

MEASURED COOLING ENERGY SAVINGS FROM REFLECTIVE ROOFING SYSTEMS IN FLORIDA: FIELD AND LABORATORY RESEARCH RESULTS

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ABSTRACT

A series of field experiments in Florida have examined the impact of reflective roof coatings on air-conditioning (AC) energy use in occupied homes. The tests were conducted on nine residential buildings from 1991 to 1994 using a before-and-after protocol where the roofs were whitened at mid-summer. Measured AC electrical savings in the buildings during similar pre- and post-retrofit periods averaged 19%, ranging from a low of 2% to a high of 43%. Utility peak coincident peak savings averaged 22%. Cooling energy reductions appear

to depend on ceiling insulation level, roof solar reflectance, air duct system location, and air conditioner sizing relative to load.

A complementary thermal study of the effect of reflective roofing systems has been conducted in a side-by-side roof test facility. Ceiling heat flux reductions up to 60% were measured from reflective roofing in these experiments. However, the test results have also shown degradation in solar reflectance and associated thermal performance after a year of exposure.

INTRODUCTION

Past building research indicates that roof and wall colors have significant impacts on space-cooling energy use (Givoni 1976). Simulations show that a reflective roof color can cut cooling loads by 10% to 60% in buildings, with the higher values associated with uninsulated roof systems (Reagan and Acklam 1979; Anderson 1989; Griggs and Shipp 1988; Taha et al. 1988).

Reflective surfaces may have specific advantages over competing roof-related energy conservation options such as increased attic insulation and radiant barriers. Evidence suggests that increasing the community-wide albedo of roofs could serve to reduce the neighborhood ambient air temperature and reduce the magnitude of the urban heat island effect (Bretz et al. 1992). Each 1°C change in urban air temperature has been shown to be associated with a 2% to 3% savings for the system-wide summer utility load in mid-latitude cities (Akbari et al. 1990).

PREVIOUS RESEARCH

Givoni and Hoffman (1968, 1972) performed early experiments in Israel on small buildings with different exterior colors. They found that unventilated buildings with white walls were approximately 3.0°C cooler in summer than when the same buildings were painted

gray. Similar experiments with black and white test buildings were carried out in Delhi, India, in 1990 (Bansal et al. 1992). This work found that measured air temperatures within the white building were 4°C to 8°C cooler than the dark building during mid-summer conditions, depending on the level of ventilation.

Measurements using six small roof models have been conducted to evaluate the thermal performance of various types and colors of roofing systems (Chandra and Moalla 1992). Test cases have included dark asphalt shingles, white asphalt shingles, and asphalt shingles with a reflective ceramic coating and a series of red tile configurations. Monitoring showed that roof sections with white reflective coatings exhibited superior thermal performance to conventional roofing systems. However, the results also showed that conventional white asphalt shingles provided poor performance relative to reflective coatings. Laboratory tests indicated the elastomeric coatings have solar reflectances of 0.65 to 0.72, while nominally white asphalt shingles had reflectivities of only 0.25 (Anderson et al. 1991; Parker et al. 1993a). By comparison, black asphalt shingles had a reflectivity of 0.05 and gray shingles had a tested value of 0.22. Measured reflectances for a variety of building materials are contained in complementary work by several researchers (Reagan and Acklam 1979; Parker et al. 1993a; Taha et al. 1992).

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Experimentation with model roofs and side-by-side testing of roofing structures has also been performed at a national laboratory (Griggs and Shipp 1988). This work also found that reflective roofing systems can significantly reduce the heat flux through roofs. A highly instrumented test building showed that reflective coatings reduced the peak heat flux on the underside of the roof decking by up to 82 W/m² relative to a black-colored EPDM roof section (Anderson et al. 1991). This represented a reduction in overall roof-related cooling load of 75%. In a 465-m² structure without roof insulation, this would represent a reduction in the building thermal load of 10.8 tons (38 kW_e) of air conditioning.

One of the earliest whole-building studies measuring cooling energy savings from reflective roof coatings was performed by an electric utility in southern Mississippi (Boutwell and Salinas 1986). Two identical side-by-side commercial office buildings were monitored, in which one had its roof coated with a reflective white elastomeric coating. Both buildings had RSI-2 (m²·°C/W) insulation installed in the roof system. Summertime air conditioning was reduced by 21.9% in the building with the reflective roof coating.

Researchers at a U.S. laboratory have examined the savings of reflective roofing systems in three buildings in Sacramento, California (Akbari et al. 1992; Parker et al. 1994). One building was an occupied residence located in an older section of Sacramento with RSI-2 ceiling insulation under a composite shingle roof. The initial roof reflectivity was measured at 0.18, which was increased to 0.81 by application of an elastomeric roof coating. The air-conditioning load in the building was reduced by 69%, with a 28% reduction in the peak electrical demand. The savings amounted to an energy use reduction of approximately 12 kWh per day, with a 2.3-kW reduction in peak power demand. The second and third buildings were test bungalows at a school site. Both buildings had metal roofs, one that was uncoated and the other painted brown. Both had attic insulation of approximately RSI-3.3. In both cases the buildings' corrugated metal roof albedo was increased to approximately 70%. Measured air-conditioning energy use was reduced by approximately 40% for the brown-roofed building and by approximately 50% for the coated metallic roof surface. Although reflective building surfaces show great potential in California, the much higher levels of humidity and nighttime temperatures in Florida make prospects for near-elimination of space-cooling energy use very unlikely.

FIELD EXPERIMENTS

In the summer of 1991 a preliminary experiment was conducted. The first test building (designated site 0) was a 167-m² detached single-family home in Merritt Island, Florida. The structure was single-story and of concrete block construction. The pitched roof faced north-south with plywood decking covered by green/

gray asphalt shingles. The attic of the home was well insulated with approximately two inches of fiberglass covered by an additional six inches of cellulose insulation, yielding an approximate nominal thermal resistance of RSI-4.4 (m²·°C/W). Beginning in May 1991, the air conditioner of the home was submetered and daily readings were taken. The thermostat was maintained at a constant setting of 26°C. In addition to the daily air conditioner consumption readings, a data logger recorded the underside roof deck temperature, attic air temperature, and living room temperature every 30 minutes.

The reflective roof was applied on September 5, 1991. The roof reflectivity was measured to increase from 0.22 to 0.73 after the coating was applied. Spot measurements under full sun at mid-summer showed shingle surface temperatures of 71°C to 77°C prior to the roof treatment as compared with 43°C after the coating was applied. Analysis indicated a 10.5% savings of the reflective roof coating (38.7 kWh/day vs. 34.7 kWh/day).

It was recognized that the test house likely understated the average savings of a reflective roof system in existing Florida homes. The attics of most of the state's residences are much less insulated than the test house and often have air leakage from the attic space into the conditioned interior. Therefore, more typical residences were identified for our more detailed experiments the following year. With equipment to instrument two buildings, we looked to find a residence with typical levels of ceiling insulation (approximately RSI-2 for existing Florida homes) and a second structure with no insulation. The data from site 1 would be used to obtain results from a more typical existing residential building, while site 2 would be used to help define the maximum savings potential for reflective roof coatings in Florida. A second shortcoming of the initial experiment was its lack of information on how the reflective roof coating affected the peak cooling demand profile. Consequently, the 15-minute air-conditioning electricity demand was submetered in our follow-up study.

DETAILED MONITORING

The measurement plan for the project was based on a set of established residential audit and instrumentation procedures. Since individual buildings were monitored, a before-and-after experimental design was utilized to isolate the effect of applying reflective roof coatings. Collected weather data were also used to identify before and after periods with similar conditions.

All homes were audited prior to the beginning of the monitoring period according to an established DOE protocol for existing residential buildings. The audit examines all the characteristics of the building that may be related to energy use. Table 1 lists the measurements taken at the various sites.

TABLE 1 Reflective Roof Study Monitoring Data Set

	Units
Local meteorological conditions	
• Ambient air temperature	°C
• Insolation	W/m ²
• Ambient relative humidity	%
• Wind speed	mps
Interior Conditions	
• Interior living-room air temperature	°C
• Kitchen air temperature	°C
• Ceiling surface temperature	°C
• Slab floor temperature	°C
• Interior relative humidity	°C
Roof/Attic/Garage Conditions	
• Roof surface temperature	°C
• Roof decking temperature	°C
• Attic air temperature	°C
• Garage temperature	°C
Space Cooling Energy Use	
• Air conditioner watt-hours	W-hrs

A detailed description of the audit, instrumentation, and calibration is contained in the source report (Parker et al. 1993c). Multichannel data loggers were used for the collection and storage of data. All instruments were scanned every five seconds, with integrated averages and totals output to final storage every 15 minutes. Data were removed periodically using an on-site personal computer for sites 0, 1, and 2; data were transferred via modem to a mainframe computer on a daily basis for sites 3 through 8. Roof reflectivity measurements were made with a precision spectral pyranometer (PSP) that is sensitive to radiant energy in the 0.28- to 2.8-micrometer range. The calibrated PSP was alternately faced up

and down to gauge the portion of the incident solar radiation being reflected from the roof surface.¹

DESCRIPTION OF THE BUILDINGS

The physical characteristics of interest for the nine buildings in the field study are summarized in Table 2. Buildings were chosen for the study based on their differing characteristics that may provide insight into the savings potential of reflective roofing systems. Thus, for a small sample, the buildings represent a variety of locations, roofing systems, attic insulation levels, AC efficiencies, and AC system configurations.

In each building the cooling system thermostat was set by the occupants to their desired temperature, after which a lock box was installed to prevent tampering during the experiments. In each home, the building had its roof coated at mid-summer. A white ceramic coating was used at site 0, a white cementitious coating was used on the gravel roof at site 4, and an acrylic elastomeric coating was used at all other sites.

RESULTS

All of the buildings were air conditioned for a period before and after the roofs were coated. Although the homes were occupied, efforts were made to ensure that conditions of use remained as constant as possible.

¹Although, roof solar reflectivity, or albedo, is a fundamental characteristic controlling roof surface thermal performance, it is not the only relevant parameter. Roof surface infrared emissivity can be important, since low values of emittance can partially obviate the benefits of reflective properties. With low-surface emittance, solar radiation absorbed by the roof surface is not readily re-emitted. The properties of reflectivity (albedo) and emittance vary independently. All things equal, a low-emittance, high-albedo roof coating (such as an aluminum flake paint) would be less desirable than a high-reflectance white paint with normal emissivity (0.80 – 0.95) since a low-emittance surface would tend to remain hotter.

TABLE 2 Reflective Roofing Study Building Characteristics

Site No.	Location of Site	Conditioned Floor Area (m ²)	Attic Insulation (m ² ·°C/W)	Roof Type	AC SCOP ^c	AC Capacity (kW _p)	Duct Location
0	Central FL	167	R-4.4	Shingle	2.05	10.6	Attic ^a
1	Central FL	120	R-2.0	Shingle	1.90	8.4	Attic
2	Central FL	113	R-0.0	Bitumen	2.72	8.8	Attic
3	West FL	84	R-0.0	Shingle	2.64	5.3	None
4	South FL	125	~R-2.0	Gravel	3.28	10.6	Attic ^b
5	Central FL	158	R-1.8	Tile	2.05	10.6	Attic
6	Central FL	140	R-3.3	Shingle	2.93	10.6	Attic
7	Central FL	170	R-3.3	Shingle	2.93	10.6	Attic
8	Central FL	130	R-1.6	Metal	2.64	21.2	Attic

^aDucts were sealed

^bLeaky ducts observed on site

^cSCOP = Seasonal Coefficient of Performance (SEER/3.413)

TABLE 3 Results of Field Tests of Reflective Roof Coatings

Test Site	Albedo Before	Albedo After	Energy Use (kWh/day)			Reduction in Utility Coincident Peak Demand (5-6 p.m.)
			Before	After	Savings	
Site 0						
Merritt Island, white elastomeric coating on asphalt shingles, concrete block with R-4.4 ceiling insulation, attic duct system	0.22	0.73	38.7	34.7	4.0 (11%)	Not Measured
Site 1						
Cocoa Beach, white elastomeric coating on asphalt shingles and flat gravel, R-2 attic insulation, attic duct system	0.21	0.73	40.6	30.3	10.3 (25%)	661W (28%)
Site 2						
Cocoa Beach, white elastomeric coating on tar paper; flat roof and no attic insulation, attic duct system	0.20	0.73	35.5	20.1	15.4 (43%)	858W (38%)
Site 3						
West Florida, white elastomeric coating on asphalt shingles, no attic insulation, no attic duct system	0.08	0.61	22.4	16.8	5.6 (25%)	496W (30%)
Site 4						
Miami, white coating for gravel roof, R-2 attic insulation, attic duct system	0.31	0.61	51.9	43.9	8.0 (15%)	444W (16%)
Site 5						
Merritt Island, white elastomeric coating on tile roof, R-1.8 attic insulation, attic duct system	0.20	0.64	57.5	45.9	11.6 (20%)	988W (23%)
Site 6						
Palm Bay, white elastomeric coating on shingle roof, R-3.3 attic insulation, attic duct system	0.15	0.59	34.1	30.9	3.2 (10%)	354W (16%)
Site 7						
Palm Bay, white elastomeric coating on shingle roof, R-3.3 attic insulation, attic duct system	0.22	0.64	41.1	40.2	0.9 (2%)	304W (12%)
Site 8						
Cape Canaveral, white elastomeric coating on metal roof, R-2 attic insulation, attic duct system	N/A	0.64	34.6	27.0	7.6 (22%)	201W (12%)
Averages	0.20	0.66	39.6	32.2	7.4 (19%)	427W (22%)

Three different methods of estimating the savings were used to ensure that the results were stable and not due to differences in weather. These included

- using long pre- and post-retrofit data periods with similar weather conditions,
- statistically matched days pre- and post-retrofit with similar profiles of ambient air temperature and insolation,
- a statistical model of pre- and post-retrofit air-conditioning loads against ambient air temperature and insolation (and interior electrical use for sites 6, 7, and 8).

The three calculation methods resulted in similar estimates for savings at each of the sites. Use of the long-term pre- and post-period data with similar weather conditions was determined to yield the most reliable and least biased estimates. The results for each site are summarized in Table 3. More complete documentation of the data and analysis is contained in the source reports (Parker et al. 1993b, 1994).

Site 1

Site 1 represents a fairly typical existing Florida home with a conditioned floor area of 120 m². The attic is insulated to approximately RSI-2, but the air conditioner is more than 15 years old and inefficient. The measured air-conditioning energy and attic temperatures, shown in Figure 1 during the week of the treatment, illustrate the impact of the reflective coating. Although air temperatures and solar radiation were comparable, air-conditioning power was reduced by an average 25% from 1,690 W to 1,264 W. The average electrical demand of the air-conditioning system during the utility coincident peak period (between 5 and 6 p.m.) was 2,373 W before the coating and 1,712 W after the application. This 661-W savings represents a 28% reduction in peak power demand attributable to the coating. Figure 1a shows the change in the attic and air conditioner performance during the week it was retrofitted.

Site 2

Site 2 represented an ideal application for a reflective roof coating. Like many other 1960s vintage Florida

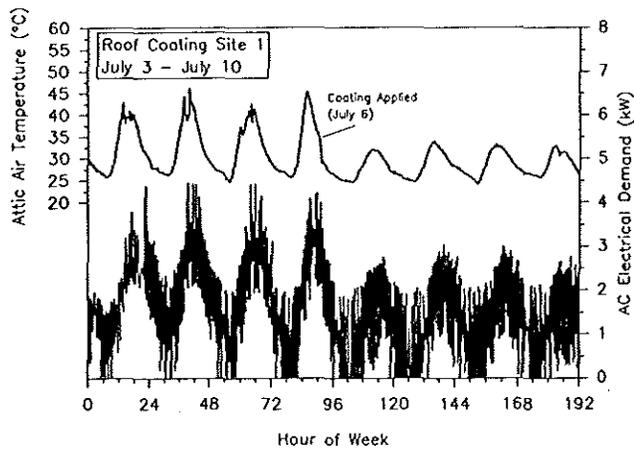


Figure 1a Site 1 attic temperatures and AC load profiles during week of roof coating.

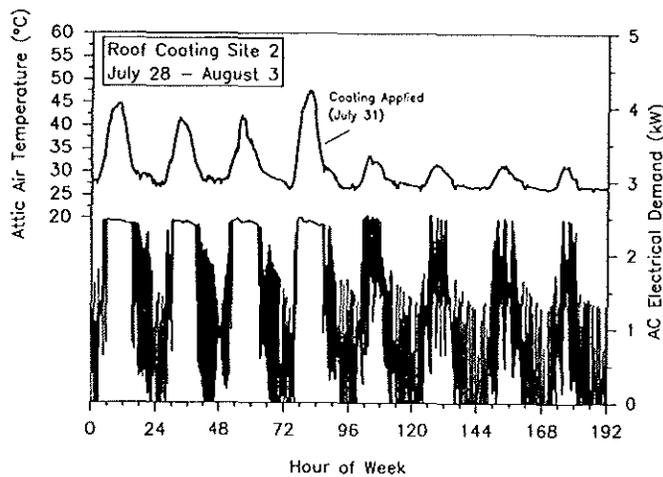


Figure 1b Site 2 attic temperatures and AC load profiles during week of roof coating.

homes, the house has a flat roof that has no space available with which to insulate the ceiling assembly. Prior to the coating, the 8.8-kW_t air conditioner was unable to control the interior temperature adequately, running continuously each day from noon until 7 p.m., when the thermostat was again satisfied. Figure 1b shows the measured AC energy use and roof airspace temperatures during the week when the coating was applied.

The reduction to the roof airspace temperature is striking, as is the change in air conditioner load profile. Before the coating was applied, the air conditioner ran at maximum power, with an electrical demand of approximately 2,300 W. Unable to control the comfort, the interior temperature daily ranged above the thermostat setpoint by 2°C or more. The average electrical demand of the air-conditioning system during the utility coincident peak period (5 to 6 p.m.) was 2,243 W before the coating and 1,385 W after the application, a 38% reduction in peak power demand attributable to the roof treatment.

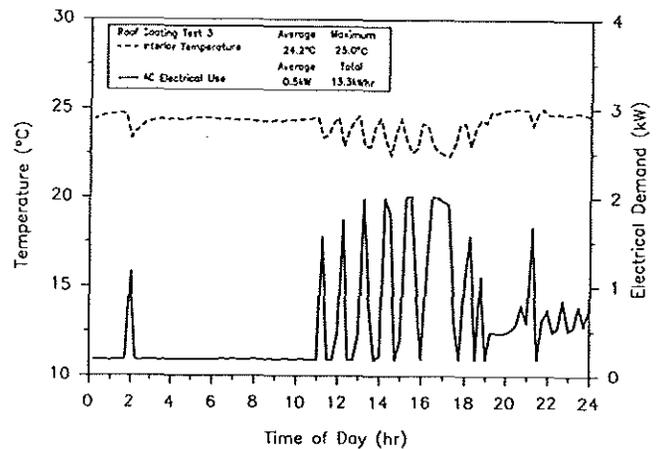
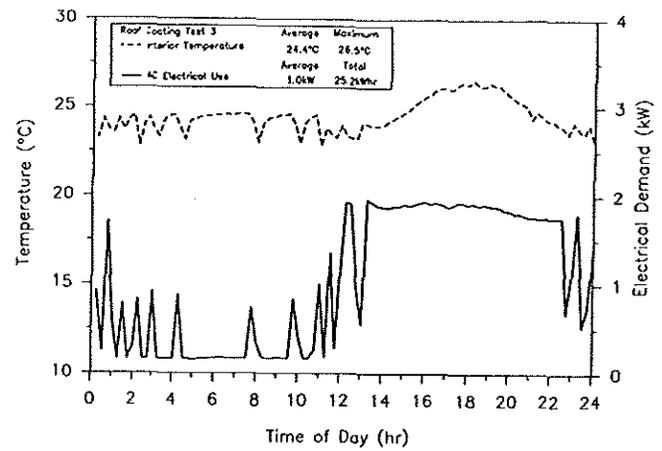


Figure 2 Site 3 extreme day air-conditioning demand before and after roof coating.

Average air conditioner electricity consumption dropped from 1,478 to 838 W after the application, a reduction in cooling energy use of 43%. Measured savings would also likely have been higher had the house possessed a larger air conditioner that could have met the elevated cooling loads prior to the retrofit. Regardless, these results indicate large potential cooling energy savings from whitening the roofs of Florida homes without ceiling insulation.

Site 3

Site 3 was unique in that the small house was cooled with a through-the-wall air conditioner and had no attic duct system, as was the case in all the other sites. The attic above the dropped ceiling was found to contain no insulation and the 5.3-kW_t air conditioner was unable to control the temperature condition adequately inside prior to coating. Figure 2 shows two very hot but otherwise comparable days before and after the roof coating. The air conditioner runs constantly from 1 to 10 p.m., although it is unable to satisfy the thermostat. After the coating, the air conditioner cycles on and off during the

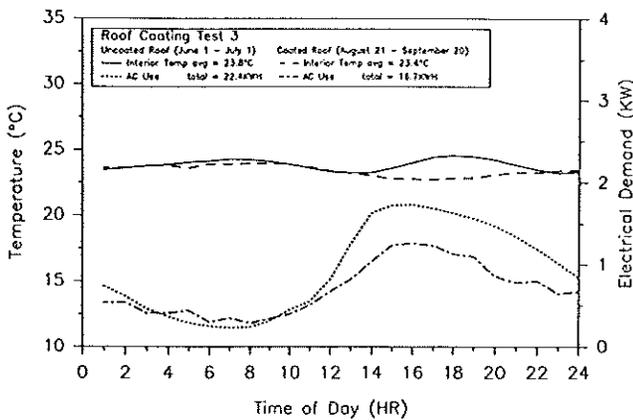


Figure 3a Site 3 average AC electricity use and interior air temperature before and after coating.

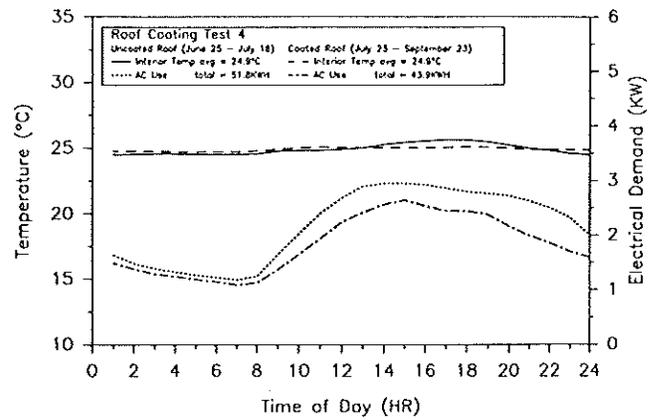


Figure 4a Site 4 AC electricity use and interior air temperatures before and after coating.

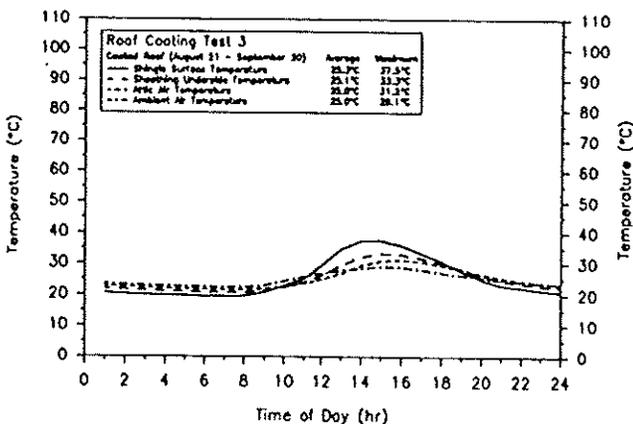
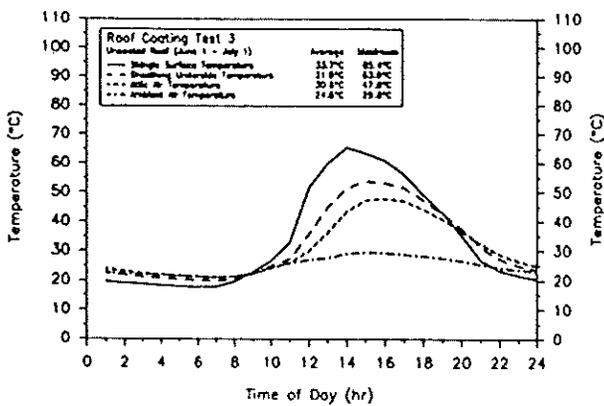


Figure 3b Site 3 (asphalt single roof) hourly average temperatures a) uncoated, b) after coating.

same period, maintaining improved interior comfort while reducing the utility coincident peak demand (5 to 6 p.m.) by nearly 960 W. The total daily air-conditioning use was 11.9 kWh lower in the period after the coating—a reduction of 47% under peak-day conditions. Figure 3 shows the average daily AC demand profile and temperature conditions for site 3 during month-long periods with similar weather conditions before and after the roof coating. Average daily AC savings totaled 5.6 kWh,

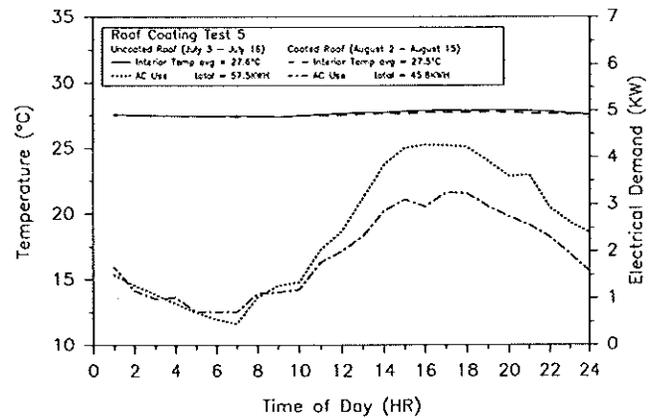


Figure 4b Site 5 AC electricity use and interior air temperatures before and after coating.

or 25%, during the summer period. Peak demand savings average 30% (496 W).

Site 4

Site 4 was selected to see how whitening of a gravel roof (common in southern Florida) might reduce energy use and because the household members had complained to the local utility of high utility bills. The ceiling is rather well insulated for a Miami home (RSI-2 to RSI-3.3 blown fiberglass) and the 10.6-kW_e air conditioner is relatively efficient. However, while performing the audit of the home, a large duct system supply leak in an inaccessible portion of the attic was located with the infrared camera. The leak was not repaired, although the roof was coated with a white cementitious gravel roof coating after a significant period of data had been collected. The average AC and interior temperature profiles are shown in Figure 4a for two periods before and after the coating was applied. Although the fractional savings of AC energy were in the low range at site 4 (15%), the absolute value (8.0 kWh/day) reflects the very high cooling energy budget at the location.

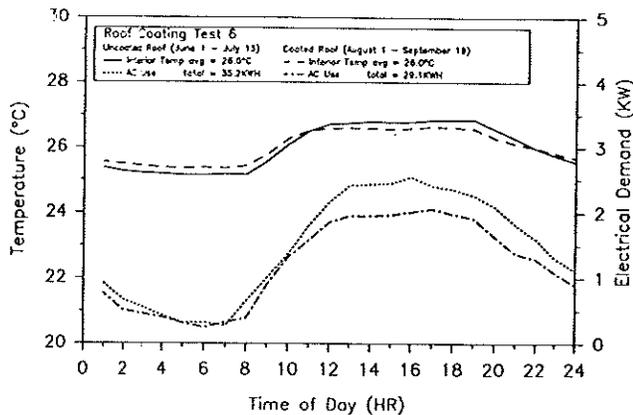


Figure 5a Average electrical use and interior air temperatures at Site 6 before and after coating.

Site 5

Site 5 was chosen for an experiment because of its tile roof. The cement barrel tiles were old and stained gray. The house also had relatively poor ceiling insulation and a low-efficiency air conditioner. The measured solar albedo was 20% before coating; after being coated with a sprayed-on white elastomeric mastic it was 64%. The absolute savings at this site were quite large, at 11.6 kWh/day with a 988-W reduction in coincident peak cooling demand. The average AC demand profiles for two 13-day periods before and after the coating are shown in Figure 4b.

Site 6

Site 6 was the first of two homes selected to investigate the savings potential for residences typifying new construction in Florida. This wood-frame house was constructed in 1993 and has cathedral ceilings in the main living area and 2.5-m ceilings in the bedrooms. The roof system is composed of light gray shingles over wood sheathing and conventional trusses. Fiberglass insulation is blown in the attic to a depth equivalent to RSI-3.3. The split AC system is rated at 10.6 kW_i and has the air handler located in the unconditioned garage; flexible ductwork runs through the attic. A similar monitoring protocol was used for the 1994 experiments but with the added element of submetering all major interior electrical appliances and plug loads so that the impact of internal gain levels could be properly taken into account.

Analysis based on daily averaged data shows a 17% reduction in cooling energy use (Figure 5a) for aggregate periods with similar conditions before and after application of the roof coating. This value is larger than the 10% savings predicted from regression models of AC use against $\Delta T (T_{amb} - T_{int})$, solar irradiance, and miscellaneous electrical use (lighting, refrigerator, etc.). The discrepancy may be due to the 9% reduction in interior appliance energy use from the uncoated to coated roof period. However, the statistical model, which showed

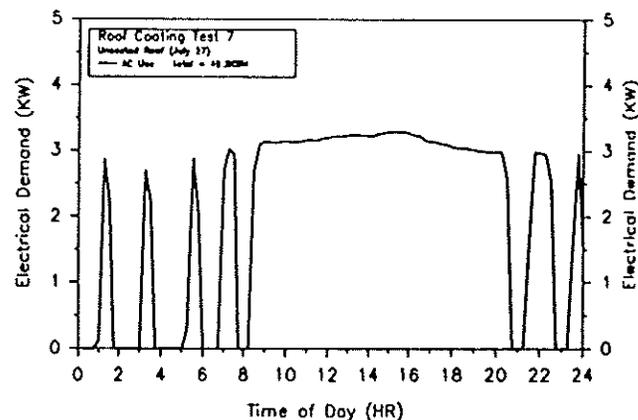
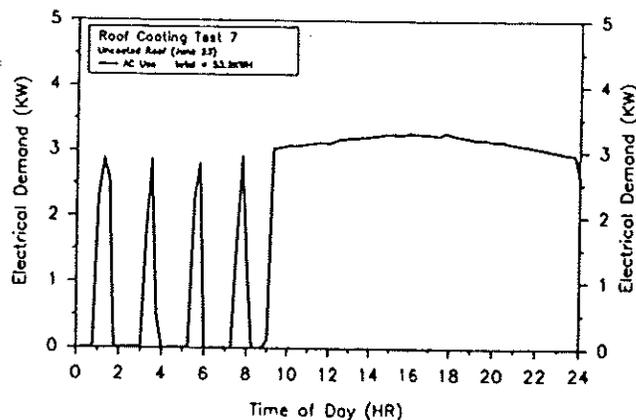


Figure 5b Site 7 extreme day AC demand before and after roof coating.

internal appliance electricity use to have a significant impact on AC demand, properly accounts for changes in the parameters and appears to more accurately describe the savings potential.

Site 7

Site 7 was the second newly constructed residence identified for reflective roof testing. The house is located approximately 100 meters from site 6 and was also built in 1993. Light gray shingles, wood sheathing, and trusses make up the roof system, and blown fiberglass insulates the attic to RSI-3.3. Construction is very similar to that at site 6. The 10.6-kW_i AC system was installed with the air handler in unconditioned space and the distribution system in the attic.

The long-term analysis for the complete pre- and post- intervals at this site indicated a 3% increase in air conditioner use. However, the roof system temperatures had decreased, interior air temperatures were maintained more evenly, and a peak reduction of 12% was realized. The measured increase in AC demand during the different time periods may be attributed to two factors. First, the interior air temperature was maintained at a relatively low level (23°C). The unit was required to

run at capacity for a large portion of the day in both the pre- and post- periods to maintain the temperature (Figure 5b). With the AC running continuously, there was little opportunity for savings but the desired setpoint was more closely maintained. A second factor causing greater cooling requirements at site 7 is the 20% increase in internal appliance use in the post- period. The increased appliance use presents a significantly higher internal load that the cooling equipment must remove.

Coupled with the continuous operation of the AC unit, the increased appliance gains provide an explanation for the lack of savings during the long-term pre- and post- periods. A multiple-regression model for site 7, which uses the complete before and after periods and accounts for weather- and internal-gain-related influences, estimates the savings to be 2%. The authors believe the statistical model provides the most credible estimate of the savings levels, although the changed internal loads decrease the validity of this field test relative to the others.

Site 8

Site 8 is a recent vintage double-wide manufactured home used for office space at our institution. The roof material is corrugated metal and the fiberglass batts in the attic space have an R-value of approximately 1.9 $\text{m}^2\cdot\text{C}/\text{W}$. Two 10.6-kW_t packaged AC units are mounted on the exterior wall of the structure, and the ductwork is run through the unconditioned roof-ceiling space.

A savings of 22% was found using the aggregate pre- and post- periods for site 8. Although the before period was limited to six days prior to the coating application, the daily averaged data matched well. Miscellaneous use (mainly lighting) in this building remained fairly constant during the periods of data collection, and internal temperatures were maintained more consistently after the roof was coated. Regression analysis similar to that used for sites 6 and 7 also estimated the savings to be 22%. The results appear to reinforce the conventional wisdom that reflective roofs have significant potential for reduction of cooling energy use in manufactured homes.

ANALYSIS AND INTERPRETATION OF FIELD DATA

Infrared thermography was used before and after application of the roof coatings to help understand how heat gains to the building interior were affected. Pertinent infrared images are reproduced in the source reports (Parker et al. 1993b, 1994). At sites 1, 4, and 7 before the coatings, the IR camera clearly identified voids in the blown insulation where the ceiling met the top plate of the concrete block walls. Although the voids in the insulation were still visible after the roof coatings,

a large reduction in the ceiling heat fluxes was observed. The potential effect of such insulation voids is well understood. For instance, a 1,300-ft² ceiling uniformly insulated to RSI-3.3 ($\text{m}^2\cdot\text{C}/\text{W}$) would have its heat gain rate nearly doubled with 90% of its area insulated to RSI-3.5, but 10% when insulated to RSI-0.4.

There may be other factors at work that help explain the large savings observed at the various sites. Heat gain to attic-mounted air distribution systems has been calculated to be as large in magnitude as the change in heat flux of an insulated ceiling interface (Parker et al. 1993c). Also, low-density insulation thermal conductivities may be compromised by temperature conditions present in attics. The temperature dependence of thermal insulation is widely acknowledged (ASHRAE 1993; Turner and Malloy 1981). Low-density insulations are particularly susceptible to increased thermal conductivity over the temperature range of interest (e.g., insulation conductivity is rated at 24°C, while attic temperatures may reach 55°C during summer days). At densities of commonly used building insulations (16 kg/m^3), the apparent thermal conductivity may be increased by as much as 15% by an increase of 17°C in the mean temperature (Tye et al. 1980).

Regardless of the apparent superior cooling-related performance of reflective roof materials, simulation analysis suggests that part of the summer space-cooling energy savings of reflective roofs may be offset by increased winter heating needs. There are reasons to believe the impact may be diminished, since winter solar irradiance values are typically much lower than during summer conditions and peak heating demand frequently takes place during nighttime hours. Obviously, however, the absolute values of relative space-conditioning energy used for space cooling vs. heating will influence the potential impact and hence will be linked to climate.

FLEXIBLE ROOF TEST FACILITY

Since roof solar reflectance is the fundamental property influencing the above-described savings, the degradation of surface reflectance over time can potentially affect savings persistence. Other relevant research to the above field studies has been performed in Florida at a roof facility. This consists of a 24 ft by 48 ft (7.3 m by 14.6 m) building with the roof segmented into six individual test cells. Temperature and heat flux data are being collected for different roof configurations. These include conventional asphalt shingle roofs, similar sections with radiant barriers, colored tiles roofs, and a shingle roof section covered with a white elastomeric coating.

The east-west orientation of the building provides a north-south exposure of the different roofing products under test. The six individual test bays (detail A, Figure 6) span three two-foot trusses, or six feet, and are sepa-

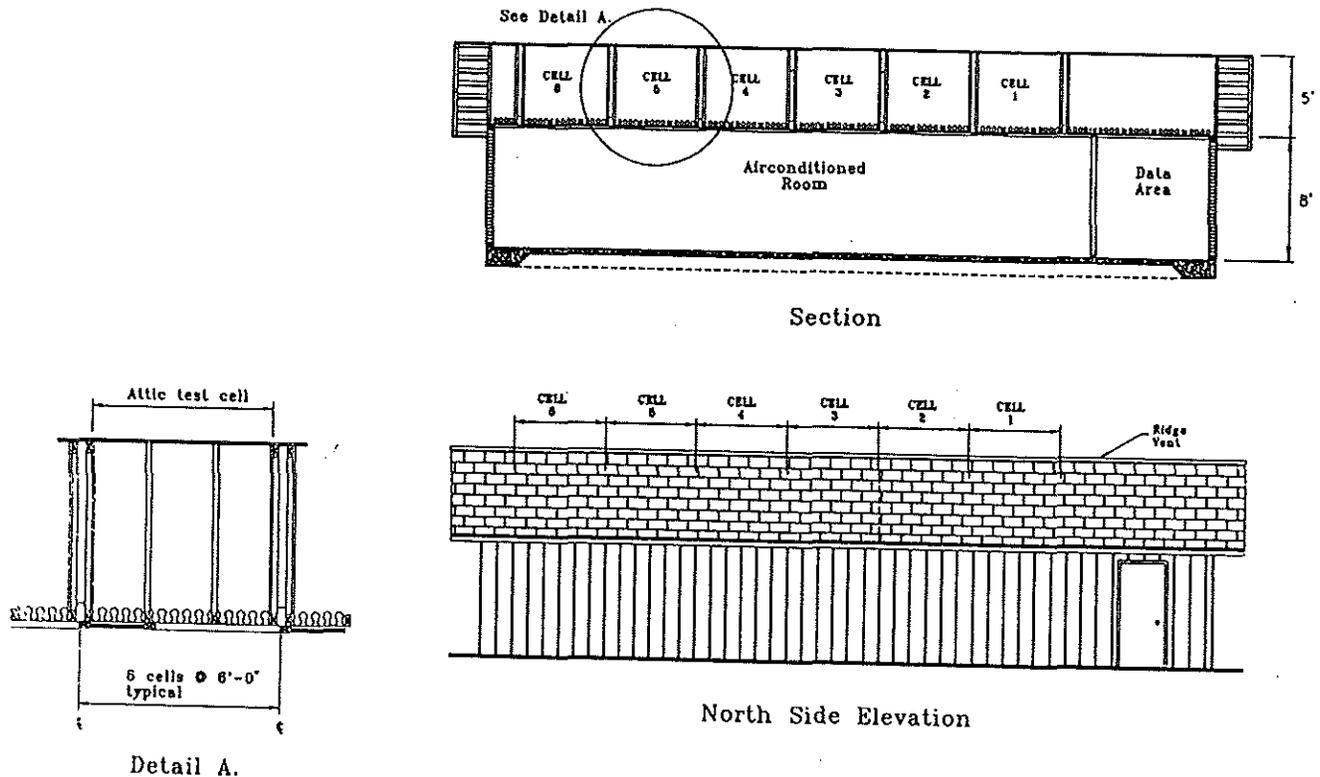


Figure 6 Flexible Root Test Facility (FRF).

rated by insulated partition walls. The attic floor is insulated to $R-19 \text{ ft}^2 \cdot \text{h} \cdot ^\circ\text{F}/\text{Btu}$ ($\text{RSI } 3.3 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$), with the partition walls insulated to approximately $R-20$ ($\text{RSI}-3.5$) to thermally isolate the cells from each other. The interior of the facility is a single, open conditioned space.

Measurement data available from the site include temperatures from the interior, exterior, and attic of the building. A meteorological station incorporating ambient dry-bulb temperature, solar radiation, wind speed, and wind direction is located at the site. Data are recorded on a 180-channel data logger and stored on a mainframe computer. This system allows for sophisticated analysis employing real data recorded in a full-scale, residential environment without the attendant difficulties found when monitoring occupied dwellings.

The facility allows the simultaneous testing of six different residential roofing systems. Testing has been conducted on black-and-white shingled roofs, both with and without radiant barrier systems. Research has also been conducted on different ridge and soffit vent configurations.

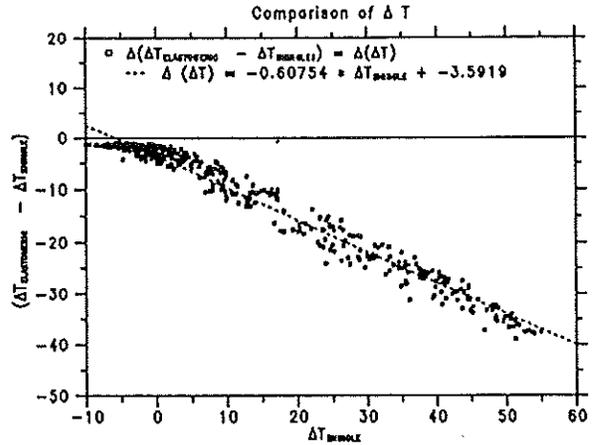
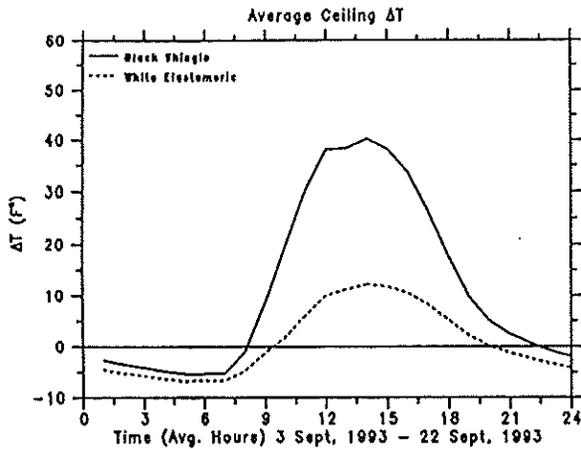
The discussion in this paper will confine itself to a comparison of the data on the white vs. black shingle

sections. An elastomeric roof coating was applied to the black shingle roof of cell 6 on September 2, 1993. The paint was applied with a roller, with the job requiring three coats. The temperature difference (ΔT) across the ceiling was reduced by approximately 60%. As time passed, this reduction became less pronounced. When the coating was applied, glare from the roof's solar reflectance was great enough to cause visual discomfort. During the first winter, the reflectance was noticeably lower and the roof developed a green algae growing on its surface.

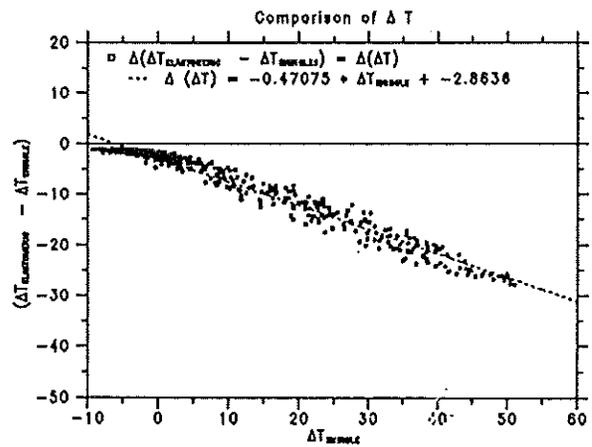
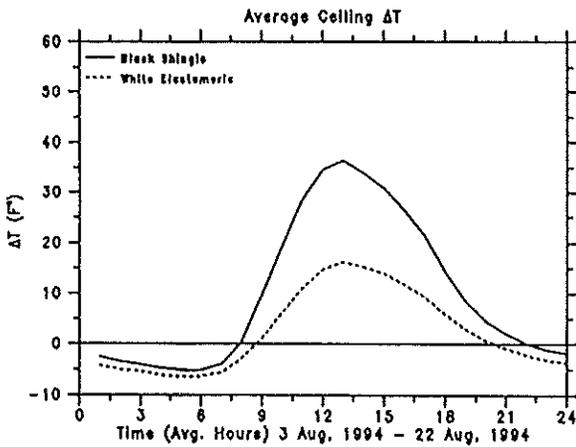
An illustration of the energy-savings potential and the degradation problem of reflective roofing systems is shown in Figure 7. The graphs present the ceiling ΔT reported from cell 6 (elastomeric) and cell 5 (black shingles). The ΔT s are calculated by subtracting the interior drywall temperature from the insulation surface temperature. The upper pair of graphs represents the period directly following installation, while the lower pair represent the installation after 350 days of exposure.

The graphs on the left side of Figure 7 plot the time-averaged ΔT s for the test periods reported (x-axis). The

Initial Installation



One-Year Exposure



South Component

Figure 7 Measured change in ceiling heat flux reduction from white vs. black shingle roof over a one-year period.

area between the two lines on these graphs represents the heat flux reduction provided by the elastomeric roof system. For example, when first installed, the black shingle roof had a ΔT of approximately 40°F (22°C) during the fourteenth hour. The elastomeric roof had a ΔT of approximately 10°F (5.6°C) for the same period. This difference is quantified by the graphs on the right-hand side of the plot.

The graphs on the right-hand side of the figure chart the heat flux reduction of the two roofing systems. The difference between the ΔT s of the two roofs (elastomeric minus black shingle) is plotted vs. the ΔT of the black shingle roof. When the points generated by this plot are regression fit to a linear equation, the results indicate the fractional heat flux reduction between the two cells.

The x-axis of the right-hand graphs represent the ΔT of the black shingle roof. The y-axis values are ΔT differ-

ences found by subtracting the ΔT of the elastomeric roof from that of the black shingle roof. The points on the graph represent the ΔT difference at that particular ΔT of the black shingle roof. If these values are subjected to a linear fit, the result represents the fractional heat flux reduction with an offset. The resulting linear fit is represented by the dashed line through the points. The equation generated by the fit is shown at the top of the graph.

Together, the two sets of graphs illustrate both the performance potential and the degradation of the elastomeric coating. The ceiling heat flux reduction delivered by the elastomeric coating was reduced by more than 13% after 350 days of exposure—from 60% to 47%. The initial heat flux reduction (60%) was greater than any of the other tested combinations (tile, radiant barriers, etc.). A preliminary report on this research is available (Beal and Chandra 1994).

Samples of the elastomeric coating were tested for solar reflectance using ASTM Test E-903. Initially, the coated shingle had a solar reflectance of 0.71. After exposure, the solar reflectance of a sample was reduced to 0.59, or a 17% reduction in solar reflectance. Most of the observed surface discoloration appeared to come from blue-green algae (*Gloeocapsa magma*), although some of the reduced reflectance was also due to dust and dirt accumulation. A plot of the spectral reflectance of the original and aged coated samples showed that the reduced reflectance is concentrated in the visible range. Thus, although the data show a considerable heat flux reduction potential from the white roof surface, some method of mitigating reflectance degradation is vital to maintaining performance as well as an aesthetically acceptable appearance. Conversations with materials specialists in the coatings industry suggest that microbial-resistant formulations centered around the use of zinc oxide are readily available to treat the identified problem.

Researchers have been re-examining the roof solar reflectance of the coated field sites every six months. The observed degradation in solar reflectance has been 5% and 11% at sites 1 and 2, respectively, over a two-year period. However, the white ceramic coating applied in 1991 at site 0 degraded by 37% over a three-year period. The most significant work on this issue has been performed at two national laboratories (Bretz and Akbari 1993; Byerley and Christian 1994). Evidence of mold, mildew, and blue-green algae has been observed, particularly on shaded portions of the roof at site 3. Dirt accumulation was also in evidence but appeared to be less of a contributing factor to the lowered reflectance.

A noted effect of such white roof systems is that their exposed surfaces are wet for much longer periods than conventional types. This occurs because the lower roof-decking-attic temperatures cause the roof surface to fall below the dew point earlier each evening. Then, during the morning hours, the accumulated surface moisture takes a much longer time to evaporate since the roof system is slow to warm. Based on our observations of a number of white roofs, including those not part of our research, it appears that the reflectivity degradation rate will depend on roofing system geometry and smoothness, roof slope, and ambient relative humidities and dust levels. Pitched standing-seam metal roofs appear to have the fewest problems of the types observed.

CONCLUSIONS

Field research has examined the effect of reflective roof coatings on submetered air-conditioning consumption in a series of tests in eight homes in Florida. Coatings were applied to the residences at mid-summer after an initial period of monitoring. Using weather periods with similar temperatures and solar insolation, air-conditioning energy use was reduced by 2% to 43% at the

various sites.² The average drop in space-cooling energy use was 7.4 kWh/day, or 19% of the pre-application air-conditioning consumption. Utility coincident peak electrical demand reduction between 5 and 6 p.m. varied from 201 to 988 W (12% to 38%). Peak reduction for the homes averaged 427 W, or 22%. Other factors being equal, savings levels appeared to be strongly influenced by pre-existing ceiling insulation levels and whether the thermal distribution system was located in the attic.

Average electricity consumption for central air conditioning in single-family homes in Florida is approximately 4,400 kWh/yr (SRC 1993). Based on a savings level of 10% to 40%, reflective roofs can be expected to reduce household electricity use by 440 to 1,760 kWh/yr—an annual savings of \$35 to \$140 at current electricity rates.

Further research at a reconfigurable roof test facility showed that reflective roof coatings could reduce ceiling heat fluxes by up to 60% over dark shingles. However, the same testing showed significant degradation in the measured solar reflectance over a year-long period. Reductions to ceiling heat flux degraded by 22% relative to the original value (60% to 47%) against a 17% reduction in measured solar reflectance (71% to 59%). Microbial growth (blue-green algae) and dirt accumulation were seen as primarily responsible for the degradation.

The investigators conclude that the use of reflective roofs in Florida can represent an attractive option to reducing space-cooling energy. The data collected so far suggest that air-conditioning savings averaging 2% to 40% can be realized, with the larger reductions associated with poorly insulated roof assemblies or buildings with excessive attic air infiltration due to air handler return air leakage. Reflective coatings may be particularly appropriate for existing Florida residences in which the roof structure makes it difficult to retrofit insulation. Key research issues remaining for development of the technology include climate-related heating interactions and development of roofing materials that are resistant to solar reflectance degradation.

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²When Site 7, which experienced elevated internal gains in the post period, is removed from the data set, the percentage of savings range from 9% to 43%. The average electricity savings then becomes 8.2 kWh/day (21%).

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