FLORIDA SOLAR ENERGY CENTER®

CONTRACT REPORT

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

Stage Gate 1B

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Disclaimer

Evaluation of the *NightCool* Nocturnal Radiation Cooling Concept: Annual Performance Assessment in Scale Test Buildings
Stage Gate 1B

Danny S. Parker and John R. Sherwin

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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.

An initial report describes a detailed simulation model of the relevant night cooling phenomenon, examining potential performance (Parker, 2005). A second report summarized an experimental evaluation of concept performance using two highly instrumented test sheds using short term data in the autumn of 2006 (Parker, 2007). These evaluated 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.

Here, similar data is presented on the long-term comparative with all of *NightCool* system fully operational, with circulating fans when attic conditions are favorable for nocturnal cooling and with conventional air conditioning at other times. Data is included for a full year of the cooling season in Central Florida, which stretches from April to November of 2007.

Average long-term performance was lower than the previous simulation analysis. The delivered cooling rate, at an interior set point temperature of 78ºF, averaged about 1.5 - 3.0 Btu/hr/ft^2 (5 - 10 W/m^2) of roof surface on the average 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 depending on the season. Annual savings averaged 15% from April-October, while maintaining a lower relative humidity during the cool humid months of February and March, when compared to the control building. Daily runtime fractions during which the *NightCool* fan operated varied from 12% (3 hours) in August - September to 36% (8 hours) in May. Over a typical 6 hour operating period, this would produce about 0.2 ton-hours of sensible cooling or 2 ton-hours in a full scale home. Average long-term monthly energy efficiency ratios (EERs) ranged from 16 - 32 Btu/Wh with a mean of 25 Btu/Wh over the cooling season. As expected, performance was best during the spring and fall months.

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Executive Summary

Overview of System Evaluation

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).

For a typical roof (225 square meters), this represents a cooling potential of 5,000 - 14,000 Watts or about 1.7 - 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.

A big problem with previous night sky radiation cooling concepts has 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 main zone 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 main zone 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 dampers 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 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.

Key Results

The empirical evaluation of the concept is being accomplished by using two highly instrumented side-by-side 12' 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 an evaluation of the performance of *NightCool* under standard operating conditions during March 1, 2007 - January 31, 2008. Air conditioning was used in both test buildings, but when favorable attic temperature conditions were met, *NightCool* was activated with fan circulation in the experimental test building. Sensible internal heat gains were added similar in scale to what would be seen in an occupied home.

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. A daytime temperature of 78°F (26°C) was maintained in both test buildings. Measured cooling energy savings averaged 15% over the 8 month test period stretching from April - November of 2007. Monthly performance indices were produced as shown in Figure E-2. Daily *NightCool* system Energy Efficiency Ratios (EERs) averaged 24.9 Btu/Wh over the summer to fall test period – somewhat lower than simulations conducted earlier. This level of performance compared favorably to an EER for the vapor compression air conditioner of about 9 Btu/Wh. This level of performance also exceeds the performance of any air source equipment currently available.

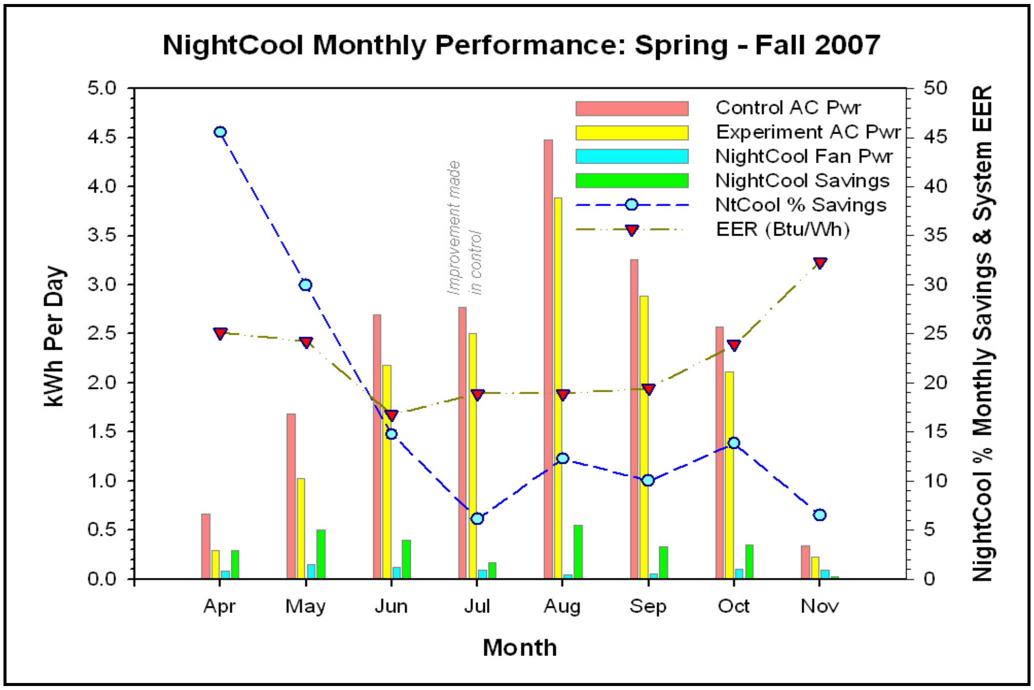

Figure E-2. Monthly average performance of *NightCool* system in 2007.

The delivered cooling rate averaged about 1.5 - 3.0 Btu/hr/ft^2 (5-10 W/m^2) of roof surface on the average 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 depending on the season. Daily runtime fractions during which the *NightCool* fan operated varied from 12% (3 hours) in August - September to 36% (8 hours) in May. Over a typical 6 hour operating period, this would produce about 0.2 ton-hours of sensible cooling or 2 ton-hours in a full scale home. Moreover, since a solar dehumidification element was activated in January 2008, the interior relative humidity level has averaged 7% lower than the control.

Stage Gate Status

The *NightCool* technology is assessed as a *System Evaluation* (1B) according to the documented Building America Gate process. This includes both *Must Meet* and *Should Meet* criteria which are briefly summarized here.

Must Meet Criteria:

Energy Savings

Measured annual energy savings in the test buildings were a 15% reduction in electrical space cooling in Central Florida's climate. Several factors account for the relatively low energy savings: a cooler interior average temperature maintained in the *NightCool* building and both experiment and control having no duct losses where as most homes in Sunbelt homes with slab on grade construction would have losses unobserved in the control home. On the other hand, the control building had a dark shingle (conventional practice) roof against the white metal roof on the *NightCool* building. These influences are more fully detailed in the full report along with planned evaluation in 2008 to correct for potential bias and obtain the best possible experimental results.

The average air conditioning consumption in Central Florida is about 6,400 kWh per year (Parker, 2000). The concept site energy savings depends on the basis from which the calculations are made the most conservative estimate (comparison has a white roof and interior ducts) is 10% and the most optimistic is roughly 25% (control has attic ducts and a dark roof). This would represent savings of 640 - 1600 kWh/year depending on the roofing system assumed, the comparative temperatures maintained and the location of the duct system. Since the reduction is to electricity consumption, source energy savings called for within the gate process would be roughly three times the absolute value of the savings would vary from 6.5 to 16.4 million Btu/year per site in Central Florida.

The saving in other climates would much greater. For instance, as shown in the early theoretical analysis done (Parker, 2005), the estimates for summer cooling indicated only about 15 kWh of potential cooling per day in a 2000 ft^2 home in Tampa against 50 kWh for Atlanta, GA and 62 kWh in Baltimore.

Other Benefits

As previously described, the *NightCool* buildings maintained a cooler temperature– averaging about 77.4°F rather than the 77.8°F in the control. Generally, this lower temperature would be perceived as being more comfortable than that maintained in the control.

A second and much larger benefit has been the ability the NightCool system to maintain a lower interior humidity since the attic solar dehumidification system was properly configured in mid January 2008. In many Florida homes, high interior moisture conditions are experienced in summer and early spring months where there is little space conditioning. However, Nightcool showed considerably reduced interior moisture levels under such conditions. For instance, the interior relative humidity in February and March of 2008 when averaged 64.1% and 57.5% in the experiment – a very significant 6.6% difference in relative humidity. This is important because interior humidities above 60% generally favor molds, mildew and dust mites– all of which are important allergens for household occupants (Chandra et al., 1997).

A final benefit is that with SIPs used for the attic floor within the NightCool concept, this would result in a large storage space unobstructed by trusses. As storage space is highly valued in slab on grade houses, this area would likely be highly valued by consumers.

Performance and Prescriptive Based Code Approval

These criteria requires that the technology meets performance-based safety, health and building code requirements in new homes. We examined the various facets of the concept: sealed attic construction, control ventilation dampers and fans. Thus, all potential issues with the technology relative to Code Approval appear either resolved or easy to address.

Should Meet Criteria

Cost Advantage

The *NightCool* system would appear fairly neutral relative to cost. The largest expense are the SIPs panels for the roof construction and the dampers and controls.

Reliability Advantage

A clear advantage of the *NightCool* system is that even with failure of the main cooling system, the *NighCool* system can still operate and maintain a much cooler building interior. This was clearly shown in the 2nd project report (Parker and Sherwin, 2005) which showed the *NightCool* system by itself could maintain summer interior nighttime temperature to be less than 82°F (reaching 74°F by 7 AM) even without vapor compression air conditioning (see Figures 16 and 17 of that report). Now, with the solar dehumidification system operating, the revised system will provide some dehumidification as well.

Manufacturer/ Supplier and Builder Commitment

Within the project we have had large interest from the metal roofing consortium and individual metal roofing suppliers. Letters demonstrating this interest were included in the previous report. We have another commitment recently from a thin-film PV supplier: Advanced Green Technologies (AGT; http://www.agt.com/). AGT is interested in cooperating and exploring new technologies with high potential in the green construction area. One added interest relative to *NightCool* would be the potential of cooling the PV system to achieve better performance as well as the possibility of scavenging some winter afternoon heat in colder climates.

Gaps Analysis

Within the gaps analysis, we attempt to examine technical, performance and market barriers for the NightCool system based on lessons leaned thus far in system measurement. Here we examined the needs for further experimentation and refinement of the dehumidification system, refinement of the energy savings performance and potential enhancements to the operational concept, evaluation of the system in other climates and performance with Building Integrated PV. Remaining potential issues include: potential winter roof condensation problems within the concept, better coupling of air to the roof radiator for better performance and refinement of the dehumidification system sorption materials. These issues are more fully described in the full report.

Conclusions

The experimental data collected indicates that *NightCool* could be a promising system technology for low-energy homes particularly in more temperature climates or as a high efficiency dehumidification system in hot-humid climates. We plan to continue experimental and analytical work on the *NightCool* concept throughout 2008, concentrating on improving the dehumidification performance of the concept and refining the operational configuration. We will also retrofit the control building a white metal roof so that the *NightCool* specific savings can be isolated against the "best in class" roof technology. Work in 2009 will evaluate performance when combined with Building Integrated Photovoltaics (BIPV).

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 80ºF (27ºC) 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 Wh/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.[1]

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 the potential rate of cooling can be practically obtained. However, passive systems with very little air velocity under the radiator (i.e. with free convection) 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.

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[1] 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 - 3ºF – 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.

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.

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.

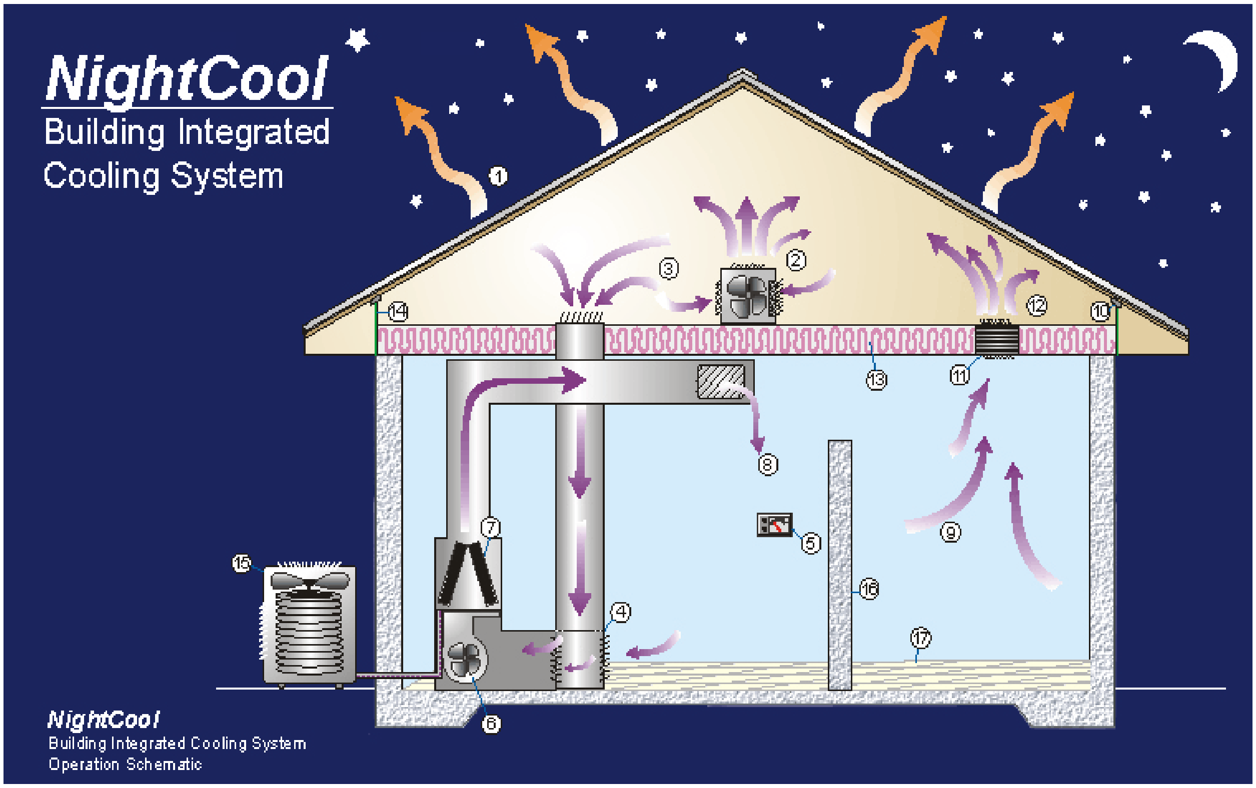

Figure 1. Schematic of *NightCool* concept.

1. White metal roof on metal battens (no decking). Both sides are surfaced for high emissivity. A temperature probe measures roof underside temperature.
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%.
3. Baffled inlet frill from attic for nighttime operation.
4. Room return inlet (for daytime operation). Closed by damper at night when temperature conditions are met.
5. Thermostat (compares roof surface temperature and setting to determine vapor compression vs. nighttime cooling operation).
6. Variable speed air handler fan with electronically commutated motor.
7. Vapor compression air conditioner cooling coil.
8. Interior duct system with supply outlet.
9. Interior room air return to attic during evening hours when Night Cool is activated.
10. Roofline drip collection system with drain.
11. Ceiling return for *NightCool* operation mode.
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 main zone is de-coupled from the roof and heat gain to the attic space is minimized by the white reflective metal roof (solar absorptance = ≈0.35). 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 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 gypsum 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 $Btu/hr{\cdot}ft^{2}{\cdot}{}^{o}F$, 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.

To approximate typical internal mass in residential buildings, twenty hollow core concrete blocks were located on the north side of both buildings.[2]

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

An 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.

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[2] The medium concrete blocks have the following measured characteristics: 33.5 lbs (15.2 kg) each; Gross volume: 908 cubic inches (14891 cm^3); Net volume: 494 cubic inches (8,101 cm^3); Specific Weight: 117.2 lbs/cubic foot (1883 kg/m^3).

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

The interior temperature and relative humidity conditions are measured at the center of each main zone room, both in the control and the experiment using a type-T thermocouple shielded in a gill plate and a RTD temperature and humidity measurement device (Figure 11).

Figure 11. Image of interior configuration in the *NightCool* building interior showing temperature and relative humidity measurement in the center of the building. Note also, the space circulation fan, wall air conditioner and twenty hollow concrete blocks used to simulate typical occupancy.

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 (sensible + latent)	Hourly Fraction	Indicated Sensible *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 (kWh/d)	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 12 shows the measured power of the lamps and fans simulating internal gains in the two test buildings over a two day period in November.

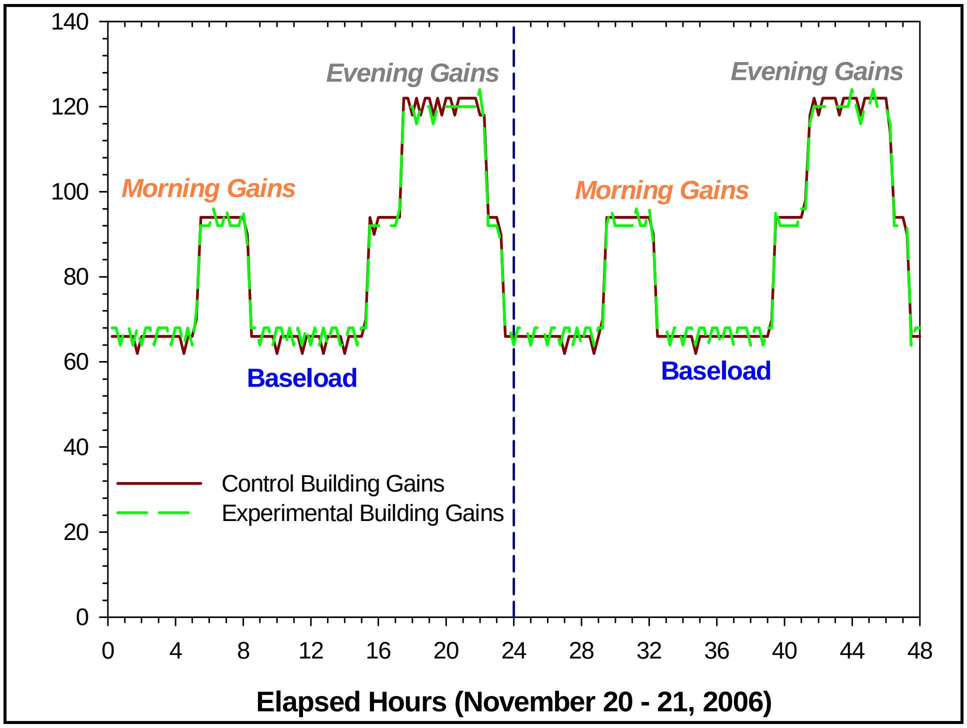

Figure 12. 24-hour measured internal gains schedule for *NightCool* test buildings (Watts).

To the above schedule for appliances, we then added another 30 Watts to account for sensible heat produced by people within the home with the idea that approximately 300 Watts would be present in a full scale home and one tenth that level in our scale building. (Latent heat from people was added separately). Total sensible heat released in the buildings then averaged about 2.6 kWh/day.

Latent Internal Moisture Generation

On August 29th, 2007, we added latent heat gains to the profile for humidity control experiments with a controlled humidifier (see Figure 13) which injects 0.5 liters of water added to each test building each 24 hours. This moisture generation level is one half that specified in ASHRAE Standard 160 which our research would indicate is too high. The level of moisture is identical to that which we are using in the Manufactured Housing Laboratory and would correspond to a daily moisture release rate of 5 liters per day in a full scale 2000 square foot home. The moisture is added at a constant rate over the day with 5 ml added to the humidifier every 15 minutes.

Figure 13. Interior humidifier used in both control and experimental building to add 0.5 liters of water and internal latent load each day.

Components 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^{o}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 15 shows the registers and circulation fan.

Figure 15. 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

Attic Air Flow Control Dampers

Prior to the long term monitoring, two motorized 16-inch dampers (*ZTECH 16RDNO; 24 Volt AC*) were added to the supply and return air respectively so that the air from the main zone to the attic is closed when the attic is at a higher temperature than the main zone or when the attic is being ventilated. When unpowered, the dampers are normally open. The dampers are shown in Figure 16.

Figure 16. Return and supply side motorized dampers. These close air circulation to the attic when the attic temperature is higher than the main zone.

The dampers are open for passive cooling when the attic is cooler than the main zone (warm air rises to the *NightCool* attic and then falls as it is cooled to the main zone). Always, when the attic temperature drops below 75°F the dampers are open for cooled air to circulate to the main zone.

Enthalpy Based Attic Ventilation

To provide humidity control using the *NightCool* configuration, we desired to add attic ventilation to the otherwise sealed attic when the outside absolute humidity ratio is less than that inside the attic.

In the summer of 2007, two four watt DC ventilation fans (*Radio Shack 12V, 3.84 W*) were added to the otherwise sealed *NightCool* attic – one for supply ventilation feeding in 40 cfm of outside air from the south east side soffit and the other exhausting warm moist air from the attic western side ridge and exhausting that air out of the north soffit.[3] The fans and simple duct work are shown in Figure 17.

Figure 17. Supply and exhaust attic ventilation fans. These 4-watt fans provide 40 cfm of balanced supply and exhaust air flow when the absolute humidity ratio outdoors is less than that inside the attic space.

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[3] The fans have a nominal flow of 60 cfm; the 40 cfm flow achieved by the fans were tested by Neil Moyer using a calibrated *Duct Blaster* and a plenum box.

The status of the fans are determined every five minutes according to the current attic interior absolute humidity ($W_{interior}$) and that outside ($W_{outdoor}$). If the exterior humidity is lower than that inside, the ventilation fans are activated. Otherwise they remain unpowered. Note that this ventilation configuration was only made active on 16 January 2008.

Wall Air Conditioners

As shown in Figure 18, 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 data acquisition system 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 18. Experimental *NightCool* building showing central data acquisition system and wall-mounted air conditioner.

Measured air flow: 141 CFM[4]
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

Passive and Short Term Experimental Results

The first monitoring phase in 2006 evaluated the thermal performance of the comparative buildings without *NightCool* operating (null test) and several other configurations with the *NightCool* system operating with and without supplemental air conditioning over short periods. These results are documented in the preceding report (Parker and Sherwin, 2006).

Long Term *NightCool* Cooling Performance

The monitoring in 2007 evaluated the fully operational *NightCool* system with supplemental air conditioning used when interior temperatures rose above 78°F.

NightCool Activation Conditions

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[4] 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.

- Attic Temperature < 75.5°F
- Attic Temperature < Interior air temperature
- Interior Air Temperature > 74°F

Conditions are evaluated every 10 seconds with a decision made every five minutes in terms of whether air conditioning or *NightCool* is activated. Once that decision is made, the control logic remains operational for the entire five minute period. The controls are performed by the data logger – a Campbell CR10X– which measures the various temperature and humidity conditions and operates the system.

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.[5] 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.

Typical Daily Performance

The three figures below illustrate the performance of the *NightCool* system taken directly from the project on-line data website (http://infomonitors.com/ntc/). The data show performance on 12 April 2007 under good performance conditions for the *NightCool* concept. Figure 19 shows the recorded weather temperature conditions on this relatively clear spring day. There was very warm weather in the afternoon with a good amount of cooling necessary in both buildings. The air temperature reaches a maximum of 85.5°F, with relatively high moisture (dewpoint averages 69°F). However, with a clear sky the measured sky temperature drops below 50°F after sunset – ideal for nocturnal cooling.

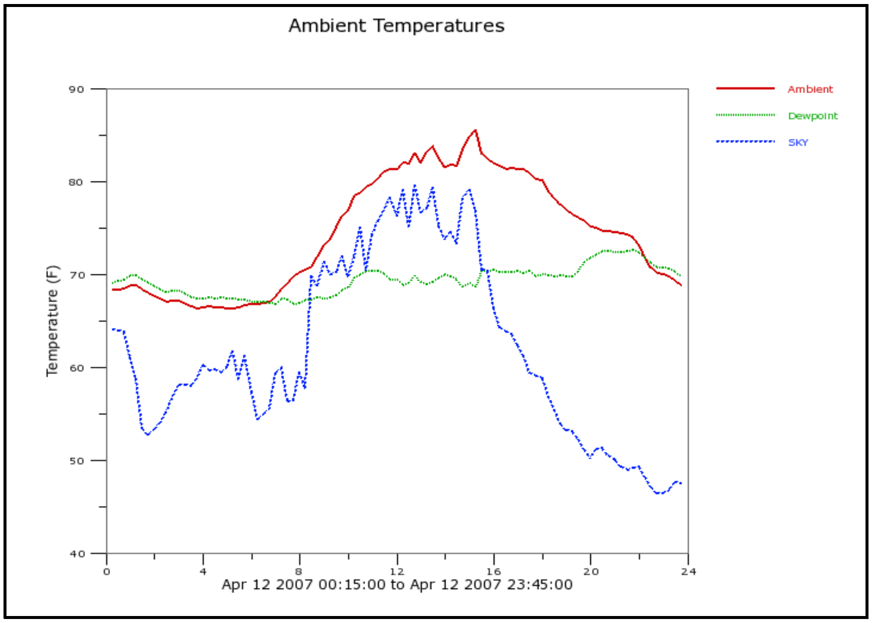

Figure 19. Outdoor temperature conditions on 12 April 2007 (ambient, dewpoint and sky temperature)

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[5] Note that if higher room temperatures can be tolerated, NightCool performance increases dramatically. See Figure 16 and 17 and associated discussion in preceding report (Parker and Sherwin, 2007).

The second plot, Figure 20, plots the measured air conditioner and *NightCool* fan power. Over the course of the day, *Nightcool* reduced cooling use by 52% including the energy use of the circulating fans. The control building used 1.22 kWh for cooling over the day while the air conditioner in *Nightcool* used 0.51 kWh and the fans another 0.12 kWh. Also, as shown in Figure 21, the *Nightcool* system resulted in improved comfort in the experimental building with lower and more even interior temperatures. This shows the good potential performance in central Florida in spring and around the drier part of the U.S. in early or late summer.

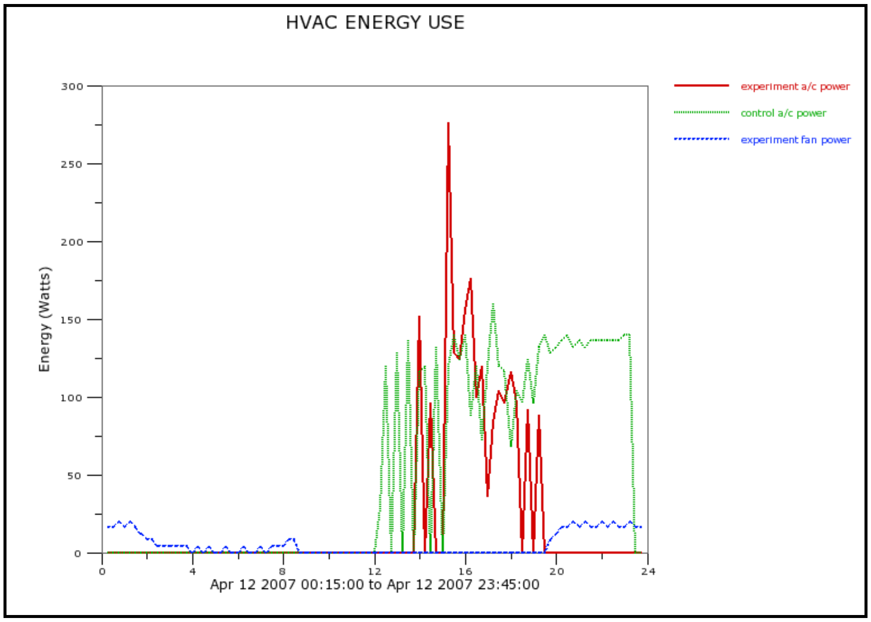

Figure 20. Control AC (red), *NightCool* AC (green) and *NightCool* fan energy use on 12 April 2007.

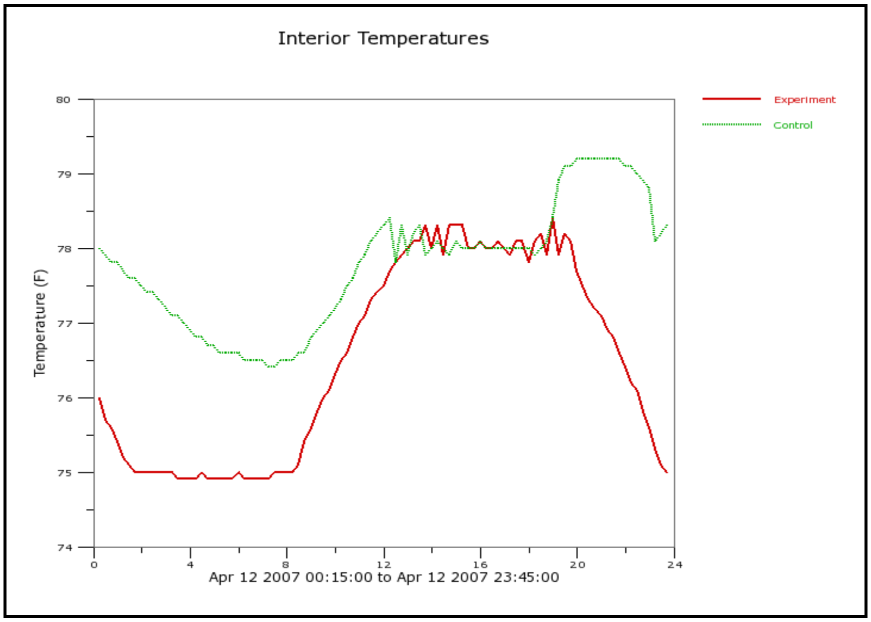

Figure 21.Interior temperatures on 12 April 2007.

Long-Term Performance

Below, we summarize the collected data for a full year for the cooling season in Central Florida, which stretches from April to November of 2007. Within the monitoring, mechanical 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. Air conditioner cooling energy use averaged 4.6 kWh/day in the control building against 3.6 kWh in the experimental building, which also used 0.2 kWh/day for the circulation fans.

Measured cooling energy savings between the control and *NightCool* building averaged 15% over the 8 month test period stretching from April - November of 2007. The comparative profiles of measured performance over the 24-daily cycle from April to November are shown in Figure 22. Note that a 15% energy savings is seen regardless of the fact that the *NightCool* system averages an interior air temperature about half a degree cooler than in the control.

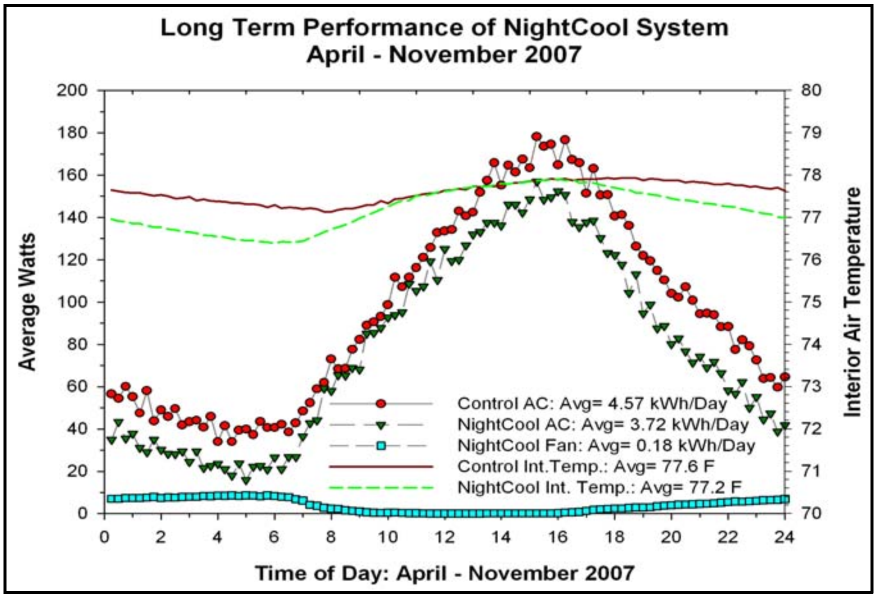

Figure 22. Comparative cooling performance of the Control and *NightCool* building air conditioning system and system fans over the daily cycle from April - November of 2007.

Monthly performance indices were also produced. Daily *NightCool* system Energy Efficiency Ratios (EERs) averaged 24.9 Btu/Wh over the summer to fall test period – somewhat lower than simulations conducted earlier (See Appendix A for a more complete discussion of this issue). However, a mid-summer adjustment to the system activation attic temperature was found to improve the performance by about 2 Btu/Wh after June. In any case, this level of performance compared favorably to an EER for the vapor compression air conditioner of about 9 Btu/Wh. This level of performance also exceeds the performance of any air source equipment currently available.

Figure 23 shows the monthly predicted performance indices in terms of monthly energy savings in absolute and percentage terms as well as the *NightCool* system EER. Table 3 numerically summarizes the detailed performance in terms of energy, efficiency, thermal and comfort related performance.

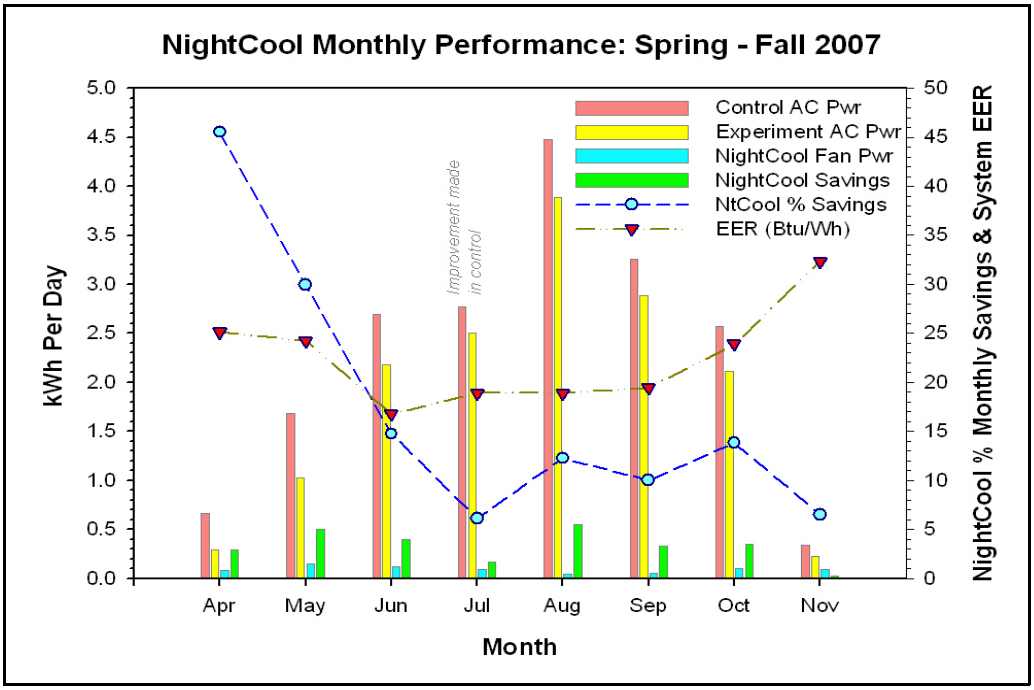

Figure 23. Monthly average performance of *NightCool* system in 2007.

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 21, taken from the measurement period of 20-23 October 2006, clearly shows the need for supplemental dehumidification with the *NightCool* system even before humidification was added.

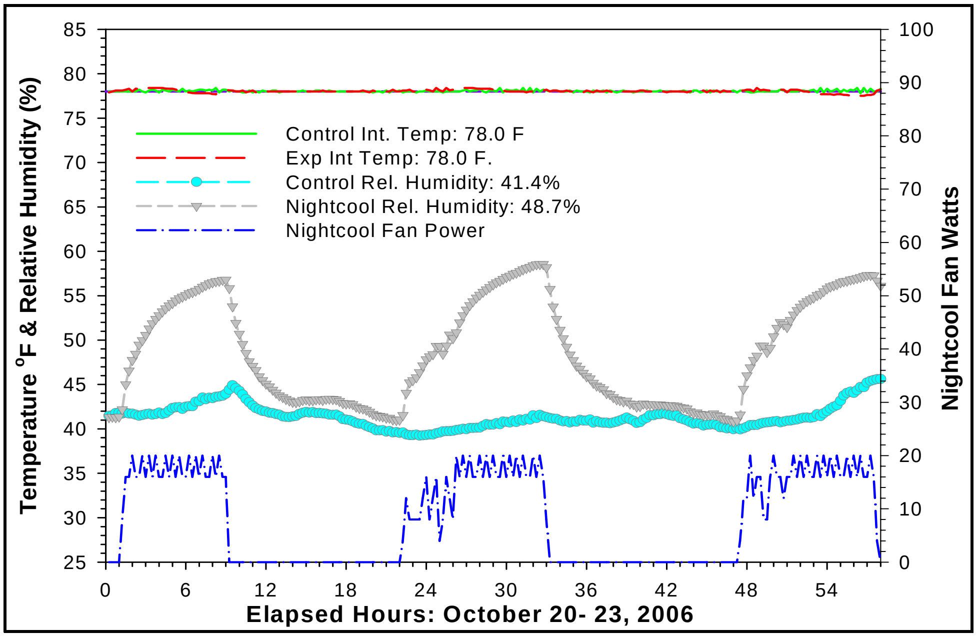

Figure 24. Comparative interior relative humidity in control and *NightCool* test buildings. AC is used in both buildings, but *NightCool* is activated at night in the experimental facility.

Table 3. *NightCool* Performance 2007

Power & Efficiency

	April	*May*	*June*	*July*	*August*	*September*	*October*	*November*
Experiment AC (kWh/day)	0.292	1.027	2.176	2.507	3.886	2.881	2.109	0.224
Experiment Fans k(Wh/day)	0.080	0.151	0.121	0.094	0.046	0.049	0.104	0.095
Control AC (kWh/day)	0.683	1.682	2.694	2.767	4.481	3.257	2.567	0.341
Experiment Lights (kWh/day)	2.723	2.682	2.660	2.575	2.641	2.698	2.693	2.694
Control Lights (kWh/day)	2.722	2.702	2.687	2.342	2.654	2.700	2.698	2.710
EER (Btu/Wh)	24.6	23.9	16.5	18.6	18.6	19.3	23.6	31.8
RTF (run-time-fraction)*	0.185	0.358	0.291	0.216	0.120	0.118	0.250	0.227
ΔT (°F) (T_{return} - T_{supply})	2.73°	2.65°	1.83°	2.07°	2.07°	2.14°	2.62°	3.53°
Percent *Nightcool* Savings	45.5%	30.0%	14.7%	6.0%	12.3%	10.0%	13.8%	6.5%

Building Conditions

	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Experiment Roof Surface (°)	72.8	40.5	115.0	77.8	52.4	110.5	82.1	63.8	126.2	84.1	68.0	124.6	87.3	67.2	125.4	83.2	68.8	123.8	80.5	61.5	116.6	68.9	40.5	108.3
Control Roof Surface (°)	84.5	39.4	160.5	88.5	51.9	159.1	92.7	63.4	175.6	94.9	67.2	175.8	99.8	66.1	176.5	92.8	67.9	170.2	88.8	60.8	160.4	78.5	40.2	149.8
Experiment Attic Temp. (°)	73.8	44.1	103.3	79.9	56.0	104.4	83.8	69.1	113.8	85.2	73.6	112.7	86.2	26.7	116.1	83.5	74.1	109.7	80.8	66.8	102.2	68.5	43.7	93.6
Control Attic Temp (°)	81.0	48.9	121.7	85.7	60.0	122.0	90.0	69.5	131.6	91.8	73.0	131.6	94.9	73.2	131.8	89.2	72.9	125.5	85.6	67.0	116.8	74.7	46.9	107.4
Experiment Room Temp. (°)	77.3	71.9	84.6	78.9	75.5	80.5	80.1	77.0	81.6	79.9	78.1	83.9	74.6	25.7	80.4	79.2	78.0	80.2	79.1	76.2	80.1	76.5	70.4	80.1
Control Attic Temp. (°)	77.9	71.9	80.9	79.1	75.7	82.0	79.2	78.2	80.1	79.0	59.3	80.8	78.7	69.1	80.3	78.6	77.7	79.5	78.6	77.3	79.4	77.0	70.0	79.4
Experiment Room RH (%)	47.5	30.9	64.4	45.4	36.2	57.3	44.0	36.4	56.0	43.9	35.7	58.7	39.5	33.8	58.1	41.8	35.5	56.8	46.7	37.3	65.7	53.0	36.5	67.0
Control Room RH (%)	45.1	28.2	65.3	40.5	33.8	59.5	40.3	35.7	55.1	41.9	36.8	61.7	39.2	35.0	48.2	42.7	38.1	54.5	44.4	36.8	60.0	54.8	32.2	67.0

Weather Conditions

	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Ambient Temp. (°F)	69.6	45.9	87.6	74.5	56.4	85.5	78.5	66.3	93.0	79.9	71.5	93.4	82.9	73.0	94.2	80.2	71.2	93.0	78.3	65.1	89.6	67.5	45.3	83.9
Ambient RH (%)	67.3	14.8	100.0	68.5	37.9	100.0	77.7	36.9	100.0	82.9	43.0	100.0	76.3	40.2	100.0	79.7	42.9	100.0	79.4	42.9	100.0	76.3	29.0	100.0
Solar (w/m^2)	250.0	0.0	1037.0	253.5	0.0	1158.0	235.0	0.0	1081.0	210.9	0.0	1033.0	235.5	0.0	1007.0	181.6	0.0	931.0	150.5	0.0	860.0	151.6	0.0	736.0
Dewpoint (°F)	57.9	22.8	75.0	64.0	43.7	72.9	71.6	59.0	79.7	74.9	68.0	79.1	75.0	64.0	80.2	73.6	58.5	80.2	71.7	57.3	79.5	59.8	29.4	76.9
Sky Temp. (°F)	50.1	6.7	80.2	58.6	32.4	80.8	66.8	49.0	91.5	70.5	47.7	92.3	70.8	53.9	93.1	69.6	50.0	88.9	67.7	47.8	84.9	49.0	1.3	77.7

* *Nightcool* Fan run-time fraction

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.

Attic Solar Desiccant System to Provide Moisture Control

As detailed in the previous report, using even a small amount of standard dehumidifier power would adversely impact the system efficiency since that process is inherently energy intensive. Thus, we conceived use of the solar daytime attic heat to dry attic wood and a clay desiccant with enthalpy controlled ventilation to exhaust the moisture. This approach is similar to the solar dehumidification scheme described by Areemit and Sakamoto (2005) – which showed a 7plywood attic could achieve effective dehmidification with COPs exceeding 15 – three times as great as standard electric dehumidifiers.[6]

Over the project monitoring period, we installed 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 activate, closing to the main zone, but activating powered ventilation of the attic to allow low-power ventilation of the attic to remove heat and desorbed moisture from the desiccant bed

As shown the previous report, 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.

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[6] This work at the University of Tokyo showed dehumificication rates of 25 g/hr (0.02L)/M^2 using a standard wood-framed sealed attic with euthalpy controlled attic ventilation.

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 25 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 about ten percent less expensive than the same amount of silica gel. Cost is generally around $1 per pound.

Montmorillonite clay is a naturally occurring porous adsorbent.[7] The clay will successfully regenerate for repeated use at very low temperatures without substantial deterioration or swelling. Figure 26 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.

This would indicate that potentially a 10% 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 3 pounds of moisture capacity in the 192 ft^2 *NightCool* building. Even, assuming 15% effective moisture capacitance from the desiccant, this would indicate about 20-40 pounds of desiccant clay for the envisioned application in the test building.

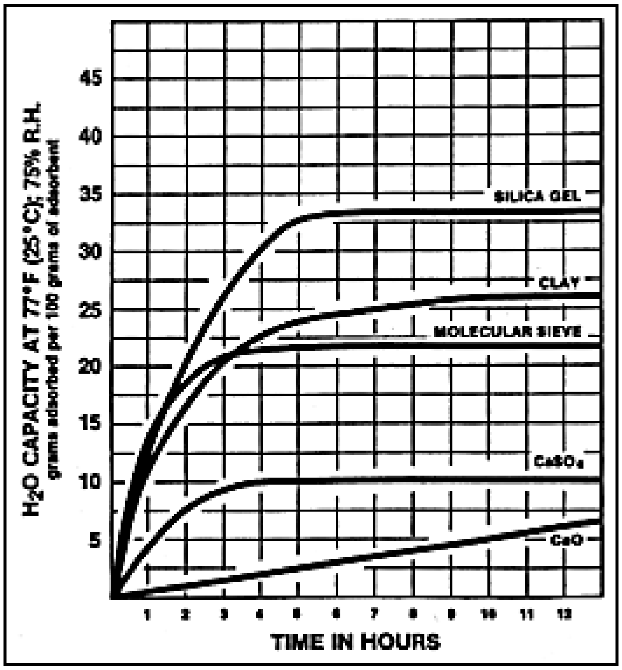

Figure 25. Comparative water adsorption capacity at 77°F against time for various desiccants.

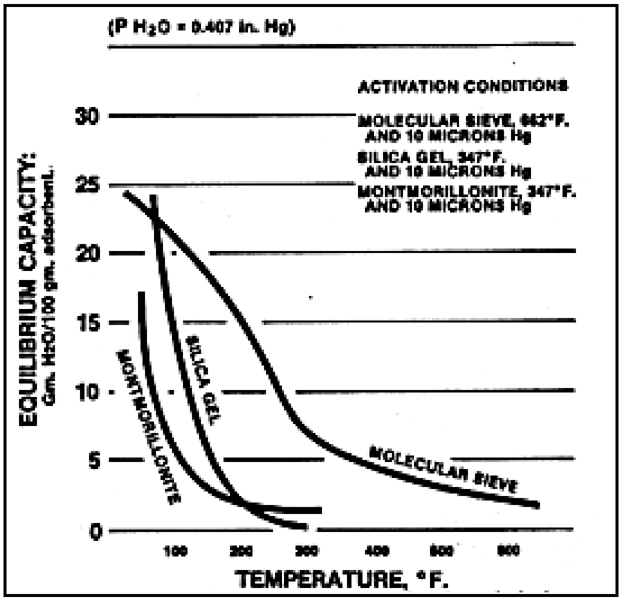

Figure 26. Equilibrium moisture capacity of clay vs. other desiccants against environmental temperature.

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[7] 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.

Latent Moisture Capacitance

Currently, we expose the clay material in pre-manufactured tyvek desiccant packets friction fitted next to the metal roof decking 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 are to 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 is drawn in from the attic vent fans and exhausted from the opposing side. Not only does 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. Thus, this ventilation would have added benefit if combined with Building Integrated PV added to the metal roof where photovoltaic operating temperature would be reduced.

We also initially considered testing of a roofing system underlayment that was originally designed to stop condensation. Unfortunately, this system which we originally evaluated showed that it functioned only when condensation was reached under the attic. However, our testing revealed that it was very desirable to have a desiccant system which would function both in condensing situations as well as non-condensing circumstances.

Thus, our dehumidification configuration uses the clay desiccant packs previously described. These are 3-oz (85 g) clay desiccant packs as shown in Figure 27.

These absorb moisture if the temperature is less than 80°F and begin giving back up moisture at 90°F. Although, they fully regenerate at 245°F, the moisture sorption/desorption curve shown in Figure 26 indicates that they sharply shed moisture when surround temperature exceed 100°F as can be expected in the *NightCool* attic during summer conditions.

Figure 27. Single 3 oz. clay desiccant pak used in *NightCool* attic.

We added the desiccant packs in two installments, each inserting 150 Desi-Paks between the roof and the wood rafter in the attic as shown in Figure 28. On 24 March 2007 we added 150 desiccant packs and later on 17 August 2007, we added the other 150. The total net weight of clay desiccant added to the attic total 900 ounces (56 lbs or 25.6 kg).

It is noteworthy, however, that with no way for the moisture to be removed from the building we saw only a temporary benefit from adding the desiccant packs as shown in Figure 29 and 30.

Figure 28. Desiccant paks friction fit between rafters and metal roof.

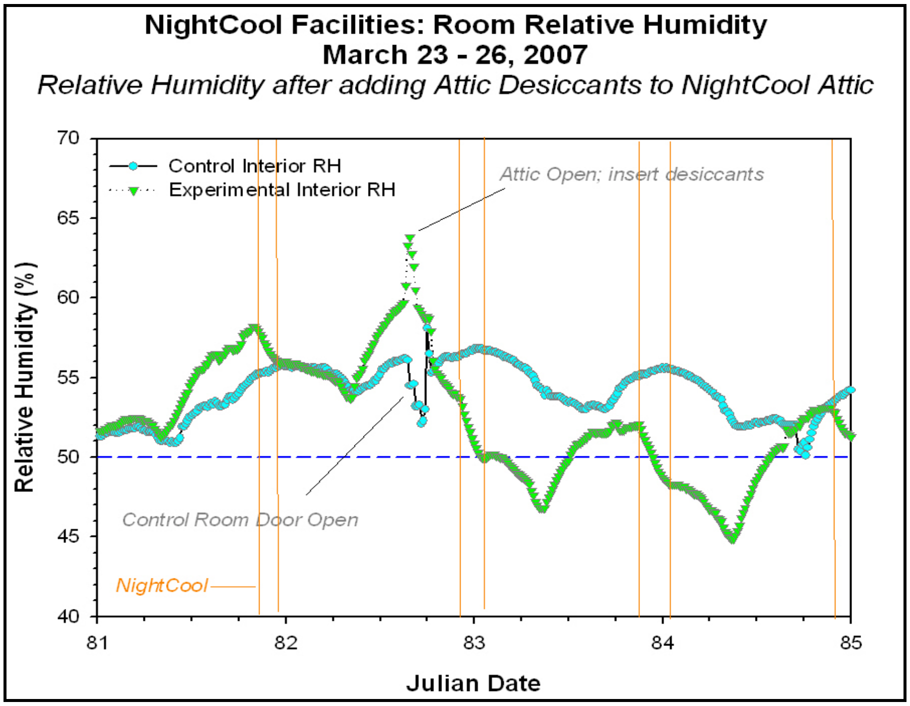

Figure 29. Temporary reduction in attic relative humidity from addition of 150 desiccant packs on 23 March 2007.

In Figure 30 we show the potential of adding forced attic ventilation based on absolute humidity ratio difference as evidenced by the measured air dewpoint in the *NightCool* attic during daytime and night-time periods.

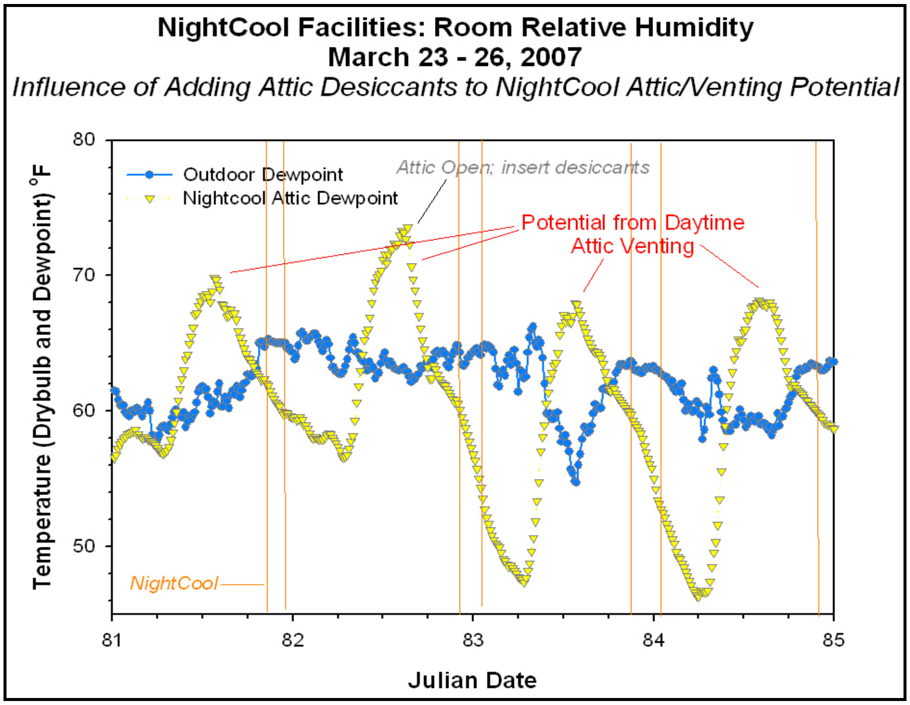

Figure 30. Temporary reduction in attic dew-point from addition of 150 desiccant packs on 24 March 2007 and illustration of how enthalpy based attic ventilation could be used to exhaust collected interior moisture.

Solar Dehumidification: Initial Results

In January 2008 we began controlling the experimental facility attic ventilation based on the difference in the attic to outdoor absolute humidity. In this mode of operation the sun's heat warms the attic and drys the desiccants activating the attic ventilation fans and thereby removing moisture. During the night the ventilation ends and the desiccant reabsorbs moisture from the space – during *NightCool* operation.

Since the change in controlled attic ventilation we have seen beneficial reduction in relative humidity. Since that time we have seen substantially lower relative humidity in the main zone in the *NightCool* attic. Figure 31 shows the measured interior relative humidity in the control and *NightCool* main zone interior after the implementation of enthalpy based attic ventilation in mid January 2008. The data is for 1 February to 2 March 2008.

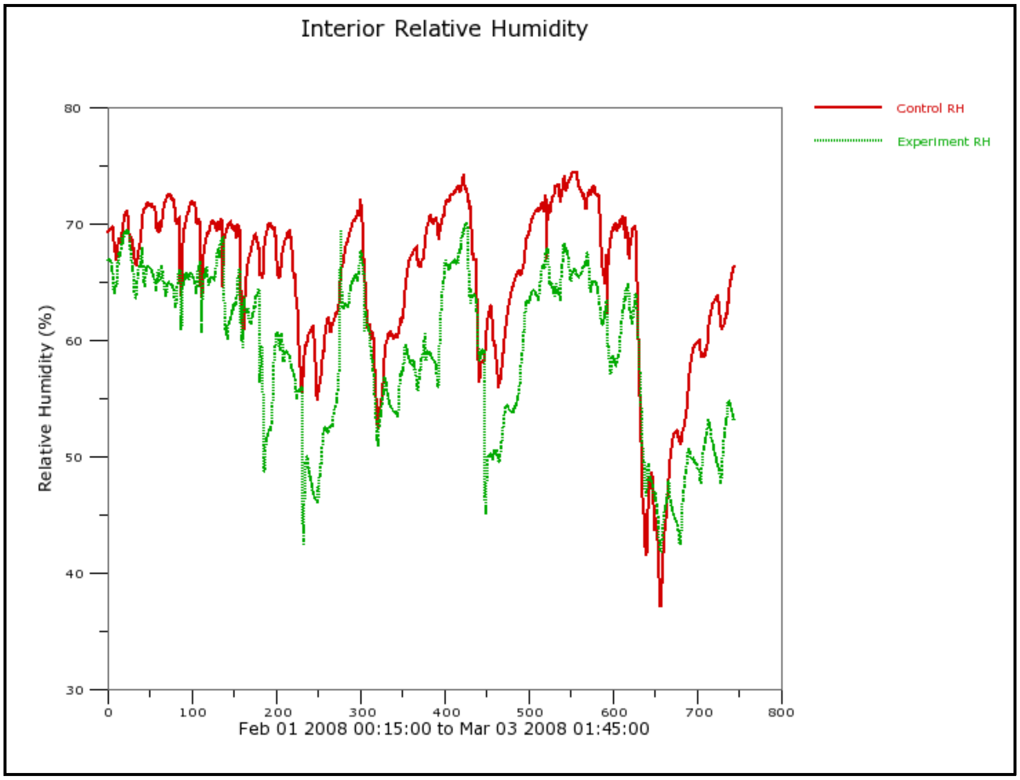

Figure 31. Comparative main zone interior relative humidity during February 2008 with enthalpy controlled solar attic ventilation to dehumidify using roof-mounted desiccants.

After the enthalpy based ventilation system was activated with the desiccant system, the average February interior main zone relative humidity averaged 65.6% in the control building against 59.7% in the *NightCool* building – a significant reduction in interior relative humidity during a seasonal period of minimal space conditioning. This is also a time where many buildings in Florida experience moisture problems.

Monitoring throughout the rest of 2008 will evaluate performance of the solar dehumidification system with *NightCool*. We will also measure the pre-cycle moisture asorptance and desorptance of attic wood members and the clay disiccants.

Potential Integration of *NightCool* with Solar Power Production with Heating and 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 32 shows one such system using the *Unisolar* BIPV product as installed in a low energy home in New Smyrna Beach, Florida.

Figure 32. 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 17). Another advantage will be that with the darker roof system the effectiveness of the solar dehumidification system will be improved similar to that achieved by Areemit and Sakamoto (2005).

During winter mornings and afternoons, however, collected heat from the darker BIPV would be conveyed by fans as useful heat to the interior space to offset a portion of space heating needs. As shown by collected data in the previous report, heat can be collected during winter afternoons by the roof system down to afternoon outdoor air temperatures of 60°F. With a darker BIPV roof and a sealed attic, heating should be available down to outdoor temperatures of 50-55°F. Further data to evaluate heat collection will have to await addition of a BIPV roof to *NightCool* in 2009.

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 with daytime venting.
    - * Greater solar dehumidification potential due to higher daytime attic temperatures.

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

- Daytime heating during mild clear 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).

Stage Gate Process Evaluation of *NightCool*

The *NightCool* technology is assessed as a *System Evaluation* according to the documented Building America Gate process. This includes both *Must Meet* and *Should Meet* criteria.

The *Must Meet* criteria are:

- Whole Building Source Energy Savings and other benefits
- Performance Based Code Approval

The *Should Meet* criteria area:

- Prescriptive-Based Code Approval
- Cost Advantage
- Reliability Advantage
- Manufacturer Supplier/Builder Commitment
- Gaps Analysis

We address each of the criteria below.

Must Meet: Whole Building Source Energy Savings and Other Benefits

Energy Savings

Measured annual energy savings in the test buildings were a 15% reduction in electrical space cooling in Central Florida’s climate. The comparison was between the control building with dark shingles and a ventilated attic and R-30 ceiling insulation and the *NightCool* configuration which is detailed in the report. However, as described in the body of the report, the actual achieved savings in real homes will vary depending on several factors.

Interior Temperature

Interior temperature maintained. The *NightCool* building maintained a temperature approximately 0.4°F cooler than the Control structure. Based on previous monitoring as well as simulation, we know that each degree Fahrenheit lower will increase cooling loads by approximately 10% (Parker, 2000b). Thus, we would expect that savings would be 4% higher had the control building been required to maintain 77.6°F rather than 78°F as was actually implemented and monitored. This may be altered in future monitoring to provide better comparability in system performance.

Duct System Location

Standard construction houses in southern climates have ducts in the attic whereas the *NightCool* system has no losses like this since the concept specifically assumes that the ducts are located within the conditioned space. However, the *NightCool* Control, being cooled by a through-the-wall air conditioner has essentially a perfect interior duct system with uniform R-30 ceiling insulation and no attic penetrations. The *NightCool* experimental building has a similar system. Thus, the savings of *NightCool* vs. the control would be substantially greater if the Control had ducts in the attic. For instance, in experiments done for Florida Power and Light Company, we found that a white metal roof would produce cooling energy savings of 23% with lower R-19 ceiling insulation and an attic duct system. Similarly, an analysis using DOE-2.1E withing *EnergyGauge USA* found that with the ducts inside the conditioned space and R-30 uniform insulation, the predicted savings from a white roof would drop to only about 9%. Thus, duct location is a major HVAC system impact.

Differing Roof Solar Reflectance

The control test building had a roof solar reflectance of about 8% compared with the 65% reflectance of the *NightCool* roof. Thus, the white roof is likely responsible for a portion of the savings seen from the *NightCool* experiment.

Measured space cooling in the *NightCool* building from April - October 2007 was 464 kWh (19 kWh used for *NightCool* fan). During the same time period, the control building used. 546 kWh in the Control (15% savings). Given the 1:10 scale of the buildings, this would suggest a consumption of 4640 kWh for a full scale *NightCool* building against 5460 kWh for a similar control.

We simulated the control building using DOE-2.1E within EnergyGauge USA. It predicts the control will use 529 kWh using Tampa TMY2 weather data. If the control is changed to a white roof with an absorptance of 35% as with the *NightCool* roof, the predicted consumption drops to 482 kWh-- a savings of 8.9%.

Final Estimate of Concept Savings

The average measured savings from the *NightCool* experiment in 2007 was 15%. However, the foregoing analysis would seem to indicate that the savings of *NightCool* were about 6% had we had the same roof material in the Control. Contrary to that influence, had we had maintained the same temperatures within the structures, the savings would likely have been about 10% even with the same roofing system. However, if we compare to standard buildings with dark roof and ducts within the attic space, the concept savings would likely exceed 25%.

The average air conditioning consumption in Central Florida is about 6,400 kWh per year (Parker, 2000). The concept site energy savings depends on the basis from which the calculations are made the most conservative estimate (comparison has a white roof and interior ducts) is 10% and the most optimistic is roughly 25% (control has attic ducts and a dark roof). This would represent savings of 640 - 1600 kWh/year depending on the roofing system assumed, the comparative temperatures maintained and the location of the duct system.

Since the reduction is to electricity consumption, source energy savings called for within the gate process would be roughly three times the absolute value of the savings would vary from 6.5 to 16.4 million Btu/year per site in Central Florida.

The saving in other climates would much greater. For instance, as shown in the early theoretical analysis done (Parker, 2005), the estimates for summer cooling indicated only about 15 kWh of potential cooling per day in a 2000 ft^2 home in Tampa against 50 kWh for Atlanta, GA and 62 kWh in Baltimore.[8] Although much of this available cooling could not be utilized, it does suggest the relative magnitude of the concept's potential in other climates.

Other Benefits

As previously described, the *NightCool* buildings maintained a cooler temperature– averaging about 77.4°F rather than the 77.8°F in the control. Generally, this lower temperature would be perceived as being more comfortable than that maintained in the control.

A second and much larger benefit has been the ability the *NightCool* system to maintain a lower interior humidity since the attic solar dehumidification system was properly configured in mid January 2008. In many Florida homes, high interior moisture conditions are experienced in summer and early spring months where there is little space conditioning. However, *NightCool* showed considerably reduced interior moisture levels under such conditions. For instance, the interior relative humidity in February and March of 2008 when averaged 64.1% and 57.5% in the experiment– a very significant 6.6% difference in relative humidity. This is important because interior humidities above 60% generally favor molds, mildew and dust mites– all of which are important allergens for household occupants (Chandra et al., 1997).

Moreover, we believe it is clear that if a whole house dehumidifier was used to control interior RH to less than 60%, that the *NightCool* building with its solar dehumification system would show dramatically lower space conditioning energy consumption. For instance, Chandra et al. (1997) showed that to maintain lower interior moisture levels that whole house dehumidifiers used an average of 3.5 -11.0 kWh day. As air conditioning in Florida averages about kWh/day from April - October, this is an increase to space conditioning electrical consumption by 13- 41% beyond cooling needs.

Although not demonstrated within our monitoring protocol thus far, should ventilation air be added to the home, the use of supply fan ventilation using the tempered source air from the *NightCool* attic during evening hours would substantially reduce the temperature and humidity load of the introduced air to the house interior.

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[8] The measured energy savings in the tenth scale *NightCool* buildings averaged about 0.4 kWh/day against the 1.5 kWh predicted to be theoretically available.

A final benefit is that with SIPs used for the attic floor within the *NightCool* concept, this would result in a large storage space unobstructed by trusses. As storage space is highly valued in slab on grade houses, this area would likely be highly valued by consumers.

Performance and Prescriptive Based Code Approval
These criteria requires that the technology meets performance-based safety, health and building code requirements in new homes. The unique elements called out for the technology are thus scrutinized here:

- Sealed attic construction: the code issues associated with this building feature have already been addressed within its wide application in Building America projects. One potential advantage, however, is that *NightCool* does not have spray insulation on the roof decking which has created some fire spread concern. There are no unfavorable code issues.

- Highly insulated SIPs panels in the ceiling. These are conventional building insulation panels and are covered on both sides– on one by gypsum and the other by metal. These are already approved for use in buildings and are conventional.

- Exposed roofing installed directly on cross battens. Although metal roofing is conventionally installed on wood decking, cross battens as used in the *NightCool* configuration are the most common installation system for both metal and tile in Europe. Cross-batten installations are also common in commercial buildings in the U.S. Thus, while metal installation on battens is not yet common in residences, the issues associated with code approval have already been addressed, both relative to structure and wind resistance.

- Dampers and fan circulation from the attic space. There could potentially be fire spread concerns such that smoke from fire which started in the *NightCool* attic could be broadcast throughout the house. However, this issue is easily addressed as with whole house fans now. The dampers in the system would be interlinked with smoke detectors such that dampers would shut and fans turn off if smoke was detected.

Thus, all potential issues with the technology relative to Code Approval appear either resolved or easy to address.

Cost Advantage
The *NightCool* system would appear fairly neutral relative to cost. While there would dampers and fans and controls required for the system, the *NightCool* roof would obviate the need for roof decking. Less wood would be used for the cross-battens for the roof installation.

The fan air volume from the attic is modest; the fully functional *NightCool* system would use the home's variable speed air handler to deliver cooled air from the attic space to the conditioned zone so that the main cost would be the dampers which are approximately $300 to the two 16" models which would be needed.

The SIPs panels would cost more than for fiberglass insulation, but SIPs panels are already cost effective and used in many building applications. Although the cost of the R-30 polystyrene SIPs panels are about four times the cost of a standard framed and insulated ceiling, the SIPs also eliminate the need to standard trusses so that the incremental cost for 2,000 ft^2 home would be low. It would also be possible to use conventional fiberglass insulation for the concept, built as field constructed structural panels. Thus, the likely incremental cost for the ceiling insulation element is likely less than $1000.

Reliability Advantage

A clear advantage of the *NightCool* system is that even with failure of the main cooling system, the *NightCool* system can still operate and maintain a much cooler building interior. This was clearly shown in the 2nd project report (Parker and Sherwin, 2005) which showed the *NightCool* system by itself could maintain summer interior nighttime temperature to be less than 82°F (reaching 74°F by 7 AM) even without vapor compression air conditioning (see Figure 16 and 17 of that report). Operating EERs were very high in this configuration: 44 Btu/Wh. Now, with the solar dehumidification system operating, the revised system will provide some dehumidification as well.

Also, even in the event of total electrical power failure, the *NightCool* system showed that with the system dampers open, the natural attic convection to the interior would produce enough natural cooling such that the interior temperature would be held to an average of 80°F (maximum temperatures of 83°F at 3 PM and minimum of 78°F at 7 AM), even in late August (see Figure 13 of the same report).

It must be underscored that the above advantages are all the more compelling in more moderate climates where *NightCool* could often satisfy much of the home's cooling needs. The improved efficiency and dehumidification performance of the *NightCool* system could add to the desirability of the system for new low energy housing– particularly for housing located in places with large daily summertime diurnal temperature swings.

Manufacturer/ Supplier and Builder Commitment

Within the project we have had large interest from the metal roofing consortium and individual metal roofing suppliers. Letters demonstrating this interest were included in the previous report.

We have another commitment recently from a thin-film PV supplier: Advanced Green Technologies (AGT). Mr. Rob Kornahrens CEO, and Mr. Jack Castro, of AGT, visited FSEC to examine the *NightCool* concept on 21 March 2008 with interest to using the technology in full scale building application with their products. AGT is interested in cooperating and exploring new technologies with high potential in the green construction area. One added interest relative to *NightCool* would be the potential of cooling the PV system to achieve better performance as well as the possibility of scavenging some winter afternoon heat in colder climates. Other info about AGT can be found at:
http://www.agt.com/.

Gaps Analysis

Within the gaps analysis, we attempt to examine technical, performance and market barriers for the *NightCool* system based on lessons leaned thus far in system measurement.

- Dehumidification: The first identified gap was the lack of dehumidification within the originally implemented system. This has since been addressed and the newly available solar dehumidification system has provided approximately 6% lower humidity during the months of February and March of 2008 when space conditioning needs are at a minimum in Central Florida. Thus, this potential shortcoming has been converted from a deficiency into a technology strength for *NightCool*. A similar system using attic solar dehumidification has been studied in Japan, showing dehumidification COPs of approximately 15 (Areemit and Sakamoto, 2005). This is about three times more efficient than the best vapor compression dehumidifier. Accordingly, we will study the efficiency of the *NightCool* solar dehumidification cycle in much greater detail in a second report in 2008. We hope to see if it might be possible to simply use the wood in the attic in a conventional counter-batten arrangement to provide the necessary latent absorption capacity. Experiments being done this spring and summer should provide answers to this important research question.

- Energy Savings: The measured energy savings in 2007 was 15% compared with a dark shingle roof in the control with no duct losses. However, one concern is how the *NightCool* system will compare in performance when evaluated against the control with a white metal roof which is the "best in-class" technology– even if not always considered aesthetically acceptable. To address this gap, a white metal roof is being installed on the *NightCool* control building in April of 2008 so that data for the remainder of the year will compare the best conventional ventilated roofing system against the *NightCool* system. We will, however, lower the set temperature in the control to approximate the average daily temperature being maintained in the *NightCool* building.

- Performance with BIPV: this has been identified as an important factor to be evaluated within the final technical evaluation of *NightCool*. The darker roofing with BIPV will have several impacts with the *NightCool* system:
    - Higher attic temperatures will increase cooling loads, but also improve the performance of the dehumidification cycle.
    - Greater heating of the attic space would allow higher potential for winter afternoon heating in colder climates.
    - Afternoon attic ventilation, which is common with *NightCool*, will reduce PV modules temperatures increasing operating efficiency in a never-before-tested energy trade-off.

Assuming the research goes forward, BIPV will be evaluated within *NightCool* in 2009.

- Climate Related Performance: *NightCool* has only been tested in an experimental facility in a hot and humid climate– the worst climate for its performance. Based on the simulation analysis in the early theoretical report (Parker, 2005), performance should be two to four times more productive in climates such as Phoenix, Atlanta and Baltimore, respectively. Assuming good research results and approval for the continuation of the research, testing in full scale homes could begin in 2010. We would also need to examine any potential issues with roof-level condensation problems during winter in colder climates.

- Controls: The controls for the system are currently being accomplished using the system data acquisition system. Should the system appear fruitful relative to reducing heating and cooling, a more simplified control integrated circuit would have to be developed. This would include interior, attic and attic relative humidity transducers that would control the auxiliary air conditioners, *NightCool* fan and attic ventilation system.

Conclusions

This report describes the experimentally tested potential of a novel residential night cooling concept. *NightCool* uses a home's metal roof under a sealed attic as a large radiator to the night sky 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. Solar dehumidification also appears feasible and some enhancements to the implemented configuration are being considered.

An initial report described a detailed simulation model of the relevant night cooling phenomenon and examined potential performance (Parker, 2005). A second report experimentally evaluated the concept thermal, passive and dynamic performance using two highly instrumented test sheds using short term data in the autumn of 2006 (Parker, 2007).

Within this report, data is presented on the long-term performance with the fully operational *NightCool* system. This includes circulating fans when attic conditions are favorable for nocturnal cooling and conventional air conditioning at other times. Data comprises a full year of the cooling season in Central Florida, which stretches from April to November of 2007. Within the monitoring, vapor-compression air conditioning is used in the control and the experimental unit during daytime, and with the *NightCool* fan circulation system used during evenings. A temperature of 78°F was maintained in both test buildings. Measured cooling energy savings between the control and *NightCool* building averaged 15% over the eight month test period. Air conditioner cooling energy use averaged 4.6 kWh/day in the control building against 3.6 kWh in the experimental building, which also used 0.2 kWh/day for the circulation fans.

Average long-term performance was somewhat lower than the previous simulation analysis. The delivered seasonal cooling rate averaged about 1.5 - 3.0 Btu/hr/ft^2 (5 - 10 W/m^2) of roof surface on the average 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 depending on the season. Daily runtime fractions during which the *NightCool* fan operated varied from 12% (3 hours) in August - September to 36% or 8 hours in May. Over a typical 6 hour operating period, this would produce about 0.2 ton-hours of sensible cooling or 2 ton-hours in a full scale home. Average long-term monthly energy efficiency ratios (EERs) ranged from 16 - 32 Btu/Wh with a mean of 25 Btu/Wh over the cooling season. As expected, performance was best during the spring and fall months. However, this level of performance exceeds the performance of any air source equipment currently available.

Over the monitoring period, a clay desiccant-based dehumidification system was added to the *NightCool* attic, although not activated. This consisted of 300 3-oz Desi-Paks sandwiched up against the underside of the metal roof deck so that the heated roof can solar dry the desiccants during the day with moisture reabsorption at night during nocturnal cooling. Little impact was seen from the addition of the moisture internal capacity until the attic ventilation system was activated based on attic to exterior absolute humidity difference beginning in January 2008.

After the enthalpy based ventilation system was activated with the desiccants in place, the average February 2008 interior main zone relative humidity averaged 65.6% in the control building against 59.7% in the *NightCool* building– a significant reduction in interior relative humidity during a period of minimal space conditioning where many buildings in Florida experience moisture problems.

The experimental data collected thus far indicate that *NightCool* could be a promising system technology for very low energy homes. Future work in 2008 will concentrate on more detailed evaluation and refinement of the *NightCool* dehumidification system and long-term data collection in the current control configuration. We will also give the control building a white metal roof so that the *NightCool* specific savings can be isolated against the “best in class” roof technology.

In 2009 we plan to mate the concept with Building Integrated Photovoltaics (BIPV) to provide combined solar electric power, nighttime cooling and winter afternoon heating. This will likely be a collaborative effort between the metal roofing and photovoltaic industries.

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Appendix A
Comparison of Monitored Data with Simulation Predictions

A previous report used a detailed simulation to predict *NightCool* system performance (Parker, 2005). The calculated 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 long-term monitored performance was lower relative to the simulated results. In the eight month long monitoring period above, the average cooling rate varied from 1.5 - 3 Btu/sqft of ceiling area or 285 to 570 Btu/hr (84 W to 167 W), in absolute terms. As the measured fan power was 18 Watts, the system's sensible EERs varied from 16 - 32 Btu/Wh. The average observed return to supply temperature difference was about 2.5°F over the annual cooling season. Thus, the average performance was:

Cooling Capacity = 2.5 * 150 cfm * 1.08 = 405 Btu hr (119 W)

EER = 405/ 18 Watts = 23 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 about 40% lower than that simulated. However, based on the measurement and simulation, we have a convincing explanation for the discrepancy.

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 33 below, the estimated cooling capacity of the system is 2,157 W at 78°F.[9] 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 72°F, the *NightCool* system would typically operate at a midpoint between 78°F and 72°F. At 75°F, where the system typically operated, the simulation indicated a cooling capacity for the full scale building of only 720 Watts. This would imply a cooling rate of about 410 Btu/hr (120 Watts) in the scale buildings versus the 119 Watts actually achieved. Thus, the actual buildings appear to operate very similarly to predicted at the as-operated lower return temperature. However, this important fact was not accounted for in the original simulation study.

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

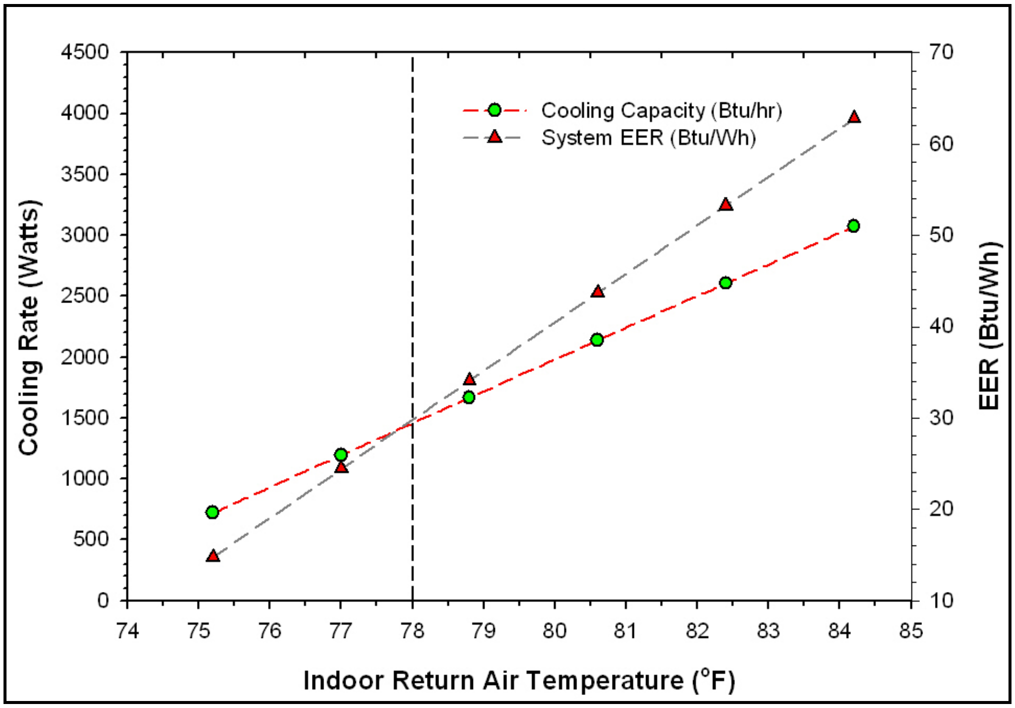

Figure 33. Simulated influence of indoor return air temperature to predicted performance.

The overall energy reduction over the year was 15%. 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 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.