BENEFITS AND TRADE-OFFS

of Low-Slope Roofing System Insulation and Reflectance

By Linlin Xing and Thomas J. Taylor

INTRODUCTION

Increasingly, roof systems are being required to supply more benefits than basic protection from weather. In addition to the aesthetic aspects of residential roofing material design, both residential and commercial roofs are now seen as significant contributors to the energy usage of buildings. According to the U.S. Department of Energy, one-third of all energy consumption in the U.S. is used to condition and light buildings.

Roof systems make two main contributions to building energy use by virtue of their reflective and insulative properties. Reflectance is important to reduce heat gain and thereby lower building cooling costs. Conversely, insulation has traditionally been viewed as reducing heat loss, with greater insulation prescribed in colder zones. However, insulation also acts to reduce heat flow into buildings, leading to the question: When is it appropriate to focus on improving reflectivity and when to focus on insulation?

This article examines the benefits and trade-offs associated with improved roofing membrane reflectivity versus improved insulation for low-slope buildings. In addition, the effects of climate zones and geographical location within the U.S. are examined.

Clearly, any discussion of reflectivity and insulation must take into account any associated building codes, and these are also reviewed.

ROOF MEMBRANE REFLECTANCE

By designing membranes with higher reflectance, it is possible to lower the heat gain experienced by the total roof system. Such reflective systems are referred to as cool roofs and potentially provide for lowered cooling demand for building interiors.

In simple terms, a cool roof is highly reflective and can return a substantial portion of the sun's energy back to the atmosphere. Therefore, the surface stays cooler and transfers less heat into the building. An additional feature of a cool roof is that it can more easily emit the small amounts of heat that are absorbed. By combining high reflectivity and high emittance, it is possible to substantially reduce the heat load on the system.

The highest reflectivities are being achieved by single-ply thermoplastic membranes and by various coatings. Single-ply systems typically achieve high reflectivity by incorporating titanium dioxide as a pigment. This mineral reflects light and heat across a broad portion of the sun's spectrum and is extremely white in appearance.

Solar energy consists of 5% ultraviolet light, 43% visible light, and 52% near infrared. The different colors perceived by the human eye are dependent on which wavelengths of visible light are reflected by objects. Over 50% of solar energy is near infrared light, which contributes to heat buildup if absorbed by roofing materials.

With the reduced temperatures provided by reflective roofing materials, there are not only environmental benefits such as energy savings and reduction of the heat island effect, but also potential improvements to the longevity of these materials. It is recognized that since heat accelerates the degradation of polymeric membranes, technology that lowers temperatures should result in better retention of their physical properties. The reduced thermal expansion and contraction due to the reduced temperatures with reflective pigments also help to extend the life of roofing materials.

COOL ROOFING STANDARDS AND CODES

Cool roofing standards are based on both solar reflectance and emissivity.

The solar reflectance (SR) is intended to indicate how much of the sun's ultraviolet, visible, and infrared energy (i.e., solar flux) is reflected. SR is defined as the fraction of solar flux reflected by a surface, expressed as a percent or within the range of 0.00 to 1.00. Measurement is done using the methods described by the American Society for Testing and Materials' (ASTM) Standard E903, ASTM C1549, or ASTM E1918.

ASTM E903 measures solar reflectance over the wavelength range of 250 to 2500 nm using integrating spheres. Such integrating spheres ensure that specular, direct, and scattered reflections are measured. By using a commercial portable solar reflectometer, which is calibrated using specimens of known SR, ASTM C1549 determines SR from measurements at four wavelengths in the solar spectrum: 380 nm,

500 nm, 650 nm, and 1220 nm. ASTM C1549 shows the comparison results between C1549 and E903 methods. The SR results at air mass 1.5 measured per ASTM C1549 are generally 1.9% greater than those obtained with ASTM E903.

ASTM discontinued E903 in August 2005 in accordance with section 10.5.3.1 of the Regulations Governing ASTM Technical Committees, which requires that standards be updated by the end of the eighth year since the last approval date. ASTM E1918 covers the SR measurement for various horizontal and low-sloped surfaces and materials in the field, using a pyranometer. The test method is intended for use when the angle of the sun to the surface is less than 45 degrees. The SR data reviewed in this paper is measured per ASTM C1549.

While SR defines the percentage of all solar radiation that is immediately reflected from a material surface, any energy that is not reflected from a surface is absorbed by the material. The emissivity, or thermal emittance (TE), is a measure of how much absorbed energy is radiated from a material. TE is defined as the ratio of the radiant heat flux emitted by a sample to that emitted by a black-body radiator at the same temperature. Measurement is done using ASTM C1371 or ASTM E408. ASTM C1371 is the standard test method for determination of emittance of materials near room temperature using portable emissometers. ASTM E408 is the standard test method for total normal emittance of surfaces using inspection-meter techniques. The TE data reviewed in this paper is measured per ASTM C1371.

The solar reflectance index (SRI) is a commonly used value that incorporates both solar reflectance and emittance into a single value. SRI measures the relative Ts (steady-state surface temperature) of a surface under the sun with respect to the standard white (SRI=100, for a sample with reflectivity of 0.80 and emissivity of 0.90) and standard black (SRI=0, for a sample with reflectivity of 0.05 and emissivity of 0.90) under the standard solar and ambient conditions. SRI is calculated using equations based on previously measured values of solar reflectance and emittance as laid out in ASTM E1980.

Due to the accumulation of surface particles like dew, dust, and air pollutants on roof materials, as well as the material's aging, the SR tends to decrease over time. Also, the roof slope affects aged SR, with steeper slopes accumulating less dirt and particles through dislodging.

For a material to be qualified as an ENERGYSTAR® product, in addition to the initial SR, the SR after aging for a minimum of three years must be measured by following the guidelines of ENERGYSTAR® Version 2.0 Program Requirements for Roof Products.

There are national and local programs or policies related to cool roofing, each with its own unique criteria and definitions.

- The ENERGYSTAR® Roof Products Program was introduced by the Environmental Protection Agency (EPA) in 1998. The EPA estimates that an ENERGYSTAR®-labeled roof can reduce a roof temperature by as much as 100°F.
- Established in 1998 as a nonprofit organization, the Cool Roof Rating Council (CRRC) is now recognized by the California Energy Commission (CEC) as the sole entity responsible for labeling roofing products that are allowed in the California Energy Code Title 24. To be Title 24-compliant, the roofing material has to meet prescriptive requirements of 0.70 SR and 0.75 TE and be a CRRC-listed product.
- Started in 2000, the U.S. Green Building Council's Leadership in Environmental and Energy Design (LEED) program has gained in popularity in the construction industry. LEED is a whole-building design program that encourages an integrated design and construction process whereby points are awarded for the use of sustainable products or building practices.

Table 1 lists some of the programs, criteria, and related test methods.

LOW-SLOPE THERMAL INSULATION

Unlike residential roofing, the vast majority of low-slope insulation is rigid. Premanufactured rigid insulation is formed into boards from either fibrous materials or plastic foams. Alternatively, in the case of foam insulation, it is sometimes formed in place, using special equipment to meter, mix, and spray reactive chemicals onto the deck.

Heat transfer from a hot to a cold surface involves a combination of conduction, convection, and radiation. Thermal insulation functions by reducing conductive and radiative transfer and eliminating convection. It should be noted that convection is

PROGRAM	POLICY REQUIREMENTS	MIN. INITIAL SOLAR REFLECTANCE	MIN. AGED SOLAR REFLECTANCE	MIN. EMISSIVITY	TEST METHODS
Title 24 (CA Energy Code)	Required	0.70	None	0.75 (ASTM C1371)	SR: ASTM E903, E1918, C1549, CRRC Test Method #1 TE: ASTM C1371
Energy Star Low Slope (<2:12) Steep Slope (>2:12)	N/A N/A	0.65 0.25	0.50 0.15	None None	SR: ASTM E903, C1549, CRRC Test Method #1
LEED Low Slope (<2:12) Steep Slope (>2:12)	Credit	SRI: 78 min SRI: 29 min		0.90 for 75% of the roof surface (ASTM E408)	SRI: ASTM E1980 TE: E408

"Required" refers to policies where cool roofs are not mandatory, but an energy penalty is given if one is not used.
"Credit" refers to policies where cool roofs are not mandatory, but an energy credit is earned if one is used.

Table 1

only eliminated if all air spaces between the hot and cold surfaces are filled with insulation. If there are gaps, such as between insulation boards, then convection occurs, and a thermal short circuit exists.

An important characteristic of insulating materials is the thermal resistance or R-value. The value is calculated from the material thermal conductivity (k), units (Btu-in)/(hr•ft²•˚F), and product thickness (L), using the following equation:

$$R = \frac{L}{k}$$

This is often expressed as R per inch to enable a comparison of the effectiveness of various materials to be compared. Plastic or polymer-type insulation includes polystyrene, polyurethane, and polyisocyanurate. Polyisocyanurate or "iso" provides the best insulating value per inch, typically R-5.8 to 6.5, with the most commercially available product being at R-6/in.

ENERGY SAVINGS MODELS

Several tools exist to calculate estimates of energy savings due to different roofing systems. A calculator published by Oak Ridge National Laboratories (ORNL), shown online at **http://www.ornl.gov/sci/ roofs+walls/facts/CoolCalcEnergy.htm**, considers SR and emissivity for the membrane, insulation value, and energy costs. Another version has been made available by the ENERGYSTAR® organization, at **http://roofcalc.cadmusdev.com/RoofCalc BuildingInput.aspx**. This calculator is similar to the ORNL version but does not consider membrane emissivity.

For this study, preliminary work showed some differences between the two calculators, which depended largely on the geographic location of buildings. This is to be expected given that the ENERGY-STAR® model does not include emissivity. In practice, low emissivity can be a benefit in northern latitudes during cooler months, while high emissivity is required for southern regions, where building cooling is more important. Based on the preliminary work, the ORNL model was used for the work described here.

For the ORNL calculator, the air conditioner efficiency (coefficient of performance) was set as 2.0, and the heating system efficiency was set as 0.7 (i.e., both were assumed to be average). Heating was assumed to be gas-based. For any energy savings calculation, it is critical to have valid energy costs. For this study, commercial 2008 natural gas and electricity cost data were obtained from the Energy Information Administration (EIA) data published at **http://www.eia.doe.gov/.** For the gas costs, a conversion factor of 100 cubic feet = 1 Therm, was used. Yearly average energy costs were used throughout.

ROOF SYSTEM COMPARISONS

The impacts of the three factors – insulation (R-value), solar reflectance (SR), and thermal emittance (TE) – on energy savings of low-slope systems were evaluated with ORNL's energy-saving model. Unless otherwise noted, the annual energy saving displayed herein is based on calculation compared to a black surface.

INSULATION (R-VALUE) WITH HIGH REFLECTANCE MEMBRANES

The roofing insulation R-values used are listed in *Table 2*.

To study the impact of roofing insulation R-value on energy savings for different areas, a typical commercially available, white, single-ply membrane with 0.78 initial SR and 0.90 initial emissivity, commonly used in low-slope systems, was selected, and its annual energy saving was calculated (*Figure 1*).

For the calculations shown in *Figure 1*, an average power cost was used. However, it should be noted that there can be significant differences in terms of both electricity and gas costs across the U.S.

As shown in *Figure 1*, the annual energy savings are realized most when a white membrane is used in combination with 5 to 25 R-value roofing insulation in Florida, California, and Texas. For roofing insulation with an R-value over 25, the energy

R-Value (hr•ft²•°F)/Btu	Example Configuration to Achieve R-Value
5	1.5-in-thick wood fiberboard insulation on a 0.75-in-thick plywood deck
13	2-in-thick aged polyisocyanurate insulation on a 20-gauge Type B metal deck
25	4-in-thick aged polyisocyanurate insulation on a 20-gauge Type B metal deck
32	5-in-thick aged polyisocyanurate insulation on a 20-gauge Type B metal deck

Table 2 – R-values of roofing insulation, quoted from ORNL paper "Effect of Solar Radiation Control on Energy Costs – A Radiation Control Fact Sheet for Low-Slope Roofs," by T.W. Petrie et al.
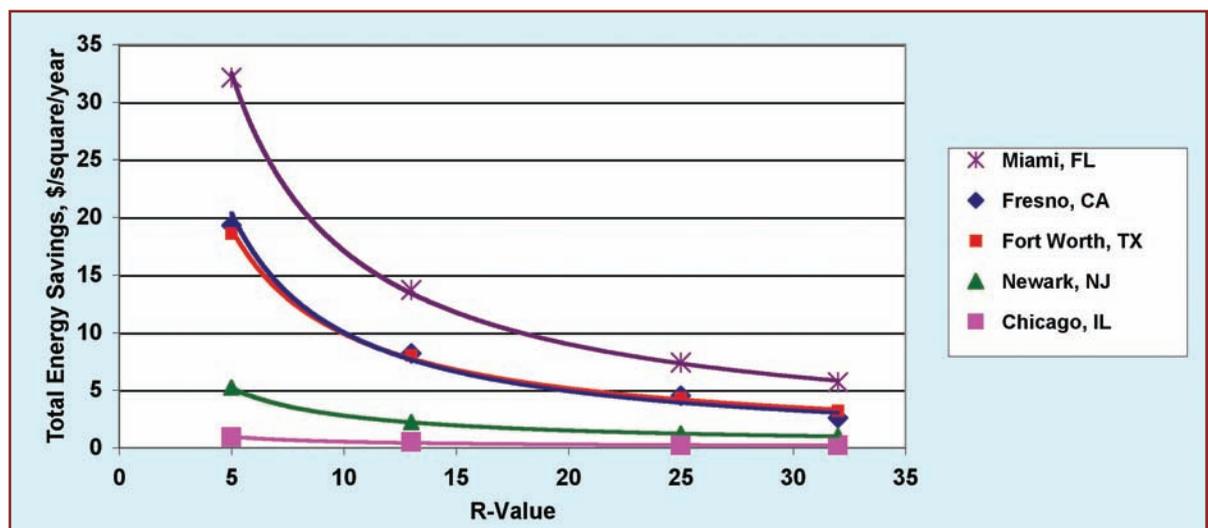

Figure 1 – Total annual energy savings vs. R-value of insulation with a reflective membrane (TSR = 0.78, E = 0.90) compared to a black roof. Assumes electricity cost of $0.1028/kWhr and gas cost of $12.91/1000 cf.

saving with white membrane is reduced but may still be significant. The large differences between the savings achieved in some states versus others are best understood by considering summer versus winter energy usage as a function of climate. *Figure 2* shows the climate zones delineated by DOE/International Energy Conservation Code (IECC) for the U.S.
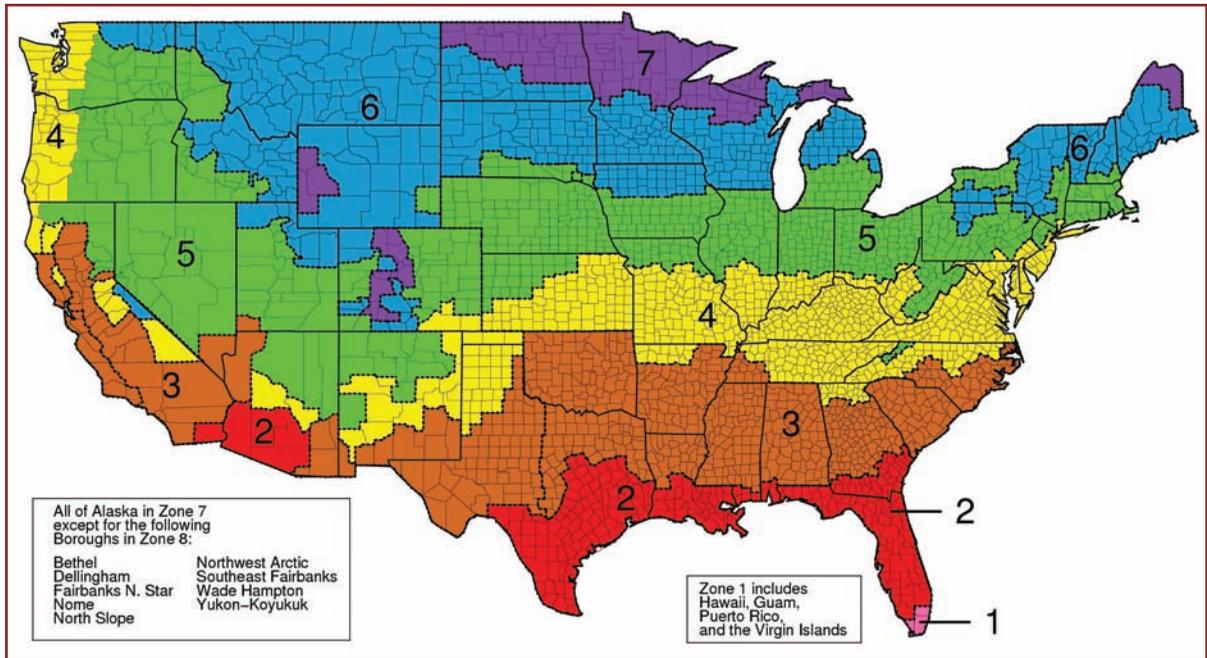

Figure 2 – 2004 International Energy Conservation Code (IECC) U.S. climate zones.

In hot, sunny regions such as Zones 1 through 3, cooling loads dominate annualized energy usage, and therefore, reflective membranes provide for significant energy savings. However, in colder regions such as Zones 6 and 7, heating loads dominate and membranes that absorb solar heat can actually slightly lower energy usage.

This can be illustrated by the cooling versus heating data that were combined for *Figure 1*. *Figure 3* shows the individual contributions for each city, assuming an R-13 insulation value. Note that positive numbers reflect a savings, while negative numbers represent a cost increase.

These data clearly show that cities with the greatest savings achieve those savings through a reduction in cooling costs and are
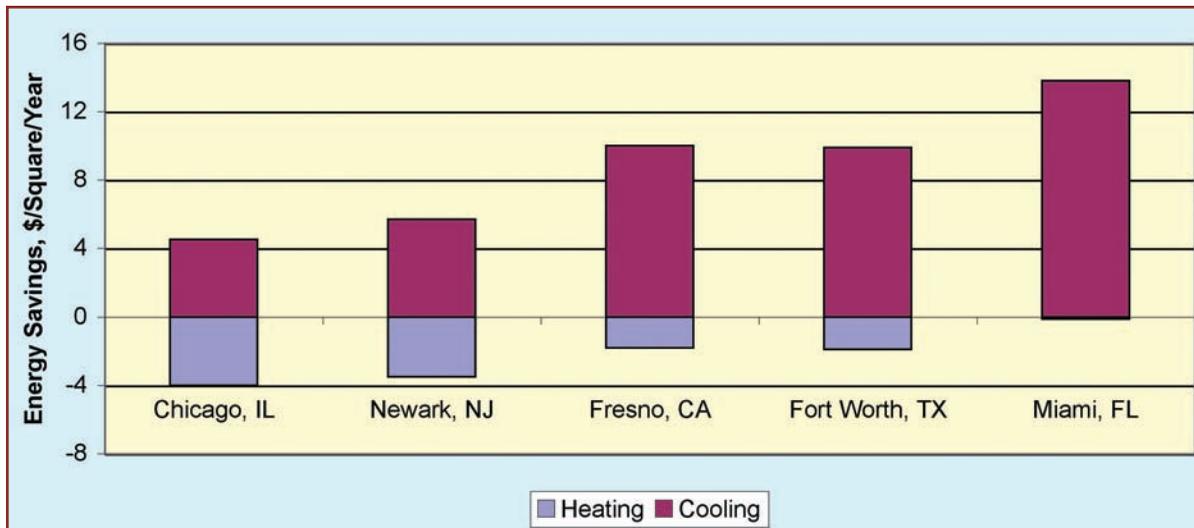
Figure 3 – Annual heating and cooling saving vs. location for a reflective membrane (TSR = 0.78, E = 0.90) compared to a black roof over R-13 insulation.

situated in hotter zones. In contrast, in Chicago and Newark, where heating costs dominate, the cooling savings are almost canceled out by the increase in heating costs. In the case of Zones 5 through 7 (*Figure 2*), the analysis would need to be done on a case-by-case basis. For an existing building, that analysis would examine previous years' heating and cooling ex-

penses. If cooling is the larger expense, then a highly reflective roof membrane would be appropriate. For new buildings, the analysis would have to take into account wall-to-roof areas, insulation levels used in walls, intended building use, and local energy costs.

It is important to note that all the savings data shown here are based on the

ORNL model using average heating and cooling system efficiencies. This may be appropriate for making reroofing choices between reflective versus absorptive roof membranes. However, for new buildings, conditioning system efficiencies are most likely much greater.

The data shown in *Figure 3* suggest that white, highly reflective membranes cause an increase in heating costs relative to dark membranes, depending on location. This is clearly the case for Chicago and Newark. However, it must be noted that cooling costs dominate commercial building energy costs. Consequently, arguments that darker membranes have a role in controlling energy costs in northern climates cannot be justified by the data.

Clearly, however, as insulation value increases, the influence of membrane temperature on internal building temperature is minimized. This indicates that there are diminishing returns to the cost of a highly reflective roof; or, put another way, the payback period will be longer. Nevertheless, there are savings to be achieved – especially in sunnier regions, regardless of the insulation value.

As energy costs escalate, then clearly the value of the savings will also increase. This is shown in *Figure 4*, with a projected future cost of gas being $25/1000 cf and electricity being $17/kWhr.

However, in those northerly zones where the heating increases and cooling savings balance out, there is no change. Again, it should be noted that the data assume average energy costs across the U.S.

CONCLUSIONS

1. In every case examined, the use of highly reflective roof membranes results in energy savings for commercial buildings, regardless of the insulation level used.
2. Energy costs incurred by commercial buildings are dominated by cooling costs. Therefore, the contribution of less-reflective roofs in low-

ering heating costs in northern climes is not significant to overall energy-cost reduction. In other words, the value of black roofs in lowering heating costs is outweighed by lower cooling costs given by highly reflective membranes.

3. Not unexpectedly, the modeling shows that the value of highly reflective roofing is greatest in U.S. Climate Zones 1 through 3. Within these three zones, further calculation may not be required, and white roofing may be assumed to always provide substantial savings.

4. For U.S. Climate Zones 4 through 7, while white reflective roofing has cost savings, these may be very small, depending on individual building design. It is strongly recommended that in these zones, an analysis be done on a case-by-case basis. Such an analysis would involve estimating likely annual heating and cooling costs. In situations where cooling costs are projected to dominate, then white reflective roofing will offer savings.
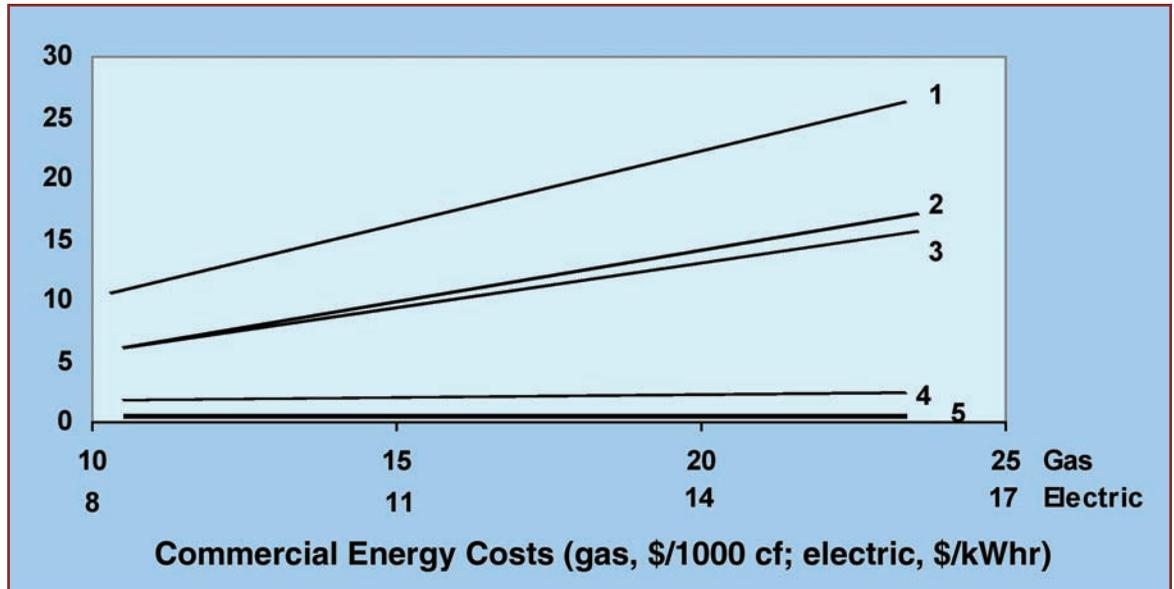

Figure 4 – Annual total energy savings vs. energy costs for a reflective membrane (TSR = 0.78, E = 0.90) compared to a black roof, for five different locations: 1. Miami, FL; 2. Fort Worth, TX; 3. Fresno, CA; 4, Newark, NJ; 5, Chicago, IL.

Thomas J. Taylor

Thomas J. Taylor is the director of low-slope research and development for GAF Materials Corporation. This position involves new product development as well as marketing and manufacturing support. Tom has over 18 years of experience in the building products industry, all working for manufacturing organizations. He received his PhD in chemistry from the University of Salford, England, and holds approximately 30 patents.

Linlin Xing

Linlin Xing is a principal scientist of the research and development department for GAF Materials Corporation. She has over 11 years of industrial experience. She received her PhD from the Department of Polymers and Coatings at North Dakota State University. Xing is a recipient of the 1998 Roon Foundation Award from the Federation of Societies for Coatings Technology (FSCT). She has published over 20 technical articles and holds eight U.S. patents and one Chinese patent. She may be reached at lxing@gaf.com.