A Water-Ballasted Lifetime Energy Saving Roof System: Demonstration Project

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Conventional flat and low slope roofs have significant failure rates and contribute to building cooling loads. The WBPMR system, developed under the California Energy Commission's Energy Technologies Advancement Program (ETAP) provides complete membrane protection from the outdoor environment and reduces cooling energy consumption by more than 50% for typical dry climate applications. The system, which requires level roof construction, may be used in either new or retrofit applications. System components include a single-ply roofing membrane; 3.5" water ballast; coated, interlocking extruded polystyrene panels floating on the ballast water; distribution piping within the ballast water connected to spray heads flush-mounted in the floating panels; a pump/filter system & controls; and (optional) components for delivering cooling to occupied space. Water is sprayed above the panels at night and cooled by evaporation and radiation to the cool night sky.

The cooled water reverses normal roof heat gains and contributes a substantial building cooling function. In dry climates, the system may cool directly through the roof deck. In more humid climates, an insulating layer between membrane and roof deck (to prevent condensation on the roof underside) allows system use as a chilled water storage reservoir under peak cooling conditions and as a "free cooling" system under mild conditions.

System details, a calibrated hourly energy performance simulation, marketing studies, economic studies, and a fully monitored 6500 ft^2 demonstration installation have been completed in the ETAP project. The demonstration project, located in downtown Sacramento, has shown effective performance of all system details, and has verified the system's substantial cooling capability. After the night spray cycle, the 14,000 gallon water volume is typically 5 to 10 °F below the minimum night temperature. The formerly uncooled building has considerably lower indoor temperatures with the WBPMR in comparable summer weather.

Economic studies for a range of building types and California climates generally indicate system paybacks of three years or less in preferred applications. When extended roof life, electric demand savings, and fire protection value are considered, projected paybacks are immediate for some building types.

Introduction

Background

This paper describes the design, monitoring, performance, and economic evaluation of a water-ballasted, protected membrane roof (WBPMR) for commercial buildings with filtration and night spray cooling of the ballast water.

As shown in Figure 1, conventional flat and low slope roofs are subject to significant environmental degradation and therefore have relatively high failure rates (Cullen 1988). Conventional roofs also generate significant building cooling loads during summer daytime hours. The WBPMR system provides complete membrane protection from the outdoor environment. WBPMR water cannot freeze because it is in thermal contact with indoor space in winter. Unlike "dry ballast" protected membrane roof systems which can experience erosional damage in storms because excess water overflows through clogproof drains rather than running across the membrane surface. Rain water partially compensates for evaporative losses.

WBPMR system components include a single-ply roofing membrane; 3.5" water ballast; coated interlocking extruded polystyrene panels floating on the ballast water; distribution piping within the ballast water, connected to spray heads flush-mounted in the floating panels; a pump/filter system and controls; overflow drains below

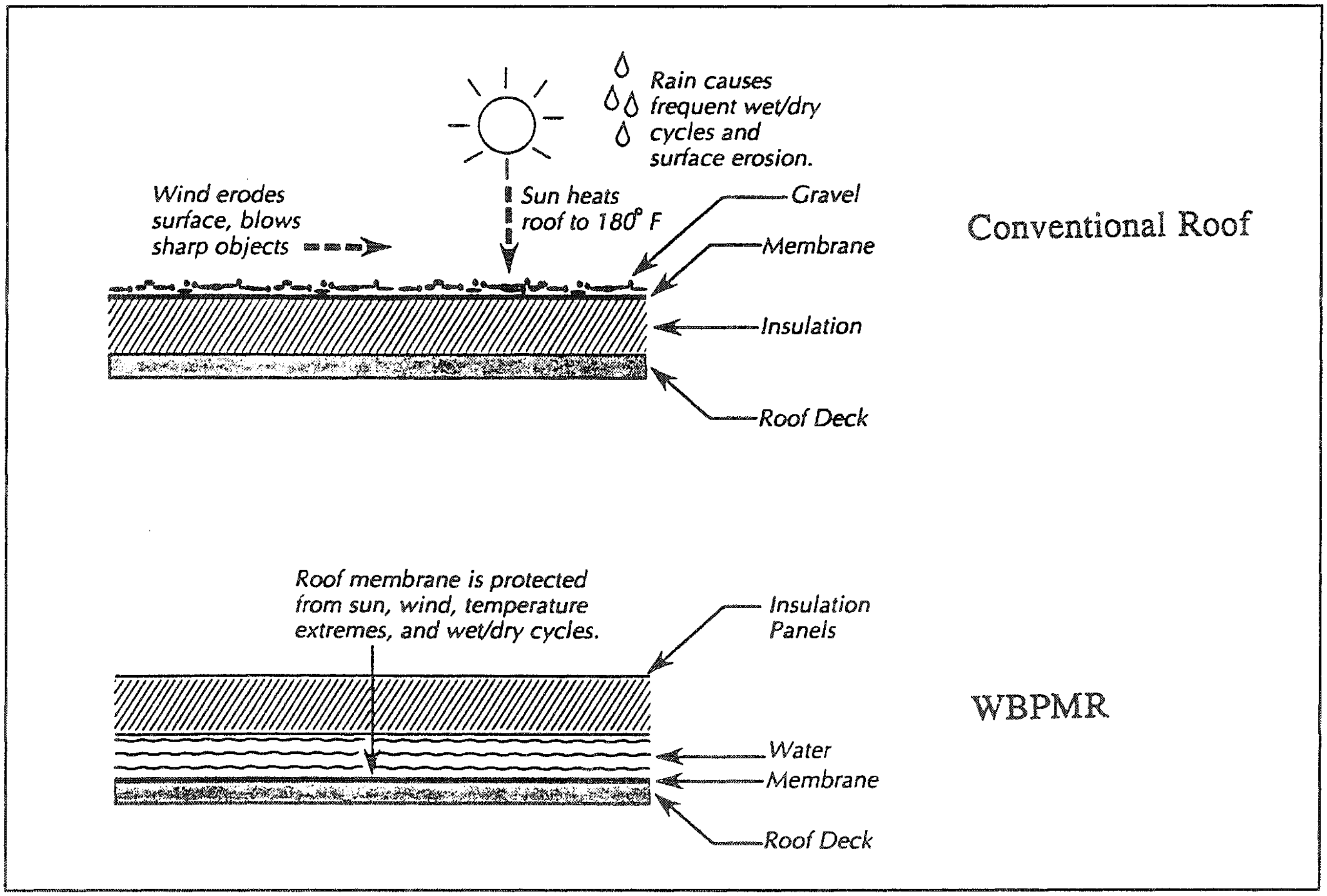

Figure 1. Exposure Comparison

the panels; an automatic refill system; and (optional) components for delivering cooling to the occupied space. Water is sprayed above the panels at night and passively cooled by evaporation and radiation to the cool night sky. During the daytime, the cooled water reverses normal roof heat gains and contributes a substantial building cooling function. Figure 2 shows typical day and night WBPMR conditions. In dry climates, the system may cool directly through the roof deck or via a pumped fan coil loop. In more humid climates an insulating layer between membrane and roof deck (to prevent condensation on the roof underside) and a pumped chilled water fan coil allow auxiliary cooling of the water ballast, to shift compressor operation off-peak, in mid-summer conditions. In addition to durability and energy cost benefits, the WBPMR offers fire protection and environmental advantages. Like other "natural" cooling systems, the WBPMR mitigates both ozone-depletion and global warming problems by reducing use of HCFC's and fossil-fueled generating plants.

The ETAP project (DEG 1992) was designed to complete WBPMR system development, construct a full-scale demonstration project, obtain detailed thermal performance monitoring data, develop a calibrated model, and generate simulation based performance and economic projections for a range of climates and non-residential building types in California.

Objectives

Specific project objectives were:

(1) To determine WBPMR night heat rejection characteristics on a full-scale demonstration project

(2) To determine demonstration system thermal performance and efficiency

(3) To develop a calibrated heat rejection algorithm for incorporation into an hourly simulation model

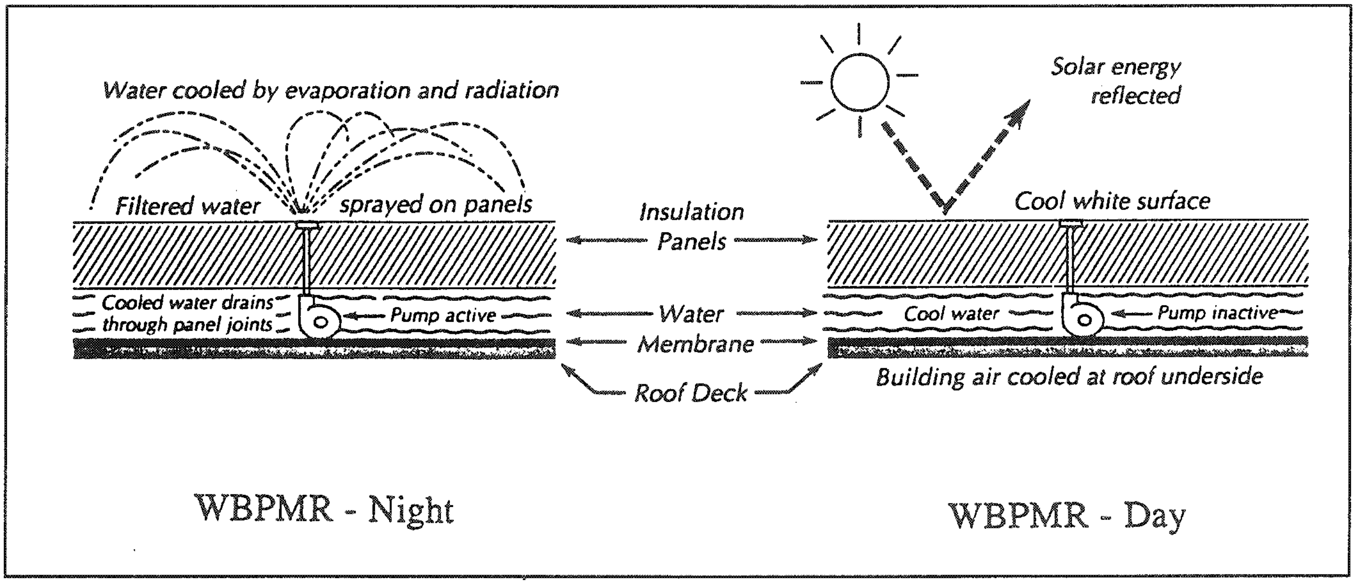

Figure 2. WBPMR Night & Day

(4) To present preliminary data on WBPMR water quality & use, and operation & maintenance requirements

(5) To generate WBPMR economic value estimates based on simulation performance projections

This paper describes the WBPMR demonstration project and monitoring results; presents the calibrated heat rejection algorithm; and provides sample performance and economic projections for a retail store application in Sacramento. A second paper provides detailed performance and economic projections (Bourne and Rainer, 1992).

Project Description

Demonstration project installation was originally intended for a new commercial building in Winters, California. Cancellation of the Winters project led to selection of an alternate site, an existing one story shipping and warehouse building at the Office of State Printing (OSP) in Sacramento. The WBPMR was installed at no expense to OSP, in exchange for monitoring access.

Building Description. The 144' by 280' "Book Storage Warehouse" (BSW) extends north/south with shipping docks on both ends. Completed in 1956, the BSW has a prestressed concrete roof structure designed, at the time, to support a future second floor. (The 3.5" WBPMR water layer imposes 18.2 #/ft² live load vs. a typical 20 #/ft² assumption. No additional live load can be imposed because weight on the floating panels displaces water rather than increasing the imposed load. The ETAP project report includes structural engineering analyses.) The 3" concrete deck is surfaced with 2" fiberboard insulation and a built-up roof. Ceiling height is 18' at the roof deck underside. The 10" thick concrete walls are uninsulated. Large overhead rolling doors provide shipping access at two locations on the south side and one each on the north and east sides.

The BSW interior houses approximately 20 shipping department employees in its two southern structural bays, each 35' wide. The remainder of the building is used to store raw and printed paper products. Space heating is provided by gas-fired unit heaters located near the ceiling. The only mechanical cooling system on the building is a 2 ton rooftop unit installed to cool a 500 ft² manager's office in the southeast corner. Ten large turbine-ventilators cover 42" square roof openings; three are located over the occupied south end. The BSW is occupied from 7 AM through 4 PM on weekdays only.

WBPMR Installation. Project budget constraints limited WBPMR area to 6500 ft² for the demonstration project, prompting a decision to place the system over only the occupied south end of the BSW (but occupied space was not physically separated from warehouse space). The WBPMR was placed atop the existing roof, with primary cooling delivery via fan coil loop to occupied space below.

On-roof WBPMR demonstration project components include a perimeter "curb" system; an EPDM rubber single-ply roofing membrane placed over a gypsum board separator; distribution piping placed on the roof membrane; 3" thick, 4' x 8' interlocking polystyrene panels with integral spray heads on 12' centers, connected to distribution piping below; a hardware module including pump, filter, and automatic valves; and controls to regulate pump and valve operation. New electrical wiring and a large custom fan coil were installed below the roof. The 60' by 108' WBPMR contains approximately 14,300 gallons when filled to its specified 3.5" water depth. After a shakedown period for both WBPMR and monitoring systems, detailed monitoring began on September 6, 1991.

Methodology

Monitoring

Temperatures (outdoor, indoor, water ballast, roof underside, insulation surface), flow rates (both in spray and fan coil delivery modes), and fan coil and pump energy consumption were monitored at 15 minute intervals. Wet bulb temperatures were obtained from the Executive Airport weather station, a Federal Aviation Administration site located in southwest Sacramento approximately five miles from the project. The onsite datalogger was connected via modem to a host computer in the DEG office for immediate raw data review. DEG personnel visited the site at least twice per week through the cooling monitoring period. Water quality was tested on four occasions during the monitoring period. A water meter on the float-sensor controlled automatic refill line provided water use data during the monitoring period.

Operating Modes

Spray Cycle. A ten hour night spray cycle, from 9 PM to 7 AM, was used throughout the September 6 to October 23 test period. A more sophisticated control strategy will be developed and implemented based on parametric runs with the calibrated simulation program. In the spray cycle, a 1.5 horsepower high efficiency pump circulates WBPMR water through a sand filter and onto the panels through 45 spray heads at a total flow rate of about 60 gpm.

Cooling Delivery Cycle. Two fan coil scheduling strategies were used during the monitoring period. Through September 25, the fan coil was allowed to run in a "no lockout" mode to achieve the thermostat setting 24 hours a day, maximizing fan coil operation, cooling delivery, and diurnal water temperature range. During this period, the longer cooling delivery cycles caused relatively higher water temperatures, cooling rates, and parasitic energy use. Beginning September 26, the programmable datalogger clock was used to "lock out" the fan coil during non-occupancy. This operating strategy significantly reduced fan coil operation and average water temperatures.

Thermal Performance

Comfort Impact. Comfort impact was measured by "before and after" monitoring of indoor temperature, and by informal interviews with building occupants. Pre-WBPMR data were recorded from July 19 through August 12. Indoor sensors were placed in two vertical arrays of three, each relatively centrally located in the occupied south end and the north (storage) end, respectively. Each array included one at 5' height, one at 13' height, and one secured to the underside of the 3" thick concrete roof deck.

Spray Cycle Cooling Rate. Determination of night cooling rate under varying outdoor conditions was the key thermal performance monitoring objective. Instrumentation was installed to derive cooling rate data by measuring the water flow rate and average temperature drop between the pump suction and the water returning from the panel surface into the water storage layer. Calibrated thermocouple probes were placed in the pump suction line and in 1/4" diameter panel center holes through which water drains during the spray cycle. Eight such "drain probes" distributed throughout the WBPMR array were connected in a parallel thermocouple grid to provide an average temperature reading for water returning to the storage layer. Probes were observed during spray operation and appeared to be well-wetted. Average storage water temperatures were recorded using a similar grid. Individual thermocouples were also placed at each grid point in the water layer.

Algorithm Calibration. Considerable cooling rate data were gathered during the 45 day operating period. Only data from October 16 to October 20 were used for model calibration, for three reasons:

(1) Overspray caused by wind and/or irregular spray patterns from the original perimeter heads caused visible ponding around the WBPMR area. The 24 perimeter heads were replaced on October 8 with inward-directed heads to reduce overspray. This change had little impact on cooling rate despite reducing the effective "spray area" from 6500 to 4600 ft^2.

(2) During head replacement, PVC cuttings left from piping assembly were found to be partially clogging virtually all the original perimeter heads; the cuttings may have affected prior spray cooling rates. Cleaning of the 21 interior spray heads on October 16 showed additional blockage.

(3) Weather data for the period were representative of typical summer conditions.

A three term cooling rate algorithm (one term each for convection, evaporation, and radiation) developed in 1990 from WBPMR prototype test results was recalibrated by minimizing Chi-square "total cooling" differences for the five day calibration period. Constants for the three terms were modified to achieve a best fit. The algorithm was then incorporated into the WBPMR hourly building simulation program.

Cooling Delivery. Cooling delivery from the system is accomplished by pumping chilled water to a fan coil in occupied space. The WBPMR also reverses the typical downward summer heat flow direction through the roof. Roof system heat flows were much smaller (due to roof deck insulation) than pumped loop heat flows, and were evaluated by calculation from temperatures and known heat transmission parameters. Fan coil cooling delivery rate was determined by subtracting estimated hourly (up and down) water-to-air roof transfers from total cooling based on measured water flow rate and ballast water temperature drop, in a statistical analysis over all fan coil operating hours.

Efficiency. For the previously uncooled BSW, system cooling efficiency was defined as the ratio of total cooling delivered to total energy input. Expressed as "EER's", WBPMR efficiencies were computed from "spray mode only," "overall direct contact", and "overall with fan coil delivery" perspectives. Overall perspectives include ceiling heat flow effects and cooling delivery parasitic energy.

Annual Performance and Economic Projections. An hourly building energy simulation program was modified to incorporate control logic and the spray cooling performance algorithm to model WBPMR performance. Detailed performance and economic evaluations performed under the ETAP contract are presented in a companion paper (Bourne and Rainer, 1992). Sacramento cases are presented here for a 50,000 ft^2 warehouse without auxiliary cooling and a 50,000 ft^2 one-story retail building. R19 roof insulation was assumed for both base case systems. Utility cost and key building input assumptions are provided in Tables 1 and 2, respectively.

Table 1. Sacramento Utility Rates

Summary (May-Oct)	
$/kWh	$.05835
$/kW	$ 8.60
$/therm	$.5007
Winter (Nov-April)	
$/kWh	$.05786
$/kW	$ 7.10
R therm	$.6760

Table 2. Simulation Input Assumptions

Input Assumption	Warehouse	Retail
Weekday Occupancy	7AM-6PM	8AM-10PM
Saturday Occupancy	None	8AM-10PM
Sunday Occupancy	None	10AM-6PM
Density (ft^2/occupant)	1000	167
Cooling Setpoint	None	75°F
Cooling Setback	None	85°F
Heating Setpoint	55°F	70°F
Heating Setback	55°F	65°F
Delivery System	Direct	Fan coil

Table 3 shows incremental cost assumptions (including 20% overhead and profit) used in the economic analyses. Total projected WBPMR incremental cost for the retail building with fan coil delivery is $2.55/ft^2, before credits for reduced conventional cooling capacity. The WBPMR system is assumed to last 30 years, while the conventional roof is assumed to be replaced after 15 years. Simple paybacks were computed with and without a roof

Table 3. Incremental Cost Assumptions	
Roof membrane + insulation	$\$1.44/ft^2$
System controls + hardware	$\$.40/ft^2$
Fan coil components	$\$.53/ft^2$
Added structural costs	$\$.18/ft^2$
Capacity savings	($1000/ton)
Conventional roof replacement	($\$2.00/ft^2$)

replacement credit. The WBPMR reduces conventional maintenance costs by eliminating drain clogging and reducing conventional cooling system size and annual operating hours (thereby extending cooling system life). WBPMR system maintenance costs for pump service and panel recoating were estimated to be slightly less than the conventional roof and cooling system maintenance savings.

Results

Weather

1991 Sacramento weather cooperated with the demonstration project! Temperatures were near normal during the July 19-August 12 pre-WBPMR monitoring period, cooler than normal during the August 15-30 installation period, and much warmer than normal during the September 1-October 23 cooling monitoring period (October was the hottest on record in Sacramento). The model calibration period (October 16-20) had night temperatures slightly cooler than 30 year July and August averages but warmer than September and October averages. Since considerable WBPMR cooling contribution will typically occur in late spring and early fall, the selected calibration period appears representative of full cooling season weather.

Indoor Comfort Impact

Monitoring prior to WBPMR installation (July 19 to August 12) identified typical building operating patterns and temperature profiles, as shown in Figure 3. For typical mid-summer weather conditions with outdoor highs ranging from 90-104°F and lows from 59-71°F, the ceiling underside temperature ranged from 88-103°F. Indoor air cooled from highs of 86-91°F at the end of occupancy to morning temperatures of 82-86°F, immediately prior to occupancy. Indoor temperatures dropped to 69-78°F when the doors were opened, then rose and exceeded 80°F by late morning. By mid-afternoon the occupied indoor environment was clearly uncomfortable under typical summer weather conditions.

Figure 4 shows outdoor, indoor, & WBPMR water temperatures, and fan coil duty cycles for the September 22-25 period, without fan coil lockout. Daytime highs were 98-100°F and night lows were 64-70°F. Water temperature ranged from 57-70°F, with approximately 10°F typical daily range. With a 75°F indoor thermostat setting, the fan coil operated 16 to 21 hours per day, and maintained indoor temperatures below 78°F except for a brief period on September 25, when several midday door openings caused a brief temperature spike to 80°F. Ceiling underside temperatures were typically in the mid 70's with only a 2-3°F daily variation. Reducing the ceiling underside temperature by approximately 20°F significantly improved comfort.

Figure 5 shows subsequent operation with similar outdoor temperatures but with fan coil operation allowed only during occupancy hours. The fan coil typically operated from 10 AM until 4 PM, and maintained indoor temperatures below 80°F. Indoor temperatures rose to 81°F-83°F after occupancy. The "flat top" water temperature profiles indicate that (unlike the "no lockout" control) active cooling delivery terminated before the spray cycle began.

Spray Cycle Cooling Rate

Figures 4 and 5 show relatively linear spray cycle water temperature drops, although average hourly cooling rates varied with water and air temperatures. End of cycle water temperatures were 5-9°F below the minimum outdoor dry bulb temperature for the night. Later, when cooling delivery rates were lower, water temperatures sometimes dropped 12°F below the outdoor air low. Both of these performance characteristics suggest significant radiative heat transfer. Under convective and evaporative modes alone, the cooling rate would have decreased noticeably as the water temperature approached the wet bulb temperature. The linear water temperature drop suggests that radiative transfer to the night environment increases as evaporative cooling decreases through the night cycle.

Average hourly cooling rate vs. time is shown in Figure 6 for four individual weeks and the four week average. Fan coil operation was allowed continuously in the first two weeks shown, and only during occupant hours in the

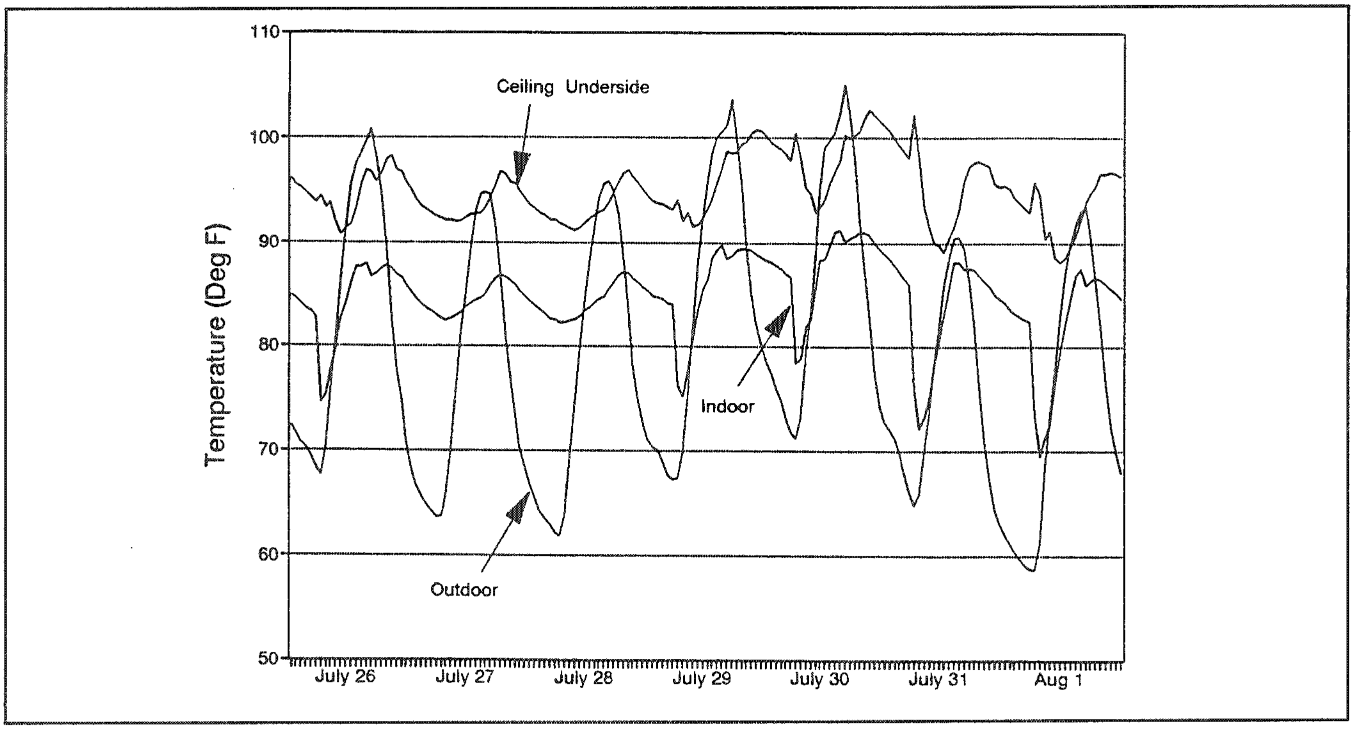

Figure 3. Pre-WBPMR Temperature Profiles

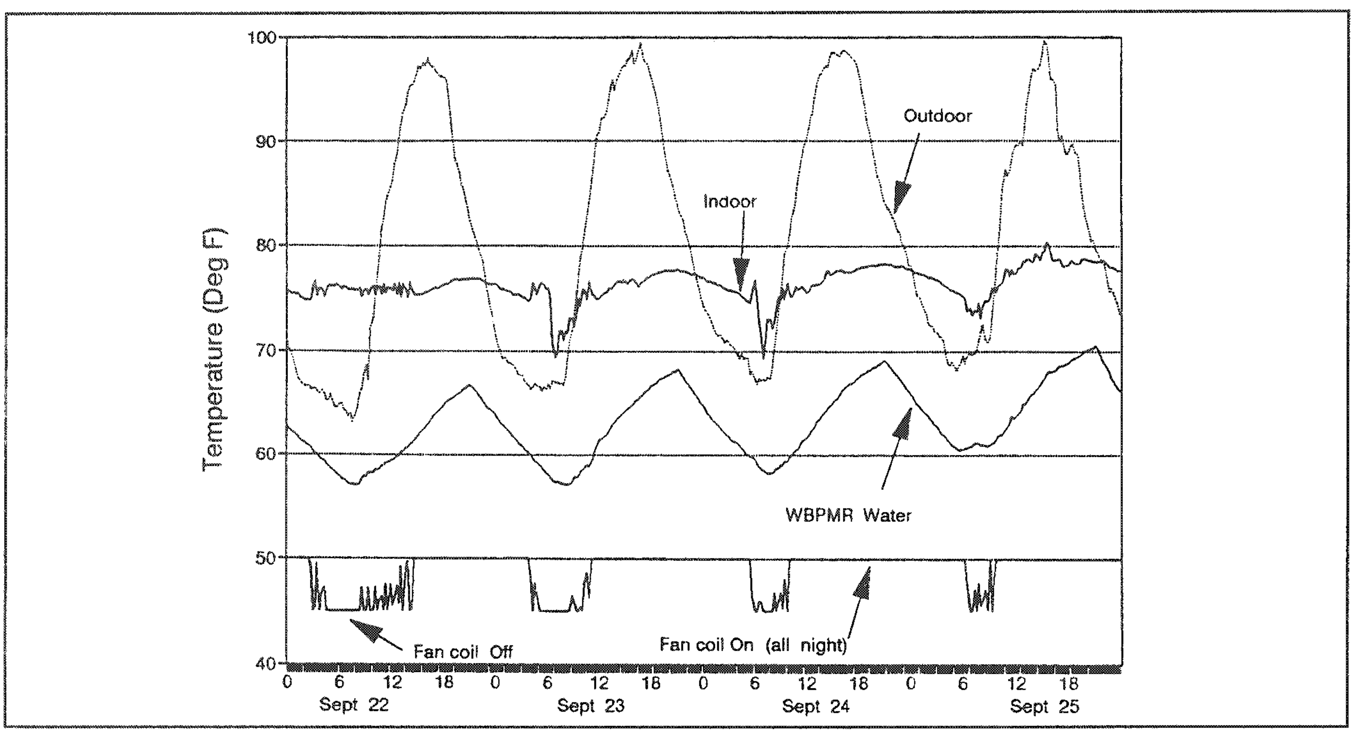

Figure 4. Typical "No Lockout" Profiles

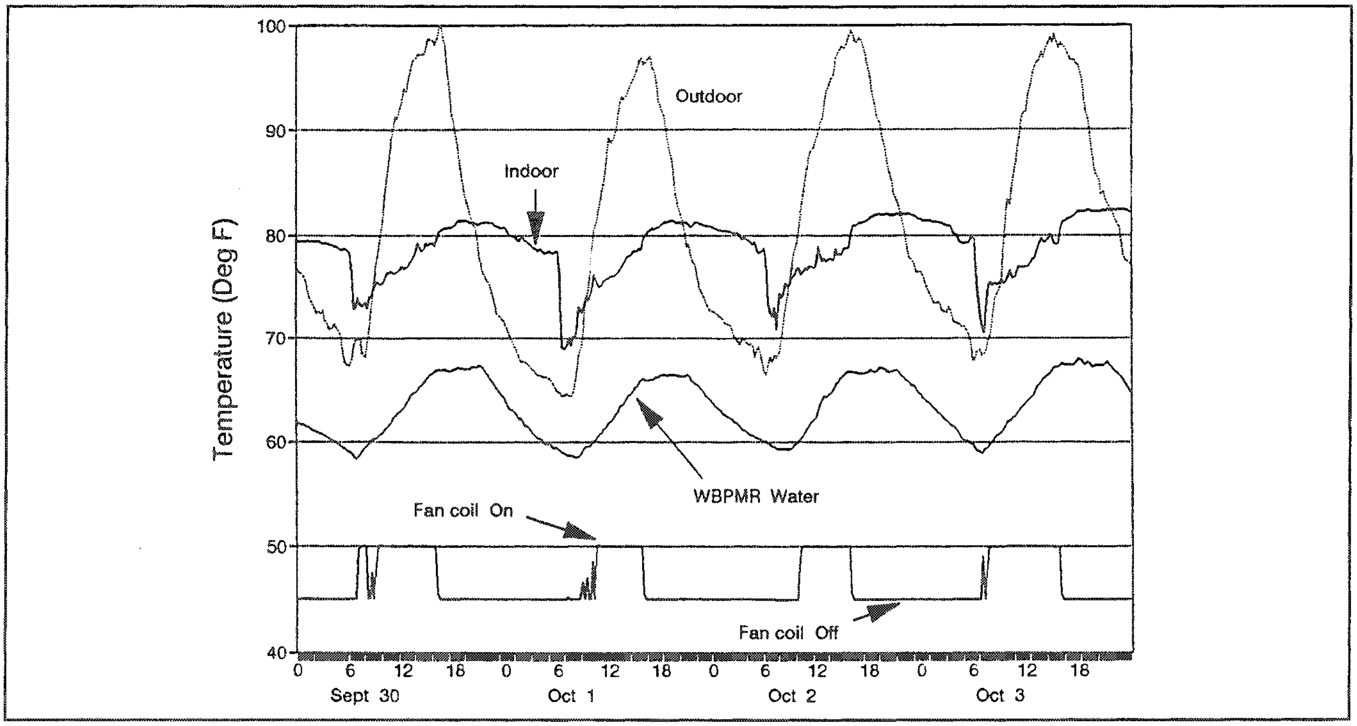

Figure 5. Typical "Lockout" Profiles

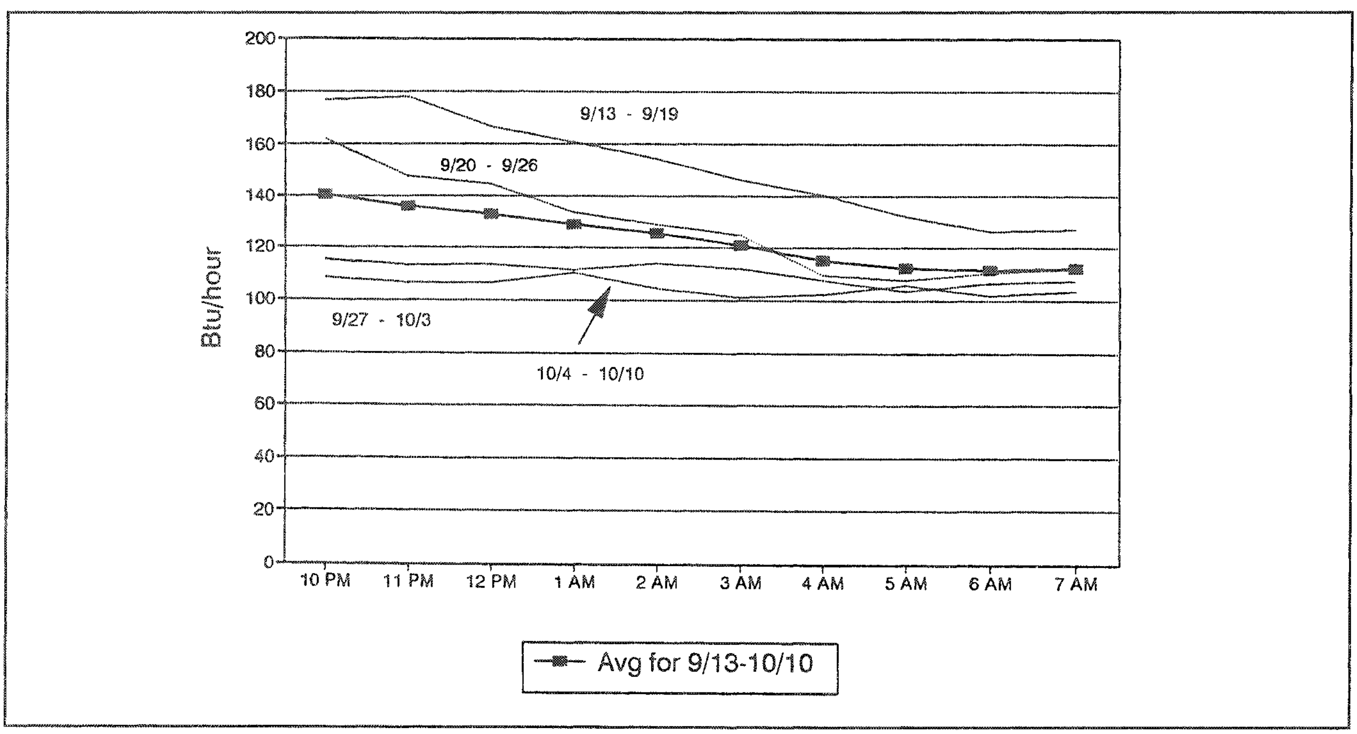

Figure 6. Average Spray Cooling Rate

second two weeks. As a result, water temperatures were higher in the first two weeks, increasing spray cooling rates. Performance was better the first week than the second due to lower night temperatures. In the last two weeks shown, water temperatures were lower and night air temperatures remained relatively high. In these conditions, the average hourly cooling rates were quite uniform at approximately 24 Btu/hr-ft^2. These results again suggest that radiative transfers become dominant with cooler water, either when it starts cooler or becomes cooler through the cycle.

The four week average line smooths wrinkles but retains a curious feature of each weekly plot: the cooling rate shows a slight increase for the last hour of operation. Weather data explain the phenomenon; the average wet bulb depression increased between 6 and 7 AM. Since cooling rates were significant at both 10 PM and 7 AM, the results suggest that a longer spray cycle could be used under some high load conditions.

Total WBPMR Thermal Impact

Total WBPMR cooling contribution (cooling delivered via fan coil plus net WBPMR roof heat flow impact) through the seven week cooling monitoring period was approximately 54 million Btu's. Benefits were reduced during cooler weather near the end of October, when reduced fan coil operation caused lower water temperatures and reduced heat rejection. Also, conventional roof temperatures were cooler, reducing the WBPMR's value in reversing roof heat gains.

Model Calibration

Model calibration was performed for the October 16-20 period to achieve a best fit between predicted and measured spray cycle heat rejection. The final calibrated algorithm is provided as Equation (1). The convective term is a function of the temperature difference between WBPMR water and outdoor dry bulb (T_W and T_{db}), the evaporative term is a function of the wet bulb depression (T_{db} - T_{wb}), and the radiative term is a fourth order function of T_W and T_{sky}.

$$Q/(ft^2\text{-}hr) = 1.16*(T_W-T_{db}) + 1.68*(T_{db}-T_{wb}) \quad (1)$$

$$+ 0.125*(\Omega_a-\Omega_b)$$

where $\Omega_a = 0.01*(T_W+460)^4$

and $\Omega_b = 0.01*(T_{sky}+460)^4$

Table 4 lists outdoor weather conditions and predicted and measured ten hour heat rejection values for the calibration spray cycles.

Table 4. Calibration Comparison

Spray Cycle	Ave T_{db}	Ave T_{wb}	Qu	Qa	(Qa-Qu)/Qu
October 16-17	69.0	58.1	1042	1086	+4.2%
October 17-18	65.0	58.3	837	892	+6.6%
October 18-19	69.5	59.4	965	793	-17.8%
October 19-20	68.0	54.3	1129	1243	+10.1%
October 20-21	67.5	53.3	1162	1168	+0.5%

Qu = measured cooling, kBtu/cycle.
Qa = cooling predicted by best fit algorithm, kBtu/cycle.

System Efficiency

Efficiencies were computed for the spray cooling cycle alone, and for overall WBPMR impact including reversal of conventional roof downward summer heat flow. Figure 7 shows average "full cycle" night spray efficiency vs. average "water-to-outdoor" temperature difference during the spray cycle. Full cycle EER's ranged from 50 to 100, increasing with warmer water and cooler air.

Average daily monitored system EER's (including ceiling heat flow impacts) were unrealistically lowered by use of the spray pump to deliver WBPMR water to the fan coil in series with the filter, and by the full ten hour spray operation even in mild weather. For more accurate prediction of overall EER's, fan coil parasitic energy was reduced to reflect use of a high efficiency, low-head pump bypassing the filter.

A direct contact WBPMR configuration, without insulation between water and conditioned space below, would reduce parasitic energy consumption. Smart spray cycle control might be required for the direct contact WBPMR to prevent overcooling in moderate weather.

Figure 8 shows projected overall daily EER vs. average WBPMR water temperature as adjusted to represent both the efficient pump and direct contact configurations. Projected direct contact EER's are more favorable due to reduced parasitic energy and increased cooling delivery. Reduced control of cooling delivery with the direct contact

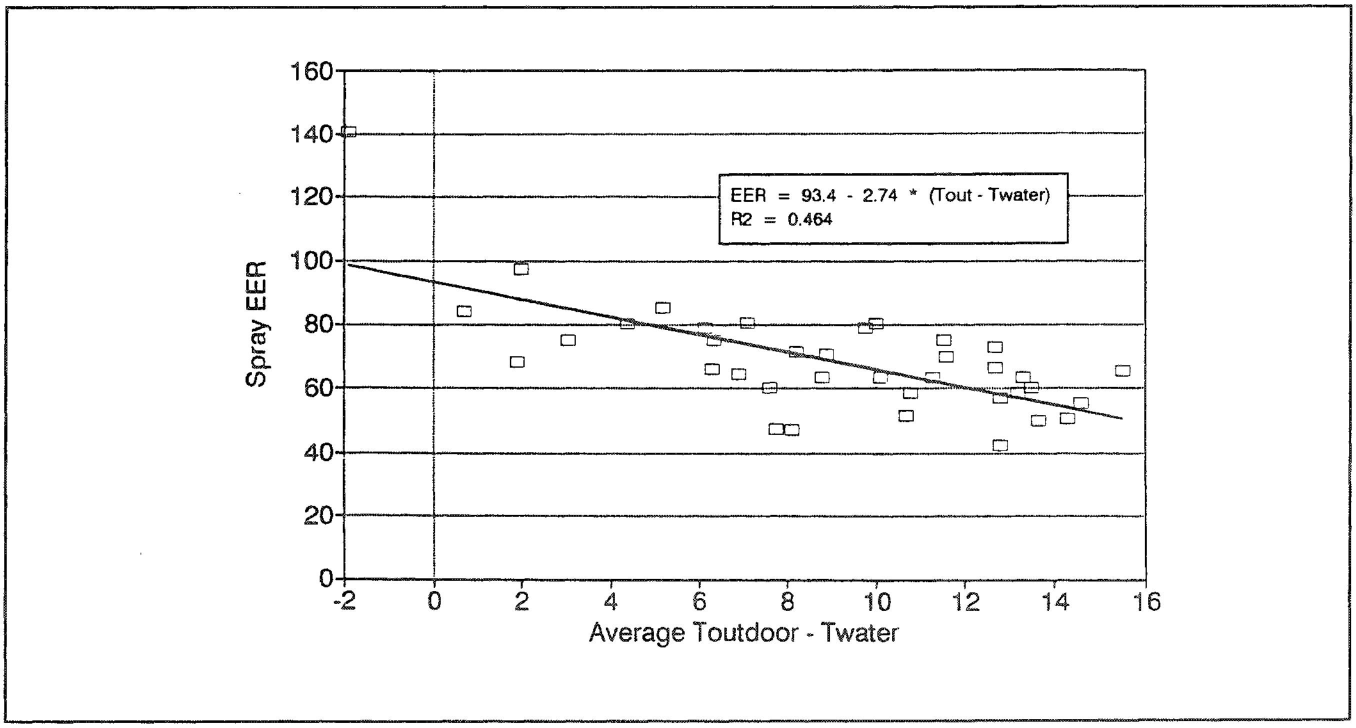

Figure 7. Spray Cycle Efficiency (EER)

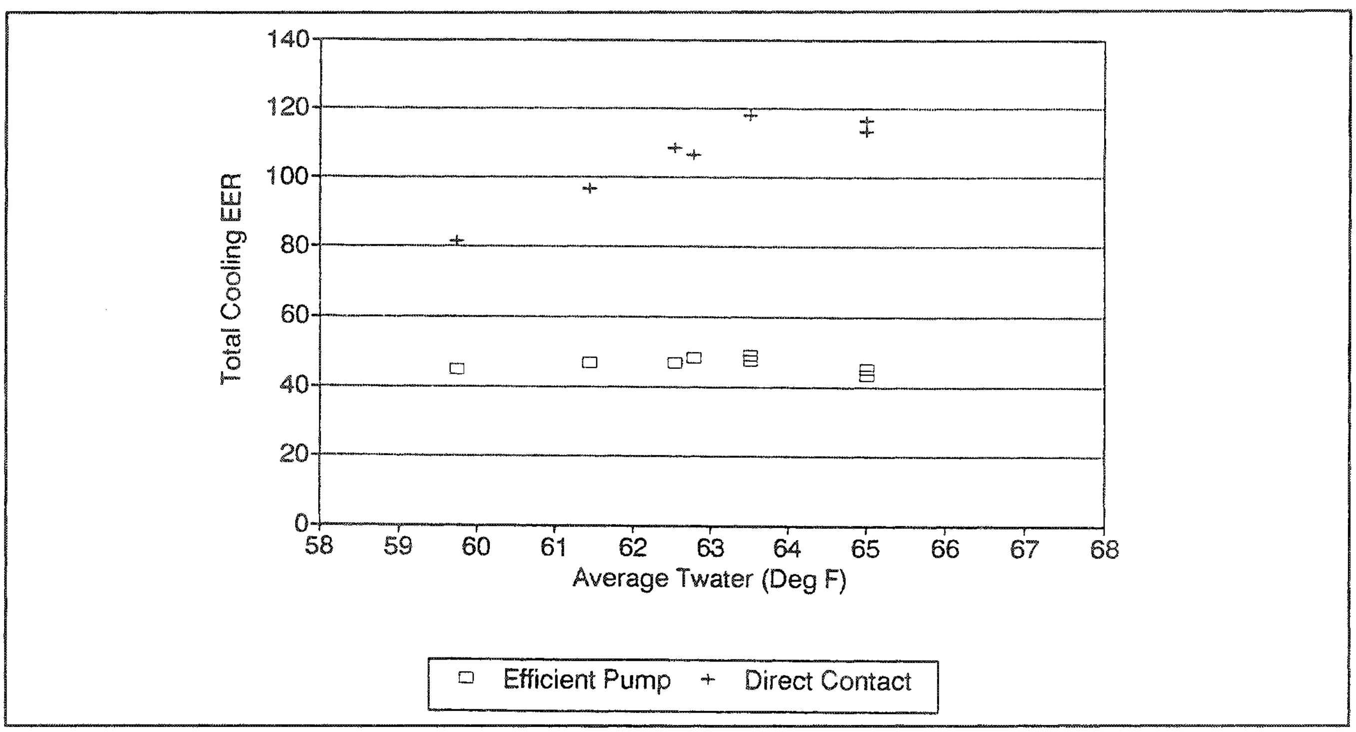

Figure 8. Projected EER's vs. Twater

WBPMR system may be undesirable for certain building types and/or occupancy patterns.

Heating Season Performance

During a typical three day midwinter period, system water remained at a steady 56°F with indoor temperatures at 65°F and outdoors ranging from 35 to 55°F. Simplified steady-state heat transfer calculations indicate R16.5 added value of the WBPMR system. Other commercial building types with higher internal or solar gains could show added benefits from the increased thermal mass of the WBPMR system.

Water Use and Water Quality

Water use monitoring was not conclusive. Excessive overspray occurred until replacement of perimeter heads on October 7, and a sticking water meter sensor contaminated data thereafter. Personnel activities on the panels also caused frequent water loss due to wave action. For the September 12-26 two week period prior to changing perimeter heads, 4544 gallons were added while the system provided approximately 25 million effective cooling Btu's. A direct evaporative cooler delivering 25 million Btu's would have consumed approximately 3400 gallons. Additional data will be obtained to more accurately determine system water use. (Water costs for economic evaluations, based on the monitored water use rate and typical Sacramento water rates, were estimated to be less than 0.6% of annual energy cost savings.)

Water quality analysis was performed by two laboratories. A Davis lab reported pH, total dissolved solids, and microbial colony counts for WBPMR water at three dates and for site tap water taken October 3. WBPMR water became mildly acidic (pH slightly less than 7) during cooling operation, and became more acidic after cooling operation ended (pH 6.0 to 6.5 in the last report). Total dissolved solids doubled compared to site tap water by October 3 (the system had not been backwashed in the prior two weeks), but were lower in December, perhaps due to reduced circulation and/or precipitation. Water quality is not expected to adversely affect fan coil performance.

In the first and second samples, two bacterial counts were higher than in the site tap water, but only two colony types were found compared to three in the tap water. In the third sample, taken more than a month after cooling operation was terminated, one of the colonies noted earlier appeared to have grown larger, and two other colonies were also present. The fourth sample, sent to a lab in Hayward, tested negative for legionella. Additional tests at the Hayward laboratory identified the three species. All are common water contaminants and not considered dangerous. Since several of the species were present in BSW tap water and may be common in other outdoor locations, it is not clear that water treatment for bacterial growth is necessary.

Service and Maintenance Considerations

The WBPMR system worked reliably throughout the monitoring period. Despite considerable windblown dirt from excavation to the south, the filter maintained water clarity when backwashed at approximately three week intervals. Two maintenance issues not noted previously in this paper are:

1. panel breakage: Several of the 204 polystyrene panels have broken. The breaks, which have typically occurred under foot traffic, affect appearance but not performance. Panel breakage could be eliminated by using thicker or stronger panels, or adding panel center supports.

2. damage from birds: During the winter, coated surfaces of many panels were punctured by sharp objects assumed to be bird beaks. The birds may be attracted by an odor from the panels. Possible remedies include a heavier surface coating, bird-repelling devices, and chemical changes to the panels.

Annual Performance and Economic Projections

Table 5 compares projected indoor temperatures and heating and cooling energy use for warehouse building base case and WBPMR systems. The WBPMR should significantly improve summer comfort with only a modest energy expenditure. Projected gas consumption is reduced 14% by the WBPMR thermal mass.

Table 5. Warehouse Simulation Results

	Base Case	WBPMR
Peak indoor temperature	91°F	73°F
Indoor temp > 85°F (hours)	97	0
Annual heating therms	1845	1580

Annual base case cooling loads of 62 kBtu/ft^2 were projected for the retail building. Table 6 summarizes performance projections for base case and WBPMR simulations. Significant WBPMR cooling energy and peak demand savings (53% and 34%, respectively), and modest heating energy savings (7%) are projected.

Table 6. Retail Simulation Results

	Base Case	WBPMR
Annual cooling kWh	316000	148000
Cooling capacity (tons)	233	154
Annual heating therms	8785	8198
% Savings		
Cooling kWh		53%
Cooling capacity		34%
Heating therms		7%

Table 7 summarizes economic projections for the retail building with "stage 1" WBPMR fan coil and "stage 2" auxiliary cooling. Projected paybacks are immediate with the roof replacement credit and less than three years without. Economics could be further improved with utility credits, higher utility rates, or improved cooling delivery control to further reduce peak electrical demand (i.e. delayed WBPMR delivery to minimize on-peak demand).

Table 7. Retail Economic Projections

Total incremental cost	$48,280
Annual utility savings	$16,605
Roof replacement NPV	$48,100
Simple payback (w/o reroof)	2.90 years
Simple payback (with reroof)	0.01 years

Conclusions

(1) Reliability: The demonstration WBPMR has performed reliably and delivered substantial cooling. Experience gained during demonstration project monitoring will help maximize operating efficiencies and system durability.

(2) Comfort: The demonstration system has provided full cooling comfort in the occupied area of the BSW, despite application to less than 20% of the building. Comfort benefits derive both from cool air delivery and from reduced mean radiant temperature (cooler ceiling).

(3) Cooling Rate: Operating for ten hours, the spray cycle can deliver up to 275 Btu/ft^2-night under typical operating conditions. Adding benefits from reversing normal downward summer ceiling heat flow, the WBPMR cooling contribution rises by another 50 Btu/ft^2-night in summer.

(4) Cooling Efficiency: Spray cycle EER ranged from 95 (for equal "full cycle average" water and outdoor air temperatures), down to 58 with full cycle average water 15°F cooler than outdoor air. Adding the ceiling heat flow reversal benefit, projected overall cooling EER's will exceed 100 in simple "direct contact" applications. Additional efficiency improvements are expected from smart controls which delay and shorten mild weather spray cycles.

(5) Winter Impact: Winter WBPMR water temperatures reflect the expected thermal benefits from added insulation and thermal mass.

(6) Water Use: Inward-directed perimeter spray heads should be used to minimize overspray. Water use at the BSW site prior to installation of inward-directed perimeter heads was 30% higher than for equivalent direct evaporative cooling. Insufficient clean data were available to determine water use after changing of perimeter heads.

(7) Water Quality: The filter maintains excellent water clarity. Several bacterial colonies were found in water samples, none considered dangerous. No Legionella organisms were found. pH became slightly acidic in winter, but not enough to endanger metallic system components.

(8) Maintenance: The overall goal of minimizing service requirements appears to have been achieved (with the self-cleaning system design and permanent sand filter with automatic backwash) based on demonstration project

monitoring. Several minor problems justify panel improvements to prevent breakage and bird-inflicted damage.

(9) Economics: The calibrated WBPMR simulation model projects favorable owner economics for a Sacramento retail application. Less than 3 year simple payback is projected based on utility bill savings alone; adding a roof replacement credit generates immediate payback.

Acknowledgements

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