NIGHTCOOL: AN INNOVATIVE RESIDENTIAL NOCTURNAL RADIATION COOLING CONCEPT

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ABSTRACT

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 building space cooling. A typical roof at 75EF will radiate at about 55-60 W/m^2 to clear night sky and about 25 W/m^2 to a cloudy sky. For a typical roof (250 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. However, various physical constraints (differential approach temperature, fan power, convection and conductance) limits what can be actually achieved. Further a big problem with night sky radiation cooling concepts have been that they have typically required exotic building configurations. These have included very expensive "roof ponds" or movable roof insulation with massive roofs so that heat is not gained during daytime hours. In this paper, we describe an innovative night sky building cooling system that avoids these drawbacks. Its configuration and predicted performance is summarized.

INTRODUCTION

An evaluation has been conducted of the potential of a night sky cooling system to substantially reduce space cooling needs in homes in Northern climates. The paper describes the innovative residential cooling system which uses nocturnal night sky radiation from a roof integrated radiator. The system uses a sealed attic covered by a highly conductive metal roof 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 an interior control humidistat.

The paper describes a detailed simulation model of the relevant physical night cooling phenomenon, examining each particular parameter which was found to have an appreciable impact on performance. A 225 square meter metal roof structure is modeled in Tampa, Florida (an unfavorable climate) and in other locations with greater sky radiation potential. Under a series of standard nighttime conditions approximating humid nighttime summer weather, the model predicts a cooling rate of about 2,140 Watts. The model features several enhancements (such as constraining the radiator temperature to the dew point temperature) never before incorporated into such a model. The evaluation examines major weather-related influences on achieved cooling performance are outdoor air temperature, dew point 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 predicts an average summer cooling benefit of about 15 kWh per day for 1.4 kWh of fan power for a system seasonal coefficient of performance (COP) of about 10.8 W/Wh. Performance in less humid climates with more diurnal temperature swing was predicted to be substantially better. A follow-up experimental plan is described to obtain empirical data on concept performance using two highly instrumented test sheds.

BACKGROUND

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 (Givoni, 1982; Santamouris and Asimakopoulos, 1996). The night cooling resource is large and enticing for residential energy-efficiency applications. On a clear desert night, a typical sky-facing surface at 27°C will cool at a rate of about 75 W/m^2. In a humid climate with the greater atmospheric moisture, the rate drops to about 60 W/m^2 (Martin and Berdahl, 1984) 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. Average potential daily July cooling for a radiator at 22°C amounts to 63 - 110 Wh/m^2 of roof surface in U.S. climate locations – the lower value being representative of a humid region like that in Florida (Clark, 1981).

For a typical roof (225 square meters), this represents a cooling potential of 6,000 - 14,000 Watts of cooling potential each summer night if the roof night sky radiation could be effectively captured. 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. However, various physical limitations (differential approach temperature, fan power, convection and conductance) limits what can be actually achieved, so that perhaps half of this cooling rate can be practically obtained. Even so, careful examination of vapor compression space cooling in many homes in hot and humid Florida shows that typical homes 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 greatly reduce space cooling.

A large problem with previous night sky radiation cooling concepts have been that they have typically required exotic building configurations (e.g. Hay, 1978; Fairey et al., 1990). These have included very expensive "roof ponds," desiccant cycles or, at the very least, movable roof insulation with massive roofs so that heat is not gained during daytime hours. These systems have often proved overly expensive, unreliable or too complex in application.

To address these limitations, an innovative residential night cooling system is described as shown in Figure 1. The key element of this configuration is that rather than using movable insulation with a massive roof or roof ponds, the insulation is installed conventionally on the ceiling using structurally insulated panels of RSI -5.3 m^2-K/W. The system utilizes a highly conductive metal roof on metal battens over a sealed, unventilated attic with an integrated dehumidification system.

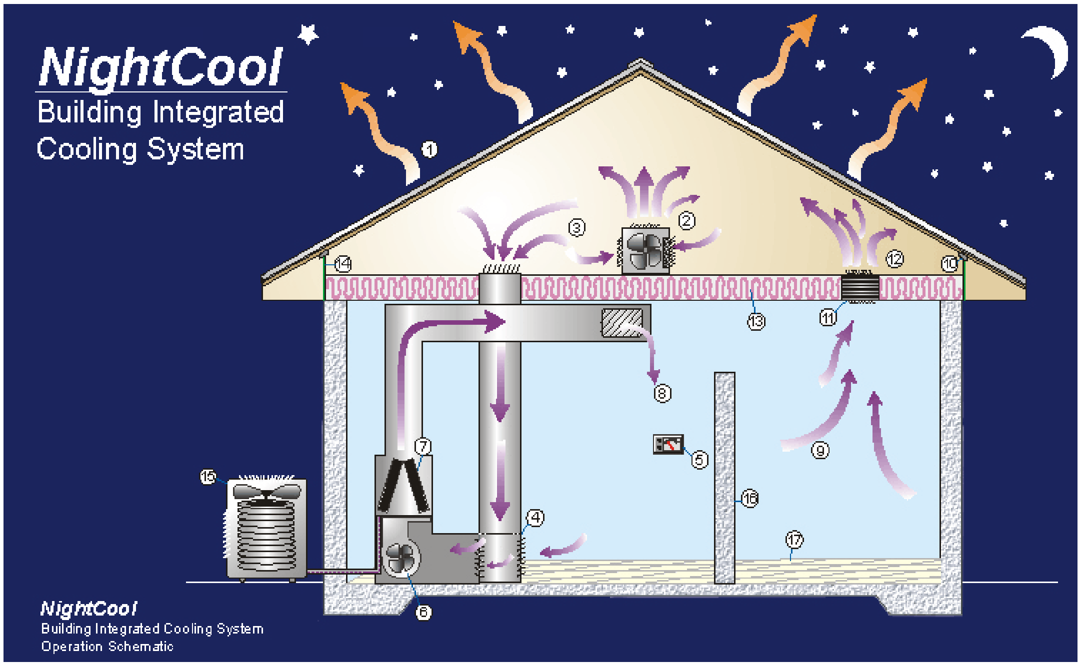

Figure 1. Schematic of *NightCool* concept.

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. RSI-5 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. During this time the space is conventionally cooled with a small air conditioner if necessary. 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 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 fan speed is increased. If the interior air temperature does not cool sufficiently or the relative humidity is not kept within bounds (<60% RH) the compressor is energized to supplement the sky radiation cooling. The massive construction of interior tile floors and concrete walls) will store sensible cooling to reduce daytime space conditioning needs. The concept may also be able to help with daytime heating needs in cold climates as well by using a darker roof as a solar collector.

SIMULATION MODEL

Within the assessment, we created a simulation model of the *NightCool* cooling system to examine the fundamental relationships influencing performance. The computer simulation extends work by Givoni (1994). The calculations evaluate performance based on physical principles. The simulation has been used to evaluate the impact of various physical system parameters (roof conductivity, view factors, system air flow rate etc) as well as various system values (return air temperatures and flow rates) as well as weather conditions. In this way, it is possible to determine the critical system parameters to improve system performance. As example, Figure 2 below shows the *NightCool* model performance sensitivity to outdoor air temperature. Note that cooling capacity falls to zero at 29°C.

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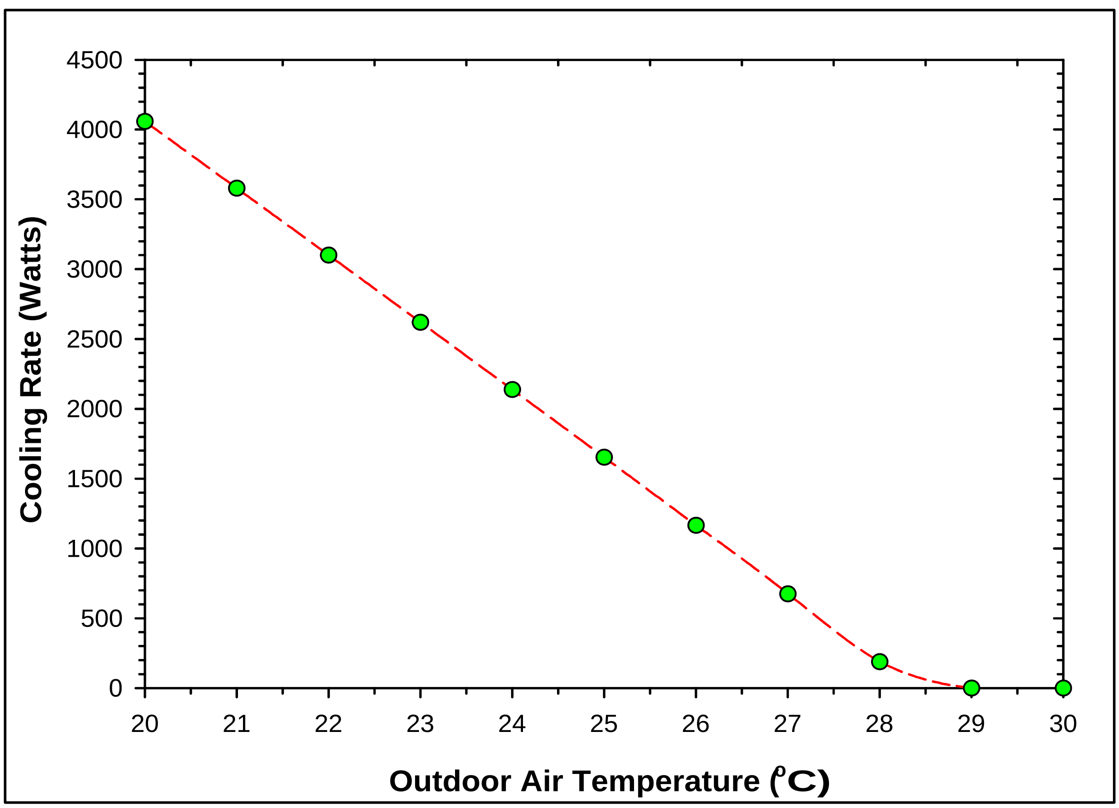

Figure 2. Sensitivity of model performance to outdoor temperature

The full project report contains sensitivities to a host of factors as well as predicted performance under hourly weather conditions in varied climates (Parker, 2005). Briefly, results showed that the performance of the system is strongly impacted by outdoor and indoor air temperatures, attic air flow rate and fan and motor efficiencies. More minor influences included roof tilt, outdoor dew point, roof surface emittance. Moderate influences included sky cloudiness and roof level wind speed. Generally, the results suggest that a low static pressure and efficient fan system with an efficient motor drive will be required to obtain best performance

PREDICTED PERFORMANCE

Using hourly TMY weather data, the simulation shows that in Tampa, Florida from June - September, the system can produce an average of 15 kWh of cooling per day at a use in fan power of about 1.4 kWh for a system COP of about 10.8 – considerably more efficient than conventional vapor compression air conditioning equipment. As expected, predicted performance in less humid and more temperate climates showed even greater potential. Phoenix, Arizona– a hot desert climate-- demonstrated a daily average summer cooling potential of 23 kWh at a COP of 17.9 W/Wh. Performance in the more temperate locations of Atlanta, Georgia and Baltimore, Maryland was even better – 50 and 62 kWh of daily cooling available at COPs greater than 20 W/Wh. The latter would be more similar to potentials expected in more temperate Southern European climates. Figure 3 shows the performance of the system in early October in Tampa which would approximate summer cooling potential in more moderate climates.

Note the poor predicted performance on warm cloudy and rainy days such as those seen from Julian days 274-276 (October 1- 3). Note also that cooling is generally only available during evening hours so that some sensible cooling storage will be necessary for best function.

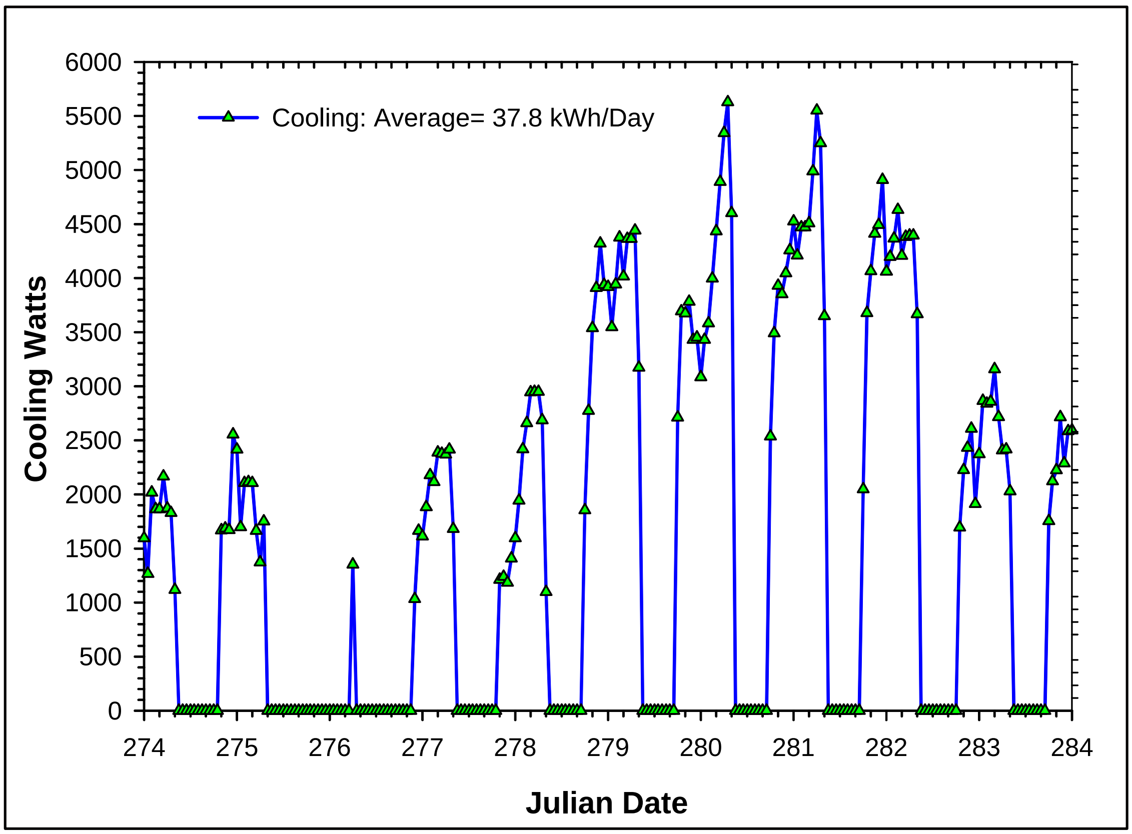

Figure 3. Predicted performance of system October 1 -10th

EMPIRICAL EVALUATION OF CONCEPT

An empirical evaluation of the concept is being accomplished by using two highly instrumented side-by-side 3m x 5m test sheds located at the Florida Solar Energy Center (Figure 4). One of the test sheds will be configured like a conventional home with a dark shingle roof and insulated ceiling under a ventilated attic. The experimental shed will feature a white reflective roof on battens with a sealed attic where the air from the shed interior can be linked to the sealed attic and roof radiator when the roof temperature drops below the room target cooling temperature. Figure 5 shows an interior view of the exposed metal roof on metal battens in the sealed attic of the experimental *NightCool* facility during the construction process.

Figure 4. *NightCool* demonstration test buildings under construction

Figure 5: Interior exposed metal roof in attic of *NightCool* test building

Figure 6 shows preliminary data indicating the performance of the two completed building shells during the late summer of 2005.

During this phase of the monitoring, no fans are used to circulate air to the attic space; heat transfer is via internal radiation and free convection only. Thus, the performance results are very conservative relative to what should be achievable with the final configuration. Even so, note that the early data show the interior temperature at 2 meters is approximately 1-2°C lower than the control building even with no forced air circulation on clear nights. Also, the temperatures at mid-day indicates temperatures up to 2°C cooler in the improved building with the white metal roof. As expected, the preliminary data show better cooling related performance during clear nights and more poor performance under cloudy conditions. However, note that under cloudy and rainy conditions during Tropical Storm Ophelia, the interior temperature in the experimental building are very close to the 25°C comfort target.

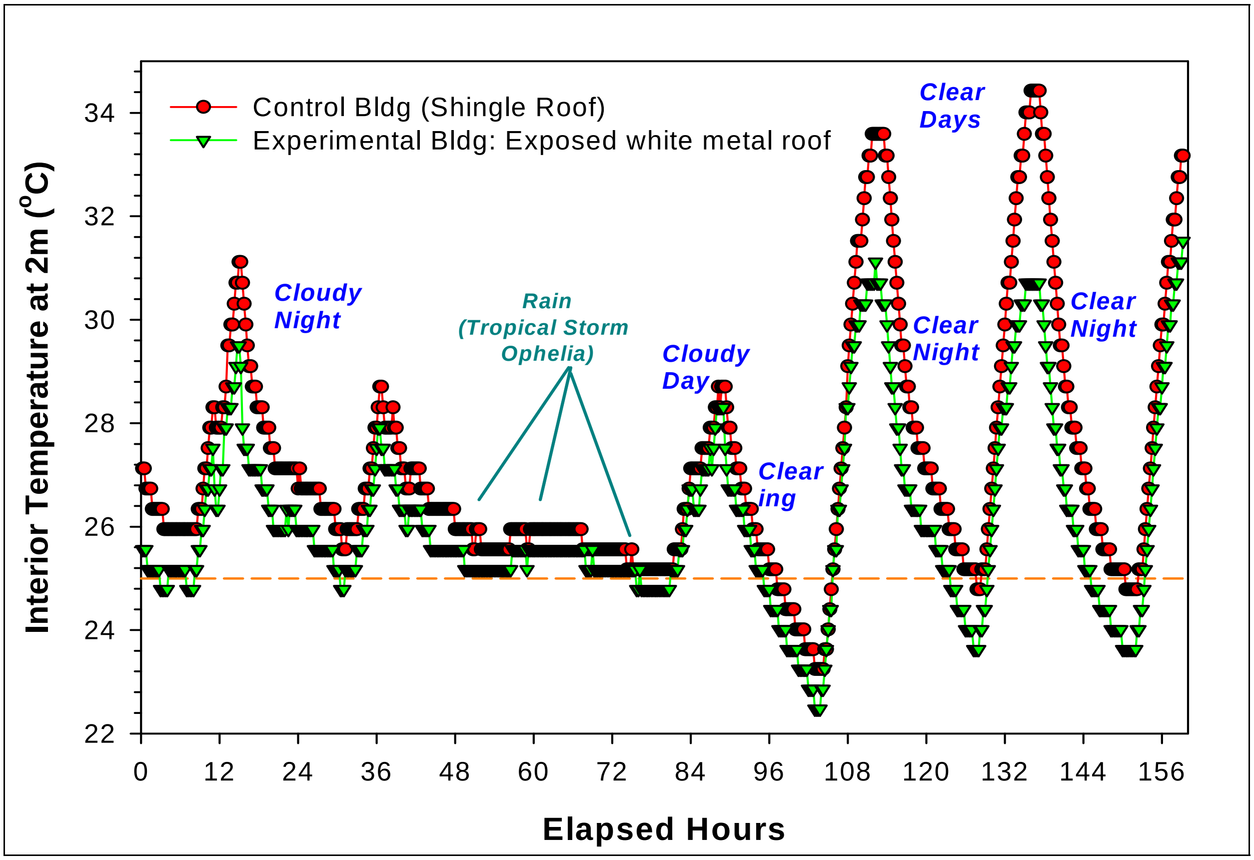

Figure 6: Measured thermal performance of control and experimental buildings from 6-12 September 2005.

FUTURE WORK

Extensive data on comparative energy and thermal performance of these two test facilities will be collected and analyzed in 2006-2007. The evaluation will explore sensitivity in performance to weather conditions, fan air flow and power and other critical parameters. A more complete evaluation of the real-world application of the concept should be available in the next two years.

ACKNOWLEDGMENT

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