Designing Low-Emittance Low-Slope Roofs that Comply with California Title 24 Requirements

William (Bill) Miller, PhD
Member ASHRAE

Lee Shoemaker, PhD

Andre Desjarlais

Scott Kriner

Russ Dunlap

Adam Youngquist

ABSTRACT

Numerical simulations investigated the effects of thermal emittance, solar reflectance, and roof insulation on low-slope roof heat transfer for nonresidential buildings located in the 16 climate zones of California. The cooling and heating seasonal roof heat transfers are compared to data for low-slope roofs having 0.55 solar reflectance and 0.75 thermal emittance. Recommendations are provided that enable bare and acrylic-coated metal roofs to comply with California's building efficiency standards.

INTRODUCTION

The California Code of Regulations, termed herein as 2005 Title 24, require either a performance or a prescriptive approach for demonstrating the energy-efficiency compliance of buildings in California (CEC 2005). The performance approach allows the building owner to simulate the energy usage of the proposed building using an approved whole building model such as DOE-2.1E. Alternatively, for the prescriptive aproach, the building owner can use the Overall Envelope Approach (OEA) that is documented in 2005 Title 24, Section 143 (b). This approach requires that each building component meet or surpass the respective component requirements in 2005 Title 24. It establishes two prescriptions for the initial solar reflectance of low-slope nonresidential cool roofs: (1) solar reflectance equal to 0.70 (ρ_{HE}) for a roof with an emittance greater than or equal to 0.75 (ε_{HE}), which combination shall be abbreviated SR70E75 and (2) an adjusted solar reflectance ($\rho_{LE\ initial}$) for a roof with an initial emittance less than 0.75 (ε_{LE}) The second prescription assumes the same tradeoffs between solar reflectance, thermal emittance, and roof insulation across all climate zones, and is calculated by

$$\rho_{LE\ initial} = \rho_{HE\ initial} + 0.34^{*}(\varepsilon_{HE} - \varepsilon_{LE}) \qquad (1)$$

where

$\rho_{LE\ initial}$ = minimum initial solar reflectance required for a low-emittance cool roof

$\rho_{HE\ initial}$ = 0.70, initial solar reflectance for the high-emittance cool roof

0.34 = gain coefficient for SR70E75 combination [See Levinson et al. (2005) for other combinations.]

ε_{HE} = 0.75, thermal emittance of the high-emittance cool roof (assumed constant despite aging)

ε_{LE} = initial thermal emittance of the low-emittance roof (assumed constant despite aging)

The term 0.34 in Equation 1 was calculated by Levinson et al. (2005) using ASTM E1980-98 values[1] for irradiance, surface convection, sky temperature, and outdoor air temperature. In fact, all of these values vary not only from climate zone to climate zone, but also from hour to hour due to changing weather. The constant 0.34 represents a gain coefficient describing the change in solar reflectance for a given change in thermal emittance, including a factor of 0.7 for the effects of soiling. Without this factor, the gain is 0.236. Therefore, Equation 1 predicts the minimum initial solar reflectance that includes the effects of soiling. Rearranging Equation 1 yields

1. Moderate-wind standard conditions.

William Miller *works for the Engineering Science and Technology Division and* ***Andre Desjarlais*** *manages the Building Envelope Program at Oak Ridge National Laboratory, Oak Ridge, TN.* ***Lee Shoemaker*** *is acting technical director of the Metal Building Manufacturers Association.* ***Scott Kriner*** *is technical director of the Metal Construction Association.* ***Russ Dunlap*** *and* ***Adam Youngquist*** *are students in the department of Mechanical Engineering, University of Tennessee, Knoxville.*

$$\frac{(\rho_{LE\ initial} - \rho_{HE\ initial})}{(\varepsilon_{HE} - \varepsilon_{LE})} = \frac{\Delta\rho}{\Delta\varepsilon} = 0.34 \text{ in Title 24} \tag{2}$$

The intent of Equation 1 rearranged as Equation 2 is to define initial minimum solar reflectance values for low-emittance roofs that yield the same performance for them as for ones with the Title 24 high-performance radiative properties SR70E75. The formulation is based on both roofs having the same surface temperature in their aged condition.

Certain metal roof products made of 55% Al-Zn metallic-coated steel[2] that is also coated with a clear acrylic dichromate layer and unpainted 55% Al-Zn-coated steel sheet have an initial solar reflectance of about 0.67 and an initial thermal emittance of about 0.15. Therefore, because the thermal emittance is low, based on Equation 1 these metal roof products would require a minimum initial solar reflectance ($\rho_{LE\ initial}$) exceeding 0.904, which is not achievable. To use acrylic-coated or unpainted Al-Zn-coated steel on a low-slope nonresidential building would require the building owner to apply other energy-efficient strategies to demonstrate compliance with Title 24.

This paper presents an alternative approach for developing ways to meet prescriptive requirements for low-slope roofing. Equal heat fluxes are required through the ceilings or decks of roofs having different combinations of surface radiative properties. Comparisons are made to the approach in Equation 1. The intent is to show how acrylic-coated steel can meet Title 24 prescriptive requirements with this alternative approach.

PRESCRIPTIVE REQUIREMENT FOR LOW-EMITTANCE LOW-SLOPE ROOFS

The formulation of Equation 1 for the prescriptive cool roof is based on energy balances for two low-slope nonresidential roofs, one having 2005 Title 24 solar reflectance of 0.70 and thermal emittance of 0.75 (referred to, respectively, as $_{HE}$ and ε_{HE}) and the other having the minimum initial solar reflectance required for a low-emittance roof (referred to, respectively, as $_{LE}$ and ε_{LE}). The energy balances for the two roof systems take the form

$$q''_{HE\ Roof}\Big|_{surface} = (1-\rho_{HE})I_{solar} - \varepsilon_{HE}\sigma(T_{HE}^4 - T_{sky}^4) - \bar{h}(T_{HE} - T_{air}) \tag{3}$$

and

$$q''_{LE\ Roof}\Big|_{surface} = (1-\rho_{LE})I_{solar} - \varepsilon_{LE}\sigma(T_{LE}^4 - T_{sky}^4) - \bar{h}(T_{LE} - T_{air}) \tag{4}$$

[2] Processed similar to hot-dipped galvanized steel. This steel is exposed to a molten bath composed of 55% Al-43.5% Zn -1.5% Si at a temperature of 1100°F (593°C). The coating is solidified rapidly to enhance both the microstructure and the corrosion resistance.

where

q''	=	heat flow per unit roof area
I_{solar}	=	solar insolation
σ	=	Stefan-Boltzmann constant
T_{sky}	=	absolute sky temperature
T_{air}	=	air temperature
$\bar{h}$	=	convection coefficient at the roof surface

Levinson et al. (2005) assumed the roof surfaces were adiabatic and subtracted (4) from (3) yielding

$$\begin{aligned} 0 &= I_{solar}(\rho_{LE} - \rho_{HE}) + \sigma(\varepsilon_{LE}T_{LE}^4 - \varepsilon_{HE}T_{HE}^4) \\ &\quad -\sigma(\varepsilon_{LE} - \varepsilon_{HE})\, T_{sky}^4 + \bar{h}(T_{LE} - T_{HE}) \end{aligned} \tag{5}$$

To obtain Equation 1 requires that the temperature of the high-emittance roof (T_{LE}) equals the temperature of the low-emittance roof (T_{LE}). Then the last term on the right-hand side of Equation 5 cancels identically. Thus, the low-emittance roof must be more reflective than the high-emittance one—enough for the aged low-emittance roof to have the same temperature as the aged white roof. These requirements yield

$$\rho_{LE} = \rho_{HE} + \frac{\sigma}{I_{solar}}(T_{cool}^4 - T_{sky}^4)(\varepsilon_{HE} - \varepsilon_{LE}) \tag{6}$$

Further details to justify the values for the parameters in Equation 6 that reduce it to Equation 1 are provided by Levinson et al. (2005). The fundamental requirements of Equation 1 are an adiabatic surface and the common value of surface temperature. The tradeoff is specification of the increased solar reflectance for the low-emittance surface to meet these requirements.

The alternative approach explored in this paper is to require equal heat flows through the ceiling or deck under low-slope roofs ("roof load") with higher- and lower-emittance surfaces. The solar reflectance is fixed for the high-emittance surface, and the solar reflectance of the lower-emittance surface or the insulation level under it are possible tradeoffs. This equal-load approach is believed more representative of field performance than the currently acepted approach because it includes the effects of roof insulation and other materials in the roof, much like Title 24's OEA. The gain coefficient equivalent to 0.34 in Equation 2 should better predict ceiling load. Therefore, the method should better show the solar reflectance premium for roofing surfaces with low thermal emittance. The goal of Title 24 is to limit building energy consumption. An equal-ceiling-load approach better reflects this goal while taking into account tradeoffs for the entire roof, not just the surface.

NUMERICAL CODE "STAR" USED FOR CONSTANT-LOAD APPROACH

Low-slope roofs are often constructed of metal decking that supports a layer of insulation and the covering, whether a single-ply membrane, bare or painted metal, or built-up-roof membrane. The heat flow entering or leaving a low-slope roof is driven by the difference between the exterior surface temperature of the roof and the indoor temperature. The exterior temperature is affected by the surface properties of solar reflectance and thermal emittance; the amount of roof insulation; and the exposure of the surface to climatic elements like wind speed, solar radiation, and humidity. A numerical computer code, "STAR," solves for the temperature profiles through the roof. Wilkes (1989) formulated the code using an implicit discretization technique to model the transient one-dimensional heat flow through the exterior roof cover, through multiple layers of roof materials including insulation, and through the supporting structure (e.g., a metal deck). The model accounts for temperature-dependent thermal properties. Wilkes validated the model against bare concrete paver roofs and showed the effect of temperature-dependent insulation properties on the accuracy of prediction. Petrie et al. (1998 and 2001) validated the model against some 24 different low-slope roof coatings over lightweight roofs. Miller and Atchley (2001) validated the code against single-ply thermoplastic membranes over lightweight roofs.

STAR was also validated against field data for low-slope roofs covered by acrylic-coated Al-Zn-coated steel in anticipation of conducting this emittance sensitivity study. The acrylic-coated Al-Zn-coated test roof had been exposed for 1½ years on the Envelope Systems Research Apparatus (ESRA) at a U.S. national laboratory in Oak Ridge, Tennessee. An aged solar reflectance of 0.59 and aged thermal emittance of 0.17 were used to predict the measured deck heat flows through R-5 (RSI-0.9) insulation. The error between the measured and predicted heat flows was about 3.5% of the measured values for data collected during August 2000 on the ESRA.

STAR SIMULATIONS

The STAR numerical code simulated the heat transfer across the roof deck of a low-slope nonresidential building to determine the interaction of solar reflectance and thermal emittance in California's diverse climates. The simulations assumed polyisocyanurate board insulation faced with aluminum foil. Thermal conductivity data were gleaned from the American Society for Testing and Materials (ASTM) and fitted as a function of insulation temperature specified by ASTM at 40, 75, and 110°F (4.4, 23.9, and 43.3°C) (ASTM 2004). The R-value[3] was fixed at either R-11 (RSI-1.9) or R-19 (RSI-3.3), depending on the climate zone. Climate zones 6 through 9, representing Los Angeles Beach, San Diego, El Toro, and Burbank, required R-11 (RSI-1.9) roof insulation according to Title 24; elsewhere in California Title 24 prescribes R-19 (RSI-3.3) roof insulation.

The CTZ2 weather database (CEC 1992) was used and is the same weather database used by the California Energy Commission Title 24 energy standards. The database contains 16 weather files, one for each of the 16 climate zones of California. Each file includes 8760 h (1 year) of typical weather data. The STAR code reads each hour of the CTZ2 weather data and selects the global horizontal solar irradiance, ambient air temperature and humidity, barometric pressure, wind speed, and cloud cover. It calculates the cooling[4] and heating loads on an hour-by-hour basis for each climate zone. The cases studied have the radiative properties for the 2005 Title 24 initial and aged prescriptive cases (SR70E75 and SR55E75); for the Title 24 defined dark roof (SR20E90); and for a dark, heat-absorbing, built-up roof (SR05E90).

Gain Coefficients Based on Equivalent Cooling Loads

Gain coefficients without the effect of soiling, to represent the change in solar reflectance per unit change in emittance (Equation 2), were computed by STAR. They were the slope in each zone computed from the best fit of results for the range of low-emittance values that yielded the same cooling load as the respective base cases. Gains are shown in the four rightmost columns of Table 1. The roof R-value was set to 2005 Title 24 requirements for each climatic zone. Averaging the gain coefficients over the 16 climate zones for initial and aged prescriptive cases SR70E75 and SR55E75 yielded gains of 0.240 and 0.313, respectively (in the second-to-last row of Table 1). In their work, Levinson et al. (2005) derived a gain of 0.236 for initial radiative properties, and a gain of 0.34 for aged radiative properties (in the last row of Table 1). Again, the gain coefficient of 0.34 accounts for the effect of soiling.

STAR yielded values similar to those computed by Levinson et al. (2005). They imposed equal surface temperatures for the high- and low-emittance roofs over the daylight hours for which ASTM 1980 irradiance [317 Btu/(h·ft) or 1000 W/m] is valid. STAR summed over hours that yielded equal roof cooling loads for the building under the decks of the two roofs. With lightweight roofs, not much energy is stored in the roof itself. It makes sense that a method based on surface temperatures gives results not very different from one based on deck heat flows for lightweight roofs having identical R-values and types of roof insulation and when both are for daylight hours with strong solar irradiance.

As the cooling load increases from that of the SR70E75 combination to that of the SR05E90 combination, so does the gain coefficient. The coefficient also increases as the cooling load [seen by increase in cooling degree days (CDDs), Table 1] increases for a given radiative combination. The greater the magnitude of load for comfort cooling, the greater the gain coefficient. Its behavior is complicated but shows that a greater change in thermal emittance is needed as compared to the change in solar reflectance to get the same cooling load for

3. The R-values reported herein are based on a temperature of 75°F (23.9°C).

4. Cooling load is defined here as the seasonal total heat flow entering the conditioned space. Heating load is defined as the seasonal total heat flow leaving the conditioned space.

Table 1. Best Fit of Gain Coefficients Computed by STAR for the 16 Climate Zones to Yield ρ_{LE} over the Range of ε_{LE} with Cooling Load Equal to That of Each Base

Zone	City	Cooling Degree Days*	SR70E75 Initial	SR55E75 Aged	SR20E90 Initial	SR05E90 Initial
			STAR-Computed Gain Coefficients ($\Delta\rho/\Delta\varepsilon$)			
01	Arcata	1	0.207	0.277	0.413	0.482
03	Oakland	89	0.207	0.268	0.393	0.456
05	Santa Maria	97	0.218	0.283	0.413	0.479
04	Sunnyvale	220	0.216	0.287	0.424	0.494
06	Los Angeles	498	0.213	0.278	0.409	0.475
16	Mt. Shasta	571	0.246	0.323	0.470	0.545
07	San Diego	695	0.210	0.277	0.410	0.478
08	El Toro	867	0.236	0.312	0.458	0.532
02	Santa Rosa	952	0.262	0.341	0.490	0.567
09	Burbank	1091	0.247	0.322	0.466	0.539
12	Sacramento	1202	0.236	0.307	0.445	0.516
10	Riverside	1350	0.266	0.349	0.501	0.579
13	Fresno	1844	0.262	0.344	0.496	0.574
11	Red Bluff	1968	0.255	0.326	0.464	0.536
14	China Lake	2827	0.279	0.358	0.501	0.575
15	El Centro	4308	0.279	0.358	0.501	0.576
Average All Zones			0.240	0.313	0.453	0.525
2005 Title 24			0.236	0.34		

* Degree days based on 65°F (18.3°C).

the respective base cases SR70E75, SR55E75, SR20E90, and SR05E90 (Table 1). In other words, the cooling load is more sensitive to changes in solar reflectance than to changes in thermal emittance.

One cannot take just any solar-reflectance and thermal-emittance pair and deduce the tradeoff for solar reflectance with a different thermal emittance using Equation 1. For the 2005 Title 24 SR70E75 case having a gain coefficient of 0.236, the minimal initial solar reflectance ranges from about 0.62 for $\varepsilon = 0.95$ to about 0.95 for $\varepsilon = 0.05$. For the aged radiative property SR55E75 case, the minimum aged solar reflectance ranges from 0.50 for $\varepsilon = 0.95$ to about 0.77 for $\varepsilon = 0.05$.

The gain coefficients in Table 1 can be used in the following equation to calculate the minimum solar reflectance needed to match the seasonal cooling load for the respective base cases SR70E75, SR55E75, SR20E90, and SR05E90.

$$\rho_{LE} = \rho_{base} + \frac{\Delta\rho}{\Delta\varepsilon}(\varepsilon_{base} - \varepsilon_{LE}) \tag{7}$$

It is interesting to note that the gain coefficients are somewhat dependent on climate. The gain coefficient increases as the magnitude of the cooling load increases (as seen by the increase in CDDs, Table 1). For aged radiative properties (SR55E75), the gain coefficients range from 0.28 for Arcata (CDDs = 1) to a gain of 0.36 for El Centro (CDDs = 4308).

Regression analysis showed that the gain coefficients of Table 1 correlated very well with surface temperature and solar irradiance. The root mean square error for the fit was 0.98, and the absolute average error compared to the data in Table 1 was about ± 3%. The regression fit takes the form

$$\frac{\Delta\rho}{\Delta\varepsilon} = 0.8086 - 0.00107(I_{solar}) - 0.4019(\eta) \tag{8}$$

where

I_{solar} = Solar irradiance (Btu/[h·ft^2] for constant shown) averaged over all daylight periods of the year when the outdoor temperature exceeded 65°F (18.3°C). A separate value was generated in each climate zone. The average of the values for all 16 climate zones was 201.4 Btu/(h·ft^2) (635 W/m^2).

η = Nondimensional temperature,

$$\frac{T_{black\ max} - T_{cool}}{T_{black\ max} - T_{white\ min}}$$

$T_{black\ max}$ = Surface temperature of a roof having 0.05 solar reflectance and 0.90 thermal emittance. It is the maximum surface temperature computed for the 16 climate zones.

$T_{white\ min}$ = Surface temperature of a roof having 0.80 solar reflectance and 0.90 thermal emittance. It is the coolest surface temperature computed for the 16 climate zones.

The regression variable η is of the same form as the Solar Reflectance Index (SRI)[5], with the exception of values for the temperatures of the black-and-white surfaces. In Equation 8 they are the maximum and minimum computed values for all 16 climate zones, respectively, rather than the black-and-white surface temperatures computed for each zone in the SRI formulation. For this study the maximum temperature for a black surface was observed in Fresno and was 149°F (65°C). The minimum cooling-season temperature for a cool white surface was found in Arcata and was 76.2°F (24.6°C). The procedure yielded a better regression fit than fits based on the SRI approach. The two independent regression variables (η and I_{solar}) resulted in an excellent correlation that fit all data for the respective base cases (SR70E75, SR55E75, SR20E90, and SR05E90 in Table 1). Figure 1 compares the correlation to the data. The average I_{solar} for all 16 climate zones was used to generate the solid line (Equation 8).

A surface energy balance neglecting conduction into the roof (an adiabatic surface) yielded surface temperatures within ± 0.5°F (0.28°C) of STAR simulations, including conduction into the roof. The comparison was made over daylight periods when outdoor air temperature exceeded 65°F (18.3°C). The surface temperature of the respective base case (SR70E75, SR55E75, SR20E90, or SR05E90) was calculated for the adiabatic surface. The resulting T_{cool} was used to generate η, from which Equation 8 yielded a gain coefficient. The gain coefficient was used in Equation 7 to determine the minimum solar reflectance needed for a low-emittance roof to have the same cooling load as the various base roofs (SR70E75, SR55E75, etc.).

The minimal solar reflectance computed by STAR, the regression fit, and the Title 24 prescriptive requirement for aged radiative properties (SR55E75) are listed in Table 2. Solar reflectance for the Title 24 prescription exceeded that computed by STAR by about 6%. This is good agreement in light of the differences between the methods. Title 24 used solar irradiance, sky temperature, and convective coefficients from ASTM E1980-98, while STAR used daylight averages

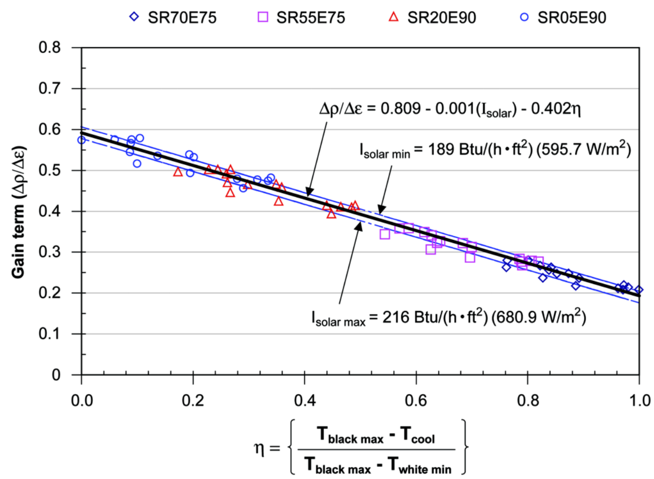

Figure 1 *Correlation for determining the minimum solar reflectance needed to achieve equal cooling loads for the respective base case cooling loads designated as SR70E75, SR55E75, SR20E90, and SR05E90 with* I_{solar} = *201.4 Btu/(h·ft²) (634.9 W/m²).*

from the CTZ2 weather. The regression fit (Equation 8) was slightly higher than STAR results but within 3% of them.

PERFORMANCE OF AGED ACRYLIC-COATED, AL-ZN-COATED STEEL

Figure 2 shows roof surface temperatures (upper) and deck heat flows (lower) for Sacramento, California, using aged radiative properties for acrylic-coated 55% Al-Zn-coated steel and for the 2005 Title 24 prescriptive cases. Surface temperatures for aged acrylic-coated steel (SR55E15) with R-19 (RSI-5.3) insulation were about 25°F (13.9°C) higher at solar noon on July 29th in Sacramento than those observed for the prescriptive case (SR55E75). (See "square" symbols versus "circle" symbols in the upper half of Figure 2.) The higher surface temperature in turn caused the seasonal cooling load due to the low-slope roof to be about 73% higher than that calculated for the prescriptive case. (See "square" symbols versus "circle" symbols in the lower half of Figure 2.) Optimizing solar reflectance to match the cooling load of the prescriptive case required an aged ρ_{LE} of about 0.734, while 2005 Title 24 predicted a value of 0.754 for aged materials. The 0.734 minimum solar reflectance caused the cooling load for aged acrylic-coated steel to be within 1% of that for the prescriptive case (SR55E75). The SR75E15 radiative properties caused the annual cooling load to be about 7% lower than the cooling load for the (SR55E75) case. (See the lower half of Figure 2.)

Increasing the solar reflectance from 0.55 to 0.734 eliminated the mismatch in roof cooling load. However, it is interesting to note that the SR73E15 roof ("plus" symbol in Figure 2) had daytime surface temperatures and heat flows that were

[5] The SRI is a measure of the constructed surface's ability to reflect solar radiation and emit thermal radiation. It is defined so that a standard black (reflectance 0.05, emittance 0.90) is 0 and a standard white (reflectance 0.80, emittance 0.90) is 100. SRI combines effects of reflectance and emittance into one number.

Table 2. The Minimal Solar Reflectance Calculated by Equations 7 and 8 (Correlation) and Computed by STAR to Have the Same Cooling Load as SR55E75 (Aged Roof) and by Equation 1 (Title 24) to Have the Same Surface Temperature as the Aged SR55E75 Roof

Zone	City	Cooling Degree Days	Heating Degree Days	Aged $\rho_{LE\ min}$ for SR55E15 SR55E75 Used as Base		
				Correlation	STAR	Title 24*
03	Oakland	89	2840	0.731	0.711	0.754
06	Los Angeles	498	1439	0.743	0.717	0.754
12	Sacramento	1202	2697	0.763	0.734	0.754
15	El Centro	4308	1031	0.787	0.765	0.754

*The gain coefficient used by Title 24 is computed using Equation 1 for the ASTM E1980-98 moderate-wind standard conditions.

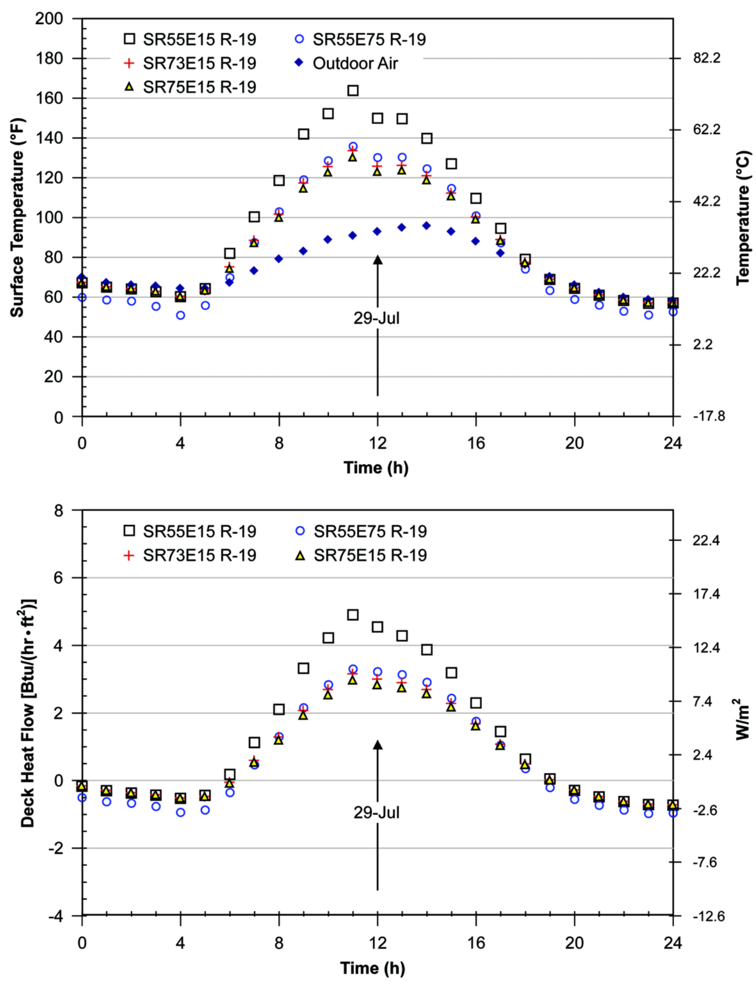

Figure 2 *Roof surface temperatures (upper) and deck heat flows (lower) for Sacramento, California, using aged radiative properties for acrylic-coated 55% Al-Zn-coated steel and for the 2005 Title 24 prescriptive cases. Conversions: °C =(5/9)(°F – 32); W/m^2 = 3.152 * Btu/(h·ft^2).*

slightly lower than predicted for the SR55E75 case. (See "plus" symbols versus "circle" symbols in Figure 2.) The minimum initial solar reflectance[6] needed for aged acrylic-coated steel to match the cooling load of the SR55E75 prescriptive requirement did not yield equal surface temperatures during the daylight hours. The results show that the minimum solar reflectance roof (SR73E15) and the Title 24 prescriptive roof (SR75E15) do not operate at the same surface temperature as the SR55E75 roof.

Sensitivity to Solar Reflectance and Thermal Emittance

Miller et al. (2005) exposed acrylic-coated 55% Al-Zn-coated steel in several U.S. climates and measured soiling losses (Figure 3). Solar reflectance dropped from an initial value of 0.67 to about 0.55 after 3 years of exposure (Figure 3), which is very similar to the aging estimates provided by Levinson et al. (2005). Thermal emittance remained relatively constant at about 0.15. Therefore, acrylic-coated steel needs an aged minimum solar reflectance of about 0.73 in Sacramento and about 0.76 in El Centro (Table 2) for it to comply with the prescriptive case. Rather than increasing solar reflectance, some researchers are attempting to increase the thermal emittance of acrylic-coated steel by modifying the clear acrylic dichromate layer. Results are promising, with thermal emittance increasing from 0.15 to as high as 0.73 with solar reflectance at about 0.63. Hence, for these improved radiative properties, the 55% AL-Zn-coated steel requires a minimum initial solar reflectance of 0.71 rather than the 0.904 value discussed earlier for the SR67E15 case.

We ran several simulations for Sacramento (zone 12) and El Centro (zone 15) to observe the sensitivity of the roof cooling load to changes in thermal emitance and in solar reflectance. Solar reflectance was fixed at an aged value of 0.55, and the thermal emittance was varied from 0.05 to 0.95. Then the thermal emittance was fixed at 0.75, and the solar reflectance varied from 0.05 to 0.90. Results in Figure 4 show that the slopes of the thermal emittance curves (dashed in Figure 4) are less than those of the curves of solar reflectance (solid in Figure 4). This indicates that roof load is more sensitive to changes in solar reflectance than to changes in thermal emittance. For zone 15 (El Centro), increasing the thermal emittance from 0.05 to 0.90 for a fixed reflectance of 0.55 caused a 7000 Btu/ft (79.5 MJ/m^2) drop in annual cooling load. Increasing solar reflectance from 0.05 to 0.90 for a fixed emittance of 0.75 caused an 11,000 Btu/ft (125 MJ/m^2) drop. It is also apparent from Figure 4 that the hotter the climate, the greater the effect of changing the thermal emittance or the solar reflectance. (See curves for Sacramento versus El Centro in Figure 3.)

Adding Insulation to Compensate for Low Emittance

In determining tradeoffs for low-emittance roofs, there is an outstanding advantage to equating deck heat flows (cooling loads) rather than outside surface temperatures of the higher- and lower-emittance roofs. The level of roof insulation can

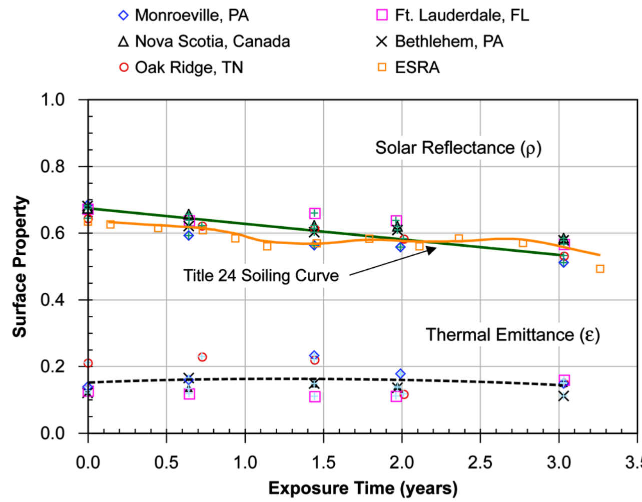

Figure 3 *The effect of soiling on the solar reflectance and thermal emittance of acrylic-coated 55% Al-Zn-coated steel exposed in several U.S. climates. Title 24 soiling curve is provided by Levinson et al (2005).*

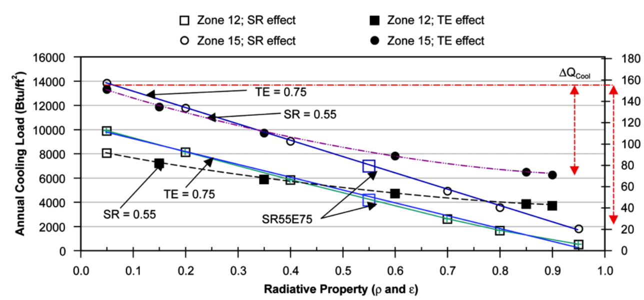

Figure 4 *Annual cooling load for climate zones 12 and 15 showing effect of thermal emittance with solar reflectance fixed at 0.55 and the effect of solar reflectance with thermal emittance fixed at 0.75. Conversion: MJ/m^2 = 0.01136 *Btu/(ft^2)*

also be used to decrease cooling load. A third set of runs was made for acrylic-coated steel (SR55E15) exposed in the 16 climate zones to determine the level of roof insulation needed to match the SR55E75 prescriptive case. The simulations were conducted to better understand the effects of adding insulation on the seasonal energy gains to the building. STAR determined that about an R-30 (RSI-5.3) level of polyisocyanurate insulation was needed to match the annual cooling load of the SR55E75 prescriptive requirement with 2005 Title 24 levels of insulation.

A comparison is shown in Figure 5 of the acrylic-coated steel roof having R-19 (RSI-3.3) and R-30 (RSI-5.3) levels of insulation. Increasing the insulation had little effect on the surface temperatures of the two steel roof systems. (See "square" symbols versus "plus" symbols in the upper half of

6. The minimum initial solar reflectance was based on cooling loads calculated when the outdoor air temperature exceeded 65°F (18.3°C) and the solar irradiance exceeded 55 Btu/(h·ft) (173.4 W/m^2).

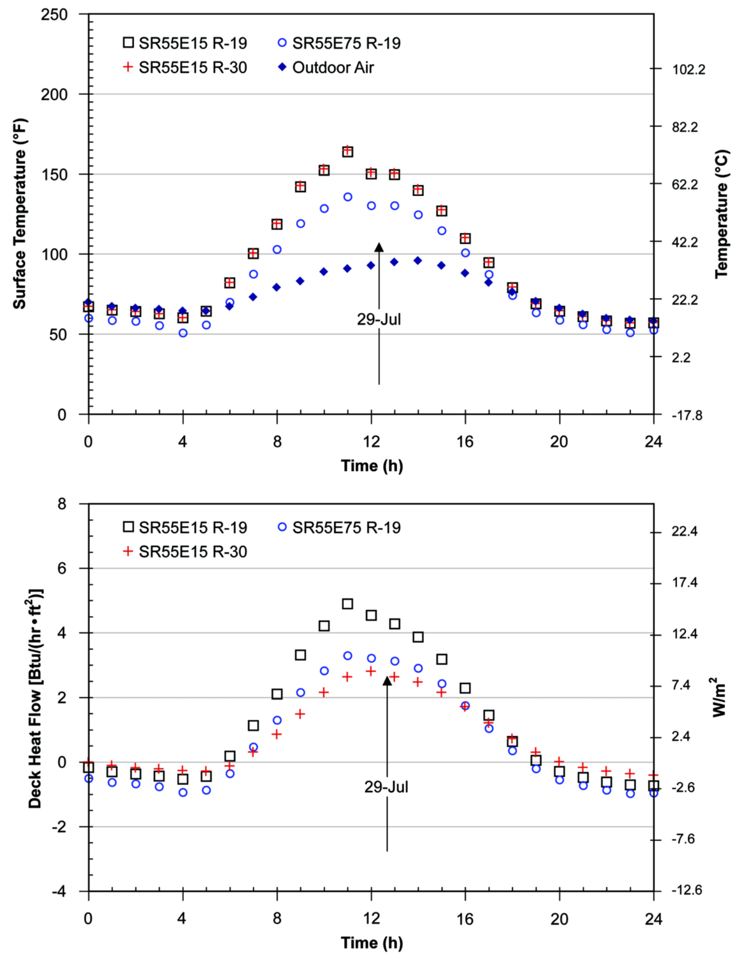

Figure 5 *Roof surface temperature (top) and deck heat flows (bottom) for Sacramento, California, with aged acrylic-coated 55% Al-Zn-coated steel (SR55E15) having R-19 (RSI-3.3) and R-33 (RSI-5.8) levels of roof insulation and 2005 Title 24 base case (SR55E75) with R-19 (RSI-3.3) insulation. Conversion: °C = (5/9) (°F – 32); $W/m^2 = 3.152 *Btu/(h{\cdot}ft^2)$.*

Figure 5.) However, the surface temperature for both systems are about 20°F (11.1°C) higher than for the SR55E75 prescriptive roof with R-19 (RSI-3.3) insulation on this hot July afternoon with daily peak air temperature of about 95°F (35°C). The heat flow through the deck of the acrylic-coated steel roof with R-30 (RSI-5.3) insulation, although matched over the cooling season to the SR55E75 prescriptive roof, was lower than the SR55E75 roof during the hot summer daytime hours. (See “plus” symbols versus “circle” symbols in the lower half of Figure 5.) At night the loss to the sky was also less than that observed for the 2005 Title 24 SR55E75 roof because of the added insulation and the material’s lower thermal emittance. It is also very important to note that equal outside and inside surface temperatures (SR55E15 with R-19 or RSI-3.3 and SR55E15 with R-30 or RSI-5.3) did not yield equal loads because of the different thicknesses of the insulation.

The results for roofs with aged acrylic-coated steel materials having more insulation are somewhat counterintuitive for Time-Dependent Valuation (TDV) economic impact because of nighttime effects on cooling load. However, they make good physical sense. Matching cooling load by adding insulation causes less heat gain during the daytime and less heat loss during the nighttime. This observation is also easily seen by viewing a snapshot in time of the heat flows through the respective roof systems. (See lower halves of Figures 2 and 5.) Changing the solar reflectance to match the seasonal cooling load causes fewer afternoon and late-night differences in heat flows relative to the SR55E75 prescriptive case than does adding insulation to match the seasonal cooling load. The load at solar noon for the SR73E15 roof is about 0.3 Btu/(h·ft) (0.95 W/m^2) lower than that of the SR55E75 roof. (See lower half of Figure 2.) The load for the SR55E15 roof with R-30 (RSI-5.3) insulation is about 0.8 Btu/(h·ft) (2.5 W/m^2) lower than that of the SR55E75 roof. (See lower half of Figure 5.) There is also a greater benefit for adding the insulation at night.(See lower half of Figure 5.)

OVERALL ENVELOPE APPROACH

The simulations conducted to match cooling load for 2005 Title 24 prescriptions appear to show that adding more insulation has a better economic impact in terms of TDV of peak energy use than improving the solar reflectance of the low-emittance roof product. The R-value of insulation derived from the 2005 Title 24 OEA was therefore compared to STAR results for adding R-value to achieve equal seasonal cooling loads. The 2005 Title 24 procedures include a dependence on solar reflectance and thermal emittance in the OEA for building designs. For low-slope roofs on nonresidential buildings, the standard heat-gain equation uses an initial solar reflectance of 0.70, and the equation degrades the reflectance to account for the effect of weathering. The portion of the heat-gain equation applicable to a cool roof takes the following form:

$$HG_{std} = \sum_{i=1}^{nR} ([A_{Ri} \times U_{Ri}] \times \{TF + WF_{Ri} \times SF \times [1.0 - \{0.2 + 0.7 \times (\rho_{std} - 0.2)\}]\}) \quad (9)$$

The form of the heat gain for the proposed roof product is similar to HG_{std}. However, the solar reflectance of the proposed roof product ρ_{prop} is modified by an algorithm that accounts for the effects of the product's thermal emittance. The heat gain for the proposed roof is as follows:

$$HG_{prop} = \sum_{i=1}^{nR} ([A_{Ri} \times U_{Ri}] \times \{TF + WF_{Ri} \times SF \times [1.0 - \{0.2 + 0.7 \times (\rho_{prop} - 0.2)\}]\}) \quad (10)$$

where

A = exterior roof area of the proposed building

U = applicable roof overall heat-transfer coefficient (CEC 2005, U-factor in Table 143-A)

TF = temperature factor for envelope construction, assuming medium mass (CEC 2005, Table 143-D)

WF = weighting factor for the roof of a standard building (CEC 2005, Table 143-E)

SF = solar factor (CEC 2005, TAble 143-D)

ρ_{std} = initial solar reflectance of 0.70 for low-slope nonresidential standard buildings

ρ_{prop} = initial solar reflectance of the proposed roof product. For roofs with $\varepsilon < 0.75$, the solar reflectance shall be calculated using the following equation:

$$\rho_{E(0.75)} = -0.448 + 1.121\rho_{prop} + 0.524\varepsilon \quad (11)$$

The solar reflectance, $\rho_{E(0.75)}$, is a reduced initial solar reflectance with thermal emittance of 0.75 for a roof that has the same aged surface temperature as the proposed roof having ρ_{prop} and ε_{prop}. The empirical fit (Equation 11) was derived from data calculated from Equation 6 when it is solved for ρ_H with ρ_{LE} and ε_{LE} used as inputs (CEC 2005).

A review of the OEA is displayed in Figure 6 for a roof with an area of 1000 ft^2 (92.9 m^2). The heat gain for the roof on the standard building was based on aged radiative properties for the SR70E75 prescription. The heat gain for the proposed roof (SR55E15) was based on the 2005 Title 24 algorithm (using Equation 11, columns highlighted in light gray). STAR used aged properties for acrylic-coated steel and determined the amount of roof insulation (column highlighted in dark gray) needed to match the seasonal cooling load for the SR55E75 prescriptive case. As indicated in the earlier discussion, STAR showed that the acrylic-coated steel roof (SR55E15) increased the heat gain about 73% above the heat gain for the SR55E75 roof. Therefore, to comply with the envelope approach, the practitioner/designer must use other energy-efficient strategies to compensate for the higher heat gain through the roof and/or add more insulation to the low-slope roof. As an example, in Sacramento the 2005 Title 24 OEA recommends R-25.5 (RSI-4.5) with acrylic-coated steel. STAR suggests a higher R-29.3 (RSI-5.2) to match the seasonal cooling load of 4160 Btu/ft^2 (17.3 MJ/m^2). In general, as CDDs increase above 1000°F-d (556°C-d), the STAR-computed R-values were about 15% higher than those found by the OEA (Table 2). Exceptions are those for El Toro, Burbank, and Mt. Shasta, all of which have STAR-computed R-values within about 4% of OEA R-values. Neglecting the temperature factor (TF) in the OEA calculation changes the OEA computation for R-value. STAR yields R-values within 6% of those computed by the OEA without TF.

TIME-DEPENDENT VALUATION OF ROOF ENERGY

Title 24 bases the consumption of building energy and the subsequent energy savings on TDV calculations, which apply an hour-by-hour time-dependent weighting to site energy use. The method places a higher monetary premium on energy consumed during hot summer afternoons than energy usage occurring during off-peak hours. The rationale behind the TDV methodology is to adjust the building design for best performance during periods of high energy costs. The savings in heat transfer crossing the roof boundary were converted into site energy assuming the performance of a commercial-sized heating, ventilation, and air-conditioning (HVAC) unit. Data were gleaned from a Public Interest Energy Research study (CEC 1999) for the performance of air-conditioning units tested in northern and central California. The Energy Efficiency Ratio of the HVAC unit was used at each hour of CTZ2 weather data along with hourly TDV values to convert roof heat transfer to cool-roof energy in units of BTUs of natural gas (BTU$_{NG}$). Eley (2002) describes the procedure used to calculate TDV energy for a cool roof.

STAR computed the TDV energies and their costs for climate zones 3, 6, 12, and 15 to show potential energy tradeoffs between radiative properties and roof insulation for acrylic-coated steel roofs having aged radiative properties.

				Overall Envelope Approach				STAR Simulation	
				Standard Cooling (SR55E75)		Proposed Cooling (SR55E15)		SR55E15	SR55E75
Climate		Cooling	Heating	$Uroof_{STD}$	HG_{STD}	HG^1_{prop}	$R\_Value^1_{reqd}$	R_Value^2	Cooling Load
Zone	City	Degree Days 65°F (18.3°C) Base		Btu/(hr·ft^2·°F)	Btu/(hr·°F)	Btu/(hr·°F)	hr·ft^2·°F/Btu-in	hr·ft^2·°F/Btu-in	Btu/(yr ft^2)
01	Arcata	1	4953	0.0510	2885.0	4237.8	28.8	10.7	1533.4
02	Santa_Rosa	952	3026	0.0510	4768.7	6372.4	26.2	29.6	3922.4
03	Oakland	89	2840	0.0510	3347.0	4549.8	26.7	22.7	2538.3
04	Sunnyvale	220	2643	0.0510	3876.0	5239.7	26.5	27.2	3769.2
05	Santa_Maria	97	2966	0.0510	3143.6	4271.0	26.6	26.8	2991.6
06	Los_Angeles	498	1439	0.0760	4901.5	6651.3	17.9	14.8	5463.6
07	San_Diego	695	1220	0.0760	4951.7	6764.0	18.0	15.5	5915.1
08	El_Toro	867	1523	0.0760	5870.5	7911.8	17.7	16.8	7675.7
09	Burbank	1091	1609	0.0760	6436.4	8456.9	17.3	17.4	7630.4
10	Riverside	1350	2030	0.0510	4664.3	6090.1	25.6	30.3	5242.1
11	Red_Bluff	1968	2847	0.0510	4532.0	5816.6	25.2	30.3	4188.6
12	Sacramento	1202	2697	0.0510	4394.4	5711.7	25.5	29.3	4160.2
13	Fresno	1844	2647	0.0510	4768.5	6245.9	25.7	30.5	5568.8
14	China_Lake	2827	2407	0.0510	5383.7	6988.9	25.5	30.2	5125.6
15	El_Centro	4308	1031	0.0510	4892.0	6178.0	24.8	31.5	6963.6
16	Mt_Shasta	571	5532	0.0510	4198.7	5697.0	26.6	27.2	2887.2

[1]Title 24 Fit: Eq. 11; HG_{STD} and HG_{prop} based on 1000 ft^2 (92.9 m^2).

[2]Insulation reqd for aged AC steel (SR55E15) to Match SR55E75 Seasonal Cooling Load

Conversion: W/(m^2 · K) = 5.678*Btu/(hr·ft^2·°F)

Figure 6 *Overall envelope approach for aged acrylic-coated 55% Al-Zn-coated steel (SR55E15) on nonresidential low-slope roofs exposed in the 16 climate zones in California.*

The results are shown in Figure 7. Note that the computed energies in Figure 7 do not include interactions with the dynamics of the building but are compared to whole-building DOE-2.1E simulation results for a prototypical Title 24 building (Levinson et al. 2005).

The largest affordable 15-year cost premium of about \$1.01/ft^2 (\$10.87/m^2) occurs during the cooling season in El Centro, climate zone 15. In Sacramento, either increasing solar reflectance to 0.734 or adding about 1½ in. of polyisocyanurate insulation (R-19 to R-30) (RSI-3.3 to RSI-5.3) would save 7071.1 BTU_{NG}/year/ft^2 (80 MJ/m^2/year) of roof during peak demand, which would save about \$0.53/ft^2 (\$5.70/m^2). Note also that acrylic-coated steel yields heating-energy savings for all zones due to its low thermal emittance, which lessens radiative heat loss to the sky. Annual premiums for the heating season are shown as negative currency because the low-emittance roof has less energy loss. The very mild climate in zone 3 still shows cooling-energy savings; however, the incremental benefit of energy savings is less than \$0.32/ft^2 (\$3.45/m^2). Results computed by Levinson et al. (2005) for DOE-2.1E simulations of a prototypical Title 24 building are also provided in Figure 7. The DOE-2.1E study estimated cool-roof electricity savings using an aged cool roof (SR55E90) as compared to a dark roof (SR20E90). Their results were scaled to a $\Delta\rho$ equivalent to the $\Delta\varepsilon$ used in this study. Results for zone 3 were very reasonable, while those for Sacramento were within \$0.06/ft^2 (\$0.64/m^2). STAR does not consider whole-building interactions of the roof to the walls, building infiltration, or internal loading, etc., yet the results were within reason, with the greatest differences observed where the magnitude of cooling load was the largest (El Centro, Figure 7). Researchers estimate that increasing the thermal emittance of acrylic-coated steel through modification of the clear acrylic dichromate layer will cost about 2 to 4¢/ft^2 of steel (22 to 43¢/m^2) as compared to painting the steel, which is estimated at about \$0.25/ft^2 (\$2.70/m^2). Adding insulation will require an additional 2 in. of polyisocyanurate to increase the R-value from R-19 (RSI-3.3) to about R-30 (RSI-5.3) for aged acrylic-coated steel exposed in Sacramento. The estimated material cost for 2 in. of polyisocyanurate insulation in the Midwest is about \$0.60/ft^2 (\$6.45/m^2).[7] Hence, in terms of TDV economics, adding insulation has at least a 15-year payback period, while modifying radiative properties appears more cost effective, provided that modifications to the radiative properties of acrylic-coated steel cost only about 2 to 4¢/ft^2 (22 to 43¢/m^2) of steel.

CONCLUSIONS

Gain coefficients computed by STAR and those published by Title 24 are similar, validating the correctness of the two different approaches for estimating the minimum solar reflectance needed by a low-emittance roof for it to be equivalent to the prescriptive roofs. Equal outside surface temperatures (2005 Title 24) yielded minimum solar reflectance values that were about 0.03 higher than those generated by STAR for equal deck heat flows (cooling loads) for the SR55E75 base

7. Private communication made with manufacturer's representative for low-slope roof systems.

	2005 Title 24	AC Steel	[2]Net Present Value		Affordable Premium		Title 24 NPV Savings[3]
	SR55E75	SR55E15	SR55E75	SR55E15	Cost	Energy	DOE2.1E (energy
	(BTU_{NG}/yr ft^2)		\$/ft² over 15 Years		\$/ft² over 15 Years	(BTU_{NG}/yr ft^2)	\$/ft² over 15 Years
***Zone 03, 89 CDD*[1]**							
Cool	5807	10112	\$0.432	\$0.753	\$0.321	4305.3	
Heat	8349	6363	\$0.622	\$0.474	-\$0.148	-1985.5	
Annual	14155	16475	\$1.054	\$1.227	\$0.173	2,319.8	\$0.169
***Zone 06, 498 CDD*[1]**							
Cool	13924	23778	\$1.037	\$1.770	\$0.734	9853.3	
Heat	9928	7040	\$0.739	\$0.524	-\$0.215	-2888.2	
Annual	23852	30817	\$1.776	\$2.294	\$0.519	6,965.1	\$0.356
***Zone 12, 1202 CDD*[1]**							
Cool	11041	18112	\$0.822	\$1.348	\$0.526	7071.1	
Heat	9189	6789	\$0.684	\$0.505	-\$0.179	-2400.4	
Annual	20230	24901	\$1.506	\$1.854	\$0.348	4,670.6	\$0.288
***Zone 15, 4308 CDD*[1]**							
Cool	21960	35526	\$1.635	\$2.645	\$1.010	13565.9	
Heat	5433	3306	\$0.404	\$0.246	-\$0.158	-2126.4	
Annual	27393	38832	\$2.039	\$2.891	\$0.852	11,439.4	\$0.447

[1] Cooling Degree Days based on 65°F (18.3°C).

[2] TDV energy is converted to nominal present value cost based on a 15-year forecast of electric and gas prices.

[3] Levinson et al. (2005) Table 7 (\$energy for prototypical Title 24 building). Title 24 data scaled to $\Delta\rho$ equivalent to $\Delta\varepsilon$ of 0.60 = (0.75 - 0.15) used herein.

Figure 7 *TDV energy and cost of energy for the aged prescriptive case SR55E75 and for aged acrylic-coated Al-Zn-coated steel based on STAR computation for roof only.*

case. Therefore, equal outside surface temperatures yielded minimum solar reflectance values that reduced the cooling load to about 6% below that of the prescriptive case (SR55E75). The constant-cooling-load approach matched the annual cooling load of roofs covered by aged acrylic-coated steel to that of the prescriptive case and thereby yielded a more realistic solar reflectance premium for roofing surfaces with low thermal emittance. It included the effect of roof insulation and the effect of night-sky radiation where some comfort cooling was still required at night.

A correlation was generated for predicting the minimum solar reflectance that makes a low-emittance roof have the same cooling load as the initial or aged prescriptive cases. The correlation is also useful for other more heat-absorbing roof systems. Future plans are to incorporate the correlation into algorithms for a low-slope and possibly steep-slope roof calculator.

The TDV of energy shows a 15-year savings of about \$0.85/ft^2 (\$9.15/m^2) of a roof in El Centro for adding insulation or increasing solar reflectance of acrylic-coated steel. In Sacramento the cost premium is about \$0.35/ft^2 (\$3.76/m^2). Therefore, in terms of material costs, modifying the radiative properties of the steel is more cost effective than adding additional insulation for compliance with 2005 Title 24, if it only costs 2 to 4¢/ft^2 of steel (22 to 43¢/m^2), as the research indicates.

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