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CONTRACT REPORT

Experimental Evaluation of the *NightCool* Nocturnal Radiation Cooling Concept: Performance Assessment in Scale Test Buildings

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Disclaimer

Experimental Evaluation of the *NightCool* Nocturnal Radiation Cooling Concept: Performance Assessment in Scale Test Buildings

Executive Summary

Using a building's roof to take advantage of long-wave radiation to the night sky has been long identified as a potentially productive means to reduce space cooling in buildings. The night cooling resource is large and enticing for residential energy-efficiency applications. On a clear desert night, a typical sky-facing surface at 80°F (27°C) will cool at a rate of about 70 W/m^2. In a humid climate with the greater atmospheric moisture, the rate drops to about 60 W/m^2 (Clark, 1981). Fifty percent cloud cover will reduce this rate in half.

For a typical roof (225 square meters), this represents a cooling potential of 6,000 - 14,000 Watts or about 1.5 - 4.0 tons of cooling potential each summer night if all roof surface night sky radiation could be effectively captured. However, the various physical properties (lower roof surface temperatures, fan power, convection and conductance) limit what can be actually achieved, so that considerably less than half of this cooling rate can be practically obtained. Even so, in many North American locations, the available nocturnal cooling exceeds the nighttime cooling loads.

A big problem with previous night sky radiation cooling concepts have been that they have typically required exotic building configurations. These have included very expensive "roof ponds" or, at the very least, movable roof insulation with massive roofs so that heat is not gained during daytime hours. To address such limitations, an innovative residential night cooling system was designed. The key element of the *NightCool* configuration is that rather than using movable insulation with a massive roof or roof ponds, the insulation is installed conventionally on the internal ceiling. The system utilizes a metal roof over a sealed attic with a main to attic zone air circulation system.

During the day, the building is de-coupled from the roof and heat gain to the attic space is minimized by the white reflective metal roof. During this time the space is conventionally cooled with a small air conditioner. However, at night as the interior surface of the metal roof in the attic space falls well below the desired interior thermostat set-point, the return air for the air conditioner is channeled through the attic space by means of electrically controlled louvers with a low power variable speed fan. The warm air from the interior then goes to the attic and warms the interior side of the metal roof which then radiates the heat away to the night sky.

As increased cooling is required, the air handler runtime is increased. If the interior air temperature does not cool sufficiently the compressor is energized to supplement the sky radiation cooling. The massive construction of interior tile floors (and potentially concrete walls) store sensible cooling to reduce daytime space conditioning needs. The concept may also be able to help with daytime heating needs in cold climates by using a darker roof as a solar collector. There is potential for mating the concept with Building Integrated Photovoltaics (BIPV) for combined heating, cooling and solar electric power production.

The empirical evaluation of the concept is being accomplished by using two highly instrumented side-by-side 10' x 16' test sheds located at the Florida Solar Energy Center. One of the test sheds is

configured like a conventional home with a dark shingle roof and insulated ceiling under a ventilated attic. The experimental building features a white reflective roof on battens with a sealed attic where the air from the interior can be linked to the sealed attic and roof radiator when the roof temperature drops below the room target cooling temperature.

Figure E-1. *NightCool* side-by-side buildings under test.

This report provides a brief evaluation of the performance of *NightCool* under both summer and autumn weather conditions. Four experimental configurations were evaluated:

- No *NightCool* cooling with the experimental attics sealed to the interior (Null test): September 2nd - 4th, 2006.
- *NightCool* by convective air movement to the building only (open aperture to the attic so that cooled night air could drop out of the attic into the interior to be replaced by warmer air below): August 26th - 28th, 2006.
- No air conditioning in either test building, but *NightCool* activated with fan circulation in experimental test building: September 27th - 28th, 2006.
- Air conditioning in both test buildings, but when favorable attic temperature conditions are met, *NightCool* activated with fan circulation in experimental test building: October 20th - November 6th, 2006.

The last experiment, with supplemental air conditioning and *NightCool* operating in the experimental facility was evaluated under varied summer and autumn weather conditions.

The experiments show that the experimental prototype performed better thermally under passive configurations. With the *NightCool* linkage to the main zone disabled (null test) the average nighttime temperatures in the unconditioned experimental and control test buildings from 8 PM to 8 AM was 82.0°F and 82.6°F respectively when the outdoor air temperature averaged 74°F. This shows the experimental building runs slightly cooler at night, largely because of the lower attic temperatures across the insulation and the effectiveness of the R-30 SIPs panels in the ceiling against the R-30 fiberglass batts in the control. Otherwise, thermal performance was similar.

However, in the second configuration with an attic hatch opened to the attic to allow warm air to naturally convect into the attic and heavier cool air to naturally convect to the interior below, the *NightCool* building showed superior performance. The experimental building's interior ran 1.9°F cooler during nighttime hours without any mechanical air movement to aid heat transfer. This is about three times the temperature drop seen without any nighttime cooling and a good demonstration of nocturnal cooling within the concept without any fan power.

Detailed data was also obtained on the system with air conditioning used in the control and the experimental unit during daytime, and with the *NightCool* fan circulation system used during evenings.[1] A daytime temperature of 78°F was maintained in both test buildings. Measured cooling energy savings varied from 17% under warm, cloudy conditions to 53% during milder periods. This was true even though the *NightCool* system maintained an average temperature 1°F lower than the control building. Daily *NightCool* system Energy Efficiency Ratios (EERs) averaged 31.0 Btu/Wh over the four summer to fall test periods – in line with simulations conducted earlier. The nightly system EERs varied from a low of 23.2 to a high of 43.2 Btu/Wh, the highest performance being seen during tests with higher return air temperatures and during periods with cooler and more clear nighttime conditions. As expected performance was worse under cloudier humid conditions. Cooling rates also varied over the course of each evening, generally improving to a maximum point in the pre-down hours. The maximum nightly EERs varied between 35.4 (warm cloudy evening) to 69.1 Btu/Wh (clear and more cool conditions). In all cases, this level of performance compared favorably to an EER for the vapor compression air conditioner of about 9 Btu/Wh.

The delivered cooling rate averaged 2 - 4 Btu/hr/ft^2 (6 -13 W/m^2) of roof surface each evening, implying that *NightCool* in a full scale 2,000 square foot home would cool at a rate of 4,000 - 8,000 Btu/hr. Over a typical 10 hour operating period, this would produce 3 to 7 ton-hours of sensible cooling. The favorable experimental data collected so far indicates that *NightCool* can be a promising system technology for 50% or higher benchmark homes in hot-arid, hot-dry/mixed, mixed and humid climates. We plan to continue experimental and analytical work on the *NightCool* concept through out 2007 concentrating on improving the dehumidification performance of the concept and collecting data for a wide variety of operating conditions. We have presented the concept and data from *NightCool* test sheds to the cool metal roofing coalition. This industry group has enthusiastically endorsed the concept and plans to work with us in implementing the concept in future prototype homes.

[1] We would not recommend consumers open their attics in the fashion done in these experiments. To function, one must have fully exposed metal roofing with uniform, non-fibrous ceiling insulation down below. This is quite different from the configuration in most homes. Also, air system filters would be required in any real world application of the *NightCool* system.

Experimental Evaluation of the *NightCool* Nocturnal Radiation Cooling Concept: Performance Assessment in Scale Test Buildings

Danny S. Parker and John R. Sherwin
January 2007

Abstract

An experimental evaluation has been conducted on a night sky cooling system designed to substantially reduce space cooling needs in homes in North American climates. The system uses a sealed attic covered by a highly conductive metal roof (a roof integrated radiator) which is selectively linked by air flow to the main zone with the attic zone to provide cooling– largely during nighttime hours. Available house mass is used to store sensible cooling. Additional dehumidification is done during the evening hours as warranted by interior conditions.

A previous report describes a detailed simulation model of the relevant night cooling phenomenon, examining potential performance. Here, we summarize an experimental evaluation of concept performance using two highly instrumented test sheds. Data is presented on the comparative passive performance of the building thermal performance under static conditions (*NightCool* not operating), and also in a circumstance where *NightCool* is operating via natural convection alone between the interior of the test building and the sealed attic.

Further tests show the performance of the full implementation of the concept with circulating fans when attic conditions are favorable for nocturnal cooling and with conventional air conditioning at other times. Achieved performance is consistent with the previous simulation analysis. Cooling rates were in the range of 2 - 4 Btu/ft^2/hr of conditioned floor area under roof – from one third to two-thirds of a ton of sensible cooling in a 2,000 ft^2 home. Substituting for nighttime air conditioning, cooling energy reductions of 17-53% were demonstrated with nightly energy efficiency ratios (EERs) ranging from 23 - 43 Btu/Wh.

Introduction

Using a building's roof to take advantage of radiation to the night sky as a heat sink has been long identified as a potentially productive means to reduce space cooling. Radiative cooling to the night sky is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower temperature (Martin and Berdahl, 1984). In the case of buildings, the cooled surfaces are those of the building shell and the heat sink is the sky since the sky temperature is lower than the temperature of most earth bound objects.

The night cooling resource is large and enticing for residential energy-efficiency applications. On a clear desert night, a typical sky-facing surface at 80°F (27°C) will cool at a rate of about 70 W/m^2 (Givoni, 1994; Clark, 1981). In a humid climate with the greater atmospheric moisture, the rate drops to about 60 W/m^2. Night-time cloud cover is an important variable as well. With 50% cloud cover in a humid climate, the cooling rate drops to about 40 W/m^2 and only about 7 W/m^2 under completely overcast skies. In many North American locations, the available nocturnal cooling exceeds the nighttime cooling loads and in arid desert climates may be considerably in excess of total daily cooling requirements. Careful examination of air conditioner operation in many homes in Florida (Parker, 2002) shows that typical residences experience cooling loads averaging 33 kWh per day from June - September with roughly 9.2 kWh (28%) of this air conditioning coming between the hours of 9 PM and 7 AM when night sky radiation could substantially reduce cooling needs.

Over a 10 hour night, theoretically night sky radiation amounts to about 250 - 450 W/m^2 if all could be effectively utilized. However, that is not easily achieved. Winds add heat to the roof by convection and thus reduce beneficial heat transfer from night sky radiation. Under an average wind speed of 2 mph (0.9 m/s) – the potential diminishes by about half of the above. Also, water condensation – dew – limits the temperature depression that can be achieved for exposed surfaces.[2]

Only a portion of the potential cooling can be obtained since the heat must be transferred from the building to the radiator and then to the sky. The rest will cool the radiator down until it gains more heat from surrounding air or reaches the dew point and is effectively lost for cooling purposes. Various physical limitations (differential approach temperature, fan power, convection and roof conductance) limits what can be achieved, so that perhaps half of this rate of cooling can be practically obtained. However, passive systems with very little air velocity under the radiator (or those with a small circulation fan) still will achieve delivered net cooling rates of 1 - 5 W/m^2. With 200 m^2 of roof in a typical home that adds up to a nearly free cooling rate of 200 - 1,000 Watts (700 - 3,400 Btu/hr). Systems with higher air flow rates (800 cfm or 1,360 m^3/hr), can achieve net cooling rates about twice that level.

Extensive work has examined the use of exotic night cooling schemes: roof ponds, massive roofs with moveable insulation, combined desiccant and radiative cycles and other technologies (Hay, 1978; Fairey, et al, 1990; Givoni, 1994). Often, however, issues such as operational complexity and parasitic fan power have made them unpromising.

Description of the *NightCool* Concept

We have devised an innovative night cooling system consisting of a metal roof serving as a large area, low mass highly-conductive radiator (see Figure 1). The metal roof could be used at night during spring, autumn and acceptable summer periods to perform sensible cooling. It could also be used for heating during winter daytime operation where low-grade heat from the metal roof could be used to heat the home during midday and late afternoon hours when weather conditions are beneficial. Building Integrated Photovoltaics (BIPV) could be used with the metal roofing system to generate electric power.

[2] With surfaces exposed to night sky radiation under still air conditions, there is some degree of surface radiative sub-cooling below the dew point, by 1 - 3°F – a fact long known to plant physiologists (e.g., C.A. Brewer and W. K. Smith, "Leaf Surface Wetness and Gas Exchange in the Pond Lily," American Journal of Botany, 82 (10), 1271-1277, 1995.

A recurring problem with night sky radiation cooling concepts has been the requirement of exotic building configurations. These have included very expensive "roof ponds" or, at the very least, movable roof insulation with massive roofs so that heat is not gained during daytime hours (Hay, 1978; Givoni, 1994). The key element of the described configuration is that rather than using movable insulation with a massive roof or roof ponds, the insulation is installed conventionally on the ceiling. The operation of the system is detailed in the attached schematic.

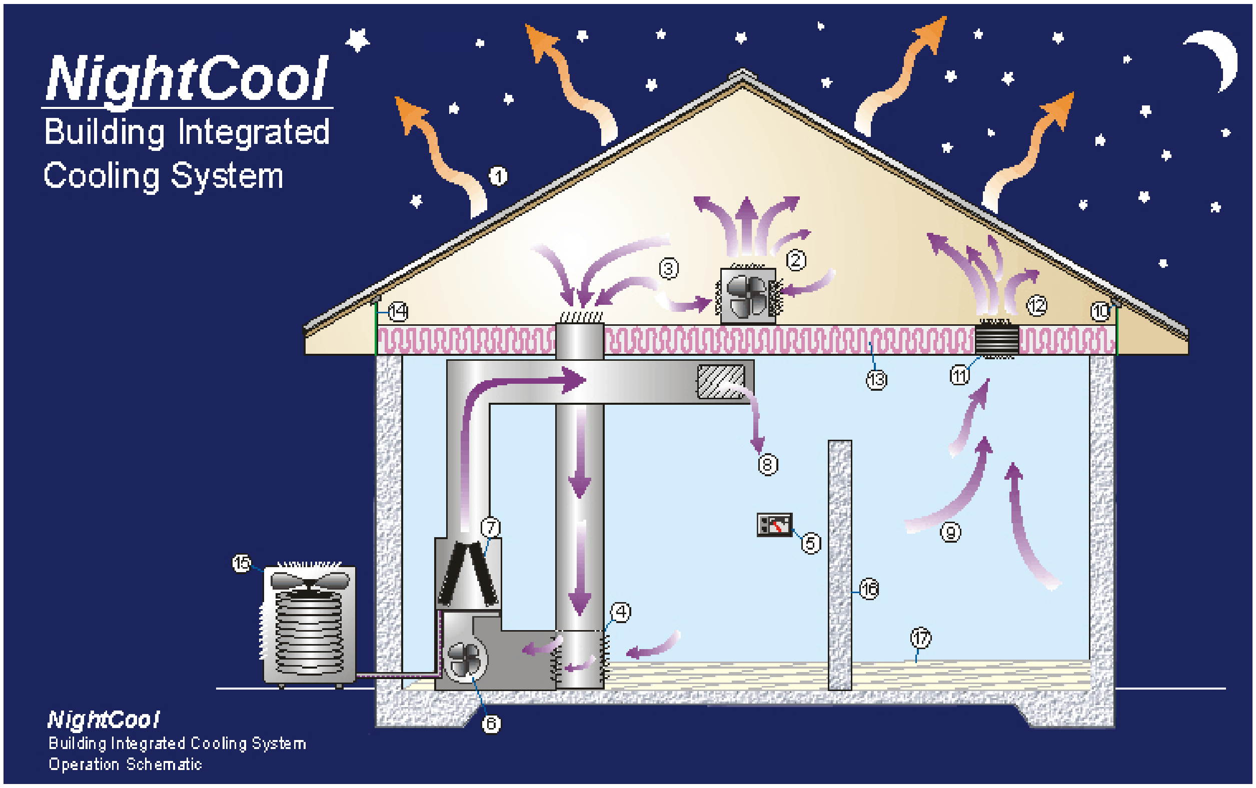

Figure 1. Schematic of *NightCool* concept.

1. White metal roof on metal battens (no decking). Both sides are surfaced for high emissivity. A temperature probe measures roof underside temperature.	7. Vapor compression air conditioner cooling coil.
2. Small capacity dehumidifer (such as *Whirlpool AD40DBK*); operates only during evening hours when thermostat and roof temperature monitor calls for cooling and attic relative humidity is greater than 55%.	8. Interior duct system with supply outlet.
3. Baffled inlet frill from attic for nighttime operation.	9. Interior room air return to attic during evening hours when Night Cool is activated.
4. Room return inlet (for daytime operation). Closed by damper at night when temperature conditions are met.	10. Roofline drip collection system with drain.
5. Thermostat (compares roof surface temperature and setting to determine vapor compression vs. nighttime cooling operation).	11. Ceiling return for *NightCool* operation mode.
6. Variable speed air handler fan with electronically commutated motor.	12. Attic air connects to cool roof for nocturnal cooling.
	13. R-20 ceiling insulation.
	14. Sealed attic construction with top plate baffles (tested and sealed system).
	15. Air conditioner outdoor unit (condenser).
	16. Concrete interior walls (thermal mass for sensible cool storage).
	17. Tile floor (add thermal mass).

During the day, the building is de-coupled from the roof and heat gain to the attic space is minimized by the white reflective metal roof. At this time the space is conventionally cooled with an appropriately sized air conditioner. However, at night as the interior surface of the metal roof in the attic space falls two degrees below the desired interior thermostat set point, the return air for the air conditioner is channeled through the attic space by way of electrically controlled louvers with the variable speed fan. The warm air from the interior then goes to the attic and warms the interior side of the metal roof which then radiates the heat away to the night sky.

As increased cooling is required, the air handler fan speed or runtime is increased. If the interior air temperature does not cool sufficiently the air conditioner is energized to supplement the sky radiation cooling. Also, if temperature conditions are satisfied, but relative humidity is not, a dehumidifer (note 2 on Figure 1) or other dehumidification system is energized. The massive construction of the home interior (tile floor and concrete interior walls) stores sensible cooling to reduce space conditioning needs during the following day.

Theoretical Thermal Performance

The theoretical performance of the *NightCool* concept has been extensively simulated through a detailed calculation model. The results of this work were previously described in detail in an earlier project report (Parker, 2005).

Within that work, a 225 square meter metal roof structure was modeled in Tampa, Florida. Under a series of standard nighttime conditions approximating humid nighttime summer weather, the model predicts a cooling rate of about 2,140 Watts (7,300 Btu/hr). The model features several enhancements (such as constraining the radiator temperature to the dewpoint temperature) never before incorporated into such a model. It was found that the major weather-related influences on achieved cooling performance are outdoor air temperature, dewpoint temperature, cloudiness and wind speed. Physical factors with a large influence are the system return air temperature (and hence radiator temperature) air flow rate and fan and motor efficiency.

For Tampa, Florida, the model predicted an average summer cooling benefit of about 15 kWh per day for 1.4 kWh of fan power for a system seasonal energy efficiency ratio (SEER) of about 37 Btu/Wh. Performance in less humid climates with more diurnal temperature swing was predicted to be substantially better

Small Scale Test Buildings

To verify the potential of the concept, the radiative cooling system is being tested in two 12 x 16' test structures (192 ft^2 of conditioned area). These highly instrumented buildings are located just south of the Building Science Lab at the Florida Solar Energy Center (FSEC) in Cocoa, Florida. Figure 2 shows a schematic of how the simplified experimental buildings function. Figure 3 shows the completed side by side test buildings.

Figure 2. *NightCool* test building schematic.

Figure 3. Completed side-by-side test buildings at Florida Solar Energy Center.

The control building has dark brown asphalt shingles with a solar reflectance of 8% over a standard ½" plywood decking on rafters. The vented attic in the control building has 1:300 soffit ventilation. The ceiling is insulated with ten-inch R-30 fiberglass batts over ½" dry wall, although the gable end walls are not insulated. The roof of the control building is shown in Figure 4. The interior of the conventional ventilated attic of the control building is shown in Figure 5.

Figure 4. Control test building with conventional asphalt shingle roof covering a ventilated attic.

Figure 5. Interior of ventilated control attic with R-30 fiberglass insulation.

The experimental unit has a white metal 5-vee roof on metal battens and a sealed attic, which can be convectively linked to the main zone by a powered circulation fan. The white metal roof had an initial solar reflectance of 65% (Figure 6).

Figure 6. *NightCool* test building with metal roof.

Figure 7 shows an interior view of the exposed metal roof on metal battens in the sealed attic of the experimental *NightCool* facility. Note the sealing of the soffit vents with insulation inserts and sealant foam. The white metal roofing is installed on metal battens so that it is directly exposed to the attic below. This produces strong radiational and convective linkage between the fully exposed roof and the sealed attic interior.

Figure 7. Interior detail of experimental *NightCool* sealed attic with exposed metal roofing on metal battens. Note thermocouple measuring underside of roof temperature.

Figure 8 shows the R-30 SIPs panels during the installation. This also gives a good view of the exposed metal roofing in the experimental facility. Unlike the control attic, the gable ends have been dry walled to allow the attic of the experimental facility to be effectively sealed.

Figure 8. R-30 SIPs panels during installation in the ceiling in the *NightCool* experimental facility.

The ceiling of the experimental facility consists of R-30 structurally insulated panels – a 10" sandwich of polystyrene faced with sheetrock on the interior (Figure 9).

Figure 9. R-30 polystyrene structurally insulated panel (SIPs) ceiling in the experimental *NightCool* building showing cut-out for attic hatch.

Both units have uninsulated 6" concrete slab floors with an area of 192 square feet. The frame walls in both are insulated with R-13 fiberglass batt insulation, covered with R-6 exterior iscyanurate sheathing, and protected by beige concrete board lapped siding. Similar insulated metal doors are located in each prototype on the north side of the building.

On October 20, 2006, we used SF_6 tracer gas to test the *in situ* infiltration rate of the control and *NightCool* buildings with the air conditioning off, but with the *NightCool* air circulation grills open. The measured infiltration rates were 0.27 ACH in the control and 0.34 ACH in the *NightCool* test building – a fairly similar result.

Each test building has four 32" x 32" double-glazed solar control windows. The single-hung windows have air leakage rating of 0.1. These have a NFRC rated U-factor of 0.35 Btu/hr/ft^2-F, a solar heat gain coefficient of 0.35 and a visible transmittance of 60%. The windows are covered with white interior blinds. In each test building, one window is located on the east and west exposure and two are located on the south. The glazed area is 28.4 square feet for a glazing to floor ratio of 15% – similar to prevailing residential construction practice in Central Florida. In future experiments, additional mass will be located in the *NightCool* building to examine how this change influences performance.

As the experimental test building for evaluating the concept is scaled to be one tenth of the size of the theoretical buildings in the simulation exercise, we would expect to see about 1.5 kWh per day of cooling in summer months with the small scale buildings.

Instrumentation and Monitoring

A extensive monitoring protocol was developed for the project as shown by the detailed instrumentation see Table 1. A key measurement in the *NightCool* building involves measuring air mass flow with the return and supply temperatures from the sealed attic space under the radiatively coupled roof.

Figure 10 shows the project weather tower installed at the site. Measurements include outdoor temperature, wind speed at roof height, insolation, relative humidity, rainfall and sky infrared emittance.

Figure 10. Project weather tower is attached to the control building on the northeast side.

Weather parameters including temperature, humidity insolation, windspeed and a pyrgeometer are used to determine potential night cooling along with nighttime heat dissipated to the integral night sky radiator system.

Small 5,000 Btu/hr room air conditioners are installed to supply supplemental cooling although these were not active for all experiments. Internal loads are simulated by switching on and off interior lamps using wall timers. Electricity consumption data is collected for air conditioner, internal loads and *NightCool* fan power.

Table 1
Instrumentation Channel Map for *NightCool* Experiment

Weather	*Units*
Dry Bulb	°F
Relative Humidity	%
Horizontal Insolation	W/m^2
Wind Speed (roof top)	mph
Wind Direction (degrees)	0-360
Horizontal Infrared Irradiance	W/m^2
Rain	inches
Ground temperature at 1 ft depth	°F
Roof condensate measurement (south)	lb.
Thermal	
Roof surface temperature (north and south)	°F
Roof underside temperature (north and south; metal roof or sheathing)	°F
Attic air temperature (mid attic)	°F
Ceiling sheet rock temperature (inside surface, north and south)	°F
Inlet air temperature to circulation fan	°F
Attic outlet temperature to room	°F
Interior Temperature by control thermostat (wall)	°F
Interior Room temperature at room center	°F
Slab interior surface temperature by wall	°F
Slab interior surface temperature at mid width (center)	°F
Slab interior surface temperature at quarter width	°F
Humidity	
Attic relative humidity (mid attic)	%
Interior Humidity by thermostat	%
Power (1 Wh/pulse)	
AC unit power	Wh
Dehumidifier power	Wh
Attic circulation fan power (exp only)	Wh
Lighting power & indoor circulation fan (Internal loads	Wh

Simulated Occupancy and Sensible Internal Gains

Although both test buildings are unoccupied, we simulate the impact of released internal heat gains in a fashion that scales a typical occupied home. Given that the test buildings are one-tenth the size of typical homes, this process is straightforward. The typical internal gain profile was taken from the assumptions used in the IECC for standard home operating condition for a 2,000 square foot home (IECC, 2005). Note that a standard home has a total daily gain of about 79,000 Btu or 23,000 Wh. Reflecting occupancy patterns, the distribution is bi-modal with higher gains in the mornings and more in the evening hours. We reduce the total by 18% to account for the latent fraction and then divide the hourly gains by ten to yield scaled values for our experiments. Table 2 shows the calculations by hour.

Table 2
Scaling Internal Gain Levels for *NightCool*

Hour	Gain Watts IECC	Hourly Fraction	Indicated *NightCool* Watts	Experiment Applied Watts
1	759	0.470	62	60
2	738	0.457	61	60
3	740	0.458	61	60
4	749	0.464	61	60
5	778	0.600	64	60
6	970	0.642	80	85
7	1,037	0.624	85	85
8	1,008	0.488	83	85
9	788	0.458	65	60
10	741	0.425	61	60
11	687	0.422	56	60
12	681	0.449	56	60
13	726	0.433	60	60
14	699	0.456	57	60
15	737	0.549	60	60
16	887	0.635	73	85
17	1,026	0.826	84	85
18	1,335	0.834	109	110
19	1,348	0.970	111	110
20	1,568	1.000	129	110
21	1,616	0.929	132	110
22	1,501	0.702	123	110
23	1,135	0.541	93	85
24	874	0.630	72	85
Total	23,129			
Btu/day	78,938	Total Btu/day		
Latent	13,970	18% Latent (Btu/day)		
Sensible	64,968	Total sensible Btu/day		

To approximate the gain load shape, we simplified the gains into three tier levels as shown in the final column: 60 Watts, 85 Watts, 110 Watts. This schedule was implemented using three lamps and two digital timers in each test building along with a constantly operating circulation fan. The circulation fan provides good thermal mixing of interior air in each building.

- One 40 Watt circulation fan with a 18 Watt CFL on for 24 hours of each day.
- One 25 Watt lamp on when 85W is called for
- One added 25W lamp on when 110 W is called for.

Figure 11 shows the measured power of the lamps and fans simulating internal gains in the two test buildings over a two day period in November.

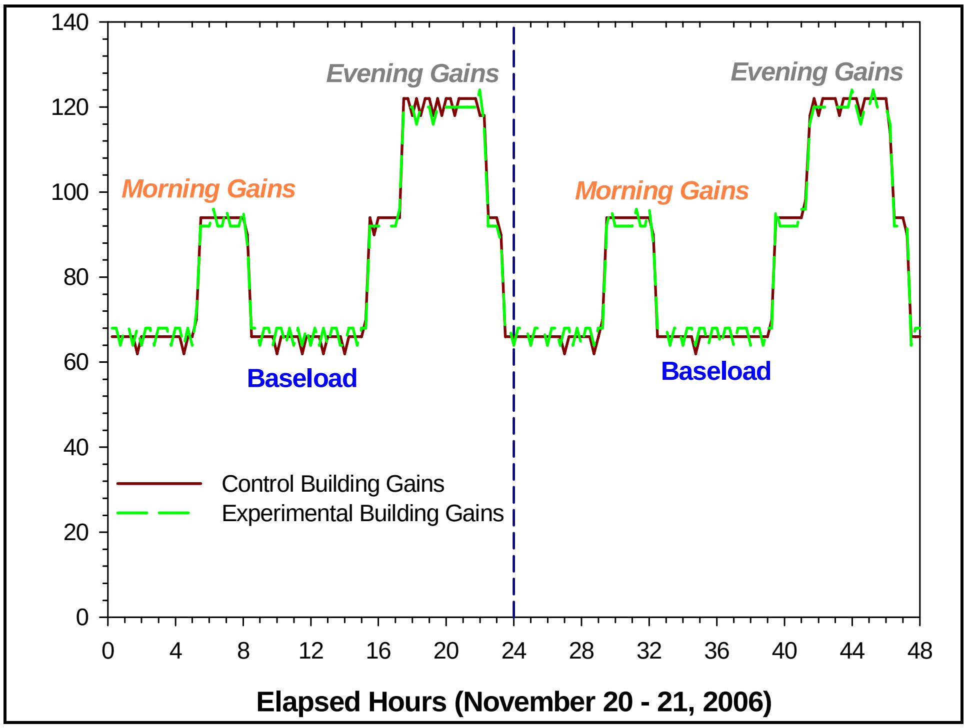

Figure 11. 24-hour measured internal gains schedule for *NightCool* test buildings (Watts).

In 2007, we will add latent heat gains to the profile for humidity control experiments.

Experimental Results in Static Configuration

The first monitoring phase evaluated the thermal performance of the comparative buildings without *NightCool* operating. In attached plot, the experimental test building and control are both in free float condition from Saturday, September 2nd through September 4th, 2006. Here, the attic hatch to the *NightCool* attic was sealed so that cooled night air in the attic could not naturally convect with the interior down below. Figure 12 details the observed thermal conditions in the two test buildings.

Not surprisingly, the interior temperatures of the two buildings look fairly similar. The *NightCool* building is about half a degree cooler at night – mainly because the attic above the insulation is cooler. It is also somewhat cooler during the day as the white roofed attic is cooler than that in the control.

Also, note that without heat being added to the *NightCool* attic, the attic air temperature drops quite low – the attic reaches 69.3°F on September 4th, 2006 at 7:15 AM with the simultaneous roof underside temperature at 67.9°F. These were slightly below the coincident outdoor dewpoint temperatures of 71.4°F, however, no evidence of interior condensation was observed.

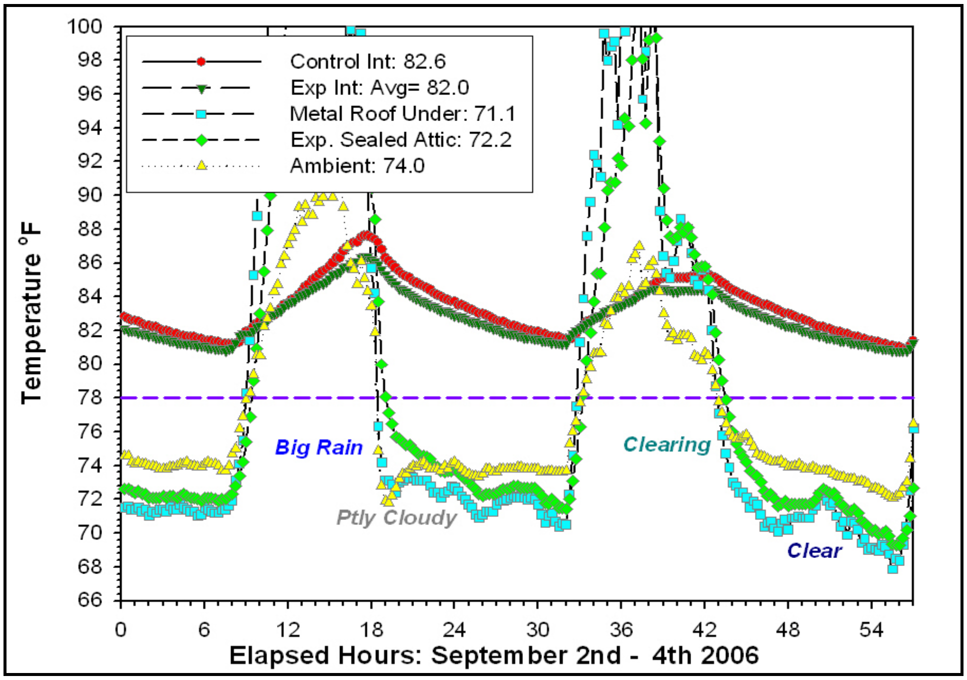

Figure 12. Null Test: comparative interior temperatures Control and *NightCool* test buildings; Free Float: no attic convection (avg. temps from 8PM to 8AM).

Although not utilized, the observed attic/roof temperatures showed a good potential for nighttime cooling – the *NightCool* attic averages 6°F cooler than our target temperature (78°F).

Performance with Natural Convection Cooling

During a second phase of the monitoring, no fans are used to circulate air to the attic space although the attic hatch was open. In this case, the Nightsky system was operating only by passive air circulation; heat transfer is via internal radiation and free convection where cooled attic air drops to the main conditioned zone via buoyancy. The data reflects a passive configuration with no mechanical air movement to the sealed attic of the *NightCool* cell. However, as shown in the Figure 13, superior thermal performance is seen in the data taken under summer conditions in Central Florida: hot in the day, and cloudy and humid at night.

The passive system performance data is from Saturday, August 26th and Sunday August 27th. Note that the *NightCool* building's interior below the R-30 SIPs panel runs about 2°F cooler than in the control building during evening hours. The situation in the sealed attic reflects the good night cooling potential. Although its temperatures are still quite high during daytime hours, at night, it falls quickly and drops well below our target temperature of 78°F by 8 PM (It reaches below 76.4°F by that time on Saturday, the 26th). The metal roof underside temperature drops still lower reaching a low of 69.6°F at 5:15 AM on Sunday morning. The mid attic air temperature under the metal roof was 70.8°F at the same time. Note that these temperatures are lower than the coincident ambient air temperature.

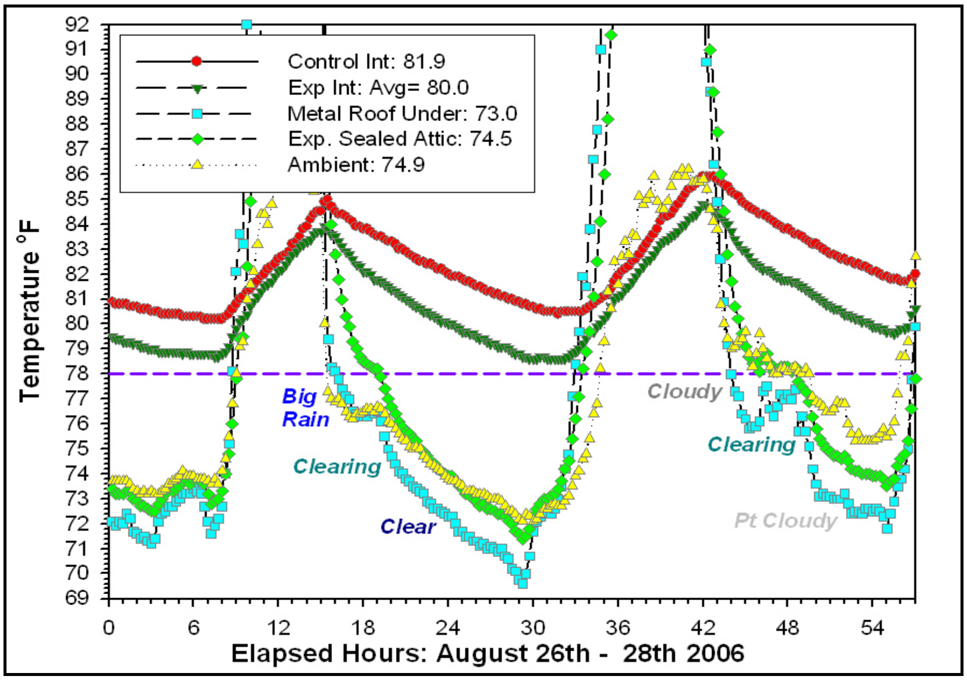

Figure 13. *NightCool* by natural convection only: comparative interior temperatures Control and *NightCool* test buildings free float condition (avg. temps from 8PM to 8AM).

These data indicate significant nighttime cooling potential in a passive configuration even in Central Florida's hot humid summer. Moving warm air from the interior space by fans with the active *NightCool* system will result in a corresponding warmer radiator, leading to even better utilization of the night sky heat loss mechanism (a warm radiator can substantially increase the radiation to the sky as the differences are to the 4th power according to the Stefan-Boltzmann constant).

Componets and Control of *NightCool* Circulation System

Two ceiling mounted registers were cut out from the R-30 SIPs panel ceiling of the experimental building. A *Fantech FR125* centrifugal fan was installed on one side to circulate air from the main zone to the attic space when temperature conditions are met. Generally the *NightCool* system is activated when the attic air temperature falls below 74°F. To maintain the main interior zone under a positive pressure, the fan drew air from the sealed attic with return air entering from a passive register on the opposite side of the room. Figure 14 shows the registers and circulation fan.

Figure 14. High efficiency 150 cfm centrifugal fan and supply and return registers; the current arrangement uses attic depressurization and main zone positive pressure with a single fan operating; the high efficiency fan draws only 18 Watts when operating at full speed.

All measurements are uniformly made by the project data acquisition system (DAS) and control is achieved by using the *Campbell CR10* digital IO ports.

NightCool Fan System

NightCool fan: measured air flow: 152 cfm (using Duct Blaster)

NightCool Fan Power: 18 Watts

Wall Air Conditioners

As shown in Figure 15, both the experimental and control buildings are cooled by two small window unit air conditioners (*General Electric AKN05LAG1*). These AC systems are operated by the DAS to obtain very fine temperature control of the interior space which is set to 78°F. These have a nominal capacity of 5,000 Btu/hr and an EER of 9.7 Btu/Wh. Based on measurements, we determined that they draw about 520 Watts when running at 85°F outdoor condition.

Figure 15. Experimental *NightCool* building showing central data acquisition system and wall-mounted air conditioner.

Measured air flow: 141 CFM[3]
Fan power = 55 Watts without compressor
Temperature drop at 85 F condition: 24 F
Sensible Capacity= 3,650 Btu/hr
Sensible EER = 7.0 Btu/Wh

Performance of *NightCool* without Air Conditioning

NightCool is not designed to provide cooling during the middle of Central Florida's hot summer – perhaps a few hours each evening at most. However, it should provide significant nighttime summer cooling in more temperate latitudes with greater daily temperature swing. Even with Central Florida's nine month cooling season, *NightCool* holds out the promise to potentially cut the air conditioning season back to four months. In dry climates with clear night skies, such as California, *NightCool* could largely replace vapor compression AC equipment.

Data taken on September 27th-28th, 2006 show the performance of the *NightCool* system with the system fans operating, but without air conditioning in either the control building or in the experimental facility. Table 3 and Figures 16 and 17 summarize the data:

Table 3
NightCool Performance without Air Conditioning

Average conditions during *NightCool* operation (8 PM - 8 AM)
Control Interior: 83.3°F
NightCool Interior: 78.3°F
Measured supply fan flow rate: 135 cfm
Supply and Return Fan Power during Cooling: 25.6 Watts
Avg. return temperature to sealed attic: 78.9°F
Avg supply temperature to main zone: 71.2°F
Avg *NightCool* cooling rate: 1,133 Btu/hr (332 W)
EER = 44.3 Btu/Wh
Morning interior temperatures at 8 AM before system shut down
NightCool: 74.5°F
Control: 81.0°F
6.5°F difference

[3] When the wall air conditioners are operating, no induced interior pressure differences can be measured with unit on or off which is indicative of no induced pressure differences from AC operation.

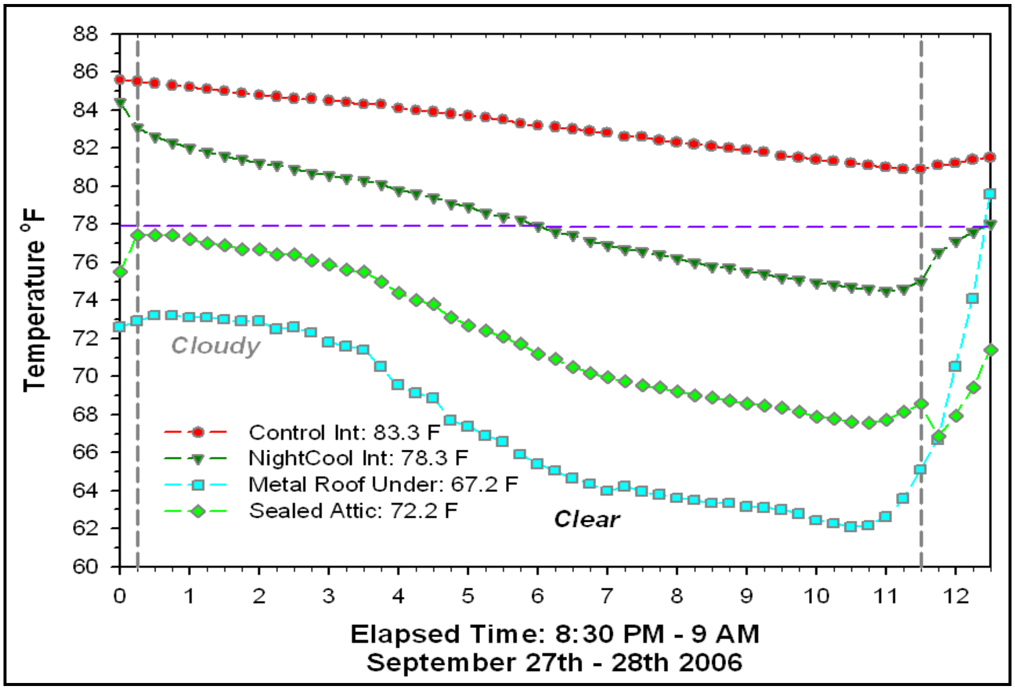

Figure 16. *NightCool* thermal performance with fans operating but no air conditioning. For comparison control building interior temperature is shown in red; *NightCool* temperature is green triangles.

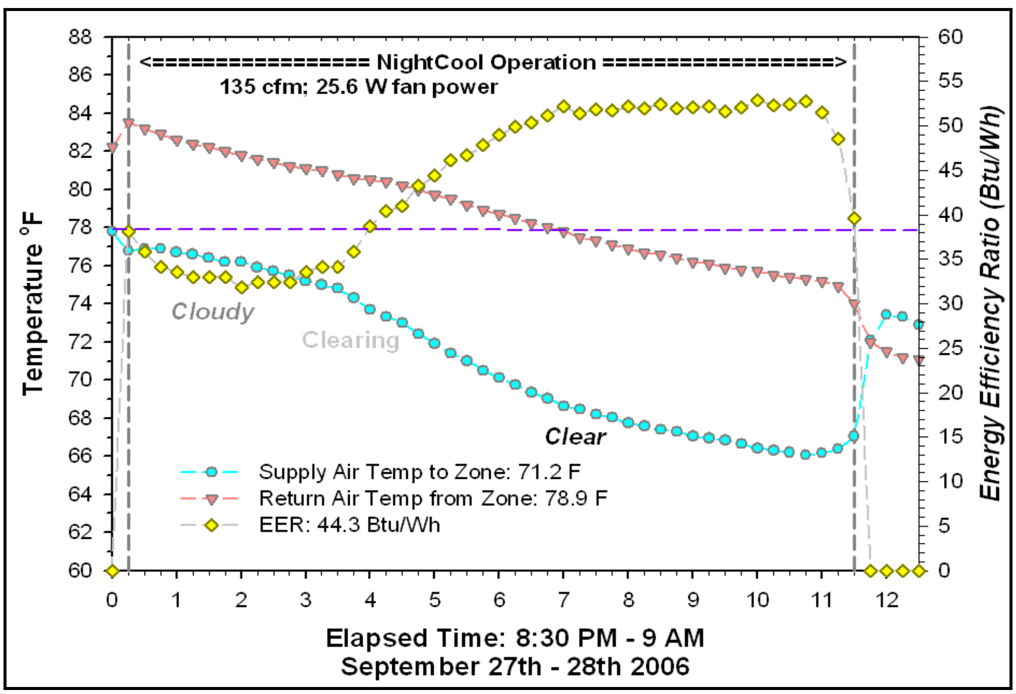

Figure 17. *NightCool* system performance with circulation fans operating, but no air conditioning. Supply and return temperatures are shown along with 15-minute system EER.

The average temperature drop from the return to supply side of the *NightCool* circulation system was 7.7°F. Average nighttime cooling rate was 1,130 Btu/hr (322 W). EER varied over the night from a low of 32 Btu/Wh at start up to a high of 53 Btu/Wh after the skies cleared.

NightCool Performance with Air Conditioning under Typical Summer Conditions

The final phase of the monitoring in 2006 evaluated the fully operational *NightCool* system with supplemental air conditioning used when interior temperatures rose above 78°F.

<u>*NightCool* Activation Conditions</u>

- Attic Temperature < 74°F
- Attic Temperature < Interior air temperature
- Interior Air Temperature > 74°F

Conditions are evaluated ever 10 seconds. When *NightCool* is activated, the air conditioning system is turned off. Conversely, if the indoor air temperature is above 78°F, the room air conditioner is activated and *NightCool* fans cannot be activated. As set up, the *NightCool* system will cool the interior space down to 74°F, prior to being turned off. The cut off prevents overcooling of the conditioned interior.

Florida's October weather often contains days which are very warm and similar to average summer conditions. The plots shown in Figure 18 and 19 show performance on October 20th - 23rd, 2006 when the daytime outdoor temperatures were hot and nighttime conditions were warm and cloudy – adverse conditions for the nocturnal cooling.

Figure 18 shows the thermal conditions over the two-day period, while Figure 19 shows the *NightCool* and measured AC power in the two buildings with integral loads imposed.

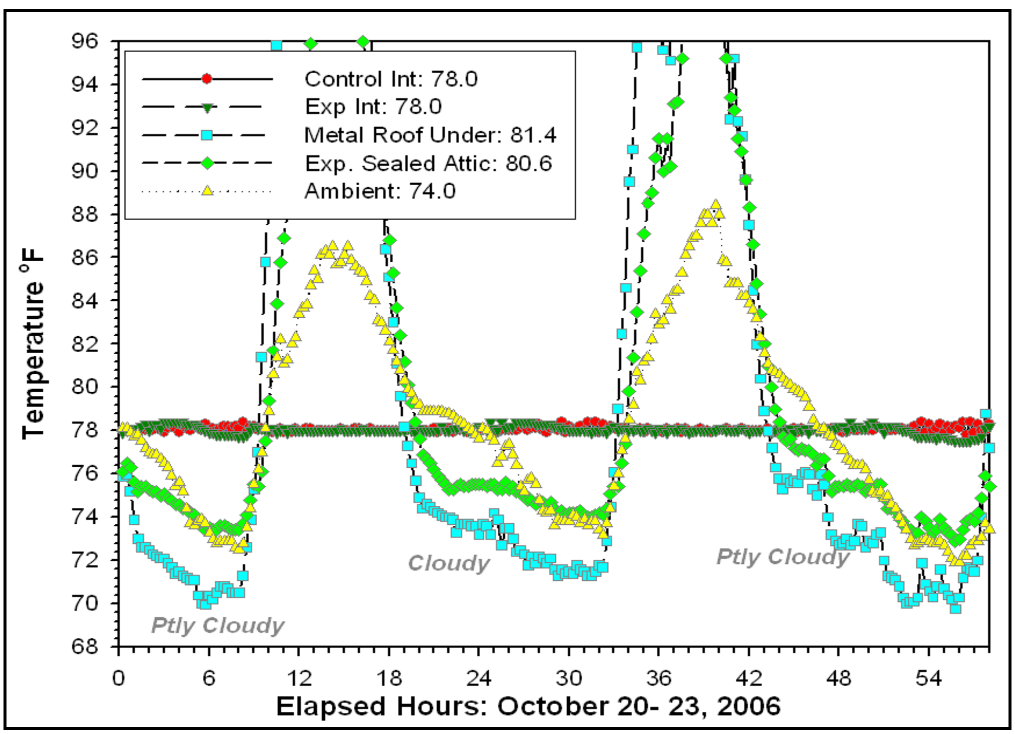

Figure 18. Comparative interior temperatures in control and *NightCool* test buildings. AC in both buildings; *NightCool* in experimental.

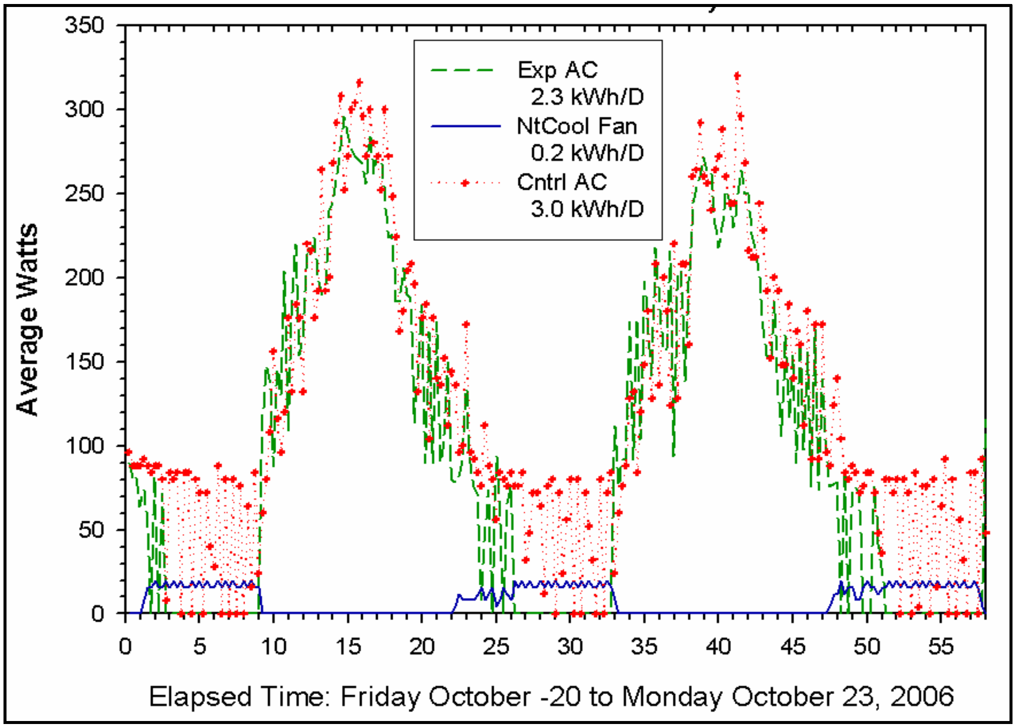

Figure 19. *NightCool* performance, October 20-23, 2006; warm cloudy conditions.

Both buildings are air conditioned but the *NightCool* system operates when attic temperature conditions are appropriate. Note, the very precise interior temperature control in both buildings. Even during the very warm and cloudy nighttime conditions, the *NightCool* system is able to reduce daily space cooling energy use by 17% over the control home. Measured savings were 0.5 kWh per day which would have been approximately 5 kWh per day in a full scale 2000 square foot home.

Performance under Summer Mild Conditions, 2006

The plots in Figures 20 and 21 show performance under mild weather conditions over a 24-hour period from October 31st - November 1st, 2006 which included short heavy rains. The system control and configuration was exactly the same as in the earlier test.

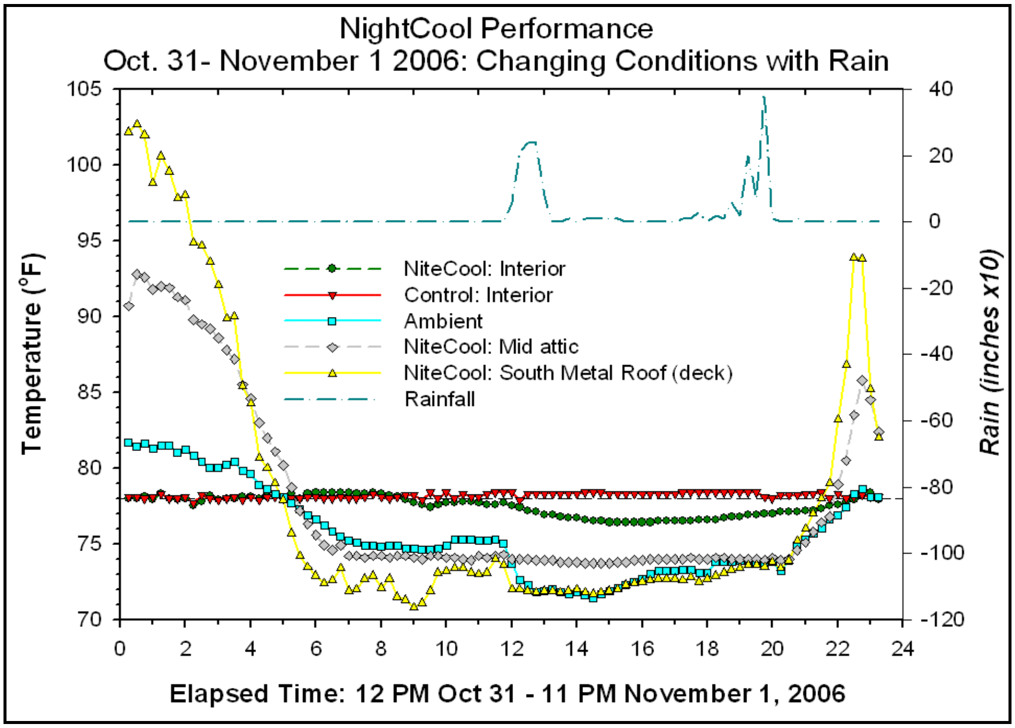

Figure 20. Temperature conditions on interior of *NightCool* and Control building, ambient air temperature and *NightCool* attic/roof.

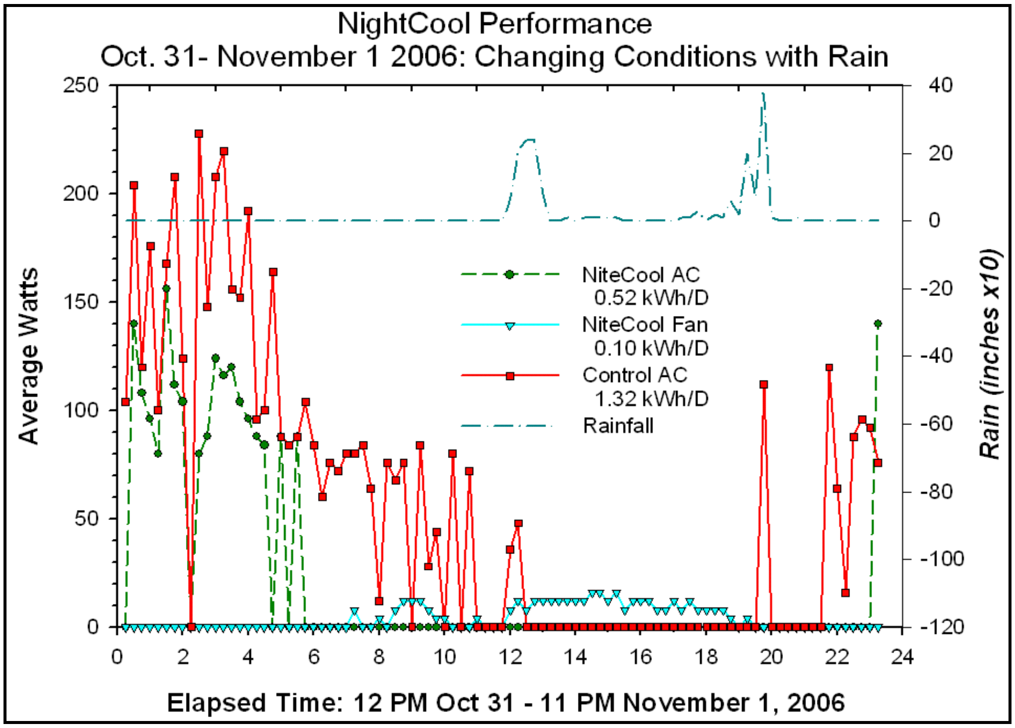

Figure 21. Comparison of AC and *NightCool* fan power with AC power in the control.

Note that the experimental building remains cooler inside than the control – particularly at night, yet uses about 53% less energy than the AC system in the control. The cooling energy savings were about 0.7 kWh/day and would have been about 7 kWh/day in a full scale home. This indicates potential savings of cooling energy of up to 50% under mild summer conditions.

Performance under Mild Autumn Conditions

A third test in the *NightCool* evaluated performance from November 3rd - 6th, 2006 in autumn in Central Florida. Note that these conditions would be similar to those encountered in most of the temperate United States during fall in the month of October. There are two plots (Figures 22 and 23); one for *NightCool* thermal performance and the other comparing energy use. Measured infrared Sky emittance is also superimposed on the energy plot.

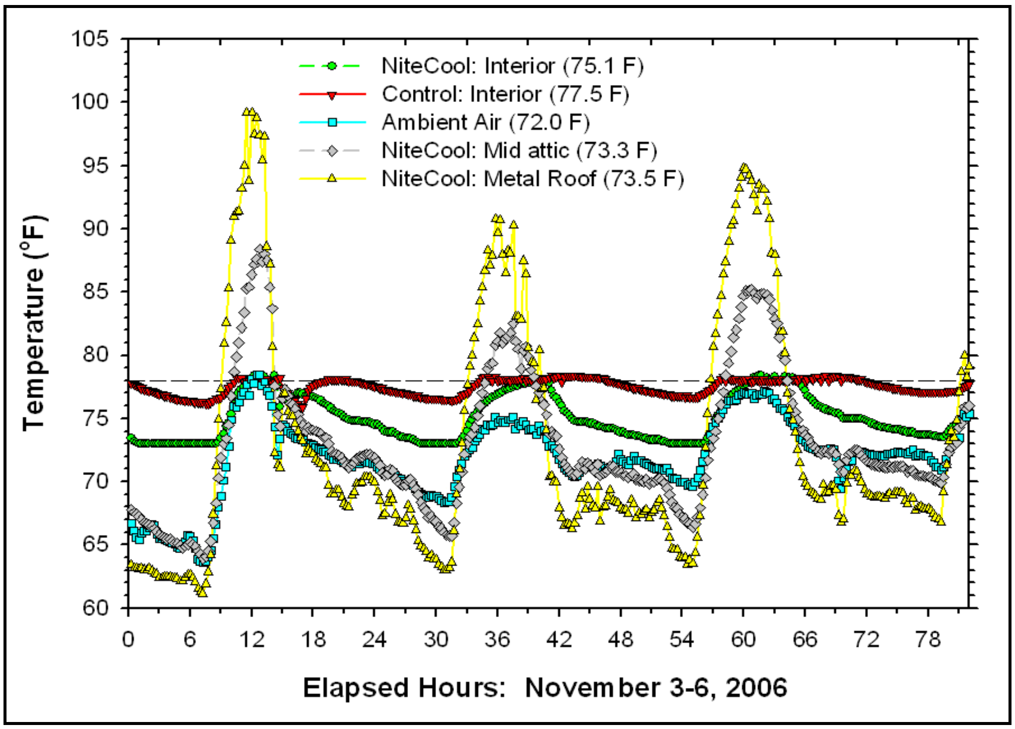

Figure 22. *NightCool* thermal performance under mild autumn-like conditions. Note that the *NightCool* building was maintained at a substantially cooler temperature.

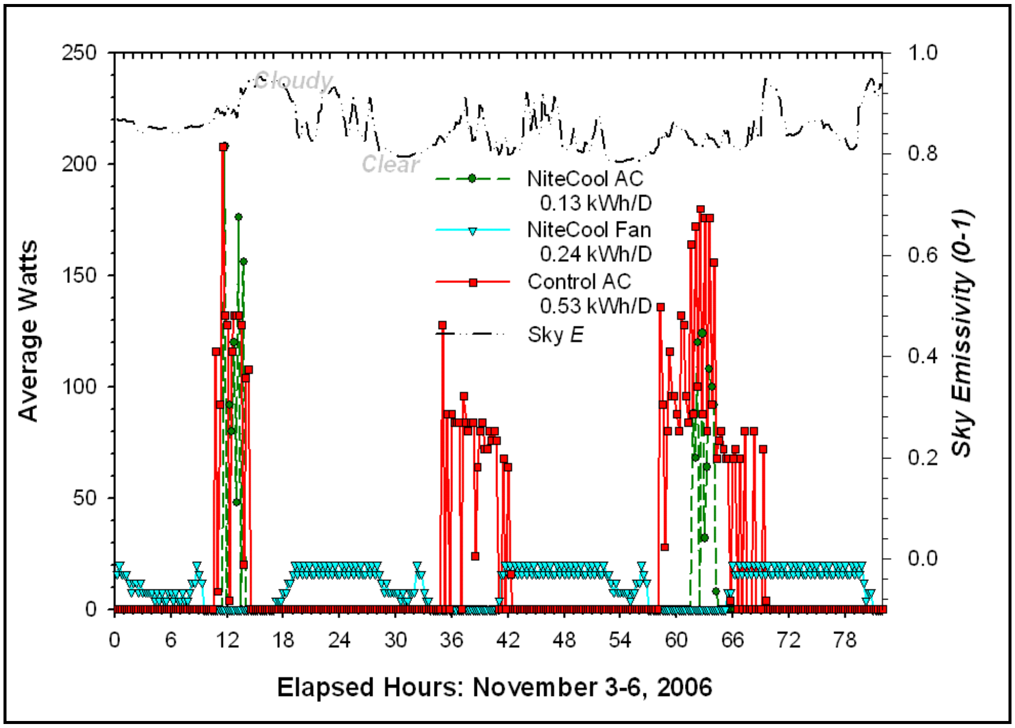

Figure 23. *NightCool* energy performance under mild conditions.

Average savings of *NightCool* (fan and AC) over the conventional AC system in the control was 30% (0.16 kWh/day), although the experimental system maintained an average interior temperature about 2.4°F lower than the control.

Comparison with Simulation Predictions

A previous report used a detailed simulation to predict *NightCool* system performance (Parker, 2005). The calculated a baseline system nighttime cooling rate in that evaluation was 2,157 Watts (7,360 Btu/hr) in a 2000 square foot building in typical Tampa summer conditions. Estimated fan power to provide this performance level was 235 Watts for an Energy Efficiency Ratio of 31 Btu/Wh.

The monitored performance in the first phase of the measurement shown here was favorable relative to the simulated results. In the various periods monitored above, the average cooling rate varied from 2.5 - 6 Btu/sqft of ceiling area or 480 to 1152 Btu/hr (141 W to 338 W), in absolute terms. As the measured fan power was 18 Watts, the system sensible EERs varied from 27 - 64 Btu/Wh. The average observed return to supply temperature difference was about 3.5°F including periods with both hot and mild conditions. Thus, the average performance was:

Cooling Capacity = 3.5 * 150 cfm * 1.08 = 570 Btu hr (167 W)

EER = 570/ 18 Watts = 32 Btu/Wh

Since the *NightCool* test buildings have a ceiling area of 192 ft^2 against 2,000 ft^2 for the full scale simulation, we would expect the simulation results to average about 710 Btu/hr (207 Watts) for the

1/10th scale buildings. As shown above the measured performance was similar to that simulated, although lower by about 20%. However, based on the measurement and simulation, we have a convincing explanation for the slight shortfall.

In the simulation analysis a number of input parameters were to be important relative to the model predictions. One of the most sensitive parameters was the maintained interior air temperature and the return air temperature to the *NightCool* radiator. Within the simulation, we assumed a return temperature of 78°F. For instance, as shown in Figure 24 below, the estimated cooling capacity of the system is 2,157 W at 78°F.[4] However, at 75°F (24°C), it is only 720 Watts. Conversely at 82°F, the capacity increases to 2,605 Watts – a four-fold increase relative to a change in the assumed return air temperature of only 7°F. What was not accounted for was that in sub-cooling the experimental building's interior temperature down to a minimum of 74°F, the *NightCool* system would typically operate at a midpoint between 78°F and 74°F. At 77°F, where the system typically operated, the simulation indicated a cooling capacity for the full scale building of only 1,195 Watts. This would imply a cooling rate of about 410 Btu/hr (120 Watts) in the scale buildings versus the 167 Watts actually achieved. Thus, the actual buildings appear to operate somewhat better than the original calculations after allowance is made for the as-operated lower return temperature.

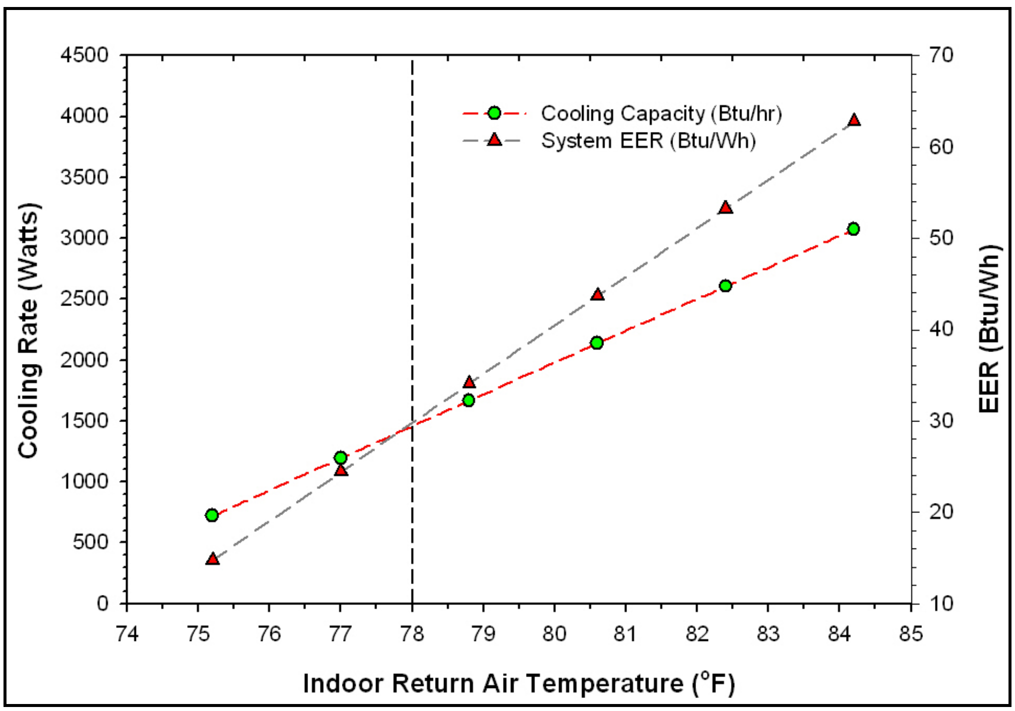

Figure 24. Simulated influence of indoor return air temperature to predicted performance.

Overall energy reductions in the various periods varied from a low of 17% to a high of 53% with a typical expected summer cooling energy reduction of about 25-30%. In interpreting these results it is important to keep in mind that the savings would have been even larger if the duct system had been in the attic in the control building as is the case for most Florida homes with slab on grade

[4] Table 8 gives the tabular results from the simulation in the original report (Parker, 2005).

construction. The wall air conditioners in the test buildings do not have attic ducts or the conduction losses or air leakage impacts associated as seen in most homes (Figure 25).

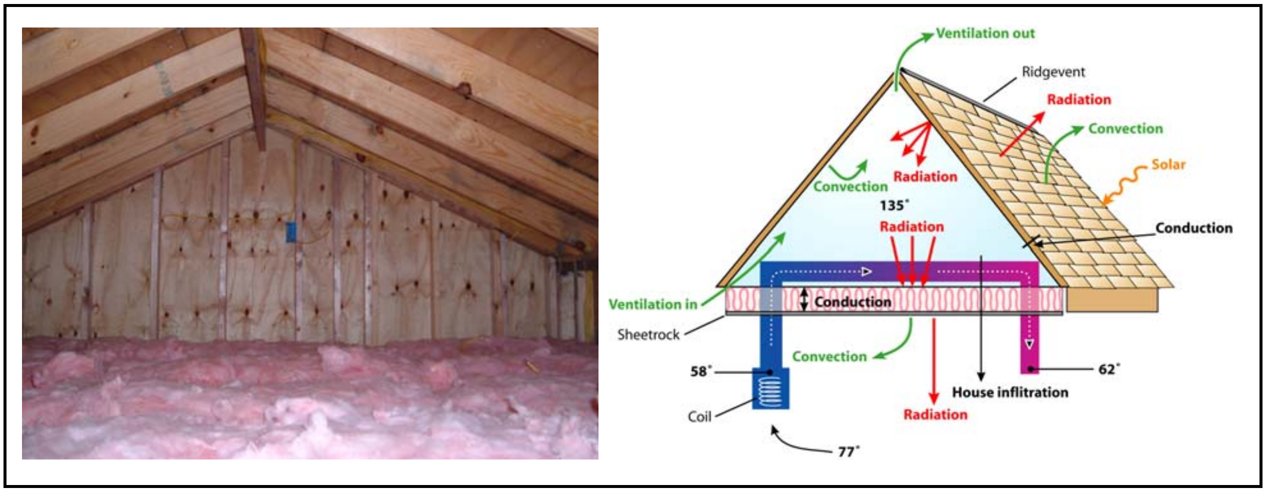

Figure 25. Attic of control building in project against the standard configuration in most sunbelt homes with attic ducts. The control building has no duct losses.

Note also from the analysis for 20 -23 October (Figure 19) that the savings are concentrated during the evening hours– daytime performance is very similar, indicating that the *NightCool* System and not the white roof is primarily responsible for the energy reductions.

Need for Supplemental Dehumidification

As originally envisioned, the *NightCool* concept can only provide low-intensity sensible cooling during nighttime hours. We anticipated that supplemental dehumidification could be provided by a dedicated space dehumidifier. As expected, Figure 26, taken from the measurement period of 20-23 October 2006, clearly shows the need for supplemental dehumidification with the *NightCool* system.

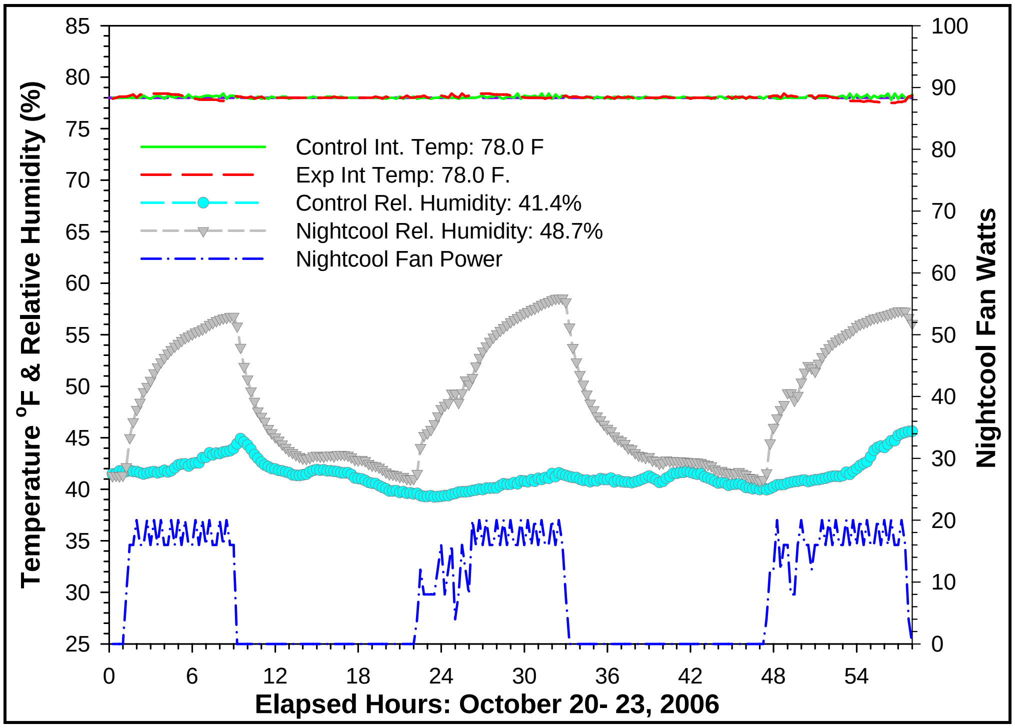

Figure 26. Comparative interior relative humidity in control and *NightCool* test buildings. AC is used in both buildings, but *NightCool* is activated at night in the experimental facility.

Each evening when the *NightCool* system operates the interior relative humidity in the experimental building climbs from about 42% to 57%. Although this is within acceptable limits (<60%), this would not be desirable in an occupied building with added interior moisture generation. By comparison, the relative humidity in the air conditioned control is fairly stable at 40 - 45% throughout the period. Although a good amount of the increase in relative humidity is due to *NightCool* cooling the space temperature below that of the control (and thereby increasing the relative humidity with a fixed amount of absolute moisture), this clearly indicates the need for supplemental dehumidification with the experimental concept.

Potential for Desiccant Attic System to Providing Moisture Control

We have begun to evaluate a drying system used in conjunction with *NightCool* where the desiccant absorps moisture from the space during the evening hours when air is circulated to the attic. Then during the daytime period, air dampers would activate, closing to the main zone, but opening on either gable end side of the attic to allow low-power ventilation of the attic to remove heat and desorbed moisture from the desiccant bed (see Figure 27).

Figure 27. Desiccant dehumidification scheme with solar-powered gable end fans, operated during the day.

As shown in Figure 22, even during autumn days, we see attic temperature exceeding 90°F for periods of time during high insolation. However, they do not go much above this temperature level. Thus, a key need is for a workable desiccant material that can be regenerated at low temperatures.

Desiccant Clays

Although silica gel is a versatile and proven desiccant, it does not regenerate until temperatures of over 240°F are obtained. Consequently, its use is not feasible with the concept. However, available montmorillonite clay desiccants regenerate at temperatures between 90°F and 120°F which may be ideal. As shown in Figure 28 desiccant clay can hold up to 20% of its dry weight as moisture with a three-hour exposure.

Also, the desiccant clay is a less costly option and generally 5 - 15% less expensive than the same amount of silica gel. Cost is generally around $1 per pound.

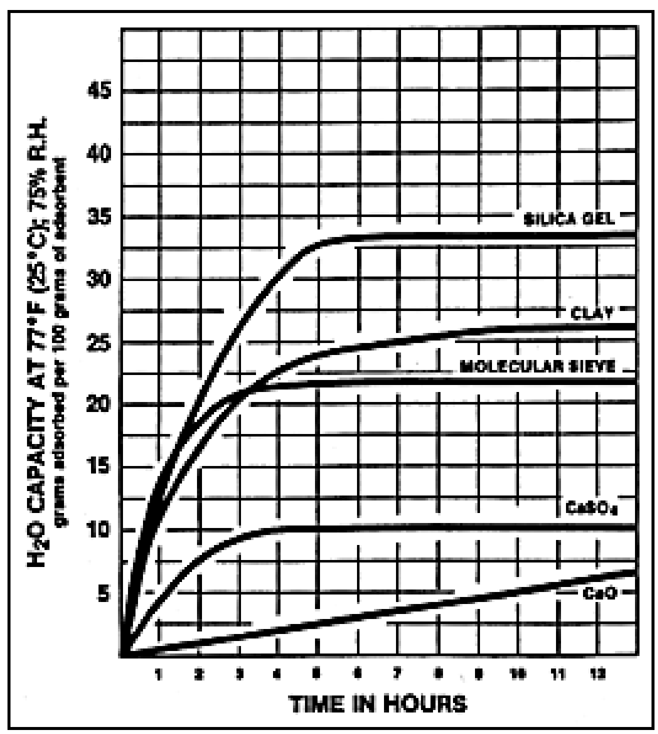

Figure 28. Comparative water adsorption capacity at 77°F against time for various desiccants.

Montmorillonite clay is a naturally occurring porous adsorbent.[5] The clay will successfully regenerate for repeated use at very low temperatures without substantial deterioration or swelling. Figure 29 shows the low regeneration temperatures as compared with standard silica gel desiccants. As shown the clay holds up to 20% of its dry weight as water, but will drop to 9% moisture content by 100°F.

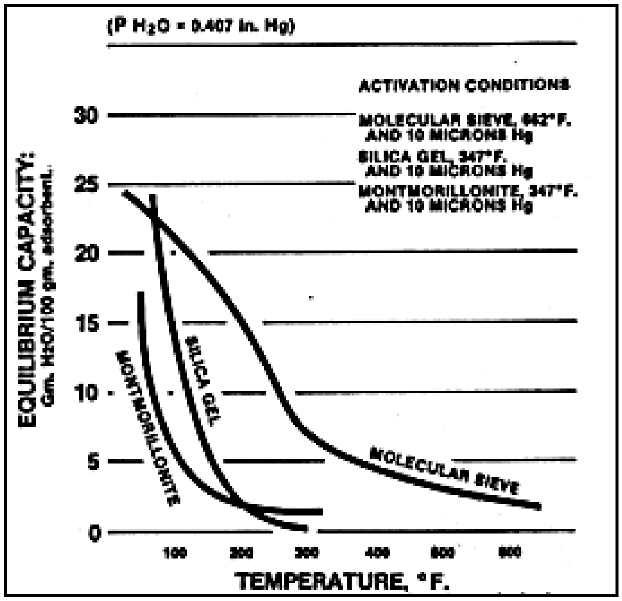

Figure 29. Equilibrium moisture capacity of clay vs. other desiccants against environmental temperature.

This would indicate that potentially a 15% usable moisture adsorption potential might be available over a daily cycle in the *NightCool* attic. Given that residential research suggests that a 1.25 gallon per 1,000 ft^2 of daily moisture removal capacity is needed in a typical home (Tenowolde and Walker, 2001), this would indicated the need for about one liter or about 2 pounds of moisture capacity in the 192 ft^2 *NightCool* building. Even, assuming 10% effective moisture capacitance from the desiccant, this would indicate about 20 pounds of desiccant clay for the envisioned application in the test building.

Currently, we would expose the clay material in pre-manufactured tyvek desiccant packets on a wire-screen platform in the attic space so that they adsorb moisture during the evening hours when interior air is circulated to the space. During the day, the desiccant packs would then be regenerated by heating them with roof-collected solar energy and introducing and then exhausting outdoor air through the attic space to remove released moisture. The air would be drawn in from dampered gable-end fans and exhausted from the opposing side. Not only would this remove collected moisture, but it would also lower the temperature of the attic space to reduce daytime sensible cooling loads across the insulated ceiling.

[5] This desiccant is derived from naturally occurring bentonite clay, and its main component is the layered mineral montmorillonite. With water molecules binding predominantly to the cation interlayers of the fine clay crystals, the absorption capacity of clay increases with rising humidity and is higher than the absorption capacity of silica gel when conditions are below 30% relative humidity. Since clay reacts relatively slowly at low as well as high humidity levels, it slowly reduces the humidity in closed environments and is easy to handle. In addition, desiccant clay granules have up to 30% greater density than either silica gel or molecular sieve beads, thereby occupying less space.

Desiccant Roof Underlayment

A second idea would be to impregnate a moisture adsorbing self-adhesive layer that could be attached to the underside of the metal roof of the *NightCool* attic. The advantage is clear: not only would lower condensing temperatures be reached sooner at night, but higher regeneration temperatures would also be obtained during daytime solar heating of the roof panels.

Such a self-adhesive sponge-like metal roof underside layer could include moisture adsorption materials such montmorillonite clay or zeolites such as titanium silicate. One product, *CondensStop*, is commercially available although its properties and capabilities have not been evaluated. The properties of the *CondenStop* material (Figure 30) is described in Appendix B.

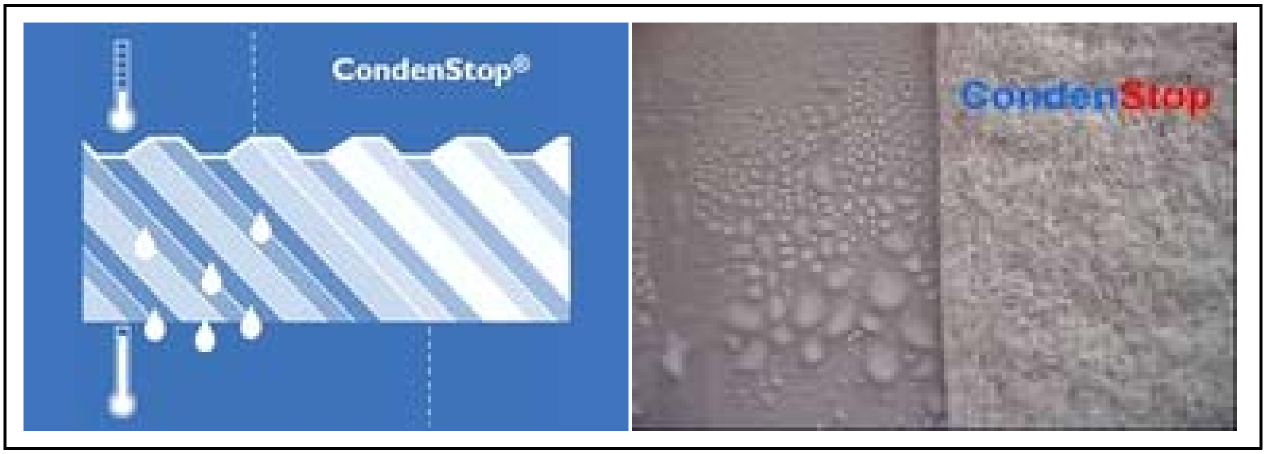

Figure 30. *CondenStop* roof underlayment desiccant material.

Manufacturer test data suggests that it can hold up to 21 lbs (9.7 liters) of water per 100 square feet of roof area. This would indicate a water holding capability in excess of 20 liters per day for the *NightCool* configuration. Based on other research (Tenowolde and Walker, 2001) the desired moisture removal rate for a 1,500 square foot building is about 2 gallons (8 liters) per day. When scaled, this would indicate that a moisture removal rate of about one liter per day for the much smaller *NightCool* building. Thus, only 10 - 20 ft^2 of the material would have to be deployed to result in a workable system in the test building.

Integration with Solar Power Production with Heating/Cooling

When mated with metal roof Building Integrated Photovoltaics (BIPV) the *NightCool* concept shows potential to achieve an integrated roof system providing electric power, as well as supplemental heating and cooling. Conceptually, within this further development of the concept, thin film PV is adhered to metal roofing which then generates electric power. Such systems have been extensively tested by the Florida Solar Energy Center and others. Figure 31 shows one such system using the *Unisolar* BIPV product as installed in a low energy home in New Smyrna Beach, Florida.

Figure 31. Thin film PV is applied directly to the standing seam metal roof.

One disadvantage with most conventional BIPV systems is that when installed on decking, it operates at higher temperatures and thus suffers losses in solar to electrical conversion efficiency (Davis, Fanney and Dougherty, 2001). Typically this represents 5-6% losses relative to bracket-mounted stand-off arrays, depending on module temperature response characteristics. With implementation of BIPV with *NightCool*, the underside of the roofing system would be metal on battens so that BIPV operating temperatures would be beneficially reduced. The transferred heat to the attic (and humidity from incorporated desiccant material would then be removed by daytime powered ventilation from the gable roof ends by small dedicated DC roof fans (See Figure 27).

During winter mornings and afternoons, however, the fans would not be operated and collected heat from the darker BIPV would be conveyed as useful heat to the interior space to offset a portion of space heating needs. Collected data from a cool day on November 13th of 2006 shows how useful heat can be collected even by a white roof system down to afternoon outdoor air temperatures of 65°F (Figure 32). With a darker roof, heating is available down to outdoor temperatures of 60°F.

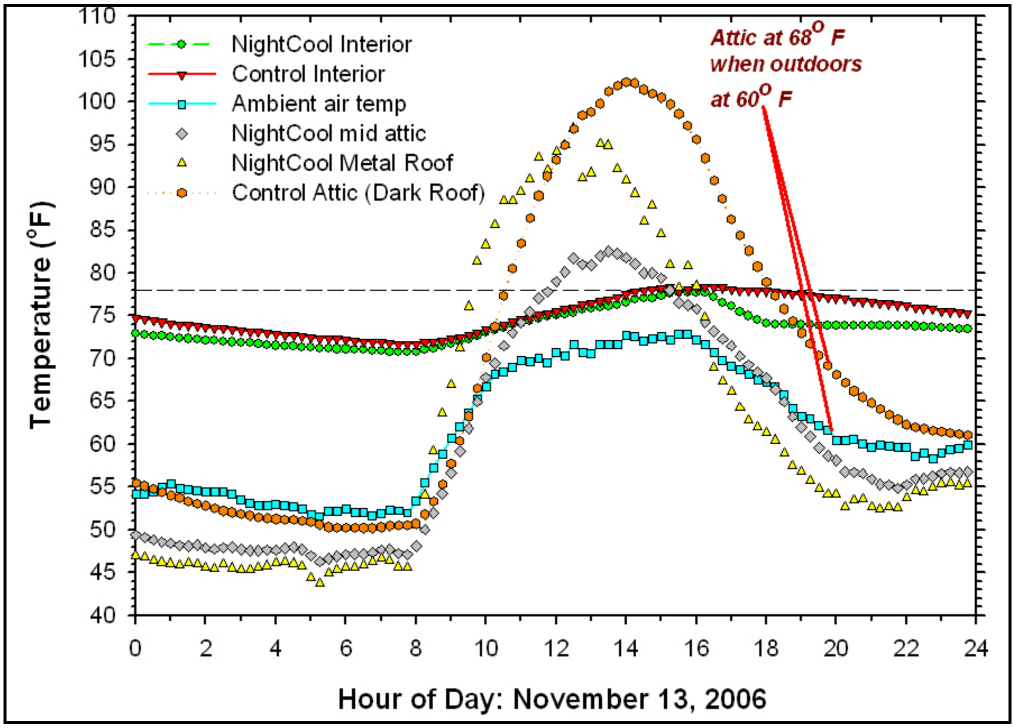

Figure 32. *NightCool* performance; clear cool conditions. Note potential for heating during late winter afternoons when outdoor temperature is 60°F.

The figure also shows the temperature in the attic with the control roof system with the darker roof– an indication of the comparative temperatures that would be available with a BIPV roofing system on colder days.

During summertime periods, daytime heat would be removed by ventilating the attic to improve BIPV operating efficiency and lower ceiling cooling loads. At night, the *NightCool* system would operate conventionally to reduce cooling needs.

The potential advantages of the fully developed *NightCool* concept:

- Building Integrated Photovoltaic (BIPV) solar electric power production
    * Lower BIPV operating temperatures and greater electrical conversion efficiency due to metal roofing batten arrangement and daytime venting.

- Nighttime nocturnal cooling using the *NightCool* cooling cycle.
    * Nighttime moisture absorption where needed

- Daytime heating during winter days to supplement mechanical space heating

This would result in a highly desirable building integrated solar power system that would also provide supplemental space cooling and heating (U.S. DOE, 2006).

Conclusions

This report has described the configuration and experimentally tested potential of a novel residential night cooling concept. *NightCool* uses a home's metal roof as a large radiator to the nightsky to provide effective nocturnal cooling. Unlike earlier, more complex night cooling configurations, the system selectively links or de-couples the homes' internal conditioned zone to the sealed attic under the radiator depending on the prevailing environmental conditions. With dark absorptive roofing, it may also be possible to use the concept for daytime space heating in colder climates when the attic space is warmer than the interior.

The report provides a brief evaluation of the performance of *NightCool* both under passive conditions with no mechanical cooling and also with auxiliary air conditioning. Four experimental configurations were evaluated:

- No *NightCool* cooling with the attics sealed to the interior (Null test)
- *NightCool* by passive-convection to the building only (open aperture to the attic so that cooled night air could drop out of the attic into the interior to be replaced by warmer air below).
- No air conditioning in either test building, but *NightCool* activated with fan circulation in experimental test building
- Air conditioning in both test buildings. However, with favorable attic temperature conditions AC is turned off and *NightCool* activated with fan circulation in experimental test building

The last experiment, with supplemental air conditioning and *NightCool* operating in the experimental facility was evaluated under varied summer and autumn weather conditions.

The experiments shows that *NightCool* performed better thermally under passive configurations. With the *NightCool* linkage to the main zone disabled (Null test), the average nighttime temperatures in the unconditioned experimental and control test buildings from 8 PM to 8 AM was similar 82.0 and 82.6°F respectively. This shows the experimental buildings runs slightly cooler at night, largely because of the lower attic temperatures across the insulation and the effectiveness of the R-30 SIPs panels in the ceiling against the R-30 fiberglass batts in the control.

However, a second passive configuration had an attic hatch opened to the sealed attic to allow warm air to naturally convect into the attic and heavier cool air to naturally fall to the interior below. Even without fans, the *NightCool* building showed superior performance. The experimental building's interior ran 1.9°F cooler during nighttime hours without any mechanical air movement to aid heat transfer– this is about three times the temperature drop seen without any passive nighttime cooling. These results show that the *NightCool* can produce passive buildings with greater nighttime comfort – even without air conditioning. Such configurations could be valuable in tropical regions in developing countries without the availability of air conditioning.

Detailed data was obtained on the system with air conditioning used in the control and the experimental unit during daytime and with the *NightCool* fan circulation system used during evenings. A daytime temperature of 78°F was maintained in both test buildings. Measured cooling energy savings varied from 17% under warm, cloudy conditions to 53% during milder periods. This savings level prevailed even though the *NightCool* system maintained an average interior temperature 1°F lower than the Control building.

Given that only a fan is required, *NightCool* efficiencies are quite good exceeding that for the very best vapor compression equipment existing today. Daily *NightCool* system Energy Efficiency Ratios (EERs) averaged 31.0 Btu/Wh over the four summer to fall test periods – in line with simulations conducted earlier. The nightly system EERs varied from a low of 23.2 to a high of 43.2 Btu/Wh, the highest performance being seen during tests with higher return air temperatures and during periods with cooler and more clear nighttime conditions. As expected performance was worse under cloudier humid conditions. Cooling rates also varied over the course of each evening, generally improving to a maximum point in the pre-dawn hours. The maximum nightly EERs varied between 35.4 (warm cloudy evening) to 69.1 Btu/Wh (clear and more cool conditions). In all cases, this level of performance compared favorably to an EER for the vapor compression air conditioner of about 9 Btu/Wh.

The delivered cooling rate averaged 2 - 4 Btu/hr/ft^2 (6 - 13 W/m^2) of roof surface each evening, implying that *NightCool* in a full scale 2,000 square foot home would cool at a rate of 4,000 - 8,000 Btu/hr. Over a typical 10 hour operating period, this would produce 3 to 7 ton-hours of sensible cooling.

We did see that interior moisture control was adversely impacted by *NightCool* operation as the cycle only provides sensible cooling. Consequently, we have begun investigating the potential of using desiccant clays for dehumidification during the summer of 2007. Montmorillonite clays hold up to 25% of their dry weight in water, and partially regenerate at temperatures as low as 100°F. Given that target moisture adsorption rates of 4-8 lbs/day would be appropriate to our application, we are looking into potential of nighttime dehumidification and daytime attic venting with solar regeneration of the desiccant. We also aim to examine metal roof underside condensation absorption schemes which may offer similar capabilities and higher regeneration temperatures.

The favorable experimental data collected thus far indicates that *NightCool* can be a promising system technology for 50% or higher level benchmark homes in hot-arid, hot-dry/mixed and mixed humid climates. In 2007, we plan to continue experimental and analytical work, concentrating on first obtaining six months of continuous data collection for the standard system under a variety of weather conditions. We will also evaluate a push vs. pull fan arrangement within the concept and also likely incorporate additional thermal capacitance into the experimental unit. During the second half of 2007, we will be conducting dehumidification experiements using *NightCool* with desiccants and daytime ventilation of the attic space to see if performance can be fully extended to humid climates.

Given the promising results thus far, we have keen interest from the metal roofing industry as shown by the letters of support in the report appendix. With favorable results in the next phase of experiments, the metal roofing industry is interested in testing *NightCool* in full scale buildings.

A further intriguing possibility is to mate the concept with Builidng Integrated Photovoltaics (BIPV) to provide combined solar electric power, nighttime cooling and winter afternoon heating. Thus, future work may also test BIPV within the concept in a cooperative arrangement with both the photovoltaics and metal roofing industry.

References

Clark, Gene, 1981. "Passive/Hybrid Comfort Cooling by Thermal Radiation," Passive Cooling: American Section of the International Solar Energy Society, Miami Beach, 1981.

Davis, Mark W., Dougherty, Brian P., and Fanney, Hunter A., 2001. "Prediction of Building Integrated Photovoltaic Cell Temperatures," Transactions of the ASME, the Journal of Solar Energy Engineering, Special Issue: Solar Thermochemical Processing, Vol. 123, No. 2, pp. 200-210, August 2001.

Fairey, Philip, W., et al., "An Analytical Assessment of the Desiccant Enhanced Radiative Cooling Concept," FSEC-PF-207-90, ASME 1990 International Solar Energy Conference, Miami, FL, April 1- 4, 1990.

Givoni, Baruch, 1994. Passive and Low Energy Cooling, Van Nostrand Reinhold, NY.

Hay, Harold R., 1978. "A Passive Heating and Cooling System from Concept to Commercialization," Proceedings of the Annual Meeting of the International Section of the Solar Energy Society, p. 262-272.

ICC, 2006. International Energy Conservation Code: 2006, International Code Council, January 2006.

Martin, Marlo and Berdahl, Paul, 1984. "Characteristics of Infrared Sky Radiation in the United States," Solar Energy, Vol. 33, pp. 321-326.

Parker, Danny S., 2005. Theoretical Evaluation of the *NightCool* Nocturnal Radiation Cooling Concept, Submitted to U.S. Department of Energy, FSEC-CR-1502-05, Florida Solar Energy Center, April.

Parker, Danny S., "Research Highlights from a Large Scale Residential Monitoring Study in a Hot Climate." Proceedings of International Symposium on Highly Efficient Use of Energy and Reduction of its Environmental Impact, pp. 108-116, Japan Society for the Promotion of Science Research for the Future Program, JPS-RFTF97P01002, Osaka, Japan, January 2002.

Tenowolde, Anton and Walker, Iain S., 2001. "Interior Moisture Design Loads for Residences," Building VIII: Performance of Exterior Envelopes of Whole Buildings VIII, American Society of Refrigerating and Air-Conditioning Engineers, Clearwater Beach, FL, December 2001.

U.S. DOE, 2006. " Building Integrated Solar Design Review Meeting: Phase 2," NREL/U.S. Department of Energy, Washington, DC, October, 5-6, 2006.

Appendix

Letters of Support