Applying Natural Cooling to Slab Floors

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ABSTRACT

"Natural cooling" systems use evaporative or night sky radiative processes to cool water for building comfort conditioning. Hydronic tubing in concrete floors facilitates operation of the natural cooling source at night when wet-bulb temperatures are lowest. Heat is thus discharged from the concrete slabs at night, and the cooled slab passively cools the building the next day. The major benefits of natural slab floor cooling are reduced (or eliminated) compressor energy consumption, reduced peak demand, and reduced blower operation for forced air cooling delivery.

This paper reviews the design and operation of three Northern California projects completed in 1997 and 1998, each using a different approach to natural cooling via the slab. All three were monitored with financial support provided by Pacific Gas and Electric Company through California public goods charges. Monitoring work evaluated key issues for these systems including performance, economics, water use, maintenance, and latent cooling. After summarizing the projects, the paper compares them and discusses their relative merits.

Background

The *Davis Texaco* convenience store uses a down-sized rooftop unit and duct system with an evaporative condenser air pre-cooler that also pre-cools ventilation air and operates in a programmed cycle to cool the floor. Monitoring data for this project show 51% cooling energy savings and 47% demand reduction with a payback of less than two years.

The *580 Howard Street* project in San Francisco uses a cooling tower connected to floor tubing in a renovated five story concrete apartment building. Controls bias the system toward night operation, and no auxiliary refrigerant-based cooling is provided. Monitoring results and economic data show that the system achieved an immediate payback.

The *All-Weather Manufacturing* facility in Vacaville uses a night roof spray water cooling system. Cooled water is captured at roof drains and returned through a filter to a storage tank. Tank water is circulated through in-floor tubing throughout the spray cycle and through zoned fan coils on demand. An off-peak, down-sized chiller is also coupled to the storage tank and the floor tubing. Monitoring data for this project show 73% cooling energy savings and 87% demand reduction with a payback of less than three years.

Cooling from the floor raises two key issues. First, will moisture condense on the floor, and does the floor surface make a difference? Second, if the cooling source is evaporative, can the system displace compressor-based cooling at peak load times? This paper discusses these issues for each of the three reported projects.

The Texaco “PreCool Plus” Project

Introduction

This project adds evaporative condenser air pre-cooling to a conventional packaged rooftop heating/cooling unit (RTU), and pre-cools condenser air, ventilation air, and the floor mass with a single evaporative unit. A detailed project report including monitoring results was completed for the local electric utility (Davis Energy Group, 1998).

RTU’s are common in small to medium-sized commercial buildings due their low initial cost and ease of installation. The low efficiencies of RTU’s can be improved by 20 to 30% in dry climates through evaporative pre-cooling of condenser air. The Davis Texaco project takes two further steps (hence the name “PreCool Plus”), operating the pre-cooler at night to cool water circulated through tubing under the building floor slab, and also pumping evaporatively-cooled water through a ventilation air coil. No moisture is added to indoor air. This system reduces cooling loads by reducing latent loads, blower heat output, and ventilation air temperatures. (The specified 870 cfm ventilation flow rate is maintained from the original design.) PreCool Plus increases efficiency by delivering efficient natural cooling from the floor and by reducing refrigerant condensing temperatures. At the Davis Texaco project, these features also facilitated RTU capacity reduction to 10 tons from 15 tons in the base case.

System Description

The Davis Texaco mini-mart, located approximately 20 miles west of Sacramento, has 3,620 ft^2 of conditioned space, and includes two fast food restaurants in addition to traditional convenience store features. The facility operates 24 hours per day, and has large internal heat gains caused by the many electric heating elements, lighting, and cooking equipment. Ceramic tile floors are used throughout. The original mechanical plan used a 15 ton RTU with a 5 hp blower motor to supply 5,500 cfm. The revised mechanical design with PreCool Plus included a 10 ton RTU with 2 hp blower to deliver 3,670 cfm. In addition to the smaller conventional components, the revised plan included the following PreCool Plus components:

1) underfloor tubing in a sand layer just beneath the floor slab
2) an evaporative pre-cooler assembly for the 10 ton RTU with custom sump box
3) a centrifugal pump
4) a ventilation air pre-cooling coil that drains to the sump
5) a microprocessor-based control system

Monitoring

The installation was completed in March, 1998 but monitoring was not begun until June. Monitoring components included a datalogger, power transducers, flow meters, and temperature and relative humidity sensors. All sensors were scanned and energy transfers were computed every 15 seconds. Data were summed or averaged, as appropriate, and stored in datalogger memory every 15 minutes. Measured parameters included RTU and pump energy consumption, indoor and outdoor temperature and relative humidity, pre-cooled condenser air temperature, water loop temperatures and flow rates, and water use.

The monitoring data were reviewed to determine overall performance and individual performance of the condenser pre-cooling, floor cooling, and ventilation air pre-cooling components. A detailed building model with inputs for ventilation air, thermostat setpoints, and building occupancy were combined with a Sacramento weather file to generate hourly cooling loads for the full year. The hourly loads were input to an EXCEL spreadsheet to compute base case energy use and demand using an efficiency curve for a typical 10 EER RTU. Results showed a maximum cooling load of 15.3 tons on the 104°F peak day, consistent with the 15 ton base case sizing. Monitoring results for each of the PreCool Plus components were included in the spreadsheet to develop energy use and demand projections with the same RTU efficiency curve. Monthly energy use and peak demand were tabulated for use in calculating annual total and individual component energy cost savings.

Results

For the June through November, 1998 monitoring period, PreCool Plus energy use averaged slightly over 100 kWh/day, with 189 kWh for the peak day. Pump energy totaled 3.8% of total HVAC energy use. Water use averaged 19 gallons per system operating hour and cost $44 for the June-November period. Average indoor temperature was quite constant during the six-month period and averaged 74.6°F. Water delivery temperature to the floor was always above the indoor dew point, so moisture could not condense on the floor.

Figure 1 plots HVAC demand, indoor and outdoor dry bulb, and outdoor wet bulb temperatures for August 4, 1998, when outdoor temperature ranged from a low of 74°F to a high of 112°F, 11°F above the local design temperature. The cooling system cycled during the night, then ran continuously from about 9 AM to nearly midnight. During this time, indoor temperatures rose from about 73°F to 78°F at 20:00 (8 PM). The outdoor wet bulb pattern for the data is unusual, as it would typically track the shape of the outdoor dry bulb temperature curve, limiting floor cooling delivery through the afternoon peak load hours. The near-constant HVAC demand from 10 AM to midnight, while outdoor temperature ranged from 85°F to 112°F, reflects the benefits of evaporative pre-cooling; data without the pre-cooler operating show RTU demand increasing approximately 1% per degree of outdoor temperature rise.

Evaporative pre-cooler operation typically reduced condenser inlet air temperatures by 20 to 30°F during peak cooling conditions, increasing capacity and efficiency while reducing power consumption. On the one afternoon when a controller fault disabled the pump, condenser inlet air quickly jumped 20°F and RTU power consumption jumped 18%. Floor cooling delivery was slightly below projections due to lower-than expected indoor temperature and water flow rate. Regression relationships were used in the spreadsheet model for floor cooling delivery rate vs. wet bulb temperature, and for ventilation air pre-cooling vs. the outdoor air-to- inlet water temperature difference (Davis Energy Group 1998).

Table 1 summarizes performance results for the 15 ton base case and 10 ton PreCool Plus systems, respectively. “Other energy” includes added condenser fan and pump energy used in the PreCool Plus system. Results indicate 51% overall energy savings with a 46% (10.6 kW) peak demand reduction. Projected annual water cost is $65 in Davis. Average annual maintenance costs were estimated at $200 to cover 2 service visits per year plus evaporative media replacement on a 5 year interval.

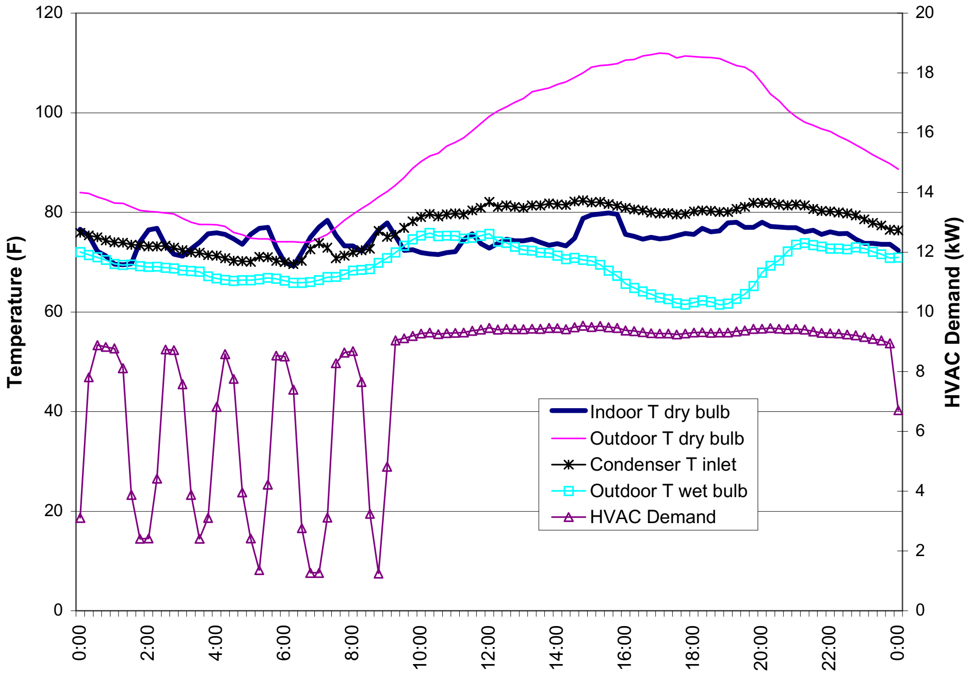

Fig. 1: Peak Summer Day PreCool Plus Performance (August 4, 1998)

Table 1: Projected Energy Use, Demand, and Operating Cost Comparison

Electrical energy (kWh)	Base Case	PreCool Plus	Savings	% Savings
Compressor & fan	29,132	15,345	13,787	47%
Supply blower	38,540	15,435	23,105	60%
Miscellaneous		2,083	(2,083)	
Total	67,671	32,863	34,809	51%
Peak demand (kW)	22.9	12.4	10.5	46%
Annual energy cost	$6,573	$3,304	$3,269	50%

The cost-effectiveness of individual PreCool Plus components was evaluated using the spreadsheet model. Energy and cooling capacity impacts were identified by adding each feature independently to the base case. Blower demand and energy savings were apportioned among the three key components based on their relative share of the 5 ton total cooling capacity reduction. Table 2 shows capacity reduction benefits and component cost distributions. All water and system maintenance costs were assigned to the pre-cooler.

Table 2: Projected NUE Component Costs and Simple Payback

Component	Annual Savings	Projected Cost	Downsizing Credit	Incremental Cost	Years Payback
Pre-cooler	$1,544	$5,865	($4,825)	$1,040	0.7
Floor cooling	$838	$3,450	($1,176)	$2,274	2.7
Ventilation air	$622	$1,035	($1,749)	($714)	Immediate
Total	$3,004	$10,350	($7,750)	$2,600	0.9

The 580 Howard Street Project

Introduction

This downtown San Francisco five-story historic building includes radiant floor heating and cooling for its 30,000 ft^2 of conditioned space. Most of the units are designed as apartments, but some are used as offices in this "work-live" facility. Lightweight concrete topping was added on each floor to accommodate floor tubing. The cooling source is a closed cooling tower sized to reject a 25 ton load. The HVAC system was commissioned in late 1998, although additional adjustments were required at the start of the 1999 cooling season.

Hard floors are provided throughout, but probably use rugs in many units. Each living unit has a programmable setback thermostat. A call for cooling opens the cooling zone valve and places the changeover valve in cooling position. The cooling tower and cooling loop pump are enabled by the cooling zone valve end switches. The cooling tower is operated in three stages: spray pump only, low speed fan, and high speed fan. An adjustable speed drive was installed to efficiently meet the pumping requirements for the distribution loop. No refrigeration-based auxiliary cooling is provided. Thus, no condensation can occur on the floor because supply water temperature stays well above the indoor dew point.

Monitoring

The 580 Howard Street project was monitored for three summer months to evaluate floor cooling performance (Davis Energy Group 1999a). The monitoring system recorded indoor and outdoor temperatures, outdoor relative humidity, flow rate and water temperatures in the floor cooling loop, and system energy use. Data were logged on 15 minute intervals and downloaded using portable PCMCIA cards. Flow and loop temperature data were sampled at 15 second intervals and Btu calculations generated a running sum over the 15 minute interval.

Results

Figure 2 shows a week of TowerSlab system operation with outdoor high temperatures ranging from 73°F to 93°F. Water inlet temperatures to the slab ranged from 0°F to 5°F above the outdoor wet bulb temperature during this period, and rose as high as 72°F on the hottest afternoon. The tower components ran steadily during this period, but circulating pump power ranged from 1.2 to 2.5 kW under variable speed control.

Table 3 presents key monitoring results, projected savings relative to a standard efficiency base case cooling system, and estimated installed economics.

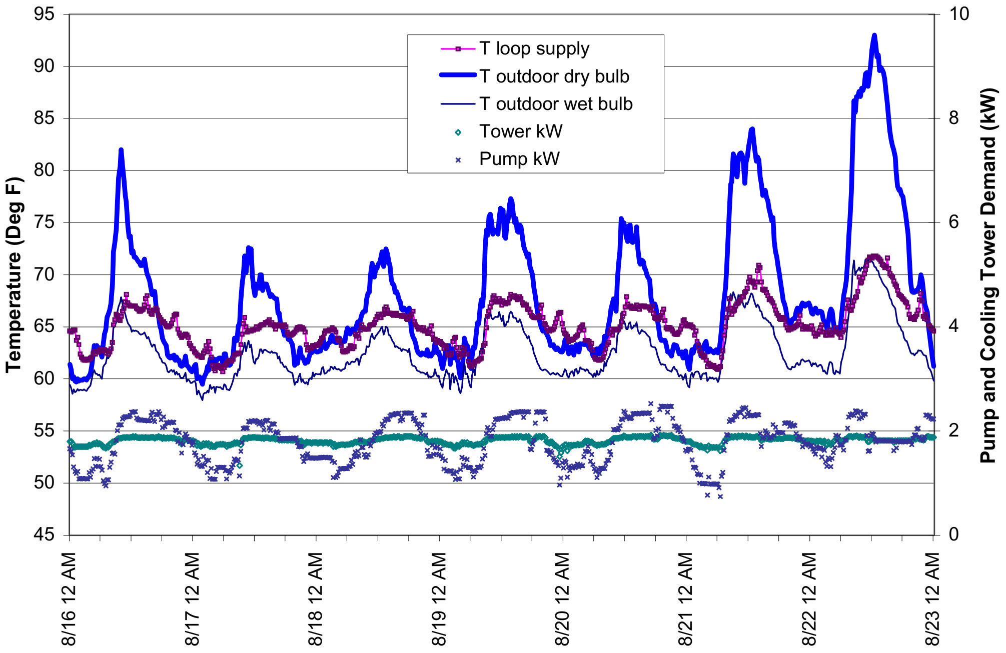

Fig. 2: TowerSlab System Operation (August 16-22, 1999)

Table 3: Summary of 580 Howard Monitoring Results

Monitoring Results	
Monitoring Period	7/1-9/30/99
# of days monitored	92
Cooling energy use (kWh)	7,640
“ kWh per 1000 ft^2	254.7
Peak cooling demand (kW)	4.8
“ kW per 1000 ft^2	0.16
Cooling delivered (ton-hrs)	13,913
Average Cooling EER	21.9
Projected Annual Savings	
Demand (kW)	25.2
% kW savings	84%
Energy (kWh)	17,920
% kWh savings	61%
Annual operating cost savings	$2,150
Overall Economics	
Installed cost	$140,000
Estimated base case cost	$500,000
Incremental cost	-$360,000

Annual operating cost savings were extrapolated to a full cooling season. A central system using ducted hydronic fan coils with boiler and chiller considered during the schematic design phase was used as the base case system. (The $500,000 cost estimate for this system prompted the developer to evaluate other HVAC alternatives.). The resulting radiant floor heating and cooling system cost approximately $140,000. Cost savings are largely attributable to elimination of the duct system, fan coils, and chiller.

The owner reports that comfort in the project is generally good, with the exception that south-facing units with high internal gains used as offices overheat on warm sunny days. Despite this limitation the owner has included TowerSlab systems on two more San Francisco apartment buildings since completion of 580 Howard Street.

All-Weather NightSky Project

Introduction

The project is a two-year old, 70,000 ft^2 building for All Weather Manufacturing Co. in Vacaville, CA. The 6,300 ft^2 office is heated and cooled by a night roof spray storage cooling ("NightSky") system that provides chilled water to in-slab tubing and to fan coils. Both the slab and fan coils deliver cooling from a thermal storage tank. Tank water is primarily cooled by the night roof spray process, but a chiller provides off-peak auxiliary tank cooling as necessary. Water sprayed on the roof at night is typically cooled to 50-60°F by evaporation and sky radiation. This cooled water is drained to the storage tank and filtered. Whenever the water is warmer than a time-dependant temperature target, the chiller operates to reach the target, and tank water circulates through the floor before entering the chiller. In midsummer months the slab is cooled throughout the night roof spray cycle. Passive cooling delivery from the slab cools the building in parallel with the "active" chilled water fan coils. During occupancy hours, a ventilation fan coil delivers tempered outdoor air into the return air plenums of the other five fan coils, reducing blower energy use.

Energy savings benefits offered by the NightSky system include increased efficiency due to night-roof spray cooling, efficient auxiliary cooling due to favorable temperatures, reduced blower heat output and energy use, and elimination of unnecessary latent cooling. These benefits and off-peak chiller operation also substantially reduce peak electrical demand. Sizing simulations showed that a 23 ton base case system could be replaced by the NightSky design with 10 ton off-peak auxiliary chiller. The floor is used for both summer cooling and winter heating, remaining idle for a month in each "swing season." The radiant floor delivers "base load" comfort, with thermostat settings maintained by the five fan coils.

Monitoring

The project was monitored with PG&E support for two midsummer weeks in 1998 and again for the last half of the 1999 summer (Davis Energy Group 1999b). Sensors used for system control were used by the monitoring system to the extent possible. New sensors added for monitoring included an indoor relative humidity sensor, an outdoor temperature and relative humidity assembly in a shaded, unsprayed location on the roof, and temperature sensors on copper piping to the roof spray array and from the roof drain returns to the storage tank. Monitored data and calculated parameters included night roof spray and chiller cooling delivered to storage, chiller peak demand, pump energy use, and fan coil energy use.

Results

System operation. The night roof-spray system cools water below outdoor wet bulb temperatures. The chiller does not operate during the noon-to-6 PM on-peak period, and operates fewer than 350 hours per year. The slab floor typically remains 2° to 4°F below air. temperature in monitored zones. Monitored indoor temperatures range from 70-76°F during occupancy hours. As the first "fully-integrated" NightSky installation, the project went through a "shakedown" period with a series of minor problems associated with hydronics and controls. These problems have been corrected and the owner is enthusiastic about the system.

Warm weather week. Figure 3 shows a selected 1998 week when outdoor highs averaged 98°F, with three days above 100°F. Chiller operation was required for four of the seven days and totaled 21 hours. In 1998, the chiller was programmed to begin operation at 5 AM if the roof spray was not achieving its temperature target. New programming in 1999 eliminated on-peak chiller operation by starting the chiller at 11 PM if the outdoor temperature is high. The 1998 data show the benefit of biasing chiller operation to night and morning hours. On July 27, when the chiller was manually activated in the afternoon, its 8 AM demand and efficiency were 9.7 kW and 12.6 EER, compared to 12.8 kW and 6.8 EER at 4 PM. Operation through 1999 confirmed that "heat storm" chiller programming automatically responds to hot weather, bringing the chiller on sooner to assure adequate thermal storage.

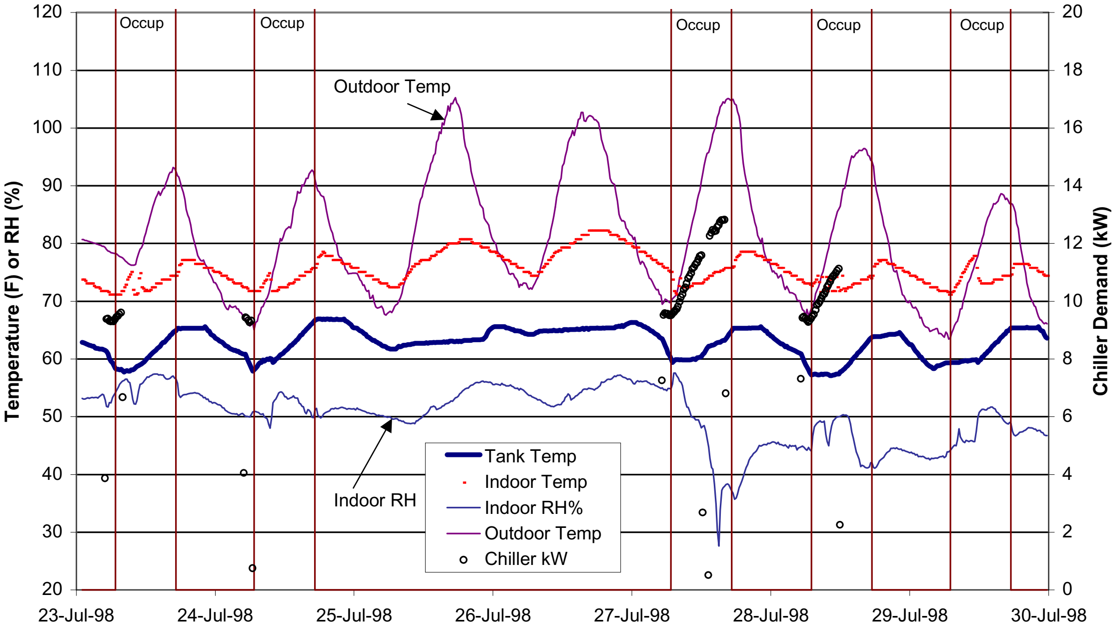

Fig. 3: Typical Week Operating Data

Table 4 compares cooling delivery and efficiency for the chiller and the night roof spray system for the week shown, when the night roof spray system delivered two-thirds of the cooling. For many milder summer weeks, the roof spray delivers all required cooling

Table 4: Comparative Cooling Performance (July 23-29, 1998)

Cooling System	MBtu's	Cooling %	kWh	EER
Chiller	2.7	33%	252	10.7
NightSky	5.4	67%	92	58.7

Parasitic energy. Run time data from the control system logs show that the five zone blowers operate an average of 5.5 hours for the five summer months and 3.9 hours per day for the remaining seven months. Monitoring data show 3.5 kW blower demand with all six units operating. The five base case RTU blowers would have consumed 5.97 kW, 11 hours per occupancy day. Thus the system reduces annual blower energy use by 75%. Pump energy lowers the net parasitic savings to 66%. Storage heat gains partially cancel savings from reduced duct gains. The 8,000 gallon cylindrical tank's estimated 5.8 million Btu annual heat gain was modeled as 3% duct gains.

Annual savings. Full year savings simulations were based on monitoring data for the completed project. Base case duct inefficiencies were estimated at 15% to reflect long duct runs through unconditioned space. Actual duct losses were estimated to be 2%, since ducts are located almost entirely in conditioned space, plus 3% losses for the storage tank and piping. Latent cooling was estimated to be 15% for the base case and zero for the actual system, which has no condensate drains and has never shown condensate in the pans. Table 5 shows electrical savings for a typical year. Cooling kWh includes spray and chiller pumps. Data verify 87% summer peak demand reduction compared to the base case.

Heating energy. The system also saves heating energy by eliminating duct and RTU cabinet losses, reducing thermal stratification, and reducing burner cycling. Countering the duct savings are piping losses and added losses from the heated slab. Based on data from a hydronic radiant floor handbook (Davis Energy Group 1999c), incremental losses were estimated to be equivalent to 3% duct losses. Piping losses were computed to be equivalent to 2% duct losses. Simulation results for the base case show 88 million Btu annual heating energy use. Reducing losses, stratification, and cycling lowers the installed system gas consumption to 55 million Btu's, but requires 190 kWh of pump operation (charged as delivery kWh in Table 5). Table 6 summarizes the system's annual cost impacts.

Table 5: Annual Electrical Savings

		Base Case	NightSky	Savings	% Savings
Annual Energy	Cooling kWh	19,587	5,250	14,337	73%
	Delivery kWh	17,074	5,733	11,341	66%
	Total kWh	36,661	10,983	25,678	70%
Peak Demand	kW @104°F	33.7	4.4	29.3	87%

Table 6: Annual Cost Impacts

Cost Category	Base Case	NightSky	Savings
Electricity			
Energy	$2,593	$656	$1,937
Demand	$1,965	$676	$1,289
Total	$4,558	$1,332	$3,226
Natural Gas	$504	$315	$189
Water	-	$20	-$20
Totals	$5,062	$1,667	$3,395
% Annual Cost Savings			67%

The NightSky system had lower duct, electrical, and gas piping costs compared to the base case, but was penalized by an unusually high chiller cost of $1100 per ton for the small 10 ton unit. For larger projects, NightSky systems can benefit from economies of scale for the chiller, storage tank, and floor tubing. Two-year paybacks are likely for projects of 30,000 ft^2 and larger. Table 7 documents projected paybacks for the All Weather project.

Table 7: Payback Analysis

Cost Category	Base Case	NightSky
Installed Costs		
HVAC Capacity	$23,000	$22,000
NightSky Components		$20,300
EMCS	$2,500	incl
Ductwork	$10,400	$6,400
Electrical & Gas Lines	$7,500	$3,200
Totals	$43,400	$51,900
NightSky Incremental Cost		$8,500
Annual Savings		$3,390
Direct Payback, years		2.5

Key Issues. With its 50/50 tile/carpet combination and circulation of tank water (sometimes chiller-cooled) through the floor, All-Weather is most vulnerable of the three projects to floor condensation. However, none has occurred through two full summers, and in fact no latent cooling has occurred in the cooling coils where condensation is even more likely. Delivery of chiller-based cooling through the floor has clearly contributed to chiller, blower, and duct down-sizing at the All-Weather project.

Natural Cooling with Slabs: Three Projects Compared

All three projects described in this paper have been completed in the last two years, and all have so far met or exceeded their overall performance expectations. The value of comparing them is limited by their variance in building type and occupancy. This section discusses both the systems and the projects to compare their simplicity, applicability, performance, economics, and maintainability.

Simplicity

The "TowerSlab" system applied at 580 Howard Street wins the simplicity contest among the three "natural slab cooling" concepts presented in this paper. This system has only two major components for space cooling- the cooling tower and the slab tubing. The other two are hybrid systems that marry natural cooling with both refrigerant-based cooling and forced air delivery systems. The PreCool Plus system, which does not include water storage, is less complex than the fully-integrated NightSky system. Installation of PreCool Plus involves addition of floor tubing and auxiliary components to a standardized down-sized RTU, while NightSky is a "built-up" system that by comparison involves more on-site work to install.

Applicability

Wide applicability of all three systems is generally limited to new construction, despite 580 Howard St. This project represents a narrow market niche- a multi-story retrofit residential building in a climate with modest cooling loads and the opportunity to add a concrete topping to existing floors. Without forced air to satisfy ventilation loads, the TowerSlab system will generally be limited to residential applications or projects where it can be integrated or placed in parallel with a down-sized forced air system. The PreCool Plus system is applicable to all new construction packaged HVAC unit installations over concrete slabs. The NightSky system is most appropriate for large low-rise buildings with low-slope roof areas. All three systems may be applied in freezing climates, with appropriate controls to drain exposed water components.

Performance

Performance criteria include comfort, efficiency, and demand reduction. The TowerSlab system rates highly on efficiency and demand reduction criteria but has comfort limitations in hot and humid weather, unless it is coupled with a compressor-based cooling system. The NightSky integrated system delivers the highest efficiency and demand reduction, and also offers excellent comfort control. It can be equipped with condensate drains and, with slight reduction in efficiency, operated with lower water temperatures to deliver latent cooling if needed. The PreCool Plus system shows significant efficiency gains and peak reduction while delivering excellent comfort. All three systems reduce cooling loads by lowering the mean radiant temperature, thereby allowing equal comfort at higher indoor temperatures, and by eliminating or minimizing blower heat output and unnecessary latent cooling.

Economics

All three natural slab cooling systems show excellent economics in applications where they result in elimination or substantial down-sizing of conventional compressor-based cooling and forced air delivery systems. Radiant floor heating systems are currently being applied mostly in "high end" custom applications and have a reputation of providing great comfort at great initial expense. Radiant cooling skeptics therefore often question economics of these systems. However, polymer tubing materials costing less than $0.30 per foot and placed on 12" centers may be quickly installed in most slabs, and increasing popularity of in-slab heating is rapidly reducing installed costs. Economies of scale offer opportunities for large floor areas delivering partial cooling and supplemented by down-sized forced air systems.

Maintainability

Maintenance and reliability are legitimate concerns for systems that incorporate open loop water circuits, as all evaporative cooling systems do. Open loop systems may experience water fouling and air entrainment that can degrade efficiency and damage system components.[1] The 580 Howard St. project minimizes water maintenance issues by using a closed cooling tower. As a result, it should require maintenance efforts similar to those for any cooling tower loop. The PreCool Plus system at the Davis Texaco site uses the rooftop sump to maintain hydraulic pressure on the system. In its first two years this system has a near-perfect reliability record. The NightSky system at All-Weather uses pool pumps to draw water from a buried storage tank, and has experienced several maintenance events when air entered the system. These problems would have been avoided with pumps placed below the storage water level. Providing automatic or pre-paid water maintenance would enhance the marketability of these natural cooling systems.

Conclusions

Experience with these three projects suggests the following conclusions:

1) Natural cooling systems that use slab floors for thermal storage and cooling delivery can reduce electrical energy use and peak demand by 45 to 75% in appropriate climates.
2) Natural slab cooling strategies are available to integrate with most building types and with most conventional HVAC systems in new buildings with "hard floors."
3) Cooling delivery from the floor may allow down-sizing of blowers and ducts, reduces cooling loads from blower motors, and reduce or eliminate unnecessary latent cooling.
4) The economics of natural slab cooling benefit significantly from their reduction or elimination of compressor-based cooling and forced air delivery systems.
5) Where peak wet bulb temperatures exceed 70°F, compressor-based floor cooling is needed if conventional cooling and duct components are down-sized.

References

Davis Energy Group. 1998. *Night Underfloor Evaporative (NUE) Cooling Demonstration Project Report.* Completed for the Pacific Gas and Electric Company.

Davis Energy Group. 1999a. *Home Cooling Program Night Floor Cooling Monitoring Report.* Completed for the Pacific Gas and Electric Company.

Davis Energy Group. 1999b. *All Weather Night Sky Project Final Report.* Completed for the Pacific Gas and Electric Company.

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[1] Since none of these systems allows contact between open loop water and indoor air, poor water quality will affect system performance but is unlikely to affect occupant health

Davis Energy Group. 1999c. *HRH Hydronic Radiant Heating Handbook.*

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