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

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Executive Summary

Roof and attic thermal performance exert a powerful influence on cooling energy use in Florida homes. Unshaded residential roofs are heated by solar radiation causing high afternoon attic air temperatures. The large influence on cooling is due to increased ceiling heat transfer as well as heat gains to the duct systems which are typically located in the attic space (Figure E-1).

The Florida Power and Light Company and the Florida Solar Energy Center instrumented six side-by-side Habitat homes in Ft. Myers, Florida with ident-ical floor plans and orientation, R-19 ceiling insulation, but with different roofing systems designed to reduce attic heat gain. A seventh house had an un-vented attic with insulation on the underside of the roof deck rather than the ceiling:

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

All seven houses were completed by June 26th, 2000 with extensive testing to assure the buildings were similar. Each home was monitored simultaneously from July 8th - 31st in an unoccupied state.

Building thermal conditions and air conditioning power were obtained on a 15-minute basis. Each of the examined alternative constructions exhibited su-perior performance to dark shingles. Figure E-2 plots the maximum daily air temperature to the maximum recorded at mid-attic in each construction.

The maximum 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. Table E-1 summarizes the metered data from the unoccupied period.

Table E-1. Cooling Performance During Unoccupied Period July 8th - 31st, 2000

Site	Total kWh	Savings kWh	Saved Percent	Demand kW	Savings kW	Saved Percent
RGS	17.03	0.00	0.0%	1.63	0.00	----
RWS	15.29	1.74	10.2%	1.44	0.19	11.80%
RSL	14.73	2.30	13.5%	1.63	0.01	0.30%
RTB	16.02	1.01	5.9%	1.57	0.06	3.70%
RWB	13.32	3.71	21.8%	1.07	0.56	34.20%
RWF	13.20	3.83	22.5%	1.02	0.61	37.50%
RWM	12.03	5.00	29.4%	0.98	0.65	39.70%

The above results are for the 1,144 square foot homes in the study. Since savings largely scale with ceiling area, the kWh and kW values should be increased by the applicable ratio. For instance, typical FPL homes of 1,770 square feet would have estimated absolute savings 55% greater than above. Also, adjustments were made for slightly different thermostat set points and measured performance of individual AC units.

Table E-2. Summary of Normalized Savings and Demand Reductions from Regression Estimates

Case Description	Cooling Savings		Peak Demand Reduction	
	kWh	Percent	kW	Percent
RGS (Control)	0	0%	0	0%
RWS (White Shingle)	300	4%	0.48	17%
RSL (Sealed Attic)	620	9%	0.13	5%
RTB (Terra Cotta Tile)	180	3%	0.36	13%
RWB (White S-Tile)	1,380	20%	0.92	32%
RWF (White Flat Tile)	1,200	17%	0.98	34%
RWM (White Metal)	1,610	23%	0.79	28%

* Percentages relative to typical values for average sized detached S. FL homes detailed in Appendix H.

Additional monitoring took place over a month long period with the homes occupied, but the thermostat set points were kept constant. Although average cooling energy use rose by 36%, analysis indicated no decrease to savings or demand reduction from the highly reflective roofing systems. The added heat gains from appliances and people increase cooling system run-time causing the duct system to run for longer periods to exchange heat from the often hot attic space.

The results in Table E-2, show essentially two classes of performance: white shingles, terra cotta tile and sealed attic construction which produce energy savings of 200 - 600 kWh/yr and demand reductions of 0.05 - 0.5 kW. Highly reflective roof systems produce energy savings of 1,000 - 1,600 kWh with demand reductions of 0.8 - 1.0 kW. A separate analysis of the data using a special version of the DOE-2.1E simulation verified the magnitude of the measured energy and demand reductions.

In summary, this evaluation strongly confirms the energy-saving benefits using more reflective roofing systems in Florida. Selection of colors with higher solar reflectance will result in tangible cooling energy savings for customers. This is particularly true for roofing materials such as tile and metal, which are currently available with solar reflectances of 65%-75% range. The selection of reflective roofing systems represents one of the most significant energy-saving options available to homeowners and builders. Such systems also strongly reduce the cooling demand during utility coincident peak periods and may be among the most effective methods for controlling demand.

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

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Background

Traditional architecture in hot climates has long recognized that light building colors can reduce cooling loads (Givoni, 1976). A good example is the recommendation appearing in House Beautiful for climate sensitive residential building practice in South Florida prior to the wide spread availability of air conditioning (Langewiesche, 1950):

> "The White Roof
>
> Your roof must be white. The white color throws much of the heat back into the sky before it ever gets into the roof. This is one climate control idea that is universally accepted in Florida right now...Insulation also is a must, of course, but without the white color, would finally get hot."

Unfortunately, this traditional wisdom has been lost during succeeding air conditioned generations. However, reinforcing the importance of light colors have been a series of simulation and experimental studies demonstrating that building reflectance can significantly impact cooling needs (Givoni and Hoffmann, 1968; Taha et al., 1988; Griggs and Shipp, 1988, Akbari et al., 1990 and Bansal et al., 1992). Full building field experiments in Florida and California over the last seven years have examined the impact of reflective roof coatings on air conditioning (AC) energy use in a series of tests on occupied buildings. In Florida, tests were conducted on 11 residential buildings using a before and after test protocol where the roofs were whitened at mid-summer. Measured AC electrical savings in the buildings during similar pre and post retrofit weather periods averaged 19% (7.7 kWh/Day) during the hottest summer months ranging from a low of 2% to a high of 43% (Parker et al., 1998). Even greater fractional savings have been reported for similar experiments in California (Akbari, et al., 1992).

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 at., 1993B). 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). Similarly, Hageman and Modera (1996) found that a large portion of the measured cooling energy savings of radiant barrier systems in field applications can be attributed to reduced heat gains to the thermal distribution system.[1]

In Florida, cooling energy reductions varied depending on roof solar reflectance, initial ceiling insulation level, the location of the air duct system, roof geometry and ventilation, and air conditioner size and efficiency.

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[1] Further benefits arise from the reduction of attic air temperature and its impact on ceiling insulation conductivity (Levinson et al., 1996).

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 similar improvements, but of unknown comparative magnitude (Beal and Chandra, 1995; Rudd, 1998; Rudd et al., 2000).

Based on testing performed at the FSEC's Flexible Roof Facility (Figure 1) from 1997 to present, we learned that of the evaluated roofing systems (radiant barriers, added ventilation, red tile, white tile and white metal roofs), white tile provided the best cooling related performance of tested options. Relative to a black asphalt shingle roof, a white tile roof produced a 76% reduction in overall summer ceiling heat flux (all test cells have R-19 ceiling insulation present). Moreover, when the outside summer air temperatures were at their peak the coincident peak attic air temperature difference which was 40°F lower in the white tile test cell (91.4°F) than the construction with black fiberglass shingles (131.5°F). The measured attic air temperature is actually lower in the attic than the ambient air temperature until 2 PM in the afternoon on a typical summer day.

Research Description

From June to September of 2000, a study was undertaken to investigate the impact of various roof constructions on space cooling energy use and peak electrical demand. 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 cooling performance on identical, unoccupied, side-by-side residences under realistic weather conditions.

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.

As much as possible the homes were of identical construction with only the roofing systems varied. The fundamental test parameters for the houses were the roofing systems used. The sites were given a three letter code to describe the particular roofing element tested:

- Dark gray fiberglass shingle (RGS)
- White fiberglass shingle (RWS)
- Terra Cotta barrel-shaped tile (RTB)
- Sealed attic with insulation on the roof plane (RSL)
- White barrel-shaped tile (RWB)
- Flat white tile (RWF)
- White 5-vee metal (RWM)

Except for the RSL, all of the roofing system types have a typical level of attic ventilation (nominally this is a 1:300 vent ratio within the uniform building code). This includes continuous perforated soffit vents with some off-ridge venting. According to the standard prevailing practice, the tile roofs had no ridge or off-ridge vents other than the standard tile roof cap.

The houses were constructed so that they are completely identical with respect to orientation, landscaping, exterior color, air conditioner model and size, thermostat and duct layout. There was one unanticipated exception to this plan. Houses RGS, RTB, RSL and RWM had 45 ft^2 of glass facing west and 15 ft^2 facing east. Due to a difference in garage location RWB, RWF and RWS had

45 ft^2 of glass facing east and 15 ft^2 facing west. As such the glass locations were mirror images of each other. The primary objective is to determine the impact of the roofing system on both cooling energy and cooling peak demand.

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. We then collected data in an occupied configuration. Data were recorded for electrical energy used for cooling, interior and roof/attic thermal conditions, as well as weather data.

The subject houses were all three bedroom, single-story dwellings located within one block of each other in the same development in Lee County, Ft. Meyers, Florida. Each is oriented similarly with their primary entrance facing south. The homes are quite similar to recent construction in South and Central Florida although smaller than average. Relevant construction details are summarized in Table 1. Detailed floor plans and sections are reproduced in Appendix A.

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 area:	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

The frame walls used 2 x 4" studs insulated with R-11 fiberglass batts and covered by R-3 styrofoam sheathing (Figure 4). Ceilings were insulated to R-19 using blown in cellulose material with a depths of approximately 6 inches.

The wall exterior was finished with vinyl siding (see Figures 5 and 6). One error made was the siding selection for the project. This resulted in different siding for the RSL (Roof Sealed Attic) site. The "champagne" siding had a laboratory tested reflectance of 50.7% against the 47.2% for "taupe" which is installed the other homes. Fortunately, this can be expected to make very little difference in the overall results, other than a very small bias in favor of better performance for the RSL case.[2]

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[2] An hourly simulation using the DOE-2.1E simulation with Tampa weather data showed less than half a percent change in cooling energy use due to this small difference in wall absorptivity. Thus, we believe the difference is likely below the level of measurement.

All the houses had similar windows and doors. The windows were uninsulated, aluminum frame, single hung units, with a shading coefficient of 0.85 – a light gray tint. The metal frame exteriors are white.

Appliances

A conventional 40 gallon electric resistance hot water tank was installed in each home in the utility room. In addition to the tank, a heat recovery unit (HRU) was also installed in each house.[3] These units supplement the water heating process by using waste heat from the air conditioning condenser units. However, within the project the HRUs were not connected for the unoccupied portion of the monitoring.

A single ceiling fan was located in the dining area although the fan was not used during the unoccupied period monitoring. Other conventional appliances were installed in the homes (electric range, dryer and refrigerators), but appliances were not powered until after occupancy.[4]

Construction of the Research Homes

The homes were constructed beginning in early April, 2000 when the foundation slabs were poured and framing began (Figure 7).

The homes were far enough along in May for the rough instrumentation to be installed (Figures 8). Thermocouples and power measurement wiring were installed first.

The homes were essentially complete by the end of June (Figure 9) and the final instru-mentation installation and calibration of equipment was finished by July 6th. Last minute corrections were made so that doors fit uniformly well before blower door tests were performed. The air conditioners were turned on, tested and the thermostats were calibrated to be similar by July 7th. On July 8th the formal project data collection began for the unoccupied period. Data collection continued in an unoccupied configuration for three weeks. Although some problems were experienced (minor vandalism), the data collection was nearly flawless.

Roofing Materials and Construction

A detailed description of the roofing system is important given the project focus. Each home has a hipped roof configuration with continuous vinyl soffit vent facia (Figure 10). Off-ridge attic ventilation is provided by scoop vents to satisfy code requirements (1:300 ventilation ratio). The roofing is over 2 x 4" trusses (12 inches on center) with ½" oriented strand-board (OSB) decking covered by an 15 lb. felt weatherproof membrane.[5]

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[3] American Equipment Systems, Trevor-Martin Corp., Clearwater, FL.

[4] Standard Appliances in the Habitat Homes: Water Heater – *Rheem 40 gallon- 81VH 40D*; Refrigerator – *Whirlpool ET18NKXJW*; Range – *Whirlpool RF302BXGW*; Washer – *Whirlpool LSQ7533JQ*; Dryer – *Whirlpool LER5636JQ*.

[5] 30 lb. felt is used with tile roof construction.

The walls meet the roof line over a double 2 x 4" top plate. The trusses on the attic floor are 24 inch on center with ½ inch gypsum sheet-rock for the interior ceiling. In all but the RSL case, the sheet rock ceiling is covered with R-19 (6 inches) of cellulose insulation. A cross section of the roofing and walls is shown in Figure 11.

Three standard roofing materials were used in this study: fiberglass shingles, galvanized sheet metal, and cement tile. The various types were:

- Terra Cotta colored barrel tile (RTB)
  - *Monier* Model #615,
    Capri Terra Cotta Slurry
- White barrel tile (RWB)
  - *Monier* Model #600,
    Capri White Slurry
- White flat tile (RWF)
  - *Monier* Model #300,
    White Flat Slurry
- White Galvanized metal (RWM)
  - *Old Florida Metal*, *Off-White*
- White fiberglass shingles[6]
  - *Owens Corning*, *Classic Shasta White*
- Dark Gray (dark colored) fiberglass shingles
  - *Owens Corning, Estate Gray*

Roofing Solar Reflectance

Laboratory reflectance measurements were taken on each of the roofing materials represented in this study. Reflectivity is a property that determines the fraction of total incident solar radiation reflected by a surface. In particular, the solar reflectance represents the degree to which radiation from the sun is absorbed by the roofing material and transmitted to the conditioned space as a cooling load. These tests were performed by *Atlas Weathering Services Group*. The results of these tests are found in Table 2. The original laboratory reflectance test reports are contained in Appendix B.

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[6] These fiberglass or composition shingles consist of asphalt on a fiberglass mat with surface ceramic granules to enhance weather resistance.

Table 2
Laboratory Measured Solar Reflectances of Utilized Roofing Materials

Specimen	% Solar Reflectance
Dark grey 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
Off-white metal (original)* (RWM)	55.5

Initially, the metal roof system was installed using an off-white color. This is seen in Figure 12.

Since this was not representative of the "whitest" metal roofs in the market-place, it was later painted to obtain what might be expected by selecting conventional reflective white metal products.

Initial Problem Metal Roofing Color Selection

When we obtained the sample of the white metal roofing after its installation, FSEC noted that the roof did not appear very reflective (Figure 13). The installed roofing panels were more of an off white – very light gray color or bone. We visibly compared it with the white metal which one of the re-port's authors had installed on the roof of his house. This was "Brite White" 5-vee metal from McElroy Metals.[7] The McElroy sample was tested at 68% by DSET laboratories.

FSEC attended the Florida Roofing, Sheet Metal and Air Conditioning Contractor's Association convention in Orlando in June 2000 to speak to all representatives selling metal roofing. We found that many contractors use *Kynar 5000/Hylar5000* factory applied polymer coatings. The color pallette includes several whites: Stone White, Bone White (the brightest) and Sandstone (the darkest).

The original beige 5-vee panel roof sample from Old Florida Metal had an overall solar reflectance of 55.5% (15.3% UV, 57.8 visible; 55.7 IR). Due to this low value, both FPL and FSEC decided that this shortcoming would bias against the metal products in the tests. *Bradco Supply* specified "white" on their order as typically done when a customer requested white for a 26-gauge metal roof. The "standard" white metal roofing material delivered to the job site was one of the darker shades of white similar to sandstone. This was not discovered until after the roof was installed.[8]

For a successful utility program, we anticipate that each manufacturer should have respective samples evaluated to demonstrate achievement of the 65% minimum reflectance. Also, the common bone white has a reflectance of about that value (66%).

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[7] McElroy Metals, Phone: 1-800-950-6533.

[8] It turns out that we have already evaluated most of the Kynar finishes on metal samples (Clad Tex Metals). The solar reflectance of Bone White was 66.1% and the Sandstone on their samples was 50.1%.

To address the limitation with the installed system, we had the metal roof painted with a gloss enamel ("standard white") by a local contractor. The roof was repainted on Saturday July 2nd and July 3rd. The tested reflectance of the painted roof section was evaluated at 65% (see Appendix B). Thus, the resulting reflectance came in very close to the level of reflectances which would be obtained from choosing the whitest metal roofing materials.

The ceiling insulation in the six homes with the standard application consists of 20 bags of *U.S. Fiber, Inc.*, spray applied blanket light density cellulose insulation. The specific characteristics and performance data for the insulation is provided in Appendix C. The insulation has a rated thermal resistance of 3.70 ft^2-hr-°F/Btu per inch at an application density of 1.24 lbs/ft^3. To yield a target of R-19 with 2 x 4" studs on 24-inch centers, the applications guide calls for 17.41 bags per thousand square feet of floor area. With the ceiling area (1144 ft^2), this works out to 19.92 bags per house, indicating that the proper bag count was installed. The application depth for R-19 is then 5.135 inches.

The insulation in each home was qualitatively evaluated to examine (see below) the insulation application quality. With any insulation, the evenness of the insulation is important given parallel heat transfer. At a depth of 5.135" inches the insulation has a rated R-value of 19 (R-3.7 per inch). An ruler was used to evaluate the insulation depth at several locations at each home:

Table 3
Audit Evaluation of Ceiling Insulation

Site	Case Insulation Depth/Evenness
RWB	4" to 7", mostly 5 ½" to 6"
RTB	Mostly 5" to 6" and even
RWM	Mostly 5" to 6" and fairly even
RWS	5" to 7", mostly 6" and even
RGS	3 ½" to 7", mostly 4" to 5"
RWF	4" to 7", mostly 4" to 5"

This would indicate that most of the homes likely have R-19, although the control (RGS) and the roof with flat white tile (RWF) may have closer to R-17. Although this should be considered in the simulation analysis, it does not bias the results since the insulation applications in the study represent real world results.

Sealed Attic Construction RSL

The seventh house (RSL) tested a new approach to residential insulation: an attic completely sealed with a spray foam insulation applied to the underside of the roof decking (see Figure 14) in place of conventional blown in or batt insulation. The fundamental goal in this scheme is to insulate the house at the roof decking rather than at the surface of the living space ceiling. This essentially places the attic space within the insulated envelope of the home. Two primary advantages are significantly less heat load with in the attic space where the duct system is located as well as reduced humidity and infiltration. Research since 1996 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.[9] 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 the attic space becomes a semi-conditioned space and surface areas are increased relative to the conventional case. Overall performance is complex. Thus, this construction was an excellent choice for an evaluation within our project.

The roofing system on the RSL home was identical to that in the control home, dark gray composition shingle over roofing felt and decking (Figure 14). 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 *Demilec* insulating foam (Figure 15).[10] Application thickness was targeted to achieve an R-19 application – similar in thermal resistance to the cellulose insulation in the other homes. Foam thickness and consistency was verified at the time of application. Careful attention was paid to make certain the attic was sealed, particularly along the top plate and ridge.

Demilec is a water-blown semi-rigid poly-urethane foam insulation with a nominal density of 0.45 - 0.5 lbs/ft^3 and an R-value of 3.81 ft^2-hr- °F/Btu/inch. The product also claims to help improve air sealing of the home by controlling leakage from building joints. Other performance characteristics and associated data are provided in Appendix C. The appearance of the final application on the roof deck of the sealed attic is shown in Figure 16.

House Air Tightness

A *Minneapolis Blower Door* was used to mea-sure the airtightness of the houses. Since outside air infiltration and duct leakage can dramatically effect air conditioning system performance, it was important to make sure that the subject houses were similar in terms of air leakage. Figure 17 shows a test in progress.

The test results are detailed in Table 4 and Appendix D. The data indicates that the houses were of similar tightness and therefore discrepancies in thermal performance are not attributed to differences in construction.

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[9] Recently, *Certainteed Corp*. has refused to warranty shingles used with sealed attic construction longer than ten years due to “increase blistering” of the shingle products.

[10] *Demilec* USA, Grand Prairie, Texas, (972-647-0561).

Table 4
Blower Door Measured Air Tightness

House Id	ACH@50 Pa Pressure
Gray shingle (RGS)	6.9
White shingle (RWS)	5.7
Sealed attic (RSL)	4.5
Terra cotta barrel (RTB)	6.0
White barrel (RWB)	5.6
White flat tile (RWF)	5.5
White metal (RWM)	5.7

However, the tests did reveal the home with the sealed attic had the lowest leakage as tested by the blower door – approximately 35% lower than the control home. This is a commonly cited benefit of the roof deck insulation method (see Appendix C).

Tracer Gas Infiltration Rate Testing

On August 4th, FSEC evaluated the infiltration rates in the homes with the air handlers on and off using sulfur hexafluoride tracer gas decay. This method gives an accurate snapshot of the actual building air infiltration rates under evaluated conditions. If homes have considerable duct leakage, the infiltration rate will often rise by a factor of two or more when the air handler operates.

Tested under relatively still wind conditions, results showed the houses to be very air tight even with the air handlers on. The full tracer gas test results are contained in Appendix E with the essential data summarized in Table 5.

Table 5
Trace Gas Infiltration Test Results

Site	ACH Off	ACH On
Control (RGS: Roof Gray Shingle)	0.068	0.173
RWS (Roof White Shingle)	0.129	0.118
RTB (Roof Terra Cotta Barrel)	0.073	0.178
RSL (Roof Sealed Attic)	0.146	0.146
RWF (Roof White Flat Tile)	0.135	0.153
RWB (Roof White Barrel Tile)	0.158	0.128
RWM (Roof White Metal)	0.104	0.123
Average	0.116	0.146

The averages (0.116 ACH Off; 0.146 ACH On) suggests very low infiltration rates and very low levels of duct leakage. These tests indicated uniformly tight houses and verified the results of other test procedures on duct leakage and air tightness.

Since ASHRAE Standard 62-89 recommends a minimum house ventilation rate of 0.35 ACH, this would suggest that modern Florida housing may require mechanical ventilation to provide suitable indoor air quality. However, this was not done for this research project. Such a change would bias results so they would be different from what would be achieved with the prevailing new construction practices.

The measured variability in air infiltration was also low, suggesting that infiltration and duct leakage are not responsible for the differences observed in the cooling data within the research project.

Duct Leakage

Duct leakage in Florida homes has been shown to be a significant problem associated with high air conditioning loads (Cummings, 1990). Also, within the research project we desired to have the duct leakage similar from one house to the next to eliminate that source of variation. The most straightforward manner to realize this goal was to seal the duct system in each home. This was done by FSEC during the different phases in which the duct systems were fabricated.

A Duct Blaster™ (Figure 18) testing device was used to determine the relative leakage of the duct systems in all research homes. The test re-sults, shown in Table 6, showed that the efforts were largely successful. Although some duct leakage was measured at each home, most of it was revealed to be leaking into the conditioned space – most of it likely from the interior air handler. The most meaningful measure of duct leakage is the duct leakage to outdoors at a 25 Pa pressure.

In each of the seven homes the total CFM leakage of the duct system at 25 Pa pressure to outside the conditioned space was less than 31 CFM25 which is lower than the resolution of the measurement equipment. Given its 1,144 square feet of conditioned area in the homes , the duct leakage to outside is <0.027 cfm/ft^2. This compares to the 0.05 cfm/ft^2 proposed as a standard for low leakage new homes.

Table 6
Tested Duct Leakage of Research Homes
June 28, 2000

	Pressure Pan Average	CFM 25 Total	CFM25 Out	Q_n
Grey Shingle (RGS)	0.35	152	<31	<0.027
White Shingle (RWS)	0.17	141	<31	<0.027
Sealed Attic (RSL)	0.19	191	<31	<0.027
Terra Cotta Barrel Tile (RTB)	0.22	143	<31	<0.027
White Barrel Tile (RWB)	0.20	147	<31	<0.027
White Flat Tile (RWF)	0.18	170	<31	<0.027
White Metal (RWM)	0.24	132	<31	<0.027

Note: all leakage to outside measurements were below equipment accuracy minimum

In summary, we found that the tightness of the duct system of all the research homes were uniformly low. Duct leakage to the outside of the building was as low as had been measured by FSEC in numerous tests. Such a circumstance is ideal since duct leakage was nearly eliminated as a variable which could adversely affect the experimental results.

Air Conditioning Performance

All of the houses had identical two ton split system air conditioners with 5 kW strip heaters. The air handlers (Armstrong BCZ24B08N00A-3) were located in conditioned space in an open utility room with box returns. The Armstrong condensers (SCU10B24A-A1) have a rated load of 9.5 amps at 230 volts. The units have a nominal capacity of 22,000 Btu/hr (16,280 sensible) at the ARI 95/80/67 condition. The condensers were installed with hot water heat recovery units (HRUs) but these were disabled during the unoccupied phase of the study. The thermostats were calibrated in order to establish similar interior space conditions. Air handler air flow was determined by the resistance heat method; the full test results along with test methods are found in Appendix F. Manufacture's product literature on the AC systems is found in Appendix G. The results of the performance tests are found in Table 7.

Table 7
Air Conditioning Performance Tests

Site	Air Flow (cfm)	Sensible Cooling (btu/hr)	Latent Cooling (btu/hr)	Total Cooling (btu/hr)	EER (sensible)	EER (total)	Relative Efficiency* η
Gray shingle (RGS)	778	14,200	4,001	18,201	6.08	7.79	----
White shingle (RWS)	876	16,471	4,774	21,245	6.79	8.75	1.123
Sealed attic (RSL)	821	14,453	4,212	18,665	5.83	7.53	0.967
Terra cotta barrel tile (RTB)	871	15,810	5,756	21,566	6.29	8.58	1.101
White barrel tile (RWB)	851	15,624	5,335	20,960	6.63	8.89	1.141
White flat tile (RWF)	809	13,373	5,054	18,427	5.69	7.74	0.993
White metal (RWM)	896	14,612	5,686	20,298	5.83	8.10	1.040

*EER relative to control

Note that the AC systems were all within 14% of the field tested EER of the cooling system in the control home. These results are later used to properly normalize the final savings numbers, based on the values in the right hand column.

Monitoring and Data Acquisition.

The monitoring period for the unoccupied portion of the study took place over 22 days. A uniform instrumentation package was deployed at all the houses (with the exception of the sealed attic (RSL) and control (RGS) houses, where attic relative humidity was substituted for ambient air. All temperature measurements were taken using Type T copper-constantan thermocouples placed in similar physical locations within each house. As installed, the thermocouples have a measurement accuracy of 0.1°F.

Special effort was made to carefully instrument the roof/attic portion of the building (Figures 19 and 20). Consequently, thermocouples recorded temperatures at the roof surface, decking underside surface, mid attic air temperature, the top of the insulation, and at the interior ceiling sheet rock surface.

The decking temperature was behind the foam insulation in the case of the sealed attic home. Also in this home, the temperature measurement recorded the top of the uninsulated attic sheetrock surface instead recorded the top of the insulation surface. The difference between the top of the insulation (or sheetrock in the RSL case) can be used to estimate the ceiling heat flux to the interior of the conditioned space.

Air conditioner field performance was recorded by measuring the temperature before and after the evaporator coil only when the blower was operating. The exit air temperatures were taken by the closest and furthest supply register to help characterize sensible heat gains to the duct systems and investigate how they might be impacted by the various roofing systems. These temperatures were only recorded when the AC blower was operating.

Data was taken on a 10 second scan rate and averaged over 15 minutes. A fully instrumented meteorological weather station collected ambient air temperature, solar irradiance, wind speed, relative humidity, rain fall, and wind direction (Figure 21). A multi-channel data logger installed in each house recorded measurements and transferred data back to FSEC for archival on a dedicated main frame computer (Figure 22).

The instrumentation package consisted primarily of temperature and electrical power measurements. The recorded parameters are contained in the Table 8.

Table 8
Project Measurements for Each Site

Parameter	Units
Interior temperature (thermostat)	ºF
AC supply duct temperature	ºF
AC return duct temperature	ºF
Near supply duct temperature	ºF
Far supply duct temperature	ºF
Interior ceiling flux temperature	ºF
Attic flux temperature	ºF
Mid attic air temperature	ºF
Roof decking temperature (interior)	ºF
Roof surface temperature (exterior)	ºF
Ambient air temperature (by thermostat)	ºF
Total power	watt-hr
AC condenser power	watt-hr
Air handler / strip heat power	watt-hr
Domestic hot water power	watt-hr
Dryer power	watt-hr

Range power	watt-hr
Refrigerator power	watt-hr
Washing machine power	watt-hr
Attic relative humidity (RSL & RGS)	% rh

Flux temperatures are taken to characterize the heat flux/transfer between the attic space and interior conditioned space. These probes were located directly on top of the attic insulation and interior drywall roof surface.

Electrical power measurements were obtained using *Ohio Semitronics* watt-hour transducers. Measured air conditioner energy use was a fundamental objective of the project. However, additional end use devices were also monitored in order to effectively isolate major electrical load components. These end uses became especially important during the occupied periods of the study where internal appliance heat gain can significantly impact overall air conditioning demand.

Thermal Imaging

Thermal scans of the homes were made with an *Agema Thermavision 400 Series* Infrared System in order to allow a qualitative judgement of the relative effectiveness of the roofing systems. Color in the infrared (IR) thermography photos is proportional to temperature, with the coolest surfaces showing up as purple or blue and the hottest surfaces as orange, red and then white (see temperature scales on IR photos below). Similar temperature scales were used to make the various scans to facilitate comparison. Both indoor and outdoor scans were recorded.

Figures 23 and 24 show side-by-side visible and IR views of the right front outside of the control gray shingle house with vented attic on a warm afternoon during the unoccupied study period (July 14). The crosshair temperature on the IR photo indicates that the roof surface is between 115°F and 120°F. Figures 25 and 26 show similar photos of the white barrel tile house taken on the same afternoon, indicating much lower roof surface temperatures of under 100°F.

Figures 27 and 28 show views of the sealed attic house (also with gray shingle roof as the control house) on the same afternoon. The white on the IR photo here indicates roof temperatures above the 127°F range maximum, significantly higher than the control vented attic house. Figures 29 and 30 are side-by-side visible and IR photos of the interior hallway of the control gray shingle house. Ceiling truss members and the attic access towards the back of the photo are clearly visible. As is typically seen, the access cover surface temperature is significantly warmer than most of the ceiling surface (approximately 86°F for the cover vs. approximately 80°F for most of the ceiling).

Figures 31 and 32 are similar hallway IR photos of the sealed attic house and white barrel tile house respectively. The sealed attic ceiling surface temperature is approximately the same as the control house (the access cover however is over 6°F cooler), but the white barrel tile house ceiling is at least 3°F cooler than each of the others.

Figure 33 is a photo of the southwest corner of the control gray shingle, vented attic house. Figures 34 and 35 are matching IR photos of the interior corner, Figure 36 of the same control gray shingle house and Figure 37 of the sealed attic house. Note that the ceiling temperature of the sealed attic house is again similar to, but in this case slightly warmer than the control house. Further, note that the wall / ceiling connections are somewhat warmer for the control house, which is as expected since blown in insulation typically tapers off where the trusses meet the double 2x4 top plates. In contrast, the sprayed in insulation typically continues at full thickness to the outer edge of the walls. The white barrel tile roof house showed substantially less heat gain at the wall / ceiling connections (see Figure 34).

In summary, infrared images recorded during the study support the measured data findings that roof surfaces with significantly higher reflectivities are significantly cooler than those with lower reflectivities. The higher roof reflectivity and cooler roof surfaces then result in lower ceiling temperatures. The IR images affirm that the sealed attic roof surface was most sensitive to being heated by the sun.

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 thermo-couples 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 (Figures 37 and 38).

The maintained temperature by the thermostat was approximately 77°F, although the recorded return temperature indicated that he average temperature maintained in the homes was closer to 74°F. In any case, control of the interior thermostats quite good: all were within 0.7°F of each other after adjustment throughout the monitoring period.

To evaluate the impact of thermostat set temperature the thermostats were adjusted up one °F for four days at the end of the project before the homes were occupied. The typical increase was from 77° to 78°. This data was used to examine how the thermostat set-up influenced cooling in order to properly adjust project results. This was done by searching for days in the set-up period which had very similar weather conditions (ambient air temperature and solar radiation) to other days in the standard monitoring period.

Of the four days available, only August 4th and 5th turned out to have other days in the standard monitoring period which had very close outdoor temperatures and solar irradiance data. In actuality, three close matches were found for the hot clear weather on August 4th: July 23rd, July 25th and July 31st. For August 5th which was cooler and cloudy, a near perfect match was found on July 9th.

The measured space cooling in each of the homes with valid data (RWF and RWB were eliminated due to instrumentation problems) were compared on the days with the set-up (August 4th and 5th) to the AC power on the other days. The results showed reasonable consistency from one site to another, although RSL, the sealed attic case, showed great sensitivity to solar irradiance. 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 ºF that the temperature was increased in the set-up period. When confined only to the hot comparison day, the impact was 8.3% per ºF. Interestingly, these data compare remarkably well to the other data collected on an unoccupied FPL research home several years ago which showed an 11.9% impact per ºF (Figure 39).

Thus, the likely range for the impact of interior thermostat setpoint temperature is approximately 10% per °F. The impacts may be as low as 8% on hot sunny days and greater than 15% on cloudy, cooler days as the temperature outside approaches the thermostat setpoint.

Results over the Unoccupied Monitoring Period

The relative performance of the homes over the entire unoccupied monitoring period was evaluated. Since conditions were carefully controlled, these results are considered most indicative of relative savings among the differing roof types. The seven figures below (Fig 40 - 46) 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 40 depicts the ambient average air temperature and solar conditions over the entire unoccupied period. Figures 41, 42 and 43 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 and decking temperatures run almost 20°F hotter. Note also, that the white roofing systems (RWM, RWF and RWB) experience peak surface temperatures approximately 20°F lower than conventional construction. The terra cotta barrel tile case runs about 10° cooler.

Figure 44 shows the comparative average interior air temperatures during the unoccupied period. It shows that all homes were within 1°F of each other (measured at the hallway thermostat in each case) during the monitoring. Even so, due to the large influence of this parameter, we later make a careful attempt to adjust the monitored cooling results to account for the differences.

The measured mid attic air temperatures above the ceiling insulation also reveal 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.

As expected, the home with the sealed attic has the lowest attic temperatures reaching a maximum of 83°F compared with the 77°F being maintained in the home interior. It must be realized, however, that 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 is deceptive. Since ½ inch sheet rock only has a thermal resistance of 0.45 hr-ft^2-°F/Btu, a significant level of heat transfer takes place across the uninsulated ceiling. In 1999 we tested sealed attic construction at the FSEC's Flexible Roofing Facility and found that while this construction method reduced attic air temperatures compared to other options, it did not reduce ceiling heat transfer as well as other options. This is clearly indicated in our project data which shows the highest ceiling heat flux in the RSL case (see Figure 45). One of the reasons that the temperature conditions in the unvented attic are lower is that the ceiling and duct system is unintentionally cooling the attic space.

Figure 46 is the most important. It summarizes the measured cooling load profiles for the seven homes over the entire unoccupied monitoring period. These results are not normalized for temperature differences or air conditioning performance, but the results are still indicative relative of relative performance. 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 consumption (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% raw cooling energy reduction (14.9 kWh/day).

The true white roofing types (> 60% reflectance) clearly show their advantage. Both the white barrel and white flat tile roofs show an average 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 9 are adjusted to account for differences in interior temperature and AC performance:

Table 9
Cooling Performance During Unoccupied Period
July 8th - 31st: average ambient air temperature = 81.6°
(30 year normal average Ft. Myers temperature = 82°F)

Site	Total kWh	Savings kWh	Save %	Thermostat	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°) was very similar to the 30-year average for Ft. Myers (82°). Thus, the current data is representative of typical South Florida weather conditions.

Relative to the Terra Cotta home, the data show two distinct groups in terms of performance:

- Terra Cotta tile, white shingle and sealed attic constructions which produce approximately a 8-11% cooling energy reduction

- Reflective white roofing, giving a 19 - 24% cooling energy reduction.

It seems likely white flat tile performed slightly better than the white barrel due to its greater reflectance (see Table 1). The better performance of white metal appears to come from the fact that lower nighttime and early morning attic temperatures are achieved (see Figure 43) than those for tile. This leads to lower nighttime cooling demand (Figure 46).

Variation Due to Weather Patterns

Cloudy Days

In-depth analysis of the collected data showed that on days of lower solar radiation the sealed attic case performance improves more significantly compared to the other cases. As an example, Saturday, July 22nd was one of the cloudiest days. Figure 47 shows solar irradiance and temperature profile. The data shows a clear early morning followed by a large amount of precipitation at 11 AM (10 AM Standard Time) that results in a drop in the air temperature of 17°F in 30 minutes! As seen in Figure 48, the rain served to cool all the roofs off; the afternoon resumed partly cloudy conditions with the roofs heating back up.

Figures 49, 50 and 51 show decking, attic and interior profiles on the same day. The 22nd was also a very low cooling load day for all the homes (Figure 52). The control used 10.4 kWh whereas the house with the terra cotta tile used almost the same (10.5 kWh). The white shingle used 9.9 kWh. The white metal building used 7.4 kWh, both white flat tile and white barrel tile used 8.3 kWh and the sealed attic case used only 8.7 kWh. Thus, on a cloudier day, the sealed attic case produces savings which approach the most reflective cases.

Peak Day Performance

July 26th was one of the hottest and brightest days in the data collection period. Figure 53 shows the applicable weather data.

The data shows that during periods of high solar insolation the performance of the sealed attic case (RSL) suffers significantly. Roof temperatures and AC performance are illustrated in Figures 54 - 58. 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. Average solar irradiance was 371 W/m^2 and maximum temperature was 93.0°F.

Table 10
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

These results fit the physical phenomenon involved. The sealed roof case is sensitive to the absorbed solar radiation, since this heat must be resisted at the point of absorption (no attic ventilation to abate heat build-up). On the other hand, as solar influences go down, the advantage of having the duct system inside the insulated envelope becomes greater.

The most overcast day was July 30, 2000. Average air temperature was 75.4°F with a maximum of 85.2°F and average solar irradiance was 111 W/m^2. There was full sun for about a 30 minute period in the morning at 10 AM, but the rest of the day was overcast. Heavy rains between 6 and 7 PM EDT were experienced. Data were missing from RWB for this day due to an instrumentation problem.

Note that the absolute differences in space cooling consumption are quite small for this day so that percentage differences are exaggerated. The sealed attic performs best and the terra cotta tile roof does worse than the control, which is likely a carry-over due to higher attic temperatures from the previous day. However, the short period of solar irradiance did provide some advantage to the white highly reflective roofs relative to the other nonsealed systems (peak attic temperatures were 18° lower with the white roofs than the control).

Table 11
Cooling Energy Performance on July 30th, 2000

Site	Cooling Energy	Percent Savings	Peak Attic Temps
RGS	6.6 kWh	NA	100.6°
RWS	6.5 kWh	2%	92.6°
RSL	4.2 kWh	35%	79.7°
RTB	6.9 kWh	- 5%	84.9°
RWB	Missing	NA	81.6°
RWF	4.9 kWh	26%	81.1°
RWM	4.2 kWh	35%	84.2°

Comparison of Roofing System Impact During Occupied Monitoring Period

Analysis of data was completed for a period of one month after the homes were occupied from August 18th to September 17th, 2000. Occupants were compensated to maintain their thermostats at the same set point over the month long period so the impacts of occupancy could be gauged. In addition it was desired to ascertain if the reductions from the various roofing systems were robust enough to be observed during the occupied period.

Figure 59 depicts the average ambient air temperature and solar conditions over the month-long occupied monitoring period. Figures 60 - 64 show the roof systems thermal performance during the period.

Our analysis results in Figure 65 show the average 24-hour kW AC demand in the seven houses during the month long period in which the homes were occupied. Note that the homeowners did a very good job of not altering the thermostat setpoints during this time. This was verified daily; Figure 63 shows the good temperature correspondence.

The results show that occupancy has not altered previous findings. All homes do better than the control home with dark gray shingles. The three homes with highly reflective white roofs (shown in three shades of green in the plot) clearly outperform the other types. The home with the white shingle is better than the control until afternoon and is similar in daily performance to the home with the sealed attic. The terra cotta tile roof home falls between the others. The average AC loads measured over the month long period (August 18th - September 17th) were as follows:

Table 12
Cooling Energy Use During Occupied Period
August 18th - September 17th, 2000

Occupants	Site	Cooling Energy	kWh	Savings
4	RGS: (Roof Gray Shingle: Control)	25.8 kWh	0.0	
2	RWS: (Roof White Shingle)	21.1 kWh	4.7	19.2%
3	RSL: (Roof Sealed Attic)	21.1 kWh	4.7	19.2%
3	RTB: (Roof Terra Cotta Barrel)	20.2 kWh	5.6	21.7%
2	RWB: (Roof White Barrel)	13.6 kWh	12.2	46.3%
2	RWF: (Roof White Flat)	17.0 kWh	8.8	34.1%
4	RWM: (Roof White Metal)	19.2 kWh	6.4	25.6%

The influences are obscured somewhat by appliance con-sumption differences which have been observed to clearly influence cooling. Figure 66 shows the obvious impact of range and oven energy use on space cooling at the white barrel tile home on September 7th. The markedly higher consumption of the control home, with four occupants seems affected by such an influence as appliance loads are largest there. How-ever, the fact that the three highly reflective white roofed homes are also the same three with the lowest space cooling is hardly coincidental.

Data from the occupied period with the analysis of impacts of appliance loads on cooling use are contained in Appendix K.

Regression Analysis

We performed a series of regression analyses in order to generalize the results to typical weather conditions and to understand more about how the houses with their various roofing systems respond to weather. Weather conditions obtained at the project meteorological station were used to examine the impact on space cooling energy use in each of the research homes. The weather parameters examined included ambient air temperature, solar irradiance, absolute humidity, wind speed and rainfall. Since the homes were unoccupied for this analysis, we expected weather conditions to be primary drivers of consumption.

The regressions were attempted both on a daily and hourly cycle. We found the regressions against the hourly consumption sometimes did poorly (had low predictive capability, R^2), due to two factors. First the space cooling itself varies greatly over each hour depending on the on-off cycle frequency of the AC run-time in the previous hour. Thus, the fact that AC is high in one particular hour does not necessarily imply that the current hour weather drives demand; often the AC was mostly off in the previous hour. Secondly, thermal storage within a number of building elements results in a cooling demand which is out of phase with the weather phenomenon driving it. For instance, the highest irradiance is at its maximum around noon whereas the maximum building load happens at 3 - 4 PM. Thus, there is a time delay between the time of the maximum insolation and maximum cooling. The disparity between attic and outdoor temperatures is particularly great for RTB with the colored tile roof. The plots for the hourly regressions are provided below in Figures 67 - 73.

Both of the described problems disappear when the regression analysis is performed over a daily period. The unevenness of AC cycles average out over the 24 hours and thermal storage within building elements largely follow a diurnal daily cycle. Performing the analysis on a daily basis (24 days between July 8th - 31st) worked very well.

The most simple daily regression form was:

$$kWh = a + B(Tamb)$$

Where:

kWh = average daily space cooling kWh
Tamb = average daily outdoor air temperature (average of 24 days = 81.6°F)
B = coefficient for how cooling varies with daily average temperature
a = non-temperature related component (intercept term)

Figure 74 below shows the result of this analysis for the two most different cases, RGS – the control and RWF with the white flat tile roof.

Roof Gray Shingles:
$kWh_{RGS} = -96.0 + 1.39\,(Tamb)$ $R^2 = 0.73$

Roof White Shingles:
$kWh_{RWF} = -80.5 + 1.15\,(Tamb)$ $R^2 = 0.88$

The results from the regression tells us of several very useful influences. First, they show that on a typical summer day with average outdoor air temperature of 80°F, the home with the white tile roof uses 24% less space cooling energy than the control home. Also with an average temperature over the period of 81.6°F, the calculation shows that a 1 degree decrease in outdoor temperature will produce an 8% drop in space cooling in the control home (this verifies our estimate of the related impact of thermostat setting).

The simple regression results for the other homes are shown below and in Figures 75 - 78.

Roof White Shingle:
$kWh_{RWS} = -75.4 + 1.11\,(Tamb)$ $R^2 = 0.73$

Roof Sealed Attic:
$kWh_{RSL} = -88.6 + 1.27\,(Tamb)$ $R^2 = 0.67$

Roof Terra Cotta Barrel:
$kWh_{RTB} = -88.8 + 1.29\,(Tamb)$ $R^2 = 0.85$

Roof White Barrel:
$kWh_{RWB} = -70.9 + 1.03\,(Tamb)$ $R^2 = 0.84$

Roof White Metal:

$\text{kWh}_{RWM} = -81.2 + 1.16\ (\text{Tamb}) \qquad R^2 = 0.86$

The results also show that temperature alone can explain about 73% of the variation for the shingle roof constructions (RGS or RWS) and over 80% of the variation with the highly reflective white roofing types, but only about 66% of the variation for the sealed attic case.

Obviously, daily average solar irradiance should be important, particularly for the darker roofing types. Also early examination showed the sealed attic case cooling performance to be quite sensitive to solar irradiance. The regressions showed solar irradiance is important to predicting variation in consumption for all cases save those with the highly reflective roofing systems.

The importance of insolation on cooling can be clearly observed when daily cooling energy use is correlated to the average attic air temperature rather than the outdoor temperature. The influence of attic heat gain on space cooling is pronounced, as shown in Figure 79. Here we see that much of the scatter seen when plotted against ambient temperature for the control home (RGS) and the sealed attic case (RSL) disappears when plotted against the attic temperature. Of particular importance is the strong relationship of space cooling in the sealed attic case to small differences in the mea-sured attic air temperature. This indicates the very large sensitivity of sealed attic construction to absorbed roof solar radiation.

This argues that sealed attic construction, when used in hot climates, must use reflective roofing or light colored tile roofing materials. Otherwise cooling performance will suffer under peak load conditions.

Since attic air temperature is dependent on construction and is not an available weather parameter with which to predict performance, we did a multi-linear regression against both ambient air temperature and solar radiation for the seven homes. As expected, adding the solar term improved correlation (higher R-squared), particularly for the darker roofing types:

Roof Gray Shingle:

$\text{kWh}_{RGS} = -81.2 + 1.15\ (\text{Tamb}) + 0.0150\ (\text{Insolation}) \qquad R^2 = 0.79$

Roof White Shingle:

$\text{kWh}_{RWS} = -64.8 + 0.943\ (\text{Tamb}) + 0.0125(\text{Insolation}) \qquad R^2 = 0.80$

Roof Sealed Attic:

$\text{kWh}_{RSL} = -70.7 + 0.979\ (\text{Tamb}) + 0.0211(\text{Insolation}) \qquad R^2 = 0.81$

Roof Terra Cotta Barrel Tile:

$\text{kWh}_{RTB} = -80.4 + 1.15\ (\text{Tamb}) + 0.0100(\text{Insolation}) \qquad R^2 = 0.89$

Roof White Barrel Tile:

$\text{kWh}_{RWB} = -70.6 + 1.02\ (\text{Tamb}) + 0.0008\ (\text{Insolation}) \qquad R^2 = 0.85$

Roof White Flat Tile:

$\text{kWh}_{RWF} = -74.2 + 1.05\ (\text{Tamb}) + 0.007\ (\text{Insolation}) \qquad R^2 = 0.91$

Roof White Metal:

$$kWh_{RWM} = -75.1 + 1.05\ (Tamb) + 0.007(Insolation) \qquad R^2 = 0.87$$

Where:

Insolation = Average W/m^2 per day

The statistical models explain 80 - 90% of the measured variation in space cooling and are later used with the TMY data to estimate cooling energy savings. Note the much higher magnitude of the solar term for the sealed attic case (RSL) and the much lower value for the highly reflective white roof types (RWM, RWB and RWF). The coefficient of determination (R-squared) is improved in all cases.

We also examined the other available weather parameters. Of these, the variation in absolute moisture (W) did not show significance as a predictor, likely due to the fact that the infiltration rates in the homes are very low. However, days with heavy rainfall – notably July 22nd – showed lower cooling consumption than otherwise indicated by the major correlating factors (temperature and solar radiation). These days are indicated in the daily regression plots. That heavy rains can cool off building surfaces seems intuitively correct. Rain influence on cooling load has also been shown in a previous experimental assessment in a humid climate (Jayamaha, Wijeysundera and Chou, 1997).

Wind speed did show some influence on the performance of the vented shingle roof cases, but not with the others. We believe the influence has to do with the influence of wind speed on attic ventilation and hence on attic temperatures and cooling performance. This has been shown in a previous investigation (Beal and Chandra, 1995) which concluded that attic ventilation rates play a large role in controlling ceiling heat flux. Wind speed shows less impact on the sealed attic case since it is unventilated. With the white roof cases, the attic air temperature is similar during the daytime hours to that outside so that the heat abatement benefits of ventilation are low.

In summary, our regression analysis suggested that daily variations in weather parameters were important in determining space cooling, with temperature and solar radiation the largest influences. Wind speed and rainfall were other identified, but more minor factors.

Analysis of Energy Savings

We calculated the annual cooling energy savings of the differing roofing materials by two methods.

1) Empirically Based Estimate

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 13 which have been corrected to off-reference interior air temperatures and air conditioner performance.

The fraction of space cooling in the month of July was obtained from empirical monitoring results provided by FPL, as reproduced in Appendix H. This data shows 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. These values also allow estimation of how cooling varies in the other climate zones. 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). This is the best normalizing parameter since ceiling heat transfer directly indexes against this parameter and the size of the duct system (the other large factor in the savings) typically scales with the size of the home.

Table 13
Annual Cooling Energy Savings from Empirical Measurements

Site	Measured kWh/Day	Temp Correction AC Correction	kWh Day Estimate	Savings (kWh/day)	kWh* South	kWh* Central	kWh* North
RGS	17.03	1.000 / 1.000	17.03	0.00	0	0	0
RWS	15.29	0.988 / 1.092	16.49	0.54	110	96	77
RSL	14.73	1.054 / 1.027	15.94	1.09	223	194	155
RTB	16.02	0.984 / 0.978	15.42	1.60	329	285	228
RWB	13.32	1.021 / 0.954	14.01	3.02	618	536	428
RWF	13.20	1.049 / 1.014	12.86	4.17	852	739	591
RWM	12.03	1.028 / 1.023	12.80	4.23	864	750	599

* The estimate is based on a ratio of 6.59 for South (1/0.1517 for 15.17% of cooling in July) 5.72 for Central (1/0.156 * 1015/1141) and 4.57 for North (1/0.1878 * 980/1144). House size assumptions must be accounted for when estimating average savings or those for a specific case.

2) Regression Based Estimate

An alternative calculation was made using the daily regression results described earlier in this report The independent parameters are the daily air temperature and average solar radiation (global horizontal irradiance) which 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 a site representing North (Jacksonville), South (Miami) and Central (Orlando). The results become the estimated space cooling use for each construction. Savings are then normalized by the temperature and air conditioner performance corrections to yield final estimates. The estimates are then corrected for the size of home as with method (1). For instance, an 1,800 square foot home would have its kWh savings estimates increased by 57% (1,800/1,144).

The daily regressions were described on page 53; the regression results, temperature and AC performance corrections are reproduced in Table 14.

Table 14
Annual Cooling Energy Savings from Regression Analysis Method

Site	kWh South	kWh Savings (*)	kWh Central	kWh Savings (*)	kWh North	kWh Savings (*)
RGS	3679	0	2639	0	2239	0
RWS	3471	208 (191)	2511	128 (118)	2138	101 (93)
RSL	3242	437 (404)	2345	294 (272)	2012	227 (210)
RTB	3570	109 (113)	2544	95 (98)	2146	93 (97)
RWB	2809	870 (893)	1975	664 (682)	1641	598 (614)
RWF	2859	820 (771)	2018	621 (584)	1629	610 (573)
RWM	2584	1095 (1041)	1814	825 (784)	1519	720 (684)

(*) Normalized to correct for off-reference temperature and AC performance (see values in Table 12).

Generally, the 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). The sealed attic construction produces savings of 6 - 11% (220 - 400 kWh).

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 then be indexed the ceiling area for the site being analyzed. Considering that the typical, home in the FPL service territory likely has a ceiling area averaging about 1770 square feet, the ratio of the impact would be approximately 55% greater than that estimated here (1144 ft^2 ceiling). This also better fits the average cooling energy demand from end-use studies from FPL which show a summer peak cooling kW demand of approximately 2.9 kW (see Table 15 below) in occupied homes. Our monitoring study showed and average peak demand of 1.63 kW in the *unoccupied* control home:

Table 15
Summary of Measured FPL Cooling Consumption and Demand By DCA Climate

DCA Climate	Cooling Usage Summary			
	Annual Cooling kWh	August Cooling kWh	Summer Peak Cooling kW Demand	Total kW Demand All End-Uses
North	5218.34	924.81	2.91	4.11
Central	6506.52	970.72	2.78	3.98
South	7519.54	1117.44	2.86	4.06

The average peak demand for the study sites (based on the peak data for July 26th) are reproduced in Table 16. One caveat is that a cloudy period occurred during the peak period (see insolation plot in Figure 53), so that this method of analysis may somewhat underestimate the impact which would occur on a very hot and clear afternoon.

Table 16
Measured Cooling Peak Demand in Research Homes

Site	Demand kW	Savings kW	Normalized Demand Reduction[+] kW
RGS	1.631	0.000	0.00
RWS	1.439	0.192	0.30
RSL	1.626	0.005	0.07
RTB	1.570	0.061	0.09
RWB	1.073	0.558	0.86
RWF	1.019	0.612	0.95
RWM	0.984	0.647	1.00

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

The second method of estimating demand reductions uses hourly regression equations similar to those described in Figure 67 - 73, but with the regression data limited only to observations between 4 and 6 PM during the monitoring period. This largely accounts for cumulative heat storage in the homes coincident with the peak hours. The equations for the peak period are reproduced below:

Roof Gray Shingle:
kW_{RGS} = -7.023 - 0.0958 (Tamb) $R^2 = 0.78$

Roof White Shingle:
kW_{RWS} = -5.041 + 0.0708 (Tamb) $R^2 = 0.75$

Roof Sealed Attic:
kW_{RSL} = -7.198 + 0.0967 (Tamb) $R^2 = 0.77$

Roof Terra Cotta Barrel Tile:
kW_{RTB} = -6.164 + 0.0839 (Tamb) $R^2 = 0.45$
Roof White Barrel Tile:
kW_{RWB} = -4.42 + 0.0611 (Tamb) $R^2 = 0.68$

Roof White Flat Tile:
kW_{RWF} = -3.793 +0.0538 (Tamb) $R^2 = 0.72$

Roof White Metal:
kW_{RWM} = -5.011 + 0.0684 (Tamb) $R^2 = 0.66$

To estimate peak impacts, the above regressions were evaluated at an outdoor temperature of 92ºF – which is close to the peak design temperature at 5 PM. As shown in Table 15 above, the typical demand value for peak cooling kW does not vary to any large extent from North to South Florida.

Table 17
Regression Estimated Cooling Peak Demand in Research Homes

Site	Demand kW	Reduction kW	Normalized Demand Reduction+ kW
RGS	1.788	0.000	0.00
RWS	1.480	0.308	0.48
RSL	1.701	0.087	0.13
RTB	1.558	0.230	0.36
RWB	1.197	0.591	0.92
RWF	1.153	0.635	0.98
RWM	1.278	0.510	0.79

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

As expected, the regression analysis method estimates higher peak demand impacts. Note, however, that both of the estimates are in general agreement except for RTB where the regression based estimate produces a larger estimate. 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 produce demand reductions of 0.8 - 1.0 kW.[11]

Simulation Analysis

FSEC has developed an hourly building energy simulation software, **EnergyGauge USA**, which runs based on the DOE-2.1E 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.[12] We simulated them, both in an unoccupied and occupied configuration and tallied the cooling energy results for July using Tampa Typical Meteorological Year (TMY) data.

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[11] The percentage demand reductions were 29 - 36% although these should be considered with caution since occupied demand is likely approximately 1 kW higher.

[12] Specific modeling assumptions: Due to the audited unevenness of the ceiling insulation, we used a ceiling framing fraction of 0.2 versus 0.1 which is commonly assumed. The thermostat set-point was 74ºF versus the 77ºF measured right by the thermostat due to heat from electronics (Figure 36). This value was verified by examining the air temperature by the AC return which was typically about 3 degrees lower than that at the thermostat. We also used, blower door air tightness test values.

Table 18
Simulation Analysis Results: Unoccupied

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

Table 19
Simulation Analysis Results: Occupied

Building Site	Annual Cooling (kWh)	Annual Heating (kWh)	Cooling Savings (kW)	July Cooling kWh (kWh/D)	Peak Cooling Demand	
					(kW)	Reduction
RGS	3,546	552	----	621 (20.0)	1.78	----
RWS	3,414	582	132	600 (19.4)	1.70	0.08
RSL	3,516	580	30	616 (19.9)	1.59	0.19
RTB	3,311	538	235	582 (18.8)	1.52	0.26
RWB	3,046	644	500	571 (18.4)	1.38	0.40
RWF	3,022	654	524	535 (17.3)	1.36	0.42
RWM	3,123	702	423	554 (17.9)	1.53	0.25

When comparing with the data monitored during the occupied period, one notes that the simulation predicts very similar absolute values to the measured space cooling at the sites. The lower than predicted consumption at RWB may have to do with occupant related behavior (e.g. less appliance gains). Also, the simulation predicted savings are somewhat less than those measured within the monitoring. Even so, the direction of effect is similar. 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. The better performance of white flat tile is mainly due to its 3% better reflectance (see Table 1). The column showing heating energy use illustrates how the reflective roofing systems have greater impact in Florida on reducing space cooling than they do of increasing heating. It is important to note that the simulation results above are for the small houses monitored. Values for typically sized FPL homes would be approximately 55% greater.

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. Figure 80 illustrates the relevant thermal processes:

Florida Power and Light (FPL) and the Florida Solar Energy Center (FSEC) have instrumented six side-by-side Habitat homes in South Florida with identical floor plans and orientations but with different roofing systems designed to reduce attic heat gains. A seventh house with an unvented attic and insulated roof was added to the study by the U.S. Department of Energy. The roof systems are:

- (RGS) Standard dark shingles with standard ventilation (control home)
- (RWS) Light colored shingles
- (RTB) Terra cotta “barrel” S-tile roof
- (RWB) White “barrel” S-tile roof
- (RWF) White flat tile roof
- (RWM) White galvanized steel 5-vee roof
- (RSL) Standard dark shingles with R-19 insulation applied to the underside of the roof decking and a sealed, unvented attic.

All seven houses were completed by June 26th with extensive duct system and air conditioner performance testing done over the following week to assure that the cooling systems were similar at each home. Thermostat settings were adjusted so that they were nearly identical. The homes were monitored from July 8th - 31st in an unoccupied state. Both building thermal conditions and air conditioning power were obtained.

The data showed that solar heating had a large effect on attic thermal performance in the control home. Air conditioning data was 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 the sensitivity of the construction to periods with high solar irradiance. This construction technique is still promising, although our research points to the need for reflective roofing materials or light-colored tile roofing for good energy performance with sealed attics.

The month long data from the unoccupied test conditions gave the following results on measured cooling energy for South Florida:

Table 20
Cooling Performance During Unoccupied Period July 8th - 31st, 2000

Site	Total kWh	Savings kWh	Saved Percent	Demand kW	Savings kW	Saved Percent
RGS	17.03	0.00	0.0%	1.63	0.00	----
RWS	15.29	1.74	10.2%	1.44	0.19	11.80%
RSL	14.73	2.30	13.5%	1.63	0.01	0.30%
RTB	16.02	1.01	5.9%	1.57	0.06	3.70%
RWB	13.32	3.71	21.8%	1.07	0.56	34.20%
RWF	13.20	3.83	22.5%	1.02	0.61	37.50%
RWM	12.03	5.00	29.4%	0.98	0.65	39.70%

The above energy and demand reductions are for the 1,144 square foot homes in the study. Since they largely scale with ceiling area (and duct system size), the kWh and kW values should be increased by the applicable ratio. For instance, typical FPL homes of 1770 square feet would have estimated kWh and kW values 55% greater than those shown. Also, when applying the results to other cases, it is advisable to use absolute numbers (kW and kWh) per square foot rather than percentages. The percentages are altered by occupancy which significantly increases the total home load while the roof's impact on cooling load changes by a smaller amount.

Table 21 uses the regression analysis methods described on pages 55-57 and also makes corrections based on small differences in measured AC efficiency and interior temperature set points. The regression analysis results should be considered the most reliable savings with an uncertainty of approximately ±15%.[13] Results are scaled up for the average sized FPL home.

Table 21
Summary of Normalized Savings and Demand Reductions from Regression Estimates

Case Description	Cooling Savings		Peak Demand Reduction	
	kWh	Percent	kW	Percent
RGS (Control)	0	0%	0	0%
RWS (White Shingle)	300	4%	0.48	17%
RSL (Sealed Attic)	620	9%	0.13	5%
RTB (Terra Cotta Tile)	180	3%	0.36	13%
RWB (White S-Tile)	1,380	20%	0.92	32%
RWF (White Flat Tile)	1,200	17%	0.98	34%
RWM (White Metal)	1,610	23%	0.79	28%

* Percentages relative to typical values for average sized detached S. FL homes detailed in Appendix H.

As described in the background information, experiments have been previously conducted in 11 existing homes in Central Florida in which dark roofs were changed to a white reflective surface at mid summer and changes to air conditioning consumption were tracked. By way of comparison, the previous average before-and-after savings from these experiments showed an average 7.7 kWh/day in cooling energy reduction coupled (19%) with a load reduction of 0.55 kW (Parker et al., 1998).

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[13] This would mean that the true energy savings with an estimate of 1,000 kWh could be as low as 850 kWh or as high as 1,150 kWh.

This compares well to the monitored load reduction in the this side-by-side experiment where the highly reflective roofs with better-insulated attics provided savings of 4 - 5 kWh/day with an average peak demand reduction of approximately 0.60 kW. The similarity of the results indicates the benefits of reflective roofing are not confined to existing buildings, but strongly extends to new construction as well.

Comparison of the range of measured estimates in Table 20 with the building energy simulation results in Table 18 show good correspondence. In general, the simulated energy savings and demand reductions were about 20% lower than measured. Although the measured data should take precedence, the similarity of the simulated values gives confidence in the results.

Our project revealed essentially two classes of performance. White shingles, terra cotta tile and sealed attic construction each produced cooling energy savings of 100-400 kWh/yr and demand reductions of 0.05-0.20 kW. White highly reflective roof systems produced energy savings of 700 - 1,000 kWh with demand reductions of 0.55 - 0.65 kW for 1,144 square foot homes.

This controlled scientific experiment strongly confirms the energy-saving benefits of using more reflective roofing systems in Florida. For a given roofing material, the selection of colors with higher solar reflectance will result in tangible cooling energy savings for air conditioned homes. This is particularly true for roofing materials such as tile and metal which are currently available with solar reflectance ratings of 65%-75%.

In summary, the selection of roofs of such superior reflectance represents one of the most significant energy-saving options available to homeowners and home builders. Further, the same materials strongly reduce the house peak cooling demand during utility coincident peak periods. As a result, highly reflective roofing systems may be among the most effective methods for controlling peak cooling demand in Florida homes.

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