

Residential Attic with Radiant Barrier System: Finite Element Simulation and Parametric Study

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The current study involves developing a three-dimensional transient finite element (FE) model to evaluate the thermal performance of an attic radiant barrier system (ARBS) as an energy efficient technology. The heat transfer modes of convection, radiation, and conduction were considered in the FE model. The results from the FE analysis were then validated based on hourly experimental data collected in houses located in Zachary, Louisiana. Upon validation, the design variables and their influence on the performance of the radiant barrier insulation system were also studied. Accordingly, the existence of an air gap on both sides of the radiant barrier and the emissivity of asphalt shingle were found to have a significant effect on the performance of the radiant barrier insulation system in comparison with other design factors.

Key Words: Residential Building, Finite Element Method, Radiant Barrier, Attic Heat Transfer Modeling.

Introduction

Energy consumption is generally classified into four different sectors including industry, transportation, building and agriculture. The residential and commercial building sector is considered to be the largest energy consumer. According to the Department of Energy report, residential buildings are responsible for 22% of the total energy use in the United States (US Department of Energy, 2006). More specifically, heating and cooling systems account for 54% of the total energy consumption in residential buildings. Therefore, in the modern energy-conscious society, the reduction of energy consumption in air conditioning systems is identified as an effective way to save energy. The attic space between the roof and the ceiling of a building is responsible for a substantial portion of heat transfer. Hence, the application of energy-efficient technologies in design of the attic for residential buildings is deemed necessary. One method to reduce the heat flux in the attic is to utilize radiant reflective insulating barriers. While most traditional insulation materials resist heat flow through convection and conduction, reflective insulation targets radiation, which is the main source of heat transfer in residential buildings. In the past, radiant barrier insulations comprised only a small portion of the insulation market nationwide. However, owing to the increasing demand for more energy-efficient insulations, the market for the reflective barrier insulations has experienced a significant growth of 27% in recent years (Midwest Roofing Contractors Association, 2006). Accordingly, the performance analysis of the radiant barrier insulation systems, as well as quantifying the influence of different design parameters are of critical important for the design and construction of modern residential buildings.

There are several studies dealing with the efficacy assessment of the reflective insulation material in residential buildings. In a pioneering work, a single steady-state equation was developed by assuming a flat roof and constant ventilation rate, convection and radiation heat transfer coefficients (Joy, 1958). Later, considering different ventilation conditions, a numerical simulation was carried out to predict ceiling heat transfer in an attic of a residential house with three surfaces including two roofs and a ceiling floor (Peavy, 1979). In a noteworthy contribution, a transient heat and mass transfer model was developed to predict the ceiling heating and cooling loads and to estimate the heat flux reduction due to the application of radiant barrier in residential houses (Medina, 1998a). The model showed a good agreement with ceiling heat flux experimental results (Medina, 1998b). With the advent of fast computers in recent years, numerical techniques, such as finite element (FE), have emerged as an accurate alternative method for analysis of large domains with time-dependent and complex boundary conditions. In an interesting effort, a two dimensional and steady state FE model was developed to investigate the performance of

attic radiant barrier system (ARBS) in residential buildings (Moujaes, 2000). Results indicated that ARBS can reduce the ceiling cooling loads by 25% to 30%.

The objective of the present study is to simulate the heat transfer mechanisms in a residential building attic that features a radiant barrier system, by means of a three-dimensional (3D) transient FE method. The developed model overcomes limitations of the previous models that either adopt a two dimensional approach or assume steady-state conditions. This model considers a whole roof configuration and is capable of simulating each side of the roof individually as each side—depending on its location and orientation—can be exposed to different environmental conditions and different levels of solar radiation. The accuracy of the FE model was validated by comparing the predicted insulation temperatures with experimental measurements. Subsequently, the results of the FE model were used to assess the thermal efficiency of the radiant barrier insulation system as compared to the conventional system. In addition, the design variables and their influence on the performance of the radiant barrier insulation system were investigated based on the FE analysis.

Experimental Program

The experiments were carried out in Zachary, Louisiana. This location is characterized by a humid subtropical weather. Two houses were selected at this location. Both of them had 148 m² area and they were exactly identical in terms of their geometry, building materials, and climate conditions. The only difference between these two houses was the use of radiant barrier in one of them whereas the second one had a conventional insulation system, referred to as the control house hereafter. Radiant barrier was made of a thin layer of highly reflective aluminum that was attached to plywood, i.e. the inner side of the roof. The outer surfaces of the roofs were covered with dark asphalt shingles which are considered as low reflective materials. The ceilings were covered with polyurethane insulation (R-30). The houses were built with soffit-ridge ventilation. Each house was instrumented with several thermocouples to capture the temperatures in each layer of the roof and the ceiling. A data logger (ACR Samar Reader) was installed to record the temperatures every 4 minutes. A weather station (Davis 6152 Wireless Vantage Pro) was employed to measure and store the ambient air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation (rainfall and rain rate), and solar radiation every 4 minutes.

Finite Element Model

To calculate the temperature distribution in the roof, attic and ceiling, a 3D transient finite element model was developed using the finite element commercial software ABAQUS 6.9 (Dassault Systèmes, 2009).

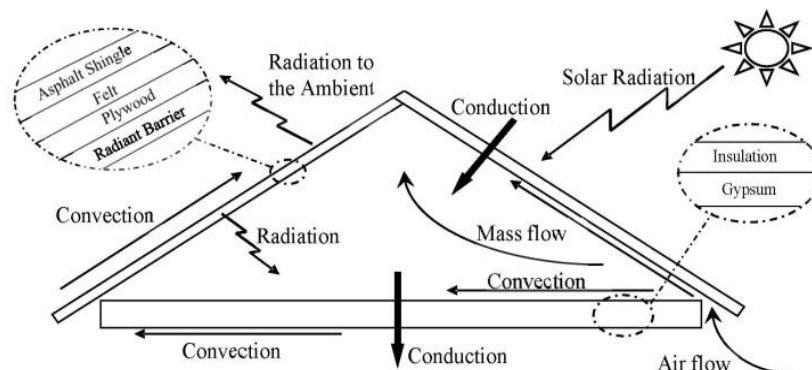


Figure 1: Schematic of the heat transfer mechanisms in the house roof

Shown in figure 1, is the sketch of an attic representing various heat transfer mechanisms that take place in the attic. The five-sided attic, which is geometrically symmetric with respect to XY and YZ planes, was simulated. The attic had two pitched roof sections, two vertical gable-end sections, and one horizontal ceiling frame. This configuration

is typical for houses constructed in the southern regions of the United States. In order to investigate the impact of the radiant barrier system on the heating and cooling load, two finite element models were developed. One model represented the roof with the radiant barrier and the other one represented the roof without the radiant barrier in the attic. The radiant barrier which was made from aluminum was simply modeled as an extra layer on the inner side of the roof which was in contact with the attic air (see figure 1). Although the physical model was symmetric, the amount of solar radiation differed from one side of the roof to the other depending on the surface orientation and inclination. Thus, in order to conduct an accurate analysis, the entire configuration of the roof was simulated in the finite element model (see figure 2). The material properties including the thickness of the each layer are provided in table 1.

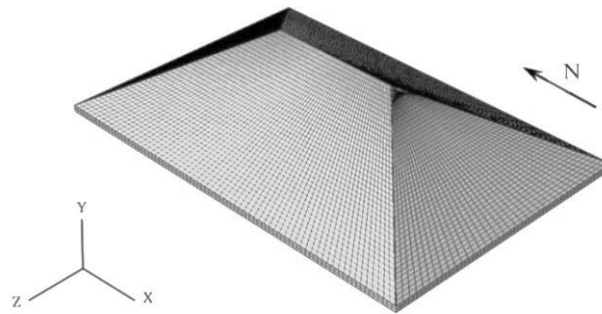


Figure 2: Finite element mesh

It is worth noting that in order to obtain mesh independent results, a mesh convergence technique was conducted and the final mesh size was selected considering both the computational efficiency and accuracy aspects. The mesh density was increased by a factor of 2 iteratively until the resulting change in the nodal temperature became negligible. Twenty-four steps were required to capture the hourly temperature variation during a day. As stated before, all of the experimental data were registered every 4 minutes. Consequently, in order to use them as an input in the model, they were averaged over an hour period. The implementation technique for each of the heat transfer mechanism in the FE model is presented in the following sections.

Table 1

Material properties used in the FE model

Material	Conductivity (W/m-°K)	Density (kg/m³)	Specific heat (J/kg-°K)	Thickness (mm)	Emissivity
Asphalt Shingle	0.121	1121.29	1260	10.2	0.97
Aluminum	250	2800	900	0.001	0.03
Felt	0.173	800.9	0.0837	1.3	-
Plywood	0.130	640.7	1507	12.7	0.8
Insulation	0.016	24	1590	25.4	0.7
Gypsum	0.159	799.3	1089	12.7	-

Conduction Heat Transfer

All of the bounding surfaces in the attic are subjected to the conduction heat transfer which is a transient phenomenon since the temperatures on all of the surfaces change with time. To model the conduction heat transfer mechanism in the roof and the ceiling, approximately 49,000 DC3D8 elements were used. Featuring a hexahedron shape with 8 nodes, these linear heat transfer elements were used for all of the materials except the air.

Radiation Heat Transfer

The outer surfaces of the roof are exposed to solar radiation. Heat flux due to solar radiation for a given day was taken experimentally from the solar sensors. Since it is difficult to measure solar radiation on the inclined surfaces, e.g. the attic surfaces, the global radiation on a horizontal surface was obtained from the weather station. The exact amount of solar radiation received by each roof depends on a variety of parameters such as inclination, orientation and geographical location (Duffie, 1974). The amount of solar radiation was used in the simulation as the heat load on the outside surfaces of the roof.

In the attic space every surface exchanges heat with every other surfaces through radiation. The radiation heat transfer inside the attic depends on view factors that are the measure of relative radiative interaction between the surfaces of the cavity space. In order to model the heat transfer due to the radiation in the enclosure (attic space), cavity option in ABAQUS was used. ABAQUS automatically calculates view factors for three-dimensional models. To do this, the cavity is considered as an ensemble of element faces corresponding to the FE discretization. These element faces can be treated as elementary areas and, accordingly, simple elemental view factors are calculated using an “area-lump” method (Sparrow, 1978).

Convection Heat Transfer

At every surface of the roof, attic, and ceiling, convection heat transfer can be significant. To calculate forced and natural convection for exterior and interior surfaces, a user subroutine was developed that calculates the forced and natural convection coefficient based on the temperature of the surface and the air, direction of heat flow, surface area, and the surface orientation. Correlations for both laminar and turbulent flows are used, with the choice depending upon the magnitude of the Rayleigh number for natural convection and Reynolds number for forced convection. For more details see the formulations provided by Chen and his coworkers and Holman (Chen, 1986), (Holman, 2002).

To model the advection, i.e. bulk motion of the air, in the attic, the convection/diffusion option in ABAQUS were utilized by means of 8-node DCC3D8 elements with forced convection/diffusion capabilities. The total number of aforementioned element was approximately 73,000. In addition, forced convection inside the roof was simulated by means of the mass heat transfer option in ABAQUS.

Simulation Procedure

Since for each time step, the surface temperature distribution is initially unknown, an iterative procedure was used. In this procedure, the surface temperature distribution was first assumed based on the previous time step. Moreover, the temperature inside the house was assumed constant at 23.9 °C for summer and 21.1 °C for winter. The initially assumed surface nodal temperatures were used to calculate the heat convection coefficients for all surface nodes. Next, the FE simulation was conducted and a new temperature distribution was obtained. The new temperature distribution was again used for calculation of the heat convection coefficients for each surface node and the procedure was repeated until the surface temperature and the heat convection coefficients change became negligible between the subsequent iterations in that time step.

Results and Discussion

Model Validation

Using the developed finite element model, the temperature distribution in the roof, attic, and ceiling were estimated for summer at different hours in a day. As many factors affect the calculated temperature distributions and heat flux in the roof, the validity of the FE model was evaluated by comparing finite element simulation results with experimental data. Figures 3 and 4 compare the results of the finite element model with experimental data in a typical day in summer. The results are presented for the insulation temperature and are given for two cases: house with radiant barrier and control house. As shown, there is a good agreement between the finite element model

prediction and experimental measurements during both peak and peak off time. The error was less than 5% for most cases.

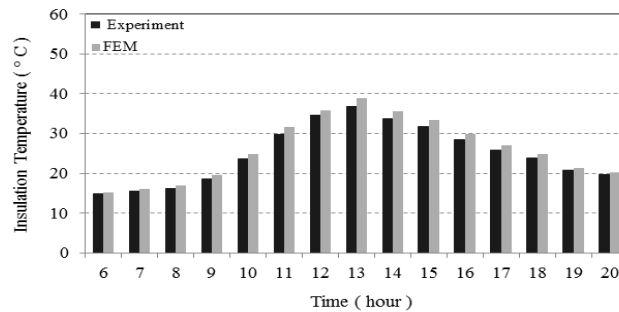


Figure 3: Insulation temperature in summer in the house with radiant barrier

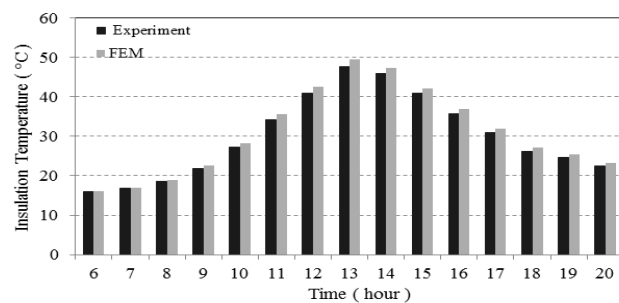


Figure 4: Insulation temperature in summer in the control house

Effect of Radiant Barrier Insulation

Comparing the temperature fields presented in figures 3 and 4, it is noted that employing a radiant barrier in the attic has a significant effect on the insulation temperature since it prevents attic surfaces from emitting heat waves toward insulation. As shown in these figures, during peak hour, the temperature of the insulation in the house with radiant barrier is 10°C lower than the control house.

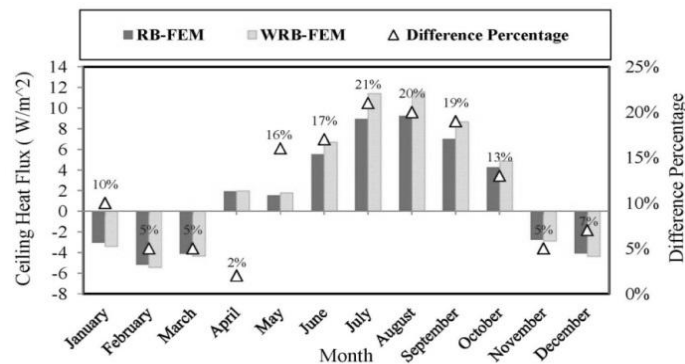


Figure 5: Performance of radiant barrier system based on FE model

Figure 5 compares the required ceiling heating-cooling loads based on FE model in the house with radiant barrier (RB-FEM) and the control house (WRB-FEM) in a typical day of each month for a year. The peak of the ceiling heat flux in the control house and the house with radiant barrier were approximately 12 W/m² and 9 W/m², respectively, showing 21% reduction due to ARBS. In addition, based on these results, it is determined that radiant barrier system decreases the annual required ceiling cooling load in the house by 18%.

Parametric Study

Upon validation of the FE model, the effect of ARBS on the insulation temperature was evaluated based on FE analysis. The influences of design variables on the performance of the radiant barrier insulation system were also investigated. In order to understand which design factors have the highest effect on the performance of attic radiant barrier system, parametric study was carried out by changing one factor at a time keeping the others constant at the low level. As a part of this parametric study, table 2 presents the factors varied in the analysis as well as the ranges considered.

Table 2

Level of factors for parametric study

Factors	Level		
	Low	Medium	High
Shingle emissivity	0.75	0.80	0.97
Air gap thickness	0	0.75	5
Radiant barrier emissivity	0.03	0.04	0.05
Radiant barrier coverage	Full	North-South	East-West

Effect of Asphalt Shingle Emissivity

The emissivity of the exterior surfaces is considered to be an important factor on heat gain or loss in buildings especially in places where the amount of solar radiation is significant. Figure 6 shows the effect of asphalt shingle emissivity on the performance of radiant barrier for a typical day in summer. It represents the insulation temperature reduction percentage in the house with radiant barrier as compared to the control house. An increase in the amount of the solar radiation absorbed by the asphalt shingle results in higher temperature of attic upper surfaces. Consequently, the radiation from the attic upper surfaces to the top of the insulation becomes more dominant and in this situation, the role of radiant barrier as a heat block becomes more pronounced. During the cooling season, by increasing the emissivity of the shingle, the insulation temperature will increase as expected. It was found that by increasing the emissivity of the shingles from 0.75 to 0.97, the temperature reduction percentage is increased from 18% to 22%, showing that the efficiency of radiant barrier is more noticeable with higher shingle emissivity.

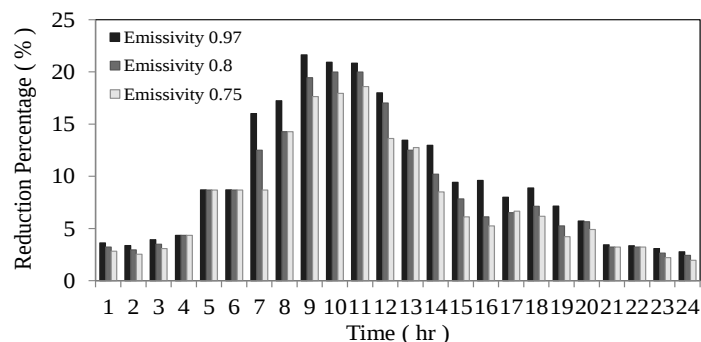


Figure 6: Effect of shingle emissivity on the insulation temperature

Effect of Air Gap Thickness

The second parameter investigated in this study was the thickness of the air gap in contact with radiant barrier. The thickness of the air gap has a significant effect on heat gain or loss in the attic because of its low thermal conductivity as it provides means to block heat in the attic. Figure 7 shows the effect of the air gap thickness on the insulation temperature reduction in cooling season. It is evident that by increasing the thickness of air gap, the insulation temperature will significantly decrease during the cooling season. As shown in figure 7, temperature is reduced by 44% when a 5 cm air gap is used whereas the temperature reduction percentage is decreased to 23% for

the case in which the radiant barrier is directly attached to plywood with no gap. As expected these results show that the thicker the air gap, the more resistance it would be to the heat transfer from plywood to the radiant barrier.

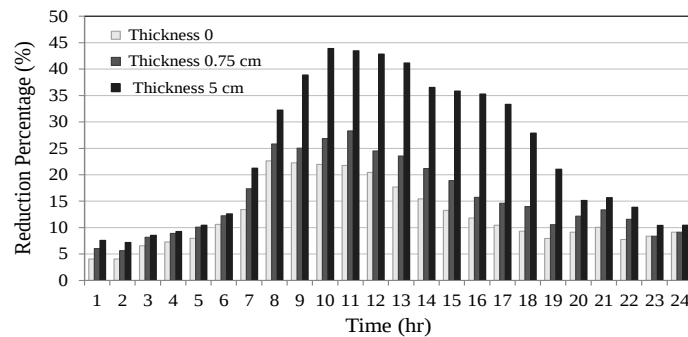


Figure 7: Effect of air gap thickness on the insulation temperature

Effect of Radiant Barrier Emissivity

The third parameter investigated in this study was the effect of the emissivity of radiant barrier on the insulation temperature. Beside the air gap thickness, the emissivity of radiant barrier can be considered as another important factor to help block most of the infrared radiation in the attic of a building. The emissivity of typical radiant barriers varies from 0.03 to 0.05. Based on this range, radiant barrier can reflect 95% to 97% of solar radiation. Figure 8 demonstrates the effect of emissivity of radiant barrier on the reduction of insulation temperature in the attic. As shown in this figure, the effect of radiant barrier emissivity was relatively small (due to small variation of emissivity). However, it is evident that lowering radiant barrier emissivity leads to more reduction in insulation temperature.

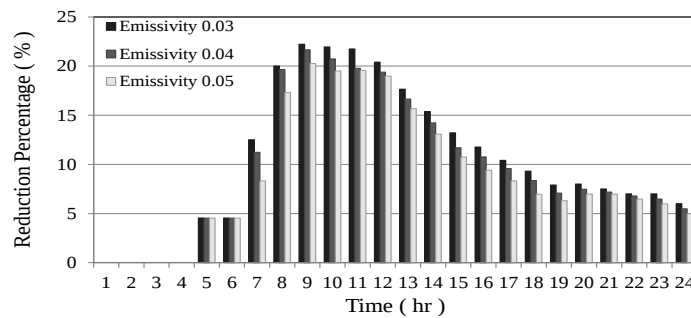


Figure 8: Effect of radiant barrier emissivity on the insulation temperature

Effect of Radiant Barrier Location

Figure 9 shows the effect of the attic radiant barrier locations on the reduction of insulation temperature. In the current study, the longer roof sides faced towards East-West. As shown, by changing the radiant barrier coverage from full to East-West and then North-South coverage, the reduction percentage of the insulation temperature is decreased from 22% to 17% and 14% during the cooling season. Therefore, the maximum benefit of radiant barrier is achieved when the entire roof is covered with the insulation system.

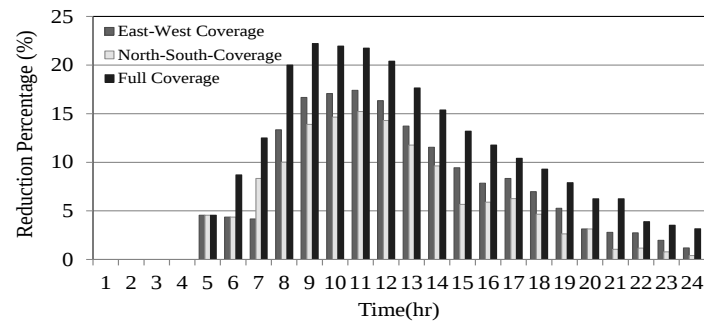


Figure 9: Effect of radiant barrier coverage in the roof on the insulation temperature

Conclusions

The objective of this study was to develop a three dimensional transient finite element model of the heat transfer processes in residential attic spaces to determine the possible energy savings gained by the use of the radiant barrier. Models for the thermal performance of attics with and without radiant barriers were developed and analyzed using ABAQUS 6.9 software. The predicted temperatures by the finite element model were compared to experimental measurements and showed good agreement with the experimental data. The error was less than 5 % for most cases. For a typical day in cooling season and during peak hour, the temperature of the insulation in the house with radiant barrier is 10°C lower than the house without radiant barrier.

A parametric study was conducted to evaluate the performance of radiant barrier as a function of shingle emissivity, thickness of air gap, radiant barrier emissivity, and location of radiant barrier in the roof. Based on the parametric study, it was also determined that the thickness of air gap had a significant effect on the performance of radiant barrier. Using radiant barrier in combination with 5 cm air gap reduced insulation temperature by 44%. The emissivity of asphalt shingle also influenced the performance of radiant barrier. Results showed that by increasing the emissivity of asphalt shingle from 0.75 to 0.95, the temperature reduction percentage changes from 18 % to 22%. However, the emissivity of radiant barrier in its typical range had no significant influence. Results showed that changing the radiant barrier coverage from full to East-West and then North-South coverage, decreases the reduction percentage of the insulation temperature 22% to 17% and 14% during the cooling season

References

- Chen, T.S., Armaly, B.F. & Ramachandran, N. (1986). Correlations for Laminar Mixed Convection Flows on Vertical, Inclined, and Horizontal Flat Plates. *Journal of Heat Transfer-Transactions of the Asme*, 108 (4), 835-840.
- Dassault Systèmes (2009). ABAQUS User Manual : version 6.9. Dassault Systèmes/Simulia Corp, Providence, RI.
- Duffie, J.A. & Beckman, W.A. (1974). *Solar energy thermal processes*. Wiley-Interscience, New York ; London.
- Holman, J.P. (2002). *Heat transfer*, 9th ed., International ed. ed. McGraw-Hill, Boston [Mass.] ; London.
- Joy, F.A. (1958). Improving Attic Space Insulating Values. *ASHRAE Transaction*, 64 251-266.
- Medina, M.A., O'Neal, D.L. & Turner, W.D. (1998a). A Transient Heat and Mass Transfer Model of Residential Attics Used to Simulate Radiant Barrier Retrofits, Part I: Development. *Journal of Solar Energy Engineering-Transactions of the Asme*, 120 (1), 32-38.
- Medina, M.A., O'Neal, D.L. & Turner, W.D. (1998b). A Transient Heat and Mass Transfer Model of Residential Attics Used to Simulate Radiant Barrier Retrofits, part II: Validation and simulations. *Journal of Solar Energy Engineering-Transactions of the Asme*, 120 (1), 39-44.
- Midwest Roofing Contractors Association (2006). Reflective Industry Continues to Grow.

Moujaes, S.F. & Alsaiegh, N.T. (2000). Numerical Heat Transfer Attic Model Using a Radiant Barrier System. *Journal of Energy Engineering-ASCE*, 126 (1), 32-51.

Peavy, B.A. (1979). A Model for Predicting the Thermal Performance of Ventilated Attic, Summer Attic and Whole House Ventilation *NBS special publication*, 548 119-149.

Sparrow, E.M. & Cess, R.D. (1978). *Radiation heat transfer*, Augmented ed. ed. Hemisphere ; New York ; London : McGraw-Hill, Washington [D.C.] ; London.

US Department of Energy (2006). Buildings energy data book.