Cool Roofs and Thermal Insulation: Energy Savings and Peak Demand Reduction

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ABSTRACT

Cool roofs are defined by the Cool Roof Rating Council as a product with solar reflectivity of at least 0.70 and infrared emissivity of at least 0.75. In its 2005 revision, Title 24, California Energy Efficiency Standards for Residential and Nonresidential Buildings, cool roofs are prescribed in the standard non-residential building. While cool roofs decrease the solar gain of buildings, thus lowering cooling energy demand, additional insulation also does it. This work investigates the levels of insulation required with a black roof to accomplish the same cooling energy demand that cool roofs have with minimum insulation requirements. Both total and peak energy demands are considered and the levels of insulation to accomplish them are different. Oak Ridge National Laboratory's Simplified Transient Analysis of Roofs (STAR) computer code was used to predict the transient heat gain and structure temperatures. The 16 Climate Zones in California were used, as well as the minimum insulation requirements dictated by 2005 Title 24 legislation. The results were compared with the results predicted by the overall envelope approach of the legislation.

INTRODUCTION

The heating and cooling demands of a building structure are affected by the thermal characteristics of its envelope. Of the thermal characteristics usually considered, radiative surface properties are often regarded as less important than thermal insulation. However, for flat commercial roofs, the solar irradiation contributes considerably to the total heat gain of the building and its solar reflectivity and thermal emissivity are very relevant in determining the cooling and heating requirements of the building.

Cool roofs are defined by the Cool Roof Rating Council as a product with solar reflectivity of at least 0.70 and infrared emissivity of at least 0.75. That is, a product that reflects most of the solar irradiation and also highly emits thermal radiation in the infrared part of the spectrum. Young (1998) and Akbari and Konopacki (1998) have shown that cool roofs can reduce the building cooling energy use by 10% to 50%. They also showed a decrease in summertime air temperature of the building surroundings of 1-2 K, reducing the Urban Heat Island Effect.

Cool roofs have been adopted as part of requirements of several programs, the most prominent of which are the 2005 version of the California Energy Efficiency Standards for Residential and Nonresidential Buildings (known as Title 24) and ENERGYSTAR®. In Title 24, cool roofs are prescribed in the standard non-residential building, requiring the heat gain of any compliant building not to exceed that of a building with a cool roof.

Upon the publication of the 2005 version of Title 24 there were questions about the effectiveness of an insulation trade-off to cool roofs in commercial buildings, with some individuals claiming that insulation would not deliver the same reduction in heat gain at peak demand hours as cool roofs. The present manuscript is an attempt to clarify the issue. It presents first how the insulation trade-off can be calculated from the Title 24 standard, followed by the findings of a numerical simulation of heat transfer in roofs with cool and dark

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membranes and different levels of insulation. Only the consequences on energy use are addressed by the present manuscript, so Urban Heat Island Effect issues are not discussed.

COMPLIANCE THROUGH 2005 TITLE 24

Part 6 of California's Title 24 standard focuses on energy conservation through construction management. Included in the October 1, 2005 legislation are cool roofs (infrared emittance 0.75 and solar reflectance 0.70). In addition to a cool roof, the current legislation requires minimum insulation levels of R-11 or R-19, depending on the climate zone.

Analysis of the legislation allows for the derivation of an insulation trade-off equation within the prescriptive method (overall envelope approach). Section 143 – Prescriptive Requirements for Building Envelopes (Page 81) states that "a building complies with this section by being designed with and having constructed and installed either (1) envelope components that comply with each of the requirements in Subsection (a) for each individual component (…), or (2) and envelope that complies with the overall requirements in Subsection (b)." Subsequent evaluation of section 143, subsection (b) revealed a way to arrange the equations to calculate the insulation trade-off of cool roofs and lower reflectivity or non-cool roofs. Listed below is the procedural breakdown of the equations mentioned above.

Heat loss and gain from the proposed building has to be less or equal to these of the standard building. During the heating season, when heat loss becomes a concern, cool roofs are detrimental and using a darker membrane with additional insulation will significantly increase the heat gain (darker membrane) and reduce the heat loss (additional insulation) from the building. Therefore, only the heat gain during the cooling season must be considered in the present analysis.

Procedure

1. The standard building heat gain (HG_{std}) is calculated using EQUATION 143-D (page 89 of the standard):

$$
\begin{aligned}
HG_{std} = & \sum_{i=1}^{nW} (A_{Wi} \times U_{Wi_{std}} \times TF_i) + \sum_{i=1}^{nF} (A_{Fi} \times U_{Fi_{std}} \times TF_i) \\
& + \sum_{i=1}^{nR} (A_{Ri} \times U_{Ri_{std}} \times TF_i) + \sum_{i=1}^{nG} (A_{Gi} \times U_{Gi_{std}} \times TF_i) \\
& + \sum_{i=1}^{nS} (A_{Si} \times U_{Si_{std}} \times TF_i) + \sum_{i=1}^{nG} (WF_{Gi} \times A_{Gi} \times RSHG_{Gi_{std}}) \times SF \\
& + \sum_{i=1}^{nS} (WF_{Si} \times A_{Si} \times SHGC_{Si_{std}}) \times SF \\
& + \sum_{i=1}^{nR} (WF_{Ri} \times A_{Ri} \times U_{Ri_{std}} \times [1-(0.2+0.7[\rho_{Ri_{std}} - 0.2])]) \times SF
\end{aligned}
$$

2. A proposed building must have the same heat gain of the standard building to comply. EQUATION 143-E (page 90 of the standard) calculates the proposed building heat gain as

$$
\begin{aligned}
HG_{prop} = & \sum_{j=1}^{nW} (A_{Wj} \times U_{Wj_{prop}} \times TF_j) + \sum_{j=1}^{nF} (A_{Fj} \times U_{Fj_{prop}} \times TF_j) \\
& + \sum_{j=1}^{nR} (A_{Rj} \times U_{Rj_{prop}} \times TF_j) + \sum_{j=1}^{nG} (A_{Gj} \times U_{Gj_{prop}} \times TF_j) \\
& + \sum_{j=1}^{nS} (A_{Sj} \times U_{Sj_{prop}} \times TF_j) + \sum_{j=1}^{nG} (WF_{Gj} \times A_{Gj} \times SHGC_{Gj_{prop}} \times OHF_j) \\
& \times SF + \sum_{j=1}^{nS} (WF_{Sj} \times A_{Sj} \times SHGC_{Sj_{prop}}) \times SF \\
& + \sum_{j=1}^{nR} (WF_{Rj} \times A_{Rj} \times U_{Rj_{prop}} \times [1-(0.2+0.7[\rho_{Ri_{prop}} - 0.2])]) \times SF
\end{aligned}
$$

3. Assuming the standard and proposed buildings are exactly the same, apart from the roof insulation and radiation properties, all but the third and final terms from equations 143-D and 143-E are the same. Subtracting equation 143-E from equation 143-D, under the above conditions,

$$
\begin{aligned}
& HG_{std} - HG_{prop} = \\
& \sum_{i=1}^{nR} [(A_{Ri} \times U_{Ristd}) \times (TF_i + WF_{Ri} \times SF \times [1-(0.2+0.7 \times [\rho_{Ristd} - 0.2])])] \\
& + - \sum_{j=1}^{nR} [(A_{Rj} \times U_{Rjprop}) \times (TF_j + WF_{Rj} \times SF \times [1-(0.2+0.7 \times [\rho_{Rjprop} - 0.2])])]
\end{aligned}
$$

4. When the standard and proposed buildings have the same heat gain, the left side of the previous equation is cancelled. Since the two buildings have exactly the same geometry, the previous equation must be satisfied for each roofing section i (or j), thus:

$$
\begin{aligned}
& U_{Rstd} \times (TF + WF_R \times SF[1-0.2+0.7[\rho_{Rstd} - 0.2]]) = \\
& U_{Rprop} \times (TF + WF_R \times SF[1-0.2+0.7[\rho_{Rprop} - 0.2]])
\end{aligned}
$$

For each roofing section, the previous equation must hold. Please note that only the roofing U-value and the roofing surface reflectance are unique on either side. Using the prescribed values in Table 143-A (Page 83 of the standard) for the standard building and the corresponding value of a proposed roofing surface reflectance, the equivalent roofing U-value for the proposed building can be calculated.

The proposed arrangement detailed above maintains the same heat gain during the cooling season. For each reflectivity lower than 70%, a different value of the insulation level can be calculated, as shown on Table 1.

NUMERICAL MODEL

Low-slope roofs are constructed of a decking that supports a layer of insulation and a cover being a single-ply

Table 1. Required Insulation Levels Rounded to the Nearest R-value for Title 24 by Equation 143-a Compliance Using Various Surface Reflectance Levels

Climate Zone	Reflectance, % {Thermal Emittance > 0.75}						
	10	20	30	40	50	60	70
1	33	31	28	26	24	21	19
2	30	28	26	24	23	21	19
3	30	28	26	25	23	21	19
4	30	28	26	25	23	21	19
5	30	28	26	25	23	21	19
6	17	16	15	14	13	12	11
7	18	16	15	14	13	12	11
8	17	16	15	14	13	12	11
9	17	16	15	14	13	12	11
10	29	27	26	24	22	21	19
11	28	27	25	24	22	21	19
12	29	27	25	24	22	21	19
13	29	27	26	24	22	21	19
14	29	27	26	24	22	21	19
15	28	26	25	23	22	20	19
16	30	28	27	25	23	21	19

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.

Thermophysical Properties

No coverboard or deck was considered in the simulation. The membrane was treated as thin, so only the properties for Polyisocyanurate were necessary. The density and specific heat were treated as constant; the density is equal to 1.249×10^{-1} kg/m^3 (2 lb/ft^3) while the specific heat is 9.211×10^{-1} kJ/kg.K (0.220 Btu/lb.°R). The thermal conductivity of Polyiso was considered a function of the temperature, increasing as the temperature increases: k [W/m.K] = $1.754\times10^{-2} + 1.153\times10^{-4}$ * T[K] (k [Btu-in/h.ft^2.°F] = 0.1216 + 0.000444 * T[°F]).

RESULTS AND DISCUSSION

The numerical code developed was used to generate hourly temperature and heat flux through the thickness of the insulation over an entire year. The CTZ2 weather database (CEC 1992) was used to simulate the weather, and is the same weather database used by the CEC Title 24 energy standards. Combinations of insulation levels and radiative transport properties were used to compare the performance of different roofing systems and identify the suitable trade-off for a dark roof. The basic case for each Climate Zone will be the minimum R-value obtained by Table 143-A of Title 24 standard (either 11 or 19) with solar reflectance of 0.55 and thermal emittance of 0.75. Note that the cool roof solar reflectance is degraded to 0.55 to account for soiling and deterioration of the cool roof membrane through use while the dark roofing membrane had solar reflectance of 0.2 and thermal emittance of 0.9, as recommended by Title 24.

Insulation trade-offs can be calculated to match the total cooling demand or to match the weighted cooling demand using the Time-Dependent Valuation (TDV) of energy[1]. In the latter, California assigned higher value of energy when the demand is near peak. Both cases are discussed.

As an example, Climate Zone 12 was selected to generate figures. Table 2 displays the summary of results obtained. Tables such as this one were obtained for each of the CA climate zones. The first line displays the prescribed case, where the R-value is 19, the solar reflectance is 0.7, and the thermal emittance is 0.75. For this case, the annual cooling load and the TDV-weighted cooling load are in yellow. In the following line, the results are for an aged cool roof with a solar reflectance of 0.55 and the cooling loads are marked green. The results show that, to perform as a cool roof with R-19, a dark roofing system needs additional insulation: for the same annual cooling load, if compared to a brand new cool roof, the dark roof requires a premium additional insulation of R-33, with a total insulation of R-52 (cooling load marked yellow); when TDV is considered, the premium drops to R-30 (TDV cooling load marked green). For Title 24 compliance, comparisons are to be made with the initially aged case: for same annual cooling load, the dark roof requires R-34 insulation (R-15 premium, cooling load marked yellow), while for same TDV annual cooling load, it requires R-33 insulation (TDV cooling load marked yellow). Through Title 24, from Table 1 in Sacramento, the R-value required is equal to R-27, which is slightly smaller than the calculated through STAR.

1. 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.

Table 2. Average Surface Temperature and Annual Cooling Load for Different Roofing System Configurations in Climate Zone 12 (Sacramento)

R-value	Solar Reflectance	Thermal Emittance	Average Surface Temperature, °F	Annual Cooling Load,[a] Btu/ft^2	TDV Annual Cooling Energy, Btu/ft^2
19	**0.7**	**0.75**	96.4	2245.4	6771.7
19	**0.55**	**0.75**	108.5	3594.4	10155.9
32			130.5	3792.9	10396.2
33			130.6	3683.6	10111.6
34			130.6	3579.6	9840.6
36			130.6	3385.1	9333.9
40			130.6	3040.0	8432.6
44	0.2	0.9	130.7	2737.9	7639.4
48			130.7	2466.9	6920.8
49			130.7	2403.0	6750.2
50			130.7	2340.4	6582.6
51			130.7	2279.2	6418.1
52			130.7	2219.1	6256.1

[a]Cooling load defined as roof heat transfer summed over cooling season when outdoor air temperature exceeds 65°F (18.3°C).

Table 3. Average Surface Temperature and Annual Heating Load for Different Roofing System Configurations in Climate Zone 12 (Sacramento)

R-value	Solar Reflectance	Thermal Emittance	Average Surface Temperature, °F	Annual Heating Load,[a] Btu/ft^2	Percentage Difference of the Basic Case
19	0.7	0.75	47.7	7216.7	8.09%
19	0.55	0.75	49.5	6676.7	Basic case
33	0.2	0.9	51.8	3559.7	-46.68%
34	0.2	0.9	51.8	3458.9	-48.19%
49	0.2	0.9	51.7	2315.5	-65.32%
52	0.2	0.9	51.7	2136.1	-68.01%

[A] Heating load defined as roof heat transfer summed over heating season when outdoor air temperature is lower than 65°F (18.3°C)

While cool roofs are excellent to reduce cooling loads in the summer, they cause a heating penalty in the winter, since the solar gain from the roof is smaller, increasing the load for the heating system. Insulation, however, reduces both the cooling and the heating loads and this fact should be considered when such a trade-off is used. Table 3 shows the effect of additional insulation on the heating load of the building in Climate Zone 12. The effect of additional insulation reduces the annual heating load as much as 68% at the same annual cooling load. For the basic case, the reduction is still substantial at 46.68-48.19%.

Table 4 is a summary of all the insulation trade-off values calculated. While the comparison with the initial reflectance cool roof is a curiosity, it shows that to reach the performance of a brand new cool roof, a significant amount of insulation is necessary. The equivalent insulation to provide the same TDV weighted annual cooling energy is slightly smaller than that for the total annual cooling load. It is also important to point out that the values calculated through this simulation are larger (a premium of between R-4 and R-6) than the one predicted by the use of the equation in the standard. While the source of this discrepancy is not known, the coefficients used in equation 143-A could have been estimated for a different range of properties than the ones used here.

Figure 1 displays the cooling load for the highest peak demand day of the year (for the cool roof system) for two roofing configurations: an aged cool roof with the minimum prescribed insulation level (R-19) and a dark roof with R-33. As expected, the peak is not exactly the same, since the insu-

Table 4. R-Value Equivalent to Cool Roof for Initial and Aged Reflectance Cool Roofs and for Both Annual Cooling Load and TDV Weighted Annual Cooling Energy

Climate Zone	With Cool Roof	Initial Reflectance		Aged Reflectance		
		Annual Cooling Load	TDV Annual Cooling Energy	Annual Cooling Load	TDV Annual Cooling Energy	143-A
1		55	55	37	37	31
2		54	52	35	34	28
3	19	57	55	38	37	28
4		54	51	35	35	28
5		50	49	35	34	28
6		42	38	23	22	16
7	11	42	39	23	22	16
8		38	35	21	21	16
9		37	33	21	20	16
10		55	51	35	34	27
11		54	50	34	33	27
12		52	49	34	33	27
13	19	52	49	33	32	27
14		55	51	34	33	27
15		47	43	32	30	26
16		55	50	35	34	28

lation trade-off of R-33 was calculated based on the equivalent TDV weighted annual cooling load to be the same.

The roofing surface temperatures are shown in Figure 2 for the same configurations discussed in the previous figure. As expected, the higher reflectance roof displays a much lower peak temperature if compared with the dark roof. It is important to note that the objective of a building energy code is not to keep temperatures low, but to reduce the heat gains and losses of a building. Despite the fact that a highly insulated roof is much warmer than a cool roof, the heat gain of the dark roof with more insulation is actually smaller than that of the cool roof.

SUMMARY

A numerical investigation of the heat transfer through a roofing system was conducted using a one-dimensional finite volume code. Several roofing configurations were modeled, varying the membrane radiative properties and the insulation levels to determine the insulation level that would produce the same annual cooling load of a cool roof with the prescribed minimum amount of insulation. All the simulations were performed in each of the 16 California Climate Zones. The following are the relevant conclusions of the work:

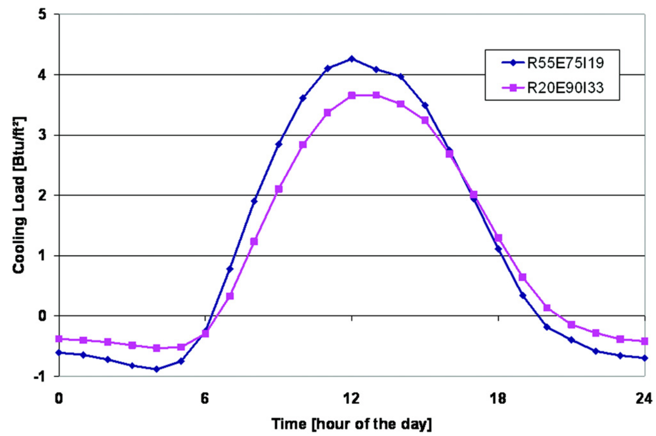

Figure 1 *Cooling load during the highest peak day in the year for both the aged cool roof and an R-33 dark roof in Sacramento, CA (climate zone 12).*

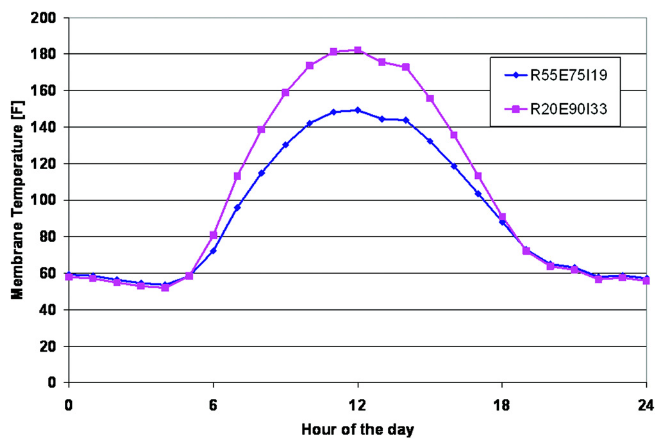

Figure 2 *Membrane temperatures during the highest peak day in the year for both the aged cool roof and an R-33 dark roof in Sacramento, CA (climate zone 12).*

1. An equivalent level of insulation under a dark roof can be determined through simulation to match the annual cooling load of a building with a cool roof.
2. While a trade-off level of insulation can be calculated through the Title 24 standard, the levels determined by the simulation were higher between R-4 and R-6.
3. There is a slight difference between the insulation equivalent using the same annual cooling load and the same TDV weighted annual cooling load.
4. The temperature of dark highly insulated roofs is higher than cool roofs with prescribed insulation levels. However, the heat flux into the building may be smaller for the hotter roof.

If different assumptions were to be used for calculation of the cooling loads, the insulation levels necessary to match the cooling load could be different. Experimental validation of the results would be necessary for use in determining specific building configurations.

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