-term monitoring equipment in two of these units and plans to do the same in one additional unit. This report describes the results of the short-term tests of three units within the 3 building complex. Testing of two units in the 5-plex, the south unit and an interior unit, was completed in December, 2007. Testing of a third unit located in a duplex was completed February, 2008. Within this report "unit 1" refers to the south end of the 5-plex, address 4657 and "unit 2" refers to the adjacent interior unit, address 4659, and "unit 3" is the south unit of the middle duplex, address 4651. Future reports will describe the results of building energy simulations and long-term performance monitoring of the homes.

Key features of each unit in the 5-plex are a well-insulated building envelope, solar hot water and space heating with condensing boiler backup, multiple zone "staple-up" radiant floor heating, a photovoltaic system, and a mini-split AC system. Unit 3 in the duplex contains most of the same features but incorporates a single zone forced air system with small diameter, high-velocity ducting in place of the radiant system. Long-term monitoring for one year has been negotiated as part of an agreement with the homebuyers. Specifications for the units are given in Table 1. A diagram of the HVAC and water heating system is shown for radiant heated units 1 and 2 in Figure 1, and for the forced air system, unit 3, in Figure 2.

Table 1. Specifications for Wonderland Row Houses.

	5-plex end unit (Unit 1)	**5-plex interior unit (Unit 2)**	**Duplex end unit (Unit 3)**
Location	4657 17th Street Boulder, CO	4659 17th Street Boulder, CO	4651 17th Street Boulder, CO
Conditioned space	1700 finished ft^2 587 ft^2 semi-finished basement[1] 2287 ft^2 total conditioned space	1258 finished ft^2 442 ft^2 semi-finished basement 1700 ft^2 total conditioned space	1700 finished ft^2 587 ft^2 semi-finished basement[2] 2287 ft^2 total conditioned space
Volume	20,330 ft^3	15,580 ft^3	20,330 ft^3
# of bedrooms	3	2	3
Ceiling	Exterior urethane foam varying from 3" in the center of the building to 0.5" on the north and south ends. ~ 2"of spray urethane inside with an additional R-19 fiberglass batt	same	same
Exterior walls	2x6 construction In cavities: approx 3" urethane foam and 2.5" of cellulose with 1" of foam on exterior	same	same
Party wall	Double 2x4 construction R-15 fiberglass batts in cavities of both stud walls	same	same
Foundation	Poured concrete 2" of foam under slab and 2" foam on interior walls of finished area	Same	same
Windows	Double glazed, argon filled, low-e, vinyl framed South, East and North windows: U = 0.29-0.31 SHGC = 0.30-0.33 VT = 0.52 – 0.63 West windows: U = 0.30 – 0.34 SHGC = 0.22 VT = 0.52	same	same

[1] The levels referred to as "basement" are at garden level, with the lower half below grade and the upper half above grade. The basement is partially dry walled and has plumbing sets for an additional bathroom. The basement is conditioned space.
[2] The levels referred to as "basement" are at garden level, with the lower half below grade and the upper half above grade. The basement is partially dry walled and has plumbing sets for an additional bathroom. The basement is conditioned space.

Heating	Munchkin boiler model MC-80 Staple-up radiant floor heating 4 zones – one for each floor Solar thermal system can contribute to space heating	same	Forced air system Nu-Air Enerboss air handler with integrated HRV 4” high velocity ducting Solar thermal system can contribute to space heating Single zone
Cooling	Minisplit AC system with three interior units	Minisplit AC system with two interior units	Central AC
DHW	Solar DHW with boiler used as backup 45-gal Superstor Ultra indirect fired water heater tank	same	same
Solar DHW/Space Combi System	3 Heliodyne Gobi 408 panels,40 degrees tilt 96 sq ft collector area 180 gallon unpressurized tank with 3” PolyIso insulation, foil faced (R- 19) Closed-loop glycol system with external heat exchanger	3 Heliodyne Gobi 408 panels, 40 degrees tilt 64 sq ft collector area 128 gallon unpressurized tank 3” PolyIso insulation, foil faced (R- 19) Closed-loop glycol system with external heat exchanger	3 Heliodyne Gobi 408 panels,40 degrees tilt 96 sq ft collector area 180 gallon unpressurized tank with 3” PolyIso insulation, foil faced (R- 19) Closed-loop glycol system with external heat exchanger
Photovoltaics	3kW DC peak rated system 14 Sunpower SPR-215-BLK-U modules	same	same
Ventilation	Two Panasonic Model FV-08VQ3 bathroom exhaust fans operated on timers to achieve ASHRAE 62.2 ventilation levels.	same	same
Lighting	Mix of incandescent and compact fluorescent lighting,	same	same

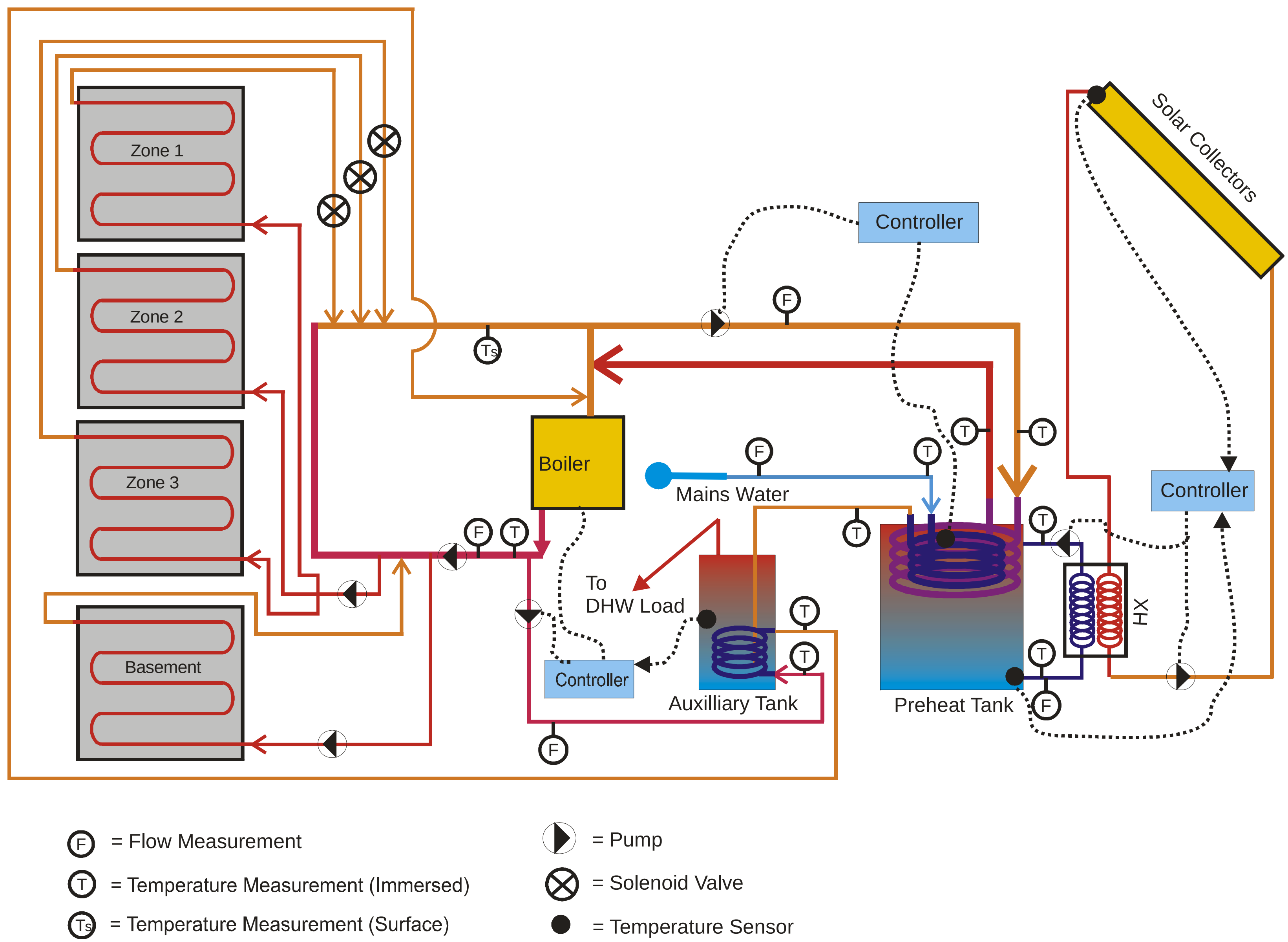


Figure 1: HVAC and water heating diagram for units 1 and 2

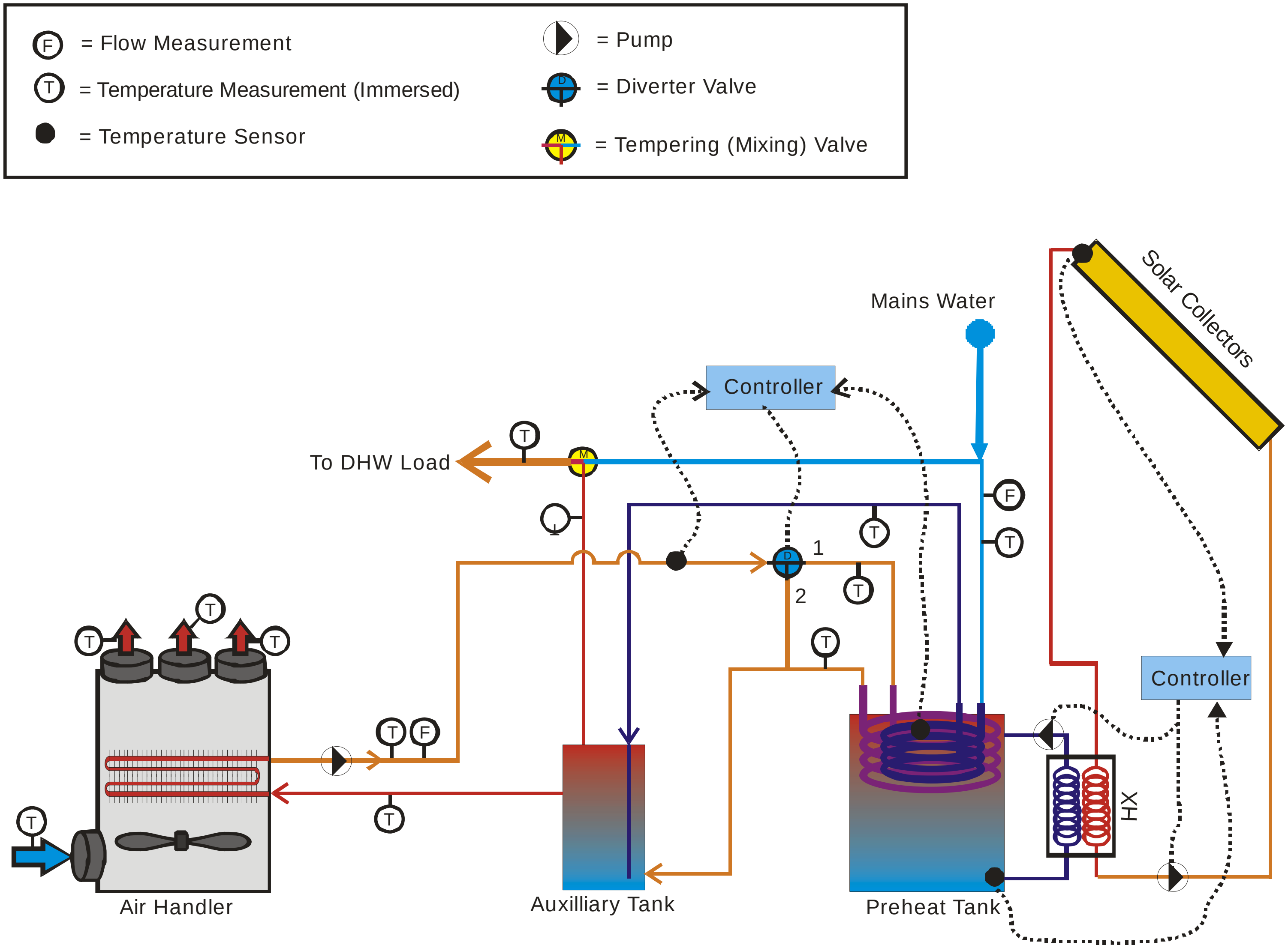


Figure 2: HVAC and water heating diagram for unit 3

Energy Expectations

From Clean Slate Energy:
Solar thermal system: 170 therms delivered annually.

From Energy Logic:
HERS index of unit 1 = 27 (27% of the energy use of the HERS benchmark home)
HERS index of unit 2 = 20 (20% of the energy use of the HERS benchmark home)
HERS index of unit 3 = 36 (36% of the energy use of the HERS benchmark home)

Research Questions for Short-Term Testing

1. What are the basic air leakage and flow characteristics of each unit measured using a blower door? What is the air leakage through the party wall between units?
2. What is the hourly air infiltration of each unit during the winter season with and without the ventilation system operating? Does the system meet the ASHRAE 62.2 recommendations?
3. What is the distribution of fresh air throughout the house?
4. What is the overall thermal conductance (UA) of an end unit and a core unit?
5. Are there any visible thermal short circuits in the building envelope as viewed with an IR camera?
6. How well does the multi-zone radiant floor heating system maintain the heating setpoints?
7. Is actual hot water flow in pipes consistent with plug flow or is there a significant boundary layer?
8. What is the AC output of the photovoltaic system?
9. For unit 3, what is the air handler flow rate during start up and continuous operation?

Short-term Test Plan

Whole house and systems checks

1. PV operation
    a. Perform curve tracing on PV systems for both units.
    b. Make long-term performance predictions based on curve traces

2. Hydronic system check
    a. Observe the operation of the SWH system. Note any concerns.

    b. Change thermostat setting and observe the operation of the hydronic heating system. Note any concerns.
    c. Force operation of the back-up water heating system and note any concerns.
    d. If possible, check the operation of the solar space heating systems. Note any concerns.

3. Building thermal load comparison: Perform co-heating tests in units 1, 2, and 3.
4. Insulation consistency check: Check consistency of insulation using an IR camera
5. Exhaust fan performance check: Measure flow rates of each exhaust fan

Hot Water Distribution Testing

1. Flow meter and thermocouple check
    a. Check consistence of flow meter reading by operating fixtures one at a time and comparing flow measurements at fixtures to total hot water flow meter. Once all meters are confirmed to be consistent, check the calibration by filling a container of known volume at one fixture and comparing to the data logger reading.
    b. Test the readings of the fixture thermocouples against a hand-held thermocouple in the water stream exiting the fixture.

2. Wait time and distribution temperature rise for hot water

These tests must be done at the beginning of the day when the distribution system has been quiescent overnight. This data will be used to interpret draw data and to check against the HWSim and TRNSYS models. Measure wait time for hot water at the end of each plumbing branch:

i. Master bathroom sink
ii. Secondary bathroom sink
iii. Kitchen sink

Record fixture and intermediate temperatures during the draw. Continue to run hot water until intermediate temperatures stabilize.

3. Overnight temperature decay in hot water distribution system

These tests will provide data for comparison to HWSim and TRNSYS distribution system modeling results.

    a. With co-heating, draw hot water from the far fixtures on each branch until the delivered and intermediate pipe temperatures have stabilized. Record all fixture and intermediate temperatures overnight as the temperatures decay to room temperature.
    b. Repeat with radiant floor system maintaining space temperatures.

4. Mixed and cold water fixture draw profiles

These results will help disaggregate cold water draws when multiple draws occur simultaneously. This info will also provide data for creating rules in the Trace Wizard software. The exact time of each controlled event must be recorded for comparison to the logged data.

a. Flush each toilet several times to test repeatability of draw pattern
b. Typical draws at the sinks, shower, and tub including maximum
c. If clothes washer is available, do a load of laundry – warm wash, cold rinse
d. Run a load of dishes through the dishwasher

5. Hot water distribution system and heating system interaction

Test impact of hot water on space heating overnight with co-heating. With co-heating test underway, fill the distribution system with hot water. Record the impact on the co-heating energy.

Infiltration/Ventilation Testing

1. Blower Door Testing
    a. Blower doors in units 1 and 2. Measure leakage rate at 50 Pa in unit 1 with and without unit 2 held at 50 Pa. The difference in these tests represents the leakage through the unit 1-2 party wall at 50 Pa.
    b. If party wall leakage is small compared to infiltration from the outside for unit 1, perform an automated multipoint blower door test in unit 1.
    c. Move unit 1 blower door to unit 3. Measure leakage rate at 50 Pa in unit 2 with and without unit 3 held at 50Pa. The difference in these tests minus the unit 1-2 party wall leakage represents the leakage through the unit 2-3 party wall at 50 Pa. (Assume that the leakage through unit 1-2 party wall is the same as measured in step a. when the pressure difference between unit 1 and 2 is reversed.)
    d. If the party wall leakage is small (< 10%) compared to the outside air infiltration, proceed with tracer gas testing.

2. Exhaust fan flow test
    a. Measure the flow rate(s) at each exhaust fan using a flow hood.

3. Tracer Gas Testing
    a. In unit 1, deploy destratification and mixing fans with the aim of creating a single well-mixed zone in the whole house. Position sampling points on each floor of the home. Perform standard tracer gas tests with ventilation off and with ventilation on. Check the data to see if single mixed zone was achieved. If single mixed zone is achievable, proceed with age-of-air testing. (Document the fan configuration need to achieve a single mixed zone.)
    b. Repeat step a. in unit 2.
    c. If single mixed zone is achievable and home is sufficiently tight, proceed with age-of-air testing. (Document the fan configuration needed to achieve a single mixed zone.)

4. Air handle flow rate
    a. In unit 3, use a flow plate to measure the operating and start-up flow rates, in CFM, of the air handler. The air handler operates in start-up mode for approximately 1 minute during start-up and shut-down.

Short-term Test Results

Whole house and system checks

1. Photovoltaic (PV) System Operation

Short-term tests were conducted on the photovoltaic array connected to unit 1 between November 19th and 20th , 2007. The tests consisted of measuring i-V (current-voltage) curves for the entire array every 5 minutes during sunlight hours. The i-V curves were measured using a capacitance-type device which measures 200 voltage and current pairs over the period of between 0.5 and 2.0 seconds. At the same time global solar radiation in the plane of the collector was measured using a Kipp and Zonen CM21 thermopile pyranometer. Also measured was the back-of-module temperature using a single type T thermocouple temporarily taped to the back of one typical module.

The test data was used to calibrate a TRNSYS[3] model used to predict annual performance using TMY (Typical Meteorological Year) data for Boulder, CO. The procedure used to calibrate the model is described by Barker[4].

The specifications of the installed components are given in Table 2.

Table 2. PV System Installed Components

		Rating
Inverter	SunPower SPR3300X	3300 watts
PV modules	SunPower SPR-215-BLK	216 watts
# modules in series per string	7	
# strings in parallel	2	
installed slope	10 degrees from horizontal	
installed azimuth	due South	

2. Observations on Short-Term Test Results

Figure 3 is a graph of all 121 curve traces, with current as a function of voltage. Figure 4 shows the same data with power as a function of voltage. In Figure 5 is shown a close-up view of 12 curve traces between 1:00 PM and 2:00 PM, revealing an anomalous shape to the curves to the left of the maximum power point. The unusual shape seems to dissipate with decreasing solar radiation (the lower curves). During the period that these curves were measured the sky was clear with no shading of the array, so PV response should

[3] Klein, S., et al., TRNSYS: A Transient System Simulation Program – Reference Manual, Solar Energy Laboratory, University of Wisconsin, 2000

[4] Barker, Greg, "Predicting Long-Term Performance of Photovoltaic Arrays Using Short-Term Test Data and an Annual Simulation Tool", ASES June 2003

have been changing quite slowly and the curves should have been smooth. A typical cause of these types of anomalous curve shapes is a mismatched array (one or more modules not operating at the same efficiency as the others). This anomaly is small and is not expected to affect overall performance appreciably. In the past, we have found that anomalies such as this can be caused by objects shading a small portion of one module of the array. It is also possible that there was a problem with the curve-tracing equipment itself. We expect to return to the site this coming summer to repeat the curve trace and investigate the anomaly further.

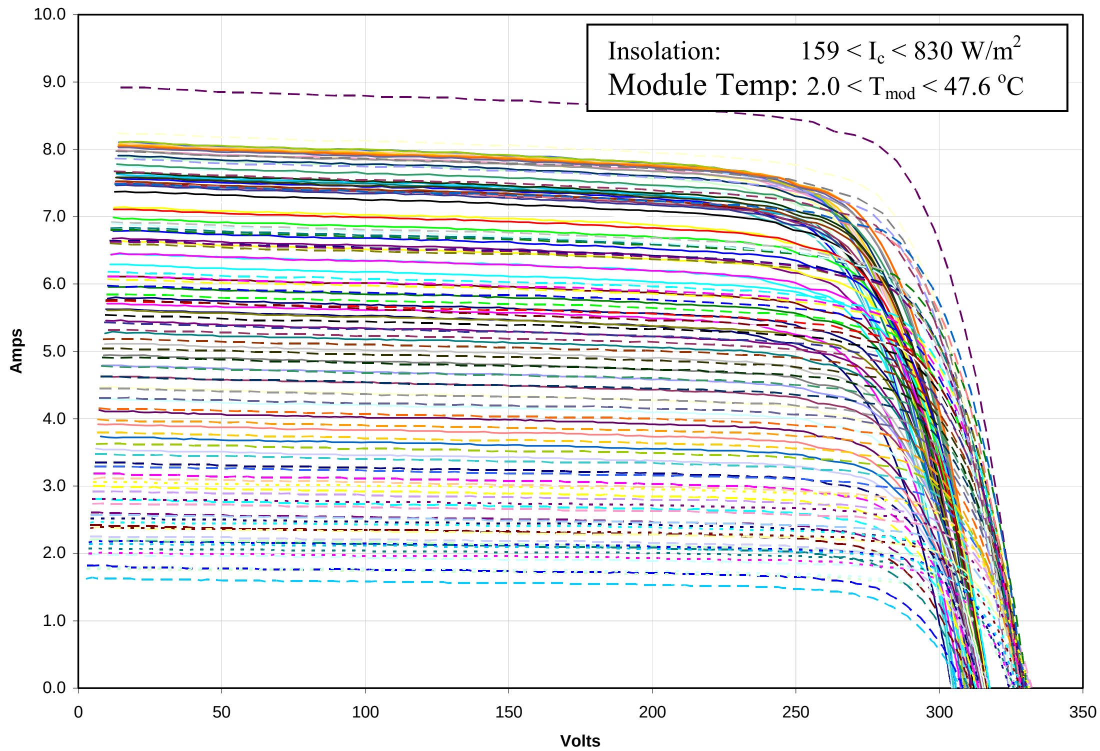


Figure 3: Set of Current-Voltage curves measured between Nov. 19, 9:25 AM and Nov. 20, 11:45 AM.

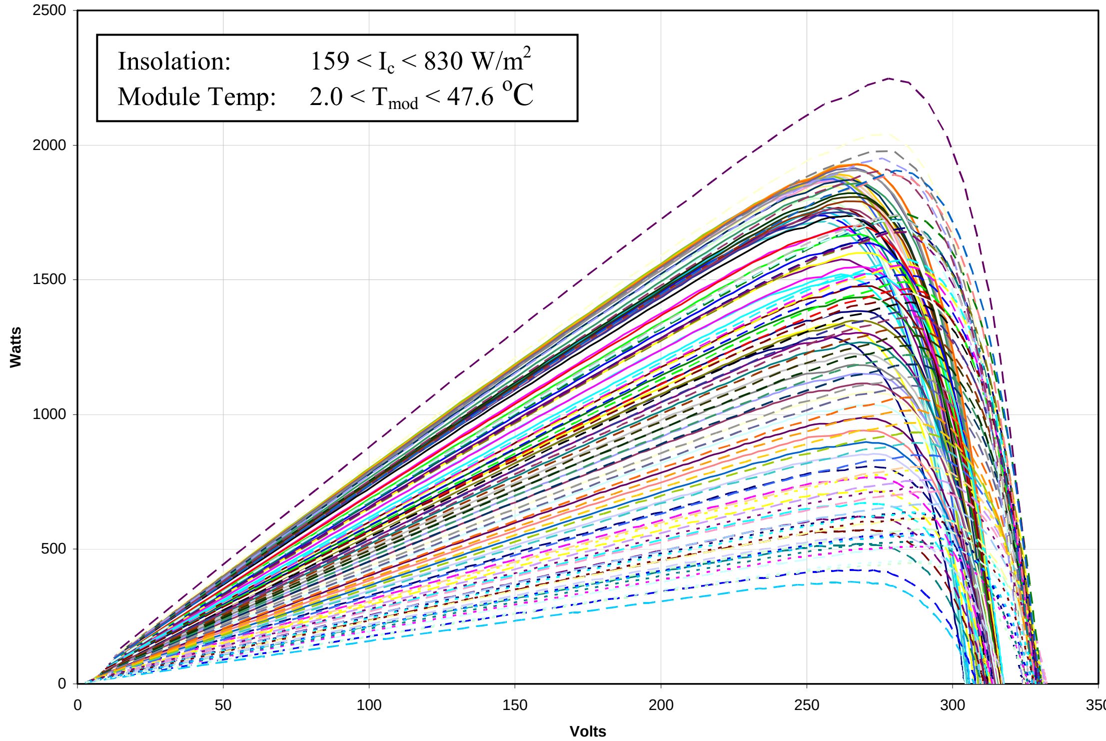


Figure 4: Set of Power-Voltage curves measured between Nov. 19, 9:25 AM and Nov. 20, 11:45 AM

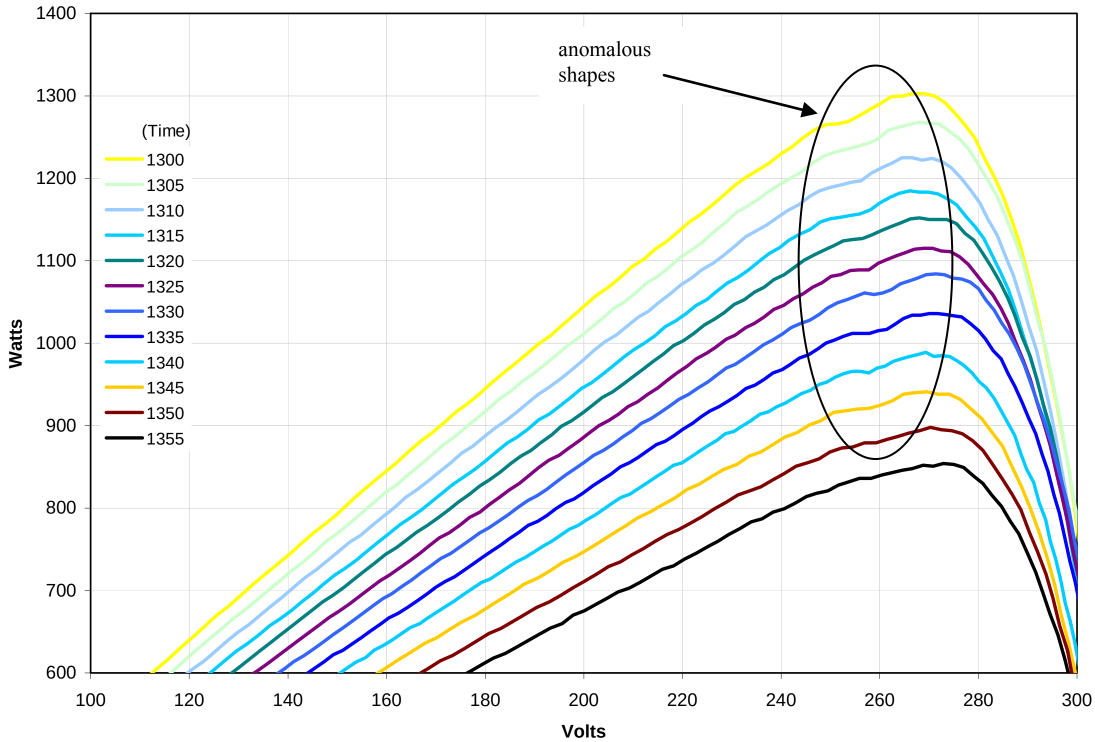


Figure 5: Power-Voltage curves measured between 1:00 PM and 2:00 PM on November 19, 2007 during clear-sky conditions.

In Table 3 a comparison is made of the performance parameters based on the manufacturer's specifications for a single module and on best-fits to the curve traces. The short-term tests predict that the maximum power output of the array will be about 7% lower than the manufacturer's specifications would predict at STC (Standard Test Conditions, T_{cell}=25 ^{o}C, I_c=1000 W/m^2).

Table 3: Comparison of manufacturer's specifications to calibrated model from short-term test, all at STC

	Manufacturer	*Calibrated Model*	*Units*	*Ratio*
i_{sc}	11.8	10.7	amps	0.907
V_{oc}	333.9	329.8	volts	0.988
i_{mp}	10.8	10.2	amps	0.944
V_{mp}	280.0	276.6	volts	0.988
P_{mp}	3024.0	2810.9	watts	0.930
α_{isc}	0.00078	0.00078 *	1/°C	1.000
β_{Voc}	-0.96	-1.05	V/°C	1.094
γ_{mp}	-0.38 ***	-0.43	%/°C	1.132
α_{imp}	N/A	-0.00019 **	1/°C	N/A
β_{Vmp}	N/A	-1.13	V/°C	N/A

* Unable to fit with certainty, so used manufacturer's specs.
** Unable to fit with certainty, so estimated based on cell material.
*** This value is given by the manufacturer as 0.38, but calculates to 0.318 from their given values of α_{isc} and β_{Voc}

Nomenclature

AM air mass
I_c global solar radiation in plane of collector array
i_{mp} current at maximum power point
i_{sc} short-circuit current
P_{mp} power at maximum power point
STC Standard Test Conditions: T_{cell}=25 °C, I_c=1000 W/m^2, AM=1.5
T_{cell} cell temperature
T_{mod} back-of-module temperaure
V_{oc} open-circuit voltage
V_{mp} voltage at maximum power point

α_{isc} temperature coefficient of short-circuit current
β_{Voc} temperature coefficient of open-circuit voltage
α_{imp} temperature coefficient of current at maximum power point
β_{Vmp} temperature coefficient of voltage at maximum power point
γ_{mp} temperature coefficient of efficiency

3. Annual Simulation Results

An annual simulation was run using the calibrated TRNSYS model driven by TM2 data for Boulder, CO. The results are given in numeric form in Table 4. The predicted AC energy delivered (columns 4 and 5 in Table 4) are shown as a bar graph in Figure 6.

It is important to note that although the modeled P_{mp} is only 7% lower than the manufacturer's value (Table 3), the modeled annual energy delivery is almost 14% lower (Table 4). This is because the modeled temperature coefficient of Pmp (γ_{mp}) is 13% greater than the manufacturer's (Table 3). We will be checking the validity of the model by comparing measured long-term performance to the performance predicted by the model driven by the measured weather data.

Table 4: Comparison of predicted monthly energy production using manufacturer's specifications and using calibrated model.

	DC Energy (kWh)		*AC Energy (kWh)*		*PV Efficiency*		*Inverter Efficiency*	
	man.	model	man.	model	man.	model	man.	model
January	294.3	246.3	272.7	228.4	18.2%	15.2%	92.7%	92.7%
February	321.4	274.4	299.6	256.3	17.9%	15.2%	93.2%	93.4%
March	489.8	426.9	459.5	401.1	17.6%	15.3%	93.8%	94.0%
April	533.4	465.9	500.3	438.0	17.2%	15.0%	93.8%	94.0%
May	584.6	510.1	548.4	479.7	16.8%	14.7%	93.8%	94.1%
June	587.4	512.0	551.0	481.8	16.5%	14.4%	93.8%	94.1%
July	579.6	505.2	543.4	475.3	16.2%	14.1%	93.8%	94.1%
August	551.7	481.0	517.3	452.6	16.2%	14.2%	93.8%	94.1%
September	485.8	423.1	455.5	397.9	16.5%	14.4%	93.8%	94.1%
October	413.5	354.4	386.3	331.9	17.0%	14.6%	93.4%	93.7%
November	303.5	254.6	281.5	236.5	17.8%	14.9%	92.8%	92.9%
December	277.1	230.7	256.2	213.6	18.2%	15.2%	92.5%	92.6%
Year	**5421.9**	**4684.6**	**5071.7**	**4393.0**	**17.0%**	**14.7%**	**93.5%**	**93.8%**

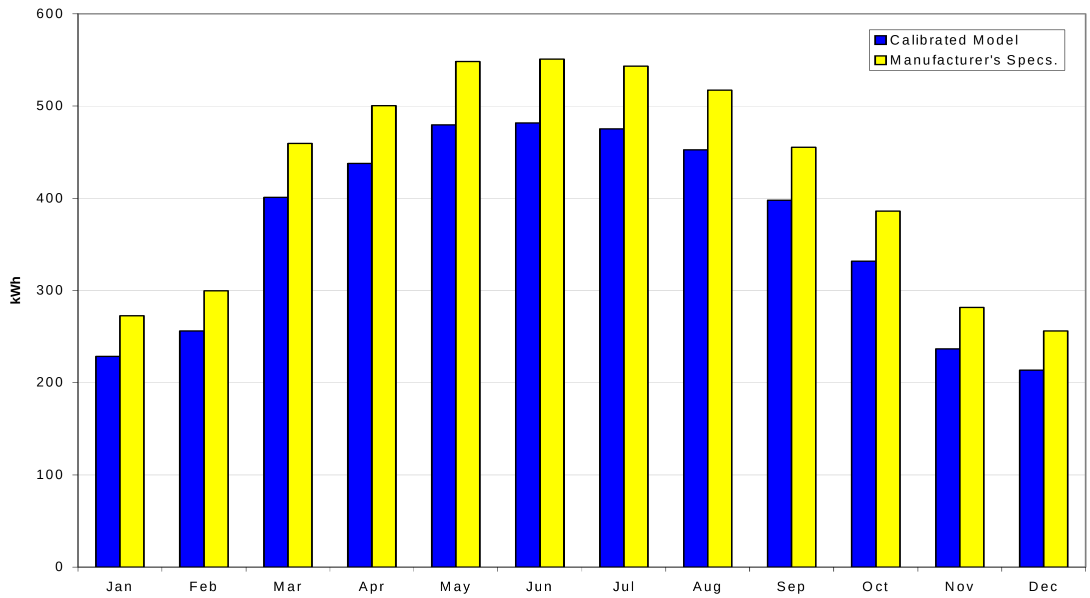


Figure 6: Monthly energy delivered by inverter, as predicted by the calibrated model based on short-term testing (blue) and as predicted using manufacturer's specifications.

Having verified the performance of the PV system in unit 1, we then compared the PV system output of units 1 and unit 2 and found the output to be identical to within our measurement accuracy. Twelve days of PV output for both systems presented in Figure 7 show that the AC output of the two systems is nearly identical.

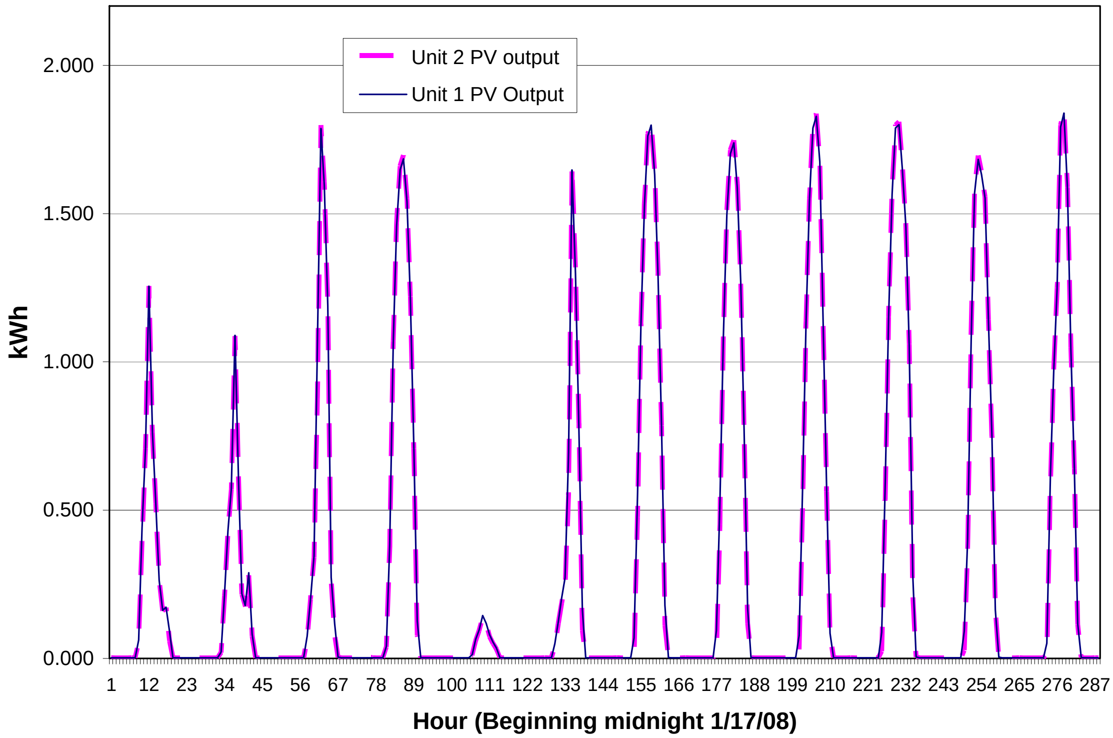


Figure 7: Output of PV systems on units 1 and 2 from 1/17/08 to 1/28/08

2. Hydronic System Check

A check of the hydronic system operation revealed several minor issues that were resolved in cooperation with the plumbing contractor who installed the boiler and radiant floor system.

3. Building Thermal Load Comparison

The heat loss from a home can be represented by the following simplified equation:

$$Q = UA_{eff}\ \Delta T$$

Where: Q = heat loss from the home
UA_{eff} = Effective overall heat transfer coefficient times the surface area
ΔT = Indoor/outdoor temperature difference

UA_{eff} is a measure of the overall thermal conductivity of the home. A lower UA_{eff} indicates a better insulated home. By measuring Q and ΔT, we were able to calculate UA_{eff} for units 1 and 2.

We used a coheating test approach to measure the difference in UA_{eff} between the units. The UA_{eff} was then normalized by conditioned floor area. The thermostats in both homes were set low to prevent the radiant floor heating system from operating and computer-controlled electrical resistance heaters were deployed throughout both homes to maintain uniform temperatures. With this configuration, the heating load can be measured by monitoring the total electricity into the home. The space temperatures on each floor of both units, the outdoor temperature, and the total electricity used in both units during the coheating test are shown in Figure 8.

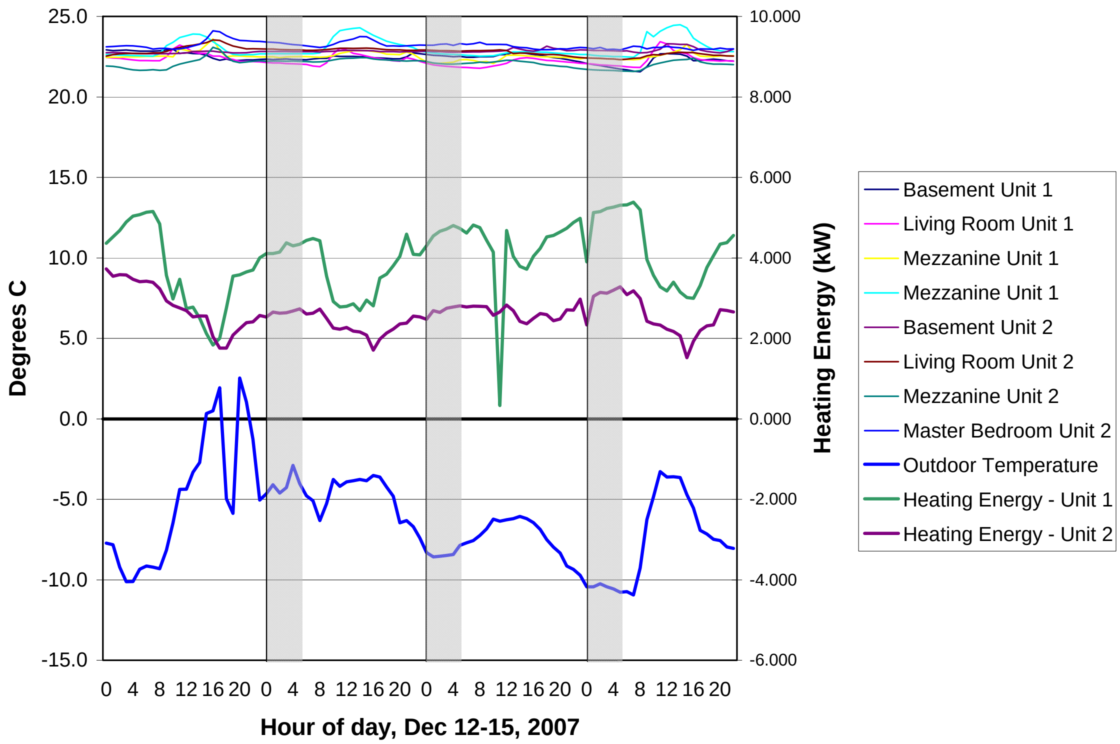


Figure 8: Temperatures and electricity use during coheating testing, Dec 12-15, 2007

As shown in Figure 8, the space temperatures on all floors of both units were within a few degrees for the entire test. The daytime temperatures in both units were elevated somewhat by solar gains on Dec 12, 13, and 15. To compare the heating loads of the two units independent of solar gains, we analyzed the heating energy during the nighttime from midnight to 5 am on Dec 13-15 (indicated by the shaded regions in Figure 8). The results, shown in Table 5, are presented as the heating load per degree of indoor/outdoor temperature difference.

Table 5: Results from the coheating testing

	Unit 1	Unit 2	Difference
Dec 13 UA_{eff} – heat loss per degree ΔT (W/^oC)	161.3	99.5	38.3%
Dec 14 UA_{eff} - heat loss per degree ΔT (W/^oC)	152.9	87.9	42.5%
Dec 15 UA_{eff} - heat loss per degree ΔT (W/^oC)	159.6	95.8	40.0%
Average UA_{eff} (W/^oC)	157.9	94.4	40.2%
Conditioned floor area (ft2)	2287	1700	25.7%
Average UA_{eff} per ft2 (W/ft^2 ^oC)	0.069	0.056	**19.6%**

With no sunlight, unit 2 requires about 20% less energy to heat per unit of floor area than unit 1 due to the fact that it is an interior unit. As illustrated in Figure 8, this difference is narrowed or eliminated during daylight hours by the greater solar gain in unit 1. For example, in the early afternoon of December 12, the total heating requirements of unit 1 were nearly identical to unit 2 due to the greater solar gain in unit 1. Therefore the heating requirements in unit 1 per square foot of conditioned space were less than those of unit 2 during this period.

Electric heaters were temporarily installed in Units 1 and 3 at Solar Row from February 18-22 to compare the space heating energy use of the two similar units in the heating season. Six heaters were installed in each unit; approximately one in each room. The heaters were controlled by a Campbell data logger with feedback from shielded thermocouples located near the center of each room with the objective of maintaining a constant and uniform temperature in the houses, especially at night. Electric power was measured at the main electric panel at each unit.

One objective of this test was to determine whether there are significant differences in the thermal envelope of the two buildings. A comparison of the period between midnight and 6 am is of interest in addressing this question because differences attributable to daytime disturbances and solar gains are minimized. Hourly data for electric power in four nighttime coheating periods is displayed in the Figure 9. In coheat period 1, the temperature in the unit adjacent to Unit 3 was controlled to about 65 F compared to 70 F in Unit 3 and is not useful for comparison. The set point in the adjacent unit was changed to 70 F on February 19 at 0900. Coheat periods 2, 3 and 4 represent a more consistent comparison of the two units. In each case, Unit 3 requires more heating than Unit 1. The ratio of power for Unit 3 to Unit 1 is 1.07 for period 2, 1.10 for period 3 and 1.04 for period 4. We have not calculated the expected difference between the units.

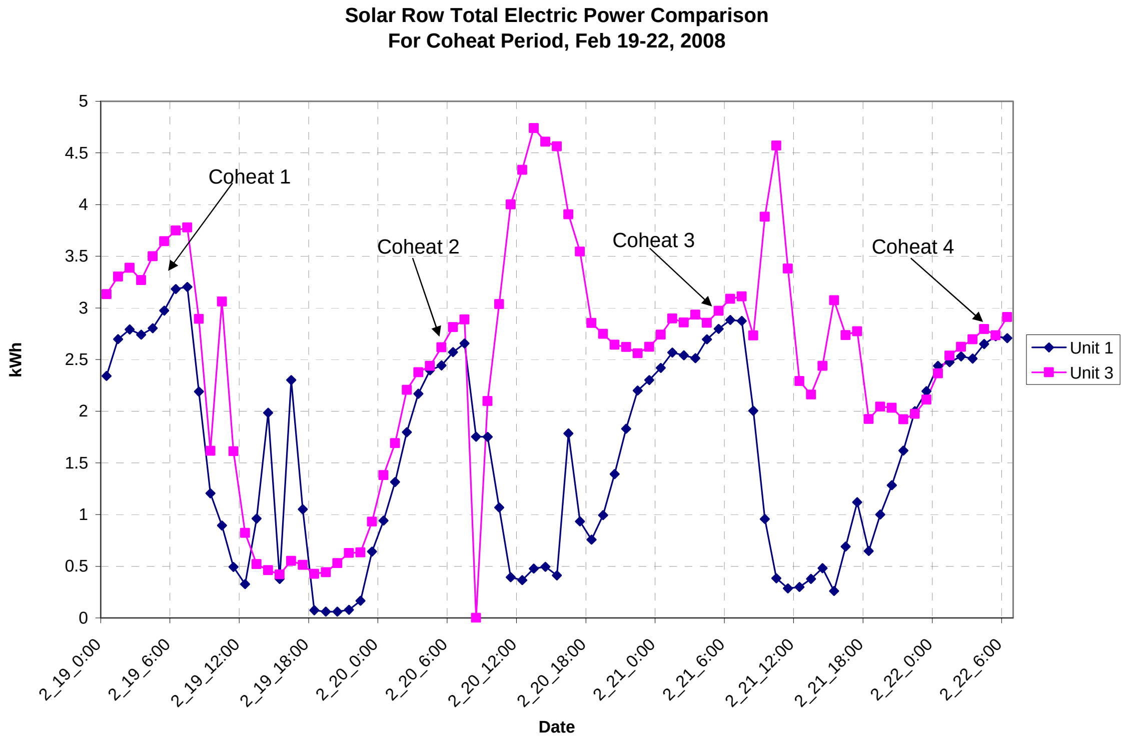


Figure 9: Coheating results for Unit 3 and the adjacent unit.

It would be of interest to compare the daytime electric power use of the two units as well, however, there were significant disturbances from workers in the units (especially Unit 3) during the day so the comparison is not useful.

4. Insulation Consistency Check

We used an infrared camera to check the consistency of the insulation in both units. Overall, the insulation appeared to be well applied without any substantial gaps or omissions.

However, there are areas in the homes with many studs side-by-side that create potentially significant thermal bypasses and lower the overall insulation level of the homes. Some examples are shown in Figure 10. These bundles of studs can be clearly seen in the thermal imaging of the finished homes. Examples are given in Figures 11 and 12.

Figure 10: Examples of side-by-side stud bundles

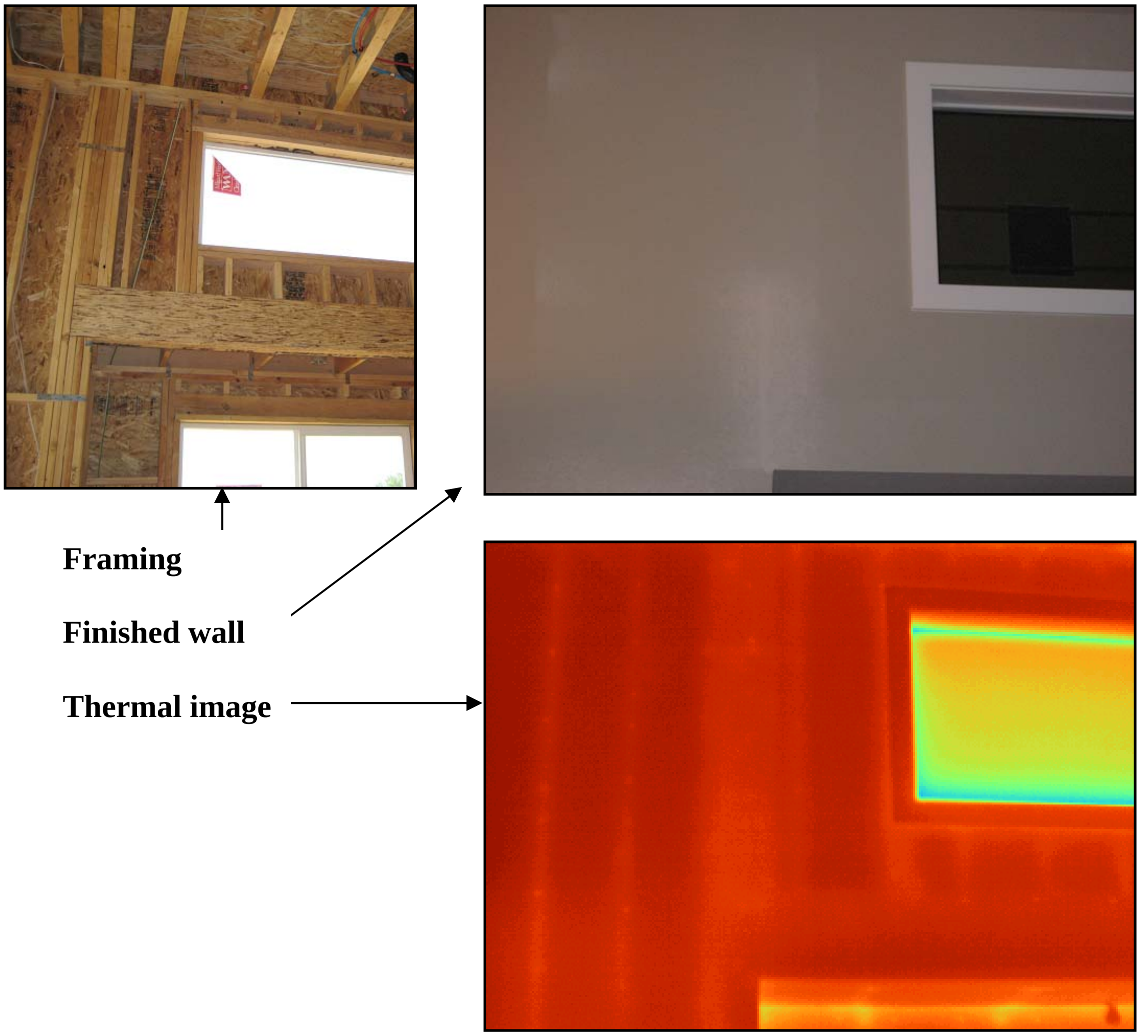


Figure 11: An example of thermal bypassing through side-by-side studs in unit 1

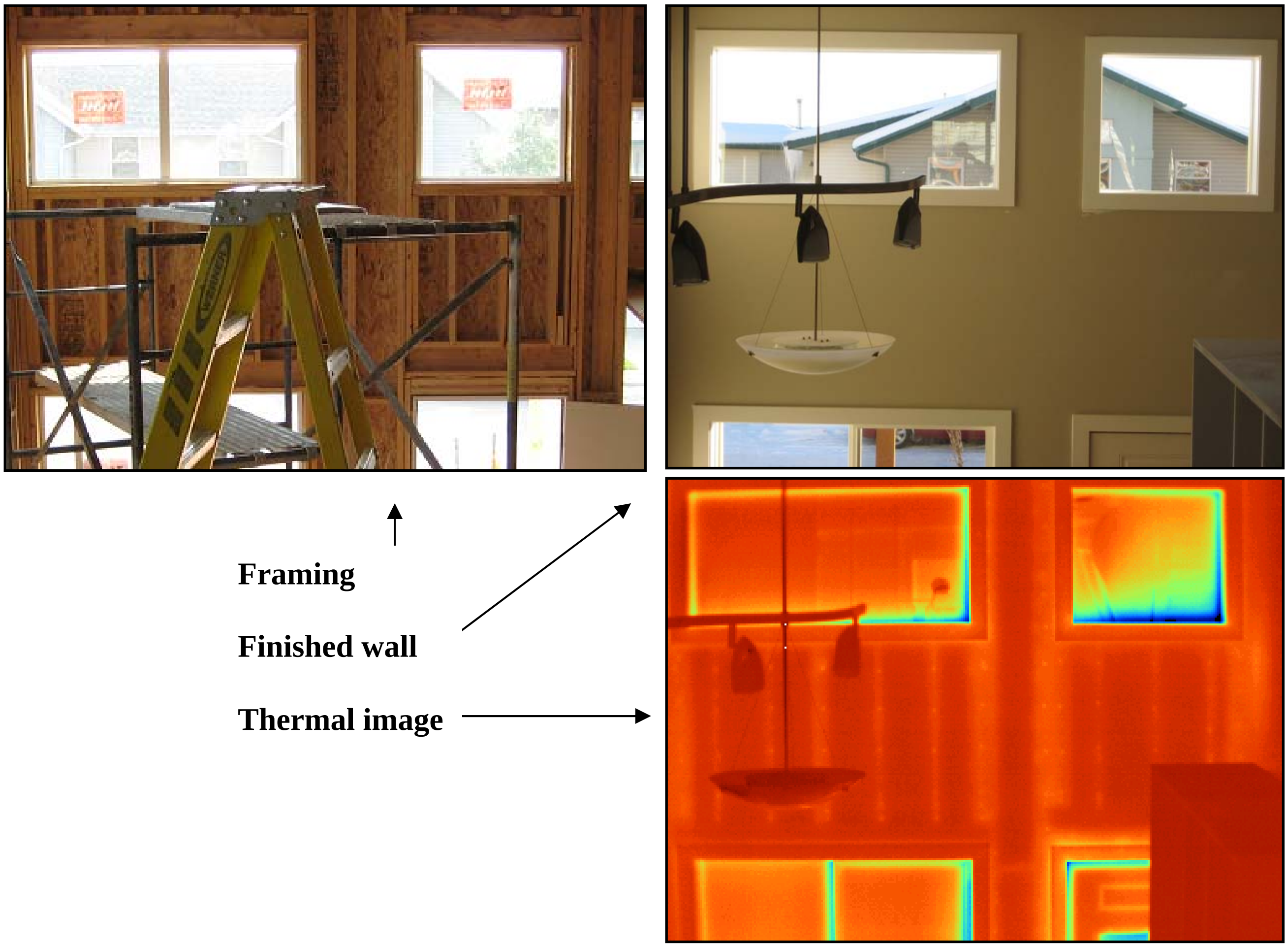
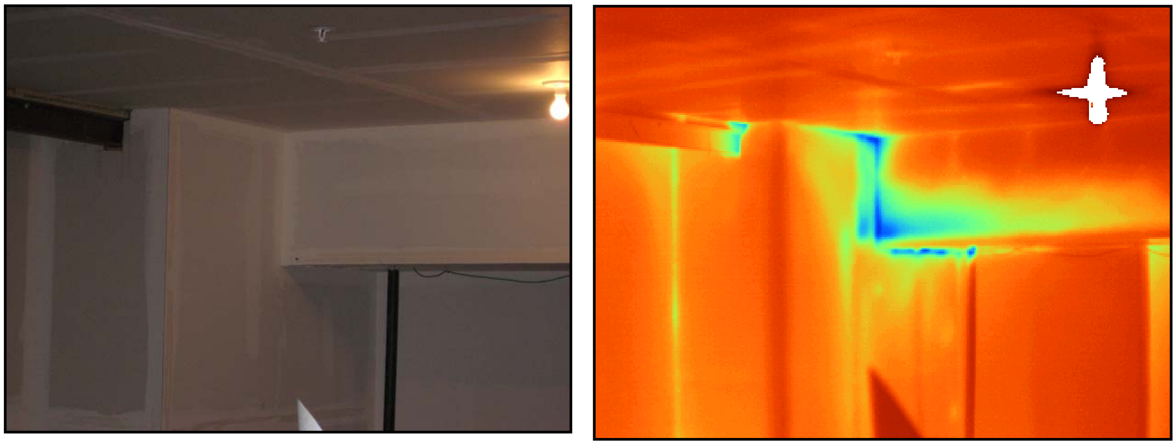


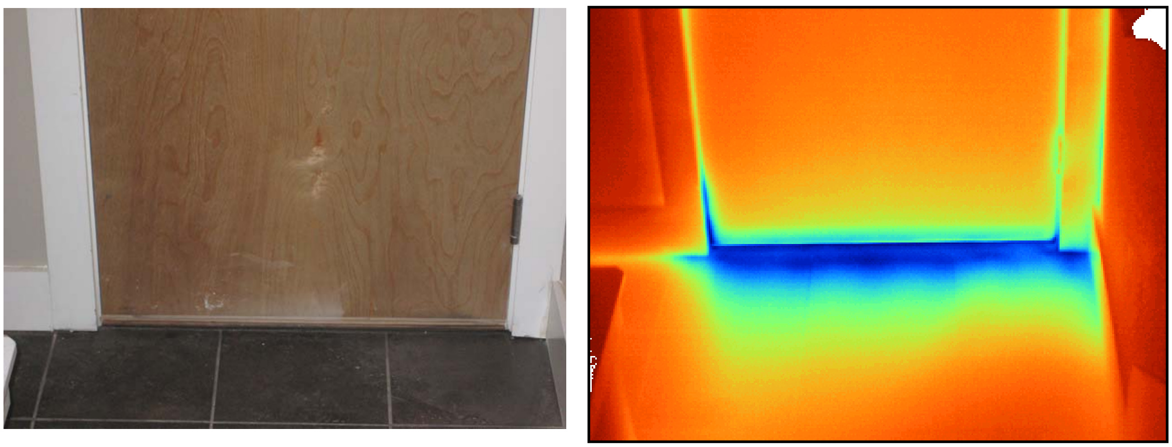
Figure 12: An example of thermal bypassing through side-by-side studs in unit 2

Many, if not all of these side-by-side stud columns may be needed to render structural integrity to the design. Therefore designs intended to achieve very high overall thermal performance should attempt to minimize these types of thermal bypasses. Architecturally interesting designs with simpler wall geometry may be able to achieve similar quality of spaces with less need for distributed side-by-side stud columns and therefore be able to achieve a higher effective R-value with the same nominal R-value insulation.

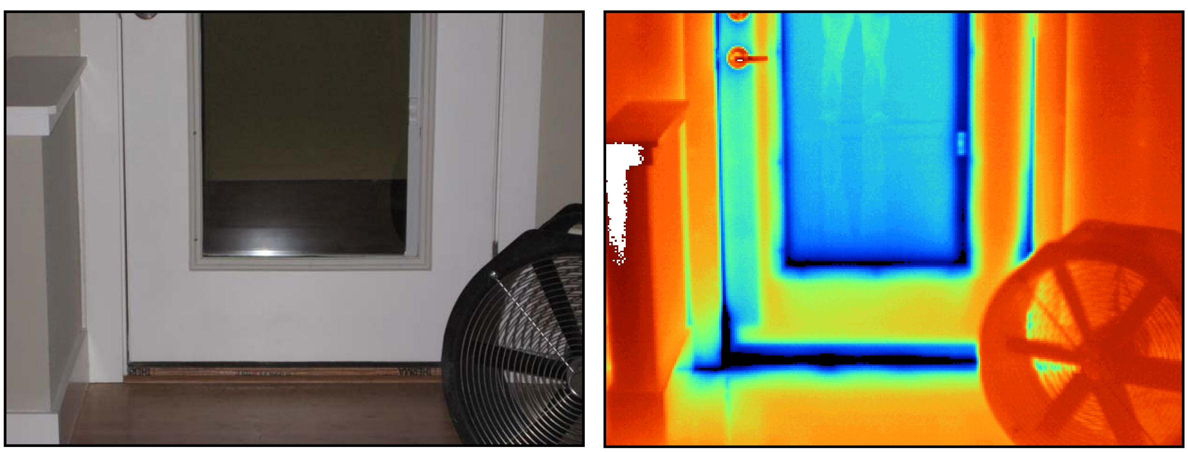
During blower door testing we noticed air leakage under exterior doors and in some other areas in both homes. The effects of these leaks can also be seen in the thermal imaging shown in Figures 13 and 14.



Unit 1 – SW corner of basement

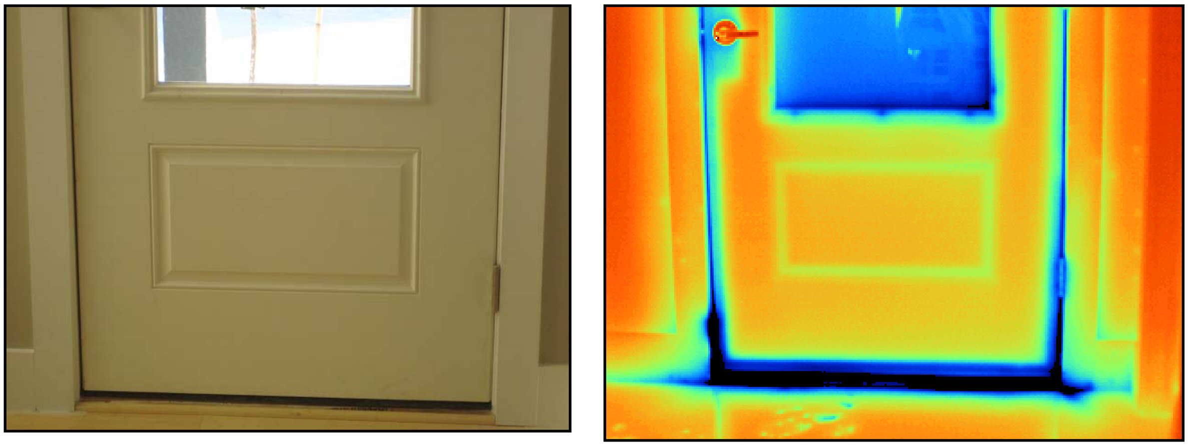


Unit 1 – Door to garage



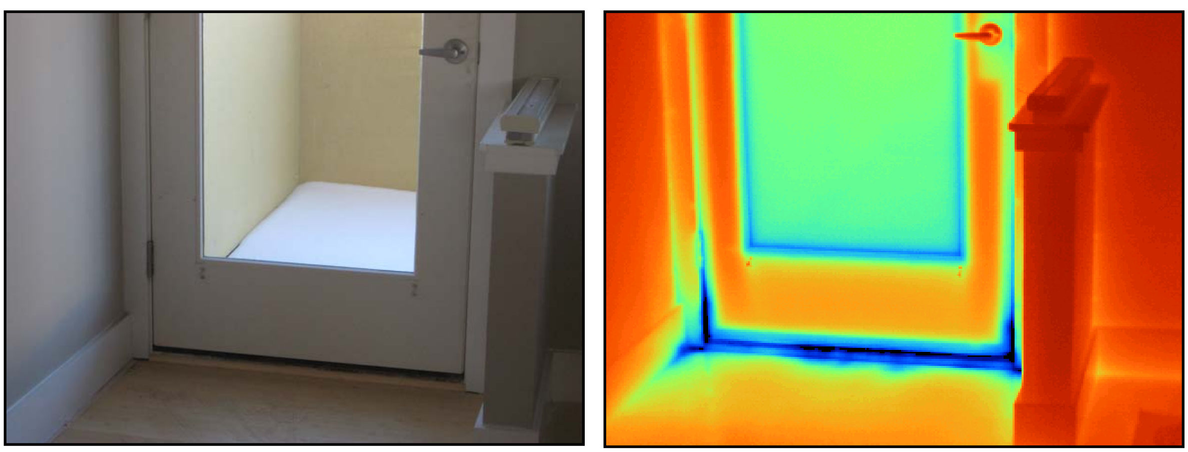
Unit 1 – Door to deck

Figure 13: Thermal images of air infiltration in unit 1



Unit 2 - Front door

Unit 2 - 1st floor ½ bath exhaust fan



Unit 2 – Door to deck

Figure 14: Thermal images of air infiltration in unit 2

Thermal images of the building's exterior show consistent insulation levels. These images also reveal some areas for potential improvement on future projects. Images of the eaves and the floor of architectural bump-outs, shown in Figure 15, indicate possible thermal bypasses in these areas. Heat loss through the whole-house exhaust fan is also clearly indicated.

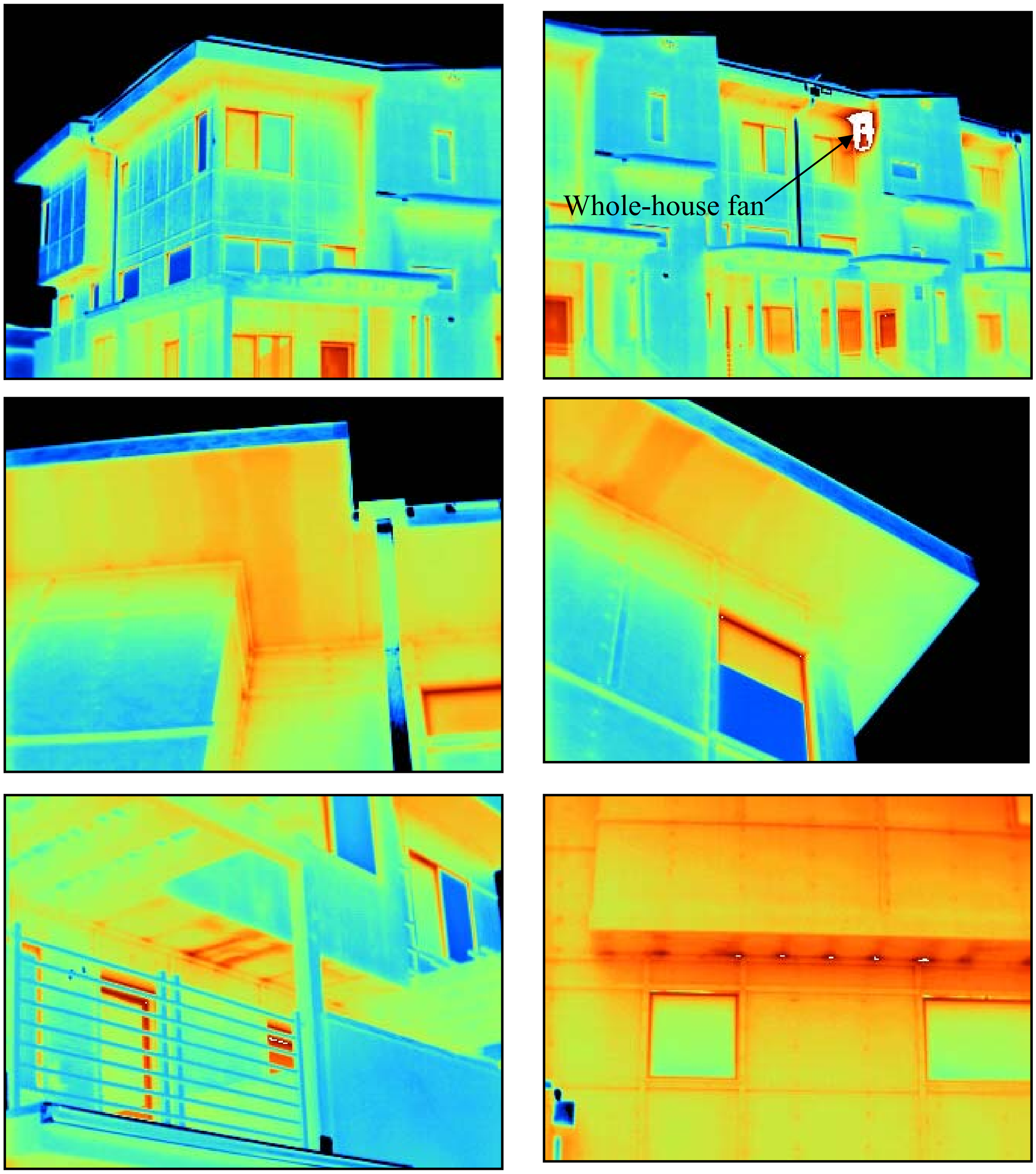


Figure 15: Thermal images of the building's exterior

Hot Water Distribution Testing

1. *Flow Meter and Thermocouple Check*
Several flow meters were checked by drawing a known amount of water from a fixture and comparing the volume against the flow meter reading. Other meters were then checked for consistency against these meters. The installed thermocouples were checked for internal consistency.

2. *Wait Time and Distribution Temperature Rise for Hot Water*
The wait time for hot water to reach the furthest fixture on each plumbing branch in unit 1 was checked on several mornings after the system had come to equilibrium overnight. The taps were open fully during these tests resulting in a flow rate of about 1.2 gpm at each fixture. Wait times for the water temperature measured at the end use to reach 105 ^{o}F are shown below for the morning of December 13, 2007.

Kitchen sink	18 seconds
Master bath sink	52 seconds
Second bath sink	67 seconds

3. *Overnight Temperature Decay in Hot Water Distribution System*
At 4 am on December 14, 2007 hot water was drawn for one minute from the fixtures at the end of each plumbing branch in unit 1- the kitchen sink, the master bath sink and 2nd bath. The temperature decay at these fixtures was recorded by our data-logging system.

4. *Mixed and Cold Water Fixture Draw Profiles*
During the day on December 14, 2007 we ran the dishwasher, flushed toilets and drew water from each fixture in unit 1 to record the draw profiles on our logging system. These profiles will be used in later analysis to help disaggregate simultaneous hot and cold water draws.

5. *Hot Water Distribution System and Heating System Interaction*
The hot water piping in unit 1 holds approximately 20 pounds of water. If the pipes are filled with 120 ^{o}F water and allowed to cool to 70 ^{o}F about 1000 Btu of heat is transferred to the home. As demonstrated in the co-heating test, the heat loss from this unit is about 160 W/^{o}C or about 300 Btu/hr ^{o}F. When it is 0 ^{o}F outside and 70 ^{o}F inside the heat loss is about 21,000 Btu/hr. Under these conditions the maximum contribution to space heating from 20 pounds of water cooling in the plumbing is about 5% if it cools in about an hour. Therefore we do not expect the water use to have a large interaction with the space heating system.

Infiltration/Ventilation Testing

1. *Blower Door Testing*

We used a blower door in each unit to test the air leakage from the units to the outside and between units. Blower door testing consisted of both single point and multipoint testing. For the single point tests the homes were depressurized to 50 Pa. For the computer-controlled multipoint tests 100 data points were taken at pressures between 15 Pa and 50 Pa. This data was used to calculate the Equivalent Leakage Area (ELA) and the exponents for an exponential curve fit. The measured ELA will be used in the simulations of the homes.

The complete set of results of the multipoint tests is given in Table 6. The results shown in red are those that will be used as input to the computer simulations of the two units. The infiltration was measured to be 4.1 ACH at 50 Pa in unit 1, 4.2 ACH at 50 Pa in unit 2, and 3.2 ACH at 50 Pa in unit 3. This indicates good air sealing of the building envelope. Infiltration rates of nearly half these levels have been measured in very tight homes. These very tight homes tend to have less geometric complexity than the Solar Row homes.

For reference, the ventilation rates required by ASHRAE 62.2 are given below:

$$Q_{fan} = 0.01A_{floor} + 7.5\,(N_{br} + 1)$$

Where : Q_{fan} = fan flow rate, cfm
A_{floor} = floor area, ft^2
N_{br} = number of bedrooms

Units 1 & 3: $Q_{fan} = 0.01(2287) + 7.5\,(3 + 1) = 53$ cfm (~.17 ACH)
Unit 2. $Q_{fan} = 0.01(1700) + 7.5\,(2 + 1) = 40$ cfm (~.17 ACH)

This includes a default credit for ventilation provided by infiltration of 2 cfm/100 ft^2 of occupiable floor space. ASHRAE 62.2 states that when infiltration is measured to be above the default rate, the ventilation requirements can be reduced by half the excess above the default rate. These default rates are given below for both units:

Units 1 & 3. Default rate = (2 cfm/100 ft^2)(2287 ft^2) = 46 cfm
Unit 2. Default rate = (2 cfm/100 ft^2)(1700 ft^2) = 34 cfm

When the natural infiltration is above these default rates, the home may be overventilated. To completely eliminate the need for mechanical ventilation in any given hour, the natural infiltration needs to be the default rate plus twice the required ventilation rate. For units 1 and 3, this occurs at a natural infiltration rate of 152 cfm. For unit 2 this occurs at 114 cfm.

We estimated the hourly infiltration for a typical year using the measured ELA, Boulder TMY2 data, and thermostat setpoints of 71 F for heating and 76 F for cooling. We applied the Lawrence Berkeley Laboratory infiltration model presented in the ASHRAE Handbook of Fundamentals. The results are shown in Figures 16 and 17. These figures show the predicted typical hourly infiltration rate for an entire year. The color of each slice represents the natural infiltration rate during that hour. Along the x-axis is each day of the year. The hour of the day is represented on the y-axis.

The natural infiltration never exceeds 152 cfm in unit 1 and exceeds 114 cfm in unit 2 for only 1 hour of the year. However, the ASHRAE 62.2 default infiltration rate is exceeded 85% to 87% of the year in both units.

Table 6. Multipoint Blower Door Results.

Test Num	Date	Conditions	Unit	Set-up	Flow @50 Pa (cfm)	Accuracy in Flow @50 Pa (± %)	EqLA (in2)	Accuracy in EqLA (± %)	ELA (in2)	Accuracy in ELA (± %)	Flow Coefficient c	Accuracy in Flow Coefficient c (± %)	Exponent n	Accuracy in Exponent n	Correlation coefficient r2	ACH @50 Pa	ACH* "Average" (SG Model)
1	12/8/2007	relatively still	1	Only dryer vent taped	2232	0.3	257.8	0.7	146.1	1.3	230.6	2.1	0.580	0.006	0.99970	6.6	0.30
2	**12/8/2007**	**relatively still**	**1**	**Dryer vent and Whole house fans taped**	**1402**	**0.5**	**148.8**	**1.3**	**80.4**	**2.2**	**118.0**	**3.6**	**0.633**	**0.010**	**0.99925**	**4.1**	**0.19**
3	12/8/2007	relatively still	1	Dryer vent, whole house and exhaust fans taped	1297	0.7	126.7	1.9	65.3	3.2	89.2	5.3	0.684	0.015	0.99863	3.8	0.18
4	12/8/2007	relatively still	1	Same as previous with a door open in unit 2	1317	0.9	132.2	2.4	69.2	4.0	96.8	6.5	0.667	0.018	0.99779	3.9	0.18
5	12/10/2007	relatively still	1	Whole house and exhaust fans taped	1256	0.2	129.4	0.6	68.7	1.0	98.2	1.6	0.652	0.004	0.99987	3.7	0.17
6	12/10/2007	relatively still	1	Whole house and exhaust fans taped	1276	1.0	113.6	2.7	55.5	4.6	70.0	7.4	0.742	0.021	0.99767	3.8	0.17
7	12/10/2007	relatively still	1	Same as previous with a door open in unit 2	1283	0.6	137.0	1.8	74.3	3.1	109.5	5.0	0.629	0.014	0.99856	3.8	0.17
8	12/10/2007	relatively still	1	Same as previous with a door open in unit 2 - 2	1264	0.3	136.3	0.9	74.3	1.6	110.4	2.6	0.623	0.007	0.99960	3.7	0.17
9	12/10/2007	relatively still	2	Whole house and exhaust fans taped - damaged blower	1007	1.2	81.2	3.8	37.5	6.3	43.4	10.2	0.804	0.028	0.99600	3.0	0.14
10	12/10/2007	relatively still	2	Whole house and exhaust fans taped - damaged blower - 2	987	1.0	87.3	3.0	42.5	5.0	53.3	8.1	0.746	0.022	0.99700	2.9	0.13
11	12/10/2007	relatively still	2	Dryer vent, whole house and exhaust fans taped	1079	0.3	106.5	0.8	55.2	1.3	76.0	2.1	0.678	0.006	0.99977	4.2	0.19
12	12/10/2007	relatively still	2	Dryer vent, whole house and exhaust fans taped - 2	1076	0.3	102.2	1.0	51.8	1.6	69.1	2.6	0.702	0.007	0.99967	4.1	0.19
13	12/10/2007	relatively still	2	Same as previous with a door open in unit 1	1077	0.3	100.5	0.9	50.4	1.5	66.1	2.4	0.713	0.007	0.99974	4.1	0.19
14	12/10/2007	relatively still	2	Same as previous with a door open in unit 1 -2	1080	0.5	102.3	1.5	51.8	2.5	68.9	4.0	0.703	0.011	0.99925	4.2	0.19
15	12/10/2007	relatively still	2	Same as previous with a door open in unit 1 and 3	1090	0.7	103.6	1.8	52.6	3.0	70.1	4.9	0.701	0.014	0.99887	4.2	0.19
16	12/10/2007	relatively still	2	Same as previous with a door open in unit 1and 3 -2	1077	0.4	104.1	1.2	53.3	2.0	72.2	3.2	0.691	0.009	0.99950	4.1	0.19
17	12/17/2007	relatively still	2	Dryer vent and whole house fan taped	1092	0.7	107.9	1.7	56.0	3.0	77.2	4.8	0.667	0.014	0.99879	4.2	0.19
18	12/17/2007	relatively still	2	Dryer vent and whole house fan taped -2	1097	0.5	108.6	1.3	56.4	2.3	77.9	3.7	0.676	0.010	0.99931	4.2	0.19
19	**12/17/2007**	**relatively still**	**2**	**Dryer vent and whole house fan taped - 3**	**1091**	**0.3**	**108.4**	**0.7**	**56.4**	**1.3**	**78.1**	**2.1**	**0.674**	**0.006**	**0.99978**	**4.2**	**0.19**
20	2/26/2008	relatively stil	3	Dryer vent, OA air for HRV taped	1109	0.5	119.2	1.4	64.8	2.3	96.2	3.8	0.625	0.011	0.99910	3.3	0.15
21	2/26/2008	relatively stil	3	Dryer vent, OA air for HRV taped - 2	1109	0.6	114.5	1.8	60.9	3.0	87.2	4.8	0.650	0.013	0.99900	3.3	0.15
22	2/26/2008	relatively stil	3	Dryer vent, OA air for HRV taped, whole house fans taped	1093	0.6	113.0	1.8	60.2	3.0	86.3	4.8	0.649	0.013	0.99900	3.2	0.15
23	**2/26/2008**	**relatively stil**	**3**	**Dryer vent, OA air for HRV taped, whole house fans taped**	**1084**	**0.5**	**116.1**	**1.3**	**63.100**	**2.2**	**93.3**	**3.5**	**0.627**	**0.010**	**0.99930**	**3.2**	**0.15**
24	2/27/2008	relatively stil	3	pressurization, whf taped	1457	0.6	141.3	1.6	72.5	2.7	98.3	4.4	0.689	0.012	0.99910	4.3	0.20
25	2/28/2008	relatively stil	3	pressurization, whf untaped	1487	0.5	144.0	1.6	73.8	2.7	100.1	4.4	0.690	0.012	0.99910	4.4	0.20

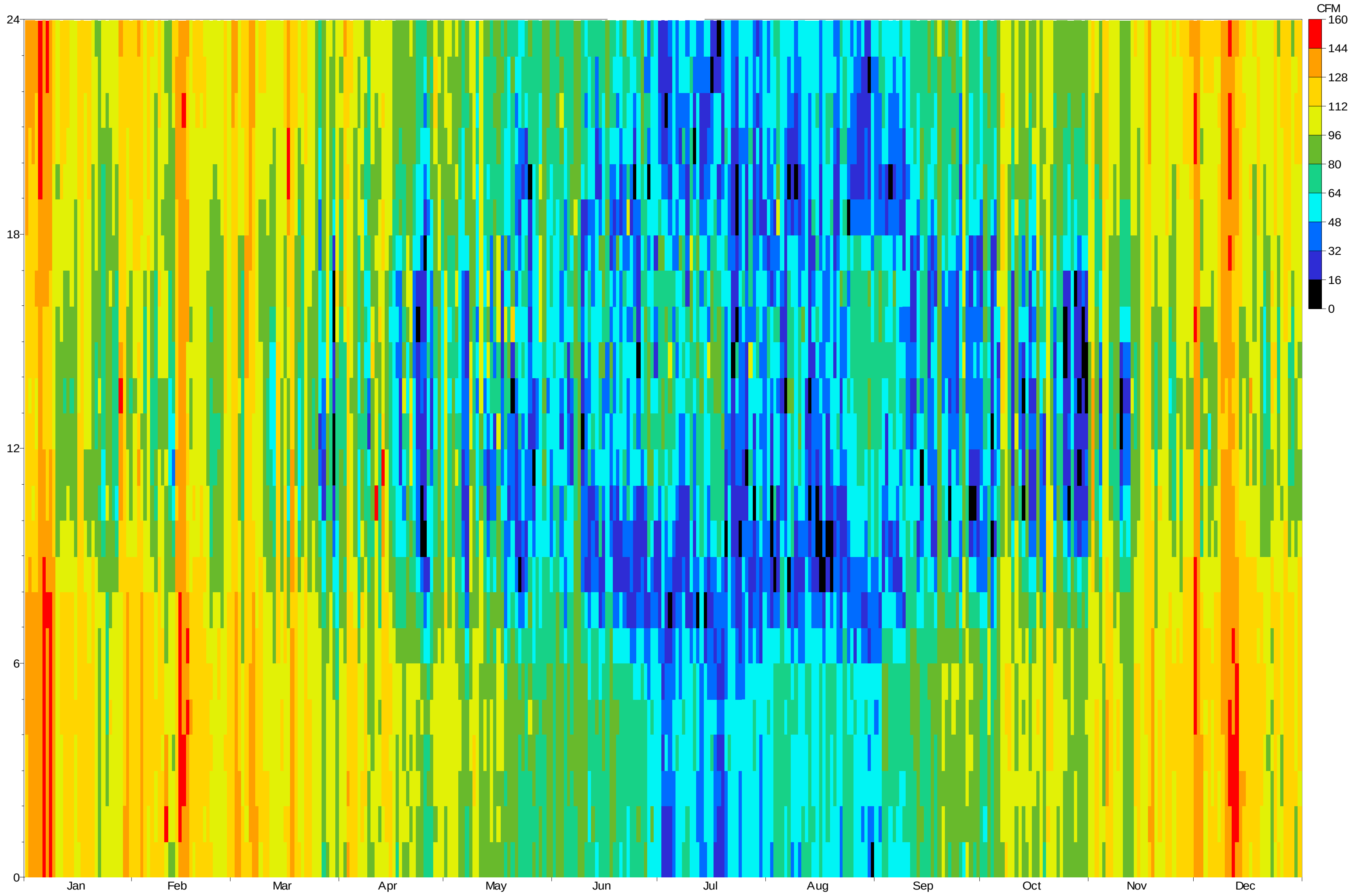


Figure 16: Typical hourly natural infiltration for unit 1

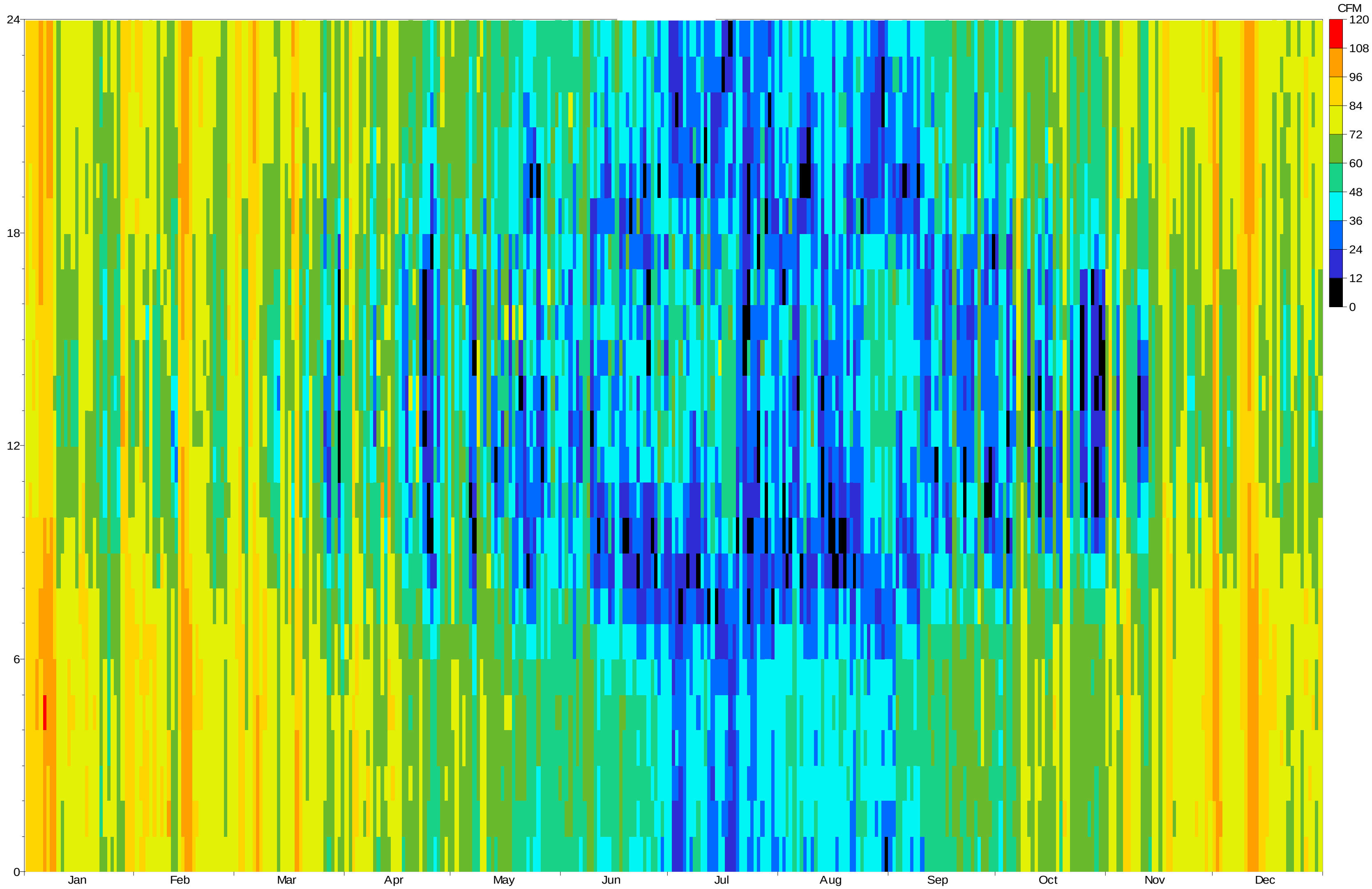


Figure 17: Typical hourly natural infiltration for unit 2

To get a qualitative idea of the importance of leakage between the units using a single blower door we tested each unit with all doors closed in the adjoining unit and with a door open in the adjoining unit. Substantial differences in these two measurements would indicate that leakage between the units is significant. Two repetitions were performed for each condition. In each case, the leakage did indeed increase when the door in the adjacent unit was opened. However, the increases in the average leakage were quite small (< 0.1%) and were smaller than the variation between repetitions under identical conditions. These tests suggested leakage between the units but were not conclusive.

To further investigate the leakage between the units we installed blower doors in both units. Using single-point tests we tested unit 1 with and without unit 2 depressurized to the same pressure. This was repeated at 50 Pa, 30 Pa, and 20 Pa. Depressurizing both units the same equalized the pressure between units thereby removing any driving force for leakage. The difference in measured leakage between these two tests is the leakage between the units at 50 Pa. The results of these tests are given in Tables 7 and 8.

Table 7: Blower door results with and without adjacent unit depressurized for units 1 and 2.

	Measured leakage (cfm)			
Pressure	**Without unit 2 depressurized**	**With unit 2 depressurized**	**Difference**	**Percent Difference**
50 Pa	1285	1086	199	15%
30 Pa	915	760	155	17%
20 Pa	665	560	105	16%

Table 8: Blower door results and without adjacent unit depressurized for unit 3.

	Measured leakage (cfm)		
Pressure	**Without adjacent unit depressurized**	**Depressurization in adjacent unit equal to that in Unit 3**	**Percent Difference**
50 Pa	1100	750	**32%**
40 Pa	930	665	**28%**
30 Pa	775	545	**30%**
20 Pa	580	400	**31%**

The area of the party wall between the units represents about 25% of the total wall and ceiling area of unit 1. For units 1 and 2 the party wall leakage is less than 25% of the total leakage we can surmise that the party wall has somewhat less leakage area per square foot than the exterior walls and ceiling. For unit 3 and it's adjacent unit, the party wall leakage is greater than 25%, indicated a larger contribution to leakage for those units. No obvious area leaks were noticed in the unit 3 duplex. The differences between the two sets of adjacent units are likely due to construction differences. However, the leakage through the party wall may be significant depending on the pressure difference between the units.

Continuing our investigation of the leakage through the party wall we measured the pressure differences between units 1 and 2 and between unit 1 and the outside while operating exhaust fans in both units. The pressures were measured in the living room of both units. The results of this investigation are shown in Figure 18. Most of the sharp spikes in the figure are exterior door openings in the units. In points 1-4 of the figure exhaust fans are operated in unit 2. In points 6-9 exhaust fans are operated in unit 1. Note that the pressure difference between unit 1 and the outside is about 7 Pa. This represents the driving force for natural infiltration on the kitchen/living room level. As fans in unit 2 are switched on the pressure difference between the units increases. When 3 of the fans are turned on the pressure difference between the units is about the same magnitude as the pressure difference between unit 1 and the outside. Each unit has 3 bathroom exhaust fans, laundry closet exhaust fan, a stove exhaust fan and a clothes dryer. Depending on how these are operated in adjacent units it is reasonable to expect that the infiltration driving force between the units may be equal to or greater than the infiltration driving force to the outside. It is reasonable to expect a significant air exchange between units under these conditions.

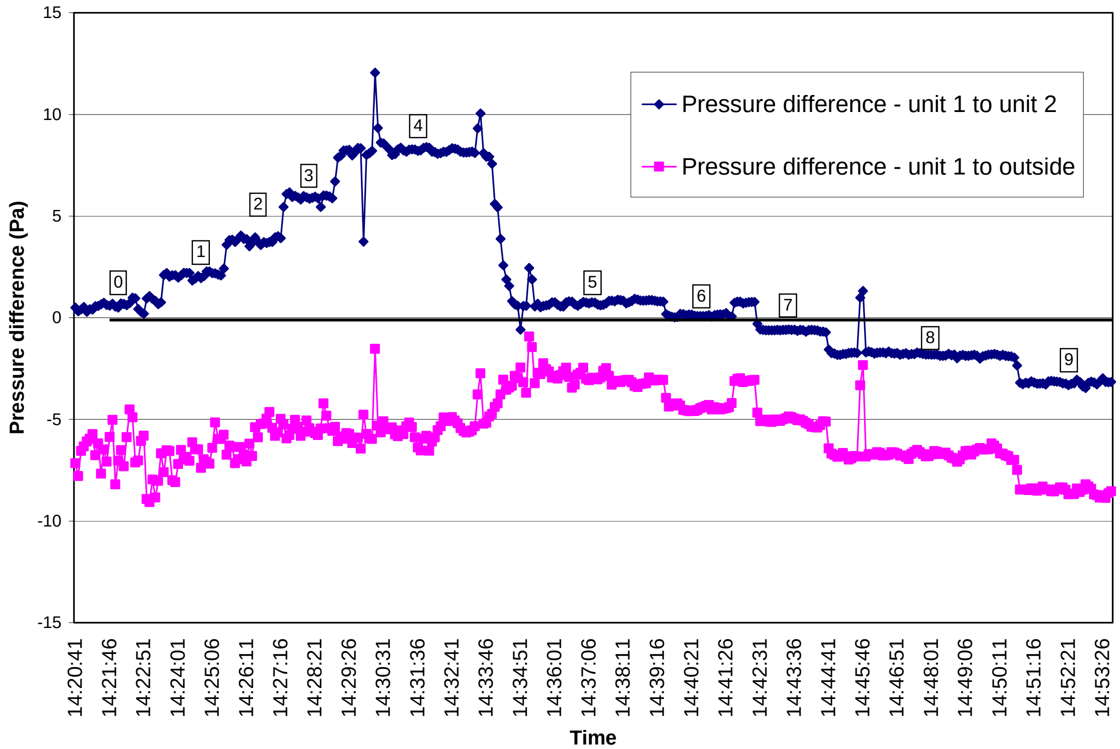


Figure 18: Pressure differences between units 1 and 2 and from unit 1 to the outside

Explanation of points on the graph
0 – No exhaust fans in either unit are operating
1 - Unit 2: east bath fan on
2 - Unit 2: east bath and laundry room fans on
3 - Unit 2: east bath, laundry room, and west bath fans on
4 - Unit 2: east bath, laundry room, west bath, and powder room fans on
5 - No exhaust fans in either unit are operating
6 – Unit 1: powder room fan on with fan grill taped off
7 - Unit 1: powder room fan on tape removed
8 - Unit 1: powder room, master bath fans on
9 - Unit 1: powder room, master bath, 2nd bath fans on

2. *Exhaust Fan Flow Test*

The flow of each exhaust fan, shown in Table 9, was measured using a flow hood on December 1, 2007. During the test there was a light breeze outdoors. The values given represent an estimated time average of the instantaneous flow. The instantaneous flow varied by several cfm. The fans were operated one at a time. The fans in the east (master) bath and the laundry room of each unit are equipped with programmable timers.

Table 9: Measured exhaust fan flows

Location of Exhaust Fan	Unit 1	Unit 2
1st floor 1/2 bath	68 cfm	74 cfm
Laundry	**41cfm**	78 cfm
2nd floor East (Master) Bath	75 cfm	80 cfm
2nd floor West Bath	82 cfm	82 cfm

The results are within expectations with the exception of the laundry room in unit 1 (shown in bold).

Energy Logic reported that the intended operation of the ventilation system in unit 1 is to run each of the two timer-equipped exhaust fans for 9.5 hours daily. If the laundry closet fan were operating as expected at about 75 cfm, the daily average flow rate for this approach would be 59 cfm. This is very close to the 53 cfm suggested by ASHRAE 62.2. With the laundry bath exhausting at only 41 cfm, the daily average flow rate drops to 46 cfm.

With no fans operating the stack effect drives natural infiltration. The stack effect depressurizes the lower floors of the home and pressurizes the upper floors, causing air flow into the lower floors and out of the upper floors. This effect is exacerbated by the tall vertical nature of these units. The exhaust fan ducts are designed to prevent air from entering the buildings when they are not in operation. However, three fans are located on the top floor which has air exiting the building under natural infiltration. Using a flow hood we measured the air movement through the exhaust fan grills in unit 2 with no fans operating. These measurements were done on December 15, 2007 with an outdoor temperature of about -3 ^{o}C. As expected, there was no flow through the grill of the fan in the powder room. Because this room is on a lower level, air would be trying to enter the building – the flap in the exhaust duct prevents flow in this direction. We measured a flow of 11 cfm through the exhaust fan grills in the east and west bathrooms. We would expect the same air to be leaving through the laundry exhaust fan grill, but our equipment could not fit behind the washer/dryer that was already installed. Assuming 11 cfm were exiting the building through the laundry exhaust fan grill, a total of 33 cfm were leaving the building through the upstairs exhaust fan ducts. This leakage goes unaccounted for in standard air leakage testing because blower doors are typically used to depressurize the whole building.

3. *Tracer Gas Testing*

A series of multi-point tracer gas tests was performed in both units during the December test period. The results of these tests primarily address Research Question 2 and characterize the hourly air exchange rate of each house during cold weather.

The tracer gas test involves releasing a small amount of sulfur hexafluoride (SF6) inside the house and measuring the change in SF6 concentration over time. The rate of decay of the concentration is used to calculate the air exchange rate. A Bruel and Kjaer (B&K) model 1302 photo-acoustic spectrometer is used to measure the SF6 concentration. A

B&K model 1303 multi point sampler is used to draw an air sample from up to six points around the house for analysis with the 1302 analyzer. Figure 19 shows a photograph of the tracer gas system installed in unit 1. In unit 1, there are six sample points including the basement, living room, second floor, master bedroom, northwest bedroom, and southwest bedroom. Unit 2 has similar sample locations, except that there are only two bedrooms. For these tests, the time interval between samples was 2 minutes, with a complete cycle through the 6 sample points taking 12 minutes. An entire tracer decay test for these houses lasted between 6 and 12 hours, depending on the actual air exchange rate.

Figure 19: Photo of tracer gas set-up in unit 1.

For all of the tracer gas tests intended to measure natural infiltration with results expressed in air changes per hour (ACH), the SF6 concentration in the house is intended to be uniform from room to room. Several fans are used to enforce the well-mixed conditions, moving air within each room as well as from floor to floor. In these four story units, the concentration tends to stratify under the strong influence of the stack effect. Temporary destratification fans were installed to move about 600 CFM from the top floor to the basement to achieve good mixing.

Table 10 summarizes the tracer gas test results averaged for each test. In unit 1, the air exchange rate varies from 0.32 ACH to 0.38 ACH and is generally correlated with the temperature difference between inside and outside. In Unit 2 there is a similar correlation with inside-outside temperature difference with the air exchange ranging from 0.22 ACH to 0.36 ACH. These results are consistent with the natural infiltration estimates based on the equivalent leakage data from the blower door test.

Table 10: Air exchange rate for each tracer gas test.

Unit	Test number	Start Day	Start Hour	End Day	End Hour	Delta T, F	Avg ACH
1	1	344	17	345	8	48.7	**0.38**
1	2	345	18	346	6	55.9	**0.38**
1	3	346	11	346	17	43.4	**0.34**
1	4	346	18	347	7	47.0	**0.32**
1	5	347	8	347	15	48.0	**0.34**
1	6	347	20	348	2	54.4	
2	1	348	12	348	20	53.2	**0.31**
2	2	348	20	349	8	58.6	**0.36**
2	3	349	12	349	21	51.0	**0.28**
2	4	349	22	350	8	47.5	**0.29**
2	5	350	9	350	19	38.7	**0.22**
2	6	350	19	351	7	46.3	**0.26**

The time series data for the measured ACH in Unit 1 is displayed in Figure 20. The multiple sample points show insignificant variation from room to room, implying that good mixing was achieved. During each test period, there was generally not much change in the measured ACH over time, indicating relatively stable weather conditions. The operating conditions for all of these tests were the same with all interior doors open, mixing fans operating continuously, exhaust fans off and inside temperature controlled using electric heaters.

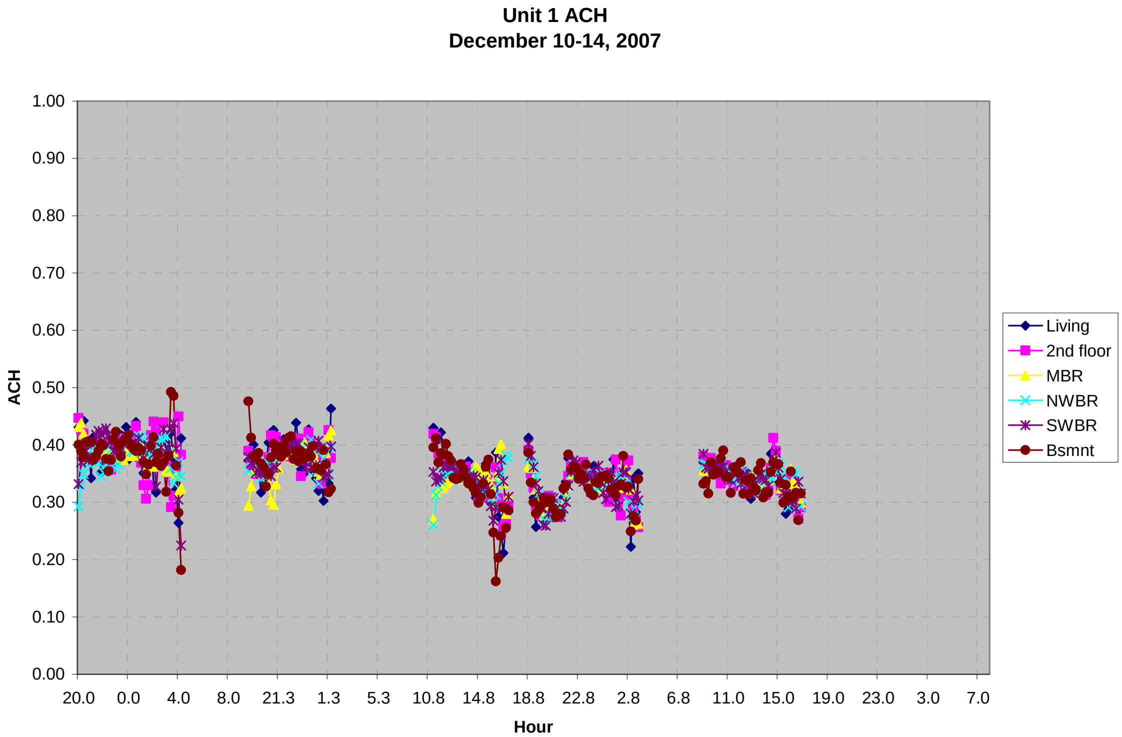


Figure 20: Air exchange rate measurements for Unit 1.

Figure 21 displays the measured ACH time series data for Unit 2. The results for these tests also show that there is insignificant variation in ACH from room to room and that weather conditions are generally stable during a particular test period. The test conditions are the same as for tests in Unit 1 (doors open, mixing fans on, no ventilation, electric heat) except for test number 4 near the middle of the graph, which includes a period of operation of the exhaust fan. The air exchange rate increases from about 0.32 ACH to about 0.42 ACH during the period of exhaust fan operation.

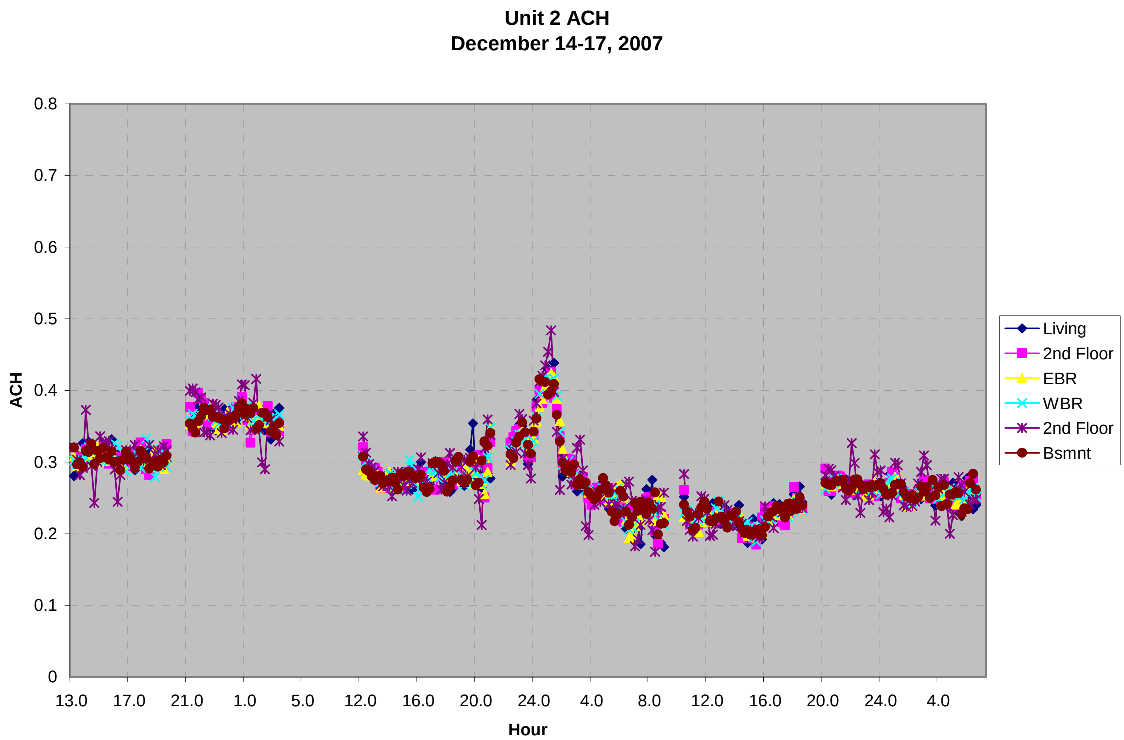


Figure 21. Air exchange rate measurements for Unit 2.

A more extensive evaluation of the ventilation system in each house was originally planned for the Solar Row houses. These tests would have attempted to characterize the room to room variation in reciprocal age of air and to evaluate certain details of the multi-zone test protocol. (See Research Question 3.) The relatively high leakage area of these units determined using the Blower Door makes them less well suited for multi-zone evaluation of the ventilation system because under the cold conditions during the test period variations in natural infiltration can be larger than the variations due to operation of the ventilation system. The four story floor plan of these units is also less desirable for multi-zone evaluation because of the room to room variation caused by the stack effect during cold weather.

The tracer gas decay number six in Unit 1 shown in Figure 22 is an example of the multi-zone variation in concentration. The concentration in the basement zone decays much faster than the concentration on the top floor bedrooms, indicating that fresh air enters at the lowest level and exits at the top. This test was not analyzed to determine reciprocal age of air because adequate initial mixing could not be achieved.

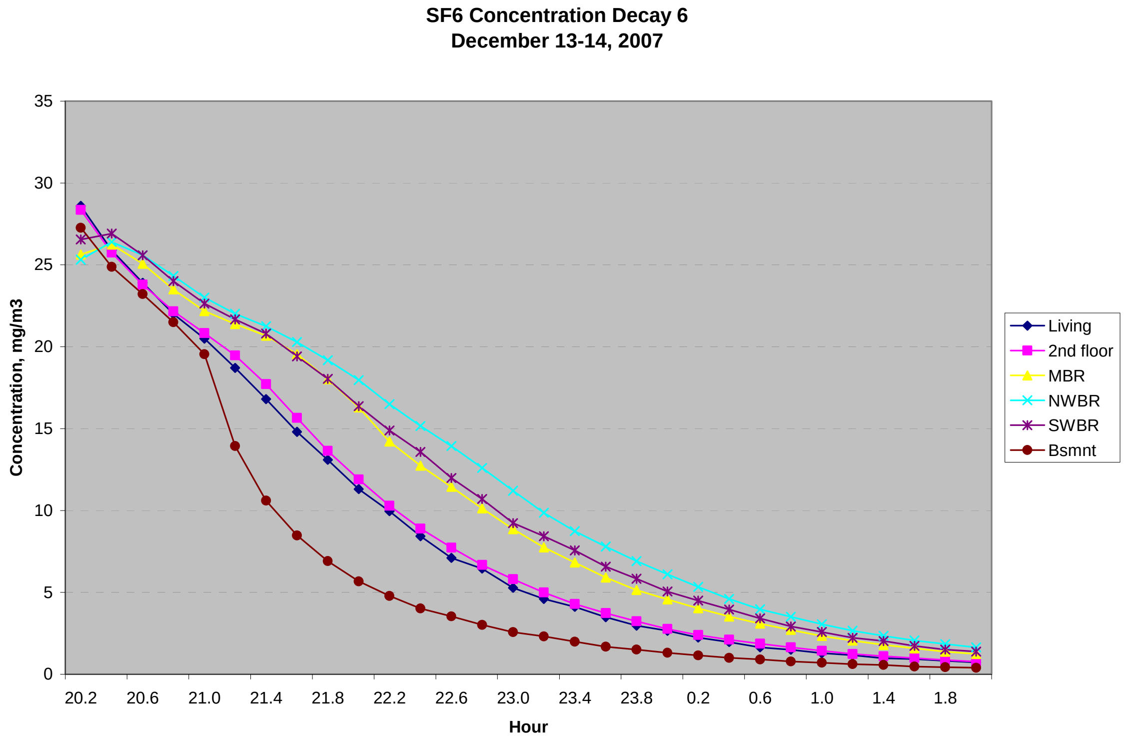


Figure 22. Unit 1, decay 6 showing the room to room variation on concentration.

Air handler flow rate

The air handler flow rate for unit 3 was measured using a calibrated flow plate from TrueFlow. The flow plate replaces the air filter in the return plenum. The flow plate uses a separate measurement of system pressure elsewhere in the system to correct for the difference in flow due to the flow plate as compared to the air filter in place. Measurements of pressure were taken in a dead corner of the supply plenum. The results of the measurements were in accordance with expected flow rates, and are summarized in Table 11.

Table 11: Air handler flow rates for unit 3.

	Supply plenum pressure with air filter (Pa)	Supply plenum pressure with flow plate (Pa)	Flow plate pressure difference (Pa)	Calculated flow rate (CFM)
Start-up	198	199	21.2	530
Normal operation	96	99	9.4	350

Lighting Inventory

We inventoried the installed light bulbs in both units on December 15, 2007. Overall we found about 35% of the installed bulbs were fluorescent tubes or compact fluorescent (CFL) bulbs. The total wattage of the fluorescent lighting was about 380 Watts in unit 1 and 280 Watts in unit 2. The incandescent lights (including halogens) totaled about 2400 Watts in each unit. Some of these fixtures are specialty fixtures that may not accept a CFL bulb. For example, the bathrooms each have 300 W light fixtures with specialty lamps over the sinks. However, if fluorescent or CFL fixtures were chosen throughout the homes, the same lighting levels could be achieved with about 1500 to 1800 Watts less installed wattage. We believe some of the incandescent lights in place during this inventory were later replaced by CFLs, but the lighting inventory has not been repeated.

Long-term Monitoring Plan and Hourly Simulation

A data acquisition system that measures hot water energy flows, electrical energy flows and weather conditions was installed for both units. We will collect comprehensive energy consumption data in all three units for a period of at least one year, beginning on the first day of the month after occupancy. We will also create detailed computer simulations of all three units using DOE2 and of the hot water distribution system using TRNSYS. The results of these simulations will be compared to the monitored performance. The simulations can then be used to predict the effect of design changes on the energy performance of the units.

Discussion of Results

The insulation levels, heating equipment efficiency, solar thermal system and PV system will all contribute to a very high level of energy efficiency in these units. We agree with the Energy Logic analysis that these homes are not likely to achieve zero energy performance with standard assumptions about occupant choices and behavior. Our computer simulations will be completed in the coming weeks and will allow us provide more detailed expectations … again with standard assumptions about occupant choices and behavior. Typically, the overall energy use in higher efficiency homes is more sensitive to occupant choices and behavior because the appliance and plug loads for very high performance homes can be more than half of the total energy use. These loads are typically out of the control of the building designer and vary considerably with different occupants. Therefore the actual performance of these homes will be strongly dependent on the occupants. Our monitoring effort will be able to shed some light on these effects.

Row housing has an inherent efficiency advantage because there is less exterior wall area per ft^2 of living space. The energy advantage of the core units is clearly demonstrated by the results of the co-heating test. Unit 2 requires about 20% less energy to heat per ft^2 of living space than unit 1 at night. During sunny days, the solar gain in unit 1 can close this gap. Of course, the north end unit will likely always require more space conditioning energy per ft^2 of living space than the core units.

Many of the south-facing windows in unit 1 have no overhangs. In the summer, solar gains through these windows will lead to higher cooling energy requirements. Although some site shading is provided by the adjacent building, properly sized overhangs on all south windows would improve the energy performance of the building. We plan to quantify this effect through simulations.

The nominal R-values for these units are quite good. However the high density of framing members will provide a thermal bypass in some areas. In addition, insulation in the floors of the numerous bump-outs in the façade could be improved. This, along with experience from zero energy homes in the U.S. and Passivhaus in Europe indicate that performance benefits can be achieved by striving for designs that are architecturally interesting while geometrically simple.

The vertical nature of row housing presents challenges for natural infiltration. The infiltration rate depends not only on leakage areas (as measured by the blower door) but also on the indoor/outdoor pressure difference driving the leakage. In a taller home, these pressure differences are higher than in a shorter home. Therefore a higher level of air sealing is required to achieve low infiltration rates. In the case of Solar Row, this effect is further exacerbated by the presence of three exhaust fans on the top floor. Because the top floor is pressurized by the stack effect, these fans will leak a substantial amount of air. The leakage from these fans does not show up during blower door testing which is typically done only under depressurized conditions.

Because this short-term testing occurred in the winter air conditioning was not tested and is not included in this report. However SEER13 mini split AC systems were installed in both units. These units are of code minimum efficiency and seem out-of-synch with the beyond-code efficiency levels of the shell and heating equipment. The comparatively low efficiency of these units will reduce the fraction of total home energy met by the PV system and make the zero energy goal more difficult to achieve.

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