TASK 2.5.7 FIELD EXPERIMENTS TO EVALUATE COOL-COLORED ROOFING

William (Bill) Miller, Ph.D.
Oak Ridge National Laboratory
Research Engineer
Building Envelope Program

Nigel Cherry, Ph.D.
Richard Allen
Monier Technical Centre
Manager and Principal Engineer,
Roof Physics & Validation Dept

Phil Childs,
Jerry Atchley
Oak Ridge National Laboratory
Building Envelope Program

Ronnen Levinson, Ph.D.
Lawrence Berkeley National Laboratory
Acting Leader, Heat Island Group

Hashem Akbari, Ph.D.
Lawrence Berkeley National Laboratory (Retired)
Founder (Heat Island Group)

Paul Berdahl, Ph.D.
Lawrence Berkeley National Laboratory
Retired (Physicist)

ABSTRACT

Aesthetically pleasing dark roofs can be formulated to reflect like a highly reflective "white" roof in the near infrared portion of the solar spectrum. New paint pigments increase the near infrared reflectance of exterior finishes by minimizing the absorption of near-infrared radiation (NIR). The boost in the NIR reflectance drops the surface temperatures of roofs and walls, which in turn reduces cooling-energy use and provides savings for the homeowner and relief for the utilities. In moderate and hot climates, a roof surface with high solar reflectance and high thermal emittance was shown by Akbari et al. (2004) and by Parker and Sherwin (1998) to reduce the exterior temperature and produce savings in comfort cooling. The new cool color pigments can potentially reduce emissions of carbon dioxide, which in turn reduces metropolitan heat buildup and urban smog. The pigments can also help conserve water resources otherwise used to clean and process fuel consumed by fossil-fuel driven power plants. Cool roofs also result in a lower ambient temperature that further decreases the need for air conditioning, retards smog formation, and improves thermal comfort.

Parker, Sonne and Sherwin (2002) demonstrated that white barrel and white flat tiles reduced cooling energy consumption by 22% of the base load used by an adjacent and identical home having direct nailed dark shingles. Part of the savings was due to the reflectance of the white tiles; however, another part was due to the mass of the tile and to the venting occurring within the double batten installation. With, Cherry and Haig (2009) have studied the influence of the thermal mass and batten space ventilation and have found that, referenced to an asphalt shingle system, it can be equivalent to an additional 28 points of solar reflectivity.

The double batten arrangement has wooden counter battens laid vertically (soffit-to-ridge) against the roof deck, and then the conventional battens are laid horizontally across the counter battens, providing a nailing surface for the concrete tile. This double batten construction forms an inclined air channel running from the soffit to the ridge. The

bottom surface of the channel is formed by the roof decking and is relatively flat and smooth. The top surface is created by the underside of the roofing tiles, and is designed to be an air permeable covering to alleviate the underside air pressure and minimize wind uplift on the tiles. The resulting air flows also have a cooling influence which further complicates prediction of the heat penetrating through the deck because an accurate measure of the airflow is required to predict the heat transfer.

Measured temperatures and heat flows at the roof surface, within the attic and at the ceiling of the houses are discussed as well as the power usage to help gauge the benefit of cool-pigmented reflective roof products fitted with and without ventilation above the roof deck. Ventilation occurring above the deck is an inherent feature for tile roof assemblies, and is formed by an air space between the exterior face of the roof sheathing and the underside of the tile. The greater the tile's profile the greater is the effect of the ventilation which herein is termed above-sheathing ventilation (ASV). However, because of the complexity of the thermally induced flow, little credit is allowed by state and federal building codes. ASHRAE (2005) provides empirical data for the effective thermal resistance of plane air spaces. A ¾-in. (0.0191-m) plane air space inclined at 45° with the horizontal has an R_{US}-0.85 (R_{SI}-0.15)[1].

Our intent is to help further deploy cool color pigments in roofs by conducting field experiments to evaluate the new cool-colored roofing materials in the hot climate of Southern California. The collected data will be used to showcase and market the performance of new cool-roof products and also to help formulate and validate computer codes capable of calculating the heat transfer occurring within the attic and the whole building.

Field measures and computer predictions showed that the demonstration home without a NIR-reflective tile coating and without above-sheathing ventilation had the greatest roof deck heat flow and subsequently the highest electrical usage. The house with both NIR paint pigments on the tile and with ASV had the least deck heat flows and therefore caused the home to consume the least amount of energy. The relative performance of the reflective coating and the ventilation individually is less obvious, but it is clear that the combination of a reflective tile with ASV is the preferred solution for the best energy saving.

FORT IRWIN CA DEMONSTRATIONS

Two pairs of single family detached homes on the campus of Fort Irwin were selected for the field study. Our intent is to use these data along with the field data for homes tested in Northern California to benchmark an energy saving calculator tool. The US Army appropriated funds for a Residential Community Initiative (RCI) to counter its growing domestic demand for energy and water consumption while at the same time making military careers more attractive by providing state-of-the art housing for Army personnel and their families. Fort Irwin is part of the RCI initiative and entered contract with Clark Construction to build some 200+ privatized dwellings.

---

[1] An effective emittance of 0.82 was assumed with a mean temperature of 90°F (32.2°C) having a 10°F (5.6°C) temperature gradient for heat flows moving downward across the air space.

DEMONSTRATION HOMES

Clark Construction agreed to temporarily set aside 4 single-family detached homes from its production schedule for ORNL and LBNL to instrument with temperature, heat flux and power measuring sensors. The plot map (Fig. 1) shows the location and orientation of the four homes selected for the study. Option 2 in the N section of the Sandy Basin community was the site selected for the 4 homes. Each home is a two-story,

Figure 1. Plot map of the Sandy Basin community on the campus of Fort Irwin, CA. Section N has 4 homes selected for demonstrating cool color pigments and above-sheathing ventilation.

four bedroom dwelling. A pair of homes has identical footprints. One pair of homes (Units N10 and N5) has 1974 square feet (183 m2) of living space, Table 1. The other pair (Units N4 and N8) has 2164 square feet of space (210 m2), Table 1. All homes have detached unconditioned two-car garages. The roofs have the same azimuth orientation to the sun; the ridge is oriented almost east and west, being 78° CW from magnetic north. Photos of the completed homes and the salient features of each demonstration home are provided in Appendix A.

All homes are equipped with the Capistrano high profile concrete tile from Eagle Roofing Products. The tile with conventional paint pigment is light brown in color. Solar reflectance of the tile is 0.24 as measured by ASTM C 1549 (ASTM 2009). Thermal emittance of the tile is 0.93 as measured by ASTM C-1371 (ASTM 2004). Solar reflectance of the cool color coated tile is 0.45; roughly double that of the conventionally painted tile.

American Roof Tile Coatings spray painted two of the demonstrations roofs (one roof nailed directly to the deck, the other tile roof attached to a double batten system) with COOLTILE IR COATINGS™. They applied two thorough under-coats of a Plaster White. The next day a Terracotta infrared reflective paint (solar reflectance of 0.48) was applied in two separate coatings. A third flash coating was also applied to simulate the variegated look of the tile's original finish. American Roof Tile Coatings applied flash coatings consisting of an IR brown flash (solar reflectance of 0.42) and a light IR yellow/clay pot flash (solar reflectance of 0.52).

Table 1. Demonstration Homes at Fort Irwin, CA being field tested for the California Energy Commission's Public Interest Energy Research project "Market Deployment of Cool-Colored Roofing Materials."

House (Style)	Address on Omaha Beach St.	Floor Plan	Living area ft^2 (m^2)	Roof System	Tile Paint Pigments
N4	4653	2 Story, 4 Bdr	2164 (210)	Double Batten[A]	IRR coating
N5	4655	2 Story, 4 Bdr	1974 (183)	Direct-to-Deck	IRR coating
N8	4661	2 Story, 4 Bdr	2164 (210)	Double Batten[A]	Conventional
N10	4665	2 Story, 4 Bdr	1974 (183)	Direct-to-Deck	Conventional

[A] **Roofs with double battens have ventilated eaves and elevated ridge FlexVent™ for cross ventilation between apposing north and south facing roofs.**

Attic Construction for the Demonstration Homes

One layer of Type 30 felt that complies with ASTM D226 serves as a waterproofing barrier between the sheathing and the tile roof. The deck sheathing is Louisiana Pacific's TechShield; it is 0.47-in (0.012-m) thick. The oriented strand board (OSB) has a perforated low emittance foil facing into the attic plenum (Fig. 2). A smaller yet thicker

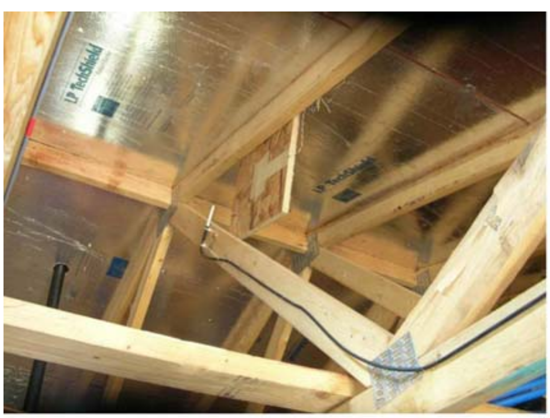


Figure 2. LP Techshield is the deck sheathing. A patch panel also made of Techshield [0.731-in (0.01857-m) thick] holds a heat flux transducer against the LP deck.

piece of LP Techshield is shown temporarily hanging from a roof rafter in Figure 2. It served as a patch panel and housed a heat flux transducer (HFT) for measuring the heat transfer across the roof deck. The panel was routed with a slot to hold the HFT flush against the LP Techshield deck. Once the roofing crews finished nailing the tile and battens, ORNL personnel secured the patch panel to the underside of the roof.

Attic truss members are spaced 24-in (0.61-m) on center. The truss system is made of 2-in by 4-in Douglas fir (pine) wood (Fig. 2). Inclination of the roof is 4-in of rise per 12-in of run (18.4°). Salient features of the roof and attic construction are in Appendix A

The attics of the four homes are not configured with ridge ventilation. Attic ventilation is provided at the soffits (2-in diameter holes), the gables (4-in diameter holes), O'Hagin vents (19-in by 7-in base) and by solar power vents installed in the roofs. The solar powered fans enhance attic ventilation during daylight hours; the fan energizes as the photovoltaic module converts the sun's energy to DC power, Figure 3. The net free ventilation area to attic floor area for soffit and gable vents is estimated at 1:300.

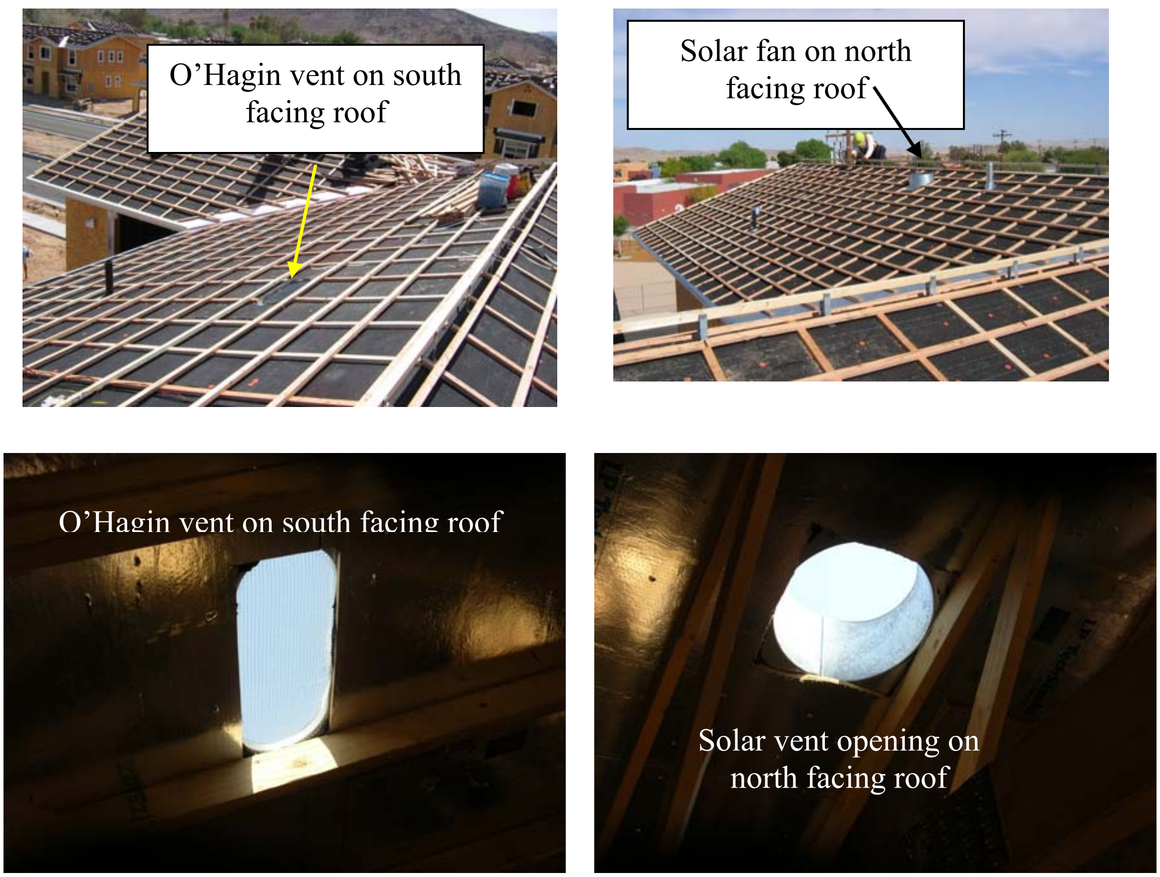


Figure 3. O'Hagin vents and solar powered fans were installed by Clark Construction to enhance attic ventilation during periods of peak irradiance.

The houses are built with the HVAC supply ducts placed between the first and second floors. The ducts run through a prefabricated truss support system. No supply ducts are installed in the attics; however, the return duct is located in the attic floor to pull air from the top of the stairwell through the duct (placed in the attic) and to the return of the HVAC air handler, which is installed in a conditioned equipment room. The equipment room is an open area on the second floor of each home located very near the stairwell. It contains the hot water heater, washer and dryer and the air handler unit. This HVAC setup is consistent for all four homes.

Eave and Ridge Detail for the Roofs of the Demonstration Homes

The pair of homes (Units N5 and N10) has the concrete tile attached directly to the roof deck. Because the Eagle's Capistrano tile has a high profile, thermally induced and wind induced convection occurs with air entering and escaping between over-lapped tiles; however, tiles placed at the eaves have metal eave closure strips installed to limit wind, fire, vermin or birds while at the same time allowing any drainage of moisture accumulated beneath the tile through weep holes fabricated in the metal closure strip. The ridge tiles for this pair of homes are fitted with weather blocking material to keep water on the surface of the tile (Fig. 4).

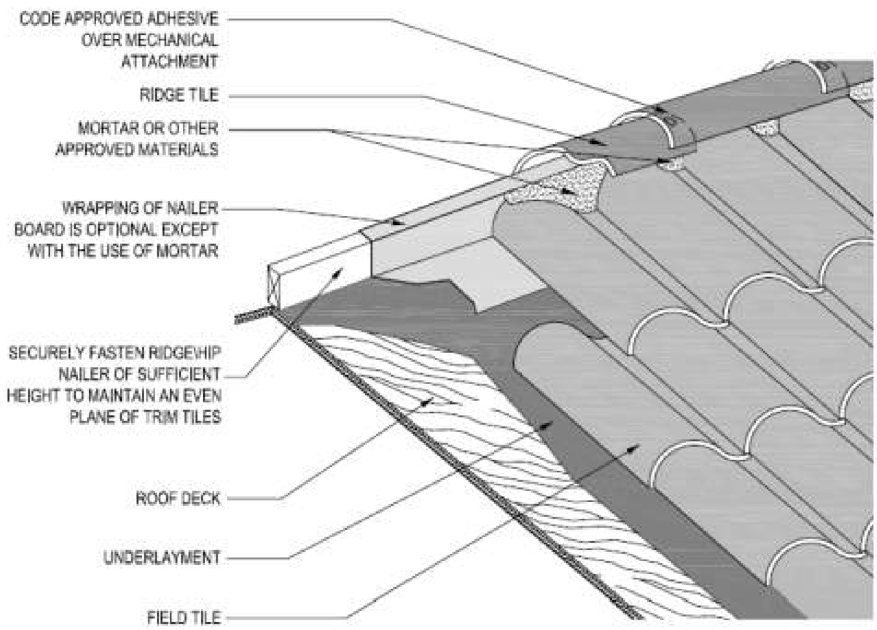


Figure 4. Ridge detail for demonstration homes N5 and N10 showing the ridge blocked.

A 2-in by 4-in nailer board is attached to the ridge with the board's 4-in dimension placed vertically up above the ridge. The roof tiles are butted to within a ½-in (0.0127-m) of the nailer board and a mastic was applied to seal the ridge.

The pair of homes (Units N4 and N8) has nominal 1-in by 2-in wood batten and counter-batten strips (i.e. double batten) installed on their roofs to elevate the concrete tile about 1½-in above the deck (Fig. 5). Spacing between the counter-battens is 16-in [0.41-m] and they run from eave to ridge. Spacing of the battens is 13½-in [0.343-m] and they run parallel to the ridge. The Capistrano tiles at the eaves are closed with bird stops to comply with regulations for fire prevention as also done for homes N5 and N10.

Figure 5. Double batten system installed on Units N4 and N8.

The ridge tile for homes N4 and N8 are configured for ventilation above the sheathing to allow air movement across to the opposing roof (Fig. 6). Nominal 2-in by 2-in wood strips are elevated above the ridge (Fig. 6) and a flexible, single-layer perforated copper sheet is fitted over the elevated ridge. The copper sheet, trade name FlexVent™ is manufactured by TRA-Mage, Inc. and has been approved by the ICC Evaluation Service (2009) for installation[2] on clay and concrete tile roofs.

Its minimum net free ventilation area is 6.72 square inches per linear foot for a 9-in wide copper sheet. FlexVent™ was evaluated in accordance with the requirements of ICC AC132 (2002) and found to pass criteria established for the net free area and for the dust accumulation of attic vents.

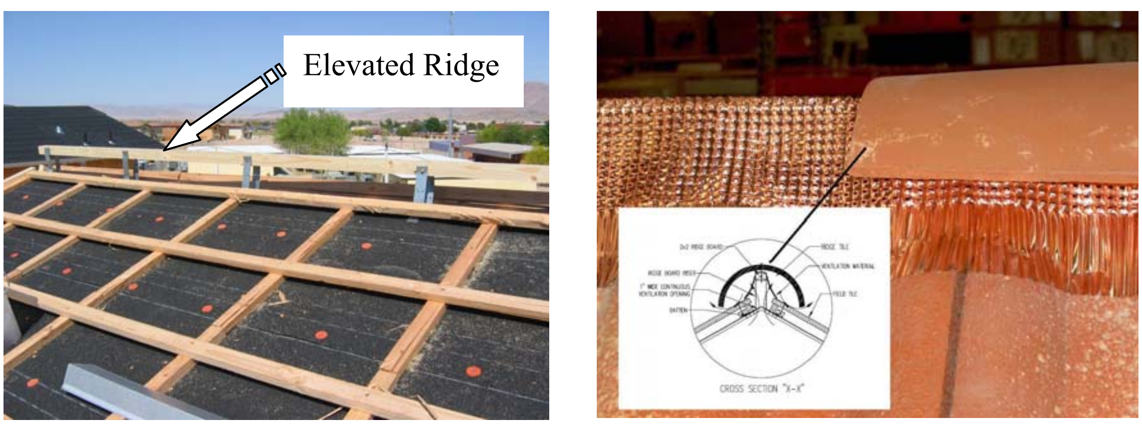


Fig.6a Ridge vent detail for homes N4 and N8

Fig. 6b FlexVent™ draped over ridge and capped by tile.

Figure 6. Elevated ridge vent (6a) and the FlexVent™ (6b) for providing natural ventilation above the sheathing from one opposing roof to the other.

[2] The web site http://www.tra-mage.com/ventilationa.html shows the installation instructions for the FlexVent™.

Instrumentation and Data Acquisition

Instrumentation was added to each demonstration home to monitor temperatures and heat flows across the roof and attic assembly and the relative humidity of the ambient air in the attic (Fig. 2 shows a thermistor used to measure attic air temperature). Sensors were also installed in the living space to measure the indoor ambient return and supply air temperatures and indoor relative humidity. Whole house power and air-conditioner power were also measured at the homes.

Roof Deck and Attic Floor (Ceiling)

The patch panel displayed in Figure 2 held a heat flux transducer against the LP Techshield roof deck. The patch panel is also LP Techshield but is 5/8-in (0.01856-m) OSB. As stated the HFT was embedded in the patch panel in a routed slot that allowed the HFT to fit flush to the surface of the OSB. Samples of the TechShield were retrieved from the construction site and tested at ORNL for thermal emittance and for thermal conductivity. Thermal emittance of the foil was 0.045 as measured using ASTM C 1371-98. The sample of LP TechShield was placed in a heat-flow metering apparatus and checked using the ASTM C518 (ASTM 2004) protocol. The thermal conductivity was measured at various heat flows through the TechShield, and it showed slight temperature dependence with board temperature; it being fitted as:

$$k_{OSB} = 5.97\times10^{-5}(T) + 0.4349 \text{ Btu/(hr ft } ^{o}\text{F)},$$

or

$$k_{OSB} = 1.86\times10^{-4}(T) + 0.0786 \text{ W/(m K)}.$$

Shunting due to the differences in thermal conductance of the HFT and the OSB was accounted for by calibrating the HFT using the ASTM C518 protocol (ASTM 2004). A guard made of the two different thicknesses of LP Techshield with a 0.15-in (0.004-m) thick HFT sandwiched between them was calibrated in a heat flow metering apparatus to eliminate 3-dimensional heat transfer effects around the HFT. However, in the field the output from the patch panel arrangement had to be adjusted for the added thermal resistance of the thicker TechShield panel. The adjustment was derived by again calibrating the HFT embedded just in the thinner piece of TechShield. The ratio of the two calibration factors then became a multiplicative factor applied to the output of the HFT to correct for the effect of the added thickness of the patch panel.

The heat flux crossing the attic floor was measured using three pairs of thermocouples that measured the temperature difference across the faced fiberglass insulation. Clark Construction installed R_{US}-38 (hr ft^2 ^{o}F)/Btu [R_{SI}-6.7 (m^2 K)/W] fiberglass insulation on the attic floor. The insulation was faced with brown Kraft paper facing up into the attic. Therefore 3 pairs of thermocouples were separated by about 2-m along the length of the attic. One thermocouple from each pair was inserted just inside the Kraft paper and taped in place, while the other 3 thermocouples from each pair were taped to the gypsum board and were in contact with the fiberglass insulation.

Weather Station

A fully instrumented meteorological weather station was available near the Ft Irwin complex and was used to collect the ambient dry bulb temperature, the relative humidity, the wind direction, the wind speed and the horizontal irradiance. The station was used to collect data for the prevailing wind speed and direction. For outdoor air temperature, sheathed thermistor probes were placed under the eave of the north facing roof of house N4 and also under the eave of the south facing wall on house N10. The thermistor probes gave good agreement during the summer; however, during the winter solar heating of the south facing wall on house N10 caused natural convection that elevated its thermistor probe's reading above that on house N4. Therefore the probe on house N4 provides a more accurate measure of the incident outdoor ambient temperature at the site.

Irradiance on the roofs was measured by pyranometers placed on each of the adjacent sloped roofs of all the homes. These measures helped prove that, for instance, the west (west??) facing roofs from a pair of homes had the same intensity of solar flux. The instruments also indicated the daylight hours and displayed peak irradiance with time of day.

Power measurements

Air-conditioner condenser power (compressor and outdoor fan) were measured with Continental Control Systems WattNode power transducers mounted inside the cover of the condenser unit. Current was measured with 30 amp Magnelab split-core current transformers. The heat pump is a Carrier split-system (Appendix A) and therefore the indoor blower power was measured with a clamp-on power meter to quantify blower usage. Ft Irwin supplied ORNL with the monthly revenue meter readings for all homes.

Data Acquisition System

Campbell Scientific micro-loggers were used for remote acquisition and recording of field data. Salient features of the micro loggers are provided in Table 2. The loggers were equipped with 4 Mbytes of memory, a 25 channel multiplexer for thermocouples, rechargeable battery, 115Vac-to-24Vdc transformer, modem, modem surge protector, weatherproof enclosure and associated cables.

The micro-logger was programmed to scan every 30 sec and reduce analog signals to the engineering units. Averages of the reduced data were electronically written to an open file every 15-min. The averages were calculated over the 15-min interval and are not running averages; they are reset after each 15-min interval. Electronic format is comma delimited for direct access by spreadsheet programs. Data files consist of one full week of data containing 672 rows of averaged measurements representing the instrument measurements written every 15-min over the 168 hours of a week. The micro logger automatically closes the existing file and opens a new data file every Friday at midnight for recording the next week of data. A dedicated desktop computer calls the micro logger and acquires the previous week of data over a modem connected to a dedicated phone line.

Table 2. Salient Features of Campbell Scientific data loggers.		
Item	**Item Description**	**CSI Part No.**
1	CR-23x Datalogger with 4 Mbytes memory	CR10X-2M
2	Array based operating system for CR-23X-4m	9801
3	Thermocouple reference thermistor for CR23X Wiring Panel	CR10XTCR
4	12 volt Power supply w/Charging regulator and rechargeable battery	PS100
5	18 volt 1.2 Amp wall charger, 6 ft.	9591
6	16-channel (4-wire) or 32-channel (2-wire) Relay Multiplexer	AM16/32
7	25-Channel Solid-State Multiplexer for Thermocouples	AM25T
8	Data cable, two peripheral connector cable for datalogger, 2 ft.	SC12
9	8-Channel Switch Closure Module	SDM-SW8A
10	Telephone Modem	COM210
11	Phone modem surge protector	6362
12	Enclosure 16/18, weather-resistant	15873

Monitoring Plan

Clark Construction and Realty suggested that ORNL pay an incentive for occupants to cooperate with the field demonstration during periods of most interest. ASHRAE's summer and winter comfort zones[3] show that a thermostat setting of about 72°F (22.2°C) would be very acceptable in the dry climate of the Mojave region surrounding Ft. Irwin. Therefore, for best occupant comfort and for simplicity the tenants were offered $200 per month; $600 per year for their cooperation. In return the tenants kept the thermostat at 72°F (22.2°C) during months of February, July and August of 2008.

FIELD RESULTS

Table 1 lists the configuration of the roofs for the four demonstration homes. The setup allows us two bases of comparison: 1) concrete tile applied directly to the deck, one coated with a cool color coating the other not coated, and 2) concrete tile elevated 1½-in above the deck, one roof coated with a cool color coating the other not coated. Houses N4 and N8 are a pair of homes (identical footprint) and have the double-batten assembly supporting the tile. Houses N5 and N10 are another pair of homes (having identical footprint) and have the tile attached directly to the deck.

The acquisition of field data for the two pair of homes started December 2007 and continued through August 2009. Results have been reduced for the complete period of study; however, presentation herein will be limited to those months where tenants kept the thermostat at the 72°F (22.2°C) control. The results that follow describe temperature and heat flow results for the roofs and attics of the demonstration homes. Afterwards, discussions about the cooling energy and whole house power measures are presented in the section on Cooling Energy Savings.

[3] ASHRAE provides data for acceptable ranges of operative temperatures for people in typical summer and winter clothing during primarily sedentary activity.

August Field Data for the Ft. Irwin Homes

As stated earlier, the Cool Tile IR COATING™ increased the solar reflectance of the medium profile concrete tile from 0.24 to 0.45. The added 21 points of solar reflectance dropped the surface temperature of the CRCM tiles consistently below those with conventional color pigments. During the afternoon hours for the week of August 1, 2008 (Figure 6) the ambient air temperatures peaked around 42°C (107.6°F). The ridge vent for the tile roofs run east-west and during the afternoon the sun's irradiance is directly incident on the south facing roofs. Again all homes have the same ridge orientation and have the same azimuth orientation to the sun (Fig. 1).

Surface Temperatures

Surface temperatures of the tile roofs with CRCMs are about 6°C (11°F) cooler during peak irradiance than the conventional pigmented color tile. Surface temperatures are almost identical for houses N4 and N5, both having infrared reflective pigments. House N5 has the tile attached directly to the deck (labeled D-t-D in Fig. 7) while the tile on

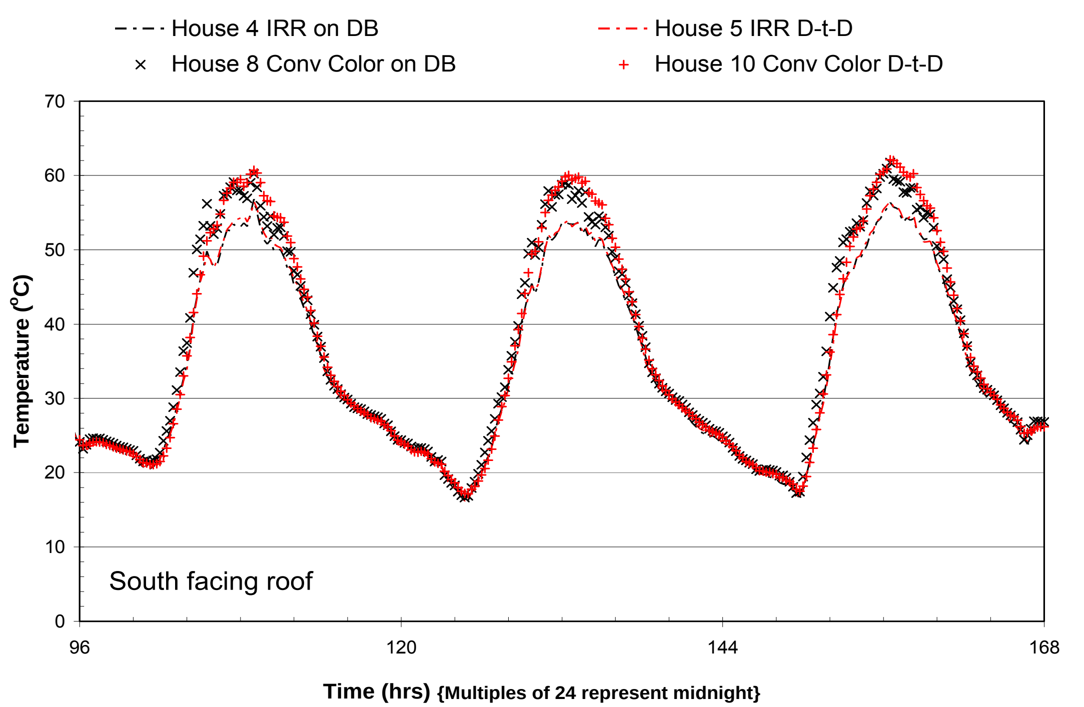


Figure 7. Surface temperature of the south facing roofs for the demonstration homes.

house N4 are on double battens (labeled DB in Fig. 7). Houses N8 and N10 also show similar roof surface temperatures. However, surface temperatures for the north facing roofs revealed that N10 had a tile surface temperature which was only about 1 to 2 ^{o}C (1.8 to 3.6^{o}F) higher than the north-facing roof of house N5 (see Appendix B, Fig. B1). All surface temperatures are observed to be within 0.5°C (1°F) around midnight, which implies their measurements are accurate to one another.

Attic Temperatures

Similar reductions occur in the attic air temperature. House N4 with double battens on the roof has an attic air temperature that is about 4°C (7.2°F) cooler than the attic air of house N8 having conventional pigmented tile, Figure 8. House N5 having CRCM tile applied direct to deck shows attic air temperatures about 2°C (3.6°F) cooler that that measured in the attic of house N10. It is interesting to note that the two homes with conventionally painted tile have peak attic air temperatures that exceed the attic air temperatures for the two other homes having IRR painted tile. However, Figure 8 also indicates that house N8 is hotter than house N10. One would expect the double battens would help reduce the attic air temperature as compared to the tile roof laid direct to the deck. The observation may perhaps be do to a difference in the performance of the solar fans actively ventilating the homes during the daylight hours. It is also interesting that the conventionally colored tile slightly lead in the occurrence of peak attic air temperature as compared to the cooler IRR tile.

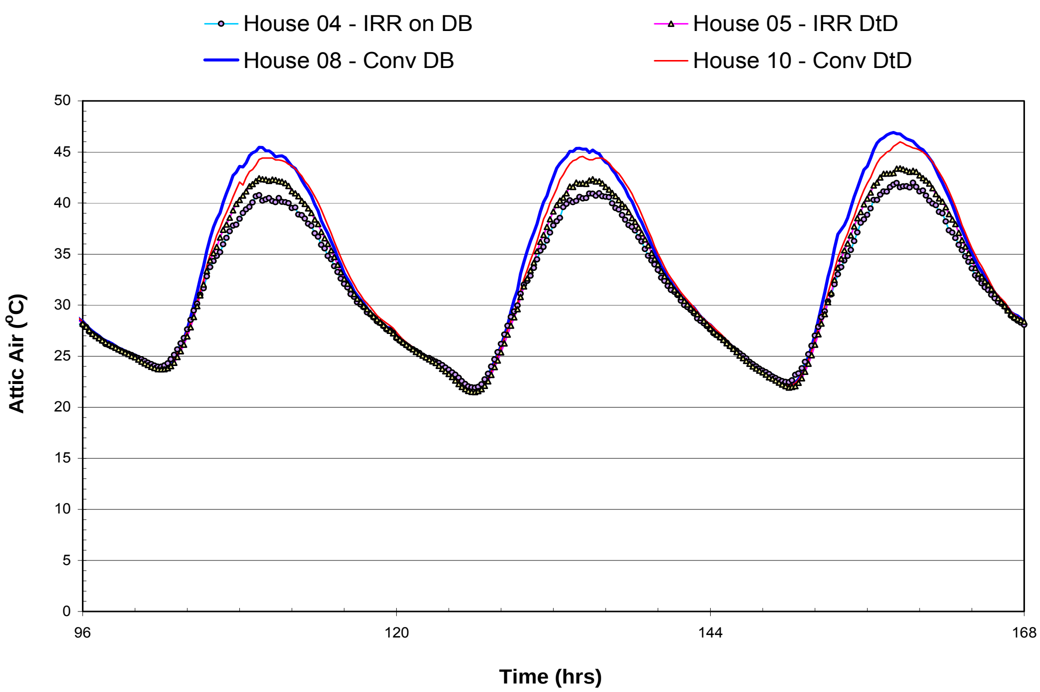


Figure 8. Attic air temperature for each house measured by sheathed thermistor probes. Figure 2 of the main text displays a thermistor attached to a truss member.

Roof deck heat flux

Heat flows measured through both the north- and south-facing roof decks of the homes show that the conventionally painted tile laid direct to deck (House N10) has the highest heat transfer crossing the deck. House N4 having tile with CRCMs and the tile elevated on battens had the lowest deck heat transfer (Fig. 9). Results however show greater

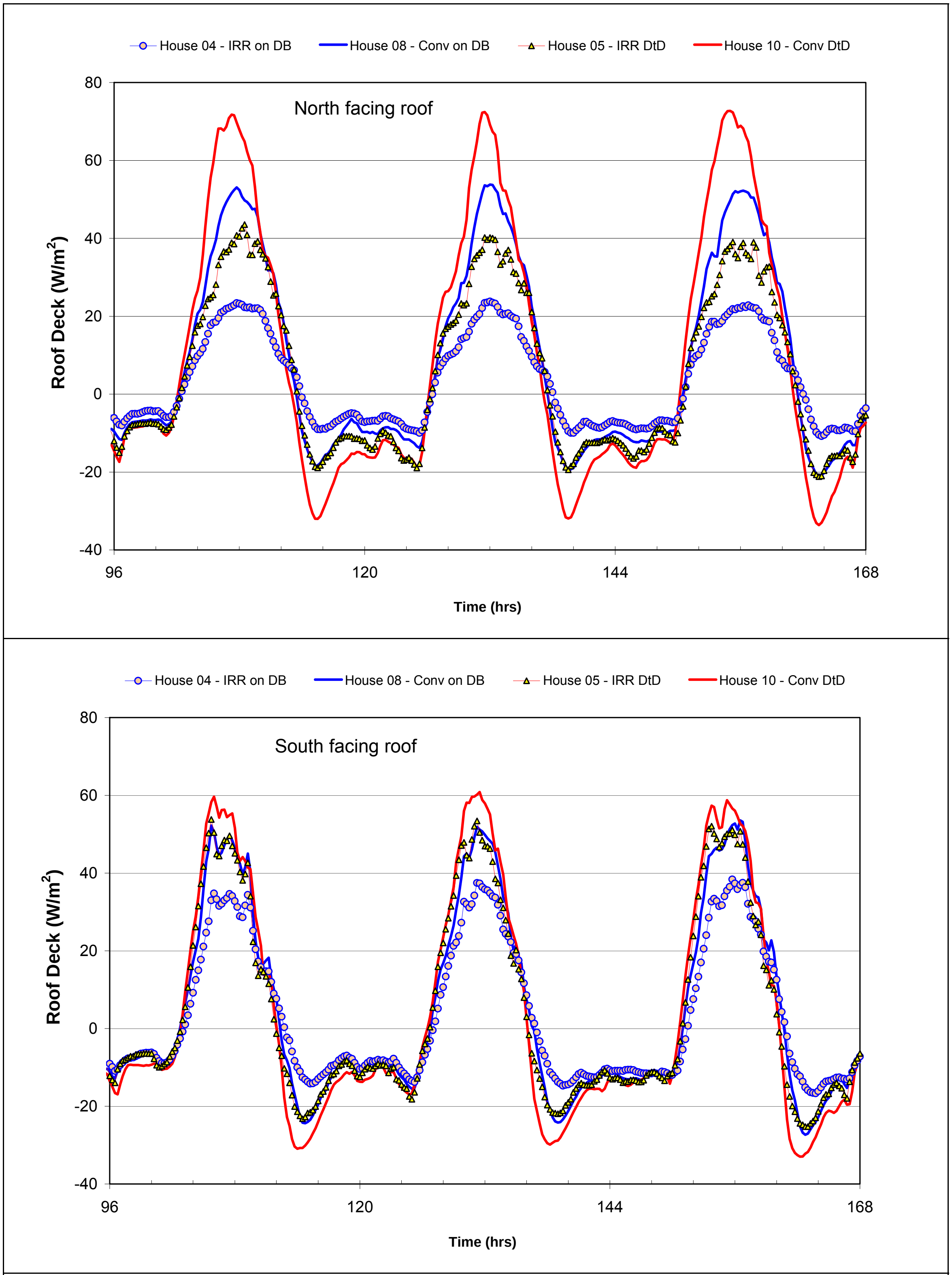


Figure 9. Heat flow crossing the north- and south-facing roof decks for August 2008.

differences on the north facing roofs as compared to the south facing roofs (Fig. 9). On the north-facing roof there is observed a definite difference in heat transfer between homes N5 and N8, indicating a possible benefit for tile painted with CRCMs as compared to tile on double battens with no cool color pigments. However, the south-facing roofs show the two assemblies have about the same heat flux penetrating into the attic, which indicates possibly that double battens are as effective as CRCMs. A closer look at the two figures reveals that the flux measured on the north-facing roofs of houses N8 and N10 exceed that measured on their respective south-facing roofs (Fig. 9). A check of the field data for October 2008 when the zenith angle of the sun is lower indicates the flux measures for all homes are consistent with a north- and south facing roof deck, Appendix B, Figure B2. The trend for the August 2008 data is therefore not as expected and confounds the data. Therefore no definitive statement will be made regarding the effectiveness of conventional pigmented tile placed on battens as compared to cool pigmented tile fastened directly to the deck. However, it is clear that the combination of a reflective tile with ASV is the preferred solution for reducing energy consumption.

Attic floor heat flux

Heat flows measured through the attic floor during the Aug 08 week of data show that house N4 incurs the least heat penetrating into the conditioned space (Fig. 10). The roof tile on house N4 is painted with COOLTILE IR COATINGS™ and has a solar reflectance of 0.45. It is very interesting that house N8 (conventional painted tile on double battens), house N5 (cool color tile laid directly to the deck) and house N10 (conventional painted tile laid direct-to-deck) all show about the same ceiling heat transfer. In comparison, the field data for October 2008 shows greater differences among houses N8, N5 and N10 (Appendix B, Fig. B3). However, the peak day heat transfer in Figure B3 is not consistent for houses N10 and N8; it swaps. The first day shows house N10 having the greatest ceiling heat flux, while on the third consecutive day house N8 has the higher peak day heat transfer. The reason behind this unexpected behavior is not clear but is believed due to the effect of the solar fans ventilating the homes. A variation in their performance could help explain the inconsistency. The October 2008 data does show that both assemblies of cool color concrete tile have lower heat transfer penetrating into the conditioned space than the conventional colored tile homes.

The results are not consistent with results shown for the roof decks. However, once again the solar fan attached to the north-facing roof deck may offer a plausible explanation to the trends. Figure 3 shows the O' Hagin vent and the solar powered exhaust vent that Clark Construction installed on all roofs. The O'Hagin vent was installed on the south-facing roofs while the solar[4] powered vent was installed on the north-facing roofs. Possibly these ventilators are affecting summertime heat flows crossing the deck, while in October with the sun lower in the sky there is less of an effect. The results are somewhat confounding because it differs from findings by Miller et al. (2005), Miller and Kosny (2008) and by Beal and Shandra (1995). All three studies showed reduced heat flows penetrating into the attic if the concrete tile was installed atop double batten systems. However, a more recent field study by Wilcox (2007) elevated

[4] SOLATUBE makes the vent. Model number for the vent is "Solar Star" The company, SOLATUBE, would not provide salient features of their product. See http://www.solatube.com/residential/product-catalog/solar-star-attic-fans/index.php

similar flat concrete tiles already on 1 by 2-in. battens an additional ⅜ in (0.0093 m) above the roof deck based on recommendations from TRI (2002, 6, 20). Wilcox's results with the additional ⅜-in (0.0093-m) air space showed no improvement over the original batten system.

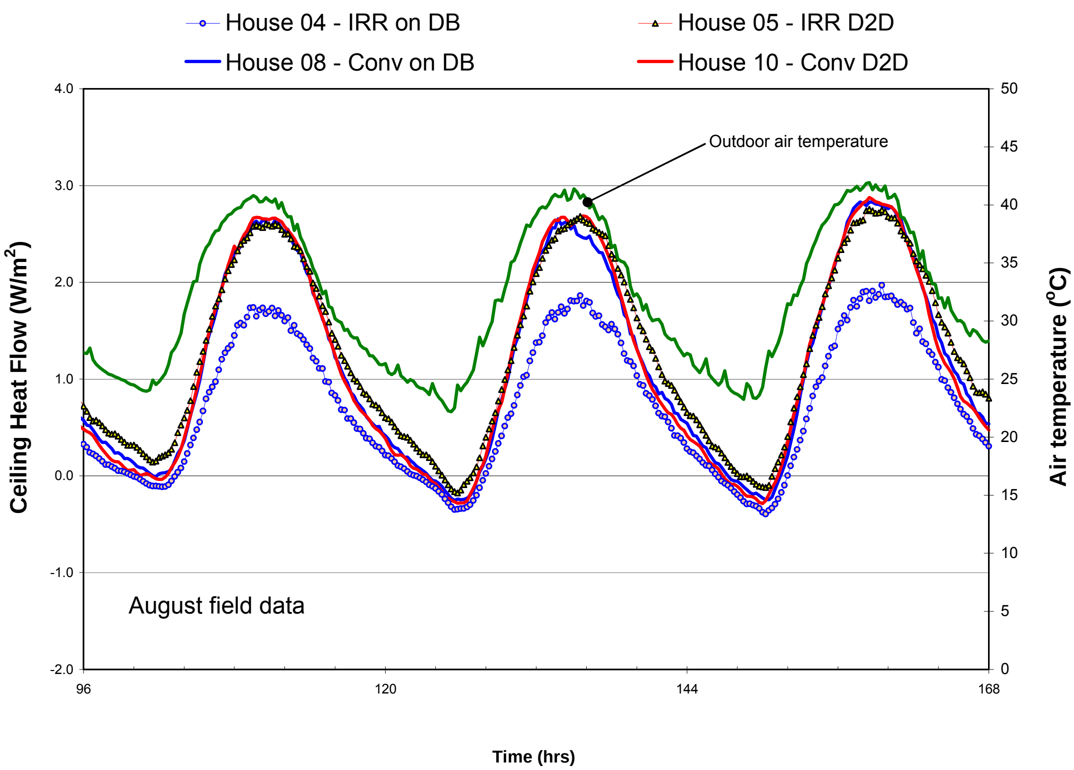


Figure 10. Ceiling heat flux data for the month of August 2008.

COOLING AND WHOLE HOUSE ENERGY

Occupancy habits are the Achilles heel of any residential demonstration. It is ironic that while the research conducted in building science targets improved energy efficiency and quality of life, the habits of people often deter energy conserving practices. Testing the homes while unoccupied would certainly help document reductions of whole house energy. As example, Parker et al. (2002) demonstrated that an unoccupied Florida home with a "white reflective" barrel-shaped concrete tile roof reduced the annual cooling energy by 22% of the energy consumed by an identical and adjacent home having an asphalt shingle roof. The cost savings due to the reduced use of comfort cooling energy was about US \$120 or about 6.7¢ per square foot per year. Parker's results have become a benchmark in the area of building science. However, Parker's results beg the question. "Are the results realistic when one considers people's occupancy habits?"

Clark Construction provided the monthly revenue meter readings for the four demonstration homes under study, Figure 11. The light blue shaded regions represent months where tenants were paid a \$200 incentive for each month they kept their thermostat at 22.2°C (72°F). During February 2008 the two homes with tile fastened directly to the deck incurred greater whole house energy consumption than the other pair of homes having tile on double battens. However, Table B.1 (Appendix B) reveals that the split system heat pump in house N5 used less energy that the other homes. During the months of July and August, 2008, home N4 used about 1700 kWh less electricity than home N8 (both homes have tile on double battens) while home N5 used 1560 kWh less electricity than home N10 (both homes have tile direct-to-deck). The homes with infrared reflective color pigments incurred greater than 35% reduction in electrical energy as compared to the homes with conventionally pigmented color tile. The summer result appears too good and some other confounding variable is affecting the field study

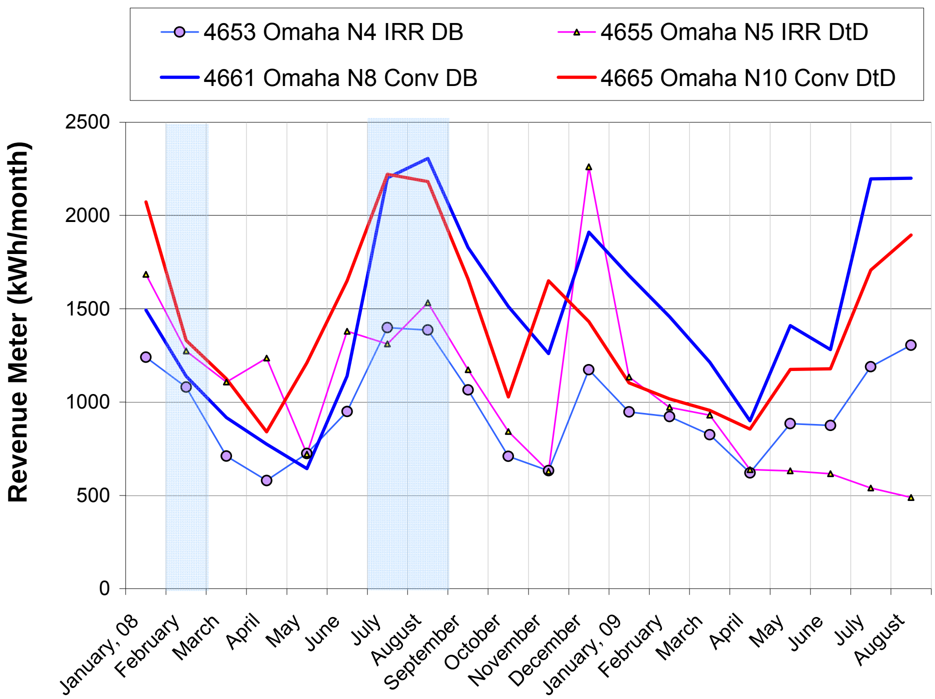


Figure 11. The revenue meter readings for the demonstration homes.

A questionnaire was therefore developed, and Clark Construction and Realty asked questions of the tenants. Results showed that the home N10 (conventional color tile fastened direct-to-deck) and house N8 (conventional color tile on double battens) had repairs made to their heat pumps. The units had lost refrigerant charge and were repaired during the summer period of control testing. Therefore, the best conclusive information gleaned from the revenue meter data is observed for house N4 having tile with cool color pigments and elevated above the deck on double battens. Results show over the 2 year course of study that this house consumed the least amount of electricity, Figure 11. It is also plausible to make a comparison between homes N4 and N5. Both homes have tile with cool coatings; however, the tile of house N4 are elevated about 1.5-in (0.038-m) above the deck. Here for the months of July and August, 2008, the heat pump of house N4 used about 110 kWh less energy than did the heat pump of house N5. Although the trend is also somewhat confounded because the return air temperature in house N4 is about 1°C warmer than in house N5, Table B.1 (Appendix B).

Regression of Field Data to Remove Effects of Occupancy

The principal focus for the field demonstrations centered on collecting attic and roof data to prove the thermal benefits of the cool pigment technology. The experiments also included air conditioning power and air-conditioning supply and return air temperatures in an effort to deduce estimates of annual savings despite the effects of occupancy habits or, put differently, poorly performing equipment, Figure 12.

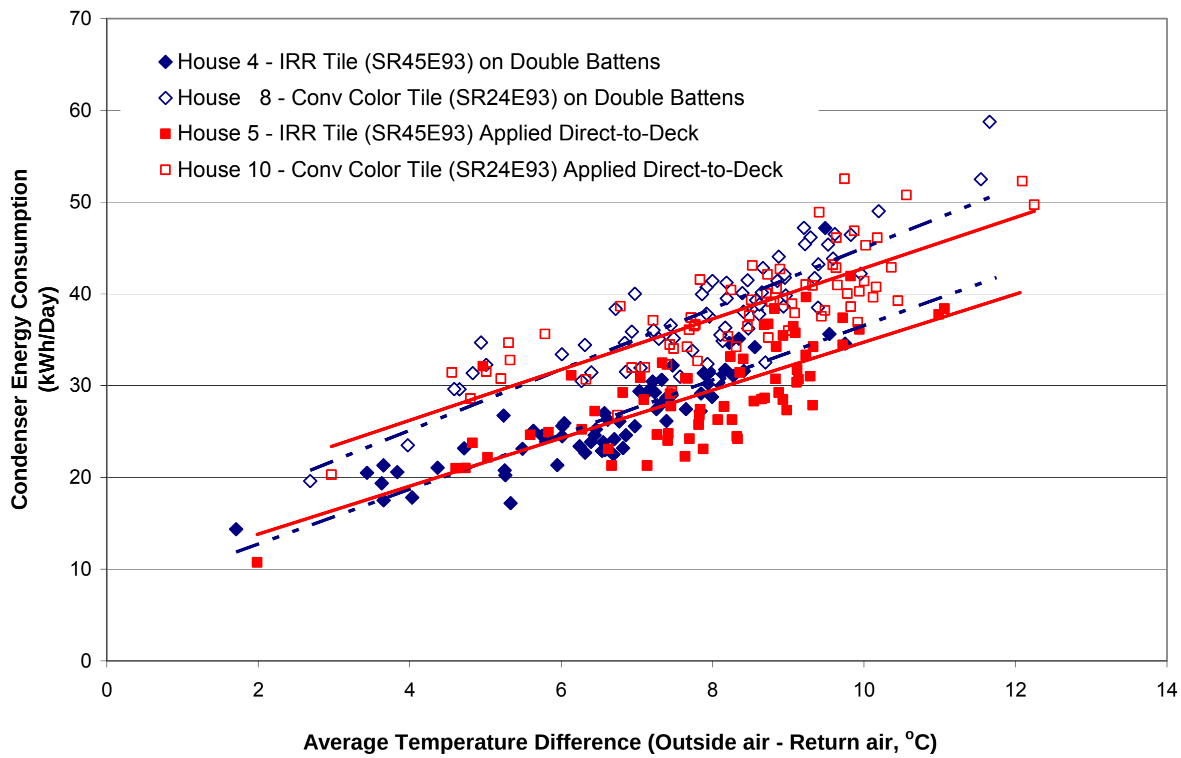


Figure 12. Condenser Energy Consumption versus the average outdoor-to-indoor temperature difference averaged over each 24-hour period of the July and August testing.

To correct for these differences, power measurements were reduced into daily electrical energy consumptions. The electrical usage of the air-conditioner was plotted against the daily average outside air-to-indoor air temperature difference, Figure 12. It is interesting to note that the hotter the outdoor air temperature the greater are the energy savings for the air-conditioners operating in the homes with CRCM roofs. The trend is slight yet could be important in terms of Time Dependent Valuation of energy that places a premium cost on energy consumed during the hottest portion of the day, Eley (2002).

The tile roofs painted with cool color pigments are observed to use less cooling energy whether the roof is nailed direct-to-deck or the tile is offset from the deck on double battens (view solid red color square and solid blue color diamonds in Fig. 12). The tile with conventional paint pigments also show similar performance whether the tile is elevated or attached directly to the deck (view open red color square to open blue color diamonds in Fig. 12). The drop in condenser kWh draw for house N4 as compared to house N8 (both on double battens) is similar to the drop in kWh draw observed for house N5 compared to house N10 (both having the tile fastened direct-to-deck). Repetition Figure 12 shows no benefit for the effect of the double batten system.

MONIER ROOF PHYSICS SOFTWARE

Monier Technical Centre (MTC) has developed a computer code that includes the effect of forced and natural convection heat transfer occurring in the vented air channel of a tile roof, [With, Cherry and Haig (2009)]. The Monier Roof Physics software (MRPS) was used to simulate heat flows through the four demonstration homes in an effort to corroborate the field measurement data. Both ORNL and MTC have expressed concern regarding the accuracy of the experimental data, specifically the effect of the occupants, inconsistency in some of the HVAC equipment and the unknown properties of some of the roofing and ventilation components.

Despite these concerns and necessary assumptions made, the MRPS simulations show good agreement with the trends and magnitude of the field measurement data. Figure 13 shows the measured and simulated heat flux for the south facing roofs. The

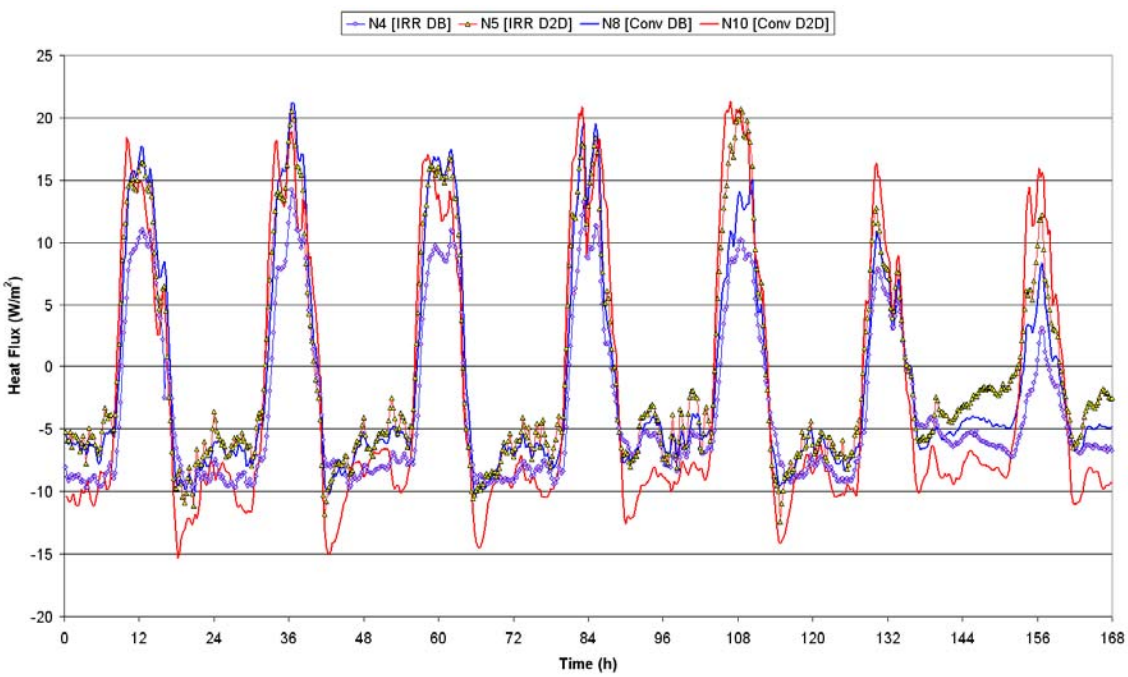


Figure 13. Field measures of the south-facing roof deck for all homes made by the MRPS code as compared to the predictions shown in Figure 14.

computer tool was able to predict the trends and magnitude of the field data. However, modeling the correct airflow and ventilation paths is critical in obtaining representative results (Figure 14), especially in winter when heat is leaving the buildings rather than entering them.

The field measurements and MRPS simulations indicate that the house without a NIR-reflective tile coating and without above-sheathing ventilation is the worst performer, and the house with both features is by far the best. The relative performance of the reflective coating and the ventilation individually is less obvious, but it is clear that the combination of a reflective tile with ASV is the preferred solution for the best energy saving.

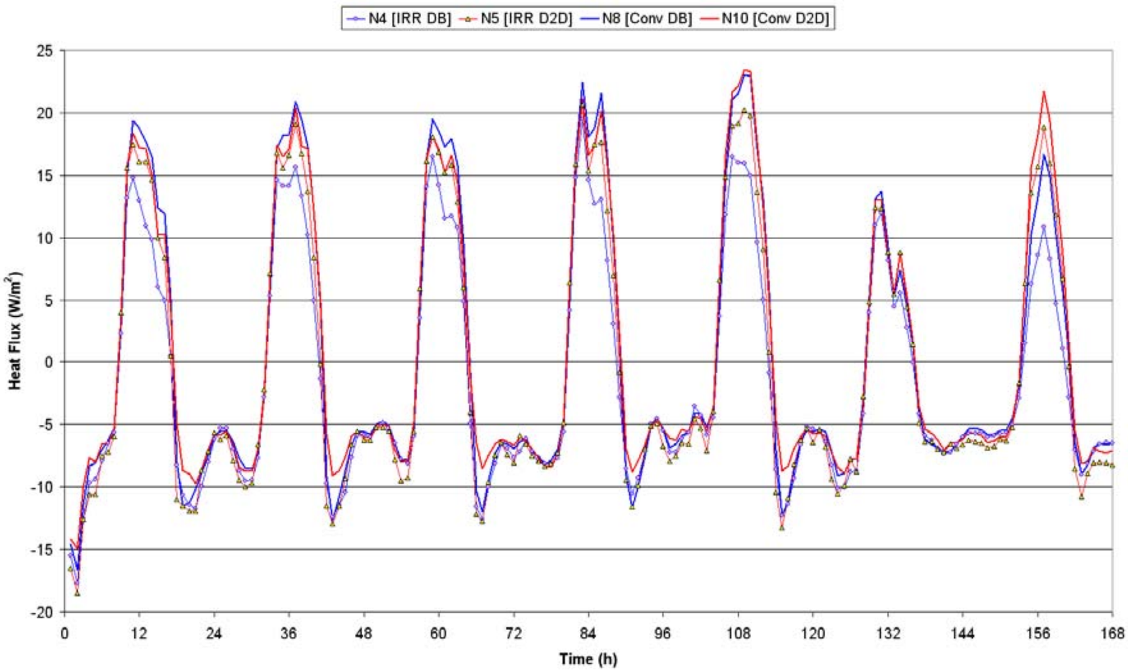


Figure 14. Predictions of the south-facing roof deck for all homes made by the MRPS code as compared to field data in Figure 13.

CONCLUSIONS

The primary purpose of the experiment was to evaluate the relative performance of a near-infrared reflective tile coating against conventional, uncoated tiles. Two of the houses were painted with the reflective coating and two were left with their original painted surfaces. In addition, one house from each pair had their tiles laid direct-to-deck and the tiles on the other two houses were laid on double-battens. This allowed for an investigation of the effect of enhanced above-sheathing ventilation.

No definitive statement can be made regarding the effectiveness of conventional pigmented tile placed on double battens as compared to cool pigmented tile fastened directly to the deck because of the effect of the occupants, inconsistency in some of the HVAC equipment and the unknown properties of some of the roofing and ventilation components. The measured attic air temperatures clearly show that the tiles coated with CRCMs perform better than those with conventional paint pigments. However, discrepancies in operation of the solar vents may be confounding the results.

Yet despite these issues the Monier Roof Physics Software has been used to simulate these scenarios in an effort to corroborate the field measurement data and the conclusions that have been drawn from them. The field measurements and MRPS simulations indicate that the house without a NIR-reflective tile coating and without above-sheathing ventilation is the worst performer, and the house with both features is by far the best. The relative performance of the reflective coating and the ventilation individually is less obvious, but it is clear that the combination of a reflective tile with ASV is the preferred solution for the best energy saving.

ACKNOWLEDGEMENTS

Funding for this project was provided by the California Energy Commission's Public Interest Energy Research program through the U. S. Department of Energy under contract DE-AC03-76SF00098. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

DISCLAIMERS

Mention of the trade names, instrument model and model number, and any commercial products in the manuscript does not represent the endorsement of the authors nor their employer, the Oak Ridge National Laboratory or the US Department of Energy.

NOMENCLATURE

ASV	Above sheathing ventilation
CRCM	Cool roof color materials
D-t-D	Direct-to-deck placement of tile roofs
DB	Double batten mounting for tile roofs
DOE	Department of Energy
ICC	International Code Council
k_{OSB}	Thermal conductivity of OSB Btu/(hr ft °F)
LP	Louisiana Pacific
MRPS	Monier Roof Physics software
NIR	Near infrared reflective
PIER	Public Interest Energy Research
RCI	Residential Community Initiative
SR	solar reflectance
TE	thermal emittance
TRI	Tile Roof Institute
R_{US}	Thermal resistance (hr ft^2 ^{o}F° per Btu
R_{SI}	Thermal resistance (m^2 K) per Watt

REFERENCES

Akbari, H., P. Berdahl, R. Levinson, R. Wiel, A. Desjarlais, W. Miller, N. Jenkins, A. Rosenfeld, and C. Scruton. 2004. "Cool Colored Materials for Roofs." In Proceedings of the ACEEE 2004 Summer Study on Energy Efficiency in Buildings, vol. 1, 1-12. Washington, D.C.: American Council for an Energy-Efficient Economy.

ASHRAE. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2005. "Thermal Resistances of Plane Air Spaces," Chapter 22.2, Table 2. In Fundamentals Handbook. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASTM. 2004. Designation C 1371-04a: Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2004. Designation C518-04: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2009. Designation C1549-09: Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer. American Society for Testing and Materials, West Conshohocken, PA.

Beal, D. and S. Chandra. 1995. "The Measured Summer Performance of Tile Roof Systems and Attic Ventilation Strategies in Hot Humid Climates." In Thermal Performance of the Exterior Envelopes of Buildings VI, 753-760. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Eley Associates. 2002. Life Cycle Cost Methodology: 2005 California Building Energy Efficiency Standards. P400-02-009. Sacramento: California Energy Commission.

ICC Evaluation Service. 2009. FLEXVENT™ Aluminum and Copper Roll Roof Ventilation. Evaluation Report ESR-1787.

ICC Evaluation Services. 2002. Shingle Vent Ii Ridge Vents For Attic Ventilation. Evaluation Report ER-5070.

Miller, W.A. and J., Kośny. 2008. "Next Generation Roofs and Attics for Homes," in ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2008.

Miller, W.A., MacDonald, W.M., Desjarlais,A.O., Atchley, J.A.,Keyhani, M., Olson, R., Vandewater, J. 2005. Experimental analysis of the natural convection effects observed within the closed cavity of tile roofs. RCI Foundation conference, "Cool Roofs: Cutting through the glare." Atlanta GA. May 12-13.

Parker, D.S., Sonne, J. K., Sherwin, J. R. 2002. "Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida," in ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2002.

Parker, D. S. and J. R. Sherwin. 1998. "Comparative Summer Attic Thermal Performance of Six Roof Constructions." ASHRAE Trans. 104, Part 2: 1084–1092.

RTI. Roof Tile Institute. 2002. Concrete and Clay Roof Tile Installation Manual for Moderate Climate Regions. ICBO ER-6034P. Eugene, Ore.: Roof Tile Institute.

Wilcox, B. 2007. "Klein House Vented Tile Experiment Results." Presentation by Public Interest Energy Research Research to the California Energy Commission.

With, G. de, Cherry, N. J. and Haig, J.R. 2008. Thermal Benefits of Tiled Roofs with Above-Sheathing Ventilation. Journal of Building Physics, Vol. 33, No. 2, October 2009, pp. 171-194.

Appendix A Salient Features of the Demonstration Homes

	N4	N8	N5	N10
Roof system				
Construction	Double-batten	Double-batten	Direct-to-deck	Direct-to-deck
Battens	1-in by 2-in	1-in by 2-in	1-in by 2-in	1-in by 2-in
DB Spacing eave to ridge [in (m)]	16 (0.406)	16 (0.406)	16 (0.406)	16 (0.406)
DB horizontal Spacing [in (m)]	13.5 (0.343)	13.5 (0.343)	13.5 (0.343)	13.5 (0.343)
Roof Pitch	4 in 12	4 in 12	4 in 12	4 in 12
Roof area [ft^2 (m^2)]	1496 (139)	1496 (139)	1382 (128)	1382 (128)
Height attic floor to Ridge [ft (m)]	18.41 (5.6)	18.41 (5.6)	18.41 (5.6)	18.41 (5.6)
Ridge length [ft (m)]	46 (14)	46 (14)	46 (14)	46 (14)
Width of roof [ft (m)]	32.8 (10)	32.8 (10)	29.5 (9)	29.5 (9)
Ridge Orientation	78° CW from magnetic North	78° CW from magnetic North	78° CW from magnetic North	78° CW from magnetic North
Ridge vent	FlexVent™ [2]	FlexVent™ [2]	NA (2 by 6 stop)	NA (2 by 6 stop)
Eave	Perforated bird stop	Perforated bird stop	Perforated bird stop	Perforated bird stop
Underlayment	Type 30 saturated felt paper	Type 30 saturated felt paper	Type 30 saturated felt paper	Type 30 saturated felt paper
Roof Tile				
Eagle Roofing Tile	Capistrano	Capistrano	Capistrano	Capistrano
Color of Tile	Dark brown [1]	Dark brown [1]	Dark brown [1]	Dark brown [1]
Solar reflectance	0.45	0.24	0.45	0.24
Thermal emittance	0.93	0.93	0.93	0.93
Tile thickness [in (mm)]	0.61 (15.5)	0.61 (15.5)	0.61 (15.5)	0.61 (15.5)
Tile length [in (m)]	17 (0.432)	17 (0.432)	17 (0.432)	17 (0.432)
Tile width [in (m)]	12⅜ (0.3143)	12⅜ (0.3143)	12⅜ (0.3143)	12⅜ (0.3143)
Thermal conductivity Btu/(hr ft °F) W/(m K)	0.867 (1.50)	0.867 (1.50)	0.867 (1.50)	0.867 (1.50)
Tiles per Square lbm kg	10.17 4.613	10.17 4.613	10.17 4.613	10.17 4.613
Density lb/ft^3 kg/m^3	137.4 (2200)	137.4 (2200)	137.4 (2200)	137.4 (2200)
Specific heat Btu/(lbm °F) J/(kg K)	0.1994 (835)	0.1994 (835)	0.1994 (835)	0.1994 (835)
Air Porosity in^2/ft^2 mm^2/m^2	1.422 (4000)	1.422 (4000)	1.422 (4000)	1.422 (4000)
Air Permeability [3]Perm in Kg/(m s Pa)	4.2996 (6.25E-012)	4.2996 (6.25E-012)	4.2996 (6.25E-012)	4.2996 (6.25E-012)

[1] Flash coating consisted of an IR brown flash (SR of 0.42) and a light IR yellow/clay pot flash (SR of 0.52).
[2] Single layer of 9-in (0.229-m) wide perforated copper sheet having 6.72 in^2 per ft (0.0142 m^2 per m) of ventilation area.
[3] Perm defined as water vapor flux through a unit thickness of homogenous material (units: Perm = grain/(hr ft^2 in of Hg)

Appendix A Salient Features of the Demonstration Homes

	N4	N8	N5	N10
Attic system				
OSB Deck [in (m)]	LP Techshield 0.47 (0.01194 m)	LP Techshield 0.47 (0.01194 m)	LP Techshield 0.47 (0.01194 m)	LP Techshield 0.47 (0.01194 m)
Emittance (facing attic)	0.045	0.045	0.045	0.045
Ceiling insulation	R_{US} 38, 12-in thick R_{SI} 6.7, 0.305-m	R_{US} 38, 12-in thick R_{SI} 6.7, 0.305-m	R_{US} 38, 12-in thick R_{SI} 6.7, 0.305-m	R_{US} 38, 12-in thick R_{SI} 6.7, 0.305-m
Pine Truss [in (m)	2 by 4 (0.051 by 0.102)	2 by 4 (0.051 by 0.102)	2 by 4 (0.051 by 0.102)	2 by 4 (0.051 by 0.102)
Truss O.C. [in (m)]	24-in (0.610) on center	24-in (0.610) on center	24-in (0.610) on center	24-in (0.610) on center
O'Hagen vents [in^2 (m^2)]	97.5 (0.063)	97.5 (0.063)	97.5 (0.063)	97.5 (0.063)
Solar Star vents[in^2 (m^2)]	138.5 (0.089)	138.5 (0.089)	138.5 (0.089)	138.5 (0.089)
Gable vents [ft^2 (m^2)]	0.785 (0.073)	0.785 (0.073)	0.524 (0.049)	0.524 (0.049)
Soffit vents [ft^2 (m^2)]	1.505 (0.140)	1.505 (0.140)	1.113 (0.103)	1.309 (0.122)
Return Duct ID [in (m)]	18 (0.457)	18 (0.457)	18 (0.457)	18 (0.457)
Duct length [ft (m)]	15 (4.57)	15 (4.57)	15 (4.57)	15 (4.57)
Duct insulation [R_{US} (R_{SI})]	R_{US} 6 (R_{SI} 1.06)	R_{US} 6 (R_{SI} 1.06)	R_{US} 6 (R_{SI} 1.06)	R_{US} 6 (R_{SI} 1.06)
Attic footprint [ft^2 (m^2)]	1082 (100)	1082 (100)	1011 (94)	1011 (94)
Heat Pump (Carrier split-system)				
Condenser	Model 25HBR342A300	Model 25HBR342A300	Model 25HBR342A300	Model 25HBR342A300
OD fan	1/8 HP, 208/230Vac	1/8 HP, 208/230Vac	1/8 HP, 208/230Vac	1/8 HP, 208/230Vac
Air handler	Model FC4DNF042	Model FC4DNF042	Model FC4DNF042	Model FC4DNF042
Blower	½ HP, 208/230Vac	½ HP, 208/230Vac	½ HP, 208/230Vac	½ HP, 208/230Vac
Metering	TXV	TXV	TXV	TXV
CFC-22 Charge [lbm (kg)]	10 (4.54)	10 (4.54)	10 (4.54)	10 (4.54)
House Interior				
Thermostat	White Rogers Model 1F72	White Rogers Model 1F72	White Rogers Model 1F72	White Rogers Model 1F72
NG Hot water	30 gal tank	30 gal tank	30 gal tank	30 gal tank
Supply Duct	1st and 2nd Floor	1st and 2nd Floor	1st and 2nd Floor	1st and 2nd Floor
Windows	Milgard (Vinyl) Double pane	Milgard (Vinyl) Double pane	Milgard (Vinyl) Double pane	Milgard (Vinyl) Double pane
Window U-factor	0.34	0.34	0.34	0.34
Window SHGC	0.20	0.20	0.20	0.20
Transmittance	0.47	0.47	0.47	0.47
House Exterior				
Garage	Detached	Detached	Detached	Detached
Wall Color	White Cream	Dark Copper	White Cream	Yellow Cream
Wall	Stucco	Stucco	Stucco	Stucco
Wall insulation [R_{US} (R_{SI})]	R_{US} 19 (R_{SI} 3.35)	R_{US} 19 (R_{SI} 3.35)	R_{US} 19 (R_{SI} 3.35)	R_{US} 19 (R_{SI} 3.35)
West Wall	Awnings over 1st Floor windows	Awnings over 1st Floor windows	Awnings over 1st Floor windows	Awnings over 1st Floor windows

Appendix A Salient Features of the Demonstration Homes

House N4 has concrete tile placed on double battens. The tile are coated with Cool Tile IR COATING™. The front door of house N4 is facing west.

House N8 has concrete tile placed on double battens. The tile have conventional paint pigments. The front door of house N8 is facing west.

Appendix A Salient Features of the Demonstration Homes

House N5 has concrete tile nailed direct to the deck. The tile are coated with Cool Tile IR COATING™. The front door of house N5 is facing west.

House N10 has concrete tile nailed direct to deck. The tile have conventional paint pigments. The front door of house N10 is facing west.

Appendix B
Additional Figures for the Demonstration Homes.

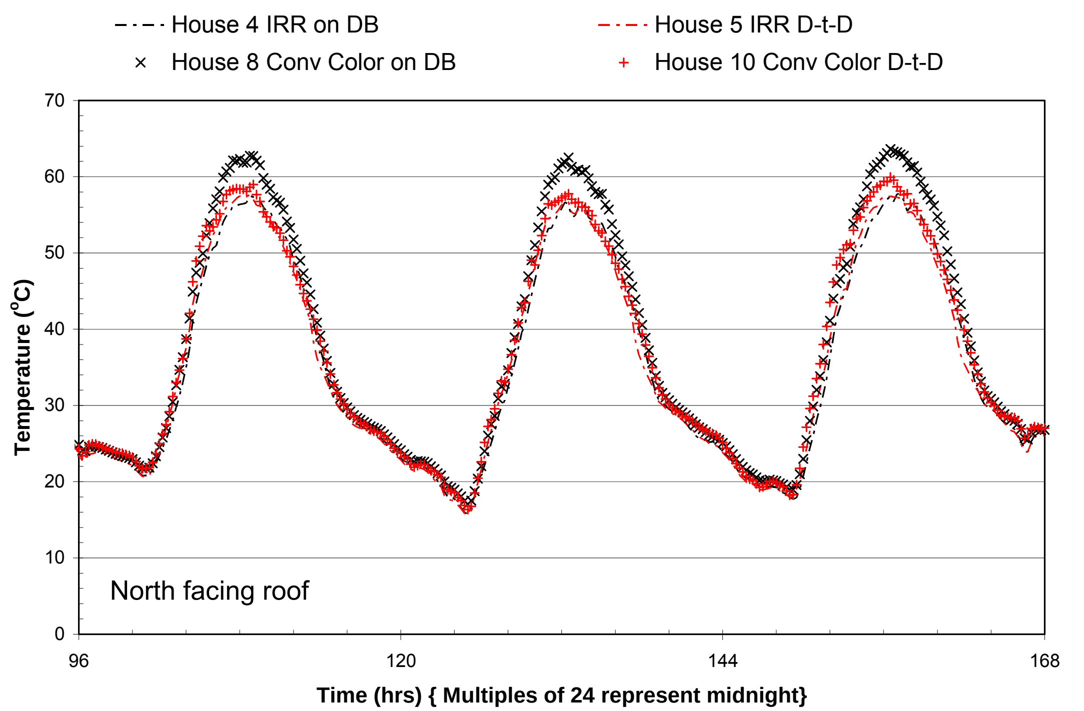
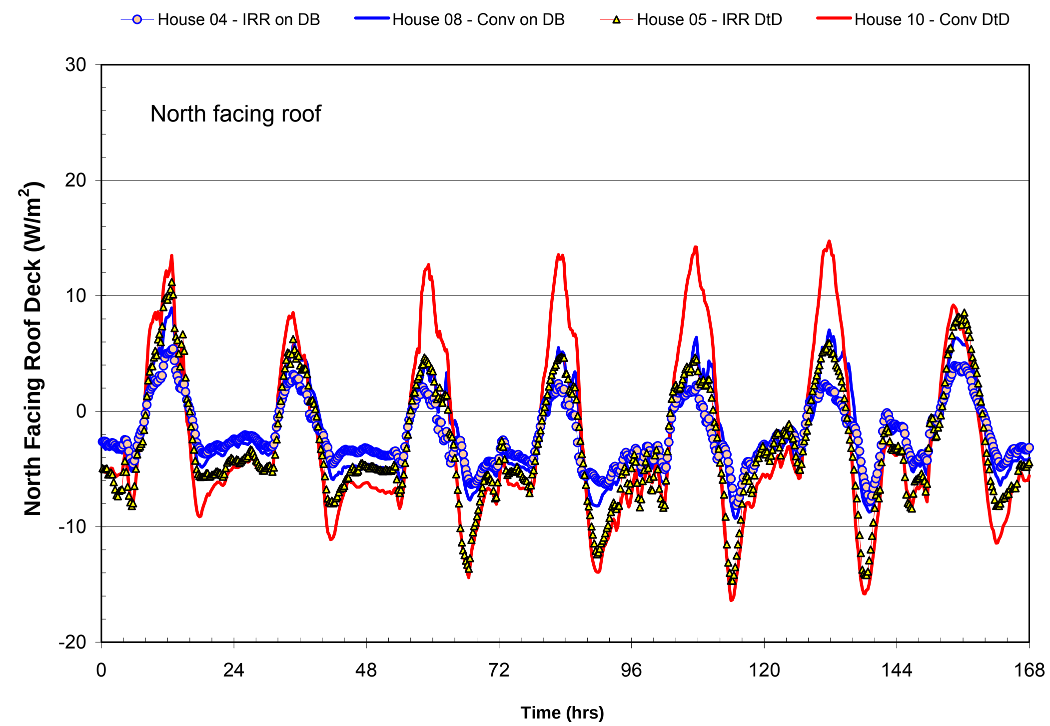


Figure B1. Surface temperature of the north facing roofs for the demonstration homes.

Appendix B
Additional Figures for the Demonstration Homes.



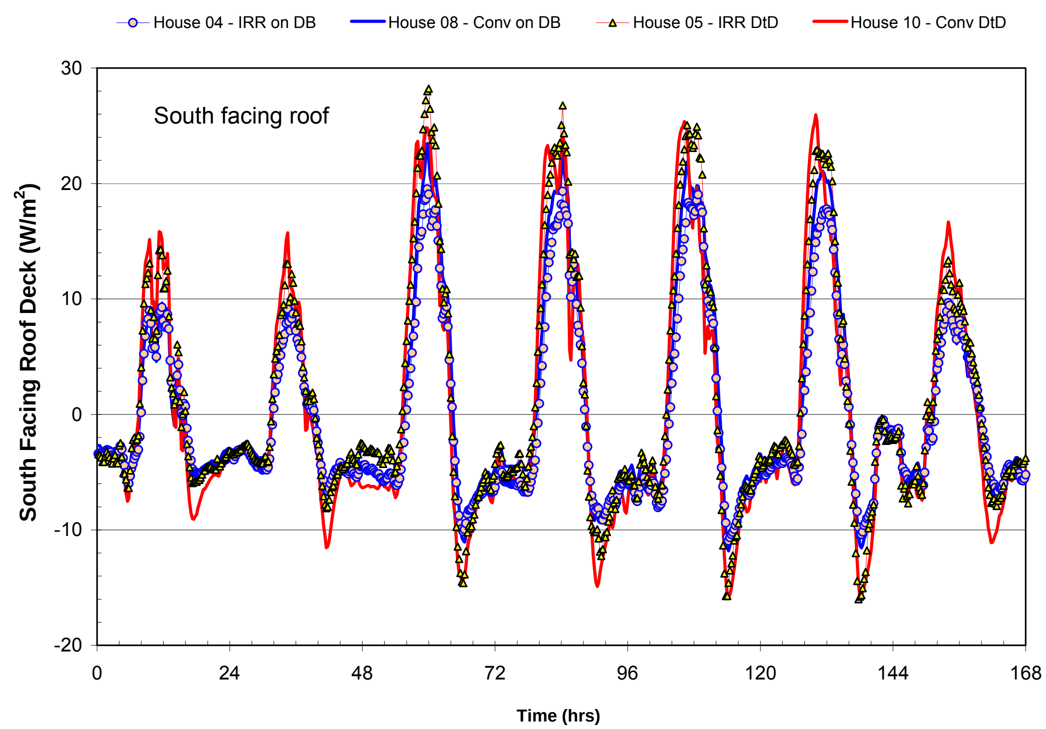


Figure B2. Heat flow crossing the north- and south-facing roof decks for all homes measured during October, 2008.

Appendix B
Additional Figures for the Demonstration Homes.

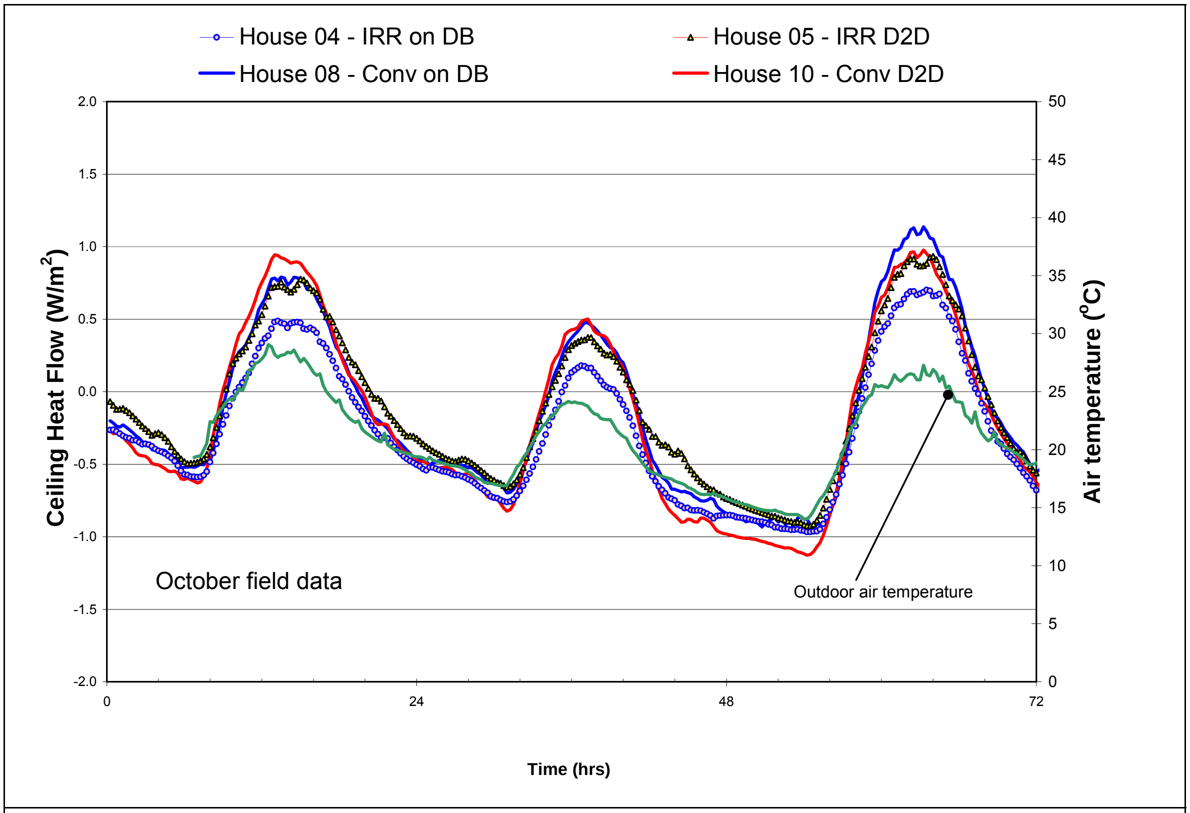


Fig. B3. Ceiling heat flux data for the month of Oct. 08.

Appendix B
Additional Figures for the Demonstration Homes.

Table B.1 Monthly averages for the outdoor air and indoor return air temperatures and the electrical energy consumed by each of the demonstration homes. Light blue shaded rows represent months where ORNL paid tenants to maintain the home's thermostat at 22.2°C (72°F).

Ft Irwin Demonstration	N4	N8	N5	N10
Parameter	IRR Tile on DB	Conv Tile on DB	IRR Tile DtD	Conv Tile DtD
	Winter 2008 (January)			
OD Ambient Air (°C)	8.3	8.3	8.3	8.3
Indoor Return Air (°C)	18.7	21.3	21.0	23.2
Total Ceiling Heat Flux (kJ/m^2)	-3,467	-2,906	-3,816	-4,566
Heat Pump (kWh)	548.9	748.1	704.5	1031.8
Whole House Power (kWh)	1240	1493	1685	2073
Monthly Utility Charge ($)[1]	$182	$219	$248	$305
	Winter 2008 (February)			
OD Ambient Air (°C)	12.0	12.0	12.0	12.0
Indoor Return Air (°C)	21.2	21.9	21.3	22.3
Total Ceiling Heat Flux (kJ/m^2)	-2,985	-2,298	-2,981	-3,277
Heat Pump (kWh)	566.8	569.8	497.5	659.5
Whole House Power (kWh)	1080	1139	1274	1331
Monthly Utility Charge ($)[1]	$159	$167	$187	$196
	Winter 2008 (March)			
OD Ambient Air (°C)	15.9	15.9	15.9	15.9
Indoor Return Air (°C)	20.4	22.3	22.3	22.9
Total Ceiling Heat Flux (kJ/m^2)	-1,822	-1,389	-2,173	-2,193
Heat Pump (kWh)	152.9	331.5	267.8	366.5
Whole House Power (kWh)	710	917	1107	1125
Monthly Utility Charge ($)[1]	$104	$135	$163	$165
	Summer 2008 (June)			
OD Ambient Air (°C)	29.6	29.6	29.6	29.6
Indoor Return Air (°C)	26.6	25.5	25.1	26.3
Total Ceiling Heat Flux (kJ/m^2)	998	1,790	1,502	1,424
Heat Pump (kWh)	434.4	584.3	1067.7	637.9
Whole House Power (kWh)	949	1140	1380	1650
Monthly Utility Charge ($)[1]	$140	$168	$203	$243
	Summer 2008 (July)			
OD Ambient Air (°C)	33.1	33.1	33.1	33.1
Indoor Return Air (°C)	26.4	25.1	25.0	24.6
Total Ceiling Heat Flux (kJ/m^2)	2,022	3,006	3,154	2,901
Heat Pump (kWh)	811.3	1109.7	867.0	1138.1
Whole House Power (kWh)	1399	2202	1312	2221
Monthly Utility Charge ($)[1]	$206	$324	$193	$326
	Summer 2008 (August)			
OD Ambient Air (°C)	32.7	32.7	32.7	32.7
Indoor Return Air (°C)	25.9	24.7	24.8	24.2
Total Ceiling Heat Flux (kJ/m^2)	1,911	2,912	3,290	2,822
Heat Pump (kWh)	798.5	1122.1	855.5	1150.8
Whole House Power (kWh)	1386	2306	1532	2182
Monthly Utility Charge ($)[1]	$204	$339	$225	$321

[1] CA Electricity (EIA 2009) 14.7¢ per kWh

Appendix B
Additional Figures for the Demonstration Homes

Instrument	*Description*	Location	Attachment	Channel	
Unit N4, North Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	12 T	
“	26 AWG Unshielded bead	Underside of Tile	Epoxy	11 T	
“	26 AWG Shielded bead	Air gap	Taped	10 T	
“	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	7 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	3	2847
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	4	56040
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	9 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	8 T	
Unit N4, South Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	6 T	
“	26 AWG Unshielded bead	Underside of Tile	Epoxy	5 T	
“	26 AWG Shielded bead	Air gap	Taped	4 T	
“	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	3 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	1	2844
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	2	56052
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	2 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	1 T	
Unit N4, Attic interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Attic air 4-ft above insulation	Run along support wire	5	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	18 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	17 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	16 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	15 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	14 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	13 T	
Unit N4, House exterior underneath soffitt					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Ambient air (shaded by soffit)	Mounted through eave	6	
Unit N4, House interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Entering return grill	Duct mounted	7	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Thermostat (in wall)	Inside Thermostat Housing	20 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Leaving evaporator coil	Run along support wire	19 T	
Wattnode transducer	Model WNA-1P-240-P	HVAC Power	Inside HVAC condenser housing	**1**	

Appendix B
Additional Figures for the Demonstration Homes.

Instrument	*Description*	Location	Attachment	Channel	
Unit N8, North Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	11 T	
"	26 AWG Unshielded bead	Underside of Tile	Epoxy	12 T	
"	26 AWG Shielded bead	Air gap	Taped	10 T	
"	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	9 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	3	2852
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	4	56050
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	8 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	7 T	
Unit N8, South Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	6 T	
"	26 AWG Unshielded bead	Underside of Tile	Epoxy	5 T	
"	26 AWG Shielded bead	Air gap	Taped	4 T	
"	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	3 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	1	2848
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	2	56051
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	2 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	1 T	
Unit N8, Attic interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Attic air 4-ft above insulation	Run along support wire	5	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	18 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	17 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	16 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	15 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	14 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	13 T	
Unit N8, House exterior underneath soffitt					
107-L35 Thermistor	DB Probe			NA	
Unit N8, House interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Entering return grill	Duct mounted	6	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Thermostat (in wall)	Inside Thermostat Housing	20 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Leaving evaporator coil	Run along support wire	19 T	
Wattnode transducer	Model WNA-1P-240-P	HVAC Power	Inside HVAC condenser housing	1	

Appendix B
Additional Figures for the Demonstration Homes.

Instrument	*Description*	Location	Attachment	Channel	
Unit N5, North Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	12 T	
"	26 AWG Unshielded bead	Underside of Tile	Epoxy	11 T	
"	26 AWG Shielded bead	Air gap	Taped	10 T	
"	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	9 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	3	2889
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	4	57172
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	8 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	7 T	
Unit N5, South Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	6 T	
"	26 AWG Unshielded bead	Underside of Tile	Epoxy	5 T	
"	26 AWG Shielded bead	Air gap	Taped	4 T	
"	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	3 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	1	2890
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	2	56162
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	2 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	1 T	
Unit N5, Attic interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Attic air 4-ft above insulation	Run along support wire	5	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	18 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	17 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	16 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	15 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	14 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	13 T	
Unit N5, House exterior underneath soffitt					
107-L35 Thermistor	DB Probe			NA	
Unit N5, House interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Entering return grill	Duct mounted	6	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Thermostat	Inside Thermostat Housing	20 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Leaving evaporator coil	Run along support wire	19 T	
Wattnode transducer	Model WNA-1P-240-P	HVAC Power	Inside HVAC condenser housing	1	

Appendix B
Additional Figures for the Demonstration Homes.

Instrument	*Description*	Location	Attachment	Channel	
Unit N10, North Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	11 T	
“	26 AWG Unshielded bead	Underside of Tile	Epoxy	12 T	
“	26 AWG Shielded bead	Air gap	Taped	10 T	
“	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	9 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	3	2866
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	4	56160
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	8 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	7 T	
Unit N10, South Facing Roof					
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Tile Surface	Epoxy	5 T	
“	26 AWG Unshielded bead	Underside of Tile	Epoxy	6 T	
“	26 AWG Shielded bead	Air gap	Taped	3 T	
“	26 AWG Unshielded bead	Topside of Deck (near HFT between OSB & paper)	Taped	4 T	
Heat Flux Transducer	2-in by 2-in by 1/8-in thick (Wh/Bk +Signal)	Underside of OSB Deck	LP panel and wood screws	1	2864
Pyranometer Li-Cor	Solar Probe (Rd/Bk Signal White Ground	Near ridge at roof gable	Epoxy	2	56161
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic 2 ft from HFT)	Taped	2 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Underside of Deck (facing attic on HFT cover)	Taped	1 T	
Unit N10, Attic interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Attic air 4-ft above insulation	Run along support wire	5	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	18 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	17 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	16 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	15 T	
Thermocouple (Type T Cu/Con)	26 AWG Shielded bead	Top of insulation	TWP X Mount Laid atop insulation	14 T	
	26 AWG Unshielded bead	Sheet rock surface facing attic	Taped	13 T	
Unit N10, House exterior underneath soffitt					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Ambient air (shaded by soffit)	Mounted through eave	6	
Unit N10, House interior					
107-L35 Thermistor	DB Probe (Bk/Rd Signal) Purple Signal Ground	Entering return grill	Duct mounted	7	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Thermostat (inside wall)	Inside Thermostat Housing	20 T	
Thermocouple (Type T Cu/Con)	26 AWG Unshielded bead	Leaving evaporator coil	Run along support wire	19 T	
Wattnode transducer	Model WNA-1P-240-P	HVAC Power	Inside HVAC condenser housing	1	