FIELD THERMAL PERFORMANCE OF RADIANT BARRIERS AND INTERIOR RADIATION CONTROL COATINGS FOR ATTIC RETROFITS

Ali Fallahi[1], David Yarbrough[2], Jan Kośny[3]

ABSTRACT

For over a century, traditional bulk insulation materials like fiberglass and cellulose have been used in attics to prevent heat from escaping or entering American homes. But times are changing and today, builders and homeowners in Southern U.S. locations are discovering that adding attic reflective insulation may offer significant gains in thermal efficiency – often far greater than the same investment in additional layers of conventional bulk insulation. According to the US Information Administration (EIA[4]), in 2009 in average more than 6% of the US household end-use energy expenditure was for space cooling (air conditioning) while in the US hot humid climate region this space cooling expenditure went up to more than 25%. In order to reduce cooling energy consumption, techniques to limit radiative heat transfer such as Radiant Barriers (RB) and Interior Radiation Control Coatings (IRCC) can be applied to existing residential attics in single family homes or light commercial buildings. RBs incorporate two layers of aluminum foil or aluminized plastic film. Aluminum has a low emissivity, absorbing and emitting a small amount of infrared radiation. IRCC work in a similar manner, but it is a coating usually sprayed on the back side of the roof deck. There are claims that RB and IRCC are easier to install and very energy efficient in retrofit projects. The goal of this study is to understand these claims with analyzing changes in the annual cooling energy consumption and peak cooling loads by both experimental and numerical approaches. In Austin, Texas, both RB and IRCC were installed in test houses and compared to a baseline house with no modifications. The test houses were instrumented and thermal and energy performances of the attics were monitored for over 6 months. In addition the whole building energy consumption before and after retrofit was compared using EnergyPlus energy consumption simulations.

1. Introduction

Attic RBs and IRCCs present a unique way of increasing the thermal performance of existing or new insulation within the space between the roof deck and ceiling level in residential and small commercial buildings. Attic RBs save energy by reducing the transfer of heat from the hot roof to the attic floor insulation in the summer. The transfer of heat from the attic floor insulation to the roof in the winter is also reduced.

Aluminum surfaces, like those found in RB applications, have thermal emittances in the range of 0.03 to 0.06. Therefore, there is very little radiant transfer across a space bounded by a RB. Most often, RBs are aluminum foil laminates or aluminized synthetic films sheets. The foils are laminated to paper, most commonly to Kraft paper, synthetic films, oriented strand board (OSB),

[1] Ali Fallahi, Ph.D., R&D staff, Building Science Engineer, Fraunhofer CSE, Boston, MA
[2] David Yarbrough, Ph.D., P.E., President, R&D Services, Cookeville, TN
[3] Jan Kośny, Ph.D., Building Enclosure Program Lead, Fraunhofer CSE, Boston, MA
[4] http://www.eia.gov/consumption/residential/data/2009/index.cfm?view=consumption#end-use

or plywood. For the aluminized synthetic films, a thin layer of aluminum particles are deposited on the films through a vacuum process. These laminates and films are characterized by having at least one low-e surface of 0.1 or less (ASTM C 1313, 2010).

IRCCs are low-e coatings or paints that, when applied (i.e., sprayed or painted) to building surface (e.g., OSB, plywood, metal siding, or plasterboard), decrease the emittance of these surfaces to 0.25 or less (ASTM C 1321, 2009). Both RBs and IRCCs have received considerable attention due to their potential to reduce the radiant heat transfer across vented spaces between roofs and ceilings of buildings (e.g., attic spaces in residential buildings). In the case of RBs, aluminum is used because it is inexpensive and is a surface that, once exposed to air, becomes covered with a layer of a transparent oxide that protects it from the atmosphere and allows it to maintain a constant emittance for long periods of time[5].

In some cases, an RB can include an enclosed air space in order to provide thermal resistance to the path between the roof sheathing and the attic floor. In this study an RB was used with an enclosed air space, which is a common configuration with multi-layer products. In some cases, there is an R-value[6] [7] associated with the reflective insulation component application. In the configuration considered in this research, the thermal performance of interior-facing RB has to be combined with the low thermal conductive performance of the enclosed air cavities.

Low-e coatings (IRCCs) have similar heat reduction principles as RBs in residential attics. IRCCs are also being studied in this work. This is a crucial study for the industry since there are very few examples of directly measured savings due to spray-applied or liquid-applied attic IRCCs.

Base on Medina (2012), experimental results highlighting cooling load and ceiling heat flux reductions produced by RBs are vary depending on nominal ceiling insulation R-value, testing protocol, climate zone, ventilation type, occupancy and duct inclusion in the attics. Medina (2012) reported that in attics with nominal insulation levels of R-11, R-19 and R-30, average space cooling reductions are 14%, 20% and 6%, respectively. He also reported the average reduction in heat flow produced by installing RBs in attics with insulation levels of R-11, R-19 and R-30 are 45%, 30% and 23%.

According to Medina (2012), laboratory-controlled experiments of IRCC applied in a flat system configuration with an insulation level of R-19, produced average heat flow reductions of 32% (vs. the same system without the application of any coatings).

Although the industry does not have software to evaluate energy savings, there is an ASTM

---

[5] http://www.lenntech.com/periodic/elements/al.htm

[6] Thermal resistances calculated for an enclosed air space with one surface having emittance 0.03 and a second surface with emittance 0.9 are 1.99 and 3.43 (ft2•h•°F/Btu) when heat directions are up at 45º and down at 45º, respectively. The thermal resistance values in the report do not include the effect of the air space between the product and the roof sheathing of the RB effect due to a low-emittance surface facing the attic floor.

[7] http://www.rimainternational.org/index.php/technical/library/residential-commercial/

consensus method for calculating RB performance (ASTM C 1340, “Standard Practice for Estimation of Heat Gain or Loss through Ceilings under Attics Containing Radiant Barriers by Use of a Computer Program”). This program is called “AtticSim” and was developed by Kenneth Wilkes. In the past, it has been used by Oak Ridge National Laboratory to generate input for two editions of DOE RB fact sheets.

Currently, RBs and IRCCs are difficult to numerically analyze using whole building energy simulation tools. In the past, DOE 2.2, EnergyPlus, and BEopt, have not had the capability for detailed attic modeling. Recently, there has been an effort to link C 1340 to DOE 2.2 and provide modeling of attic RBs. However, the status of this project is unclear. Current DOE-sponsored work with AtticSim is limited to attic RBs and does not extend to evaluations of reflective insulation assemblies.

In the current study in collaboration with a team of local companies, both RB and IRCC radiation control technologies were tested in the field condition. One type of RB product with enclosed air space and two types of IRCC products were tested. For this puporse, four test houses (two duplexes) in Austin, TX were chosen. These radiation control systems were installed in the attic of three test houses.One attic, where none of the radiation control technologies were installed, established the baseline.

All attics had heat flux transducers and thermistors installed to monitor both surface and air temperatures. Comparisons of attic air temperatures were made to assess system performance. Although heat flux is an indicator of the heating or cooling loads, air temperature reflects the unique conditions of each unit as well as the loads. These unique conditions included varying parameters within the four units that could not be changed or controlled. Notable variations between the four cases include:

- Ventilation of conditioned space– Occupants operating windows and adjusting HVAC systems varied the flow rate greatly
- Air leakage through ceiling– Craftsmanship of ceiling construction varied by apartment (i.e. holes around pipes, ducts, etc.)
- R-value of attic– Construction and insulation type and thickness varied between duplexes
- Internal temperatures– Occupants adjusted the thermostat causing non-uniform temperatures between units.

Finally, representative computer models were constructed to further enhance understanding of the radiation control systems. Comparisons to the utility consumption data were made from the simulation results.

2. Field Testing

The test houses consisted of two duplex houses in Austin, which were closely located to each other (< 0.1 miles apart). The duplexes were both constructed of 2×4 wood framing with brick or wood cladding. Duplex 1 was built between 1987 and 1997 and Duplex 2 was a pre-1987 construction. Each duplex has two attached, unconditioned garages. The windows were operable, single glazed in non-thermally-broken aluminum frames.

The attics over the garages are separated from the attics over the houses and were not installed with the radiant control technologies. In order to thermally separate the test units, the attics over the houses were divided by insulated walls for the purpose of this field study. The ceilings were flat in Duplex 1 and vaulted in Duplex 2. Overall, the insulation was very non-uniform in all test attics. In several places, the loose-fill cellulose could reach depths such that the R-values equal approximately R-30 but were lower at other places. Four different test cases were established (See Figure 1):

1. Duplex 1
   A. Nothing added to the east attic (used as baseline)
   B. IRCC (TYPE I) added to the west attic
2. Duplex 2
   A. RB added to the east attic
   B. IRCC (Type II) added to the west attic

There was no opportunity to measure the performance of the four units prior to the retrofits in order to establish a baseline in each unit without radiation control technologies. There was an option to make the aforementioned insulation levels consistent; however, this would have made the utility bill calibration comparison impossible. For this reason, it was decided to maintain post-retrofit conditions, such as infiltration and insulation, as closely as possible to the pre-retrofit conditions. The only exception to this was the addition of rigid polyisocyanurate insulation in the attic as a vertical divider to thermally separate the two units. Considering the attic air temperature difference created by applying these technologies is small, the applied insulating divider isolates the effect of each technology from each other.

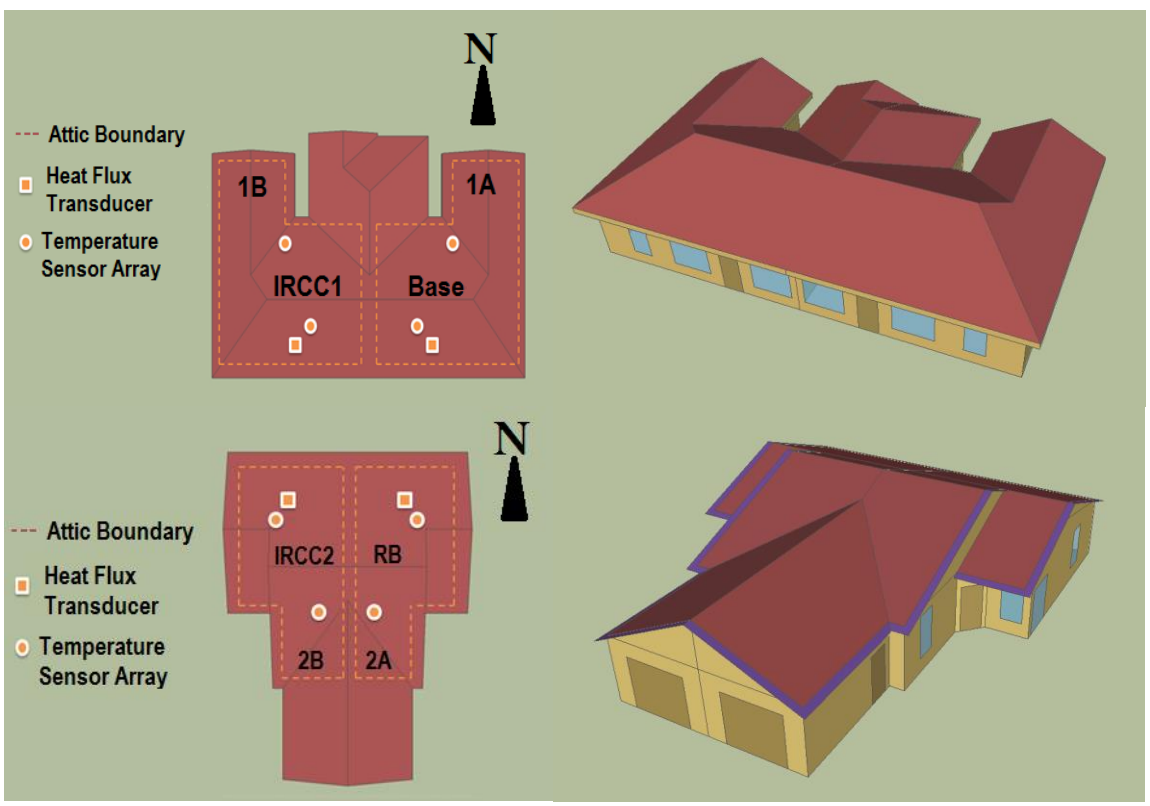

Figure 1: Test Houses in Austin, TX - Duplex 1 (top); Duplex 2 (bottom). Location of thermistor arrays and heat flow transducers inside the tested attics

2.1 Instrumentation

Each partitioned attic has been instrumented to measure thermal energy flows and included thermistor arrays for the test attics and heat flux transducers on the ceiling between the living zone and the attic zone. In addition, a weather station was installed to measure outdoor climatic parameters. The attic instrumentation diagram is illustrated in Figure 2 for the two different installed technologies.

Temperature was measured using shielded thermistors. Two arrays of thermistors were installed at each attic: one on the underside of the south-facing roof and the other under the north-facing roof. Heat flux transducers measured the energy flow through the attic floors. The heat flux transducers before deploying to the test houses were first calibrated between two pieces of gypsum in a heat flow meter.

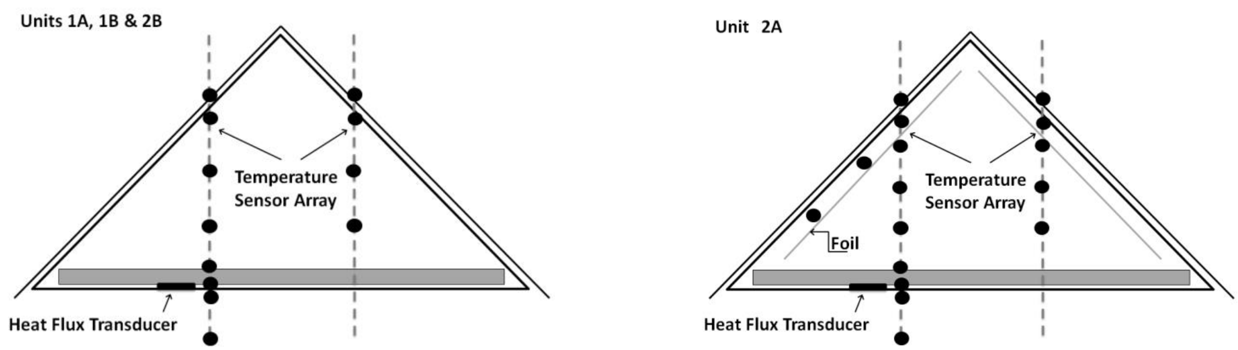

Figure 2: Diagrams of the attic sensor distributions for a RB combined with an enclosed reflective air space (right diagram), and IRCC and baseline (left diagram).

Figure 3: Installation of IRCC (left) & RB with enclosed airspace underside of the roof deck (middle, right)

2.2 Radiation Control Technology Installations

As stated earlier, two types of low-cost radiation control strategies for southern U.S. applications were installed in tested attics (Figure 3):

a) RB combined with an enclosed reflective air space installed in Duplex 2A. The installed RB in this study is an insulating product composed of multiple layers of low-e materials designed to reduce radiant heat transfer. The inside layer is a metalized polymer with emissivity of 0.04 and the outside layer is reinforced aluminum foil kraft paper with emissivity of 0.03 bonded with a fire-retardant adhesive. The layers expand when installed to form a reflective air space to provide enhanced thermal performance and protect the low-e surface from the performance reducing effects of dust accumulation.

b) spray-applied IRCC. Two types of IRCCs were sprayed: IRCC Type I- This was applied to the attic of Duplex 1B and it is capable of lowering their surface emissivity to 0.19 or lower. IRCC Type II- It was sprayed to the attic of Duplex 2B and lowers surface emissivity to 0.17 or lower.

3. Data Analysis

In the following sections, the recorded test data collected during June/July 2012 is presented and compared for all four test units. Note that all test housing units were occupied during the testing by families. Each of these families had different occupation habits and thermal comfort preferences. In each house, thermostat temperature setups were close, but not identical. Also, individual schedules for using the AC were different. In addition, the duplexes—even though they had been similarly built in relatively close time periods—had attics with different structural components, thicknesses, types of attic floor insulation and levels of attic ventilation. Significant attention was paid to the comparison of the attic air temperatures, which were considered (due to the listed above differences in the attic construction) as a best indicator of the performance differences between analyzed technologies.

The following data are summarized and analyzed below:

- Internal Air Temperature
- Roof Surface Temperature
- Attic Air Temperature
- Attic Insulation Surface Temperature
- Ceiling Heat Flux

3.1 Internal Air Temperature Comparisons

Figure 4 (Left) displays that the internal temperatures were close to 25°C in June. Most likely, residents of Units 1A and 2A preferred interior temperatures slightly above 25°C, while residents from Units 1B and 2B preferred temperatures closer to 24°C.

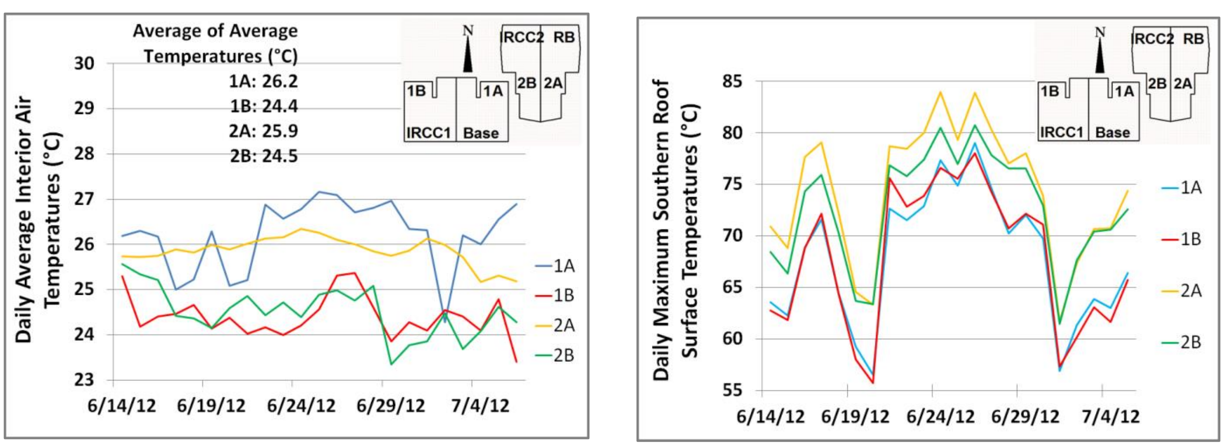

Figure 4: <u>Average</u> interior air temperatures recorded during the June/July measure period (Left); <u>Maximum</u> roof surface temperatures recorded during the June/July measure period (Right).

3.2 Attic Surface Temperature Comparison

Figure 5(Right) shows daily average surface temperature of the attic surfaces recorded during June/July. When the weather was warm in June, the roof temperatures of Duplex 2 were greater than Duplex 1. The maximum roof temperatures in June for Duplex 2 were up to 5°C hotter than Duplex 1. This was most likely due to general differences in construction of both types of attics and thermal behavior of the RB combined with the enclosed air gaps, installed under the roof deck in the test house 2A.

3.3 Attic Air Temperature Comparisons

Typically in residential attic applications, RBs and IRCCs work by reducing the amount of thermal radiation that is transferred across the air space between the roof deck and the top of the attic floor insulation. Since the amount of thermal radiation increases as the temperature of the emitting surface increases, it is critical to keep it as low as possible. This surface can be directly roof deck, foil-laminated roof deck boards, roof deck boards coated with IRCC, or RB material facing the interior of the attic.

An application of multi-foil RB in the case of Unit 2A showed that it was possible to apply radiation control technology, increase the roof deck temperature and at the same time reduce the air temperature in the attic. As depicted in Figure 4 (Right), this technology generated a slightly higher roof surface temperature compared to other test attics. However, when attic air temperatures were compared, the recorded attic temperature for Unit 2A was significantly lower comparing to other attics; see Figure 5(Left) and Figure 5(Right).

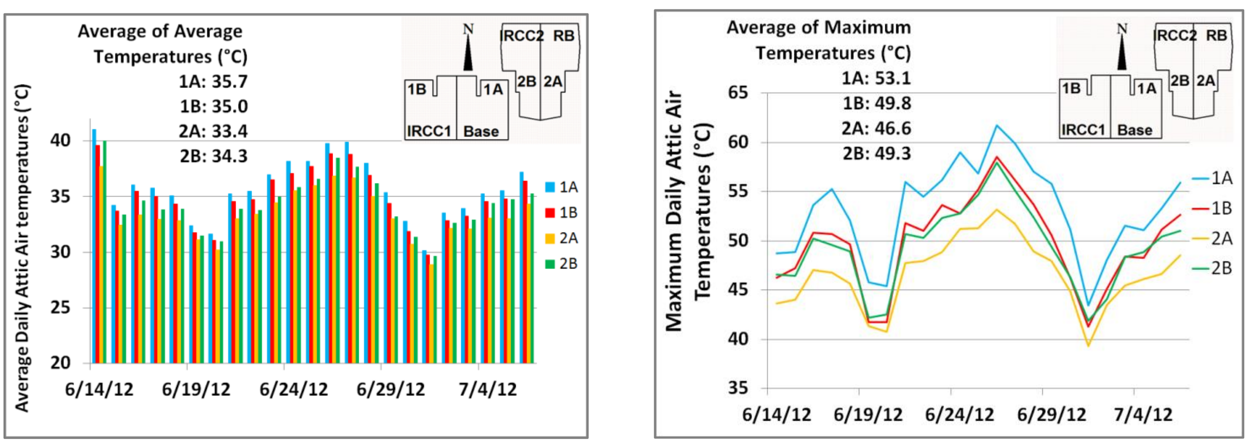

Figure 5: **<u>Average</u> daily attic air temperatures recorded in four test attics (center location) during the June/July measure period (Left); <u>Maximum</u> daily attic air temperatures recorded in four test attics (center location) during the June/July measure period (Right)**

In this study, due to the structural differences between the test attics and due to the fact that the attic floor insulations were not uniform in all the units, measurements of the attic air temperatures in the center-of-the-attic location were used as one of indirect indicators of the attic system thermal performance. The second potential performance indicator considered in this project was heat flux measured on the ceiling level. However, as shown in Figure 4(Left), the internal air temperatures were not identical in all test units. That is why direct comparisons of measured heat fluxes cannot be used as a full indicator of the attic system thermal performance.

Figure 5 shows that the attic of Duplex 1 was typically hotter than Duplex 2 in June 2012. This is consistent with the observation that the roof of Duplex 1 was cooler than Duplex 2. It is good to remember that there were some differences between both duplexes, such as the roof deck construction—rafters versus trusses—and the levels of ventilation in the attics, determined by measuring the area of the soffit vents. An average baseline attic temperature for the considered time period was 35.7°C (Figure 5 Left), while for the coolest attic 2A was only 33.4°C. This was a 2.3°C difference.

Figure 5 (Right) depicts the maximum daily attic air temperatures for June/July 2012. These temperatures reflect differences in attic-generated peak-hour cooling loads during the day. It is clear that different types of reflective insulation work effectively in southern U.S. climates. In June, the base case attic, 1A, had consistently higher maximum daily attic air temperatures. Units 1B and 2B were quite similar, but were generally a lower maximum temperature than the base case (over 3°C on average). The fact that 1B and 2B appeared similar was a different pattern than previously observed. However, examining the hotter time period in July may confirm that 2B generally had lower attic temperatures than 1B. Finally, 2A, the house with the foil technology installed, had the lowest maximum temperatures across this period by approximately 7°C, while compared to the baseline attic, 1A.

As mentioned earlier, field measurements of the attic air temperatures were used in this study, as one of the indirect indicators of the attic system thermal performance. It can be said that the attic air temperature represented thermal condition equilibrium incorporating radiation, ventilation, and convection effects together. This temperature also reflected structural differences between all test attics.

The chart in Figure 6 (Left) indicates that the foil technology was thermally more effective than both IRCC technologies. An average temperature difference between this attic and the base case was about 3.4°C, while for the IRCC technologies it was about 2.4°C. In addition, the IRCC in 2B was usually more different from the base case than the 1B case.

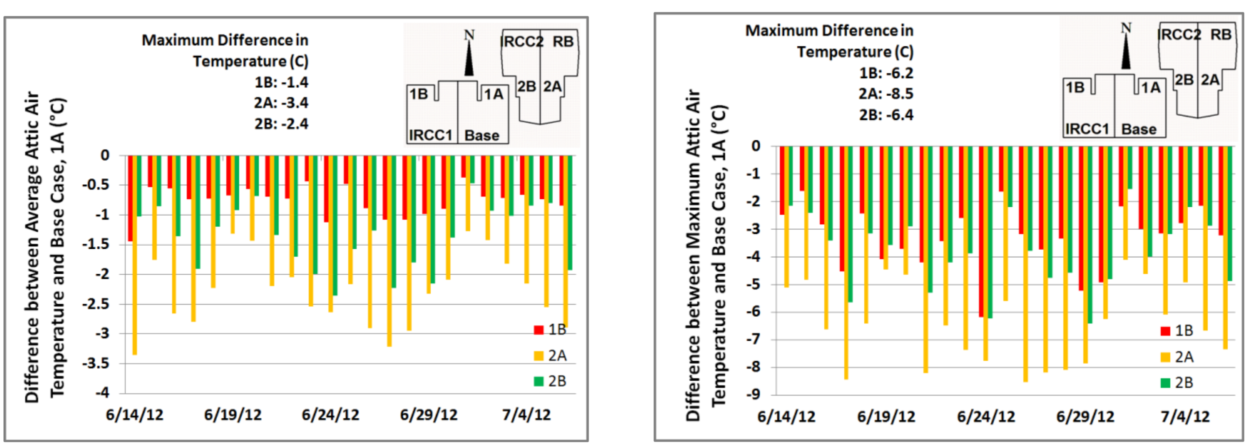

Figure 6: Differences in <u>average</u> daily attic air temperatures recorded between three test attics using radiation control technologies and a baseline attic, during the June/July measure period (Left); Differences in <u>maximum</u> daily attic air temperatures recorded between three test attics using radiation control technologies and a baseline attic, during the June/July measure period (Right)

It is important to note that 3.4°C reduction of the average attic air temperature caused by the

multi-foil RB can be an equivalent to more than 34% reduction of the attic-generated cooling loads—assuming approximate steady-state heat transfer, average attic temperature of 35°C and internal air temperature of 25°C. It has been reported that for U.S. residential houses, roofs and attics generate an average of 12% cooling energy contributions (Huang et al., 1996). In that light, potential whole building cooling energy savings may reach about 4%, depending on other building parameters and HVAC system efficiency.
Similarly, a 2.4°C reduction of the average attic air temperature due to the IRCC technology can be an equivalent to more than 24% reduction of the attic-generated cooling loads. Potential whole building cooling energy savings for this technology may be close to 3%.

Figure 6 (Right) shows clear superiority of the multi-foil radiation control technology used in the attic 2A. For this attic, maximum air temperatures were, on average, about 8.5°C lower than the base case attic. It can be also observed that IRCC systems reduced maximum attic air temperature by over 6°C.

Following earlier analyses performed for the average attic temperature, a 8.5°C reduction of the maximum attic air temperature caused by the multi-foil RB can be an equivalent to over 30% reduction of the attic-generated peak-hour cooling loads, considering maximum attic temperature of 53°C (as in Figure 5-Right) and internal air temperature of 25°C. Attic air temperature recorded in Unit 2A was the most different from the base case. Given the hotter temperatures in June, Unit 2B was typically the next most different attic temperature, as seen in Figure 6-Right.

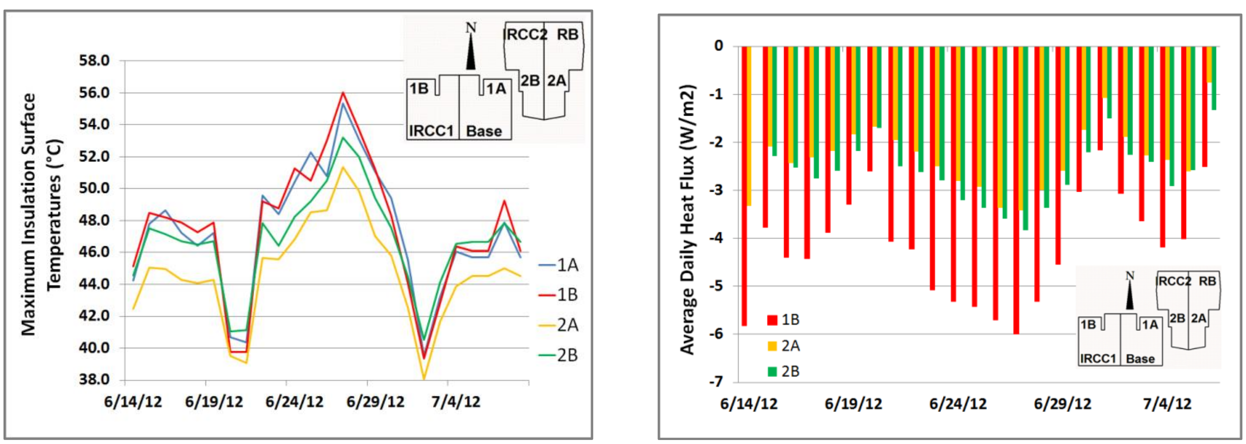

Figure 7: Maximum daily temperatures on the top surface of the attic insulation recorded in three test attics using radiation control technologies and a conventional base case, during the June/July measure period (Left); Heat fluxes recorded in test attics using radiation control technologies and a conventional base case, during the June/July measure period. Positive heat flow direction is from conditioned space to the attic (Right).

In ideal conditions (when measurement perimeters were highly controlled and the insulation layer is uniform), temperature measurements on the top of the attic insulation could be a very good direct indicator of the technology thermal performance. However, in this experiment, due to the differences in construction, thicknesses of insulation and types of insulation in the individual attics, direct thermal performance comparisons were not possible using top insulation surface temperatures.

3.4 Attic Insulation Surface Temperature Comparisons

In the hot month of June, the insulation surface temperatures were still quite similar. Unit 2A appears to have less extreme temperatures, as shown in Figure 7 (Left). Maximum day temperatures on top of the attic insulation in Unit 2A were about 4°C to 5°C lower comparing to the conventional base case attic. As mentioned earlier, these temperatures reflected the attic-generated peak hour cooling loads.

3.5 Ceiling Heat Flux Comparison

Because of different attic configurations and internal air temperatures, the heat fluxes measured on the ceiling level were not good indicators of performance compared to attic temperatures.

There were four factors that can affect this measurement: ventilation rates, R-values, internal temperatures, and air leakage through the attic ceiling. In June, the measured heat flux in the house with IRCC technology was significantly higher than in the house with the foil technology, as seen in Figure 7 (Right). The largest differences are between units 2A and 1B. Heat fluxes measured in unit 2A were between 40% and 50% lower than heat fluxes measured for unit 1B.

4. Energy Modeling

4.1 Model Description

The two duplexes in Austin were modeled using EnergyPlus to predict potential energy savings as a result of applying RB and IRCCs technologies. The houses were each modeled as three zones representing the living space, attic, and garage (a total of six zones in each duplex).

Outside boundary conditions came from a weather file for Austin's climate. Wall and ceiling constructions were modeled in THERM to determine the effective thermal conductivity of the assembly layer containing the wood studs and insulation. As stated earlier, Duplex 1 was built between 1987–1997 and Duplex 2 was built prior to 1987. Compared to parameters listed in ASHRAE Handbook of Fundamentals Chapter 15, operable single-glazed windows with non-thermally broken aluminum frames, such as those installed in the duplexes, were confirmed. Solar heat gain coefficients were set to 0.79 in the model and U-factors were 0.92 Btu/h·ft2·°F (5.2 W/m2·K). Window construction was also kept consistent throughout the models.

Roofs were modeled as shingles and plywood with addition of the appropriate paint or foil layer where applicable. A no-mass material was specified in EnergyPlus to represent the IRCC and RB technologies. The absorptance of the material was lowered to decrease the amount of radiant transfer to other surfaces in the attic zone. Because of the non-uniform levels of insulation on the attic floor, an average value was calculated for use in the model. It was determined that both duplexes had approximate R-20, despite having different compositions—7.5 inches of loose cellulose in Duplex 1 while 3.5 inches of batt insulation plus an average of 3.5 inches of loose cellulose in Duplex 2, both with framing factors of 25%. Attic ventilation rates were estimated based on measurements of the area of attic vents in each of the test houses (Atherton, 2011).

Cooling setpoints were kept for modeling purposes at 76.1°F (24°C) for all four units. The heating setpoint was 68°F (20°C). Considering stratification of the temperatures, these temperatures were very close to that which was measured in 2012 in the test houses. However, it is important to notice that due to a change of some tenants followed by a possible change of space conditioning preferences, measured temperatures in two units were about 1°C higher from the other two. Two HVAC systems were added to each building, one per conditioned zone in each duplex. The Unitary Template in EnergyPlus was used to model the forced air system with a 2.5 rated coefficient of performance (COP) single-speed direct expansion cooling coil and natural gas heating coil with an efficiency of 70%. Considering the losses due to duct leakage and the condenser unit, the overall COP of the system was reduced in the model from the manufacturer's COP. The natural gas water heater had a thermal efficiency of 80%. The models were calibrated against gas consumption data obtained from utility bills during winter. The maximum hot water flow was obtained through calibration of gas consumption with the amount reported by Texas Gas Service calculator for a typical residential single family house in Austin.

4.2 Calibration of Whole Building Energy Model

In order to predict energy consumption of the duplexes with reliable accuracy, the EnergyPlus models were calibrated against historical utility bills obtained for tested houses. For this purpose, the computer-generated energy consumptions were compared with historical energy bills for both heating and cooling seasons.

It is important to mention that, due to complexity of the test attics and the fact that buildings were occupied during the testing, it was impossible to validate the thermal simulation algorithm used for attics by EnergyPlus. Therefore, EnergyPlus simulation results (cooling energy savings) presented in this study need to be confirmed in the future either by more accurate computer models (like ATTICSIM–ASTM C1340) or by calorimetric field measurements with use of the test huts. Additionally, due to limited amount of available historical bill data, the comparison was done only for duplex 1B.

During the heating season, the main sources of energy consumption were a furnace for space heating and a water heater for domestic hot water. Based on Texas Gas Service's home energy calculator, for a typical single family house with similar characteristics to the test houses, close to 50% of total gas consumption was space heating, approximately 35% water heating and 15% was cooking. Therefore, to capture these main sources of gas consumption, a water heater, furnace and gas equipment were considered in the model. Figure 8 compares the simulated gas consumption with historical energy bill and Texas Gas Service for duplex 1B. There was a relatively good agreement between EnergyPlus-generated gas consumption and historical gas service data. Note that EnergyPlus used the actual weather file which is the observed weather data for the duration of the modeling. Figure 8 compare gas consumption of duplex 1B with historical gas bill before and after applying the radiation technology. The data confirms proper selection of the building enclosure and HVAC system parameters for whole building energy consumption simulations.

Using the actual weather data file enabled comparisons to energy consumption results generated with a use of the Texas Gas Service's home energy calculator[8]. During the cooling season, the main sources of electricity consumption were AC unit for space cooling, lighting and appliances. Again, referring to Texas Gas Service's home energy calculator, for a typical single family

---

[8] http://www.texasgasservice.com/SaveEnergyAndMoney/HomeEnergyCalculator.aspx.

house, close to 80% of total electricity consumption was for space cooling, 8.5% for lighting and close to 11.5% for appliances and others.

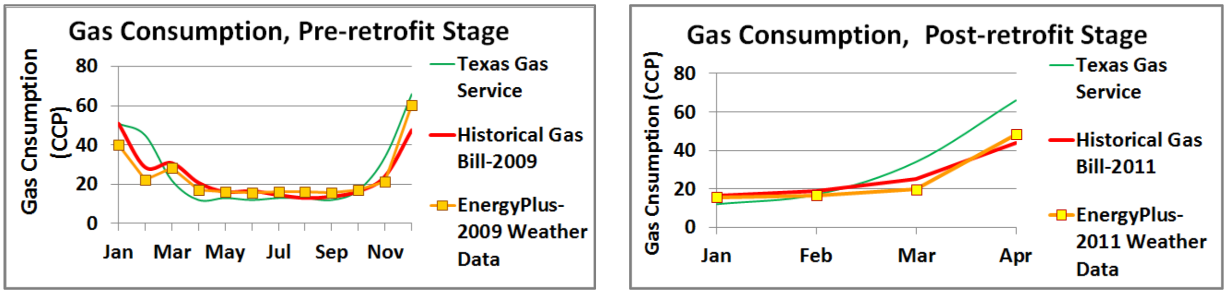

Figure 8: Comparison of monthly historical gas bill, simulated consumption, and the gas consumption by Texas Gas Service calculator. Gas consumptions are for duplex 1B before (Left) and after (Right) installing radiation control technology. The EnergyPlus simulation is based on actual weather file data from 2009 (before retrofit) and 2011 (after retrofit).

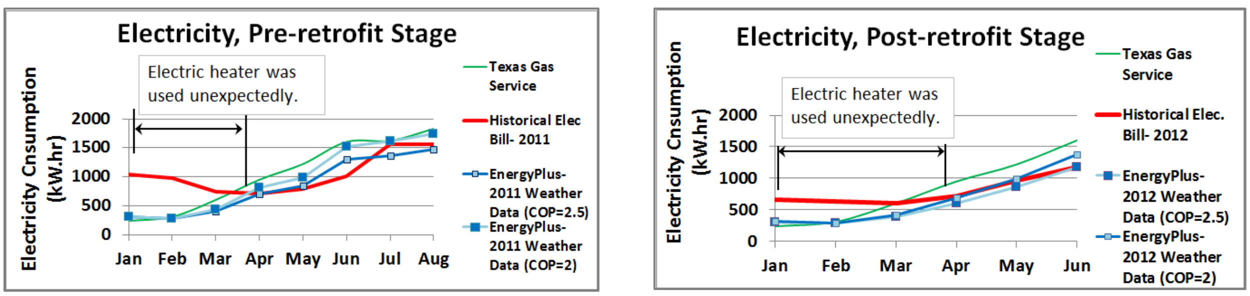

Figure 9: Comparison of monthly historical electricity bill, simulated consumption, and the electricity consumption by Texas Gas Service calculator. Electricity consumption is for Duplex 1B before (Left) and after (Right) installing radiation control technology. The EnergyPlus simulation is based on actual weather data file from 2009 (before retrofit) and 2011 (after retrofit). High electricity consumption during heating season is due to unexpected usage of the electric heater by the tenants. A cooling system with COP=2.5 was considered throughout this study; however, as a parametric study, cooling system with COP=2 was modeled and compared in this graph.

As Figure 9 shows, EnergyPlus predicted well the electricity consumption during the cooling season compared with historical electricity bill and Texas Gas Service's calculator. However, during the heating season, there were discrepancies due to the fact that the test houses were using auxiliary electricity for heating. Overall, considering the fact that the historical electricity bill was not prorated and both the AC unit set point and consumer behavior were approximated, the prediction of energy consumption particularly during the cooling season seemed in good agreement with historical bills and Texas Gas Service's calculator.

4.3 Prediction of the Cooling Energy Consumption

As described, the models' calibration was based on comparison between simulated energy use and the electricity and gas consumption data and also with historical data from the Texas Gas Service calculator. The calibrated models were simulated with a TMY3 weather file for Austin Mueller Municipal Airport to predict the electricity consumed by AC units during cooling season.

4.4 Modeling Results

In the summer, a higher infiltration rate of the attic reduced the attic temperature by exchanging the outdoor air with the attic air that was heated by the roof. The lower attic temperature reduced the heat flux through the ceiling of the living space. The wall construction and infiltration rate of the living space also affected the cooling load placed on the HVAC system. Fine tuning the IRCC and RB was required to model the emissivity within the attic space accurately and the thermal conductivity through the layer, and in the case of the RB, the air gap between the roof and the RB.

The results from EnergyPlus using a typical meteorological year (TMY3) indicate that the energy consumption is well below the range approximated based on the measurements performed during the experiment. In addition, EnergyPlus-generated cooling energy savings are at least five times lower than the earlier findings from different U.S. research studies summarized (Medina, 2012).

Cooling Energy Consumption / Test Unit	Without Radiation Control Technology	With Radiation Control Technology	Annual Cooling Energy Savings
1A (Baseline)	4333 kWh	N/A	N/A
1B (IRCC)	4326 kWh	4308 kWh	0.43%
2A (RB)	4703 kWh	4703 kWh	1.27%
2B (IRCC)	4922 kWh	4922 kWh	0.83%

Table 1. Predicted Energy cooling Consumption and Associated Savings from Radiation Control Technologies

The modeling results in Table 1 show that cooling energy is saved with the use of radiation control technologies. The table lists and compares the modeled annual cooling energy consumption of each house before and after implementing the radiation control technology. The "Annual Cooling Energy Savings" for each house in Table 1 is calculated by comparing cooling energy consumption in "Without Radiation Control Technology" and "With Radiation Control Technology" columns. The RB shows the highest savings from its lower emissivity and the air gap created between the roof and the space between the two layers of the foil. Comparing the two duplexes with IRCC installed, the results show that the attic geometry and the amount of roof coated with the low-e material make a difference in the performance.

Parametric studies of the convection coefficients, air exchange rate, set point temperature and changes of the heat transfer rate through exterior walls and windows were performed in the process of calibrating the model. Convection coefficients were specified from the ASHRAE Handbook of Fundamentals. The values for horizontal down flow were used and a slight improvement was expected from the values EnergyPlus calculated. This was expected since all roof surfaces were at angles above horizontal. The air exchange rate made little difference in the output of the model. This is likely because the exchange of air has a greater effect on the zone air temperature than the surfaces temperatures, which govern radiant heat flow. Heat flow through the exterior walls and windows had the greatest effect on the performance of the RB since heat flow through the ceiling into the conditioned zone was proportionally less than the other surfaces even though the heat flux through the ceiling remained the same.

It should be noted that the above savings have been estimated based on EnergyPlus modeling parameters close to existing test house conditions. Depending on HVAC configuration, air leakage rate, and building envelope parameters, the savings can increase close to twice the values reported in Table 1. However, they will still be significantly lower than the results of earlier experimental studies (Medina 2012). This is one of the most surprising findings from this study.

Recorded temperature and energy consumption data showed that one test unit was notably different during the winter 2011, which was evidence of an extensive use of an electric heater. The use of a supplemental heater was unexpected, and an electric heater was not instrumented. An additional challenge in modeling was caused by the fact that the tenant changed in one of the test units just before the start of measurements. Also, the inability to control setpoint differences between the units made direct comparisons difficult (since test units were occupied by tenants with various space conditioning preferences).

One of the conclusions from this study is the fact that it is extremely difficult to perform a detailed performance analysis of a single building enclosure system like RB using field test data from occupied vintage housing units. It is still unclear how well energy consumption predictions of the building systems containing RBs can be simulated using simplified Energy Plus roof/attic algorithm. The team recommends that in the future, a calorimetric type of a field experiment (with precisely measured attic air leakage rates, level of attic insulation, and with simple attic structural components) be performed in order to further validate EnergyPlus predictions in cases of RB applications. This experiment will most likely require test huts or similar small and well-instrumented test structures.

5 Conclusion

The major goal of this project was to evaluate the energy effects of RBs and IRCCs in field conditions. Major focus was paid on thermal and energy performance of the attics. During the cooling season 2012, thermal performance measurements were performed on four housing units in two residential duplexes. Three test attics were modified using RBs and IRCCs and tested, while the fourth attic stayed unmodified and was used as a base case for comparisons.

Thermal performance data was collected for each attic. Field experiments took place in Austin, Texas. All test houses were occupied during the testing by residents. The original plan was to keep internal load schedules in the test units as close as possible; however, each of these tenants had different occupation habits and thermal comfort preferences. Also, individual schedules for operating the AC were different. In addition, the test houses had attics with varying structural components, thicknesses and types of attic floor insulation, and levels of attic ventilation. All of the above factors made direct comparison of the whole building energy consumption impossible.

Measured test data confirmed earlier results from other research organizations. An average 3.4°C reduction of the average attic air temperature caused by the multi-foil RB was recorded during mid-summer 2012, and can be equivalent to over 34% reduction of the attic-generated cooling loads—assuming approximate steady-state heat transfer, average attic temperature of 35°C and internal air temperature of 25°C. This is consistent with a range of the cooling load reductions reported by Medina (2012). It has been also reported that for U.S. residential houses, roofs and attics generate an average 12% cooling energy contributions (Huang, et al., 1996). In that light, potential whole building cooling energy savings may reach about 4%, depending on other building parameters and HVAC system efficiency.

Similarly, a 2.4°C reduction of the average attic air temperature caused by the IRCC technology can be an equivalent to over 24% reduction of the attic-generated cooling loads, and potential whole building cooling energy savings for this technology may be close to 3%. Based on the recorded data, energy performance of two IRCC systems seems to be very similar considering the small differences in construction of both test attics in Duplexes 1 and 2.

An EnergyPlus computer model calibrated against both gas and electricity historical bill data for the periods of pre-retrofit and post-retrofit was used for prediction of potential cooling energy savings. The results from EnergyPlus were well below the range of cooling energy savings approximated based on the measurements performed during this experiment. In addition, EnergyPlus-generated cooling energy savings were at least four to five times lower than results available from the earlier studies (Medina, 2012). It is recommends more work on validation of whole building computer models using attic algorithms with RB.

Reference

ASHRAE. 2007. ANSI/ASHRAE 90.2. *Energy Efficient Design of Low-Rise Residential Buildings.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.;

ASTM Standard C1313. 2010. *Standard Specification for Sheet Radiant Barriers for Building Construction Applications*. ASTM International, West Conshohocken, PA, DOI: 10.1520/C1313_C1313M-10;

ASTM Standard C1340. 2010. *Standard Practice for Estimation of Heat Gain or Loss Through Ceilings Under Attics Containing Radiant Barriers by Use of a Computer Program*. ASTM International, West Conshohocken, PA, DOI: 10.1520/C1340_C1340M-10;

ASTM Standard C1321. 2009. *Standard Practice for Installation and Use of Interior Radiation Control Coating Systems (IRCCS) in Building Construction*. ASTM International, West Conshohocken, PA, DOI: 10.1520/C1321-09;

Atherton, S.A. 2011. *Residential Attic Ventilation in A Hot And Humid Climate: Effects Of Increased Ventilation On Thermal Performance And Moisture Control*. Master Thesis, University of Tennessee, Knoxville;

Handcock, E. Norton, P. and Hendron, B. 2002. *Building America System Performance Test Practices: Part 2, Air Exchange Measurements*. NREL Technical Report NREL/TP-550-30270; Accessed at: http://www.nrel.gov/docs/fy02osti/30270.pdf.

Huang, J. Hanford J. and Yang F. 1996. *Residential Heating and Cooling Loads Component Analysis*. LBNL Technical Report LBNL-44636; Accessed at: http://simulationresearch.lbl.gov/dirpubs/44636.pdf.

Medina, M. 2012. *A Comprehensive Review of Radiant Barrier Research Including Laboratory and Field Experiments*. ASHRAE Transactions. Vol. 118 Issue 1, p400;

Parker, D. S. 2005. *Literature Review of the Impact and Need for Attic Ventilation in Florida Homes*. Florida Solar Energy Center Report FSEC-CR-1496-05; Accessed at: http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1496-05.pdf

Parker, D. S. 2003. *Research highlights from a large scale residential monitoring study in a hot climate* . Energy and Buildings. 35 (9), pp. 863-87;

Parker, D. and Sherwin, J. 1998. *Comparative Summer Attic Thermal Performance of Six Roof Constructions.* Proceedings of the 1998 ASHRAE Annual Meeting. Toronto, Canada;

RIMA International. 2002. *Understanding and Using Reflective Insulation, Radiant Barriers and Radiation Control Coating* . RIMA International, Second Edition; Accessed at: http://www.rimainternational.org/pdf/handbook.pdf.

RS Means. 2011. *Building Construction Cost Data*. Norwell, USA;

Stovall, T. Yarbrough D. W. Shrestha S. Pearson T. and Arimilli R. V. 2010. *Analysis in Support of the Radiant Barrier Fact Sheet 2010 Update*. Proceedings of Thermal Performance of Exterior Envelopes of Whole Buildings XI , Florida. Accessed at: http://web.ornl.gov/sci/buildings/2012/B11%20papers/141_Stovall.pdf

Texas Gas Service, *Home Energy Calculator*; Available at: http://www.texasgasservice.com/en/SaveEnergyAndMoney/HomeEnergyCalculator.aspx

Wallace, L.A. Emmerich, S.J. and Howard-Reed, C. 2002. *Continuous measurement of air change rates in an occupied house for 1 year: the effect of temperature, wind, fan and windows*. Journal of Exposure Analysis and Environmental Epidemiology (12) pp. 296- 306.