Oak Ridge National Laboratory

Buildings Technology Center

ESTD

Engineering Science & Technology Division

Thermal Emittance Assessment for the State of California

The thermal emittance of many materials whether wood, paper, plaster, rubber, water, ice, marble, paint, clay or concrete is very high, of the order 0.90. However, shiny, bare and acrylic coated metals have a low thermal emittance, and when used as a roof cover stay warmer than does a thermoplastic or painted metal roof. Acrylic coated Galvalume® roofs have an initial measured solar reflectance of 0.67 and an initial measured thermal emittance of only 0.15, and therefore do not comply with the "cool roof" prescriptive requirements specified in California's 2005 building energy efficiency standards for non-residential buildings. The legislation has impacted the economic health of the metal roofing industry, because California is the second largest consumer of metal building products, with over $103 million sales in 2003 representing 5 to 7% of industry shipments. Therefore, the metal industry, being very concerned with the loss of revenue, requested Oak Ridge National Laboratory (ORNL) to evaluate the tradeoff between solar reflectance and thermal emittance as applied to the concept of a 2005 Title 24 "cool roof".

Executive Summary

A parametric study was performed using the numerical code Simplified Thermal Analysis of Roofs (STAR) to investigate the interdependence of thermal emittance, solar reflectance and roof insulation on low-slope roof heat transfer for nonresidential buildings in the State of California. All sixteen climate zones in California were investigated for levels of roof insulation specified in California's building energy efficiency standards for nonresidential buildings (Title 24, Part 6 of the California Code of Regulations, termed in this report as "2005 Title 24"). The cooling and heating seasonal roof heat transfer and the subsequent roof energy using Time Dependent Valuation are compared to data derived from the prescriptive requirement of 0.70-solar reflectance and 0.75-thermal emittance (SR70E75).

The STAR numerical heat transfer code was validated against field data for a low-slope acrylic coated Galvalume® roof exposed in East Tennessee's weather. Once validated, the code was used to conduct the parametric analysis of solar reflectance, thermal emittance and roof insulation in California's diverse climates. The simulations assumed polyisocyanurate board insulation faced with aluminum foil; however, because the heat transfer through the low-slope roof is essentially one-dimensional and because solar reflectance and thermal emittance are surface properties, the results are applicable to other low-slope roof constructions having different types of insulation but the same total roof R-Value.

The 2005 Title 24 establishes two prescriptive requirements for the initial solar reflectance of low-slope non-residential roofs — one for a roof with an emissivity greater than or equal to 0.75 ($\rho = 0.70$) and — one for a roof with an emissivity less than 0.75,

i.e. $\rho_{LE\ min} = 0.70 + 0.34 \times (0.75 - \varepsilon_{initial})$. The latter requirement for low-emittance roofs is shown to be too restrictive based on an evaluation of the heat flow across the roof (i.e. cooling load) that should be equal to that for a roof with emissivity greater than or equal to 0.75. STAR simulations conducted for all sixteen climate zones show the Title 24 prescriptive requirement $\rho_{LE\ min} = 0.70 + 0.34 \times (0.75 - \varepsilon_{initial})$ causes low emittance roofs to out perform the Title 24 prescriptive case SR70E75. Economic alternatives exist for trading off increased levels of insulation against Galvalume's low thermal emittance and still complying with 2005 Title 24.

Two recommendations are proposed for modifying the 2005 Title 24 building energy efficiency standards for non-residential buildings having low-emittance roofs.

1. A new correlation is proposed for determining the solar reflectance–thermal emittance tradeoff for low-emittance roofs; it being:

$$\left(\frac{\Delta\rho}{\Delta\varepsilon}\right)_{Zone} = 0.2123 + 0.0016\left(CDD_{65}\right)^{0.5} - \frac{43.2545}{HDD_{65}}$$

2. An alternative solar reflectance–thermal emittance correlation was determined for the Overall Envelope Approach (OEA). The correlation takes the form:

$$\rho_{E(75)} = -0.5253 - 0.0079 \times \left[CDD/HDD\right] + 1.412 \times \rho_{prop} + 0.3167 \times \varepsilon_{prop}$$

Thermal performance data generated from roof simulations in each of the sixteen climate zones were used to formulate the regression fits as compared to the time snapshot approach used by 2005 Title 24. The $\Delta\rho/\Delta\varepsilon$ correlation would substitute for Title 24's fixed gain term of 0.34 for determining the minimum initial solar reflectance ($\rho_{LE\ min}$) for roofs with an emittance less than 0.75. The $\rho_{E(75)}$ correlation would substitute for the existing correlation in the OEA. Analysis shows that the OEA provides the best compliance option for low-emittance roofs. The roof insulation needed to bring low-emittance roofs into compliance with 2005 Title 24 can be back calculated using the OEA (see the following tabulation for all climate zones).

	R-Value of Roof Insulation Needed for Acrylic Coated Galvalume® to have same cooling load as SR70E75 prescription. ($hr \cdot ft^2 \cdot {}^oF/Btu\text{-}in$)															
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Procedure[1]	Arcata	Santa_Rosa	Oakland	Sunnyvale	Santa_Maria	Los_Angeles	San_Diego	El_Toro	Burbank	Riverside	Red_Bluff	Sacramento	Fresno	China_Lake	El_Centro	Mt_Shasta
OEA Title 24[2]	29.3	29.3	29.3	29.3	29.3	19.7	19.7	19.7	19.7	29.3	29.3	29.3	29.3	29.3	29.3	29.3
OEA ORNL[3]	26.7	26.7	26.7	26.7	26.7	18.0	18.0	18.0	18.0	26.8	26.8	26.8	26.8	27.0	27.7	26.7

[1]Overall Envelope Approach accounts for weathering to degrade solar reflectance.

[2]Title 24 Fit: $SR_{Galv}75 = -0.448 + 1.121\rho + 0.524\varepsilon$ used in OEA for computing R-Value for equivalent roof load to SR70E75.

[3]ORNL Fit: $SR_{Galv}75 = -0.53 - 0.008(CDD/HDD) + 1.412\rho + 0.317\varepsilon$ used in OEA for computing R-Value for equivalent roof load to SR70E75.

Introduction

The California building energy efficiency standards have established a performance approach and a prescriptive approach by which the design and construction of a building can demonstrate compliance with Part 6 of the California Code of Regulations, termed here as 2005 Title 24. 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 or the building owner can alternatively use the Overall Envelope Approach (OEA) that is documented in 2005 Title 24, section 143 (b). The prescriptive approach requires that each building component comply with the respective component requirements in 2005 Title 24, and it establishes two prescriptions for the initial solar reflectance of low-slope non-residential cool roofs — one for a roof with an emissivity greater than or equal to 0.75 ($\rho = 0.70$) which shall be abbreviated as (SR70E75) and — the other for a roof with an emissivity less than 0.75, i.e. $\rho_{LE\ min} = 0.70 + 0.34 \times (0.75 - \varepsilon_{initial})$, which shall be defined as ($SR_{min}E$<75). This latter requirement ($SR_{min}E$<75) assumes the same tradeoffs between solar reflectance, thermal emittance and roof insulation across all climate zones, (see Appendix A) and may therefore not be appropriate for determining the minimum initial solar reflectance required for a low-emittance "cool roof" by the formula:

$$\rho_{min\ LE} = 0.70 + 0.34 * (0.75 - \varepsilon_{LE,INITIAL}), \qquad (1)$$

where

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

ε_{LE} = initial thermal emittance of the low-emittance roof

The derivation of Eq. 1 is provided in Appendix A. The term 0.34 in Eq. 1 is calculated from fixed values for irradiance, the surface convection, the surface temperature of the roof and the sky temperature all of which vary not only from climate zone to climate zone but from hour to hour and with changing weather. The constant (0.34) represents a gain term for the change in solar reflectance for a given change in thermal emittance, and after rearranging Eq. 1 the gain term becomes:

$$\frac{(\rho_{min\ LE} - \rho_{Title\ 24})}{(\varepsilon_{Title\ 24} - \varepsilon_{LE})} = \frac{\Delta\rho}{\Delta\varepsilon} = 0.34 \text{ by Title 24} \qquad (2)$$

where

$\rho_{Title\ 24}$ = initial solar reflectance of 0.70,

$\varepsilon_{Title\ 24}$ = initial thermal emittance of 0.75.

Acrylic coated Galvalume® does not meet the initial solar reflectance specification and requires an initial minimal solar reflectance ($\rho_{LE\ min}$) exceeding 0.904. Hence acrylic coated Galvalume®, on a low-slope non–residential building application, would require the building owner to use a building envelope performance approach and apply other energy efficient strategies to demonstrate compliance with Title 24.

Methodology

The STAR numerical code simulated the heat transfer crossing the roof of a low-slope nonresidential building to determine the role thermal emittance plays in the thermal envelope performance. The salient features of STAR are provided by Wilkes (1989) and validation of the code against ORNL field data for acrylic coated Galvalume® are discussed in Appendix B.

With STAR validated against acrylic coated Galvalume® exposed in East Tennessee's weather, we proceeded with a parametric analysis 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 was gleaned from ASTM, and fitted as a function of insulation temperature specified by ASTM at 40º, 75º and 110ºF (ASTM 2004). R-value was fixed either at R-11 or R-19 dependent on the respective climate zone. Climate zones 6 through 9, representing Los Angeles Beach, San Diego, El Toro, and Burbank, required R-11 roof insulation by Title 24; elsewhere in California Title 24 prescribes R-19 roof insulation. Please note that for consistency the R-Values reported herein are based on a temperature of 75ºF.

The CTZ2 weather database (Cal 1992) was used to simulate the weather in the sixteen different climate zones, and is the same weather database used by the CEC Title 24 energy standards. The CTZ2 weather data contains 16 weather files, one for each of the sixteen climate zones of California. Each file contains 8760 hours (one year) of metered weather data. The STAR code reads the CTZ2 weather data and inputs the global horizontal solar irradiance, the ambient air temperature and humidity, barometric pressure, wind speed and direction, and the cloud cover into the numerical routine for simulating the heat flow through the roof on an hour-by-hour basis.

Solar Reflectance and Low Thermal Emittance Tradeoff

STAR calculated the cooling and heating load[1] on an hour-by-hour basis for each zone for each of the thermal emittance and solar reflectance pairs listed in Table 1 along with the SR70E75 prescriptive case and also for acrylic coated Galvalume® having an initial solar reflectance of 0.67 and an initial thermal emittance of 0.15 (SR67E15). The reflectance and emittance pairs (Table 1) were calculated using Eq. 1 for the prescriptive requirement ($SR_{min}E<75$) for low-emittance roofs.

Table 1. Solar reflectance and thermal emittance combinations used in STAR simulations for the sixteen climatic zones in California.

Property	Title 24	Acrylic Coated Galvalume®	Title 24 Prescriptive Requirement ($SR_{min}E<75$) $\rho_{min\,LE} = 0.70 + 0.34 * (0.75 - \varepsilon_{LE,INITIAL})$				
Solar Reflectance	70	67	73	80	87	90	94
Thermal emittance	75	15	65	45	25	15	5

STAR results were further reduced to determine the minimal initial solar reflectance needed to match the cooling load for the 2005 Title 24 prescriptive case (SR70E75), and Eq. 2 was used to regress the gain term of Eq. 1 using STAR's output. The STAR simulations show that (as observed in the preliminary validations Appendix B) that the 2005 Title 24 requirement for roof products with thermal emittance < 0.75 ($SR_{min}E<75$) yields too high a solar reflectance $\rho_{min\,LE}$, which causes the $SR_{min}E<75$ to outperform the SR70E75 prescriptive case.

STAR results are shown in Figure 1 and are compared to the 2005 Title 24 gain term of 0.34. STAR computed a gain term of $\Delta\rho/\Delta\varepsilon \cong 0.239$ averaged across all climate zones. The standard deviation for the computed gain term is about ± 0.025. Climate zones

[1] Simulations computed the annual cooling and heating loads based on the outdoor air temperature. If the outdoor air exceeded 65ºF, the heat penetrating the roof was summed as a cooling load; below 65ºF the heat transfer was summed as heating load.

10, 11, 13, 14 and 15 all had gain terms greater than 0.25. These climate zones are the warmest having the greatest number of cooling degree days of the sixteen zones. Generally, the results showed an increase in the gain term as cooling load increased from one zone to another. The trend indicated that regression could formulate a prediction for

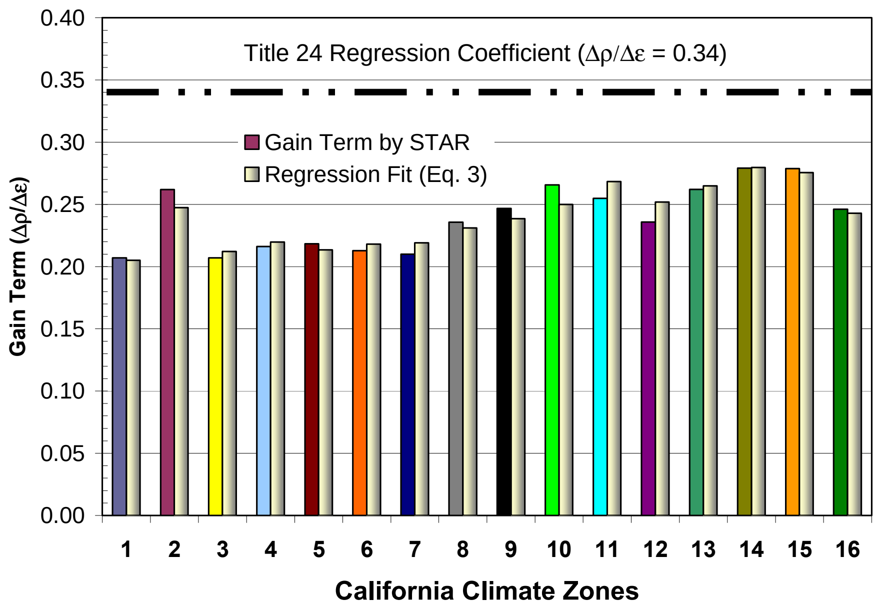

Figure 1. The gain term $\Delta\rho/\Delta\varepsilon$ derived from STAR simulations using the Table 1 pairs of reflectance and emittance for the sixteen climatic zones in California.

the gain term for each of the sixteen climate zones (see Fig. 1 for predictions). Regression analysis showed that cooling degree days and the heating degree days predicted the gain terms computed by STAR within an absolute averaged error of 3% of the STAR computation. Simply using the averaged gain term of 0.239 for all zones resulted in an absolute averaged error of 9.8%. The correlation for the gain term has the form:

$$\left(\frac{\Delta\rho}{\Delta\varepsilon}\right)_{\text{Zone}} = 0.2123 + 0.0016\left(\text{CDD}_{65}\right)^{1/2} - \frac{43.2545}{\text{HDD}_{65}} \qquad (3)$$

where

CDD_{65} Cooling Degree Days based on 65°F for each respective climate zone
HDD_{65} Heating Degree Days based on 65°F for each respective climate zone

Overall Envelope Approach (OEA)

Metallic roof surfaces having a thermal emittance < 0.75 were excluded from the 2001 overall envelope compliance approach, Levinson et al. (2005). However, 2005 Title 24 procedures are modified to include a solar reflectance and thermal-emittancedependence in the OEA for building designs having roofs with low thermal emittance. For low-slope roofs on non-residential 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 form:

$$HG_{std} = \sum_{i=1}^{nR} \left(WF_{Ri} \times A_{Ri} \times U_{Ri} \times \left[1.0 - \left\{ 0.2 + 0.7 \times \left(\rho_{Ri_{std}} - 0.2 \right) \right\} \right] \right) \times SF \qquad (4)$$

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

$$HG_{prop} = \sum_{i=1}^{nR} \left(WF_{Ri} \times A_{Ri} \times U_{Ri} \times \left[1.0 - \left\{ 0.2 + 0.7 \times \left(\rho_{Ri_{prop}} - 0.2 \right) \right\} \right] \right) \times SF \qquad (5)$$

where

- WF weighting factor for the roof of a standard building (Table 143-E)[2]
- A exterior roof area of the proposed building (ft^2)
- U applicable roof overall heat transfer coefficient (U-factor in Table 143-A)[2]
- SF solar factor from Table 143-D[2]
- ρ_{Ristd} initial solar reflectance of 0.70 for low-slope nonresidential standard buildings
- ρ_{Riprop} initial solar reflectance of the proposed roof product. For roofs with $\varepsilon <$ 0.75 the solar reflectance shall be calculated by the following equation:

$$\rho_{E(0.75)} = -0.448 + 1.121\rho_{prop} + 0.524\varepsilon \qquad (6)$$

The solar reflectance $\left(\rho_{E(0.75)}\right)$ represents the reflectance of the proposed roof product if its thermal emittance were artificially increased to 0.75. Therefore $\left(\rho_{E(0.75)}\right)$ is a reduced solar reflectance with thermal emittance of 0.75 for a roof that has the same surface temperature as the proposed roof having ρ_{prop} and ε_{prop}. The empirical fit (Eq. 6) was derived from data calculated from Equation A4 (Appendix A) where A4 is solved for ρ_{HE} with ρ_{LE} and ε_{LE} used as inputs (Levinson et al. 2005).

Output from the STAR simulations were used to develop a similar regression fit to Eq.6 using daylight surface temperatures calculated for low-slope roofs having the pairs of solar reflectance and thermal emittance (Table 1) exposed in all CA climates. Averages of the daylight surface temperature, the solar irradiance, the convective coefficient and the sky temperature were used to compute gain terms $\left(\Delta\rho / \Delta\varepsilon \right)$, which in turn were used to generate a data map of $\left(\rho_{E(0.75)}\right)$ for the Table 1 pairs of reflectance and emittance simulated for all climate zones. The regression of $\left(\rho_{E(0.75)}\right)$ against the independent variables ρ_{prop}, ε_{prop} and CDD/HDD yields the following fit:

$$\rho_{E(75)} = -0.5253 - 0.0079 \times \left[CDD/HDD \right] + 1.412 \times \rho_{prop} + 0.3167 \times \varepsilon_{prop} \qquad (7)$$

where

[2] 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings, Section 143.

ρ_{prop} initial solar reflectance of the proposed roof product.

ε_{prop} initial thermal emittance of the proposed roof product

$\rho_{E(0.75)}$ solar reflectance with thermal emittance set at 0.75 that yields the same cooling load as the proposed roof

CDD/HDD ratio of cooling degree days to heating degree days for each of the sixteen climate zones (degree days based on 65°F)

Including the ratio CDD/HDD did not affect the regression coefficients multiplying ρ_{prop} and ε_{prop} but improved the root-mean-square error from 0.975 to 0.985. The average absolute error reduced from 1.8% to 1.5 % by including CDD/HDD for the effect of climate.

A review of the OEA is displayed in Table 2 for a roof of 1000 square feet. The heat gain for the roof on the standard building is based on SR70E75. The heat gain for the proposed roof (SR67E15) is based on the 2005 Title 24 algorithm (using Eq. 6, column highlighted in yellow) and also on the empirical fit developed by ORNL (Eq. 7, column highlighted in tan). Based on the overall envelope approach, the acrylic coated Galvalume® roof (SR67E15) increases the heat gain by about 49% of the heat gain for the roof of the standard building (SR70E75). Using the ORNL correlation for $(\rho_{E(0.75)})$, Galvalume® caused the heat gain to increase about 36% over the SR70E75 standard. Therefore to comply with the envelope approach the practitioner/designer must use other energy efficient strategies to compensate for the higher heat gain and or add more insulation to the low-slope roof. The 2005 Title 24 recommendation shows that Galvalume® needs R-29.3 versus R-19 and R-19.7 versus R-11 (see yellow highlighted column, Table 2). Based on the ORNL correlation, the Galvalume® roof requires slightly less insulation; R-26.7 as compared to R-29.3 in climate zones 1-5 and 10-16. In zones 6 through 9, R-18 is needed as compared to R-19.7 by 2005 Title 24.

Table 2. Overall Envelope Approach for Acrylic Coated Galvalume® (SR67E15) Non-Residential Low-Slope Roofs Exposed in the Sixteen Climate Zones of CA.

				Standard Cooling (SR70E75)		Proposed Cooling		Insulation reqd to Match Std Cooling	
Climate	City	Cooling	Heating	$U_{roof STD}$	HG_{STD}	HG^1_{prop}	HG^2_{ORNL}	$R\_Value^1_{reqd}$	R_Value^2 ORNL
Zone		Degree Days (65°F Base)		Btu/hr·ft²·°F	Btu/hr·°F	Btu/hr·°F	Btu/hr·°F	hr·ft²·°F/Btu-in	hr·ft²·°F/Btu-in
01	Arcata	1	4953	0.0510	2732.0	4084.8	3716.1	29.3	26.7
02	Santa_Rosa	952	3026	0.0510	3238.7	4842.4	4417.9	29.3	26.7
03	Oakland	89	2840	0.0510	2429.0	3631.8	3305.0	29.3	26.7
04	Sunnyvale	220	2643	0.0510	2754.0	4117.7	3748.9	29.3	26.7
05	Santa_Maria	97	2966	0.0510	2276.6	3404.0	3097.7	29.3	26.7
06	Los_Angeles	498	1439	0.0760	3533.5	5283.3	4821.5	19.7	18.0
07	San_Diego	695	1220	0.0760	3659.7	5472.0	5003.7	19.7	18.0
08	El_Toro	867	1523	0.0760	4122.5	6163.8	5636.4	19.7	18.0
09	Burbank	1091	1609	0.0760	4080.4	6100.9	5584.3	19.7	18.0
10	Riverside	1350	2030	0.0510	2879.3	4305.1	3940.1	29.3	26.8
11	Red_Bluff	1968	2847	0.0510	2594.0	3878.6	3550.5	29.3	26.8
12	Sacramento	1202	2697	0.0510	2660.4	3977.7	3633.3	29.3	26.8
13	Fresno	1844	2647	0.0510	2983.5	4460.9	4083.8	29.3	26.8
14	China_Lake	2827	2407	0.0510	3241.7	4846.9	4456.3	29.3	27.0
15	El_Centro	4308	1031	0.0510	2597.0	3883.0	3666.0	29.3	27.7
16	Mt_Shasta	571	5532	0.0510	3025.7	4524.0	4119.5	29.3	26.7

[1] Title 24 Fit: $SR_{Galv}75 = -0.448 + 1.121\rho + 0.524\varepsilon$

[2] ORNL Fit: $SR_{Galv}75 = -0.53 - 0.008(CDD/HDD) + 1.412\rho + 0.317\varepsilon$

Physics of Roof Heat Transfer

The comfort cooling and heating energy consumed by a building is directly affected by the solar irradiance incident on the building, by the outdoor air temperature, by the level of roof, wall and foundation insulation, by the amount of fenestration, and by the building's tightness against unwanted air and moisture infiltration. The solar reflectance, the thermal emittance and the airside convective currents strongly affect the envelope's exterior temperature, which in turn drives the heat transfer across the envelope. The absorption of solar radiation (absorption = 1.0 – solar reflectance) increases the daytime surface temperature of a roof. The greater the absorption, the greater is the heat transfer crossing the roof surface and entering the conditioned space through the roof deck, which shall be called the roof cooling and heating loads. The thermal emittance produces radiative cooling during the daytime but unlike the solar reflectance, thermal emittance is active both day and night and cools the roof at night. Therefore, the minimal solar reflectance needed for a low-emittance roof $SR_{min}E<75$ that equivalences the roof load for the prescriptive case SR70E75 will not yield the same surface temperatures as proposed by Levinson et al. (2002).

Reflectance Effects

Sacramento, CA (Zone 12) simulations are shown for acrylic coated Galvalume® based on its measured initial solar reflectance and thermal emittance (SR67E15) and also based on the minimal initial solar reflectance needed to match the deck heat flow of the 2005 Title 24 roof (SR70E75), Fig. 2. A minimal initial solar reflectance was determined by running STAR in an iterative loop until the cooling load for the acrylic coated Galvalume® roof matched the cooling load for the SR70E75 prescriptive case. The cooling load is defined as the sum of hourly heat flows crossing the roof deck when the outdoor air temperature is greater than 65ºF. Climate zone 12 requires an R-19 level of insulation.

The prescriptive requirement $SR_{min}E<75$ requires the Galvalume® roof to have a minimum initial solar reflectance of 0.904; however, STAR simulation for Sacramento showed the minimal solar reflectance to be 0.848. Using the SR904E15 scenario (see Δ symbols Fig. 2) yields a roof heat flow that is about 30% less than the cooling roof load for the SR70E75 roof (see o symbols Fig. 2). The simulations show that the $SR_{min}E<75$ prescriptive requirement mandates too high an increase in solar reflectance to compensate for Galvalume's low thermal emittance. It is obvious that the SR67E15 roof operates at a hotter surface temperature then does the SR70E75 roof with R-19 insulation (view □ versus o symbols Fig. 2). Therefore the annual heat penetrating through the roof deck of the SR67E15 roof (roof cooling load) is about twice that of the SR70E75 prescriptive case. Increasing the solar reflectance from 0.67 to 0.848 eliminates the mismatch in roof cooling load; however, it is interesting to note that the SR848E15 roof (+ symbol Fig. 2) has daytime surface temperatures and heat flows that are slightly lower than that predicted for the SR70E75 case (Fig. 2). The minimal initial solar reflectance needed for Galvalume® to match the cooling load of the SR70E75 prescriptive requirement does not yield equal surface temperatures during the daylight hours. At night, the surface temperature is warmer and deck heat loss to the sky for the SR848E15 roof is lower than that observed for the SR70E75 roof because of the effect of thermal emitance. The nighttime surface temperatures and heat flows of the SR67E15 and SR848E15 roofs are identical because they have the same thermal emittance. The results show that the minimal solar reflectance roof (SR848E15) does not operate at the same surface temperature as does the SR70E75 roof. Therefore applying Time Dependent Valuation (TDV) economics will yield slightly better benefit for the SR848E15 roof as compared to the SR70E75 roof because the SR848E15 roof has slightly lower afternoon peak heat flows.

Adding More Insulation

A second set of runs were made for acrylic coated Galvalume® (SR67E15) exposed in the sixteen climate zones to determine the level of roof insulation needed to match the SR70E75 prescriptive case. The simulation was conducted to better understand the effects of adding insulation on the seasonal energy gains to the building and was conducted with initial solar reflectance data. STAR determined that an R-39.8 level of polyisocyanurate insulation was needed to match the annual cooling load of the SR70E75 prescriptive requirement (Fig. 3). Using weathered values for Title 24 (SR55E75) and SR53E15) for Galvalume®, showed that an R-35.7 is needed to match the annual cooling load of the SR55E75 base case.

A comparison (Fig. 3) of the acrylic coated Galvalume® roof having R-19 and R-39.8 levels of insulation shows that increasing the insulation had little effect on the surface temperature of the two Galvalume® roof systems, (view □ versus + symbols Fig. 3). However, the surface temperature for both systems are about 20ºF higher then the SR70E75 prescriptive roof with R-19 insulation on this hot July afternoon with peak day air temperature of about 95°F . The heat flow through the deck of the Galvalume® roof with R-39.8 insulation, although matched over the cooling season to the SR70E75 prescriptive roof, is lower than the SR70E75 roof during the hot summer daytime hours (view + versus o symbols Fig. 3). At night the loss to the sky is also less than that observed for 2005 Title 24 (SR70E75) roof because of the added insulation and the lower thermal emittance.

The results show that adding insulation will also have a better TDV economic impact than will increasing the solar reflectance, because the late afternoon heat flux penetrating the roof deck is lowest for the Galvalume® roof with R-39.8 insulation (compare SR70E75 "o symbol" and Galvalume® "+ symbol" heat flows in Fig. 2 to those same symbols for deck heat flows in Fig. 3). This observation is also easily seen by viewing a snapshot in time of the heat flows through the respective roof systems. The heat flow at discrete depths into the insulation is displayed in Figure 4 for two time stamps, one at solar noon and the other during the night at about 4 a.m. The end of each curve represents the heat penetrating into the roof deck (roof cooling load), and this heat flow value is the same quantity plotted at solar noon and at 4 a.m. in Figures 2 and 3. The comparison of the two charts in Figure 4 shows that changing the solar reflectance to match the seasonal cooling load causes less afternoon and late night differences in heat flows from the SR70E75 prescriptive case as compared to adding insulation to match the seasonal cooling load. The load at solar noon for the SR848E15 roof is about 0.24 Btu/hr ft^2 lower than that of the SR70E75 roof. In comparison, the SR67E15 roof with R-39.8 insulation is about 0.82 Btu/hr ft^2 lower than the SR70E75 base case. Also at night there is a greater benefit for adding the insulation (Fig. 4).

Time Dependent Valuation (TDV) 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 weekday afternoons as compared to 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 using the performance of a commercial size HVAC unit. Data was gleaned from a Public Interest Energy Research (PIER) study (Building End-Use Energy Efficiency 1999) for the performance of air-conditioning units tested in northern and central California (Appendix C). The Energy Efficiency Ratio (EER) of the HVAC unit was used at each hour of CTZ2 climatic weather along with hourly TDV values to convert roof heat transfer to "cool roof" energy in units of BTUs of natural gas (BTU_{NG}). Appendix C describes the procedure used to calculate TDV energy for a cool roof.

STAR computed the cooling loads and the subsequent TDV energies (Table 3) for the roof. Note that the computed energies in Table 3 do not include interactions with the dynamics of the building and should not be confused with results from whole building simulations like DOE-2.1E that use weighting functions to account for building interactions of the roof with the walls, windows and internal energy generations.

As expected, the acrylic coated Galvalume® incurs a greater cooling load and energy burden for all sixteen climate zones as compared to SR70E75 case. The TDV cooling energy for the acrylic coated Galvalume® is about twice that of the SR70E75 for all climate zones (see yellow highlighted area Table 3). However, the TDV annual energy for Galvalume® is within 10% of the annual TDV energy for the SR70E75 case for climate zones having CDD to HDD ratios less than 0.32 (see tan highlighted area for CDD/HDD ≤ 0.32). The results clearly show the higher importance placed on cooling energy consumption by the TDV analysis.

Table 3. The Annual Cooling Load and TDV Energy for acrylic coated Galvalume® (SR67E15) compared to 2005 Title 24 (SR70E75); insulation per 2005 Title 24.

Zone	City	{CDD/HDD}[1]	Cooling Load (Btu/yr ft^2)		TDV Cooling Energy (BTU_{NG}/yr ft^2)		TDV Annual Energy (BTU_{NG}/yr ft^2)	
			SR70E75	SR67E15	SR70E75	SR67E15	SR70E75	SR67E15
01	Arcata	0.000	279	642	918	2,042	10,451	7,970
03	Oakland	0.031	1002	2120	2,752	5,476	11,217	10,868
05	Santa_Maria	0.033	1345	2968	3,505	7,288	12,663	13,290
04	Sunnyvale	0.083	1855	3829	5,122	9,721	14,338	15,495
16	Mt_Shasta	0.103	1314	2971	4,298	8,884	16,545	17,921
02	Santa_Rosa	0.315	1870	4406	5,353	11,542	17,102	18,768
06	Los_Angeles	0.346	2056	4998	6,223	13,802	15,554	19,282
12	Sacramento	0.446	2262	4632	6,845	12,776	16,059	19,054
08	El_Toro	0.569	3513	8183	10,844	22,633	20,364	28,249
07	San_Diego	0.570	2401	5639	6,705	14,139	16,370	20,008
10	Riverside	0.665	2422	6074	8,273	17,974	15,299	22,214
09	Burbank	0.678	3696	8515	11,872	24,173	21,940	30,164
11	Red_Bluff	0.691	2168	4854	6,868	13,606	15,253	19,666
13	Fresno	0.697	2942	6573	9,031	17,870	16,326	22,620
14	China_Lake	1.174	2357	5991	8,710	18,512	16,690	23,018
15	El_Centro	4.178	3823	8813	14,318	27,750	18,690	30,483

[1]Cooling and Heating Degree Days based on 65°F

The TDV energy consumption is also compiled for climate zones 3, 10 and 12 to show potential energy tradeoffs between solar reflectance, insulation and low thermal emittance for an acrylic coated Galvalume® metal roof. Results show that increasing insulation would be more cost effective than trying to improve solar reflectance. In Sacramento, adding about 3.2-inches of polyisocyanurate insulation (R-19 to R-39.8) saves 6445.5 BTU_{NG} per year per square foot of roof as compared to energy savings of 1868 BTU_{NG} per year per square foot for increasing solar reflectance. Note that the savings are predominantly from the savings in heating energy for zones 10 and 12, and are due to the low thermal emittance that lessens radiative heat loss to the sky.

Climate zone 3 shows no benefit in cooling mode; however, in heating season a 4600 BTU_{NG} per year per square foot premium occurs. Hence, in terms of TDV economics, adding insulation appears more promising than does increasing solar reflectance to compensate for the metals low thermal emittance.

Table 4. The TDV Energy Savings for Improving the Solar Reflectance of Acrylic Coated Galvalume® and for Increasing the R-Value of Roof Insulation. Energy consumption is based on STAR computation for roof only.

	2005 Title 24 SR70E75	TDV Energy (BTU_{NG}/yr ft^2)		Affordable Energy Premium (BTU_{NG}/yr ft^2)	
		Minimum ρ compensating for low ε	More Insulation compensating for low ε	Minimum ρ compensating for low ε	More Insulation compensating for low ε
Zone 12, 1202 CDD [1]					
Cool	6845.3	6812.8	6473.7	32.5	371.6
Heat	9214.0	7378.1	3140.1	1835.9	6073.9
Annual	16059.3	14191.0	9613.8	1868.3	6445.5
Zone 10, 1350 CDD [1]					
Cool	8272.9	7942.7	7518.9	330.1	754.0
Heat	7026.1	5301.4	1779.8	1724.7	5246.3
Annual	15299.0	13244.2	9298.6	2054.8	6000.3
Zone 03, 89 CDD [1]					
Cool	1002.3	1012.8	995.7	-10.5	6.6
Heat	6590.4	5279.8	1996.9	1310.6	4593.4
Annual	7592.7	6292.6	2992.7	1300.1	4600.0

[1] Cooling Degree Days based on 65°F.

Nomenclature

CTZ2	California Thermal Zones Weather Data
ESRA	Envelope Systems Research Apparatus
TYM2	Typical Meteorological Year Weather Data
$NPV	Net Present Dollar Value of Energy Savings
TDV	Time Dependent Valuation
σ	Stefan-Boltzmann constant
DB	Dry Bulb temperature
$\hbar$	convective heat-transfer coefficient
Isolar	solar radiation
Tair	outside ambient air temperature
Tm	surface temperature of the metal roof
ε	thermal emittance
ρ	solar reflectance
WB	Wet Bulb temperature

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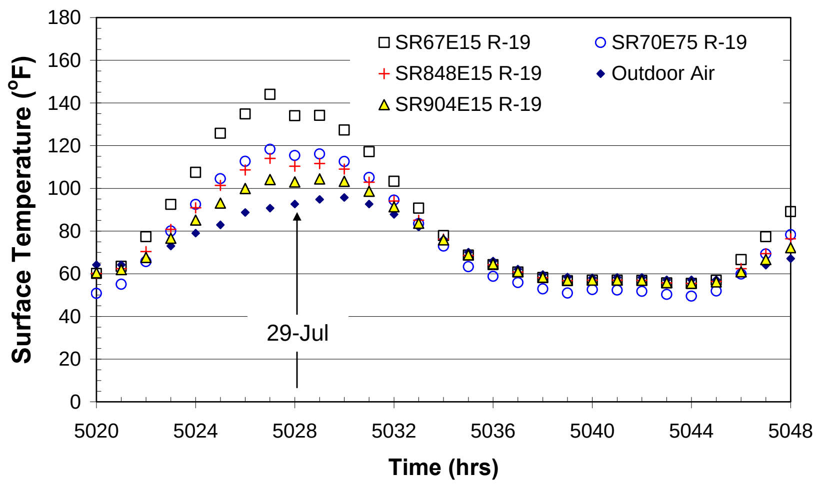

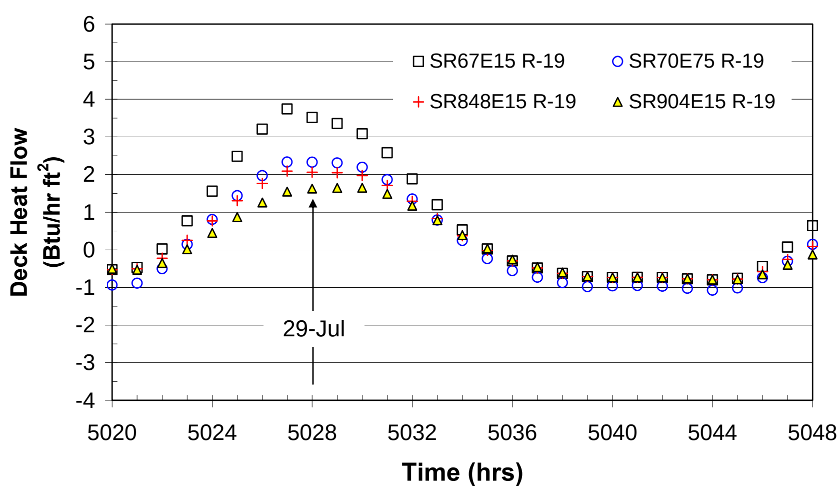

Figure 2. Roof surface temperatures and deck heat flows for Sacramento, CA with acrylic coated Galvalume® having SR67E15 and SR848E15 and the 2005 Title 24 (SR70E75).

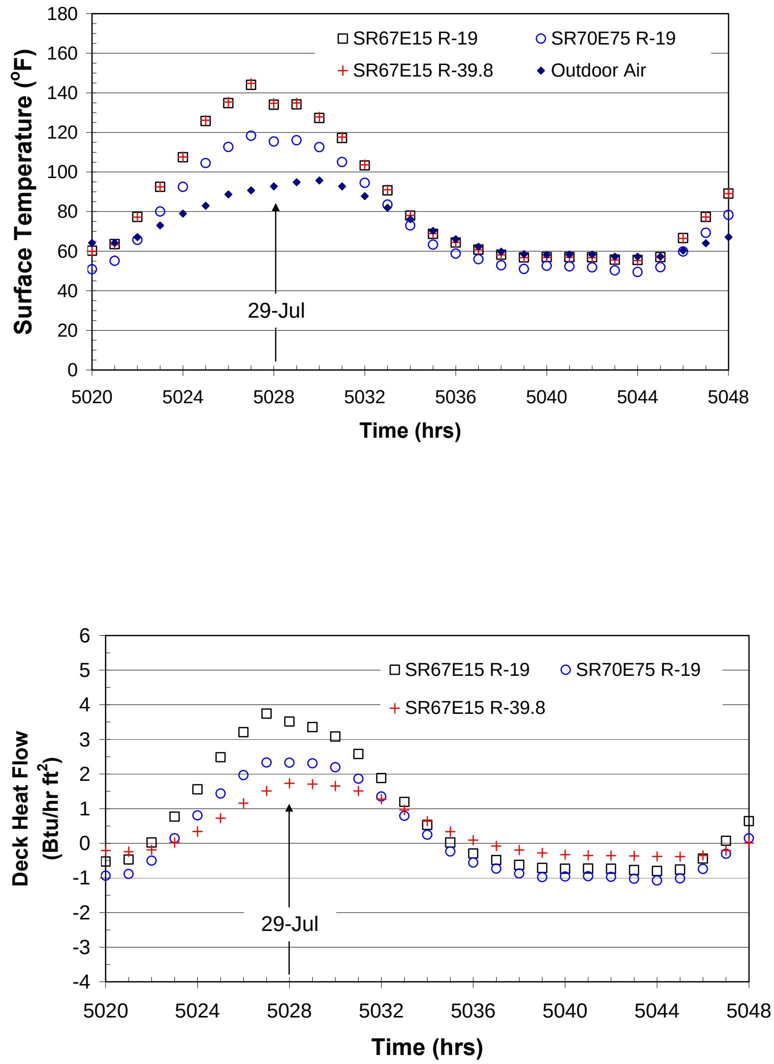

Figure 3. Roof surface temperature and deck heat flows for Sacramento, CA with acrylic coated Galvalume® (SR67E15) having R-19 and R-39.8 levels of roof insulation are compared to the 2005 Title 24 base case (SR70E75).

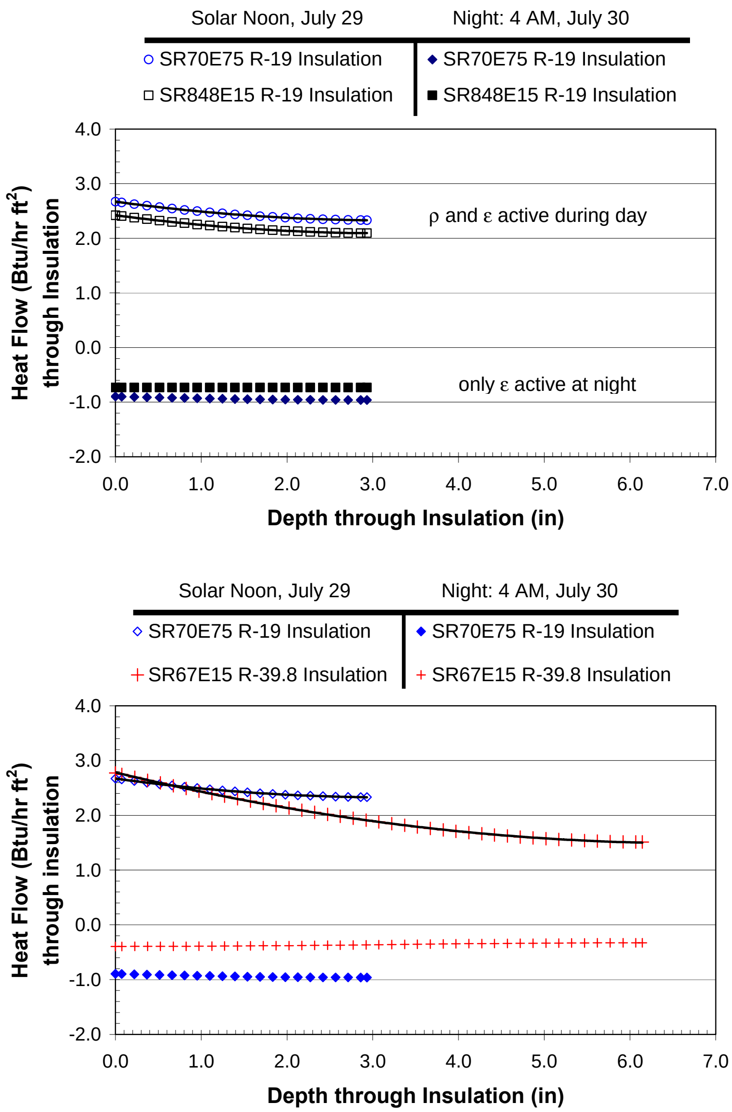

Figure 4. Heat flows at discrete depths into the polyisocyanurate insulation for SR848E15 (R-19) vs the SR70E75 (R-19) and SR67E15 (R-39.8) vs the SR70E75 (R-19).

Appendix A

Derivation of the 2005 Title 24 Variance for Low-Emittance Roofs

The formula for determining the minimal initial solar reflectance required for a low-emittance "cool roof" $\rho_{LE} = 0.70 + 0.34 * (0.75 - \varepsilon_{LE,INITIAL})$ was derived by Levinson et al 2002) 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 ρ_{HE} and ε_{HE}) and the other roof having the minimal initial solar reflectance required for a low-emittance roof (referred to respectively as ρ_{LE} and ε_{LE}).

The energy balances for the two roof systems take the form:

$$-k\left.\frac{dT}{dz}\right|_{HE\ Roof} = (1-\rho_{HE})I_{solar} - \varepsilon_{HE}\sigma\left(T_{HE}^4 - T_{sky}^4\right) - \hbar\left(T_{HE} - T_{air}\right) \quad \text{A1}$$

and

$$-k\left.\frac{dT}{dz}\right|_{LE\ Roof} = (1-\rho_{LE})I_{solar} - \varepsilon_{LE}\sigma\left(T_{LE}^4 - T_{sky}^4\right) - \hbar\left(T_{LE} - T_{air}\right) \quad \text{A2}$$

Subtracting A2 from A1 results in the following expression: A3

$$-k\left.\frac{dT}{dz}\right|_{HE} - \left(-k\left.\frac{dT}{dz}\right|_{LE}\right) = I_{Solar}\left(\rho_{LE} - \rho_{HE}\right) + \sigma\left\{\left(\varepsilon_{LE}T_{LE}^4 - \varepsilon_{HE}T_{HE}^4\right) - \left(\varepsilon_{LE} - \varepsilon_{HE}\right)T_{SKY}^4\right\} + \hbar\left(T_{LE} - T_{HE}\right)$$

During the daylight hours a low-emittance roof will be hotter than a high emittance roof provided both roofs have the same solar reflectance. Hence to have similar surface temperatures, a low-emittance roof must be more reflective than a high-emittance roof. Simulations herein showed this assumption to be correct over all hours of the diurnal cycle if and only if the two roofs have the same solar reflectance and thermal emittance; in this case of equal surface properties, the level of roof insulation does not affect the surface temperature. Trading off a higher solar reflectance to compensate for the low-thermal emittance approximates the surface temperature of the 2005 Title 24 roof; however, the surface temperatures of the two roofs are not equal because the thermal emittance is active both day and night while reflectance affects temperature and therefore heat flow during the daylight hours.

A better assumption is to therefore assume equal heat flows at the roof deck for the two roof systems. This fixes the deck temperature because the indoor air temperature and convective coefficients are the same for both roof covers on the same building. If the insulation is the same type of material like polyisocyanurate, then by Fourier conduction the surface temperatures of the two roofs are approximately the same but will differ from hour-to-hour because of the time of influence of thermal emittance versus solar reflectance. If we therefore assume as did Levinson equal surface temperatures between the two roofs (i.e., $T_{Cool} = T_{HE} = T_{LE}$), then Equation A3 reduces to the form:

$$\rho_{LE} = \rho_{HE} + \frac{\sigma}{I_{Solar}}\left\{\left(T_{Cool}^4 - T_{Sky}^4\right)\left(\varepsilon_{LE} - \varepsilon_{HE}\right)\right\} \quad \text{A4}$$

Appendix A

Derivation of the 2005 Title 24 Variance for Low-Emittance Roofs

Levinson et al (2002) poses using insolation, sky and outdoor air temperatures from moderate-wind standard conditions specified by ASTM E 1980-98. Therefore I_{solar} is set to 1000 Watts per square meter, the sky temperature is 300 K and the outdoor temperature is fixed at 310K (ASTM 1980-98). Equation A4 contains the term T_{Cool} which Levinson et al (2002) assigns the value of 332.8 K (139.3ºF) for a 2005 Title 24 aged roof having solar reflectance of 0.55 and thermal emittance of 0.75. How the surface temperature is established is not discussed; however, roof surface temperature certainly varies as it is affected by time of day, weather and by climate zone. Substituting the above values into Equation A4 results in the following expression for the minimal aged solar reflectance:

$$\rho_{LE} = \rho_{HE} + \frac{5.6685E-8\,Wm^{-2}K^{-4}}{1000\,Wm^{-2}}\left\{\left((332.8K)^4 - (300K)^4\right)(\varepsilon_{LE} - \varepsilon_{HE})\right\} \qquad A5$$

or after simplifying Equation A5 reduces to :

$$\rho_{LE} = \rho_{HE} + 0.23358\{\varepsilon_{LE} - \varepsilon_{HE}\} \qquad A6$$

To account for the loss of reflectance due to soiling Levinson et al (2002) uses the expression $\rho_{aged} = \rho_O + c(\rho_{initial} - \rho_O)$, and rearranges the expression to relate initial reflectance to aged reflectance as: $\rho_{initial} = \frac{\{\rho_{aged} + [c-1]\rho_O\}}{c}$. Therefore the aged solar reflectance term $(\rho_{LE} - \rho_{HE})_{aged}$ of Equation A6 can be related to the initial reflectance as follows: $\Delta\rho_{initial} = \frac{\Delta\rho_{aged}}{c}$ which when substituted back into A6 yields an expression for the minimum initial solar reflectance:

$$\rho_{LE} = \rho_{HE} + \frac{0.23358}{c}\{\varepsilon_{LE} - \varepsilon_{HE}\} \qquad A7$$

or in final form as presented in 2005 Title 24, the prescriptive requirement for the minimal initial solar reflectance:

$$\rho_{LE} = \rho_{HE} + 0.34\{\varepsilon_{LE} - \varepsilon_{HE}\} \qquad A8$$

Acrylic coated Galvalume® has an initial solar reflectance of 0.67 and an initial thermal emittance of 0.15. Using Eq. A8 yields for acrylic coated Galvalume® an initial solar reflectance exceeding 0.904 to meet 2005 Title 24 prescriptive requirements. The impact of the minimal initial solar reflectance on roof heat gain is further described in Appendix B for field tests conducted on the ORNL campus and simulations for East Tennessee's climate.

Appendix B

Validation of STAR Numerical Code

Low-slope roofs are constructed of metal decking that support a layer of insulation and a cover being a single-ply membrane, bare or painted metal or built up roof. The heat flow entering or leaving a low-slope roof is driven by the exterior surface temperature of the roof, which in turn is affected by the surface properties of solar reflectance and thermal emittance of the membrane, the amount of roof insulation, and the exposure of the surface to the climatic elements. A numerical computer code, termed 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 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 (1998 and 2001) validated the model against some 24 different low-slope roof coatings. Miller (2001) validated the code against single-ply TPO and PVC membranes and later against bare and painted metal roofs (Fig. B1).

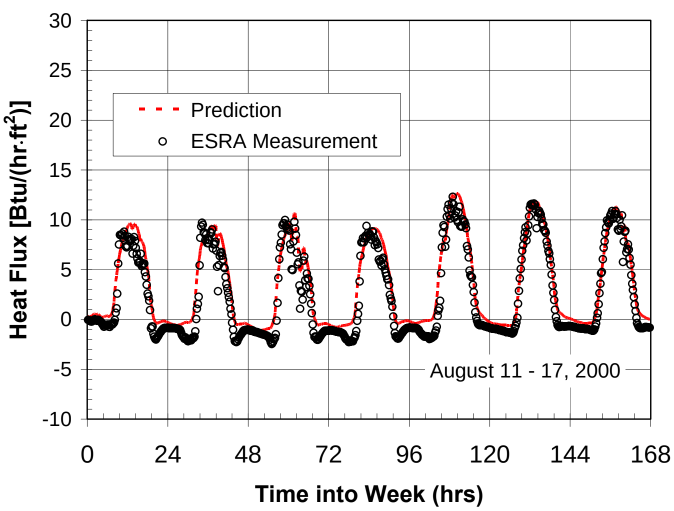

Figure B1. Validation of the STAR code against the measured heat flow penetrating a low-slope roof with acrylic coated Galvalume®.

STAR was validated against field data for acrylic coated Galvalume® low-slope roofs in preparation of conducting the emittance sensitivity study. The Galvalume® test roof had been exposed for 1½ years on the Envelope Systems Research Apparatus (ESRA) and an aged solar reflectance of 0.59 and aged thermal emittance of 0.17 was used to predict the measured deck heat flows (Fig. B1) having R-5 insulation. The error between the measured and predicted heat flow was about 3.5% of the measured value for data collected during August 2000 on the ESRA.

Once validated, STAR was used to compare 2005 Title 24 roof performance (SR70E75) against an acrylic coated Galvalume® roof (SR67E15) and against a roof with the same low thermal emittance as the Galvalume® but with the minimum solar reflectance $(\rho_{LE\,MIN})$ required by 2005 Title 24 (SR90E15). The preliminary simulations were performed using weather data for ORNL because it includes night-sky radiometer data for directly calculating the night-sky[3] temperature. Neither the California's CTZ2 (CEC 1992) nor the TMY2 (NREL 1995)weather databases provide radiant sky radiometer data and therefore simulations using California weather rely on an algorithm based on the dew point temperature of the outdoor ambient air and the metered cloud amounts to deduce sky temperature. The ORNL weather data provided a more accurate measure of sky temperature from which the effect of thermal emittance could be accessed from the following energy balance for the roof surface:

$$q_{load} = q_{in}$$

$$-k\frac{dT}{dz} = (1-\rho)I_{solar} - \varepsilon\sigma\left(T_m^4 - T_{sky}^4\right) - \hbar\left(T_m - T_{air}\right) + q_{lat}$$

From the above energy balance, it is easily seen that the effect of thermal emittance through the radiative cooling term $\varepsilon\sigma\left(T_m^4 - T_{sky}^4\right)$ is strongly dependent on the night-sky temperature. Please note that the CTZ2 weather database (CEC 1992) was used to simulate climate in the sixteen different California climate zones. However, we made a brief review of the TMY2 database (NREL 1995) versus the CTZ2 weather data (CEC 1992) to view potential differences in radiative cooling. The results for outdoor air temperature, humidity and irradiance were reasonably close; however, differences in cloud amounts between the two weather files yielded differences in computed sky temperatures that in the August time frame caused the TYM2 data to yield sky temperatures 20ºF higher than those computed using CTZ2 inputs.

The results for STAR simulations using a week of East Tennessee's August weather data that enabled direct measure of the sky temperature are displayed in Figures B2 and B3. The abscissa of both graphs is in multiples of 24, which represents midnight for each of the seven days depicted in the figures. The level of roof insulation was fixed at R-5 as was used in the actual ESRA field tests and validations of Figure B1.

Surface temperature clearly shows that the Galvalume® roof (SR67E15) is hotter at solar noon than the 2005 Title 24 roof (SR70E75) by almost 40F^{o} because of its low emittance and its lower solar reflectance (Fig. B2). In comparison, if the roof had the minimal solar reflectance needed to comply with 2005 Title 24 (SR90E15) the surface temperature is actually 20F^{o} less than that computed for the 2005 Title 24 case. Surface temperature drives the heat transfer into the roof and insulation, and if the two roof systems have the same level and type of insulation then the heat flow through the deck into the conditioned space should mimic the same trends as surface temperature.

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[3] Measures of the global infrared irradiance (q_{IR}) made by the BTC's field pyrgeometer are used to calculate the radiant sky temperature from the equation for blackbody radiation: $q_{IR} = \sigma T_{sky}^4$.

Appendix B

Validation of STAR Numerical Code

The deck heat flow (building cooling load) through the acrylic coated Galvalume® roof (SR67E15) is 70% larger than that of the 2005 Title 24 roof (Table B.1 and Fig. B3). However, the prescriptive requirement for low-emittance roofs SR90E15 yielded heat flows that were 40% less that that computed for the 2005 Title 24 prescriptive roof (Table B.1). The results, integrated over the week of simulated time, are listed in Table B.1 along with other STAR simulations showing what the solar reflectance should be for the acrylic coated Galvalume® roof to match the load for the Title 24 base case (see $\rho_{LE\ min}$ in Table B.1). An additional simulation is included with increased insulation added to the acrylic coated Galvalume® to determine what level of insulation is needed to match the Title 24 base case (see Add R-Value Table B.1).

Table B.1 Integrated Heat Flows of a Low-Slope Roof Deck for Simulations using a week of August weather for East Tennessee

		Title 24 Prescriptive Req		STAR Simulations	
		$E \geq 0.75$	$E < 0.75$[1]	$\rho_{LE\ min}$	Add R-Value
	SR67E15	SR70E75	SR90E15	**SR80E15**	SR67E15
R-Value	4.67	4.67	4.67	4.67	**10**
Qday (Btu/ft^2)	494.2	270.0	150.9	306.0	274.0
Qnight (Btu/ft^2)	-22.0	-33.9	-25.9	-23.5	-17.5
Q_{week} (Btu/ft^2)	516.1	303.9	176.8	329.5	291.5

[1] $\rho_{LE} = 0.70 + 0.34*(0.75 - \varepsilon_{LE,Initial})$

Results show that a solar reflectance of 0.80 with thermal emittance fixed at 0.15 (SR80E15) yielded similar building load to the Title 24 prescriptive case (SR70E75). Increasing the insulation from about R-5 to about R-10 also matched the roof load for the 2005 Title 24 prescriptive case. Armed with these results for East Tennessee's climate, we therefore proceeded with analysis for the 2005 Title 24 prescriptive requirement as applied to California's climatic zones. The data for East Tennessee shows the Title 24 requirement as being too restrictive causing low thermal emittance roofs to out perform the Title 24 prescriptive case. Also economic alternatives may exist by trading off increased levels of insulation against low thermal emittance that still meets building load for the Title 24 prescriptive case.

Appendix B
Validation of STAR Numerical Code

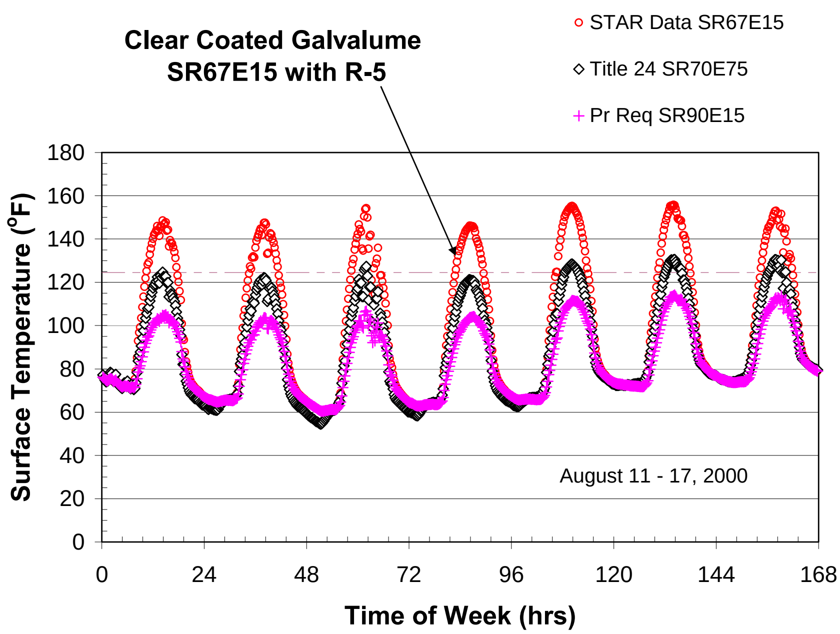

Figure B2. Surface temperature for the acrylic coated Galvalume® roof (SR67E15) as compared to the 2005 Title 24 (SR70E75) roof and the minimal solar reflectance roof (SR90E15).

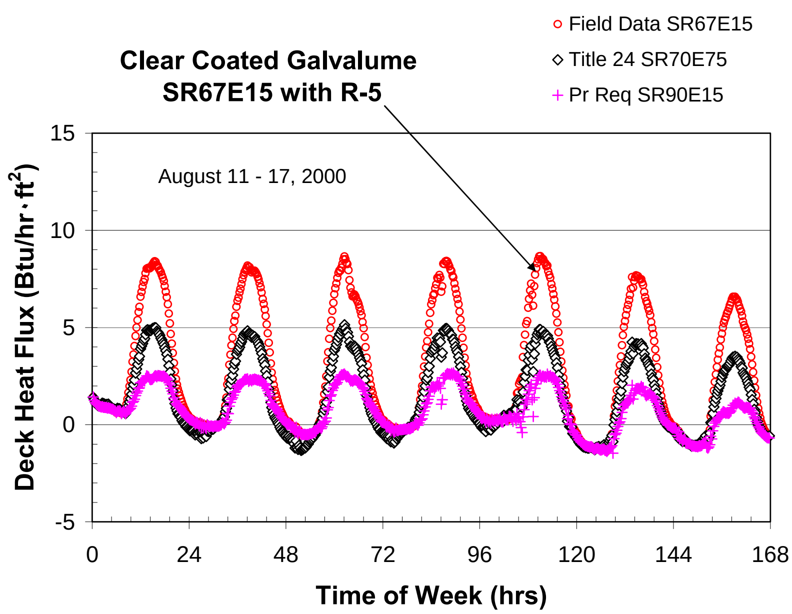

Figure B3. The deck heat flow observed for the acrylic coated Galvalume® roof (SR67E15) as compared to the 2005 Title 24 (SR70E75) roof and the minimal solar reflectance roof (SR90E15).

Appendix C

Time Dependent Valuation Economics

The time dependent valuation (TDV) of energy consumption was adopted by the Title 24 Building Energy Efficiency Standards for assigning weighted values to energy savings produced by a given energy efficiency measure used in a building. The procedure places a higher weight on the savings achieved by an energy measure that is very efficient during hot summer weekday afternoons as compared to an energy measure that is more efficient during off-peak hours. The method attempts to reflect the actual energy market, where high system demand on summer afternoons drives electricity prices much higher than during night time hours in milder weather.

TDV energy is the energy that is used at a site and consumed in producing and in delivering energy to a site. It includes power generation, transmission and distribution losses and the energy used at the building site for comfort cooling, lighting or water heating. It has units of kBtu of natural gas per kWh of electricity, and can be viewed as the amount of energy produced at the power plant needed for consuming a kWh of energy at the building site. TDV energy is calculated by multiplying the hourly "site energy" values for say a "cool roof" by the associated hourly TDV factors, based on a series of 8760 values of energy factors; one for each hour of the typical CTZ2 weather year. Each of the sixteen zones has a specific set of 8760 TDV factors for calculating residential and nonresidential building energy for a given fuel type whether electric, natural gas or propane. An example of TDV factors for nonresidential electric usage in Zone 12 (Sacramento, CA) are shown in Fig. C.1.

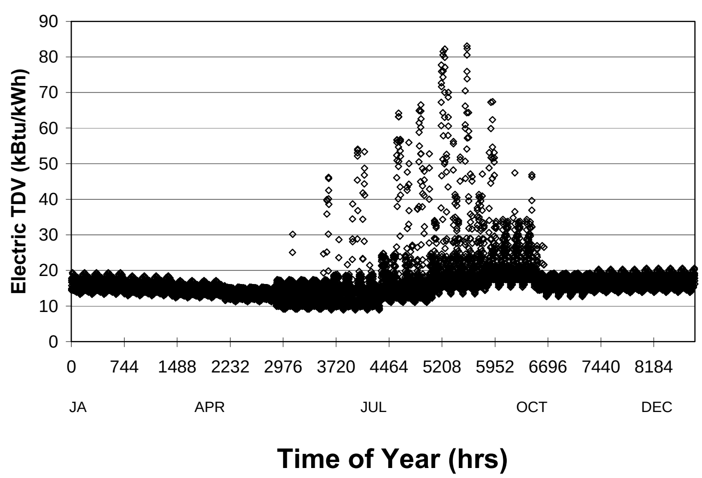

Figure C.1 TDV values for electricity applied to Sacramento, CA representing climate zone 12.

It is easily seen that TDV factors exceeding 80 kBtu per kWh are used in the hot summer months of Zone 12 to place a higher value on the cost of summertime building energy usage (Fig. C.1). Summing the products of TDV factors and "site energy" savings for each hour of the year yields the annual weighted TDV savings as given by the following expression:

$$\text{Annual TDV Savings}\left[\text{TDV kBtu}_{NG}\right]=\sum_{i=0}^{8760}\text{Energy Savings}_i\left[\text{kWh}\right]*\text{TDV Factor}_i\left[\frac{\text{TDV kBtu}_{NG}}{\text{kWh}}\right]$$

Appendix C

Time Dependent Valuation Economics

For a cool roof, the savings in heat transfer crossing the roof boundary must be converted into site energy using the performance of a commercial size HVAC unit. Data was gleaned from a PIER study (Building End-Use Energy Efficiency 1999) for the performance of air-conditioning units tested in northern and central California. The Energy Efficiency Ratio (EER) was curve fit as a function of the outdoor dry bulb temperature and the indoor dry bulb and wet bulb temperature data provided from the PIER study; the EER empirical fit takes the form:

$$\mathrm{EER} = 8.538 - 0.09377 \times \mathrm{DB}_{\mathrm{Outdoor}} + 0.056942 \times \mathrm{DB}_{\mathrm{Indoor}} + 0.059255 \times \mathrm{WB}_{\mathrm{Indoor}}$$

The fit was used to calculate EER at each hour of CTZ2 climatic weather from which the energy of the "cool roof" was calculated as follows:

$$\sum_{i=0}^{8760} \mathrm{Energy\ Savings}_i\ [\mathrm{kWh}] = \sum_{i=0}^{8760} \left[\frac{\mathrm{Qroof}_i}{\mathrm{EER}_i} \right] \qquad \text{C2}$$

For nonresidential buildings, the annual TDV savings are multiplied by a nominal present value cost of natural gas[4] (PV $\$0.0745/\mathrm{kBTU}_{NG}$ that is based on a 15-year forecast of natural gas costs for nonresidential customers. The forecasted cost is then assigned a present value by applying a 3% real (inflation adjusted) discount rate. Therefore multiplying the annual TDV savings by the PV $\$0.0745/\mathrm{kBTU}_{NG}$ yields the net present value ($NPV) cost of energy savings over a 15-year period for nonresidential buildings. To view the yearly TDV cost of energy requires determining the affordable yearly cost ($A) based on a 3% discount over the 15-year period by the formula:

$$\$A = \$NPV \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \qquad \text{C3}$$

where

i	discount rate of 3%
n	number of periods being 15 for nonresidential
$NPV	net present value forecast over 15 years for nonresidential

The $A value therefore represents the annual cost of energy savings for a given energy efficiency measure. It should be noted that the TDV methodology reflects the differences in cost values as driven by climate conditions. Therefore the extreme hot climates of California will have higher, more concentrated peak energy costs than a milder, less variable climate.

A non-TDV cost of energy savings can also be calculated based on a 15-year net present value to compare the two procedures. For non-TDV savings, the heat transfer across the roof is converted into energy by Eq. C2; however, TDV factors are set to unity and the summation of energy is multiplied by PV$1.37/kWh for electricity and by $7.30/therm for natural gas. These energy costs are based on 15-year projections of statewide annual average electricity and natural gas prices (Eley Associates 2002).

[4] This cost factor is constant across all climate zones in California.