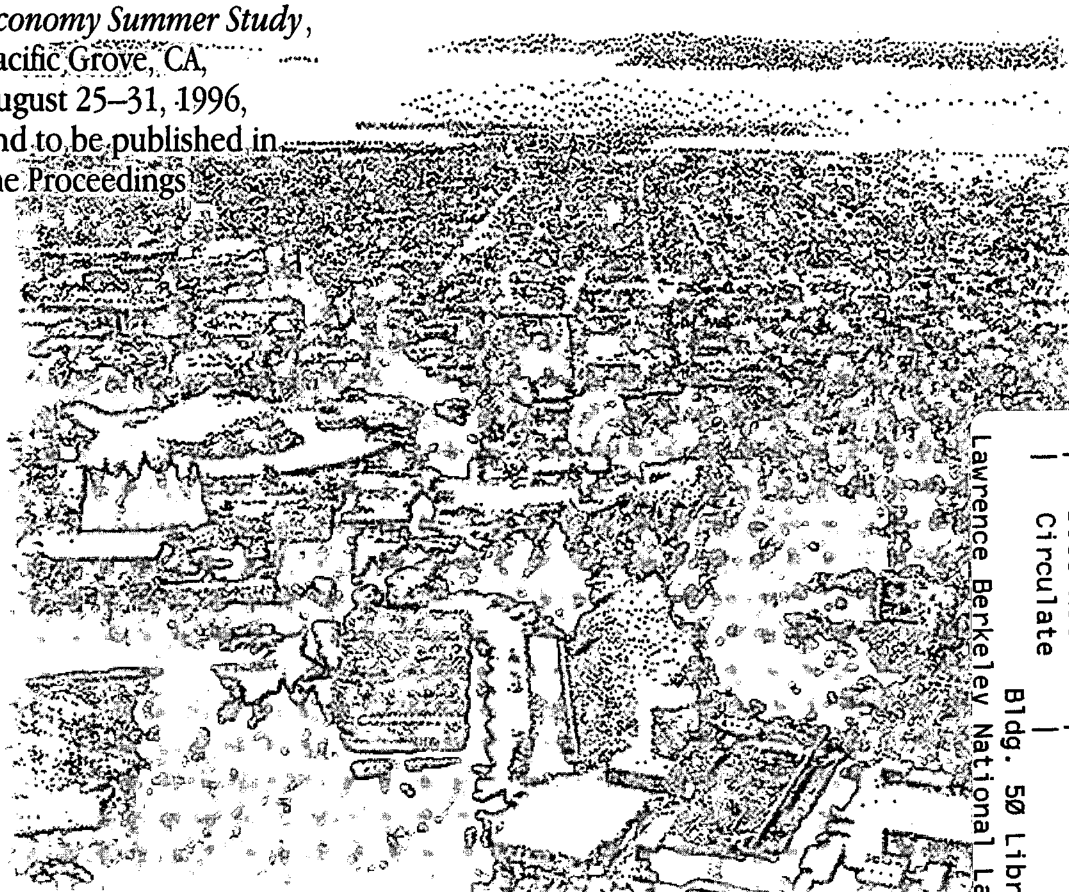
LBL-38580
UC-1600

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Modeling the Effects of Reflective Roofing

Lisa M. Gartland, Steven J. Konopacki,
and Hashem Akbari
Energy and Environment Division

August 1996
Presented at the
American Council for an Energy Efficient Economy Summer Study,
Pacific Grove, CA,
August 25–31, 1996,
and to be published in
the Proceedings



DISCLAIMER

LBL-38580
UC-1600

Modeling the Effects of Reflective Roofing

Lisa M. Gartland, Steven J. Konopacki, and Hashem Akbari

Energy & Environment Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

August 1996

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, U.S. Department of Energy under Contract. No. DE-AC03-76SF00098.

Reprinted with permission of the American Council for an Energy-Efficient Economy, Berkeley, CA, 1996.

Modeling the Effects of Reflective Roofing

Lisa M. Gartland, Steven J. Konopacki, and Hashem Akbari, Heat Island Project, Energy Analysis Program, Ernest Orlando Lawrence Berkeley National Laboratory

Roofing materials which are highly reflective to sunlight are currently being developed. Reflective roofing is an effective summertime energy saver in warm and sunny climates. It has been demonstrated to save up to 40% of the energy needed to cool a building during the summer months. Buildings without air conditioning can reduce their indoor temperatures and improve occupant comfort during the summer if highly reflective roofing materials are used.

But there are questions about the tradeoff between summer energy savings and extra wintertime energy use due to reduced heat collection by the roof. These questions are being answered by simulating buildings in various climates using the DOE-2 program (version 2.1E). Unfortunately, DOE-2 does not accurately model radiative, convective and conductive processes in the roof-attic. Radiative heat transfer from the underside of a reflective roof is much smaller than that of a roof which absorbs heat from sunlight, and must be accounted for in the building energy model. Convection correlations for the attic and the roof surface must be fine tuned. An equation to model the insulation's conductivity dependence on temperature must also be added.

A function was written to incorporate the attic heat transfer processes into the DOE-2 building energy simulation. This function adds radiative, convective and conductive equations to the energy balance of the roof. Results of the enhanced DOE-2 model were compared to measured data collected from a school bungalow in a Sacramento Municipal Utility District monitoring project, with particular attention paid to the year-round energy effects.

INTRODUCTION

Background

The use of highly reflective materials on roof surfaces has been measured to save between 10 and 50% of the energy used for summer cooling in tests performed in California and Florida.[1] In order to extrapolate these results over different seasons and to varying climate regions, it is useful to have an accurate theoretical model of a building's energy use and its interaction with roof and attic thermal processes. Unfortunately, simulations using DOE-2, the most widely used building energy model, consistently under-predict energy savings due to high albedo roof surfaces.

For example, in the study of school bungalows in Sacramento[2], the measured cooling energy savings due to changing the roof color from brown to white was 4.6 kWh/day on average. The DOE-2 simulation found average savings of only 2.9 kWh/day—off by 37%. Power savings of white roofs at peak hours was also under-predicted. The measured peak power savings was 0.56 kW, compared with a simulated peak savings of 0.28 kW, a 50% difference.

DOE-2 is an effective and computationally compact model for whole building energy use estimates, but doesn't have the level of detail necessary to account simultaneously for radiative, conductive and convective processes that may be occurring in any of the building's components. Changes in the roof's albedo dramatically affect the surface temperature of the roof—a black roof can heat to 180°F in the sun, while a white roof under the same conditions will heat to only 100°F. Heat transfer processes are dependent on the driving force of the temperature difference between the roof's surface and the inside temperature. The large variations in temperature difference due to surface condition changes are difficult to model accurately without accounting for radiative transfer. The exterior film convection correlation of DOE-2 is also suspected to yield values which are too high, and this problem is exacerbated by the surface temperature variations from a dark surface to a light surface.

A model specific to roof and attic thermal processes has been developed at Oak Ridge. RBSOR (Radiant Barrier Systems—Oak Ridge)[3] was developed to model attic heat transfer when "radiant barriers", essentially reflective surfaces, are installed inside the attic on either the roof's underside or the ceiling's topside. This model has detailed equations describing the radiation transfer between all attic surfaces, as well as free and forced convective equations to model convection inside the attic and on the roof's surface. RBSOR also calculates delays in heat fluxes through attic components due to thermal storage. This model is too large for use directly with DOE2, but the theory behind the model can be extracted and compressed into a DOE-2 function.

This paper discusses a simplified algorithm developed for use in DOE-2. This algorithm is used during load calculations to enhance the roof's heat transfer with some of RBS-OR's level of detail.

Scope

There is a need to upgrade the roof load calculations to better contrast heat transfer with and without high-albedo roofing. A function has been developed to meet that need. The function is currently applicable to flat roofs with unvented attic spaces between the roof and ceiling. It incorporates radiative transfer and free convection inside the attic, free and forced convection at the roof surface, temperature dependence of the insulating material's conductivity, and delays in heat flux due to thermal storage in the building materials.

The function's results are compared with data from a Sacramento school bungalow tested in 1992. This bungalow was tested during three different roof surface conditions—with a metal roof, when the roof was painted brown, and again when the roof was painted white.

Seasonal effects of high albedo roofs are very important. Although a white roof will save cooling energy during the summer, it will also reduce the heat gain through the roof in winter, thus adding to the heating energy use. DOE-2 is run with and without the new function to predict the total yearly energy savings of the white-roofed Sacramento school bungalow.

METHODOLOGY

The function developed has four features which are distinct from the current DOE-2 model:

(1) adds radiative exchange between the attic's roof and ceiling,

(2) calculates an attic convection coefficient based on natural convection correlations,

(3) adds an option to modify roof and/or ceiling conductivity with temperature,

(4) adds an option to use an external convection coefficient correlation with a lower convection value than that currently used in DOE2.

The function uses response factors to calculate delayed heat loads through both the roof and ceiling of the attic structure. It is currently applicable to flat roofs with unvented attic spaces.

Radiative Exchange in the Attic

The DOE2 function splits the roof construction into two separate constructions as shown in Figure 1, the roof and the ceiling. Between the roof and ceiling is an air gap or attic space. Radiative exchange occurs in this gap according to the equation,

$$\varepsilon_{pp}\sigma(Tp^4 - Tn^4), \tag{1}$$

where,

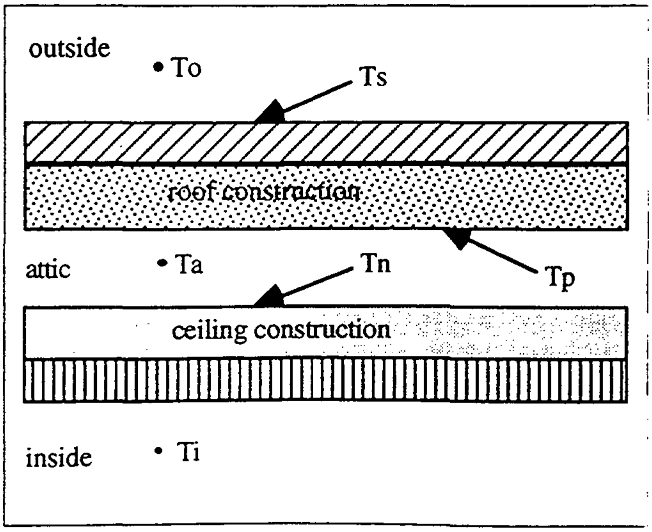
$$\varepsilon_{pp} = 1\Big/\left(\frac{1}{\varepsilon_n} + \frac{1}{\varepsilon_p} - 1\right). \tag{2}$$

The term ε_{pp} represents the effective emissivity for radiative exchange between two infinite parallel plates,[4] which in our case are assumed to be the upper side of the ceiling (surface n) and the lower side of the roof (surface p). Emissivities for common non-reflective materials in the attic space range between 0.9 and 0.95, making ε_{pp} lie typically between 0.82 and 0.90.

Attic Convection Coefficient

For the current version of this function, it is assumed there is no attic ventilation. Since the roof and ceiling are assumed to be flat, a natural convection coefficient correlation is used for a horizontal surface. The same correlation used in the

Figure 1. Designation of surface temperatures used in equations 1 through 4.



RBSOR model for a "nearly horizontal surface" (up to 2° in slope), is used here,[5] for a surface warmer than ambient conditions with Rayleigh numbers between 10^5 and 10^{11},

$$h_A = 0.58\ Ra^{0.2}(k/L), \tag{3}$$

where,

- Ra = *Rayleigh number* = GrPr,
- Gr = Grashof number = $B(Ta - Tn)L^3/v^2$,
- Pr = *Pandtl number* = $Cp\mu/k$.
- β = volume coefficient of expansion = $1/Ta$,
- L = characteristic length,
- v = kinematic viscosity,
- Cp = specific heat at constant pressure,
- μ = dynamic viscosity, and
- k = thermal conductivity.

This attic convection coefficient is highly dependent on the temperature difference between the attic air temperature and the surface temperature, (Ta-Tn). When radiative exchange in the attic is included in the model, the convection coefficient is not a very important term in the overall heat balance. When radiative exchange is not included, attic convection is of great importance.

Variation of Insulation Conductivity with Temperature

The conductivity of fiberglass insulation has been found to be temperature dependent according to the following equation:[6]

$$k_T = k_{70°F}[1 + 0.00418(T - 530)], \tag{4}$$

where T is the average insulation temperature in °R. An option in the roof-attic function is to multiply the response factors of either the roof or ceiling constructions, depending where the insulation is located, by $k_T/K_{70°F}$. This assumes that the temperature dependence can be accurately modeled by an equal change to each of the construction's response factors. The average insulation temperature is assumed to be the average of the surface temperatures on either side of the roof or ceiling construction.

External Convection Coefficient Correlation

An option in the roof-attic function is to use a lower convection value for the external film coefficient. DOE-2 currently calculates external convection for a horizontal surface using the equations:[7]

$$h_o = h_n + 1.67(h_f - h_n), \tag{5}$$

where 1.67 is the default correction value for surface roughness, h_n is the natural part of the convection coefficient,

$$h_n = 1.375|To - Ts|^{0.33}/6.238, \tag{6}$$

and h_f is the forced part of the convection coefficient on a horizontal surface,

$$h_f = 0.289\,Ws^{0.89}, \text{ for windward surface orientation,}$$
$$h_f = 0.391\,Ws^{0.614}, \text{ for leeward surface orientation,} \tag{7}$$

and Ws is the wind speed in knots and are in Btu/(hr ft² R).

The function's option to use a lower value of convection coefficient uses the same equations as in the RBSOR model:[8]

$$h_o = (h_f^3 + h_n^3)^{1/3}, \tag{8}$$

where h_n is the same natural convection coefficient from equation 3 with a temperature difference of (To-Ts) instead of (Ta-Tn), and h_f is the forced part of the convection coefficient,

$$h_f = 0.664\ \mathrm{Pr}^{1/3}\sqrt{\mathrm{Re}}, \text{ for Re} < 500{,}000,$$

$$h_f = \mathrm{Pr}^{1/3}(0.037\ \mathrm{Re}^{0.8} - 850), \text{ for Re} > 500{,}000, \tag{9}$$

and,

$$\mathrm{Re} = \text{Reynolds number} = WsL/v.$$

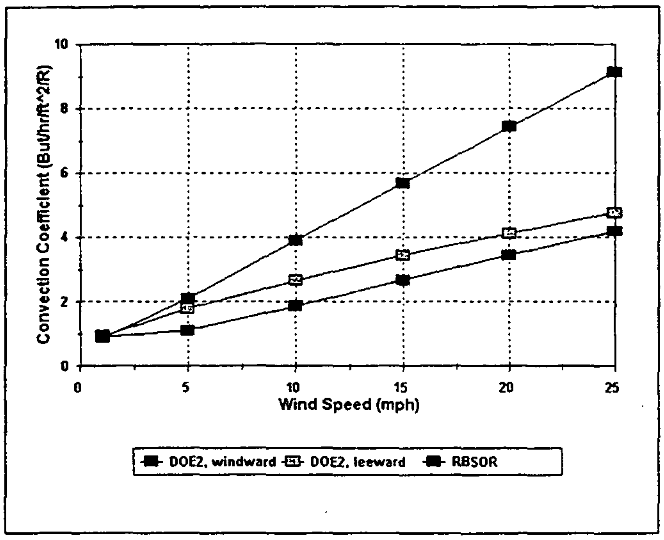
Figure 2 plots the DOE-2 and RBSOR convection coefficients versus wind speed. The RBSOR convection coefficients are about half the value of the DOE-2 windward coefficients.

Function Implementation in DOE2

The roof-attic function is called by DOE-2 as a "before" function in the ROOF command in the LOADS section of the program input. This inserts the function in the CALEXT subroutine just before the roof heat fluxes are calculated. To use the function properly, the entire roof and ceiling is modeled as a collection of layers, and then two separate "dummy" constructions are set up separately for the roof and ceiling. For example,

```
ROOF1 LAYERS
  MAT = (AR02,PW03,AL33,IN03,GP01) ..
DROOF LAYERS
  MAT = (AR02,PW03)
  INSIDE-FILM-RESISTANCE = 0.0 ..
```

Figure 2. Comparison of external convection coefficients calculated by DOE2 and RBSOR models. Calculations were made for ambient temperature of 85°F, surface temperature of 130°F, and characteristic length of 30 feet on a horizontal surface. The convection coefficients used in the RBSOR model are about half the value of the DOE2 windward coefficients.




```
DCEIL LAYERS
  MAT = (IN03,GP01) ..
ROOFCON = CONSTRUCTION
  LAYERS = ROOF1 ..
D-ROOF = CONSTRUCTION
  LAYERS = DROOF ..
D-CEIL = CONSTRUCTION
  LAYERS = DCEIL ..
```

The two "dummy" constructions are not called upon to be part of any room construction, but DOE-2 calculates their response factors. Note that the inside film resistance of the roof layer is set to zero for use with the function. These response factors are then used to solve heat balance equations for the roof and ceiling constructions.

The heat flow into the zone and the roof surface temperature, Ts, are sent back to subroutine CALEXT through the first response factors of the original roof and ceiling construction, X_0 and Y_0. By setting all other response factors of the original construction to zero, CALEXT calculates the surface temperature and heat flow from the relations,

$$T = [h_o To + \varepsilon_s \sigma (Tsky^4 - Ts_{i-1}^4) + (1 - \rho_s) Q_{sun} + X_1 T_i]/(h_o + X_1) \quad (10)$$

$$Q = Y_1 (T - Ti). \quad (11)$$

Comparison with Sacramento School Bungalow Data

Testing of a school bungalow building located in Sacramento was performed in 1992.[9] This building started with a metal roof, then the roof was successively painted brown and white. Cooling energy use and local weather conditions were monitored continuously during all three roof conditions. The data collected from this experiment are used to compare to the DOE-2 roof-attic function results to evaluate which options, or combinations of options, are most effective in predicting cooling energy.

The bungalow roof and ceiling construction consisted of a metal roof (of varying surface condition), backed by plywood and a layer of rigid R19 insulation, with a 2 foot air gap and a gypsum ceiling. It is modeled in DOE-2 by two dummy layers, one with the roof, plywood and insulation, and the other with the air gap and the ceiling material. It would have been preferable to leave the air gap out of the ceiling's dummy layer, but DOE-2 will not calculate response factors for a single material without layers.

Schedules for the bungalow's occupancy, internal temperature settings and appliance use and HVAC system information are detailed in previous work.[10]

RESULTS

To evaluate which components of the function were most effective in matching the Sacramento school bungalow data, the function was run using one of the following options at a time:

radiative transfer (ε_{pp} = 0.843 when on, ε_{pp} = 0.01 when off),
improved exterior convection correlation used from RBSOR,
insulation conductivity varied with temperature.

The attic convection correlation was not varied for this study, and no schedule or system parameters were changed.

Fan and cooling energy use results are shown in Figures 3, 4 and 5 for two days during each of the metal, brown and white roofed periods. Measured cooling energy from the test data is shown by the solid black line, and DOE-2 simulations without the function are shown by the black squares. Note that DOE-2 without the function under-predicts the energy use during both the metal and brown roofed periods, and over-predicts the energy use during the white period.

Increasing the insulation conductivity with temperature (conduction option shown by the hourglass symbol) has a negligi-

Figure 3. DOE2 simulation results for the Sacramento school bungalow in 1992 during Julian days 208 and 209, when the bungalow had a metal roof surface. Actual measured data are shown by the solid line. DOE2 results without the roof-attic function are shown, as well as results using the roof-attic function with only radiative exchange, only a lowered exterior film convection correlation, only enhanced insulation thermal conductivity with temperature, and with all radiative, convective and conduction changes.

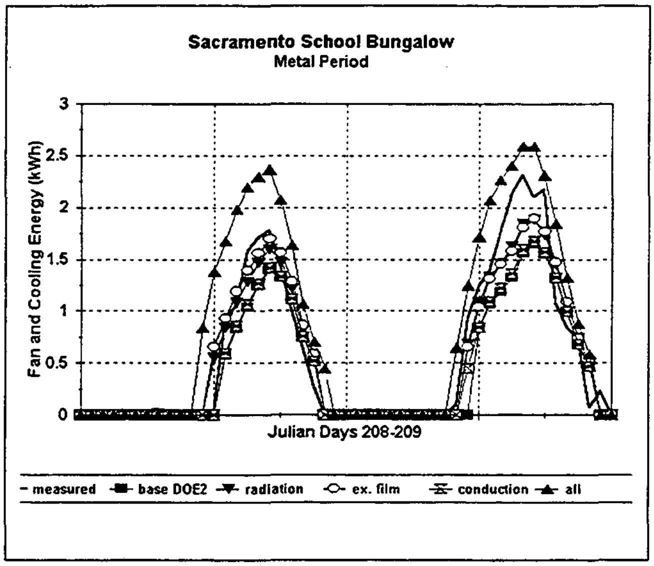
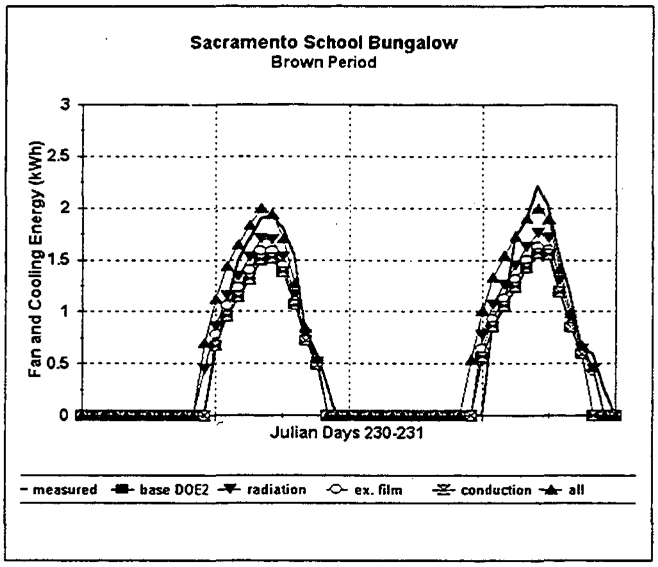


Figure 4. DOE2 simulation results for the Sacramento school bungalow in 1992 during Julian days 230 and 231, when the bungalow had a brown painted roof surface. Actual measured data are shown by the solid line. DOE2 results without the roof-attic function are shown, as well as results using the roof-attic function with only radiative exchange, only a lowered exterior film convection correlation, only enhanced insulation thermal conductivity with temperature, and with all radiative, convective and conductive changes.



ble effect in all three cases. The cooling energy use reported is for the entire building, so the effects of increased heat flux through the roof's insulation are diluted in this total value. Even though the conductivity increases by almost 20% for the brown roof, this increase appears to be offset by reductions in the temperature difference across the insulation. This result will be investigated further in future study.

Use of radiative heat transfer terms (shown by triangular symbols in Figures 3, 4 and 5) is significant during both the metal and brown roof periods, but makes little difference for the white roof. This is expected, since the white roof has a lower surface temperature, and hence a smaller attic temperature difference. Radiative heat flux increases with the fourth power of temperature, so the radiative term is more important for less reflective surfaces.

Use of the lower external film convection correlation (shown by circular symbols in Figures 3, 4 and 5) is also important for the metal and brown roofed periods, with little effect on the white roof. Decreases in film convection lead to increases in surface temperatures, which drives up the heat flux. This effect is minimal for the white roof, since its temperature is already fairly close to the ambient temperature and hence won't change much when external convection is reduced.

The convection coefficient (shown by hourglass symbols in Figures 3, 4 and 5) appears to have less effect during the brown period than the metal period. The metal roof has a lower emissivity than the brown roof. Emissivities estimated for use in DOE-2 were 0.30 and 0.95. The metal roof has more difficulty radiating to its surroundings, so the convection term is more important to the roof heat flux.

The metal roof's actual emissivity is likely to be quite different from the 0.30 estimate. Metal emissivities can vary with surface condition from 0.05, for a rather clean surface, to 0.50 for a dirty, oxidized or corroded surface. Non-metallic emissivities tend to stay between 0.90 to 0.95. Since the emissivities are most reliable for the brown and white surfaces, the function results for these cases are weighed more heavily in its evaluation.

The function results when radiation, convection and conduction changes are all used together turns out to be the most accurate simulation combination, shown by the triangular "all" symbols in Figures 3 through 5. This combination matches the brown roof results more closely yet doesn't greatly change the white roof results. The peak and total energy usages are generally over-predicted for the six days shown in these plots, although the peak is under-predicted for one day of the brown period.

Figure 5. DOE2 simulation results for the Sacramento school bungalow in 1992 during Julian days 268 and 269, when the bungalow had a white painted roof surface. Actual measured data are shown by the solid line. DOE2 results without the roof-attic function are shown, as well as results using the roof-attic function with only radiative exchange, only a lowered exterior film convection correlation, only enhanced insulation thermal conductivity with temperature, and with all radiative, convective and conductive changes.

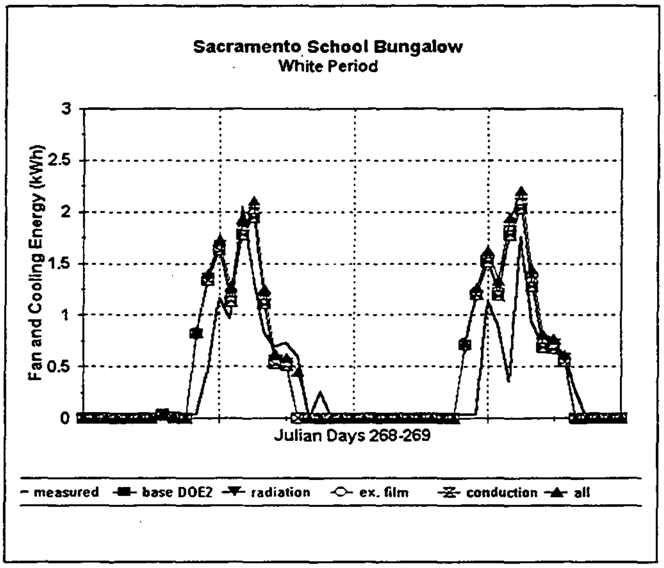
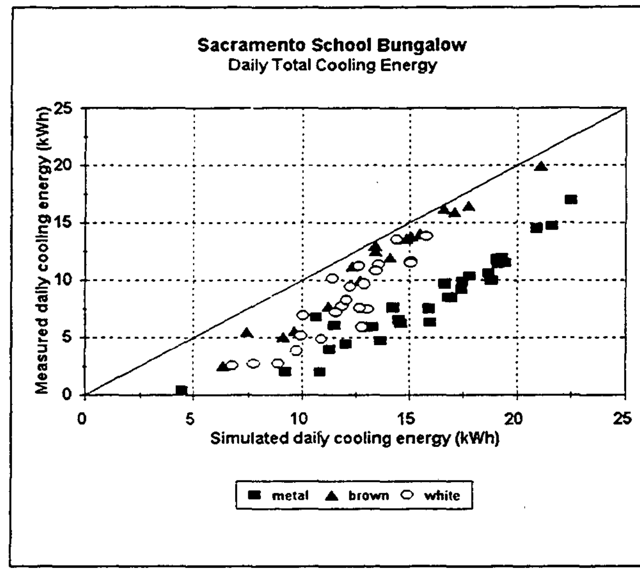


Figure 6. DOE2 simulated daily total cooling energy for the Sacramento school bungalow versus measured daily total cooling energy. The DOE2 simulation uses the roof-attic function with radiative, convective and conductive options in uses. Days with the metal, brown painted and white painted roof surfaces are identified with different symbols. The line from the bottom left corner to the top right corner represents the line where measured and simulated data are equal—the closer the data to this line, the better the simulation.



Figures 6 and 7 show the total energy use and peak demand values for all days during the 1992 study, with simulated values found using the function with radiative, convective and conductive changes. The simulated energy values versus the actual measured values are plotted for each day. The metal period's energy use is over-predicted by 5 to 7 kWh for the total energy use, and 0.5 to 1.5 kWh for the peak. This is most probably attributable to an inaccurate estimate of the metal surface's emissivity.

The daily total energy use of the white and brown surfaces is also over-predicted, but not as badly as for the metal surface. At low values, the daily total energy use of both brown and white roofs can be off by as much as 5 kWh, tightening to about 1 kWh at higher energy uses.

Referring to Figures 4 and 5, it can be seen that without using the roof-attic function the white roof energy use was being over-predicted and the brown roof was under -predicted, which meant the overall savings was being underestimated. With the function, the white and brown roof simulated results vary from the measured results according to the same linear relationship. This means the total savings predictions for a white roof versus a brown roof are much more accurate when the roof-attic function is used.

Peak energy values for the white and brown roofs are still quite unpredictable. The function tends to over-predict peaks for both roofs at high values and under-predict them at lower values. The brown roof peak prediction is more accurate. This seems reasonable given that a brown roof's higher surface temperature drives building peak loads more heavily than a white roof's.

Simulations were run for the Sacramento school bungalow for the entire year of 1992. Results of four different runs are reported in Table 1, for either a brown or white bungalow roof, with and without using the function. As expected, the cooling energy savings and the heating energy costs increase when the function is used. However, the overall yearly savings increases significantly from 122 kWh to 494 kWh—a fourfold increase. If these results are accurate, the current DOE2 simulations used to calculate energy savings are severely under-estimating the effectiveness of white roofs in saving energy.

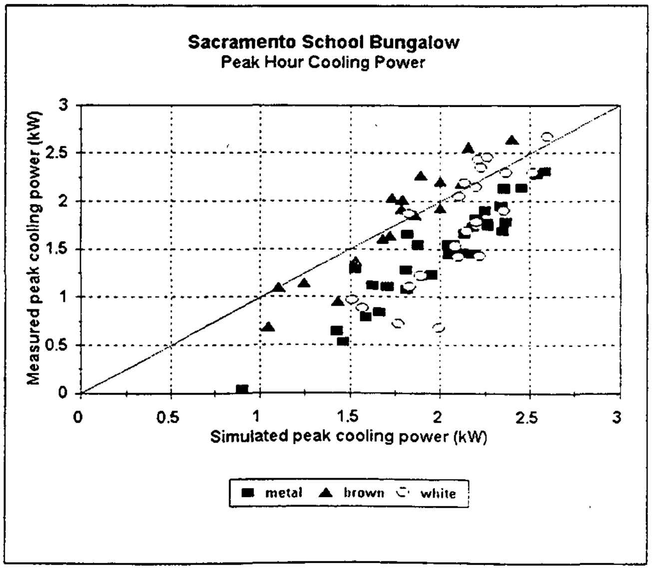
Clearly, more work is needed to fine tune the DOE2 roof-attic function. Better estimates of emissivity and exterior convection must be made. Emissivities can be found by measuring surface temperature concurrently with the long-wave energy emission from the surface. Long-wave emis-

Table 1. Results of 1992 Whole-Year DOE2 Simulations for the Sacramento School Bungalow

		Fan & Cooling Energy (kWh)	Heating Energy (kWh)	Overall Savings (kWh)
without function	brown roof	1943	2192	
	white roof	1776	2237	
	savings	+167	−45	+122
with function	brown roof	2750	2325	
	white roof	2108	2473	
	savings	+642	−148	+494

sions are measured using a pyrgeometer with a filter to block out all but the long-wave portion of the spectrum. Convection correlations can be checked by intensive study of wind speed, solar insolation and surface absorptivities and emissivities on the temperatures of various surfaces. In addition, year-round measurements need to be compared with function results to test the function's accuracy during different seasons.

Figure 7. DOE2 simulated daily peak cooling energy for the Sacramento school bungalow versus measured daily peak cooling energy. The DOE2 simulation uses the roof-attic function with radiative, convective and conductive options in uses. Days with the metal, brown painted and white painted roof surfaces are identified with different symbols. The line from the bottom left corner to the top right corner represents the line where measured and simulated data are equal—the closer the data to this line, the better the simulation.



CONCLUSIONS

The roof-attic function improves the accuracy of DOE2 in modeling the effects of high albedo roofing. The improvements are due to the function's increase of the low albedo roof's energy use estimates, while the high albedo roof energy use stays at the same level. The function enables DOE2 to account for radiative transfer and natural convection in the attic, increases in insulation conductivity with temperature, and a lower convection coefficient on the exterior surface.

The function still over-predicts the daily energy use of both high and low albedo roofs. Since the function over-predicts these energy uses by approximately the same amount, the overall energy savings can be predicted much more accurately. Cautiously stated, the yearly energy savings of a white roof may be as much as four times higher than is currently predicted by DOE2.

More work is needed to fine tune the function. Most pressing is the need for accurate emissivity measurement and external convection correlation development. Further investigation is needed on the effects of attic convection and the temperature dependency of the insulation. The function must also be matched to year-round data to judge the accuracy of its seasonal effects. Also, the function should be expanded to model sloping roofs, more complex attic geometries, and attic ventilation.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, U.S. Department of Energy, under contract No. DE-AC0376SF00098. The authors also wish to acknowledge the many developers of the DOE2 building energy model, past and present, the Sacramento Municipal Utility District for their pioneering effort in promotion and installation of high albedo roofs, and the work of previous Heat Island Group members in support of this effort.

ENDNOTES

1. Akbari et al., 1993; Akbari, Fishman and Frohnsdorff, 1994.
2. Akbari et al., 1993.
3. Wilkes, 1991.
4. Siegel and Howell, 1981.
5. Holman, 1981, p. 272-286.
6. Wilkes, 1981.
7. Winkelmann et al., 1993.
8. Holman, 1981, p. 201-202.
9. Akbari et al., 1992; Akbari et al., 1993.
10. Akbari, 1993.

REFERENCES

Akbari, H., S.E. Bretz, J.W. Hanford, D.M. Kurn, B.L. Fishman, H.G. Taha, and W. Bos. 1993. *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations and Results*. LBL-34411. Berkeley, Cal.: Lawrence Berkeley Laboratory.

Akbari, H., S.E. Bretz, J.W. Hanford, A. Rosenfeld, D. Sailor, H. Taha, and W. Bos. 1992. *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Project Design and Preliminary Results*. LBL-33342. Berkeley, Cal.: Lawrence Berkeley Laboratory.

Akbari, H., B. Fishman and G. Frohnsdorff. 1994. *Proceedings of the Workshop on Cool Building Materials*. LBL-35514. Berkeley, Cal.: Lawrence Berkeley Laboratory.

Holman, J.P. 1981. *Heat Transfer*. 5th ed. New York: McGraw-Hill Book Company.

Siegel, R. and J.R. Howell. 1981. *Thermal Radiation Heat Transfer*. 2nd ed. New York: Hemisphere Publishing Corporation.

Wilkes, K.E. 1981. "Thermophysical Properties Data Base Activities at Owens-Corning Fiberglas." *Proceedings of the ASHRAE/DOE ORNL Conference*. ASHRAE SP 28: 662-77.

Wilkes, K.E. 1991. *Thermal Model of Attic Systems with Radiant Barriers*. ORNL/CON-262. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Winkelmann, F.E., B.E. Birdsall, W.F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch and S. Gates. 1993a. *DOE-2 BDL Summary, Version 2.1 E*. LBL-34946. Berkeley, Cal.: Lawrence Berkeley Laboratory.

Winkelmann, F.E., B.E. Birdsall, W.F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch and S. Gates. 1993b. *DOE-2 Supplement Version 2.1 E*. LBL-34947. Berkeley, Cal.: Lawrence Berkeley Laboratory.

York, D.A. and C.C. Cappiello. 1981. *DOE-2 Engineers Manual, Version 2.1A*. LBL-11353. Berkeley, Cal.: Lawrence Berkeley Laboratory.

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098