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RDI Development: Wisdom Way Solar Village, Greenfield, Massachusetts Field Test Report

Technical Report
NREL/TP-550-45865
May 2009

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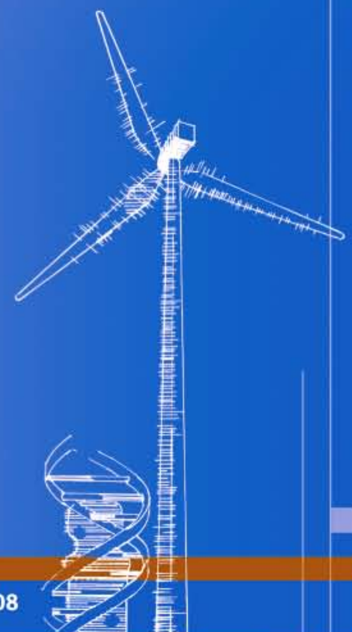

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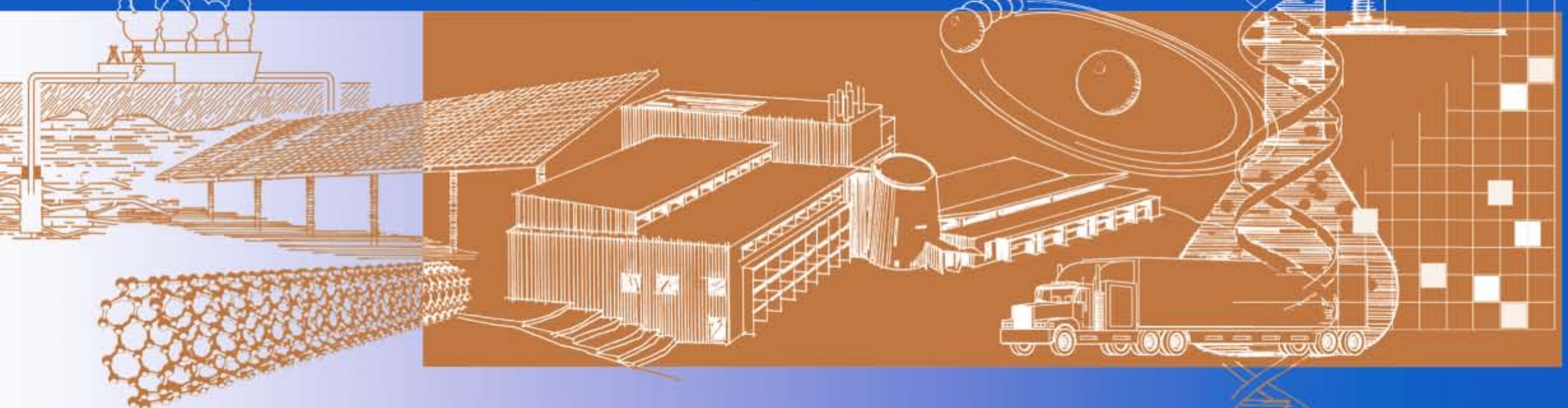

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Executive Summary

On February 16–21, 2009, the National Renewable Energy Laboratory (NREL), Mountain Energy Partnership (a subcontractor of NREL), and the Consortium of Advanced Residential Buildings conducted short-term field tests on a house in the Wisdom Way Solar Village (G3, community scale, 40% savings level, cold climate). The house design features exceptionally tight construction, highly insulated envelopes, efficient ventilation and space heating design, and on-site renewable energy.

As the technical support for the U.S. Department of Energy Building America, NREL conducted field tests to verify that the prototype houses achieve the energy efficiency goal and maintain indoor air quality and comfort. Specifically, the Wisdom Way field test is targeted at verifying the performance of the point source heating, exhaust fan ventilation, and innovative distribution/transfer fan effectiveness in air and heat distribution.

Field test results showed that the exhaust ventilation fan, in conjunction with a distribution/transfer fan, provided good distribution of ventilation throughout all rooms in the three-bedroom test unit. However, the space heater, in conjunction with the distribution/transfer fan, is not sufficient to distribute the point heating throughout the house. We recommend supplementary heating backup in the upstairs bedrooms in addition to the point source heating system for acceptable comfort conditions.

We also recommend a better air seal gasket on the attic access door; more hot water draw tests when solar water heating systems are brought online, and long-term diagnostic monitoring of the solar water heating systems.

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1.0 Introduction

Wisdom Way Solar Village is being built by RDI Development Inc. in Greenfield, Massachusetts. The village consists of 10 duplexes (20 units total, including two-, three-, and four-bedroom homes. As a G3 community in the U.S. Department of Energy Building America Initiative, the Wisdom Way Solar Village houses are predicted to achieve 40% whole-house source energy savings against the Building America benchmark. The house design features exceptionally tight construction, highly insulated building envelopes, efficient ventilation and space heating designs, and on-site renewable energy.

Table 1 shows design specifications. For a detailed description of the entire project, refer to *CARB 2008 Annual Progress Report (BP1), Appendix X: Cold Climate Case Study – RDI Wisdom Way Solar Village* [1]. (The descriptions of the house and the test unit all refer to the three-bedroom unit in the Lot 10 duplex building, unless specifically mentioned otherwise.)

Table 1. Wisdom Way Solar Village Overall Specifications

Building	Lot 10 duplex
Bedrooms	2, 3, or 4 bedrooms
Floor area	1,392 ft^2 for 3-bedroom units (not including basement)
Construction	
Foundation	Unconditioned basement; R-40 blown cellulose beneath the first floor.
Exterior walls	12-in. double wall (double 2 × 4, 16-in. OC) with R-43 dense-blown cellulose
Windows	Triple-pane low-e, vinyl-framed windows from Paradigm on the north, east, and west elevations; Paradigm double-pane low-e windows (lower cost, higher solar heat gain coefficient) on the south
Ceiling insulation	14-in. blown-in cellulose insulation (R-50+)
Miscellaneous Electrical Loads and Appliances	
Lighting	100% compact fluorescent lamps
Appliances	ENERGY STAR®-rated refrigerator and dishwasher
HVAC	
Ventilation	Efficient bathroom exhaust fan (Panasonic WhisperGreen) operating continuously meeting ASHRAE 62.2
Distribution/transfer fan	Efficient mixing fan (Panasonic WhisperGreen) drawing air from first-floor ceiling and distributing to each second-floor bedroom
Space heating	Sealed-combustion, natural gas-fired, through-the-wall unit heater in first-floor open space; Monitor GF1800, 83% annual fuel utilization efficiency
Space cooling	None
Thermostat	Programmable thermostat on unit heater
Domestic Hot Water	
Water heating	Solar hot water system with backup provided by a Rinnai tankless, natural gas-fired, sealed combustion water heater (0.82 emissions factor)
On-Site Renewable Energy	
Solar thermal	2 (for 2-bedroom units) or 3 (for 3- and 4-bedroom unit) flat-plate 29 ft^2 collectors with 110-gallon storage tanks
Solar electric	3.42-kW photovoltaic (PV) system for 3- and 4-bedroom units; 2.85-kW PV system for 2-bedroom unit

Figure 2 through Figure 4 show exterior views of the duplex (two units—two- and three-bedroom units).

Figure 1. Back south view of the duplex building

Figure 2. Front north view of the duplex building

Figure 3. Adjacent duplex under construction

Figure 4. Hatch door to basement stairway

Figure 5 to Figure 10 show the test unit floor plans and corresponding pictures for the three-bedroom unit. The red dots are tracer gas tests sampling points (see Section 5).

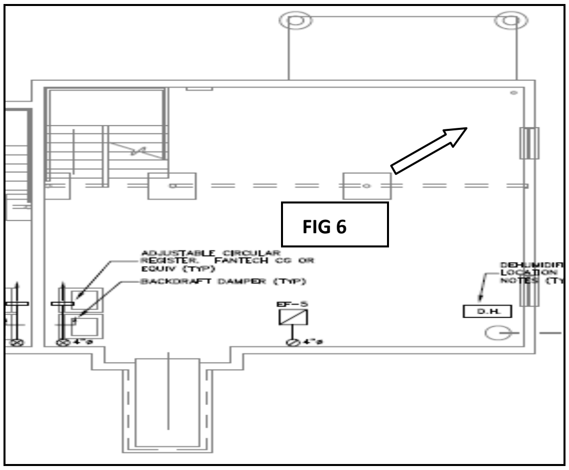

Figure 5. Basement floor plan

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Figure 6. Basement northeast corner domestic hot water setup

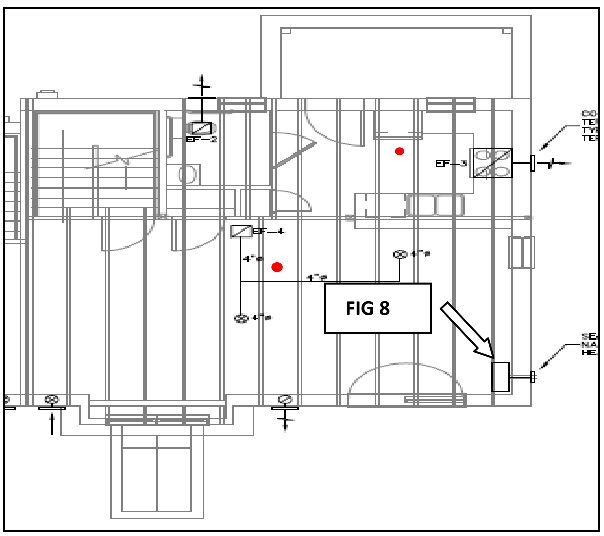

Figure 7. First floor plan

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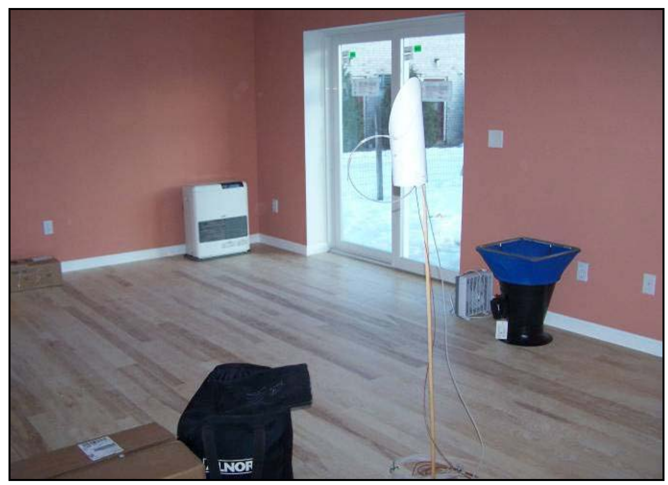

Figure 8. Living room view with space heater

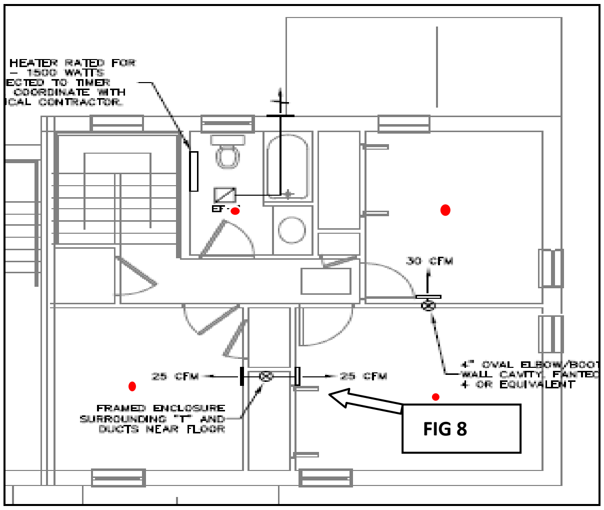

Figure 9. Second floor plan

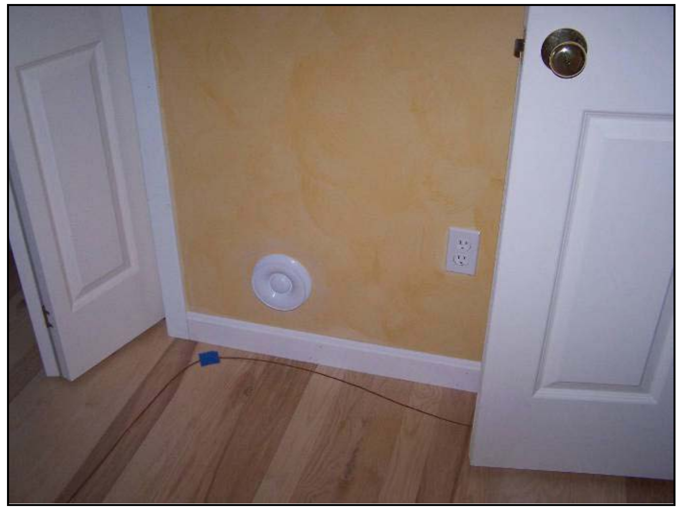

Figure 10. Second floor southeast bedroom diffuser

1.1 Ventilation Design

The mechanical ventilation requirement is achieved by a continuously operated central exhaust fan located in the second-floor main bathroom. This fan has an electronically commutated motor (ECM) and normally operates at low speed. When the occupant is in the bathroom, he or she can flip the wall switch to turn the fan to high speed. The field-tested low-speed flow is 47 cfm @ 6 W; high-speed flow is 72 cfm @ 14 W.

According to ASHRAE 62.2 [2], the mechanical ventilation rates are shown by the following equation:

$$Q_{FAN} = 0.01\ A_{FLOOR} + 7.5 \times (N_{BR} + 1)$$

Where:

Q_{FAN} = fan flow rate, cfm

A_{FLOOR} = floor area, ft^2

N_{BR} = number of bedrooms

Therefore:

$$Q_{FAN} = 0.01 \times 1{,}364 + 7.5 \times (3+1) = 43 \text{ cfm}$$

The continuously operated central exhaust fan for the Wisdom Way Solar Village house meets the requirement of ASHRAE 62.2.

To help with the uniform outside air distribution, the design incorporates a continuously operated distribution/transfer fan recessed under second-floor joists. This fan transfers the first-floor air and distributes it to every second-floor bedroom via 4-in. polyvinyl chloride (PVC) ducts. (The test unit has metal ducts installed. The rest of the community houses switched to PVC ducts for ease of installation with approval from the local building department.) Field-tested total supply flow to the bedrooms is 81 cfm, the first-floor fan grille intake flow is 90 cfm, and the fan power draw is 11 W.

Two additional spot exhaust fans or hookups are installed in the house. The first-floor bathroom exhaust fan, which is controlled with a wall switch, field test flow was at 73 cfm @ 17 W. The kitchen has an opening (taped during test) for range and cook top exhaust.

1.1.1 Exhaust Ventilation Versus Air Cycler – A Side-by-Side Comparison

Table 2 shows a simple calculation that compares the operation of this central exhaust fan with a distribution/transfer fan versus a central fan integrated supply (CFIS) ventilation (33% duty cycle) coupled with exhaust ventilation; specifically, the system used on the BSC Hilton Head Project. The CFIS system uses the central air handler fan for heating, cooling, and ventilation. To reduce the central air handler fan energy consumption, the design allows the central fan to run only one third of the hour when no heating or cooling is available, and supplements the remaining two thirds of the hour with a small bathroom exhaust fan. This ventilation concept is a hybrid of the exhaust ventilation and cycling central fan ventilation.

Table 2. Two Ventilation Systems: Side-by-Side Comparison

RDI House Ventilation System	RDI Exhaust and Transfer Fan Continuously Operated	Hilton Head Ventilation System	CFIS (33% Duty Cycle) and Coupled Exhaust Ventilation
Ventilation (outdoor air) provided (cfm)	47	Ventilation (outdoor air) provided (cfm)	50
Distribution fan (W)	17	CFIS fan mode (W)	120
Exhaust fan power low speed (W)	6	Coupled exhaust fan (W)	6
Exhaust fan power high speed (W)	14	Ventilation only operating hours (total heating and cooling hours)	4,900
Exhaust fan low speed operating hours	8,585	CFIS fan operating time in ventilation only mode (hours)	1,617
Exhaust fan high speed operating hours	175	Exhaust fan operating hours in ventilation only mode (hours)	3,283
Distribution fan kWh/year	149	CFIS fan kWh/year	194
Exhaust fan kWh/year	54	Exhaust fan kWh/year	20
Total Ventilation Fan kWh/year	**203**	**Total Ventilation Fan kWh/year**	**214**

These two systems are comparable and operate efficiently for mechanical ventilation.

1.2 Space Heating Design

Because of the highly insulated envelopes, the Consortium for Advanced Residential Buildings (CARB) used a low-cost system approach for the space heating system. Point source heating scheme is expected to work for this tightly constructed, highly insulated, and small footprint living space.

Space heating for the entire test unit is provided by the living room heater (Figure 7 and Figure 8). The Monitor GF1800 heater has a two-speed fan coupled with two-stage firing. The low-speed fan flow is 133 cfm at 10,200 Btu·h firing output; the high-speed fan flow is 176 cfm at 16,000 Btu·h firing output. The heater remains at low-speed and low-stage firing when the space temperature remains within ±2°F dead band of the set point. The heater adjusts to high-speed and high-stage firing when the temperature dead band widens (±5°F).

During the tests, the first-floor living room temperature set point is 70°F. Natural stack effect will drive the warm air from the first floor to the second floor. The distribution/transfer fan is incorporated to distribute the first-floor warm air to each bedroom. The supply flow rate is 21–24 cfm to each bedroom. The master bathroom has a 500-W baseboard heater that the occupant can turn on for showering. No supplemental heaters are installed in the upstairs bedrooms.

The second-floor bedrooms (where occupants sleep with doors closed) can raise issues for thermal comfort. Of particular concern is the northeast bedroom.

ASHRAE 55 [3] and ACCA Manual RS [4] are referenced for thermal comfort evaluation and compliance.

2.0 Field Test Plans and Research Questions

As the technical support for the Building America program, NREL conducted field tests to verify that the prototype houses achieve the energy efficiency goal and maintain indoor air quality and comfort. Specifically, the Wisdom Way house field test verified the performance of the point source heating, exhaust fan ventilation, and the innovative distribution/transfer fan effectiveness in air and heat distribution.

Research questions were asked about airtightness, indoor air quality, and indoor temperature distributions before the field tests were conducted. These questions are the guidelines behind the field tests. The research questions from the test plan draft follow:

Q.1. What is the effective leakage area (ELA) of each unit as measured with a blower door? How does this change when the adjacent unit is also pressurized (guarded)? Do the ELAs to the adjacent unit and to the outside both meet the design targets? Is the fraction of ELA in the attached wall small enough (<10% of total leakage area) that the Reciprocal Age-of-Air (RAoA) methodology can provide accurate results when only one unit is tested? Approximately how much error is introduced into the RAoA calculations?

Q.2. What is the air leakage of the distribution system? What are the installed flow rates of the ventilation and air distribution fans? What are the supply and exhaust flow rates of the distribution system? What are the power draws of the ventilation and air distribution fans in each operating state? Do all these quantities meet the design targets?

Q.3. What is the hourly air change rate of one unit in the duplex with and without the ventilation system running, as measured using a single-zone tracer gas test? Approximately what fraction is to the outside?

Q.4. What are the temperatures in various rooms throughout the duplex over consecutive 24-hour periods with each condition shown in Table 3? Does a central point in each room meet the ASHRAE Standard 55 comfort recommendations at various times during each test? Are there any noticeable hot or cold spots on interior surfaces, as measured using an infrared (IR) camera? Do temperature differentials between rooms meet ACCA Manual RS guidelines (4°F maximum)?

Table 3. Test Matrix for Measuring Uniformity of Heating and Outside Air Distribution

Case #	Doors	Exhaust Fan	Distribution/Transfer Fan
1	Closed	On	On
2	Closed	On	Off
3	Closed, see Q.5	On	Off
4	Open	On	On

Q.5. Using one unit of the duplex as the test space, what are the differences in outside air distribution (RAoA) throughout, using the operating conditions shown in Table 4? How does the outside air distribution change in Case 3 if a small opening (1 in.^{2}) is created in each bedroom to help control the location of outside air entry?

Q.6. What is the estimated difference in energy use for the installed heating and air distribution system compared to a small central furnace of similar efficiency, with an ECM motor and an AirCycler for air distribution?

Q.7. Does the solar water heating system operate as expected, based on simple commissioning tests?

Q.8. Based on the test results from the BSC Hilton Head project, and the solar domestic hot water (DHW) system design and climate for the RDI project, how often can the occupants expect hot water draws to be unmet by the tankless water heater with solar preheating?

Q.9. What are the heating temperature settings in each unit under occupied conditions?

Q.10. What are the room-to-room temperature differences under occupied conditions? Are the occupants satisfied with the temperature uniformity?

3.0 Blower Door Test

One blower door test was performed in November 2008 on the two- and three-bedroom units. Both guarded (units depressurized to 50 Pa) and unguarded (the two-bedroom unit depressurized to 50 Pa and the three-bedroom unit held at 50 Pa) blower door tests were performed. The concern was to check and ensure minimal leakage between the units through the party wall. From the two-bedroom unit test record, party wall leakage was minimal (see Table 4).

The November blower door test also calculated an ELA @ 4 Pa = 13.7 in.^{2} (guarded) and ELA @ 4 Pa = 13.5 in.^{2} (unguarded) in the two-bedroom unit. The resulting party wall leakage is 0.2 in.^{2} The air leakage between the two units through the party wall is negligible, especially when the adjacent unit is maintained at close temperatures to the test unit. This guarantees the minimal number of errors introduced into RAoA calculations (Research Question Q.1).

Table 4. Blower Door Test Results for Two-Bedroom Unit (Guarded and Unguarded)

House Pressure (Pa)	Unguarded Without Three-Bedroom Unit (Same Pressure Infiltration) (cfm)	Guarded With Three-Bedroom Unit (Same Pressure Infiltration) (cfm)	Difference/Party Wall Leakage (cfm)
60	338	291	48
50	297	257	39
40	253	222	31
20	154	139	14
10	93	88	6

Figure 11. Blower door test setup

In November 2008, the three-bedroom unit was not finished and had some unwanted envelope leakages. Another blower door test was performed on February 16, 2009, for the three-bedroom test unit only (see Figure 11). The central exhaust fan and associated distribution fan were turned off to estimate the airtightness of the envelope without the mechanical ventilation impact.

Figure 12 through Figure 16 are the IR pictures taken during the walkthrough during the blower door test to help detect major leakage areas. Leakages were detected at the attic access door, the first-floor door leading to the basement, and the bathroom exhaust fans. There was also some leakage through walls and window cracks and electrical outlets (see Figure 13 and Figure 16).

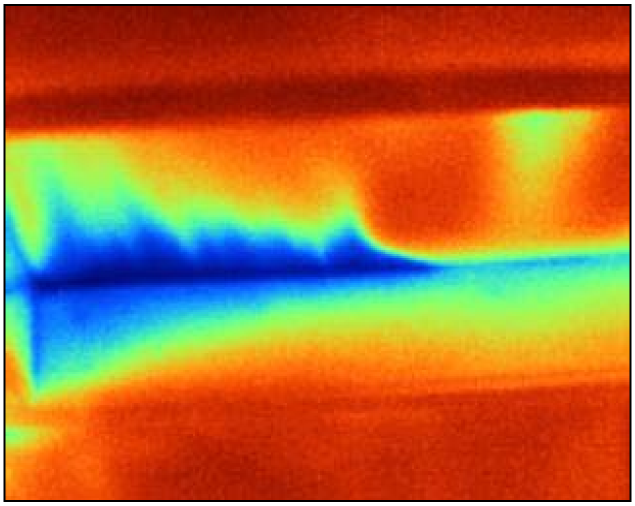

Figure 12. Attic access door during blower door test

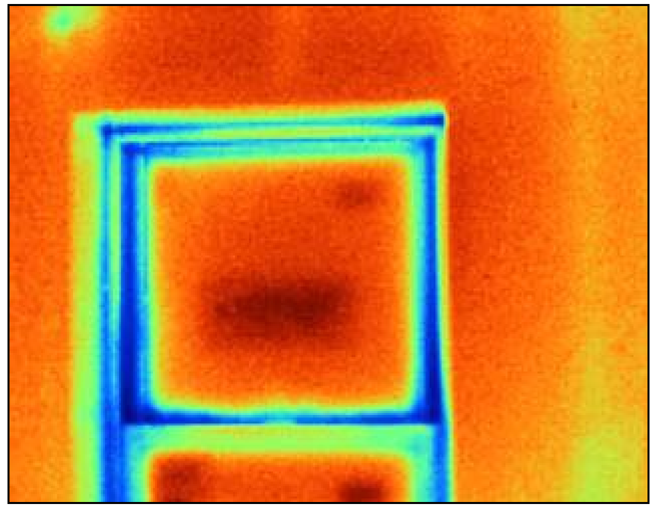

Figure 13. Window frames during blower door test

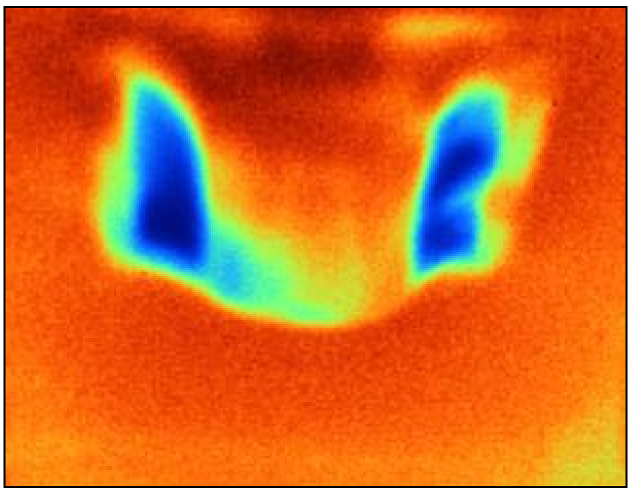

Figure 14. Central exhaust fan during blower door test

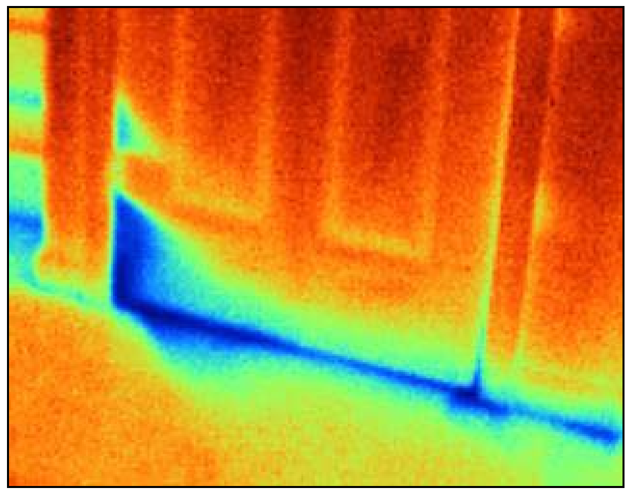

Figure 15. Basement door during blower door test

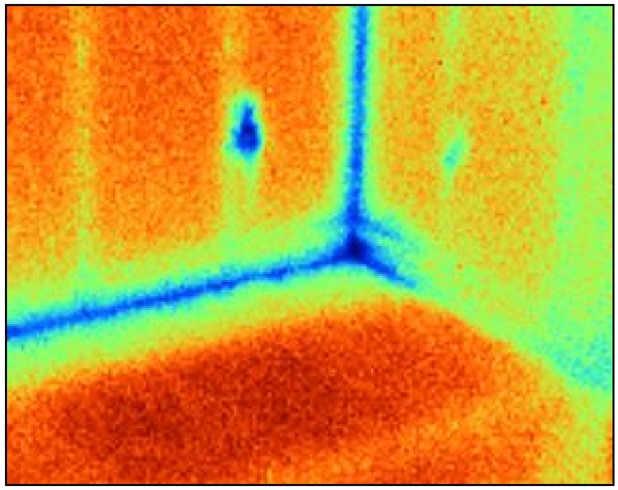

Figure 16. Electrical outlet during blower door test

Table 5 summarizes the blower door test results. According to Pennsylvania Housing Research Center (PHRC) [6] data, a tight house is one that has a natural infiltration air change rate (ACH_{nat}) of less than 0.35. The field test house ACH_{nat} is 0.07. It is exceptionally low.

Table 5. Blower Door Tests Results Calculations

@50 Pa			@ 4 Pa			@10 Pa	@ Average Natural Conditions Year Round
Air Flow	Air Change Rate	ELA (in.^{2})	Air Flow	Air Change Rate	ELA (in.^{2})	EqLA Canada* (in.^{2})	Air Change Rate
CFM_{50}	ACH_{50}	ELA_{50}	CFM_4	ACH_4	ELA_4	$ELA_{10\ Canada}$	ACH_{nat}
273	1.5	22.0	39	0.22	11.2	23.3	0.07

Floor Area A_{flr} = 1,364 ft^2, Envelope Surface Area A_{env}= 4,528 ft^2, Volume V =10,912 ft^2

*EqLA – Equivalent Leakage Area

4.0 Tracer Gas Tests

Five cases of tracer gas field tests were performed to evaluate: the air exchange rate of the entire test unit (Case 0) and the room-to-room distribution of the outside air (Cases 1 to 4). In all cases, the single-tracer concentration decay method [4,5] was used with multiple sampling points. Figure 17 through Figure 20 show the field test setup.

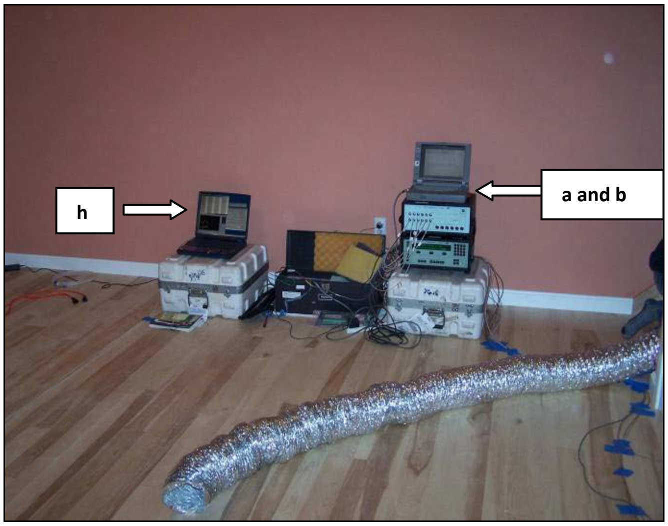

Figure 17. Tracer gas equipment setup

Figure 18. Mixing fan and duct setup

Figure 19. Room sampling stand (southeast bedroom)

Figure 20. Case 3: Introducing 1-in^2 opening

A brief description of the test equipment follows:

a. Gas analyzer

b. Multipoint sampler

c. Tubing for gas sampling, compatible with the multipoint sampler and the tracer gas

d. Wooden stands to position the sampling points near the center of each room
e. Interzonal mixing fans
f. Room temperature sensors
g. Weather station: outdoor temperature and wind speed sensors with datalogger
h. Computer and software compatible
i. Tracer gas (SF 6).

Six sampling points were installed in the central location of the following rooms (see Figure 7 and Figure 9).

- First-floor living room (Living)
- First-floor kitchen (Kitchen)
- Second-floor northeast bedroom (NE BR)
- Second-floor southeast bedroom (SE BR)
- Second-floor southwest bedroom (SW BR)
- Second-floor main bathroom (Bath)

The basement was not dosed or heated during the tracer gas tests. The first-floor door to the basement was closed but not taped. The door is designed with a spring-latch mechanism that minimizes the door undercut gap when the door closed. Figure 15 shows some leakage through the basement door gap during the blower door test. This may introduce some error into our analysis. For now, this is not counted.

The two-bedroom unit homeowner was on vacation during the field test. That unit has temperature setting of 60°–62°F (according to later meeting with homeowner). But the concern for additional error introduced into the test is minimal because the party wall leakage between the two- and three-bedroom units is minimal (0.2 in.^{2}). The party wall is also well insulated with 8–10 in. of cellulose.

4.1 Air Exchange Rate – Concentration Decay Method (Case 0)

The air exchange rate – concentration decay method test began with injecting the tracer gas and mixing it uniformly throughout the house. Then the injection ceased but the interzonal mixing fans ran continuously throughout the measurement period (well-mixed condition). All bedroom doors were left open to help with mixing. A single gas analyzer with tubing to each sampling point was used to monitor the concentration of the tracer gas as it decayed.

The central exhaust ventilation fan was turned on for the first several hours, and then turned off for the remaining test period. Outside air temperatures were 22°–37°F during the test period; the average wind speed was 0.2 mph. Figure 21 shows the test results.

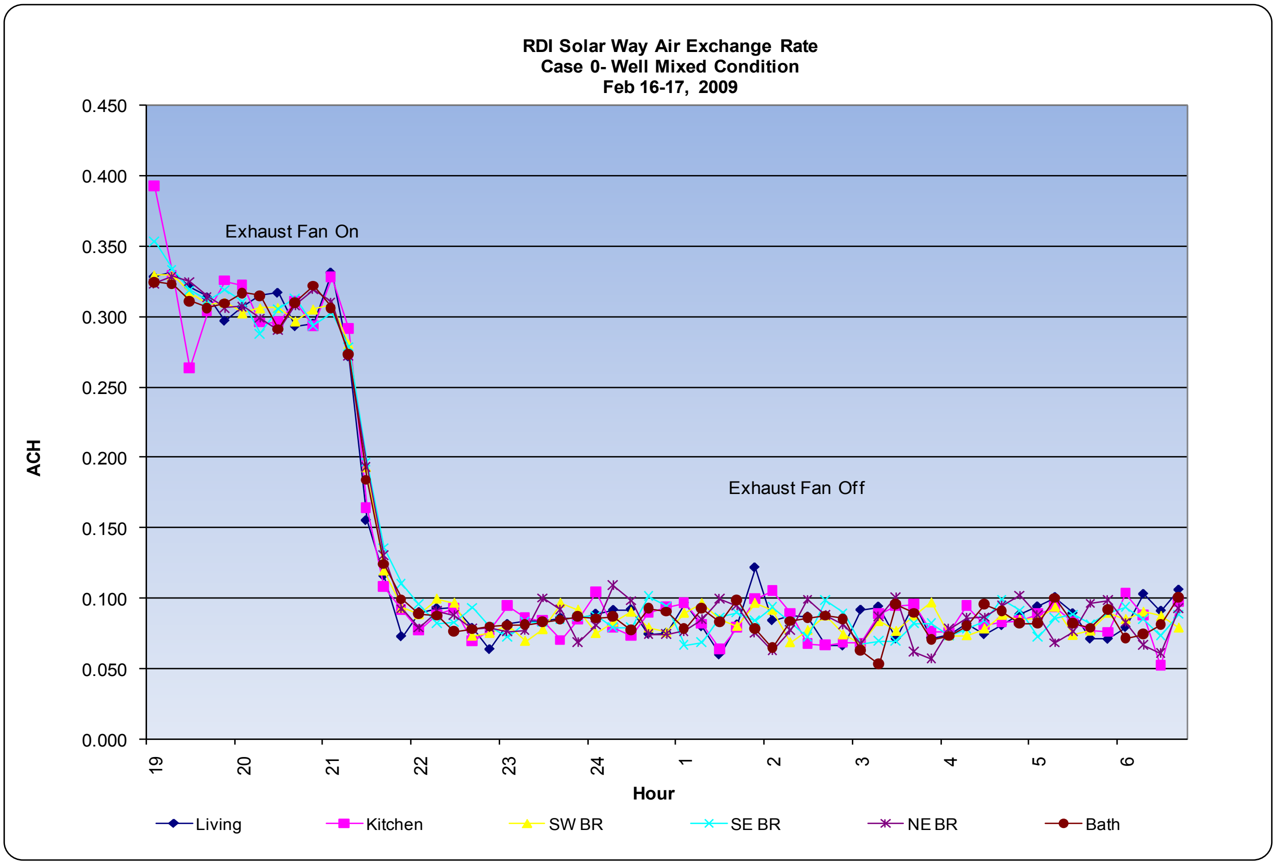

Figure 21. Air exchange rate (case 0)

4.2 Conclusions

The six sampling points (Figure 21) showed very close air exchange rates with and without the exhaust fan running. The combined ventilation rate with the exhaust fan running averages 0.32 ACH (64 cfm). The natural infiltration rate averages 0.075 ACH (14 cfm) without the central exhaust fan running. This natural infiltration ACH matches very well with the blower door test results of 0.07 ACH year average Estimated Natural Infiltration Rate (ENIR). This is probably due to the mild wind conditions throughout the Case 0 test period.

4.3 Age of Air – Concentration Decay Method (Cases 1–4)

The age of air – concentration decay method (Cases 1 to 4) was used to test room-to-room distribution of outside air. Of particular concern are the second-floor bedrooms where occupants sleep with the doors closed.

Neither space heaters nor room mixing fans were used during Cases 1 to 4. The tests conducted were under the boundary conditions of nonuniform temperature and no perfect-mixing conditions.

With this in mind, the sampling points' age of air represents only the local-mean age of air (or use RAoA as measurement unit) at the center of the rooms. However, the tests convey enough information about the outside air flow distribution throughout the house at different locations. All results and notations hereafter such as "living room" refer to the living room sample point conditions only.

The test begins with injecting a tracer gas (SF6) and mixing it uniformly throughout the home. Then injection and mixing cease and a single gas analyzer with tubing to each sampling point is used to monitor the concentration of the tracer gas as it decays.

Refer to Table 3 for the Tracer gas test matrix. All four cases have the central exhaust fan continuously running. Cases 1 and 2 have the bedroom doors closed, but the distribution/transfer fan was turned on in Case 1 and off in Case 2. Cases 1 and 2 were designed to determine the effect of the distribution/transfer fan. Case 3 was further tested to compare the distribution/transfer fan effect versus controlled outside air openings (1 $in.^2$ through window cracks [Figure 20]) into bedrooms (a leakier house). Case 4 is the same as Case 1 except the bedroom doors were closed. Case 4 was designed to determine the effect of open versus closed bedroom doors under normal operating conditions.

Age of air – concentration decay method tests normally last a few hours. Tests normally end when either the decay curve shape becomes a simple exponential, or the equivalent of 1.5 ACH has occurred. For the Wisdom Way Solar Village test unit, every test case lasted overnight, so overnight temperatures can be measured with relatively stable outside air conditions.

Figure 22 is an example of an enlarged plot of concentration decay of tracer gas for the first six hours of the test period. In all cases, test conditions were sufficiently steady to use the age-of-air method. The first-floor tracer gas concentration decayed faster than that of the second-floor rooms. In the second-floor main bathroom, where the outside air escaped last, the concentration decay rate stayed in the middle range because the exhaust fan kept the air flow rate in the room high.

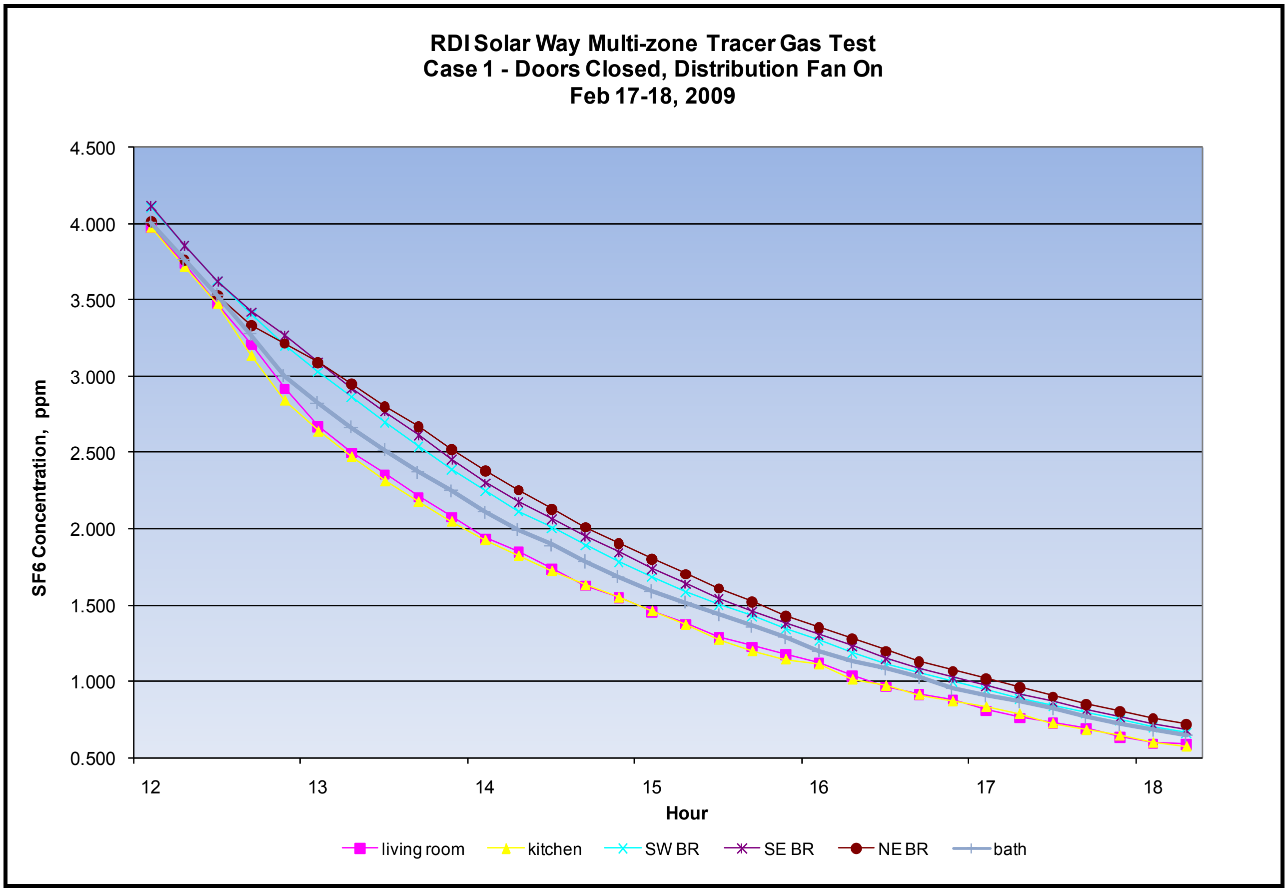

Figure 22. Concentration decay plot (case 1)

Table 6 and Figure 23 summarize the tracer gas test results using RAoA as the metric for comparison.

Table 6. RAoA Summary

Case No.	Description	RAoA					
		Living Room	Kitchen	SW BR	SE BR	NE BR	Bath
		(h^{-1})	(h^{-1})	(h^{-1})	(h^{-1})	(h^{-1})	(h^{-1})
1	Distribution fan on, doors closed	0.324	0.317	0.293	0.286	0.271	0.296
2	Distribution fan off, doors closed	0.299	0.304	0.173	0.174	0.150	0.283
3	Distribution fan off, doors closed, 1 $in.^2$ opening in each bedroom	0.262	0.265	0.211	0.173	0.215	0.247
4	Distribution fan on, door open	0.319	0.321	0.310	0.306	0.309	0.308

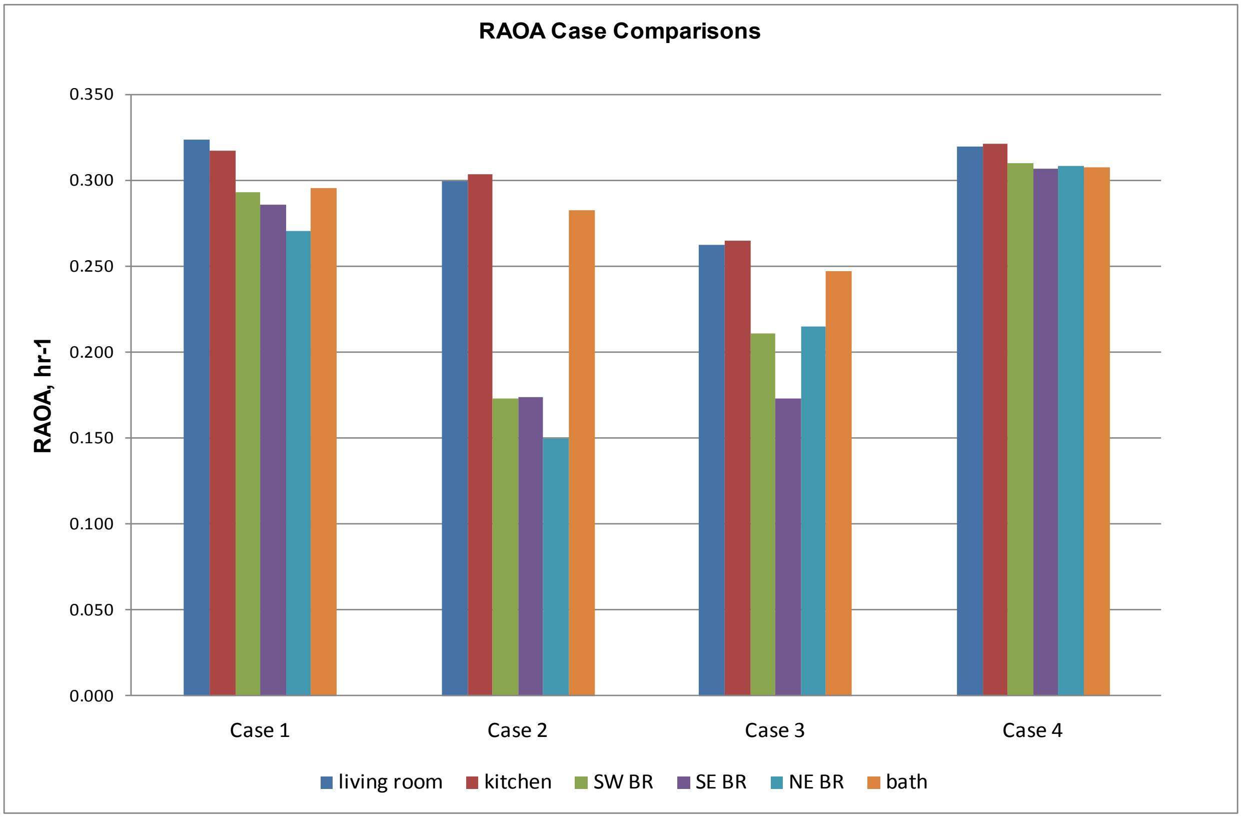

Figure 23. Tracer gas test summary (RAoA)

4.3.1 Conclusions

- A distribution/transfer fan effectively distributes outdoor air into second-floor bedrooms. Without this fan, the second-floor bedroom sampling points showed much lower RAoA (the air stays longer in the bedrooms). With the fan, the sampling points RAoA stayed close.
- Occupants will be encouraged to leave unoccupied second-floor bedroom doors open to help distribute outside air by natural stack buoyancy effect.
- One square-inch openings through the window cracks (Figure 20) in each bedroom increased outside air distribution in second-floor bedrooms. But the openings brought in unwanted natural ventilation that suppressed the outside air flow from the first floor to upstairs. This decreased the first-floor RAoA (first-floor outside air took longer to escape). The overall effect is undesirable, so this practice is not recommended.

5.0 Room Temperature Measurements

Each tracer gas test spanned overnight so that overnight room temperatures could be brought to steady conditions. Center-of-room temperatures and outside air temperatures were continuously recorded during the tests.

The Monitor heater sensor is located at the southeast corner of the unit. Space heater temperature set point was maintained at 70°F, with ±2°F of dead band. The sampled room temperatures were in the centers of the rooms.

5.1 Overnight Temperature Distribution Measurements

Figure 25 through Figure 28 show the center-of-room temperature distribution plots of Cases 0, 1, 2, 4, and 5.

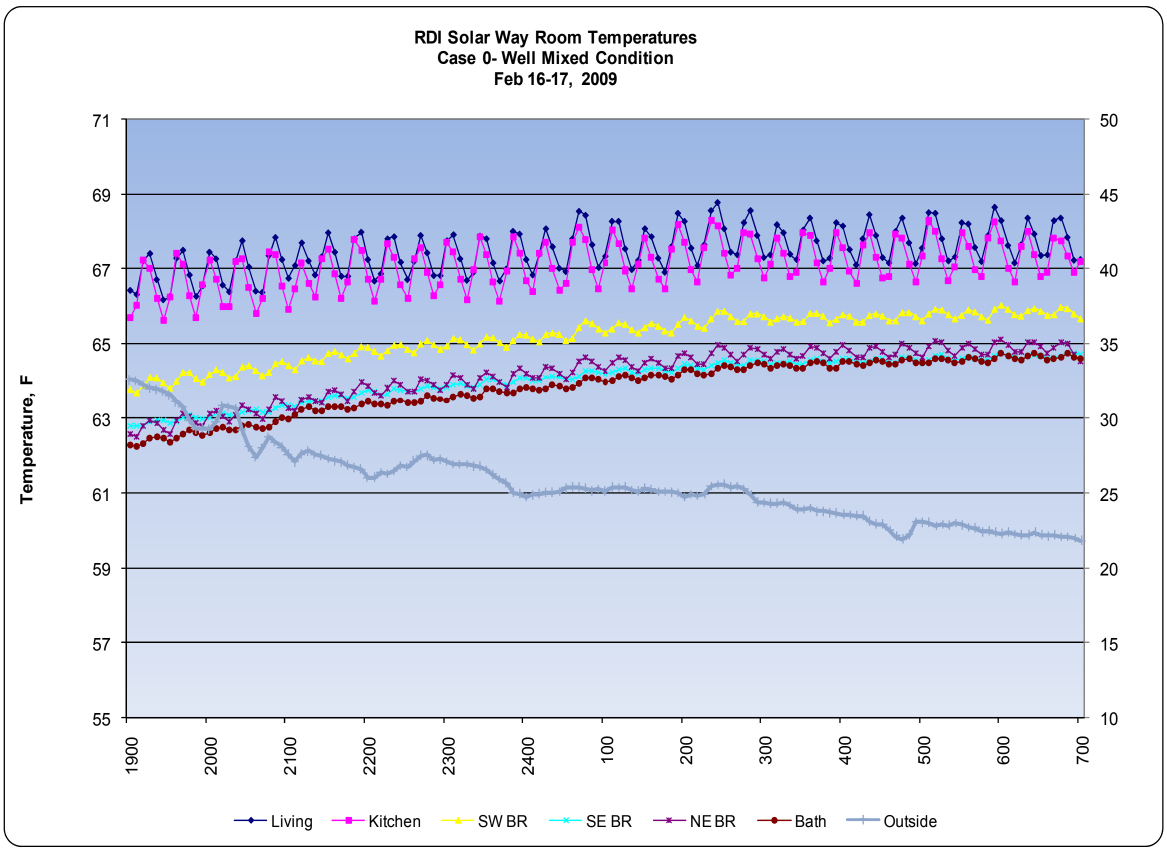

Figure 24. Temperature distribution (Case 0)

Case 5 was created as the last test metric for temperature distribution. Case 5 is the same as Case 1, except a 60-W (205 Btu·h, which corresponds to about 0.85 Met) light was installed in each bedroom to simulate heat gains from a human body. This number is slightly higher than the sleeping metabolic rate (0.7 Met), so the room temperature could be slightly lower.

Case 3 temperature measurements were not taken because 1-in.^{2} openings brought unwanted cold air into the space and made the bedrooms even colder. Room temperatures are plotted on the primary axis; outside air temperatures on the secondary axis.

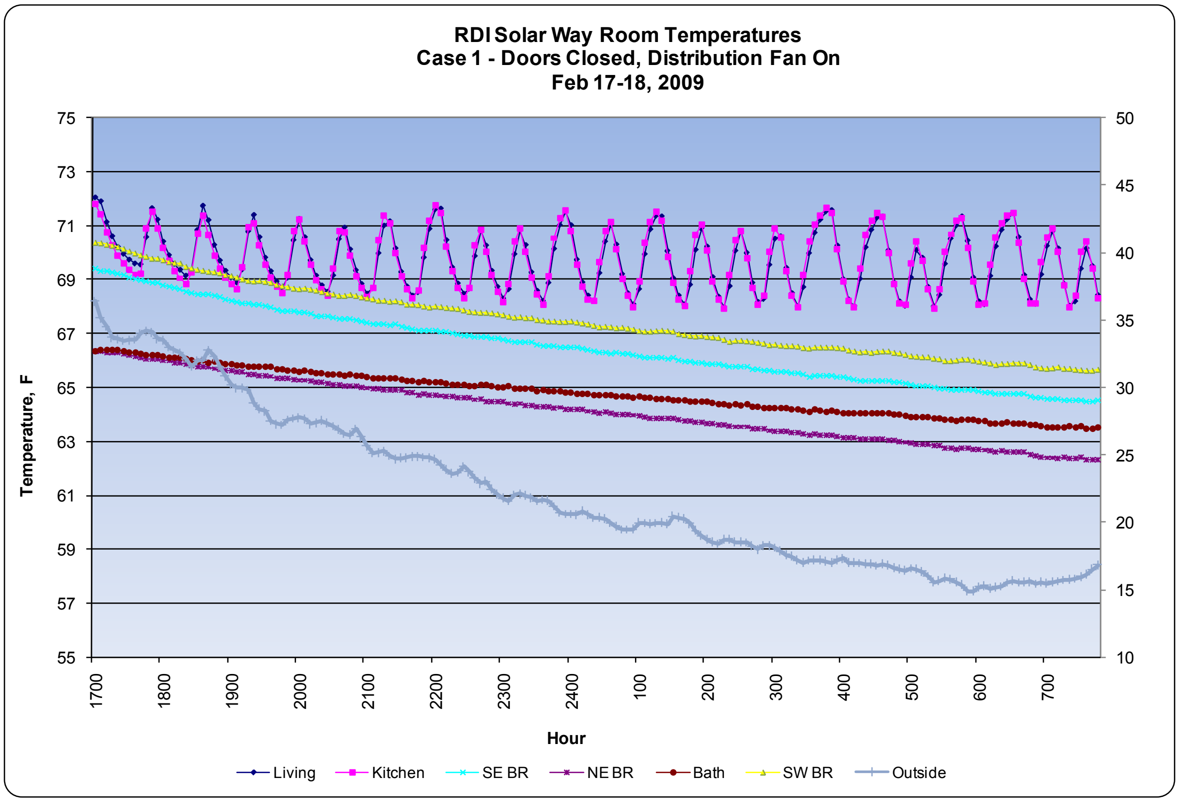

Figure 25. Temperature distribution overnight plot (Case 1)

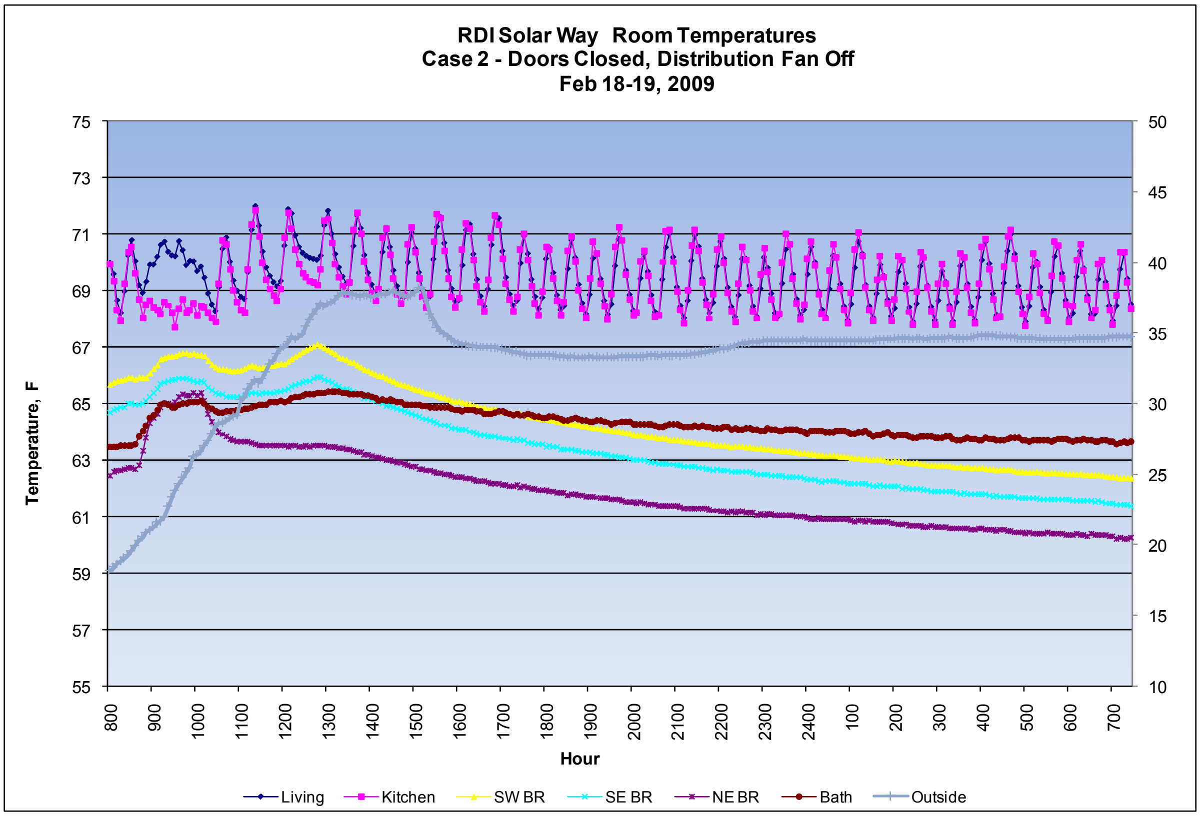

Figure 26. Temperature distribution overnight plot (Case 2)

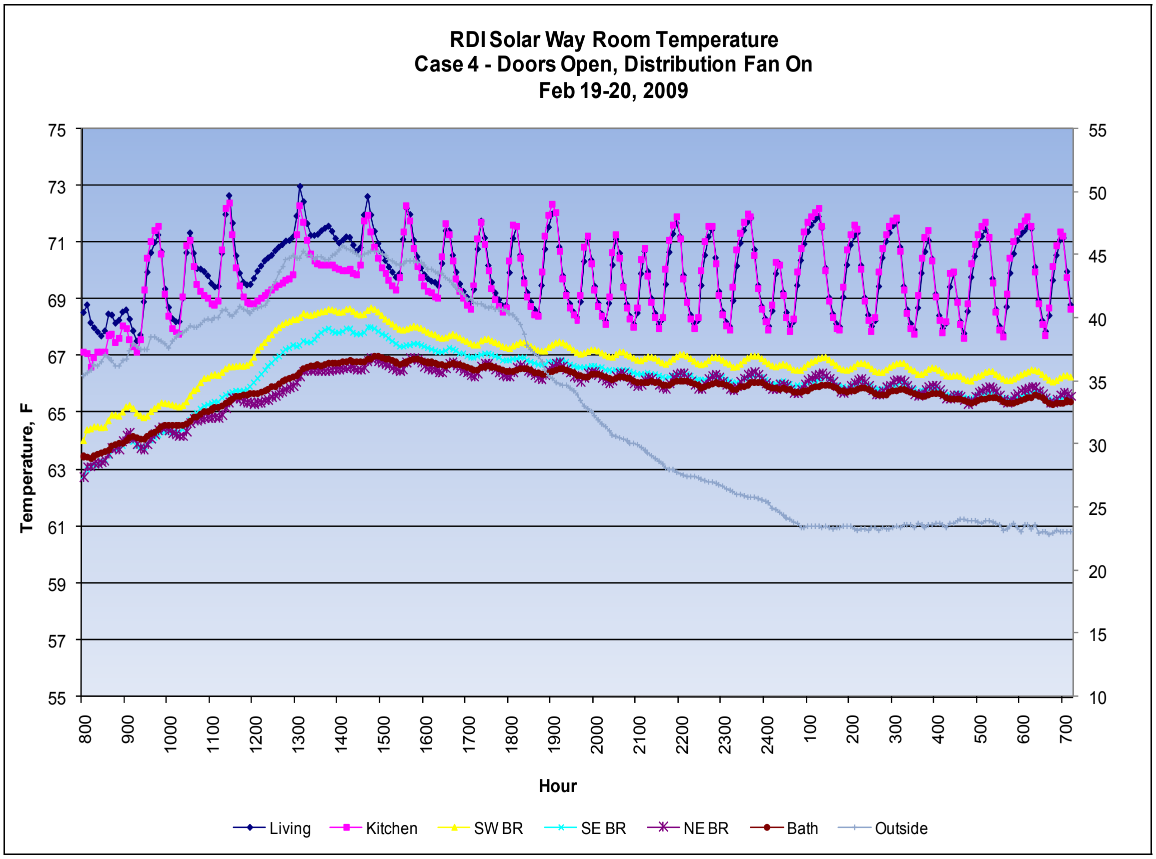

Figure 27. Temperature distribution overnight plot (Case 4)

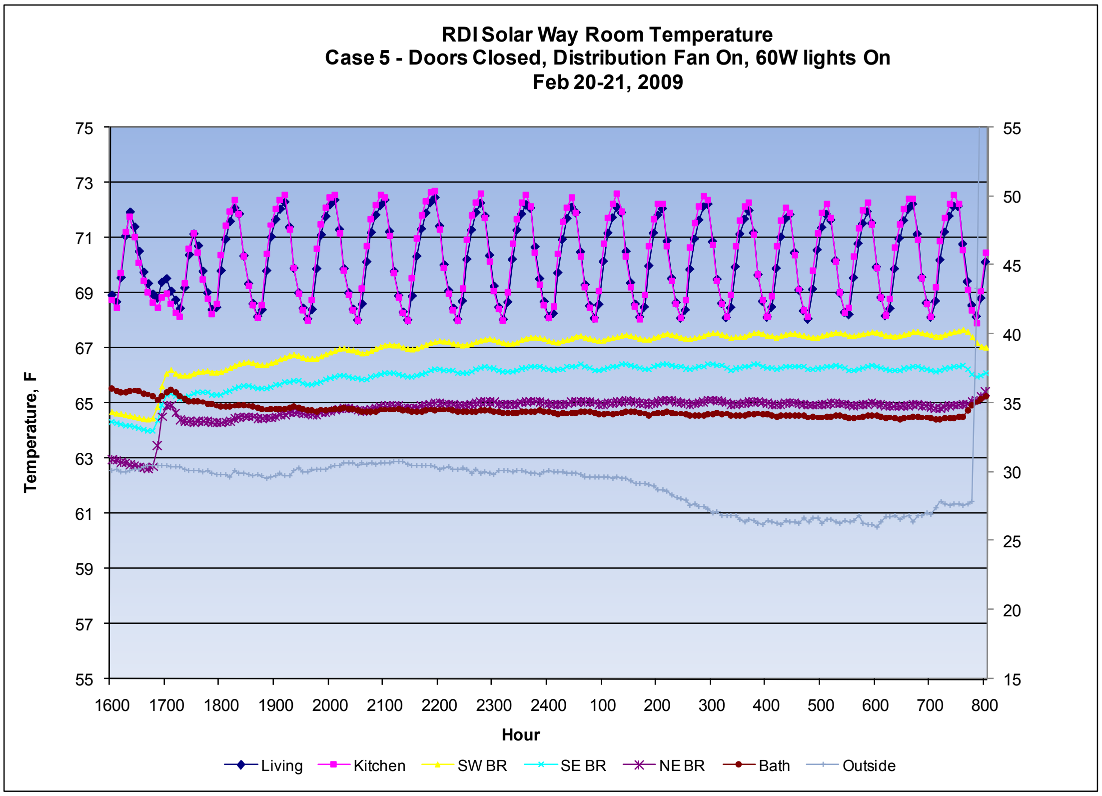

Figure 28. Temperature distribution overnight plot (Case 5)

We made the following observations:

- Case 1 experienced the lowest outside air temperature (14.92°F) for a short time. Compared to ASHRAE heating design 2°F, this outdoor condition was relatively mild. Cases 2, 4, and 5 outside temperatures were all mild (20°–35°F).
- First-floor kitchen and living room sampling point temperatures stayed very close throughout the nights. During the midmornings and early afternoons, the south-facing living room warmed from solar heat gains.
- Under well-mixed conditions (Case 0), the sampled living room temperature stayed slightly cooler (67°F) than the set point. The interzonal mixing fan continously mixed second-floor air with first-floor air and cooled the first floor air. For the other cases, the sampled living room temperatures stayed close to the heater set point (70°F) with ±2°F dead band.
- Leaving the bedroom doors open (Case 4) helps to reduce the room-to-room temperature difference.
- Operating the distribution/transfer fan (Cases 1 and 4 [Figure 27 and Figure 28]) helps to reduce room-to-room temperature difference. When Case 1 experienced the coldest outside air conditions, the upstairs bedrooms remained near 60°F.

- In all cases, the upstairs remained about 4°–7°F degrees cooler than the downstairs, varying from case to case.
- In all cases, the upstairs bedrooms had about 1°–2°F difference, varying from case to case. The southwest bedroom showed consistently higher temperatures (about 1°–2°F, varying from case to case) than the other two bedrooms because its southwest exposure had high solar heat gains.

5.2 Thermal Imaging Test (Infrared Camera)

Infrared pictures were taken to measure noticeable hot and cold spots on interior surfaces. There was normal infiltration through the wall sill plate and foundation and window and door frames. Overall, the test unit showed a consistently high insulation level.

Figure 29 through Figure 36 show thermal imaging for various places in the building. Figure 33 shows cold spots at the attic access door edge under normal operating conditions when warm air escaped. A better air seal gasket is recommended for the attic access door.

We measured surface temperature for the following surfaces during the midmorning of February 17. (To avoid disturbing the ongoing tracer gas test, we did not measure any surface temperatures in the upstairs bedrooms.)

- Living room
  - South wall: 71.5°F
  - East wall: 72°F
  - West wall: 71°F
  - North wall: 68°F
  - Floor: 69°F
  - Ceiling: 70.5°F
  - Air temperature: 73°F
- Second floor
  - Ceiling: 67°F
  - Stairway north wall: 67°F.

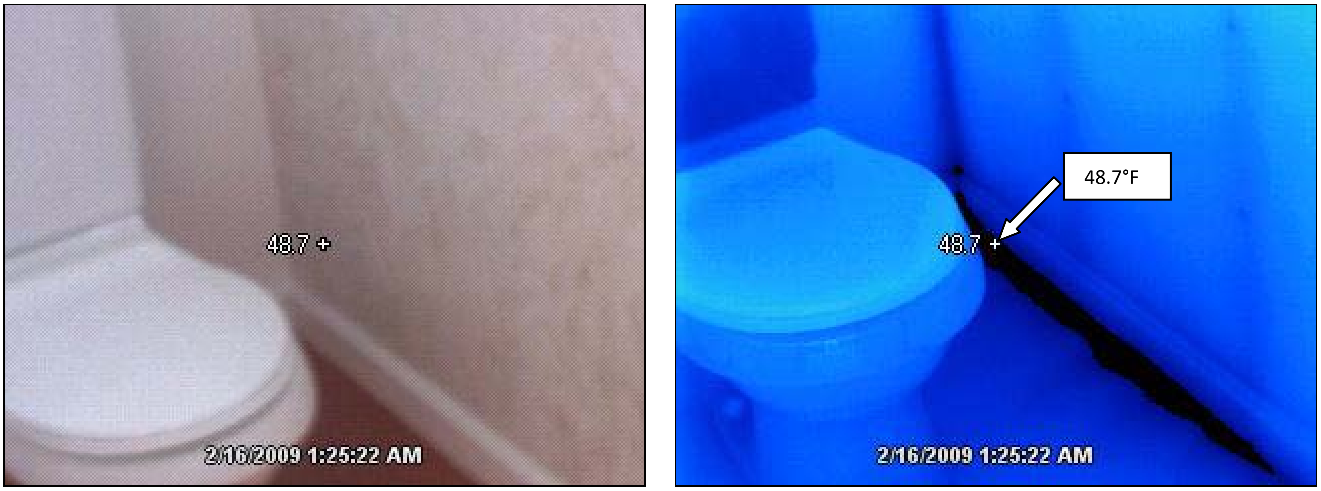

Figure 29. First-floor bathroom north corner thermal imaging

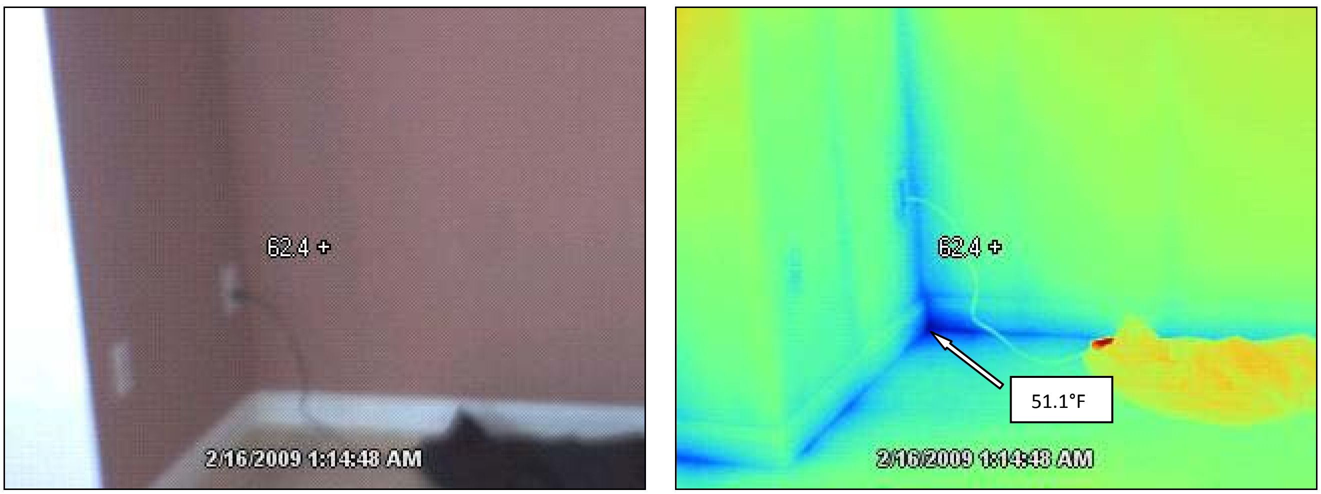

Figure 30. Living room southwest corner thermal imaging

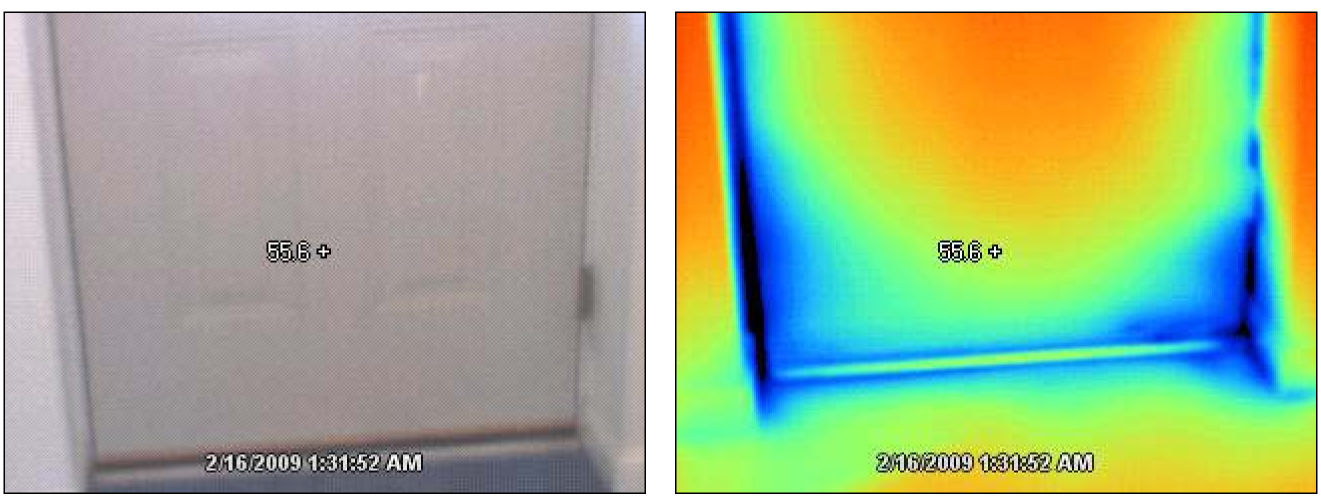

Figure 31. First-floor north entry door thermal imaging

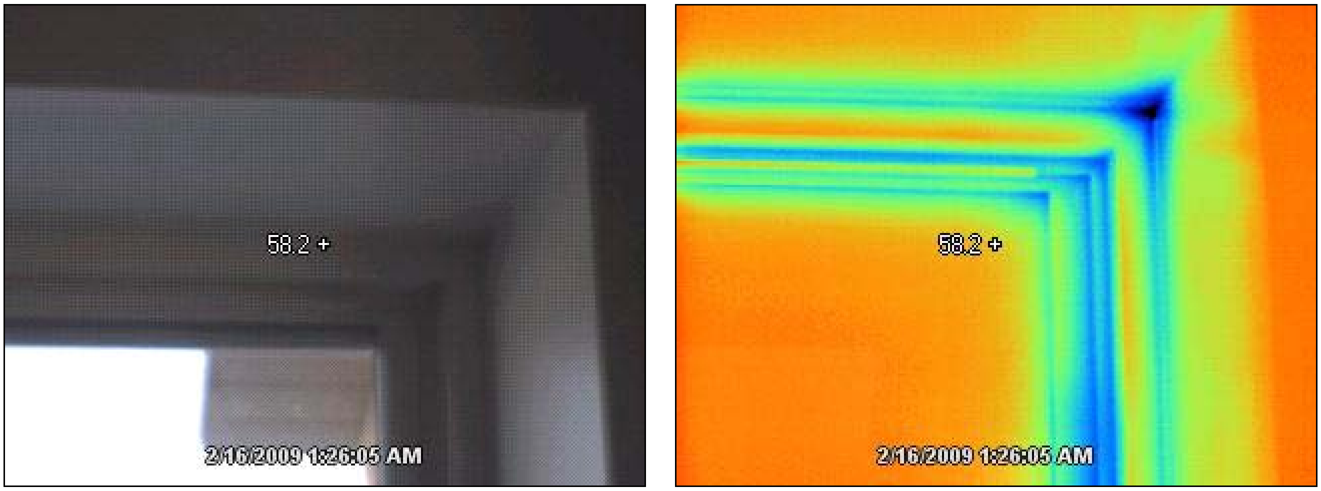

Figure 32. First-floor east window framing thermal imaging

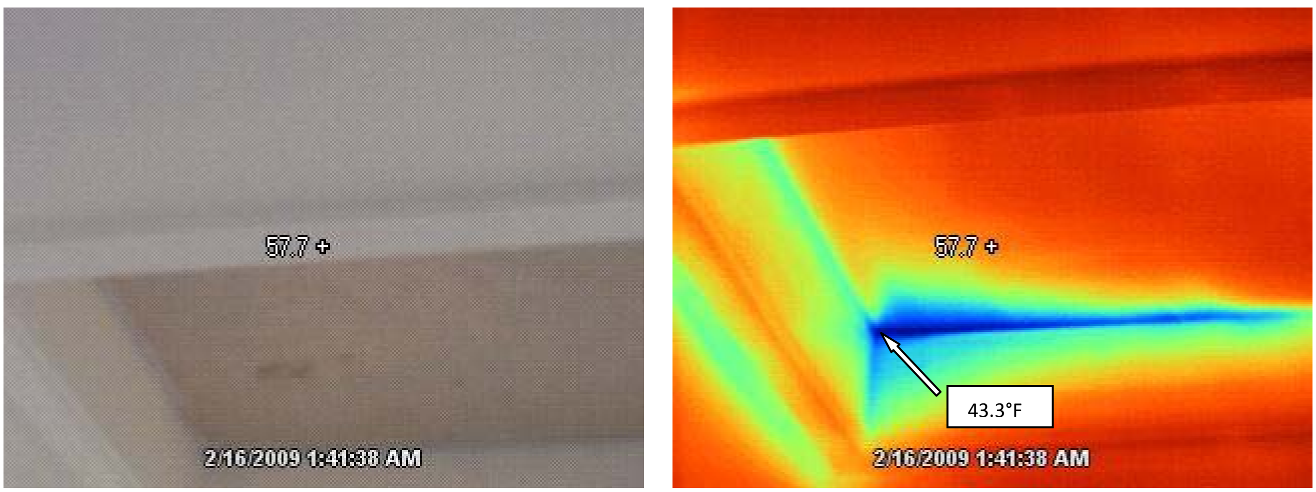

Figure 33. Attic access door thermal imaging

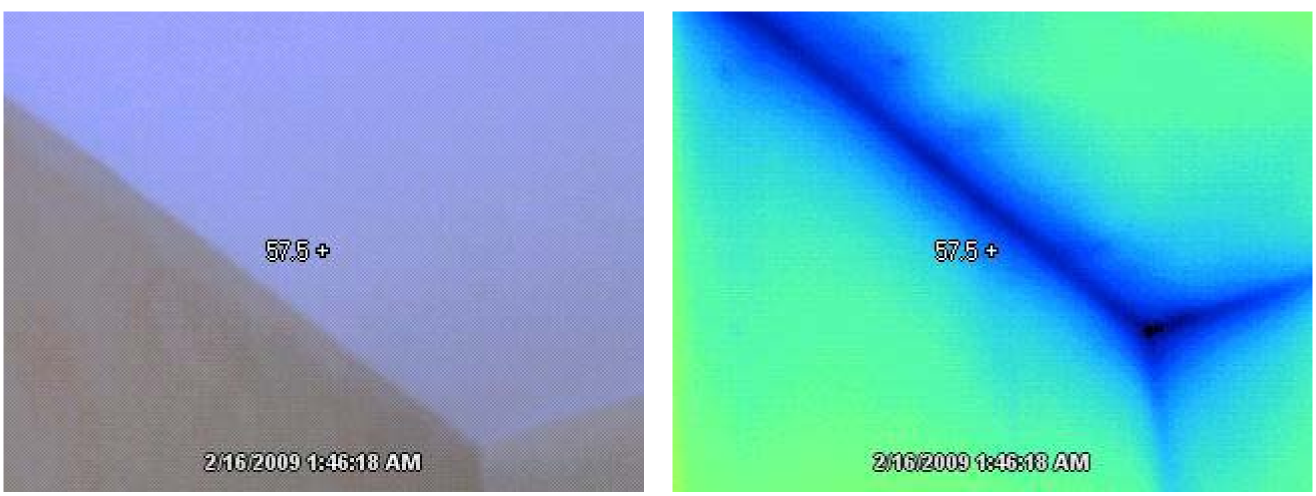

Figure 34. Southwest bedroom ceiling thermal imaging

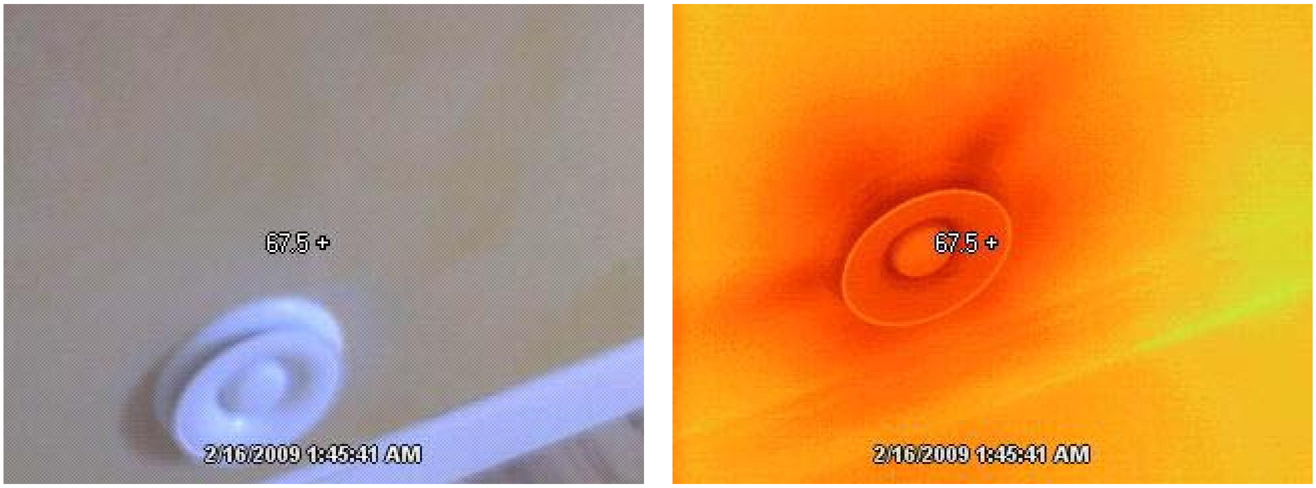

Figure 35. Southeast bedroom distribution diffuser thermal imaging

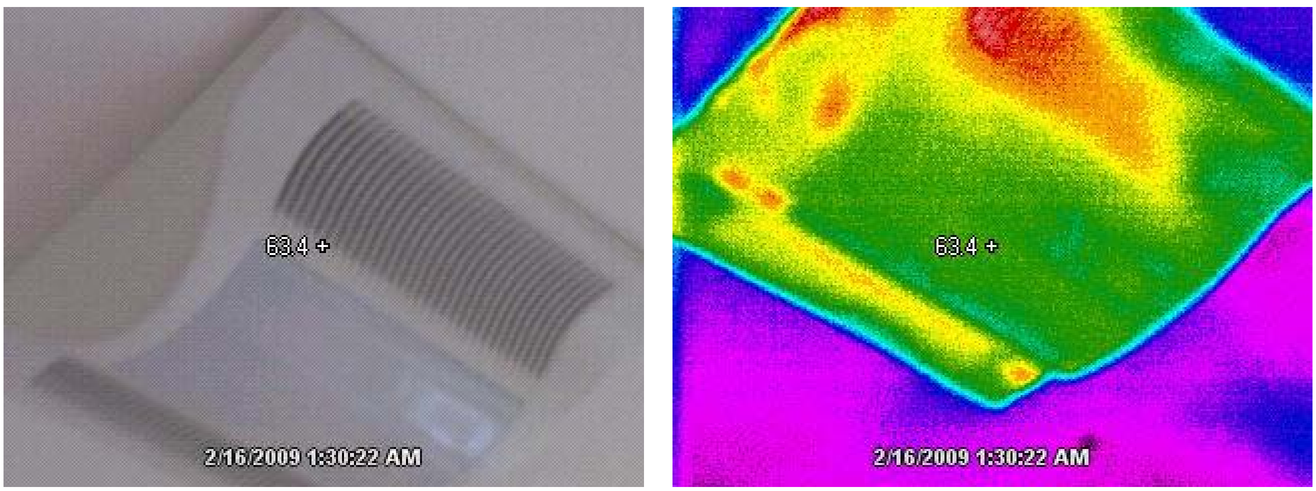

Figure 36. Central exhaust fan thermal imaging

5.3 Indoor Air Temperature Distribution Evaluation

Research question Q.11 is targeted at indoor air temperature and thermal comfort:

Q.11. What are the temperatures in various rooms throughout the duplex over consecutive 24-hour periods with each condition shown in Table 4? Does a central point in each room meet the ASHRAE Standard 55 comfort recommendations at various times during each test? Are there any noticeable hot or cold spots on interior surfaces as measured using an IR camera? Do temperature differentials between rooms meet ACCA Manual RS guidelines (4°F maximum)?

The following sections will evaluate the system according to the ACCA Manual RS guideline, ASHRAE standard 55 with thermal comfort simple analysis, and an occupant survey.

5.3.1 ACCA Manual RS Guideline Reference

Table 7 shows temperature instantaneous recordings at 6:00 a.m. near the end of the test period in February 2009. Case 5 (doors closed, transfer fan on, and 60 W simulating human body heat gain) is closest to normal operating conditions.

Table 7. Instantaneous Temperature Recordings at 6:00 a.m.

	Unit	Case 0	Case 1	Case 2	Case 4	Case 5
		2/17/09	2/18/09	2/19/09	2/20/09	2/21/09
Living Room Temperature	°F	68.28	68.18	68.04	71.28	69.94
Kitchen Temperature	°F	67.77	68.07	67.87	71.60	69.91
Southwest Bedroom Temperature	°F	66.02	65.95	62.53	66.34	67.57
Southeast Bedroom Temperature	°F	64.76	64.85	61.59	65.59	66.33
Northeast Bedroom Temperature	°F	65.12	62.69	60.35	65.79	64.99
Bathroom Temperature	°F	64.76	63.73	63.70	65.44	64.54
Basement Temperature	°F	43.51	44.39	44.62	44.53	44.67
Outside Air Temperature	°F	22.29	15.19	34.59	23.11	26.06
Wind Speed	m/s	0.20	0.20	0.20	0.81	0.20
Maximum Room Temperature	°F	68.29	68.18	68.04	71.60	69.94
Minimum Room Temperature	°F	64.76	62.69	60.35	65.59	64.99
Maximum Room to Room ΔT	°F	3.53	5.49	7.69	6.01	4.95
Average Floor to Floor ΔT	°F	2.86	3.82	5.91	5.65	4.07

The maximum temperature (occurring in the living room) is 69.94°F. The minimum room temperature (occurring in the northeast bedroom) is 64.99°F. A maximum ΔT between rooms is 5°F. It is greater than ACCA Manual RS guidelines of 4°F maximum.

Case 1 simulates no human body heat gain, and Case 1 experienced the coldest outside air temperature (15.19°F) at 6:00 a.m. The northeast bedroom temperature dropped to 62.69°F; the maximum room-to-room ΔT was 5.49°F. Under extreme winter weather conditions, the northeast bedroom room temperature may drop below 60°F.

In Cases 1 and 5, the average temperatures between the upstairs and downstairs are very close to 4°F (3.82°F Case 1; 4.07°F Case 5).

According to ACCA Manual RS, the design deviates from the 4°F rule. Of particular concern is the northeast bedroom.

5.3.2 ASHRAE Standard 55 Reference

ASHRAE standard 55 has comprehensive guidelines for thermal comfort validations. The current measurement variables are too incomplete to validate the model.

A simple analysis tool (PMVcalc) is used with the following parameters as a rough estimate. For future field tests, comfort meters will be used for verification.

The northeast bedroom was selected for calculation. The outdoor air temperature used is 16°F with indoor air temperature at 62°F, derived from test conditions. A relatively simple room mean radiant temperature calculation was performed counting all wall, ceiling, floor, and window surfaces. On cold winter nights, the room occupant will feel cool (PMV –2.2) with a clothing level of 2 when the room temperature is kept at 62°F, estimating mean radiant temperature of 61.5°F. For a highly insulated envelope, the room's mean radiant temperature is much closer to room temperature than a conventional house envelope (see Figure 37 and Figure 38).

Parameter	Input	
Clothing (clo)	2.00	[0 to 2clo]
Air temp. (°C)	16.7	[10 to 30°C]
Mean radiant temp. (°C)	16.4	[10 to 40°C]
Activity (met)	0.7	[0.8 to 4met]
Air speed (m/s)	0.10	[0 to 1m/s]
Relative humidity (%)	30.0	[30 to 70%]

Calculate PMV

Parameter	Results
Operative temp. (°C)	16.55
PMV	-2.2
PPD	84.9

Number of iterations: 6

Modified by Håkan Nilsson
Department of Technology and Built Environment
Laboratory of Ventilation and Air Quality
University of Gävle

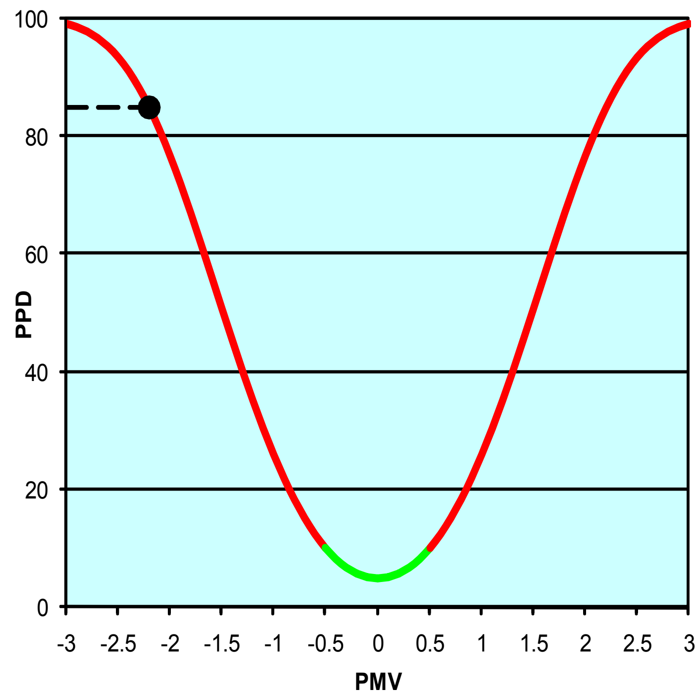

Figure 37. Northeast bedroom comfort estimate (occupant sleeping)

PPD - percent of people dissatisfied; PMV - predicted mean vote

On cold winter days, room occupants will feel cool (PMV –1.9) with a clothing level of 1 when the room temperature is kept at 62°F, estimating a mean radiant temperature of 61.5°F.

Parameter	Input	
Clothing (clo)	1.00	[0 to 2clo]
Air temp. (°C)	16.7	[10 to 30°C]
Mean radiant temp. (°C)	16.4	[10 to 40°C]
Activity (met)	1.0	[0.8 to 4met]
Air speed (m/s)	0.10	[0 to 1m/s]
Relative humidity (%)	30.0	[30 to 70%]

Calculate PMV

Parameter	Results
Operative temp. (°C)	16.55
PMV	-1.9
PPD	72.1

Number of iterations: 7

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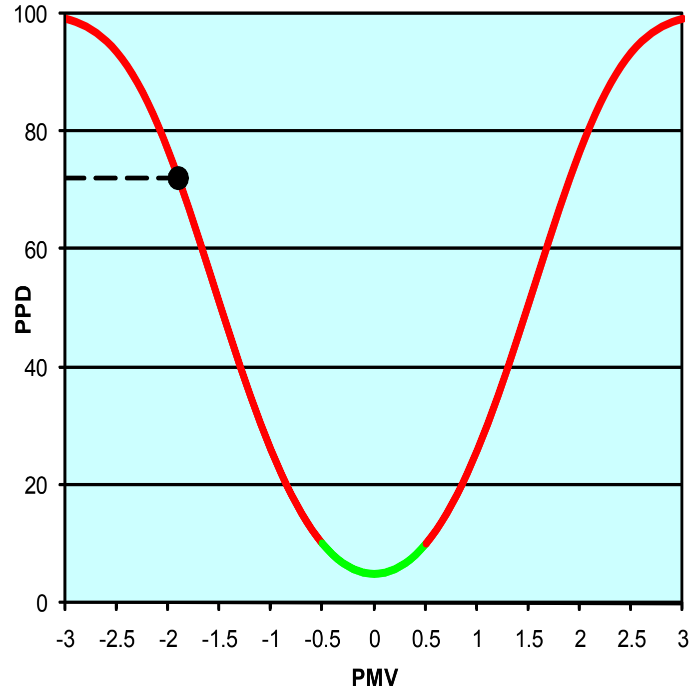

Figure 38. Northeast bedroom comfort estimate (occupant seated)

According to ASHRAE standard 55, upstairs bedrooms, particularly the northeast bedroom, will feel cool during chilly winter days or nights.

Under extreme winter conditions, homeowners are likely to increase the space temperature set point to 72°–73°F to heat the upstairs. We also recommend that homeowners leave the room doors open during the daytime when the unit is not occupied.

5.3.3 Occupant Survey (Informal Conversation)

Robb Aldrich met with the owner of the two-bedroom unit. Aldrich noted the following in an e-mail correspondence:

> He leaves his thermostat at 60°F. "Sometimes," he said, "when I come home, I'll put it up to 62°." So he likes it cool, which is probably why folks that have visited him were a bit concerned. One other interesting note he volunteered: his teenage son seems comfortable in his room with the door closed (with computer, stereo, etc. running) and hasn't wanted to turn up the heat.

When the downstairs thermostat is set to 62°F, the upstairs bedroom temperature can decrease to 55°–58°F unless the bedroom has lot of electronic equipment.

This design seems to work well for these homeowners. The question remains: Does it work for the homeowners in general?

5.3.4 Conclusions

CARB's low-cost design approach for Wisdom Way Solar Village traded the cost of a distributed space heating system toward highly insulated envelopes. A point source heating scheme is installed without supplemental heating backup.

Field measurements and analysis showed the space conditions had some deviations from ACCA Manual RS design standards and ASHRAE 55 comfort standards, even though the next door homeowner likes cool spaces. When CARB met with the homeowners, the decision was made that homeowners can install 200- to 300-W space heaters to closely control room temperatures and bring thermal comfort within neutral range.

Because Building America is targeted toward the broad outreach of general homeowner groups, this design approach is not deemed a complete success without supplemental heating backup.

We recommend that for multistory housing units in cold climates, even with highly insulated envelope construction, small supplemental space heaters are needed for a single-zone point source heating scheme. Our study and conclusion are derived from this project only.

6.0 Miscellaneous Tests

6.1 Noise Test of the Distribution Fan

Coldham & Hartman Architects conducted a noise test of the distribution/transfer fan. There were concerns about the noise the fan generated and about the noise transmission from the first floor to the bedrooms that would be created by opening a separate transmission/distribution path.

A vacuum and a hair dryer were brought into the living room space. The test set the vacuum to low speed, high speed, and high speed with hair dryer on. In each setting, the distribution/transfer fan was first left on with the bedroom doors open and then closed. The distribution/transfer fan was then turned off with the supply duct opening blanket off and the bedroom doors closed. Table 8 shows the decibel (DB) level recordings of the system.

Table 8. Distribution Fan Noise Rating Test

Description	Vacuum Low Speed	Vacuum High Speed	Vacuum High Speed With Hair Dryer
	(DB)	(DB)	(DB)
Source	57	64.5	80
Open Bedroom Door, Fan On	36	44	56
Closed Bedroom Door, Fan On	34	36.5	47
Blocked Duct, Fan Off	29	33	46.5

The vacuum and the hairdryer were then turned off so no source noise was generated. The recorded sound level was 34.5 DB with the distribution fan on. The recorded sound level was 26.5 DB with the distribution fan turned off.

This test showed that the WhisperGreen transfer fan was quiet and that the noise transmission from the first floor was not a problem.

6.2 Hot Water Draw Test

Figure 39. Hot water draw test

During the field test, the solar domestic hot water system was not functioning with a cold storage tank. The hot water draw test at the faucet on Figure 39. Hot water draw test describes the backup tankless water heater only.

The master bathroom faucet was selected as the worst case because it has the longest distance to travel from the water heater. It took 1 minute for the water to warm to 80°F, and 1 minute and 16 seconds to warm to 106°F. Further testing is needed when the rest of the houses are brought on line.

Several discussions took place about fixing the solar hot water system. It was fixed and operating properly a week after the field trip. There is concern that the solar hot water system may not perform as designed and the homeowner may be unaware of that. Long-term monitoring and diagnostics are recommended.

6.3 Duct Leakage Test

The only distribution duct in the space is on the distribution/transfer fan. Field measurement showed duct leakage of 9 cfm (±10%).

- First floor ceiling grille: 90 cfm
- Southwest bedroom: 29 cfm
- Southeast bedroom: 28 cfm
- Northeast bedroom: 24 cfm

6.4 Power Measurement

The following electrical power measurements were taken on site:

- Monitor space heater standby baseline power (including doorbell, clock, and LED light): 6 W
- Monitor space heater fan on power: 63 W
- Central exhaust fan low speed: 6 W
- Central exhaust fan high speed: 14 W
- First floor bathroom fan on: 17 W
- Distribution/transfer fan on: 11 W

7.0 Conclusions

On February 16-21, 2009, NREL, Mountain Energy Partnership, and CARB conducted short-term field tests on a three-bedroom unit in the Wisdom Way Solar Village. The field tests included: a blower door test, Tracer gas test, thermal imaging test, and other miscellaneous tests and measurements.

The blower door tests showed the test house has exceptionally tight construction with 11.2 $in.^2$ ELA at 4 Pascal.

The tracer gas tests showed good distribution of combined (mechanical and natural) ventilation throughout all rooms in the three-bedroom test unit when the exhaust ventilation fan works in conjunction with the distribution/transfer fan.

The indoor air temperature overnight measurement showed the space conditions had some deviations from ACCA Manual RS design standards and ASHRAE 55 comfort standards. The space heater, in conjunction with the distribution/transfer fan, is not sufficient to distribute the point heating throughout the house. We recommend supplementary heating backup in the upstairs bedrooms in addition to the point source heating system for acceptable comfort conditions.

We also recommend a better air seal gasket on the attic access door; more hot water draw tests when solar water heating systems are brought online, and long-term diagnostic monitoring of the solar water heating systems.

8.0 References

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14. ABSTRACT *(Maximum 200 Words)*
The National Renewable Energy Laboratory, Mountain Energy Partnership (a subcontractor of NREL), and the Consortium of Advanced Residential Buildings conducted short-term field tests on a house in the Wisdom Way Solar Village (G3, community scale, 40% savings level, cold climate). The house design features exceptionally tight construction, highly insulated envelopes, efficient ventilation and space heating design, and on-site renewable energy. NREL conducted field tests to verify that the prototype houses achieve the energy efficiency goal and maintain indoor air quality and comfort. Specifically, the Wisdom Way field test is targeted at verifying the performance of the point source heating, exhaust fan ventilation, and innovative distribution/transfer fan effectiveness in air and heat distribution.

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wisdom way solar village; building america; field test; indoor air quality; energy efficiency

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