Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida

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ABSTRACT

Roof and attic thermal performance exert a powerful influence on cooling energy use in Florida homes. The Florida Power and Light Company and the Florida Solar Energy Center instrumented six side-by-side Habitat homes in Ft. Myers, Florida with identical floor plans and orientation, R-19 ceiling insulation, but with different roofing systems designed to reduce attic heat gain. A seventh house had an unvented attic with insulation on the underside of the roof deck rather than the ceiling:

- (RGS) Standard dark shingles (control home)
- (RWB) White "Barrel" S-tile roof
- (RWS) Light colored shingles
- (RWF) White flat tile roof
- (RTB) Terra cotta S-tile roof
- (RWM) White metal roof
- (RSL) Standard dark shingles with sealed attic and R-19 roof deck insulation

Building thermal conditions and air conditioning power usage were obtained. The attic temperature during the peak summer hour is 40°F greater than ambient air temperature in the control home while no greater than ambient with highly reflective roofing systems. Light colored shingles and terra cotta roofs show temperatures in between those extremes.

Measurements showed that the three white reflective roofs would reduce cooling energy consumption by 18-26% and peak demand by 28-35%. The terra cotta tile roofs and white shingles would produce cooling savings of 3-9% and 3-5%, respectively, while the sealed attic construction with an insulated roof deck would produce reductions of 6-11%.
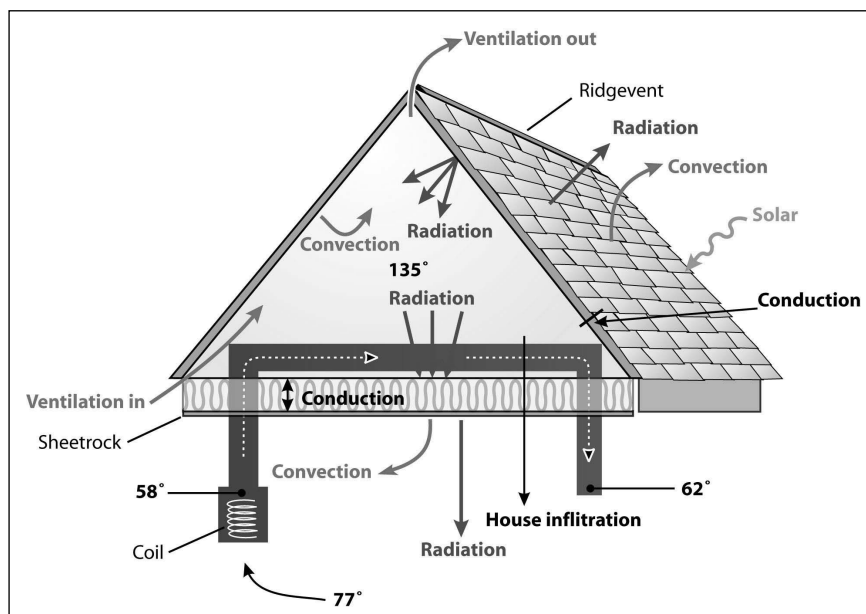
Introduction

Traditional architecture in hot climates has long recognized that light building colors can reduce cooling loads (Langewiesche, 1950; Givoni, 1976). A series of simulation and experimental studies have demonstrated that building reflectance can significantly impact cooling needs (Givoni and Hoffmann, 1968; Taha et al., 1988; Griggs and Shipp, 1988, and Bansal et al., 1992). Full building field tests in Florida and California using before-after experiments have examined the impact of reflective roofing on air conditioning (AC) energy use. In Florida tests measured AC electrical savings averaged 19% (7.7 kWh/Day) (Parker et al., 1998). Even greater fractional savings have been reported for similar experiments in California (Akbari, et al., 1992). Beyond roof reflectance, additional research has shown that other approaches such as tile roofs and unvented attics with insulation under the roof itself,

can produce cooler attics resulting in energy improvements, but of unknown comparative magnitude (Beal and Chandra, 1995; Rudd, 1998; Rudd et al., 2000).

Duct systems are often located in the attic space in Sun Belt homes with slab on grade foundations. In an early assessment of the impact of reflective roofing, infrared thermography revealed that heat gain to attic-mounted duct systems and air handlers are adversely affected by hot attics (Parker et al, 1993B). As shown in Figure 1, previous analysis has shown that attic heat gain to the thermal distribution system can increase residential cooling loads by up to 30% during peak summer periods (Parker et al., 1993; Jump et al, 1996). Further benefits arise from the reduction of attic air temperature and its impact on ceiling insulation conductivity (Levinson et al., 1996).

Figure 1. Vented Attic Thermal Processes and Interaction with Duct Heat Gain

Research Description

While previous research efforts have investigated the thermal performance of various roofing systems, this particular study represents the first time an attempt has been made to quantify roofing influence on cooling performance on identical, unoccupied, side-by-side residences. The project consisted of seven, single-family residential homes located in Ft Meyers, Florida. The focus of the study was to investigate how various roofing systems impact air conditioning electrical demand. All seven residences had a three bedroom, one bath floor plan and were of identical construction and exposure. The houses underwent a series of tests in order to ensure that the construction and mechanical systems performed similarly. The sites were given a three-letter code to describe each roofing system:

- Dark gray fiberglass shingles (RGS)
- White barrel-shaped tile (RWB)
- White fiberglass shingle (RWS)

- Flat white tile (RWF)
- Terra cotta barrel-shaped tile (RTB)
- White 5-vee metal (RWM)
- Sealed attic with insulation on the roof plane (RSL)

Monitoring collected 15-minute data on comparative performance of the seven homes in the summer of 2000 under unoccupied and carefully controlled conditions for a month. Relevant construction details are summarized in Table 1.

Table 1. Construction Characteristics for Research Homes

Floor area:	1144 ft^2 (conditioned)
Net Wall area:	770 ft^2
Window area:	101 ft^2; six single glazed units with light gray tint
	- 45 ft^2 facing east (3 units)
	- 40 ft^2 facing south (2 units)
	-15 ft^2 facing west (1 unit)
Ceiling:	1144 ft^2
Doors:	40 ft^2; 2 doors (one to unconditioned garage).
Overhang:	2 ft around entire perimeter
Ceiling Insulation:	R-19 (blown cellulose)
Wall Insulation:	R-14 (fiberglass batts R-11 with R-3 sheathing)
Wall Construction:	Wood frame (16 inches on center)
Roof Construction:	Hip roof, 18.4 degree pitch (0.15 framing fraction)
Foundation	Uninsulated, concrete slab on grade

Roofing Solar Reflectance

Laboratory reflectance measurements were taken on each of the evaluated roofing materials (Table 2). Reflectivity is the fraction of total incident solar radiation reflected by a surface.

Table 2. Laboratory Measured Solar Reflectances of Utilized Roofing Materials

Specimen	% Solar Reflectance
Dark gray shingle (RGS, RSL)	8.2
White shingle (RWS)	24.0
Terra Cotta barrel tile (RTB)	34.6
White barrel tile (RWB)	74.2
Flat white tile (RWF)	77.3
White metal (painted)* (RWM)	66.2

Sealed Attic Construction RSL

The seventh house (RSL) tested a new approach to residential insulation: an attic completely sealed and with a spray foam insulation applied to the underside of the roof

decking in place of conventional blown or batt insulation. The scheme insulates at the roof decking rather than at the surface of the living space ceiling. Two primary advantages are significantly less duct heat load within the attic space as well as reduced humidity and infiltration. Research has shown this as a promising construction technique (Rudd and Lstiburek, 1998; et al., 2000) in a series of production homes in Las Vegas, Nevada and Tucson, Arizona.

One potential disadvantage is that the roof insulation can result in significantly higher decking and roof surface temperatures. Also, the insulation at the roof deck has a more difficult task since it is working against 170° (temperature of roofing) rather than 130° (temperature on top of insulation in a conventional attic at summer peak). The ducts are exposed to less heat gain, but building heat transfer surface areas are increased relative to the conventional case.

The roofing system on the RSL home was identical to that in the control home, dark gray composition shingles over roofing felt and decking. The external appearance was like the conventional homes, however foam insulation was used in the roof deck rather than cellulose insulation in the ceiling assembly. The attic floor consisted solely of rafter and ½ inch gypsum board. The roof deck of the RSL was covered with 5 inches of insulating foam. Application thickness was targeted to achieve an R-19 application – similar in thermal resistance to the cellulose insulation in the other homes. The installed product is a semi-rigid polyurethane foam insulation with a nominal density of 0.45 - 0.5 lbs/ft^3 and an R-value of 3.81 ft^2-hr- ^{o}F/Btu/inch. The product also claims to help improve air sealing of the home by controlling leakage from building joints.

Calibrating Thermostats and Influence of Set Temperature

Since variation in interior thermostat temperature was known to be a large variable controlling differences in space cooling, special effort was made to carefully adjust the thermostats in each home so that each was closely maintaining the same interior temperature. This was done using thermocouples which measured the temperature in a central hallway by the thermostat, but not overly close to it due to the heat emitted from the electronics within the digital thermostat.

To evaluate the impact of thermostat set temperature the thermostats were adjusted up one ^{o}F for four days at the end of the project before the homes were occupied. The typical increase was from 77° to 78°. These data were used to examine how the thermostat set-up influenced cooling in order to properly adjust project results. This was accomplished by searching for days in the set-up period having similar weather conditions. As expected the impact was greatest on the cooler days where the outdoor temperature approached the thermostat set temperature and solar radiation impacts were minimized. Over the comparison, space cooling decreased by an average of 12.1% per ^{o}F that the temperature was increased. When confined only to the peak day, the impact was 8.3% per ^{o}F.

Results over the Monitoring Period

The relative performance of the homes over the entire unoccupied monitoring period was evaluated. The five figures below (Figures 2-6) show the fundamental impacts of the

roofing system on cooling energy consumption over the entire unoccupied monitoring period from July 8th - July 31st, 2000.

Figure 2 depicts the ambient average air temperature and solar conditions over the entire unoccupied period. Figures 3, 4 and 5 show the thermal influences of the roofing system. The first plot graphs the average roof surface temperature over the daily cycle. The second plot shows the corresponding temperature at the underside of the roof decking surface. Note that the roof surface temperature and decking temperature are highest with the sealed attic construction since the insulation under the decking forces much of the collected solar heat to migrate back out through the shingles. On average the shingles reach a peak temperature that is seven degrees hotter than standard construction. However, decking temperatures run almost 20°F hotter. The white roofing systems (RWM, RWF and RWB) experience peak surface temperatures approximately 20°F lower than darker shingles. The terra cotta barrel tile case runs about 10° cooler.

The measured mid attic air temperatures (Figure 5) above the ceiling insulation revealed the impact of white reflective roofs with average peak temperatures approximately 20° cooler than at the control home. Whereas the attic in the control home reaches 110°F on the typical day, the attics with the highly reflective white roofing materials only rise to about 90°F. Figure 6 shows the clear relationship between peak daily air temperature and attic temperature for the differing roofing systems.

Figure 2. Average Ambient Air Temperature and Solar Irradiance over the Unoccupied Period
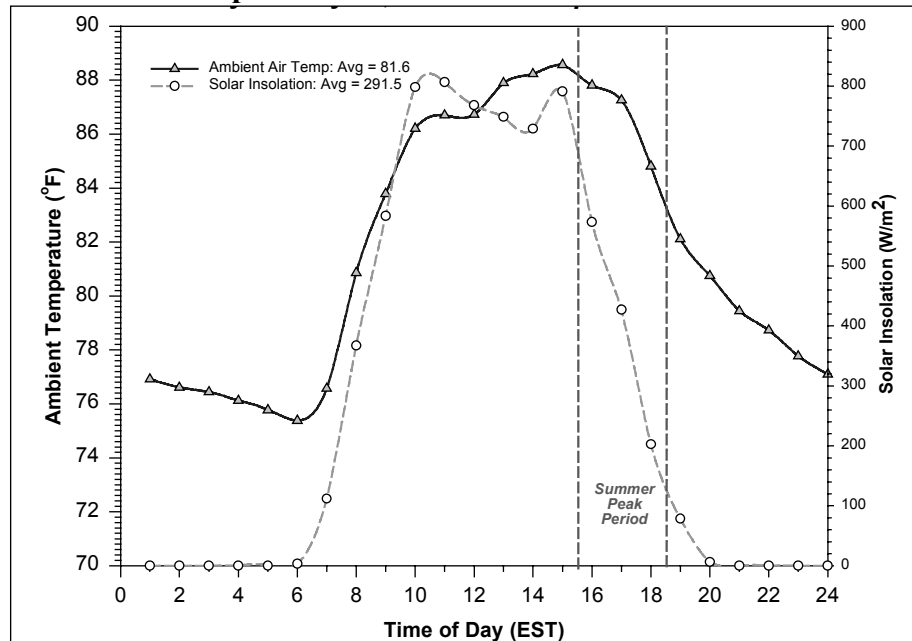
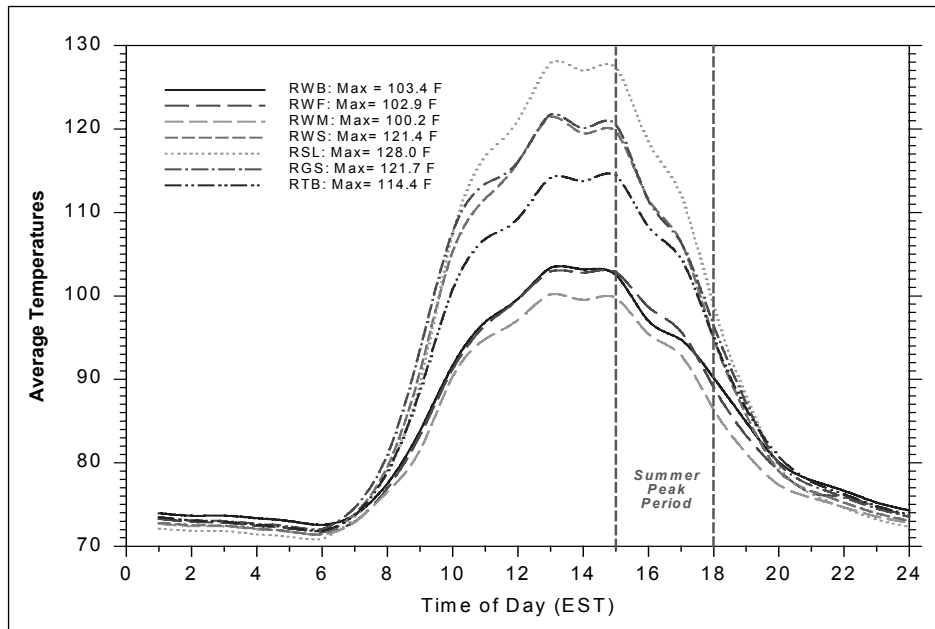**Figure 3. Average Roof Surface Temperature Profiles over the Unoccupied Period**

Legend:
RWB: Max = 103.4 F
RWF: Max= 102.9 F
RWM: Max= 100.2 F
RWS: Max= 121.4 F
RSL: Max= 128.0 F
RGS: Max= 121.7 F
RTB: Max= 114.4 F

Summer Peak Period

Average Temperatures vs. Time of Day (EST)

Figure 4. Average Roof Decking Surface Temperature Profiles over the Unoccupied Period

Legend:
RWB: Max = 90.87 F
RWF: Max= 88.78 F
RWM: Max= 94.80 F
RWS: Max= 116.06 F
RSL: Max= 135.46 F
RGS: Max= 118.18 F
RTB: Max= 102.14 F

Summer Peak Period

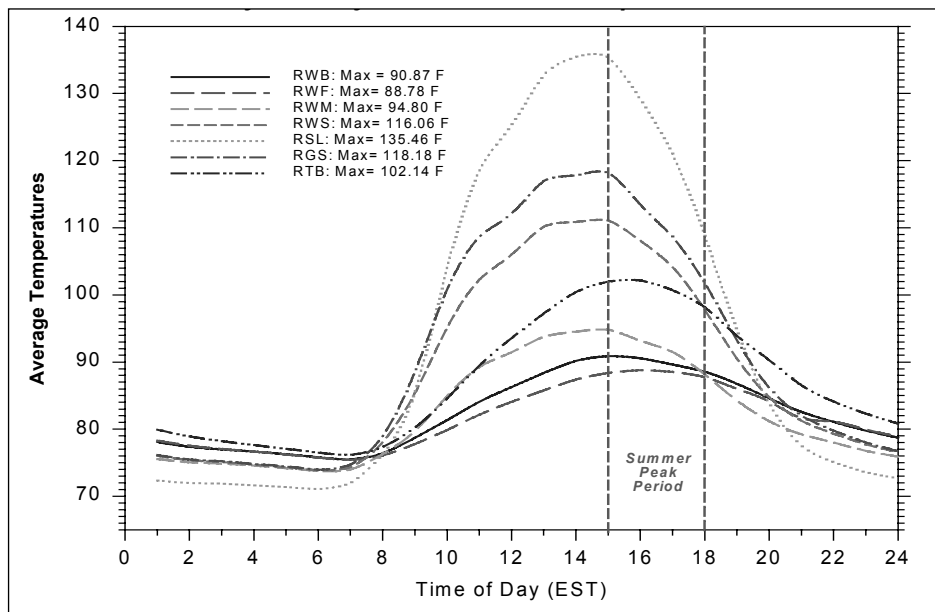Average Temperatures vs. Time of Day (EST)

1.224

Figure 5. Average Attic Air Temperature Profiles over the Unoccupied Period
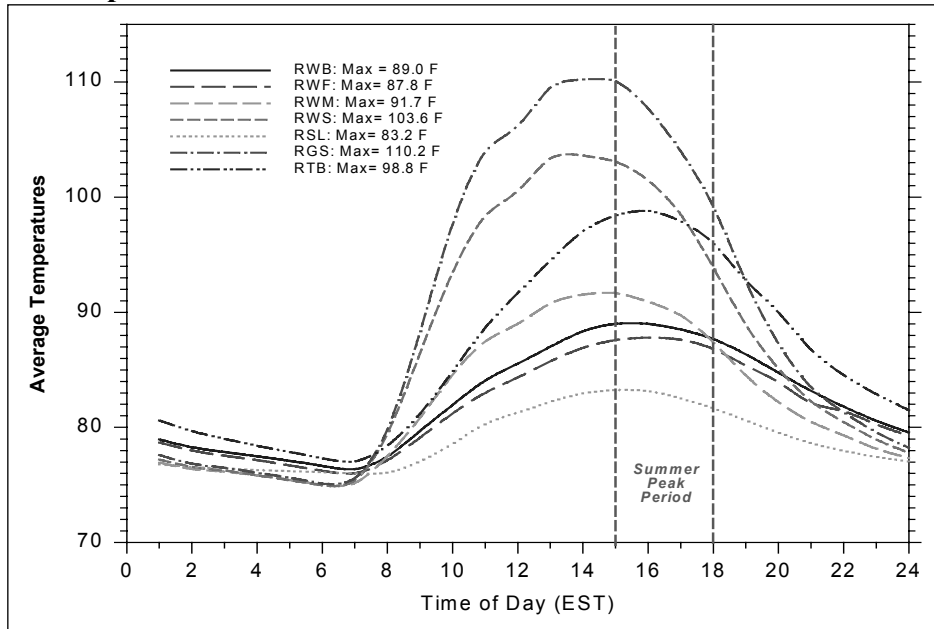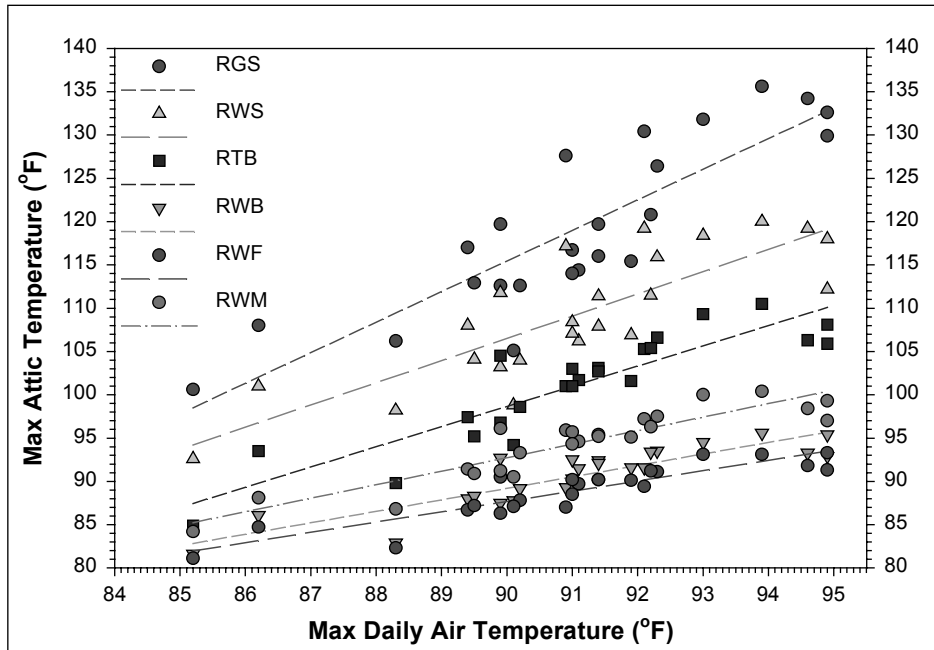

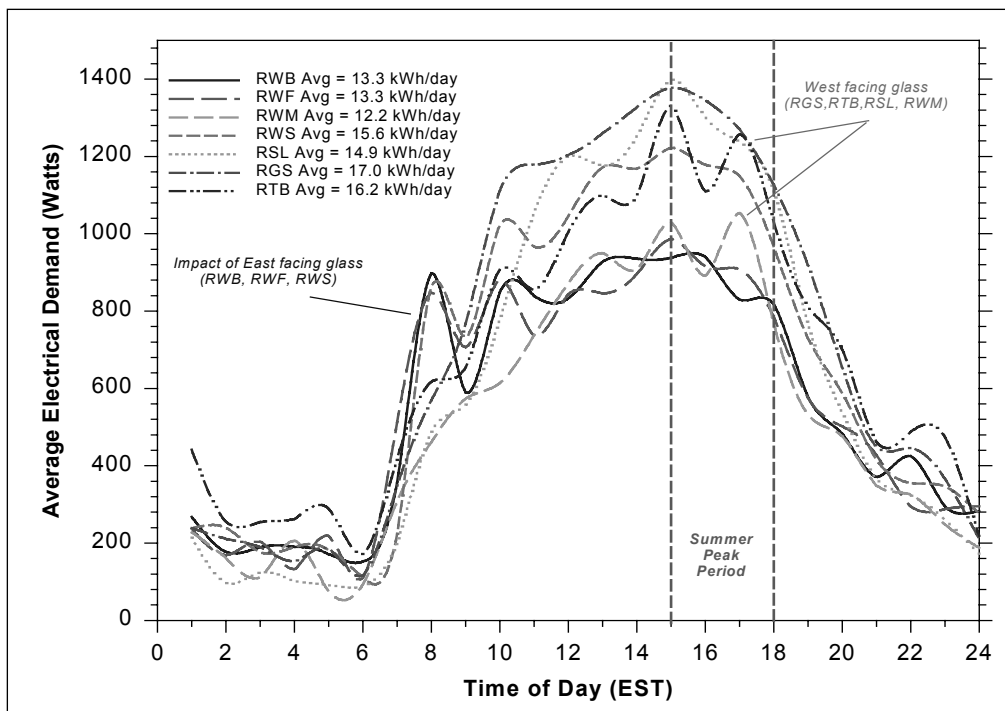**Figure 6. Relationship of Daily Peak Air to Peak Attic Temperature**

As expected, the home with the sealed attic had the lowest attic temperatures reaching a maximum of 83°F compared with the 77°F being maintained inside. However, the sealed attic case has no insulation on the ceiling floor with only studs and sheet rock. Thus, from a cooling loads perspective, the low attic temperature with this construction is deceptive. Since ½ inch sheet rock only has a thermal resistance of 0.45 hr-ft^2-^{o}F/Btu, a significant level of heat transfer takes place across the uninsulated ceiling. *While this construction method*

reduced attic air temperatures, it did not reduce ceiling heat transfer as well as other options. Ceiling heat fluxes are actually higher. In this case, the ceiling and duct system is unintentionally cooling the attic space which can lead to the false impression that roof/attic loads are lower.

Figure 7 summarizes the measured cooling load profiles for the seven homes over the unoccupied monitoring period. Not surprisingly, the control home has the highest consumption (17.0 kWh/day). The home with the terra cotta barrel tile has a slightly lower use (16.2 kWh/day) for a 5% cooling energy reduction. Next is the home with the white shingles (15.6 kWh/day) – an 8% reduction. The sealed attic comes in with a 12% cooling energy reduction (14.9 kWh/day).

Figure 7. Average Space Cooling Energy Demand Profiles over the Unoccupied Period

The true white roofing types (> 60% reflectance) clearly show their advantage. Both the white barrel and white flat tile roofs averaged a consumption of 13.3 kWh/day or a 22% cooling energy reduction, while the white metal roof shows the largest impact with a 12.2 kWh/day August consumption for a 28% reduction. The numbers in Table 3 are adjusted to account for differences in interior temperature and AC performance:

Table 3. Cooling Performance During Unoccupied Period: July 8th - 31st, 2000

Site	Total kWh	Savings kWh	Save %	Thermo-stat	Avg. Attic °F	Max. Attic °F	Temp. Adjust. %	Adjust Sav. %	Field EER	Final Sav. %
RGS	17.03	0.00	0.0	77.15°	90.8	135.6	0.0	0.0	8.30	0.0
RWS	15.29	1.74	10.2	77.03°	88.0	123.5	-1.2	11.4	9.06	10.6
RSL	14.73	2.30	13.5	77.69°	79.0	87.5	5.4	8.1	8.52	7.8
RTB	16.02	1.01	5.9	76.99°	87.2	110.5	-1.6	7.5	8.12	7.7
RWB	13.32	3.71	21.8	77.43°	82.7	95.6	2.8	19.0	8.49	18.5
RWF	13.20	3.83	22.5	77.36°	82.2	93.3	2.1	20.4	7.92	21.5
RWM	12.03	5.00	29.4	77.64°	82.9	100.7	4.9	24.5	8.42	24.0

It is noteworthy that the average July temperature during the monitoring period (81.6°F) was very similar to the 30-year average for Ft. Myers (82°F). Thus, the current data are representative of typical South Florida weather conditions. Relative to the standard control home, the data show two distinct groups in terms of performance:

- Terra Cotta tile, white shingle and sealed attic constructions produced approximately an 8-11% cooling energy reduction
- Reflective white roofing gave a 19-24% cooling energy reduction.

White flat tile performed slightly better than the white barrel due to its greater reflectance. The better performance of white metal appears to come from the fact that lower nighttime and early morning attic temperatures are achieved than those for tile or shingles, leading to lower nighttime cooling demand.

Peak Day Performance

July 26th was one of the hottest and brightest days in the data collection period and was used to evaluate peak influences. Average solar irradiance was 371 W/m^2 and maximum temperature was 93.0°F. These data show that during periods of high solar insolation the performance of the sealed attic case (RSL) suffers significantly. Decking and attic temperatures are illustrated in Figures 8 and 9. For instance, both the tile roof and white shingle did better at controlling demand than the sealed attic on this very hot day. The white metal roof did best on the hottest day although not appreciably different from the other white roofing types. Also, the savings for the white roofs relative to the control were greater than for other days.

Table 4. Summer Peak Day Cooling Performance: July 26th, 2000

Site	Cooling Energy	Savings		Peak Period*		
		kWh	Percent	Demand (kW)	Savings (kW)	Percent
RGS	18.5 kWh		----	1.631	0.000	----
RWS	16.5 kWh	2.0	11%	1.439	0.192	11.8%
RSL	16.5 kWh	2.0	11%	1.626	0.005	0.3%
RTB	17.2 kWh	1.3	7%	1.570	0.061	3.7%
RWB	13.4 kWh	5.1	28%	1.073	0.558	34.2%
RWF	14.2 kWh	4.3	23%	1.019	0.612	37.5%
RWM	12.4 kWh	6.1	33%	0.984	0.647	39.7%

* 4-6 PM

Figure 8. Roof Decking Temperature Profiles for July 26, 2000

RWB: Max = 98.1 F
RWF: Max= 94.9 F
RWM: Max= 105.9 F
RWS: Max= 129.3 F
RSL: Max= 166.2 F
RGS: Max= 143.5 F
RTB: Max= 114.3 F

Summer Peak Period
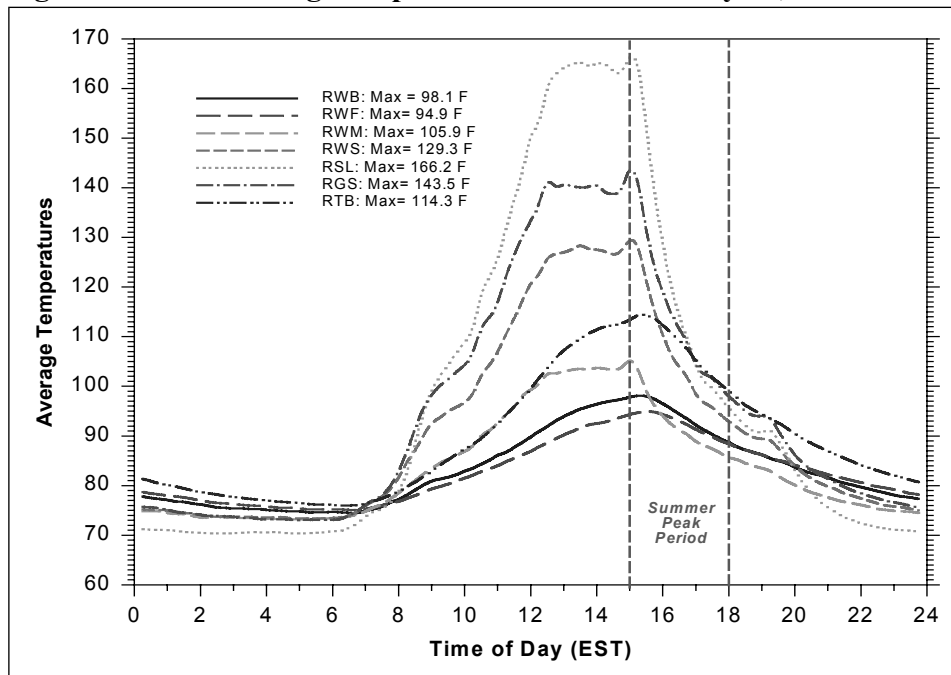
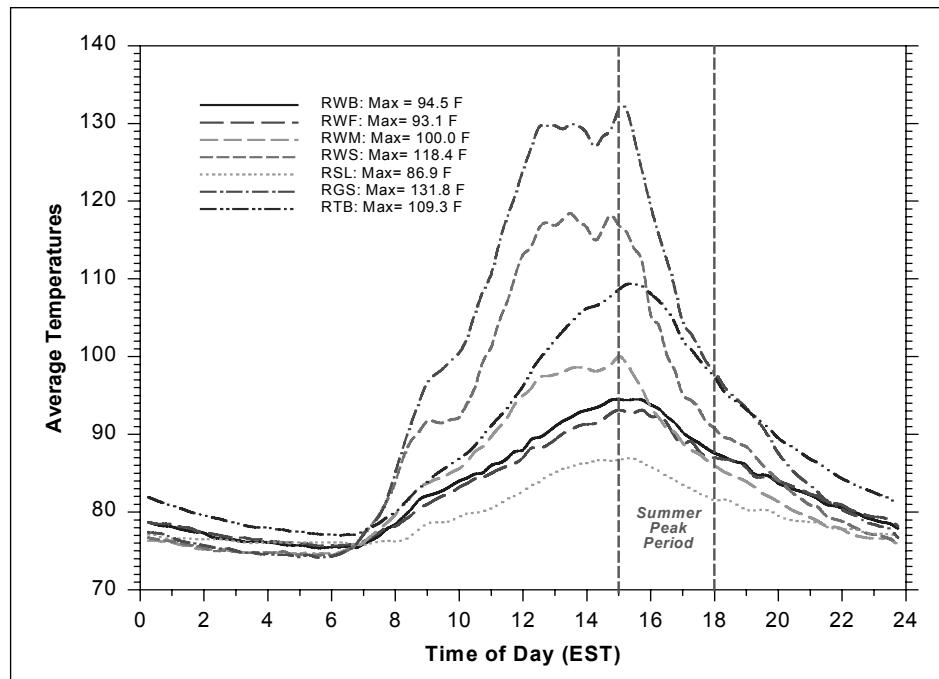Average Temperatures

Time of Day (EST)

Figure 9. Attic Temperature Profiles for July 26, 2000

Analysis of Energy Savings

We calculated the annual cooling energy savings of the differing roofing materials by two methods. First we estimated the normalized daily average reduction in cooling kWh from each construction and then multiplied this quantity by one over the fraction of average cooling which takes place in the month of July. The normalized savings are the values in Table 5 incorporating correction factors for air conditioner performance and interior temperature differences.

The fraction of space cooling in the month of July was obtained from averaged empirical monitoring results from a large sample of homes metered by the utility. These data show that 15.6% of total annual cooling in the South region occurs in the month of July. Total average cooling there for the month is 1,141 kWh or about 36.8 kWh/day. Since the homes in the Habitat study are only about 60% of the average size of a typical new home, we suggest that savings be indexed by the size of the ceiling against that in the study (1,144 ft^2).

Table 5. Annual Cooling Energy Savings from Empirical Measurements

Site	Measured kWh/Day	Temp Correction AC Correction	kWh Day Estimate	Savings (kWh/day)	Annual Savings kWh*
RGS	17.03	1.000 / 1.000	17.03	0.00	0
RWS	15.29	0.988 / 1.092	16.49	0.54	110
RSL	14.73	1.054 / 1.027	15.94	1.09	223
RTB	16.02	0.984 / 0.978	15.42	1.60	329
RWB	13.32	1.021 / 0.954	14.01	3.02	618
RWF	13.20	1.049 / 1.014	12.86	4.17	852
RWM	12.03	1.028 / 1.023	12.80	4.23	864

* The estimate is based on a ratio of 6.59 for South (1/0.1517 for 15.17% of cooling in July). House size assumptions must be accounted for when estimating average savings or those for a specific case.

An alternative calculation was made using daily regression results. The independent parameters are the daily air temperature and average solar radiation (global horizontal irradiance) that are used to estimate the daily average kWh at that temperature and irradiance value. The regressions for each home are then applied to Typical Meteorological Year (TMY) data for Miami, Florida. The results shown in Table 6 become the estimated space cooling use for each construction. Savings are then normalized by the temperature, air conditioner performance corrections and house size to yield final estimates.

Table 6. Annual Cooling Energy Savings from Regression Analysis Method

Site	kWh	kWh Savings (*)
RGS	3679	0
RWS	3471	208 (191)
RSL	3242	437 (404)
RTB	3570	109 (113)
RWB	2809	870 (893)
RWF	2859	820 (771)
RWM	2584	1095 (1041)

(*) Normalized to correct for off-reference temperature and AC performance.

Peak Demand Reduction

Summer peak demand savings were also estimated in two ways. First we used the measured demand of the seven houses between the hours of 4 and 6 PM on the peak day (July 26, 2000). This estimate should be indexed to the ceiling area for typical houses. Considering that the typical Florida home likely has a ceiling area averaging about 1770 square feet, the ratio of the impact would be approximately 55% greater than that estimated here (1,144 ft^2 ceiling). This also better fits the average cooling energy demand from end-use studies from the utility that show a summer peak AC demand of approximately 2.9 kW in occupied homes. Our monitoring study showed an average peak demand of 1.63 kW in the control home. The average peak demand for the study sites (based on the peak data for July 26th) are reproduced previously in Table 4.

The second method of estimating demand reductions used hourly regression equations. To estimate peak impacts, the regressions were evaluated at an outdoor temperature of 92°F – which is close to the peak design temperature at 5 PM.

The regression analysis method estimates in Table 7 show higher peak demand impacts. Demand reduction for the sealed attic construction is very small (<0.2 kW) whereas white shingle and terra cotta tile roof produce a demand reduction of 0.4 - 0.5 kW. The white highly reflective roofing systems produced demand reductions of 0.8 - 1.0 kW.

Table 7. Regression Estimated Cooling Peak Demand in Research Homes

Site	Demand kW	Reduction kW	Demand Reduction[+] kW	Demand Reduction %
RGS	1.788	0.000	0.00	0.0%
RWS	1.480	0.308	0.48	17.2%
RSL	1.701	0.087	0.13	4.9%
RTB	1.558	0.230	0.36	12.9%
RWB	1.197	0.591	0.92	33.0%
RWF	1.153	0.635	0.98	35.5%
RWM	1.278	0.510	0.79	28.5%

+ Normalized to 1,770 ft^2 typical home.

Simulation Analysis

FSEC has developed a hourly building energy software, EnergyGauge® USA, which runs based on the DOE-2.1E simulation engine. A key new component in this software explicitly estimates the performance of attics and the interactions of duct systems if located there. In Florida homes, ducts are almost always in the attic space and previous analysis shows that under peak conditions, the cooling system can lose up to 30% of its cooling capacity through heat transfer with the hot attic (Parker et al., 1993). The software has previously been used to estimate the impact of reflective roofing around the U.S. (Parker et al., 1998). It has been field validated in estimating the space cooling energy use of three homes in Ocala, Florida.

We created detailed input descriptions of each of the 1,114 ft^2 Habitat homes in the study (including the shading impacts of surrounding buildings) and simulated their performance to see how closely the simulation could match the measured results. Table 8 shows the results.

Table 8. Simulation Analysis Results

Building Site	Annual Cooling (kWh)	Cooling Savings (kWh)	July Cooling kWh (kWh/D)	Peak Cooling Demand	
				(kW)	Reduction
RGS	2,666	----	503 (16.2)	1.61	----
RWS	2,549	117	484 (15.6)	1.51	0.10
RSL	2,646	20	493 (15.9)	1.42	0.19
RTB	2,450	216	467 (15.1)	1.30	0.31
RWB	2,211	455	427 (13.8)	1.17	0.44
RWF	2,191	475	424 (13.7)	1.18	0.43
RWM	2,281	385	441 (14.2)	1.39	0.22

We noted that the simulation predicts very similar absolute values to the measured space cooling at the sites, although predicted savings are somewhat less than those measured. Both the monitoring and simulation shows the white roofing types to provide the greatest savings and peak demand impact, followed by the tile roof, white shingle and sealed attic construction.

Conclusions

Roof and attic thermal performance exerts a powerful influence on cooling energy use in Florida homes. Unshaded residential roofs are heated by solar radiation during the daytime hours causing high attic air temperatures. The large influence on cooling demand is due both to the impact on ceiling heat transfer as well as heat gains to the duct systems which are typically located in the attic space with slab on grade construction.

With the described project we tested six side-by-side Habitat homes in South Florida with identical floor plans and orientations using different roofing systems designed to reduce attic heat gains. A seventh house with an unvented attic and insulated roof deck was also included in the test.

The data showed that solar heating had a large effect on attic thermal performance in the control home. Air conditioning data were also collected allowing characterization of the impact on cooling energy use and peak electrical demand. Each of the examined alternative roofing systems were found to be superior to standard dark shingles, both in providing lower attic temperatures and lower AC energy use. The sealed attic construction provided modest savings to cooling energy, but no real peak reduction due to its sensitivity to periods with high solar irradiance. Our research points to the need for reflective roofing materials or light-colored tile roofing for good energy performance with sealed attics.

Our project revealed essentially two classes of performance for the 1,144 square foot homes. Analysis by two methods showed the white highly reflective roofing systems (RWF, RWB and RWM) provide annual cooling energy reductions of 600-1,100 kWh in South Florida (18-26%). Savings of terra cotta tile roofs are modest at 3-9% (100-300 kWh), while shingles provide savings of 3-5% (110-210 kWh). Sealed attic construction produced savings of 6-11% (220-400 kWh). The highly reflective roofing systems showed peak demand impacts of 28-35% (0.8-1.0 kW). White metal had the best cooling related performance. Its high conductivity coupled with nocturnal radiation resulted in lower nighttime and early morning attic temperatures that lead to a reduced cooling demand during evening hours.

In summary, the selection of roof with high solar reflectance represents one of the most significant energy-saving options available to homeowners and home builders in hot climates. Further, the same materials strongly reduce the house peak cooling demand during utility coincident peak periods – a highly desirable attribute.

Acknowledgments

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