

The effects of roof albedo modification on cooling loads of scale model residences in Tucson, Arizona

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Abstract

Data supporting reductions in cooling load and related demand for electric power possible from increasing building surface albedo are limited. Electrical use of wall-mounted air conditioners, roof temperatures, and related environmental factors were monitored during the summer of 1990 on three initially identical 1/4-scale model buildings situated in rock mulch landscapes in Tucson, Arizona. Model thermodynamic properties were scaled to approximate thermodynamic similarity with full-size buildings. With ceiling insulation of R value $5.28 \text{ m}^2 \text{ K W}^{-1}$ (R-30) installed, increasing roof albedo of the gray composition shingles (0.30 albedo, 0.94 emissivity) by painting one roof silver and another white (0.49 and 0.75 albedos, 0.70 and 0.98 emissivities, respectively) reduced daily total and hourly peak electrical use for air conditioning approximately 5% for the house with white-colored roof compared to either gray or silver-colored roofs. Larger differences were found without ceiling insulation, with daily total and peak hourly demand for houses with white compared to dark brown roofing (0.9 albedo, 0.98 emissivity) reduced 28 and 18%, respectively. Computer simulations of daily total energy use confirmed comparable savings for similar full-sized buildings. White roofs were 20 to 30°C cooler than either silver or dark-colored roofs on hot, sunny days, indicating that expected cooling due to an increase in albedo may not be realized if it is accompanied by a decrease in emissivity. Light-colored roofs, by maintaining cooler attic temperatures, may provide savings in addition to those presented here by reducing heat gain to air distribution systems located in the attic space.

Keywords: Roof albedo; Scale model residences; Roof color; Computer simulation; Arizona

1. Introduction

Microclimate around a building is determined by solar radiation (direct, diffuse, and reflected), net long wave (terrestrial) radiation between a structure and its surroundings, air temperature, relative humidity, and wind speed. These parameters directly influence primary heat transfer paths between the building and the environment: conduction through walls, roof, doors (opaque conduction), and windows (glazed conduction); solar radiation through windows (glazed solar); and sensible and latent heat gain from air leakage (infiltration). Internal gain from sources such as people, lights, and electrical appliances is also important.

Increasing a building's albedo, or reflection coefficient, defined as reflectivity weighted by the spectral energy distribution and integrated over the solar spectrum [1], will reduce opaque conduction due to diminished net solar radiation at the surface. In particular, use of light-colored roofing materials has been shown qualitatively to have the potential for reducing solar heat gain and hence air-conditioning cooling load [2]. The potential benefit of color changes will be par-

tially dependent upon the amount of roof insulation installed, with uninsulated surfaces having the largest potential for energy savings. Bansal et al. [3] performed experiments and simulations on model buildings which illustrated how exterior building color, thermal mass, ventilation, and shading can influence interior air temperature. Griggs and Shipp [4] found ~65% reduction in heat flux through a white compared to black roof section with thermal resistance of $1.32 \text{ m}^2 \text{ K W}^{-1}$ (nominal insulation of R-7.5). Anderson [5] found similar reductions for a flat concrete roof on a simple single room building using simulations. Anderson et al. [6] found simulated roof cooling loads reduced from 65 to 93% for a range of climates and roof thermal resistance values.

Reagan and Acklam [7] calculated total building heat gain reductions due to an increase in roof albedo from 0.35 to 0.75 with the total equivalent temperature differential approach. They found 6.4 and 4.8% reductions in heat gain for a July day in Tucson, Arizona, for houses with ceiling thermal resistances of 2.50 (R-11) and $5.88 \text{ m}^2 \text{ K W}^{-1}$ (R-30), respectively. Wall thermal resistances for the former were 0.34 m^2

K W^{-1} (R-0), and $1.75 \text{ m}^2 \text{ K W}^{-1}$ (R-8) for the latter. Taha et al. [8] simulated building cooling load reduction of 18.9% for four July days in Sacramento, California, for an albedo increase of both roof and walls from 0.30 to 0.90. Ceiling and wall thermal resistances were 5.28 (R-30) and $3.35 \text{ m}^2 \text{ K W}^{-1}$ (R-19), respectively.

Akbari et al. [9] reported measured cooling energy consumption for two school bungalows in Sacramento with ceiling and wall thermal resistances of 3.35 (R-19) and $1.94 \text{ m}^2 \text{ K W}^{-1}$ (R-11), respectively. After an initial comparison period during which metal roofs were unpainted and walls painted yellow, the roof and south east facing wall of one was painted brown, and then white. The white bungalow used 40 to 50% less energy than the others; peak savings were on the order of 30 to 40%. Energy use simulations calibrated with the measured data gave similar but somewhat smaller savings. Parker et al. [10,11] performed measurements of summer cooling energy savings in Florida before and after installation of reflective roof coatings. Albedos before treatment ranged from 0.08 to 0.31, and from 0.61 to 0.73 afterwards. Average reduction in air-conditioning energy use ranged from 11 to 43%, with larger savings associated with no ceiling insulation.

The objectives of this research were to measure actual cooling load and roof temperature reductions resulting from increased roof albedo, both with and without ceiling insulation, using scale model houses in Tucson, Arizona.

2. Methods

This study was performed using three 1/4-scale model houses (referred to as Houses 1, 2 and 3) located at the University of Arizona Campus Agricultural Center. Models were built in spring 1987 with similar plans and materials and the same contractor. Descriptions of building construction, experimental design, and data acquisition procedures described in McPherson et al. [12] apply to the current study so only salient points or differences from those reported there will be described here.

Models were designed to be thermodynamically similar to full-sized buildings to maximize transferability of model results. Dimensional analysis revealed that structural components (e.g. use of 2×4 inch stud walls) could be the same as for a typical full-sized frame house, if inside thermal mass was scaled down in proportion to the ratio of model/house surface area $(1/4)^2$ instead of volume $(1/4)^3$. Structural components could be the same since both thermal conductivity and heat capacity of walls and roof were found to be proportional to the ratio of model/house wall thickness. The choice of a 1:1 ratio of wall thickness allowed conductivity and heat capacity to be the same.

Interior thermal mass added to each building compensated for effects of increased surface area to volume ratio of scale model compared to full-sized buildings. Since linear building dimensions were scaled down from full size by a factor of

1/4, surface areas decreased by 1/16, and volume by 1/64. As a result, the surface area available for conducting heat increased relative to the interior volume to be warmed by a factor of 4 for the scale model buildings. Hence, decreasing internal thermal mass by a factor of $(1/4)^2$ instead of $(1/4)^3$ maintained proportionality between the surface area for heat conduction and interior thermal mass. Interior heat capacity of a typical full-sized house was estimated to be 12.8 MJ K^{-1} based on the mass and specific heat of typical materials such as walls, furniture and appliances. This was scaled to 0.8 MJ K^{-1} , and added to model buildings using fifty evenly-spaced 3.8 l plastic containers filled with water.

Heat gain/loss simulations similar to those done by Reagan and Acklam [7] were performed to confirm thermodynamic similarity of models used here, and hence applicability of present results, to full-sized buildings. A single 100 W light bulb used to represent internal gain from lights, appliances and people resulted in internal gain being $\sim 20\%$ of total heat gain for model buildings. Scaling the $\sim 800 \text{ W}$ internal gain for a typical residential building with four occupants [13] by the thermal mass factor $(1/4)^2$ gives 50 W. The larger value (100 W) was used so that internal gain for the models would be closer to the percentage of total heat gain found by Reagan and Acklam [7] of 20 to 35%.

Identical air-conditioning units, Emerson Quiet Kool model number 8LJ9H with 2.34 kW (8000 Btu h^{-1}) cooling capacity and nominal COP (coefficient of performance) of 2.1 (energy efficiency ratio of 7.2), were used. Units were obtained new in 1987 and had similar operating histories. Electrical loads consisted of the air conditioner fan and compressor, plus a single 100 W light bulb representing internal gains from lights, appliances and people. Total electrical use was monitored continuously, and recorded at 15 min intervals, by recording kWh meters on each building supplied and operated by Tucson Electric Power Company. The fan operating by itself consumed very nearly 100 W of power, so that air-conditioning electrical use for each day was found by subtracting the base load of 4.8 kWh (e.g. $200 \text{ W} \times 24 \text{ h}$) from the total electrical use for that day. Cooling load was found by multiplying this result by the COP. In this paper, daily values are reported for air-conditioning electrical use, and hourly values for total electrical use. Hourly electrical use for air conditioning can be found by subtracting the base load of 0.2 kW. Fan and light power consumption was confirmed periodically throughout the experiment by selectively turning off all other loads but the one being tested, and noting kWh meter readings.

Initial, baseline comparisons of building energy use were made June 11–17, 1990 (Table 1). Buildings were configured identically, with gray composition shingle roofs and R-30 ceiling insulation (composite R values of 0.56 and $5.28 \text{ m}^2 \text{ K W}^{-1}$ respectively). Walls (R value of $2.04 \text{ m}^2 \text{ K W}^{-1}$) were painted the same light gray, and surroundings covered with identical rock mulch. Data from this period were used to (i) confirm similarity between the three scale model buildings, and (ii) to adjust later treatment results to reduce

Table 1
Treatment summary

Name	Dates	Treatment					
		House 1 Roof color	Ceiling insulation	House 2 Roof color	Ceiling insulation	House 3 Roof color	Ceiling insulation
Baseline comparisons	6/11-17	gray	R-30	gray	R-30	gray	R-30
R-30 Trials	6/21-7/12	silver	R-30	white	R-30	gray	R-30
	7/13-20	white	R-30	white	R-30	gray	R-30
R-30/R-0 comparisons	7/21-8/3	white	R-0	white	R-30	gray	R-30
	8/4-8/18	white	R-0	white	R-30	brown	R-30
R-0 Trial	8/19-9/27	white	R-0	white	R-0	brown	R-0

variability from possible differences in air conditioner performance, building construction (e.g. air leakage rate), and/or microclimate between treatments.

Following baseline comparisons, effects of contrasting roof colors on building cooling load were evaluated, first with and then without R-30 ceiling insulation installed. From June 21 to July 20 (subsequently referred to as the R-30 trial period, Table 1), white¹ and silver² coatings were applied to roofs of Houses 1 and 2; House 3 was left unchanged (gray roof) as a control. The same white coating was applied to the roof of House 1, July 13, allowing comparisons between two white-roofed houses until July 20. On July 21, ceiling insulation was removed from House 1, and comparisons between insulated and uninsulated ceilings continued until August 18. On August 4, the roof of House 3 was changed from gray to dark brown³. From August 19 to September 27 (denoted the R-0 trial period), ceiling insulation was removed from all buildings. The resulting combination of two white-roofed (Houses 1 and 2) and one dark brown-roofed (House 3) buildings with no ceiling insulation maximized heat gain differences due to roof color contrast. Treatments will subsequently be referred to by their roof color and ceiling insulation value.

Additional measurements were made of inside and outside air temperatures, roof surface temperatures, solar radiation, ground surface albedo, net radiation and related environmental parameters as described in Ref. [12]. Albedos for various surfaces were based on simultaneous measurements of reflected solar radiation measured directly over each roof or ground surface and incoming solar radiation. A downward looking radiometer (Weathertronics model 3020) was positioned from 0.41 to 0.45 m directly above the high point of each roof (peak) in turn, 0.6 m from the gable end.

Roof temperature was measured with type T (copper–constantan, 0.4 mm diameter) thermocouples. A small

amount of clear silicon rubber caulk was applied to the soldered thermocouple junctions, which were placed on the roof and taped temporarily. After a minimum of 24 h had elapsed, tape was removed leaving the junction in close contact with the roof with minimum protuberance. Leads were kept flat against the roof in the vicinity of the junction by insertion beneath a shingle tab. Occasional surface temperature measurements of building walls and roofs were taken manually using a hand-held infrared thermometer (IRT; Everest Inter-science Model 112, 15° field of view) oriented within 20° of the surface normal; periodic calibration checks were done with a calibration source of known emissivity (Everest Inter-science Model 1000).

Temperatures and other environmental data were sampled continuously at 30 s intervals and stored as 30 min averages. Inside and outside air temperatures were not recorded from August 18 to September 3 during the R-0 trial as a result of heavy precipitation and flooding. Additional weather data, including air temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation were available on an hourly basis from an Arizona Meteorological network (AZMET) station located 360 m east of the site [14]. Suitability of using AZMET data to characterize site conditions was tested by simultaneous measurements at both locations [12]. All data were subsequently averaged or totalized, as appropriate, on an hourly basis, unless otherwise stated. Where results are expressed as (Value $\pm$ N), N is the population standard deviation. Peak hourly energy use is defined as the maximum energy use for any given hour in a 24-hour period.

3. Results and discussion

3.1. Weather

Weather ranged from strong high pressure (dry, hot, clear skies and west winds) to monsoon (higher humidity, hot, partly cloudy skies, south to east winds and occasional precipitation) conditions. These data are summarized in Figs. 1 and 2, which give average air temperature, relative humidity

¹ Kool-Kote white elastomeric mastic roof coating, Southwestern Paint and Varnish Co., Tucson, Arizona.

² Black Jack fibered aluminum roof coating, standard grade, BT-5175-5/88-1G, The Gibson-Homans Co., 1755 Enterprise Parkway, Twinsburg, OH 44087. Meets specifications TT-C-498C ASTM D2824, Type II.

³ Acrylic-Epoxy Rustic exterior finish, Dark Brown 802, Southwestern Paint and Varnish Co., Tucson, AZ 85716.

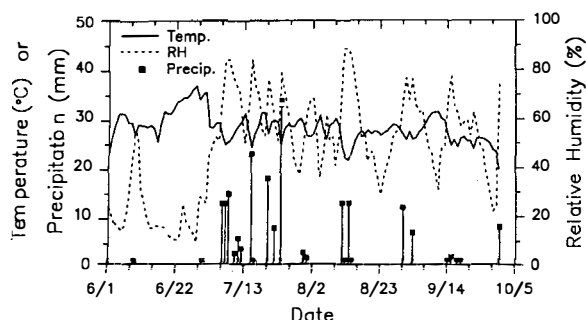


Fig. 1. Daily average air temperature, relative humidity (RH) and daily total precipitation for June–September, 1990, at the Campus Agricultural Center AZMET weather station.

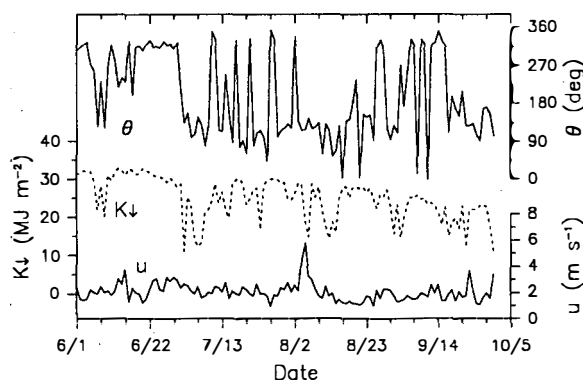


Fig. 2. Daily average wind speed (u), vector wind direction (θ) and total solar radiation ($K\downarrow$) for June–September, 1990, at the Campus Agricultural Center AZMET weather station.

and wind speed, wind direction, total solar radiation, and precipitation on a daily basis from June through September, 1990. Onset of monsoon conditions near the beginning of July were characterized by dramatic changes in wind direction and relative humidity. Precipitation from thunderstorms coincided with reduced solar insolation.

3.2. Roof and ground albedo

Ground albedo (a_{ground}) was determined directly from measured values, since the rock mulch was sufficiently large in extent to be considered an infinite plane. Due to the finite extent of roofs, however, and the need to position radiometers far enough from roofs to prevent the area shaded by the instrument from becoming too large a portion of its field of view, inverted pyranometers received reflected radiation from the surrounding ground as well as roof surface. To correct for this, view factors of the radiometer for each roof (F) were used to correct roof albedo using the expression [15]:

$$a_{\text{roof}} = 1/F[a_{\text{measured}} + (1-F)a_{\text{ground}}] \quad (1)$$

where a_{roof} is corrected roof albedo and a_{measured} is roof albedo calculated directly from measurements. The view (configuration) factor was determined from an expression for a differential planar element (the radiometer) with respect to four coplanar rectangles where the normal to the element passes

Table 2

Calculated values of surface long wave emissivity and short wave albedo. Corrected roof albedos were determined from uncorrected albedos as described in text

Roof Treatment	Emissivity	Uncorrected albedo	Corrected albedo
Gray composition	0.94	0.28	0.30
White coating	0.98	0.63	0.75
Silver coating	0.70	0.43	0.49
Brown coating	0.98	0.11	0.09
Rock ground cover		0.20	0.20

through the common corner of each rectangle ([16], factor B-3). Since the two halves of the roof make an angle of 12° with the horizontal, view factors for horizontal planes located at eave and peak height were averaged to get the final result. No attempt was made to account for the effect of ground shading by the building on a_{roof} . The largest difference between corrected and uncorrected albedos at the two heights was for the white roof, which had the largest albedo contrast with respect to the ground. Values of 0.70 and 0.80 were found for a planar roof at peak and eave height, respectively, with an average value of 0.75 (Table 2).

3.3. Roof emissivity

Roof emissivity (ϵ) was estimated from simultaneous measurements of surface mounted thermocouples (T_{roof}) and hand-held infrared thermometer (T_{IRT}) from the expression

$$\epsilon = \frac{T_{\text{IRT}}^4 - 0.38\epsilon_{\text{sky}}T_{\text{air}}^4}{T_{\text{roof}}^4 - 0.38\epsilon_{\text{sky}}T_{\text{air}}^4} \quad (2)$$

where $0.38\epsilon_{\text{sky}}T_{\text{air}}^4$ is a correction for atmospheric long wave radiation reflected from the roof. The factor 0.38 represents the fraction of atmospheric radiation in the $8\text{--}14\text{ }\mu\text{m}$ bandpass of the IRT filter at 30°C , and ϵ_{sky} is an effective emissivity (~ 0.75 here) which allows estimation of atmospheric long wave radiation from air temperature [17]. Resulting roof emissivities of white-painted, brown-painted and gray composition-shingled roofs were similar (Table 2). The low emissivity of the silver roof coating is probably due to presence of aluminum powder pigment, for which published emissivities range from 0.27 to 0.67 [18].

3.4. Temperatures

Inside air temperatures of all houses were nearly constant with air conditioners operating, and lagged air temperature when they were not (Fig. 3). Agreement between buildings was good during the baseline period, both with and without air conditioners operating (Fig. 4). Average temperatures for the baseline period were 23.9 ± 0.3 , 24.4 ± 0.3 and $24.1 \pm 0.4^\circ\text{C}$ for Houses 1 to 3, respectively, with air conditioners operating (temperature sensor accuracy was $\pm 0.2^\circ\text{C}$). With air conditioners not operating (June 18–20),

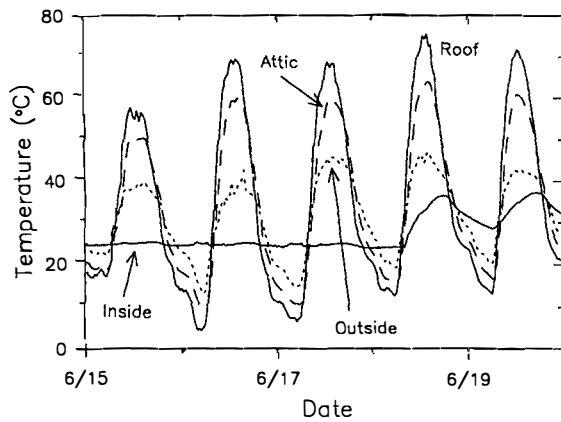


Fig. 3. Typical inside and outside air, roof and attic temperature for scale model buildings during baseline comparison period. Data is for House 1; data for Houses 2 and 3 appears virtually identical. Air conditioner was switched off 0800 6/18. Dates for Figs. 4 to 9 indicate 2400 hours.

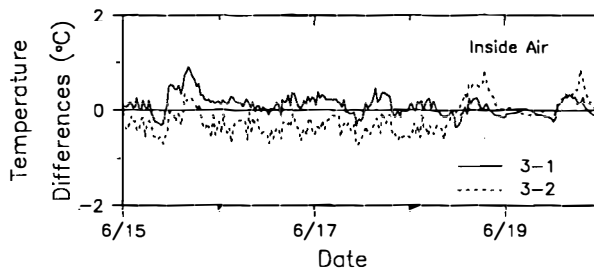


Fig. 4. Differences in inside air temperature for House 3—House 1 and House 3—House 2 during the baseline comparison period. Air conditioners were switched off 0800 6/18.

average values of inside air temperature differences agreed to within $0.1 \pm 0.3^\circ\text{C}$ for all houses. Shade from an ~ 3 m high greenhouse ~ 10 m north of Houses 2 and 3 reached House 2 first in the late afternoon, reducing its interior temperature relative to Houses 1 and 3 near 1900 h when air conditioners were not operating (Fig. 4).

During the R-30 trial, hourly averaged inside temperatures were virtually unchanged by roof color alterations, being 23.9 ± 0.3 , 24.3 ± 0.3 and $24.0 \pm 0.5^\circ\text{C}$ for gray, white, and silver treatments, respectively. During the R-0 trial, these figures were 24.1 ± 0.6 , 24.6 ± 0.6 , and $24.9 \pm 1.3^\circ\text{C}$, for the two white and one brown treatment, respectively. Standard deviations tended to be somewhat smaller when daylight data only were considered. The slightly higher overall interior temperatures during the R-0 trial are not surprising, given the fact that ceiling insulation had been removed. Air conditioners never exceeded $\sim 72\%$ of their rated capacity in any one hour period. (A 1 kW peak load minus 0.2 kW base load gives peak air conditioner electrical use of 0.8 kW, which when multiplied by the COP of 2.11 gives a cooling load of 1.7 kW, 72% of the units 2.34 kW rated capacity.)

Outside air temperature ranged from daily minimums of $12\text{--}21^\circ\text{C}$ and maximums of $39\text{--}45^\circ\text{C}$ during the baseline period (Fig. 3). Daily average differences for each treatment agreed to within $0.2 \pm 0.7^\circ\text{C}$ except on June 16 when House 3 averaged $0.4 \pm 0.8^\circ\text{C}$ warmer than House 1 (Fig. 5). Maximum temperature difference was $\pm 2.5^\circ\text{C}$, but as the value

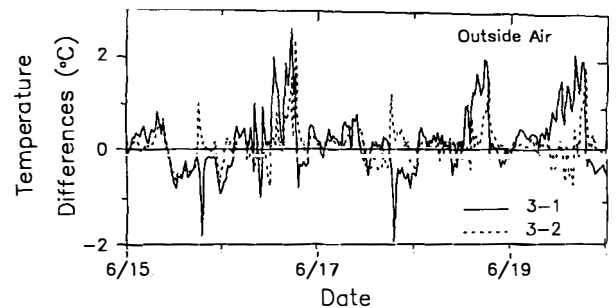


Fig. 5. Differences in outside air temperature between Houses 3 and 1 and Houses 3 and 2 during the baseline comparison period.

of standard deviation suggests differences of this size were infrequent. Each day at approximately 1900 h outside temperature at House 1 was $\sim 2^\circ\text{C}$ greater than the others for 30 to 60 min, apparently due to the previously-described afternoon shading of Houses 2 and 3. AZMET air temperature minimums were within 0.4°C of building air temperatures, but maximums were $\sim 6^\circ\text{C}$ cooler. This is not surprising, given that AZMET temperatures are measured at 1.5 m over irrigated turf, and building air temperatures at 0.7 m over rock mulch.

After roof colors were changed for the R-30 trial, outside air temperatures appeared to be slightly higher for the darker (and warmer roofs) compared to the white treatment(s), possibly due to the placement of the outside air temperature sensors under the eaves. Overall agreement was good, with differences between House 3 and Houses 1 and 2 being $0.1 \pm 0.6^\circ\text{C}$ during the baseline period, $0.5 \pm 0.7^\circ\text{C}$ for the R-30 trial, and $0.8 \pm 0.6^\circ\text{C}$ for the R-0 trial, regardless of roof color.

3.4.1. Roof temperatures

Temperatures of gray composition-shingled roofs were wide ranging during the baseline period, from minimums of $3\text{--}16^\circ\text{C}$ to maximums of $58\text{--}75^\circ\text{C}$ (Fig. 3). Minimums were $7\text{--}9^\circ\text{C}$ less than air temperature, while maximums were $19\text{--}31^\circ\text{C}$ greater. Given these temperature extremes, agreement between treatments was good (Fig. 6), with half-hourly average roof temperature differences being -0.2 ± 1.1 ,

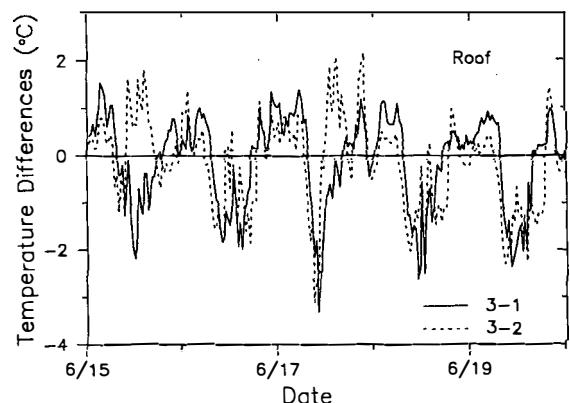


Fig. 6. Differences in roof temperature between Houses 3 and 1 and Houses 3 and 2 during the baseline comparison period.

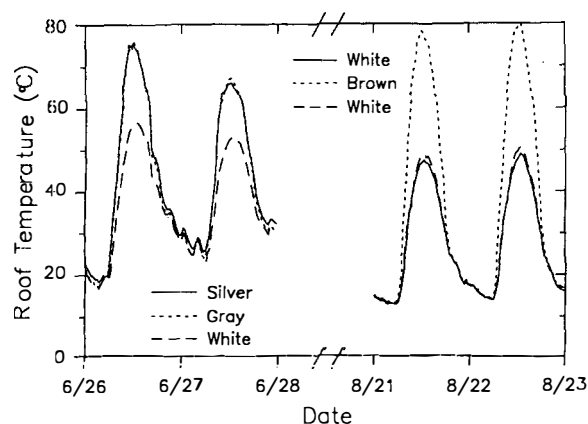


Fig. 7. Measured roof temperatures for silver, white, gray and brown roofs for portions of the baseline and R-30 trial periods, showing the effects of roof color changes.

-0.3 ± 1.0 , and $0.1 \pm 0.8^\circ\text{C}$ for Houses 3–1, 3–2, and 2–1, respectively. Differences as large as 3°C developed at mid-day, with House 3 tending to have the cooler roof. Temperature differences at night tended to be opposite in sign to daytime differences, leading to the near zero average values of the differences. Radiational cooling and calm winds were apparently responsible for the roofs cooling below air temperature at night. Variation in maximum differences during daylight hours appeared to be correlated with wind speed differences. Solar radiation was quite similar on all days (Fig. 2) with the possible exception of June 15, which had partly cloudy periods.

White roofs were up to 20°C cooler than either silver or gray roofs, and up to 30°C cooler than brown (Fig. 7). Temperatures of silver and gray roofs were similar, with gray averaging $0.4 \pm 1.3^\circ\text{C}$ warmer than silver. It appears that the cooling effect expected due to the silver roof's larger albedo in comparison to the gray roof was compensated for by the silver roof's reduced emissivity. So, while the silver roof absorbed less solar radiation than the gray roof, it was a less efficient re-radiator of the heat that was absorbed, and thus there was little net cooling of the silver-colored surface. This results in the somewhat counter-intuitive observation that a reflective silver roof may be warmer than a much darker-colored roof, depending on the values of their respective emissivities.

3.4.2. Attic temperatures

During the baseline period, attic temperatures ranged from minimums of $8\text{--}18^\circ\text{C}$ to maximums of $51\text{--}62^\circ\text{C}$. Minimums were $2\text{--}4^\circ\text{C}$ less than air temperature, and maximums $12\text{--}20^\circ\text{C}$ greater (Fig. 3). Attic temperatures tended to be higher relative to roof temperatures during the R-30 compared to the R-0 trial due to the large amount of ceiling insulation between the attic and interior conditioned space (Fig. 8). When ceiling insulation was removed, cooling of the attic from the interior conditioned space was greatly enhanced.

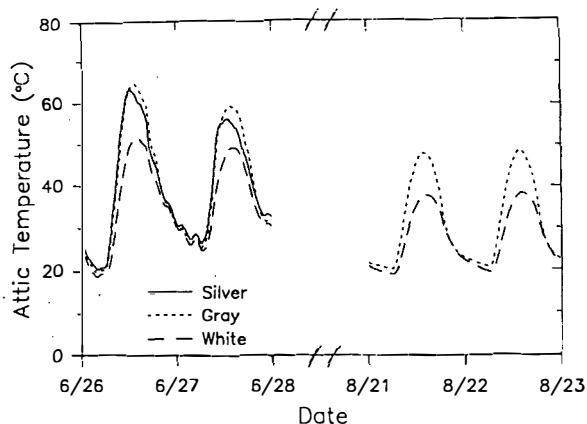


Fig. 8. Measured attic temperatures for silver, white, gray and brown roofs for portions of the baseline and R-30 trial periods, showing the effects of roof color changes.

3.5. Baseline electrical loads

Electricity use during the baseline comparison period ranged from peak hourly values of 0.38 to 0.59 kW and daily totals of 4.2 to 6.6 kWh . Daily energy use for House 2 was consistently greater than for Houses 1 and 3, by $1\text{--}8\%$ and $6\text{--}17\%$, respectively. Similar relationships were noted for peak hourly values, with House 2 being $6\text{--}11\%$ and $10\text{--}17\%$ higher than Houses 1 and 3, respectively. This was ascribed to possible differences in air conditioner performance, building construction and/or thermal environment between treatments. Regression analysis was used to remove these differences by adjusting hourly energy consumption for Houses 1 and 2 to agree with House 3 during the baseline period. Reasonable fit (standard error less than 15 W) was found using quadratic regressions with House 3 as dependent variable and either House 1 or 2 as independent variable. Corrected daily total electrical use between buildings agreed to within $2.0 \pm 1.3\%$, illustrated by plotting daily totals and differences between houses (Fig. 9(a) and (b), June 11–17; plots of corrected peak energy use were similar). All subsequent electrical use calculations are subject to these corrections. Choice of the reference house (House 3) was not critical here, since differences in energy use, not absolute values, were of primary concern in this study.

Two other periods occurred during which two of the three buildings (Houses 1 and 2) were configured identically, one with white roofs and R-30 insulation (July 13–20, Fig. 9), and the other with white roofs and no insulation (August 19 to September 27, Fig. 10). Daily total electrical use agreement between treatments for these two periods were $2.3 \pm 1.8\%$ and $-0.4 \pm 2.2\%$, respectively, using the above correction, which confirmed the similarity of building energy use over time.

3.6. Air-conditioning electrical load: R-30 ceiling insulation

Daily total energy use during the R-30 trial ranged from approximately 3 to 9 kWh (Fig. 9(a)). Gray and silver treat-

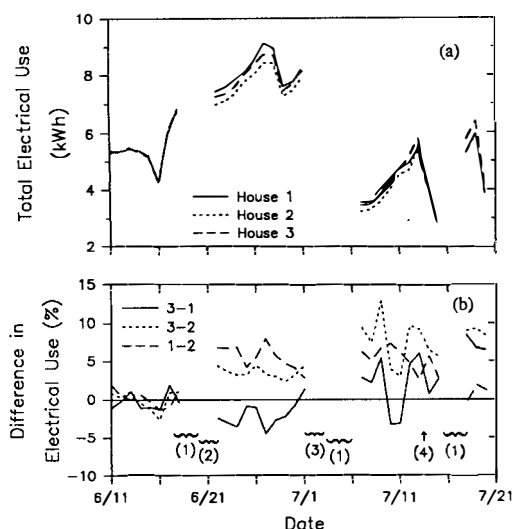


Fig. 9. Electrical use for baseline and R-30 trials. (a) Daily totals; (b) percent differences in air conditioning between houses. Numbers in parentheses are: (1), Air conditioners off; (2), Roofs 1 and 2 painted silver and white; (3), Lights off; (4), Roof 1 painted white.

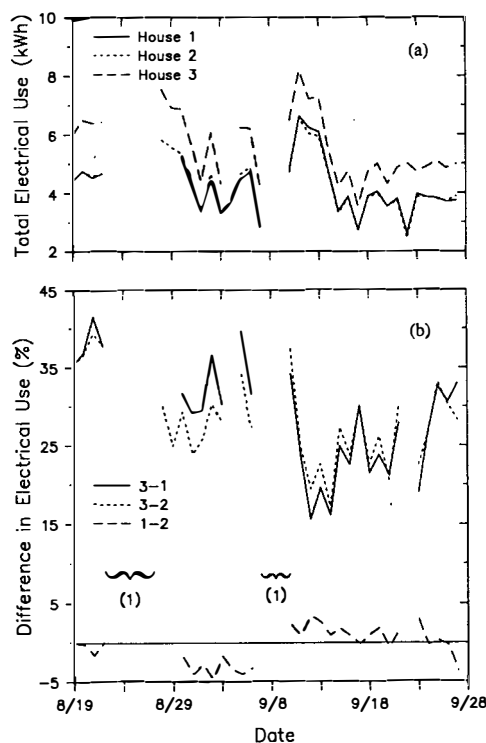


Fig. 10. Electrical use for R-0 trial period. (a) Daily totals for House 1, 2 and 3; (b) percent differences in air conditioning between House 3 and 1, 3 and 2, and 1 and 2. (1) indicates air conditioners off.

ments used $5.1 \pm 2.9\%$ and $5.7 \pm 1.3\%$ more energy, respectively, than did the white treatment (Fig. 9(b)). Hourly energy use for a typical day during the R-30 trial (June 28) revealed that most of the differences in energy use occurred from 1200 to 2000 h (Fig. 11). Differences in hourly peak energy use for the period were similar, with gray and silver treatments using $4.6 \pm 2.4\%$ and $7.1 \pm 3.3\%$ more energy, respectively, than the white treatment.

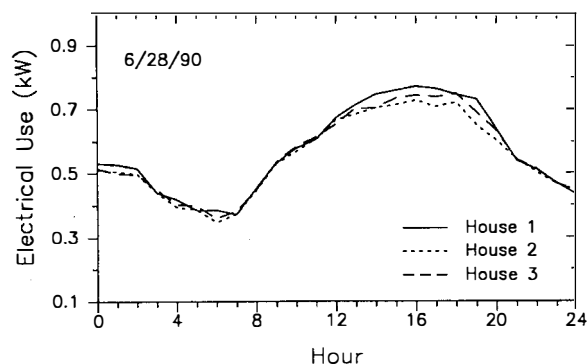


Fig. 11. Typical hourly electrical energy use during R-30 trial period for June 28, 1990, by Houses 1, 2 and 3.

Starting about July 1, there is a marked increase in the variability of daily differences between gray and both white and silver treatments. Since the difference between white and silver treatments remained relatively constant throughout this period, it appeared that the gray treatment used relatively more energy for air conditioning toward the end of the R-30 trial (e.g., July 7–9, 12) than at the beginning. Examination of available microclimate data revealed that the onset of 'monsoon' conditions at the test site in early July coincided with this change in relative air-conditioning use. In particular, for the period June 22–30 and July 10–11, when energy use for the gray treatment was consistently less than for the silver treatment (Fig. 9), daily vector-averaged wind direction was from the northwest ($323^\circ \pm 11^\circ$). Daily average relative humidities were low ($< 20\%$), and temperatures high, with maximums ranging from 35 to 47°C . These conditions were characteristic of the strong high pressure that prevailed during the end of June (an all time record high temperature for Tucson of 47°C was set on June 27, 1990). In contrast, gray treatment energy use was greater than for silver on July 7–9 and 12 (Fig. 9). While temperatures continued to be warm (31 to 39°C) during this period, winds changed dramatically and consistently to south easterly ($113^\circ \pm 21^\circ$), and average relative humidities rose to $> 60\%$ (Figs. 1 and 2).

The correlation between differences in energy use for apparently identical buildings and changing weather conditions suggests differences in building construction and/or siting as the cause. For example, increased infiltration heat gain for one building may have resulted from more air leakage on south and east exposures compared to north and west. This could result from relatively minor differences in window installation, condition of weather stripping and/or general tightness of construction. Also, although exposure was similar for all houses, winds from north east to north west at the gray treatment site may have been obstructed less by adjacent greenhouses than at the others. The overall effect of an increase in wind speed is difficult to predict, since both increased infiltration gain and reduced conduction gain as a consequence of increased convective heat loss from sunlit surfaces can result. Both the absolute value and the variability of differences between gray and white treatment daily energy use appeared to be reduced somewhat when the monsoon

days (July 7–9, 12) were not included, changing from $5.1 \pm 2.9\%$ to $3.4 \pm 0.6\%$.

From July 13, when the roof of the silver treatment was painted white, to July 20 when insulation removal began, daily energy use for white-roofed treatments agreed within $2.3 \pm 1.8\%$ (white (1) using more than white (2)), while gray used $5.2 \pm 2.6\%$ and $8.0 \pm 1.4\%$ more than the white (1) and white (2), respectively. Consistent patterns of energy use difference were observed, with the exception of July 14, when the difference between white treatments was about 6% (Fig. 9). Vector wind direction for this day was 248° , compared to $101 \pm 32^\circ$ for July 13, 15, and 18–20 (air conditioners did not operate on July 16–17). Similar to the previous period, wind direction appears to be an important influence here on relative building energy use.

Despite the overall consistency of these results, differences in energy use of $\sim 5\%$ were observed in both peak and daily average energy use for white compared to gray or silver treatments during the R-30 trial period. Other small differences between treatments, such as due to differential responses to changes in weather patterns during the measurement period, apparently played a role. For example, the silver treatment used $2.0 \pm 1.6\%$ more air conditioning than gray for the high pressure period (June 22–30, July 10–11), but $3.7 \pm 1.3\%$ less for days with monsoon activity (July 7–9 and 12). Consequently, while the 5% change found here is considered to be primarily due to differences in roof color, as a practical matter it would appear to be near the value of minimum detectable change in air-conditioning energy use for this set of buildings due to possible effects of climate and/or construction differences.

3.7. Air-conditioning electrical use: no ceiling insulation

During the period between R-30 and R-0 trials (July 21–August 18), the white/R-0 treatment had greater heat gain during daylight hours compared to either white, gray, or brown R-30 treatments. This larger roof heat gain was offset to a large extent by greater heat loss at night through the uninsulated ceiling when minimum outside air temperature fell below the thermostat set point ($\sim 24^\circ\text{C}$) by 2°C or more, a common occurrence. For example, on July 29, energy use differences between the white/R-0 treatment and white and gray R-30 treatments, respectively, were 20.3% and 16.9% after 1200 h, but -16.3% and -19.2% before 1200 h (Fig. 12). Hourly peak differences at 1600 h were 16.0 and 12.1%, respectively. Hence, during daylight hours, ceiling insulation was more effective than increased roof albedo for reducing heat gain; at night, the lack of ceiling insulation enhanced cooling of the white/R-0 treatment, reducing its air-conditioning load.

Due to these contrasting diurnal energy use patterns, comparison of daily total values often gave entirely different results. On July 29, for example, performance of the white/R-0 treatment was similar to white/R-30 and gray/R-30 on a daily total basis. The former used 8.9 and 7.5% more energy

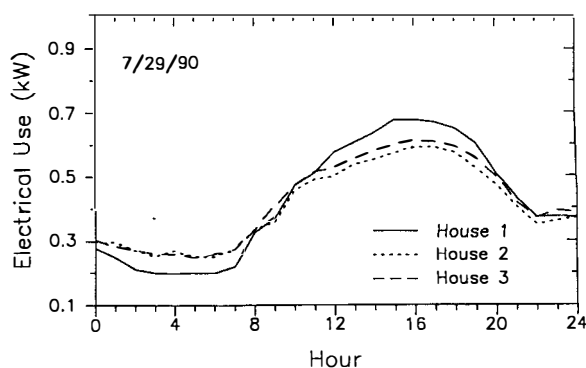


Fig. 12. Typical hourly electrical energy use during the transition period between R-30 and R-0 trial periods for July 29, 1990, by Houses 1, 2 and 3.

for air conditioning, respectively, than the latter two. Thus, with no nighttime ventilation of the conditioned space, increased roof albedo had about the same effect as ceiling insulation on reducing daily air-conditioning load. On cooler, cloudy days when daytime heat gain differences tended to be small, and nighttime heat losses large for R-0 compared to R-30 treatments, no insulation performed better than R-30. Based on these results, it would appear that nighttime ventilation of well-insulated buildings is an additional source of potential energy savings in areas like Tucson.

Daily total energy use during the R-0 trial ranged from approximately 3 to 8 kWh (Fig. 10(a)). The brown treatment used $28.5 \pm 7.0\%$ and $27.9 \pm 5.4\%$ more energy than white (Houses 1 and 2), respectively (Fig. 10(b)). Air-conditioning energy for the two white-treatments was quite similar, with House 2 using $0.4 \pm 2.2\%$ more energy than House 1. September 11 is typical of the good agreement between the two white treatments during this period; the larger energy use of the brown treatment occurring primarily during the day (Fig. 13). White (2) used somewhat less energy than White (1) during the period August 30 to September 6 (Fig. 11(b)), which may have been due in part to flooding that occurred on August 27 from a burst water main nearby. White (1), situated 30 to 60 cm lower than the others, was flooded to just above floor level, which resulted in the surroundings being wet for several days. This may have led to small reductions in air temperature and possibly cooling load; excluding this data had negligible effect on the overall results. Outside

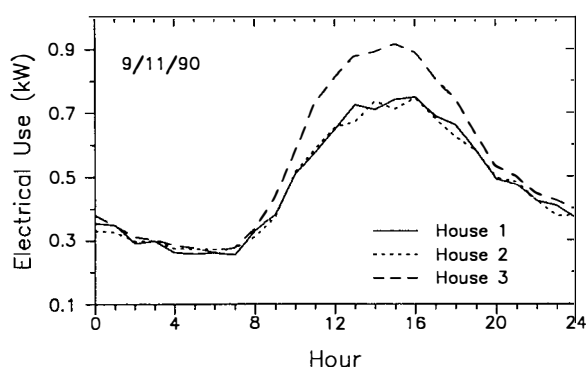


Fig. 13. Typical hourly electrical energy use during R-30 trial period for September 11, 1990, by Houses 1, 2 and 3.

air temperature was unavailable during this period as a result of the flooding. The somewhat warmer inside temperatures noted earlier for the brown treatment tend to make these results somewhat conservative, since it can be assumed that the brown treatment would have used even more energy than measured here if it had been cooled to a lower temperature closer to that of the other models. Relationships for hourly peak energy use were very similar to the daily totals, with the brown treatment using $18.5 \pm 5.4\%$ and $17.1 \pm 4.8\%$ more energy than white (1) and (2), respectively.

3.8. Comparisons of measured and simulated cooling loads

Reagan and Acklam [7] simulated reductions in building heat gain due to an increase in roof albedo. They found a 4.8% reduction in predicted heat gain by increasing roof albedo from 0.25 to 0.65 for a full-sized house on a typical day in July. The simulated house (their Case B) of slab-on-grade construction, slump block walls with R-8 insulation and flat, built-up roof with R-30 insulation was similar to the models in this study. To better compare their simulation analysis with results of this study, their analysis was extended to include roof heat gains with no ceiling insulation (roof R value of 5, U value of $1.13 \text{ W m}^{-2} \text{ K}^{-1}$), and roof albedos of 0.09 and 0.75. To include the additional roof albedos, new values of daily average total equivalent temperature differentials for a horizontal surface ($TETD_{aH}$) were estimated to be 11.0 and 3.4°C, respectively ($TETD_{aH}$ for albedos of 0.25 and 0.65 used by Reagan and Acklam were 9.1 and 4.5°C). In addition, their results were adjusted to include heat gain from single instead of double pane windows, and infiltration gain was increased from 0.5 to 1 air change per hour to simulate better the loose construction and larger surface area to volume ratio of models compared to full-sized houses. Finally, net wall heat gain was increased about 15% to account for smaller model wall albedo of ~ 0.25 (simulations used 0.45), which more than made up for the greater model wall insulation (R-11). Direct solar gain through windows was probably a somewhat higher percentage of total heat gain for the models, even though the ratio of total glazing to floor area was 6.5% for models and 8.2% for simulations. Models had window shading coefficients of 33% compared to 75% for simulations; in addition, most of the windows were on the north side for the simulations, while the models had no windows on that side.

For albedo increases from 0.30 to 0.75 (R-30 ceiling insulation) and 0.09 to 0.75 (R-0 ceiling insulation), simulated savings for the modified slump block house were found to be 5.0 and 28.3%, respectively. These compare favorably with savings measured for model buildings of 5.1 and 28.5%. Simulations revealed the relative effectiveness of roof albedo and insulation level on overall building heat gain in Tucson. For a dark roof with no insulation (Fig. 14, point A), increasing insulation to R-11 (point B) is somewhat more effective than increasing albedo to the maximum found in this study (0.75, point C). For a dark roof with intermediate (R-11)

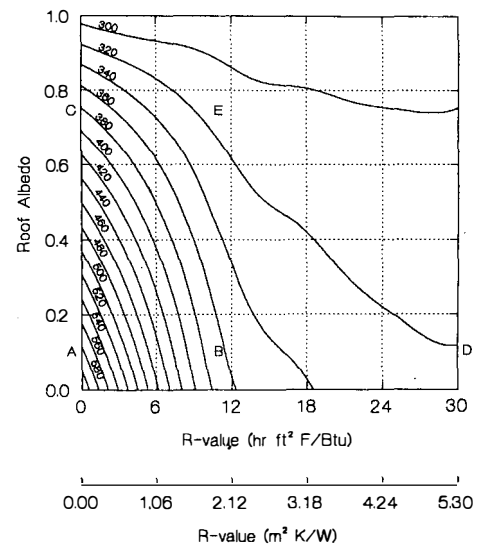


Fig. 14. Predicted total energy use (kJ day^{-1}) for a typical July day in Tucson as a function of roof albedo and insulation levels. Contour lines were fitted to simulated energy data using distance weighted least squares smoothing.

insulation (Fig. 14, point B), increasing albedo to 0.75 (point E) was somewhat more effective than increasing insulation to R-30 (point D). In general, increasing roof albedo has a larger impact on heat gain for buildings with poorly insulated ceilings, while adding ceiling insulation is more effective for darker roofs. As noted subsequently, this result may be dependent on climate.

4. Conclusions

Building air-conditioning load, roof temperature, and related environmental factors were monitored during the summer of 1990 on 1/4-scale model buildings. White roofs (~ 0.75 albedo) were up to 20°C cooler than gray (~ 0.30 albedo) or silver (~ 0.50 albedo), and up to 30°C cooler than brown (~ 0.10 albedo) roofs. Even though the silver roof was more reflective than the gray roof, their temperatures were similar. It appears that silver's greater albedo was compensated for to some extent by the lower emissivity of the silver coating. Hence, simply increasing albedo of a building surface may not be effective in reducing its temperature and heat gain if emissivity is reduced simultaneously. Lower roof temperatures, by reducing differential expansion and contraction of different roof materials (e.g. metal flashing and composition shingles), may be a factor in extending roof life, in addition to their potential effect on building heat gain. Solar reflectance of high albedo materials may degrade over time due to soiling, mold or mildew, depending on local environmental conditions, potentially reducing their effectiveness [4,19].

Reductions in total and peak air-conditioning load of approximately 5% were measured for otherwise identical white compared to gray and silver-roofed scale model buildings with R-30 ceiling insulation. Similar temperatures of

silver and gray roofs, for reasons discussed previously, were indicative of the similar energy use results for these cases. Treatment differences were small, which is attributed to heavy ceiling insulation. When ceiling insulation was removed, air-conditioning reductions were much larger for white compared to brown roofs, averaging about 28 and 18% for total and peak loads, respectively.

Comparisons of these results with a previous simulation study showed good agreement, confirming the measured results and the scaling procedure used to ensure thermodynamic similarity between the models and full-sized buildings. This indicates that results from scale models can be successfully extrapolated to the full-size case, at least for the current set of experimental conditions. Given the non-linear dependence of heat gain on atmospheric temperature and wind structure, additional research will be necessary to completely establish the range of relationships between scale model and full-sized buildings, their environment, and cooling and heating load.

Ceiling insulation was found to be more effective in reducing daytime heat gain than increased roof albedo for the buildings studied here. This was because the reduced net solar load which resulted from the larger albedo was more than compensated for by the increase in thermal resistance ($\sim$ six-fold here) resulting from addition of ceiling insulation. Increased albedo may be more effective relative to ceiling insulation in reducing air-conditioning use than predicted here for buildings with air ducts located in the attic space. Attic ducts are a common feature of the slab-on-grade construction and central air-conditioning systems typical in 'sun-belt' states. Cooler attic spaces from lighter surface colors have been shown to increase cooling savings by reducing duct losses [20].

On a 24-hour basis, increased roof albedo was found to be about as effective as addition of ceiling insulation in reducing building heat gain. This was because absence of nighttime ventilation in this study resulted in the increased daytime heat gain being largely offset by enhanced nighttime heat loss through the uninsulated ceiling when night temperatures dropped more than $\sim 2^\circ\text{C}$ below the thermostat set point. Natural ventilation during such times may be beneficial, dependent to some extent on the accompanying relative humidity of the outside air.

The contrasting results for daytime compared to 24-hour analysis point out that comparison of cumulative energy use differences must be approached with caution. Different combinations of heat gain pathways may lead to different conclusions concerning relative energy savings, based on the time interval used for accumulating the energy use totals, or on the relative magnitude of heat gain in those pathways. For example, nighttime ventilation in combination with the R-30 insulated gray/silver roof, may have improved the performance of this combination here compared to the uninsulated white roof on a 24-hour basis. Success of this idea may be limited by lack of adequate nocturnal wind, and need for manual window operation.

Climate differences are likely to influence relative savings achievable from albedo modification in different geographic regions. For example, the temperature difference between thermostat setpoint (24°C) and outside air are typically larger in Tucson than in other cooling dominated climates. The 1% summer design dry bulb temperature in Tucson is 40°C , compared to 35.6°C in Houston and 32.8°C in Miami. For similar insolation levels, larger temperature differences will make added insulation relatively more effective at reducing heat gain than increasing roof albedo. Hence, it is expected that increased surface albedo would be more effective in climates with smaller temperature differences than found in Tucson.

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References

- [1] J.L. Monteith, M.H. Unsworth, *Principles of Environmental Physics*, Edward Arnold, New York, 2nd edn., 1990.
- [2] C. Thurow, *Improving Street Climate Through Urban Design*, Americal Planning Association, Chicago, 1983.
- [3] N.K. Bansal, S.N. Garg and S. Kothari, Effect of exterior surface colour on the thermal performance of buildings, *Build. Environ.*, 27 (1992) 31.
- [4] E.I. Griggs, The impact of surface reflectance on the thermal performance of roofs: an experimental study *ASHRAE Trans.*, 94 (1988) 1626.
- [5] R.W. Anderson, Radiation control coatings: an underutilized energy conservation technology for buildings. *ASHRAE Trans.*, 95 (1989) 682.
- [6] R.W. Anderson, D.W. Yarbrough, R.S. Graves and R.L. Wendt, Preliminary assessment of radiation control coatings for buildings, in R.S. Graves and D.C. Wysocki (eds.), *Insulation Materials: Testing and Applications*, American Society for Testing and Material, Philadelphia, 1991, pp. 7–23.
- [7] J.A. Reagan and D.M. Acklam, Solar reflectivity of common roofing materials and its influence on the roof heat gain of typical southwestern USA Residences, *Energy Build.*, 2 (1979) 238.
- [8] H. Taha, H. Akbari, A. Rosenfeld and J. Huang, Residential cooling loads and the urban heat island — the effects of albedo, *Build. Environ.*, 23 (1988) 271.
- [9] H. Akbari, S.E. Bretz, J.W. Hanford, D.M. Kurn, B.L. Fishman H.G. Taha and W. Bos, Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District (SMUD) service area, *Rep. No. LBL-34411*, Lawrence Berkeley National Laboratory, Berkeley, CA, 1993.
- [10] D.S. Parker, J.B. Cummings, J.S. Sherwin, T.C. Stedman and J.E.R. McIlvaine, Measured electricity savings from reflective roof coatings applied to Florida residences, *FSEC-CR-596-93*, Florida Solar Energy Center, Cape Canaveral, FL, 1993.

- [11] D.S. Parker, S.F. Barkaszi and J.K. Sonne, Measured cooling energy savings from reflective roof coatings in Florida, *Phase II Report. FSEC-CR-688-94*, Florida Solar Energy Center, Cape Canaveral, FL, 1994.
- [12] E.G. McPherson, J.R. Simpson and M. Livingston, Effects of three landscape treatments on residential energy and water use in Tucson, Arizona, *Energy Build.*, 13 (1989) 127.
- [13] ASHRAE, *ASHRAE Handbook. Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989.
- [14] P.W. Brown, Accessing the Arizona meteorological network by computer, *Extension Report 8733*, University of Arizona Cooperative Extension, College of Agriculture, Tucson, AZ, 1989.
- [15] P. Schwerdtfeger, *Physical Principles of Micrometeorological Measurements*, Elsevier, New York, 1976.
- [16] J.R. Howell, *A Catalog of Radiation Configuration Factors*, McGraw-Hill, New York, 1982.
- [17] S.B. Idso, A set of equations for full spectrum and 8 to 14 μm thermal radiation from cloudless skies, *Water Resour. Res.*, 17 (1980) 295.
- [18] J.P. Todd and H.B. Ellis *Applied Heat Transfer*, Harper and Row, New York, 1982.
- [19] S. Bretz and H. Akbari, Durability of high albedo roof coatings and implications for cooling energy savings, *Rep. No. LBL-34974*, Lawrence Berkeley National Laboratory, Berkeley, CA, 1994.
- [20] D. Parker, P. Fairey and L. Gu, Simulation of the effects of duct leakage and heat transfer on residential space cooling energy use, *Energy Build.*, 20 (1993) 97.