Analysis in Support of the Radiant Barrier Fact Sheet 2010 Update

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ABSTRACT

Quantifying the benefits of radiant barriers is complex because the benefits depend upon the climate, attic geometry, duct arrangements, and other building parameters. Homeowners, however, require simplified guidance regarding building envelope options, even those options that seem to have no simple answers. An extensive parametric evaluation of radiant barrier installation alternatives was made using a newly expanded and benchmarked version of an attic simulation program. To complement this analysis, a detailed numerical analysis of radiation heat transfer within the attic and within the small space bounded by the rafters and the sheathing was completed. The results provide guidance for homeowners and builders.

INTRODUCTION

Extensive experimental work has identified the energy savings and peak-load reduction benefits of radiant barriers in attics in the southern climates of the U.S. Eight homes, all with air-handling equipment located in the attic, were retrofit with radiant barrier systems in 2000 in central Florida. Subsequent monitoring and data analysis showed cooling energy savings of 9%, peak load reduction of 16%, and an improvement in indoor comfort (Parker et al. 2001). Previous experimental work in Tennessee on uninhabited homes with no ductwork in the attic also showed significant cooling energy savings (Levins and Karnitz 1986a). Significant savings due to radiant barriers were also measured in controlled laboratory experiments, with and without duct systems in the attic (Petrie et al. 1998). Numerous other studies have established the energy conservation characteristics of a radiant barrier system, with and without the impact of ducts (Parker and Sherwin 1998; Levins and Karnitz 1986b; Parker et al. 1993; Wilkes 1991a). As expected, these studies point out the importance of multiple factors in determining the potential energy savings, most importantly: the climate, the amount of insulation on the floor of the attic, and the presence or absence of ductwork in the attic.

Builders are more likely to place ductwork in the attic in southern climates than in other parts of the country. In addition to providing a satisfactory cool-air distribution to ceiling registers, this location is often selected because it is economically expedient for the builder. About 80% of single family housing units (not including mobile homes) located in cooling climates (2,000 cooling degree days or more and less than 4,000 heating degree days) are built on a slab, ruling out the possibility of using basements or crawlspaces for the ductwork (Energy Information Administration 2005).

Energy-conscious consumers are faced with the decision of whether or not to include a radiant barrier in their home, and if so, what type of radiant barrier to install. A number of products are marketed as attic radiant barriers for use in residential applications. These include aluminum foil or metalized film-faced materials stapled to the bottom surface of rafters, placed on top of the attic floor insulation, roof sheathing materials with a foil-covered interior surface, and liquid-applied low-emittance coatings. The Department of Energy has long provided information fact sheets to inform consumers and to help them determine their likely energy savings. The current fact sheet, posted in the mid-1990s, provides a series of IRS-type forms for the calculation of savings.

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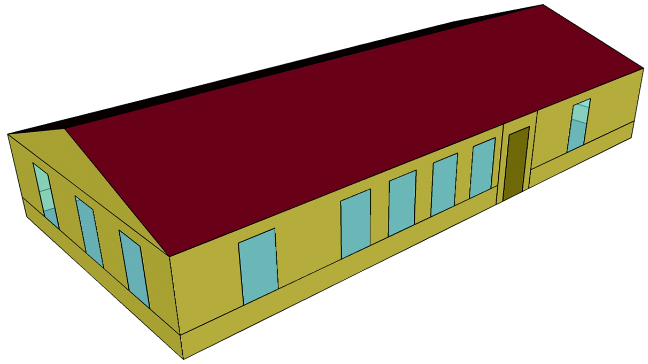

Figure 1 *Schematic of house used in EnergyPlus and AtticSim.*

The form was based on a large number of heat transfer calculations.

ANALYSIS APPROACH

The attic simulator, AtticSim, was developed to calculate the radiative, convective, and conductive energy exchanges in a specific attic geometry, with or without ducts (Wilkes 1991b; ASTM C1340 2009). This model has been benchmarked against experimental data from the controlled laboratory experiments, showing excellent accuracy for attics without ducts and moderate accuracy for attics with ducts. The attic model requires that the air temperature below the attic floor and the temperature and timing of air entering the ductwork be specified. To provide these values, a whole-building energy model, EnergyPlus, was used. This whole-building model includes leaking attic ducts and radiant energy exchange within the attic, but does not yet include radiant exchange between the attic surfaces and the duct surface (EnergyPlus 2009). These programs were coupled by using the same physical geometry and materials, the same weather data, and the same rate of duct leakage.

Both the attic and whole building calculations use a single emittance to represent the roof surface facing downward into the attic in order to maintain reasonable computation times, even though that surface can be a mixture of materials, such as reflective sheathing mounted upon a wooden rafter or truss system. This simplification was investigated during the course of this project by using different emittance values and realistic geometry in a multiple domain numerical analysis of the attic region.

COUPLED ENERGYPLUS-ATTICSIM ANALYSIS

The energy savings attributable to radiant barriers was calculated using a coupled AtticSim-EnergyPlus model. The current version of EnergyPlus (Version 4.0) ignores duct radiation heat exchange as well as duct heat transfer during conditioning equipment off-time. AtticSim is limited to simulating only the attic environment. Hence, input parameters for AtticSim, such as the temperature of the air provided by the conditioning equipment, the mean air temperature in the conditioned zone, supply air mass flow rate, duct air leakage rate, and conditioning equipment on-time were calculated using the building energy simulation program EnergyPlus. AtticSim results were used to estimate ceiling and duct heat transfers.

The Home Energy Rating System Building Energy Simulation Test (HERS BESTEST) Case L100A building model, shown in Figure 1, was used as a base building for this study (NREL/TP-472-7332a 1995). The building is a 57 ft × 27 ft single-story house with one conditioned zone, an unconditioned attic, and a vented crawl space. Although many of the homes in the southern climates are built on slabs, the crawl space foundation was retained in all zones for consistency. Because the temperature within the conditioned zone is considered to be well-mixed (i.e., no stratification), and is controlled to a setpoint, the air temperature below the attic floor (produced by EnergyPlus and used by AtticSim) should be unaffected by the foundation type. The foundation type would have a slight impact on the total house load, which would in turn impact the timing of the air entering the ductwork (the other EnergyPlus output used by the AtticSim model), but this should be a secondary effect, at worst. For example, if the total house load is changed by 10%, the total duct energy involved in the worst assumed leakage rate will change by 1.4%.

An hourly internal load schedule for the conditioned zone was also used as per the HERS BESTEST Case L100A building. The analysis was performed for eight cities, representing the eight ASHRAE climate zones, shown in Figure 2. For all climate zones, an interior 21.1°C (70°F) heating set point temperature and 23.9°C (75°F) cooling set point temperature were used.

Two levels of building quality were evaluated, one with adequate ceiling insulation (new), and one with minimal insulation (old). The new homes were taken to have code-level insulation, corresponding to R-30 for climate zones 1–3, R-38 for climate zones 4 and 5, and R-50 for climate zones 6–8. An

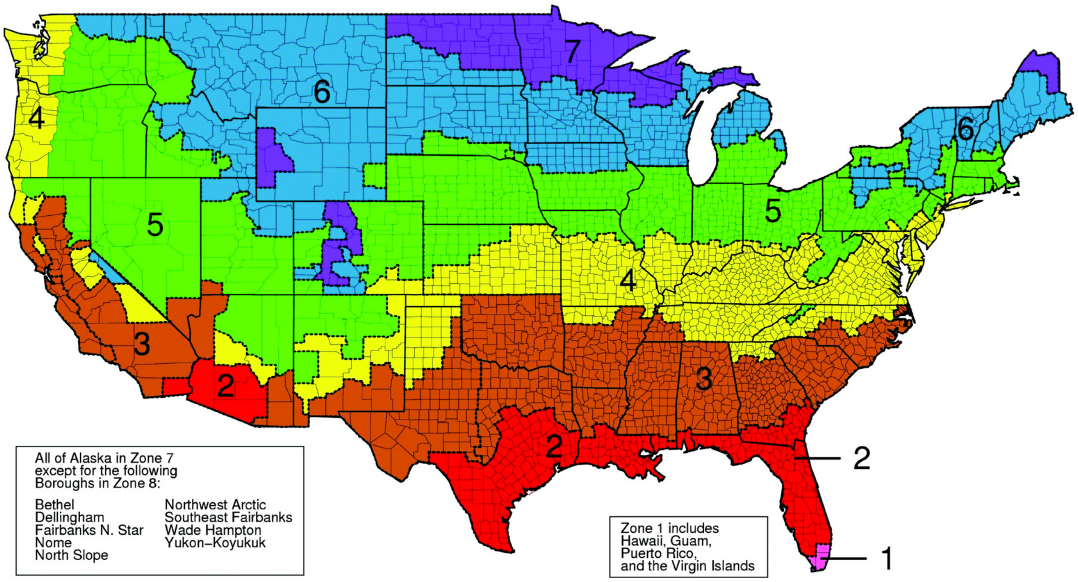

Figure 2 *Climatic zones used by ASHRAE and the IECC.*

attic insulation level of R-19 was used for the older home in all zones. Building air infiltration rates of one and two air changes per hour were used for the new and old homes, respectively. These leakage rates are consistent with those measured in a survey of 34 homes of various ages between 2004 and 2006, after adjusting the reported air change values at 50 Pa to 4 Pa, closer to the pressure difference that actually induces air exchange in homes (Antretter et al. 2007).

The study considered three cases for attic ducts, representing situations with no ducts (and therefore no duct losses), insulated and relatively tight ducts, and uninsulated leaky ducts. The leaky ducts were modeled with no insulation and 14±2% duct air leak. The better ducts were modeled with R-6 insulation and 4±1% duct air leakage. The EnergyPlus Airflow Network module was used to model the supply and return duct systems in an attic. In the Airflow Network module, the duct air leak for each moment in time is a function of four characteristic parameters (“Effective Leakage Ratio”, “Maximum Flow Rate”, “Reference Pressure Difference”, and “Air Mass Flow Exponent”) and two weather parameters (wind velocity and direction). The “Effective Leakage Ratio” was adjusted to get approximately the same duct air leakage rate, as a fraction of the total duct flow rate, for all climate zones.

To estimate the energy savings attributable to radiant barriers, four values of emittance (ε) for the downward-facing side of the interior attic space and the gable ends were considered; 0.05, 0.1, 0.2, and 0.9. The attic (that is, the top surface of the attic floor insulation) was given an emittance of 0.9. The building thermal load with no radiant barrier (ε = 0.9) was compared with the thermal loads with ε = 0.05, 0.1, and 0.2 to calculate the radiant barrier energy savings.

A DETAILED RADIATION MODEL OF THE RAFTER CAVITY SPACE WITHIN THE ATTIC ENVIRONMENT

The coupled AtticSim-EnergyPlus model requires the effective emittance of the downward-facing surfaces. In the simplest case, that of a radiant barrier stapled to the ends of the rafters, that value is well defined. However, if the radiant barrier is an integral part of the roof sheathing, supported over uncoated wood rafters, the radiation “view” facing down is a combination of both the barrier material and the wood. Previously, a projected area-weighted average was used. For example, if foil-faced sheathing was supported on 4 cm (1.5 in.) wide rafters spaced on 41 cm (16 in.) centers, the effective emittance was set equal to $(4\varepsilon_{\text{rafter}} + 37\varepsilon_{\text{foil}})/41$.

An analysis was performed to examine this simplification. The analysis divided the attic region into two sub-enclosures and a full three-dimensional surface-to-surface radiant interaction model was developed for each domain. The first region spans between the underside of the roof deck and the edges of the rafters. This region is further divided into a number of identical rafter enclosure models between two adjacent rafters, with a cross-section shown in Figure 3. The length of the unit cell in the direction perpendicular to this cross section is the length of the rafters. The temperatures of surfaces 7 to 13 were specified and a condition of symmetry with no heat flow was assumed on a plane through the center of each rafter. The second sub-enclosure, with a triangular cross-section shown in Figure 4, represents a simple attic region bounded by the top of the attic floor insulation, the two gable ends of the attic, and the plane stretched across the ends of the rafters.

For the two three-dimensional enclosures, the configurations were calculated based on three-dimensional expressions available in the literature and radiation is the only mode of heat

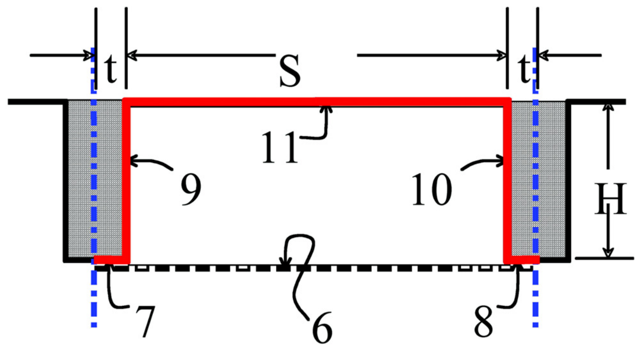

Figure 3 *Rafter Enclosure Model configuration. Surfaces 12 and 13 are at the ends of the channel.*

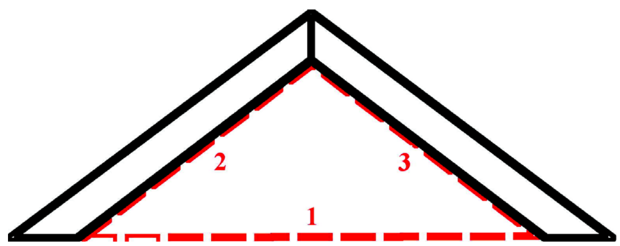

Figure 4 *Sketch of five-surface enclosure model of attic. Surfaces 4 and 5 are at the gable ends of the attic.*

transfer considered (Incropera and DeWitt 2002; Feingold 1966). Each of the surfaces in the enclosures is assumed to be diffuse gray with uniform radiosity and temperature. The temperature and emittance of surfaces 1, 4, and 5 in Figure 4 were specified for each case. These two solutions are coupled by the heat transfer, temperature, and effective emittance at the imaginary plane, identified as surface 6 in Figure 3 and surface 2 in Figure 4. The value for the effective emittance of that plane was varied parametrically to calculate the corresponding temperature and heat flux at the plane.

An integrated model combines the rafter enclosure and five-sided enclosure models into one and determines the temperature of the common plane, T_c, as a function of the emittance of the common surface, ε_c. Both enclosure models require that the emittances and temperatures of each surface be specified to calculate the radiant heat transfer for each of the surfaces. For a given emittance for surface 6 in Figure 3 (surface 2 in Figure 4), ε_c, its temperature, T_c, and heat flux can be determined by finding the temperature at which the heat transfer at that common surface is balanced between the two models. That is, for any emittance for the common surface, the surface temperature that satisfies both models corresponds to the condition where:

$$\left.\frac{q_6}{A_6}\right|_{\text{rafter enclosure model}} + \left.\frac{q_2}{A_2}\right|_{\text{five-sided enclosure model}} = 0 \qquad (1)$$

where

q_6/A_6 = heat flux across surface 6 in the rafter enclosure model (Figure 3)

q_2/A_2 = heat flux across surface 2 in the five-sided enclosure model (Figure 4)

These parametric results for q_c and T_c as a function of ε_c from the numerical analysis were then combined with an analytical model of the radiation heat transfer within the rafter domain. Looking at the general case for the rectangular region, shown in Figure 5, the heat flux across the common plane (note that in this convention, q_c will be negative when $T_h > T_c$) can be expressed as

$$q_c = \frac{\sigma(T_c^4 - T_h^4)}{\frac{1}{A_c}\left[\frac{1}{\varepsilon_c} + \frac{A_c}{A_h}\left(\frac{1-\varepsilon_h}{\varepsilon_h}\right)\right]} \qquad (2)$$

where

c and h surfaces are defined in Figure 5

q = heat flux, W/m^2

σ = Stefan-Boltzmann constant W/(m$^2\cdot$K^4),

T = temperature (K),

A = area (m^2), and

ε = emittance.

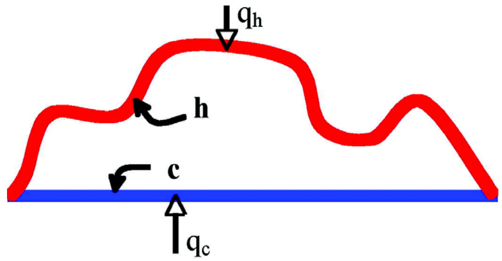

Figure 5 *General case for the rafter enclosure model.*

Table 1. Calculated Effective Emittance for Use with Whole House-Attic Model

Case Name	Roof Pitch	Rafter Spacing [cm (in.)]	Rafter Width[A] [cm(in.)]	Season[B]	Effective Values for Surface 6 in Figure 3 (which is also Surface 2 in Figure 3)			Simple Area, Averaged ε
					T (C)	Q (kW/m²)	ε	
Foil radiant barrier stapled to the bottom of rafters [C]	Any	Any	Any	Any	–	–	0.05	0.05
All wood (Rafter and sheathing surface emittance of 0.9)	3	41 (16)	14 (5.5)	Summer	52	3.6	0.73	0.90
	3	41 (16)	14 (5.5)	Winter	–5.2	1.7	0.73	0.90
Foil-faced oriented strand board sheathing (Rafter emittance of 0.9 sheathing emittance of 0.1)	3	41 (16)	14 (5.5)	Summer	50	1.0	0.25	0.18
	3	41 (16)	14 (5.5)	Winter	–3.2	–0.50	0.26	0.18
	6	61 (24)	14 (5.5)	Summer	50	0.82	0.19	0.15
	6	61 (24)	28 (11.5)	Summer	50	0.51	0.21	0.15
	3	41 (16)	14 (5.5)[D]	Summer	50	0.77	0.19	0.18
	3	41 (16)	14 (5.5)[D]	Winter	–3.0	–0.36	0.19	0.18
Liquid-applied radiation coating (Rafter and sheathing surface emittance of 0.2)	3	41 (16)	14 (5.5)	Summer	50	0.85	0.21	0.20
	3	41 (16)	14 (5.5)	Winter	–3.1	–0.40	0.21	0.20
	6	61 (24)	14 (5.5)	Summer	50	0.86	0.20	0.20
	6	61 (24)	28 (11.5)	Summer	50	0.86	0.20	0.20
	3	41 (16)	14 (5.5)[D]	Summer	50	0.80	0.19	0.20
	3	41 (16)	14 (5.5)[D]	Winter	–3.0	–0.37	0.20	0.20

[A] All rafters 4 cm (1.5 in.) thick
[B] The temperatures used for the summer condition were 38°C (100°F), 66°C (150°F), and 66°C (150°F) at the top of the attic floor insulation, at the bottom of the attic sheathing, and at the gable ends of the attic, respectively. The temperatures used for the winter condition were 4.4, –18, and –18°C (40, 0, and 0°F) at the top of the attic floor insulation, at the bottom of the attic sheathing, and at the gable ends of the attic, respectively. During the summer the rafter temperature was 5.6°C (10°F) less than the sheathing temperature and during the winter the rafter temperature was 5.6°C (10°F) greater than the sheathing temperature.
[C] Not modeled because the emittance of the plane across the bottom of the rafters is known
[D] Temperature profile applied along width of rafter (fin effect)

Solving for the emittance of the hot surface for the case where the hot and cold areas are equal, that is, as the hot surface approaches the imaginary flat cold surface, the effective emittance of that surface can be expressed as

$$\varepsilon_{\text{effective, analytical}} = \left[\left(\frac{\sigma\left(T_c^{\,4} - T_h^{\,4}\right)}{\left(q_c / A_c\right)} - \frac{1}{\varepsilon_c}\right) + 1\right]^{-1} \tag{3}$$

The opposing surface temperature, T_h, was taken to be the area-weighted average of the surface temperatures 7 to 11 in the rafter enclosure model (Figure 3). The temperatures and heat fluxes from the full three-dimensional radiation models were used to calculate this effective emittance and compared to the assumed ε_c to find that point where the two values were equal.

$$\varepsilon_{\text{effective}} = \varepsilon_c \text{ that corresponds to}$$
$$\varepsilon_{\text{effective, analytical}}(\varepsilon_c, T_c, q_c) = \varepsilon_{c,\text{ numerical}}(T_c, q_c) \tag{4}$$

Table 1 summarizes the effective emittance for 14 combinations of materials and surface temperatures. For the summer conditions, the sheathing, gable ends, attic floor insulation, and rafter temperatures, respectively, were set equal to 339, 339, 311, and 333 K (150, 150, 100, and 140°F). For the winter conditions, the sheathing, attic floor insulation, and rafter temperatures, respectively, were 255, 255, 261, and 277 K (0, 0, 10, and 40°F). These temperatures are consistent with those measured at an experimental attic facility (Miller et al. 2007). The attic modeled here was 8.5 m × 12.8 m (28 ft × 42 ft) with a roof pitch (rise units for every 12 units of run) of either 3 or 6 (corresponding to roof angles of 14° and 27°).

In the equation for effective emittance of the imaginary slant surfaces of attic, the T_c and q_c are a part of the solution obtained in the numerical analysis. In other words, effective emittance is just what the name implies, but is not a property of any real surface unless one actually places a surface in there. Effective emittance depends on all input parameters. Other than the geometry, the significant parameters are the temperatures and the emittance of all other surfaces. So the values for the summer and winter seasons need not be the same.

For the cases where the foil-faced sheathing is placed upon wooden rafters, the overall effective emittance is greater than that of the foil because the foil is recessed within the rafter space and surrounded by materials with a greater emittance. The impact of this recessed effect is most marked in the case where the larger rafters, 4 cm × 28 cm (nominal 2 in. × 12 in.), are used.

RESULTS

To evaluate the potential economic savings due to radiant barriers, state average fuel prices and representative HVAC system efficiencies were applied to the calculated energy savings. For heat pumps and air conditioners, the seasonal efficiencies required in the 2006 Department of Energy standards were used, a Seasonal Energy Efficiency Ratio of 13 and a Heating Season Performance Factor of 7.7, to translate energy savings to electricity savings. For gas furnaces, an efficiency of 0.85 was assumed. Table 2 shows the energy prices used for each analysis location. For all locations, the lesser of the gas heat cost or the electric heat cost was used along with the electric air conditioning.

The results of the parametric evaluation showed that the savings estimates are most sensitive to the climate, then the presence and condition of the ductwork, and finally the effective emittance of the downward facing surface of the roof sheathing (in the range evaluated, from 0.05 to 0.20). Figure 6 shows the annual savings for a 143 m^3 (1540 ft^2) house for cases with no ducts, insulated ducts with a low leakage rate, and uninsulated ducts with a high leakage rate. Values are shown for attics with code-level insulation and houses with only R-19 attic floor insulation.

The influence of climate is immediately obvious, with the savings in zones 4 and 5 about half those in zones 1 and 2. The savings for houses with well-insulated low-leakage attic ducts (labeled "good" in Figure 6) versus houses with no ducts is

Table 2. Energy Prices Taken from EIA 2008 State Average Residential Retail Prices

Zone	City	Electricity (¢ per kWh)	Natural gas ($/1000 ft^3)
1	Miami, FL	11.17	21.29
2	Austin, TX	10.32	13.79
3	Atlanta, GA	9.12	18.5
4	Baltimore, MD	12.36	16.05
5	Chicago, IL	8.52	12.09
6	Minneapolis, MN	7.57	11.3
7	Fargo, ND	6.35	10.34
8	Fairbanks, AK	14.16	8.72

about a factor of two, although the savings for both are small. The savings for houses with poorly-insulated leaking ducts (labeled "poor" in Figure 6) are much greater in Zones 1 and 2, but the impact of duct condition is much less in colder climates, as shown in both Figure 6 and Figure 7. The influence of attic surface emittance on annual savings is relatively small in the range from 0.05 to 0.3, as shown in Figure 8 and by the closeness of the two points shown for each zone/duct condition in Figure 6. The two values shown for each case in this figure correspond to radiant barrier effective emittance of 0.05 (typical for a foil-faced barrier stapled to the bottom of the rafters) and 0.2 (representing a liquid-applied radiation coating covering both the sheathing underside and all exposed rafters). The savings for these two cases are very similar.

DISCUSSION

Our more recent whole-house models are able to provide detailed duct leakage and system run time information

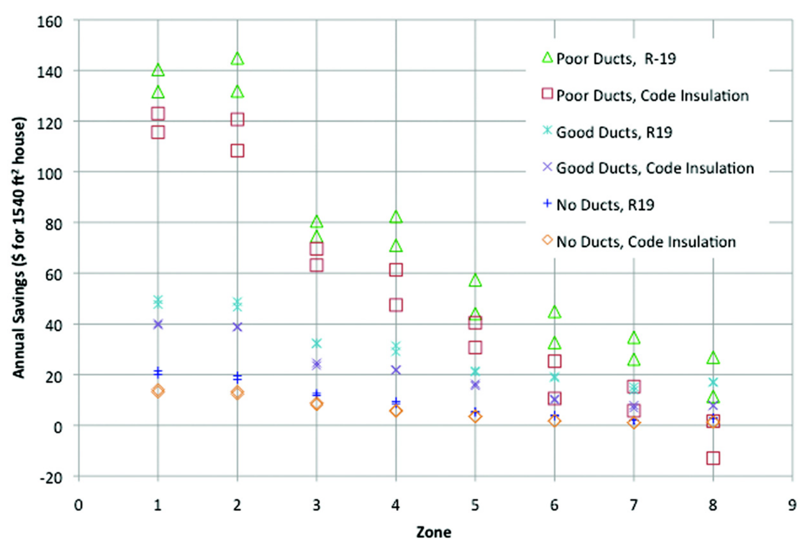

Figure 6 *Individual values shown for radiant barrier emittances of 0.05 and 0.20.*

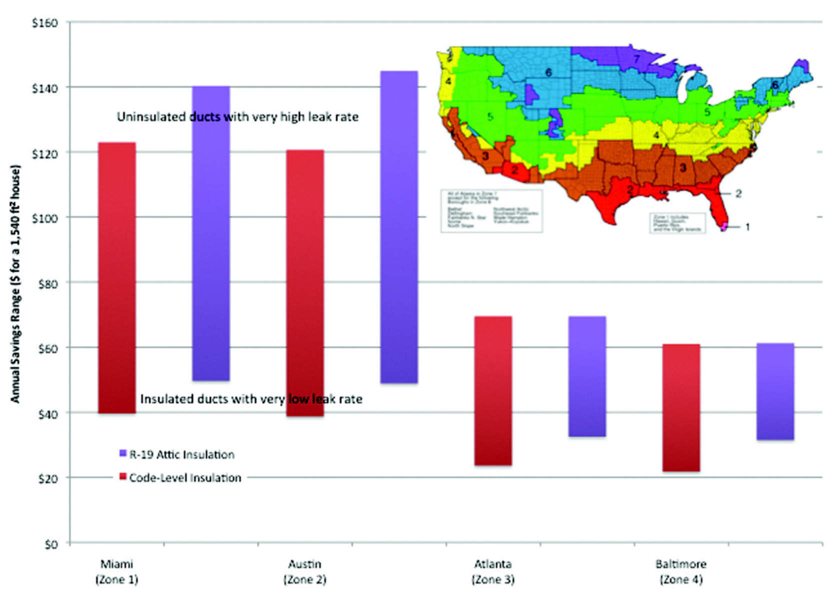

Figure 7 *Range of savings for attics with ducts in poor to good conditions for radiant barrier emittances up to 0.2.*

unavailable with previous hourly models. This more detailed information from the whole house model has in turn enabled us to better apply the attic model to examine the impact of duct leakage. These analyses revealed that the spread in radiant barrier savings estimates is extremely sensitive to this value, especially in the southern climates where radiant barrier savings are positive (see Figure 6 and Figure 7). Moreover, the results were less sensitive to the attic surface emittance for values between 0.05 and 0.3, as shown in Figure 8 for Zone 1.

Previous tools provided to consumers accommodated a large number of inputs, for heating and cooling system efficiency, local utility costs, local installed insulation costs, four levels of attic floor insulation, three different radiant barrier locations, and afforded a selection from 27 locations to match their climate. Fuel cost escalation factors were provided to help the consumer make a life-cycle cost calculation. Savings values were provided for two conditions, with or without ducts in the attic.

However, duct conditions can vary widely and are seldom well-characterized. Most customers will have no idea whether their ducts are leaking 5 or 20% of their conditioned air, or how much insulation is on the ductwork. Moreover, the savings calculations, both for the existing guidance and this new version, are based on a single attic geometry with a single whole-house model. Given these two factors, a detailed consumer tool asking for a host of specific values is likely to create an artificial perception of accuracy. At this point, it is likely that a range of values will be used to provide the information to the consumer, perhaps a graphic similar to Figure 7.

The detailed radiation analysis of the rafter cavity space within the attic environment was initiated because both the AtticSim and EnergyPlus models use a single surface to represent the downward facing side of the attic sheathing. The geometry in most real attics is much more complex; and the radiation heat transfer between this complex surface and the rest of the attic environment is of great interest when comparing the different types of radiant barrier products. Specifically, what is the performance difference between one product that covers every surface with a moderately low emittance coating versus another product that places a very-low emittance on a portion of the downward-facing surface?

The results for this numerical model showed a greater difference from the simple area-average model than was initially expected for the case of the foil-faced sheathing placed upon wood rafters. This difference was less when a temperature gradient was placed on the rafters to better reflect their thermal performance as fins. There were also small differences between the summer and winter effective emittance for the same geometry. This seasonal difference exemplifies one of the model limitations. The use of an artificial surface concept carries the drawback that the ‘properties’ of this artificial surface depend on the boundary temperatures as well as the geometry and radiation properties of the surrounding real surfaces. This numerical analysis is currently being extended to the point of a complete coupling of the two radiation domains without the use of the artificial surface concept. The expanded analysis will help us to make a more informed choice of an “effective” emittance for use in the simpler attic models.

CONCLUSIONS

Detailed consumer savings calculations are likely to provide a false sense of accuracy considering that the results are extremely sensitive to a factor, duct leakage, that most consumers will be unable to quantify. The update to the Radiant Barrier Factsheet will therefore likely delete the existing

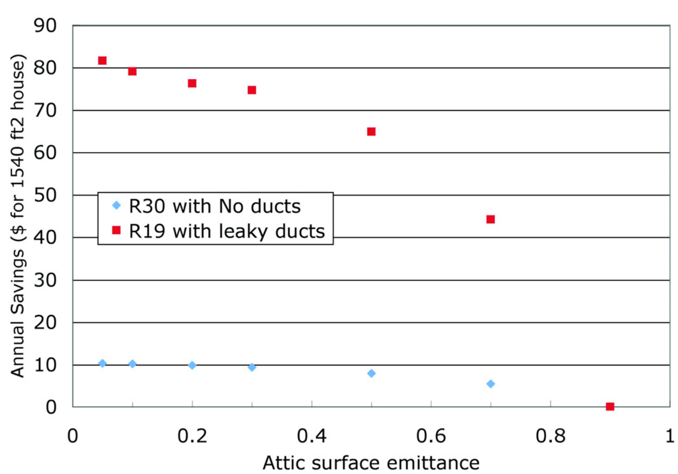

Figure 8 *Annual savings for a house in Zone 1 for various values of radiant barrier surface emittance applied to the underside of the roof only (not on the gable ends).*

calculator model and provide a more generalized guidance with regard to savings magnitudes.

The Fact Sheet guidance will likely include a statement to the effect that: "If you have poorly insulated and leaking ducts in the attic in climate zones 1 and 2 (e.g., Florida, southern parts of Texas), radiant barriers will save $50 to $150 per year. For other conditions and locations, savings will be much smaller or negative."

The numerical analysis shows that the effective emittance of the downward-facing roof surface is very similar for roof sheathing materials with a foil-covered interior surface, and liquid-applied low-emittance coatings. Furthermore, the savings for an emittance ranging from 0.05 to 0.2 were very similar, so consumers will be advised that these two approaches, as well as the use of aluminum foil or metalized film-faced materials stapled to the bottom surface of rafters, should provide similar savings.

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