A Water-Ballasted Lifetime Energy-Saving Roof System: Economic Projections

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ABSTRACT

Many conventional low-slope roofs have significant failure rates and, with summer daytime surface temperatures warmer than indoors, contribute to building cooling loads. The water-ballasted protected membrane roof (WBPMR) system, developed under the California Energy Commission's Energy Technologies Advancement Program (ETAP), provides complete membrane protection from the outdoor environment and can satisfy more than 50% of typical building cooling loads in dry climates. This paper summarizes WBPMR economic projections for large "new construction" nonresidential applications. An hourly energy performance simulation program was calibrated using monitoring results from a 6500 ft² WBPMR demonstration project. The simulation and detailed cost estimates were used to evaluate system economics for four building types in six California locations. Results indicate rapid paybacks for WBPMR applications on California buildings with significant cooling loads. When extended roof life, electric demand savings, and fire protection value are considered, projected paybacks are immediate for some building types.

INTRODUCTION

Background

As shown schematically in Figure 1, conventional low-slope roofs are subject to environmental degradation (weathering) that may contribute to roof failure. Since average daytime roof temperatures are typically above indoor temperatures, conventional roofs also increase building cooling loads during summer daytime hours. The water-ballasted protected membrane roof (WBPMR) system, developed under the California Energy Commission's Energy Technologies Advancement Program (ETAP), provides complete membrane protection from the outdoor environment and can satisfy more than 50% of building cooling loads in typical dry-climate locations. WBPMR system development has been supported by several major roofing industry participants. System components include a single-ply roofing membrane (most available single-ply materials are frequently used for other water-containment applications, including pond linings); approximately 3.5-inch water ballast; interlocking extruded polystyrene panels with a fire-resistant coating, floating on the ballast water; distribution piping either in or below the panel layer, connected to spray heads flush-mounted in the panels; a pump/filter system and controls; and (optional) active components for delivering cooling to the occupied space.

Rainwater passes through WBPMR panel joints and overflows at the protected "below panel" drains. The panel layer acts as a giant screen, preventing large debris from entering the ballast water; as a result, drains cannot clog. The interlocking panels are secured in place by water adhesion. An automatic refill system replaces evaporated water, and a filter system with automatic backwash removes particulates. Experience indicates that the low water temperatures minimize water treatment needs. WBPMR spray can evaporatively precool economizer intake air at rooftop cooling units, but care must be taken not to adversely affect building latent cooling loads.

Figure 2 shows (schematically) typical day and night WBPMR conditions. In the cooling season, WBPMR water is sprayed above the panels at night and 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. In dry climates, the system may cool directly through the roof deck or via a pumped fan coil loop. The spray pump in Figure 2 is part of a swimming pool pump/filter package, rather than being submersed as shown in the schematic.

When cooling directly through the roof deck ("direct cooling" configuration), the deck underside may be exposed as the room ceiling or a suspended ceiling may be provided to create a plenum through which room air is circulated on cooling demand. A fan coil loop provides a third (and most controllable) cooling delivery alternative. An insulating layer between membrane and roof deck (to prevent condensation on the roof underside) may be used with fan coil delivery to allow auxiliary cooling of the water ballast under peak cooling conditions. The system is applicable to freezing climates because the water remains below insulation in the absence of cooling loads. Water remains in place through the heating season, when its thermal mass slightly reduces heating loads and helps prevent building freeze damage in power outages.

Despite WBPMR technical merits, slow market implementation is anticipated due to "water-on-the-roof" fears, building code hurdles, and the degree of integration required with building HVAC systems. Additional discus-

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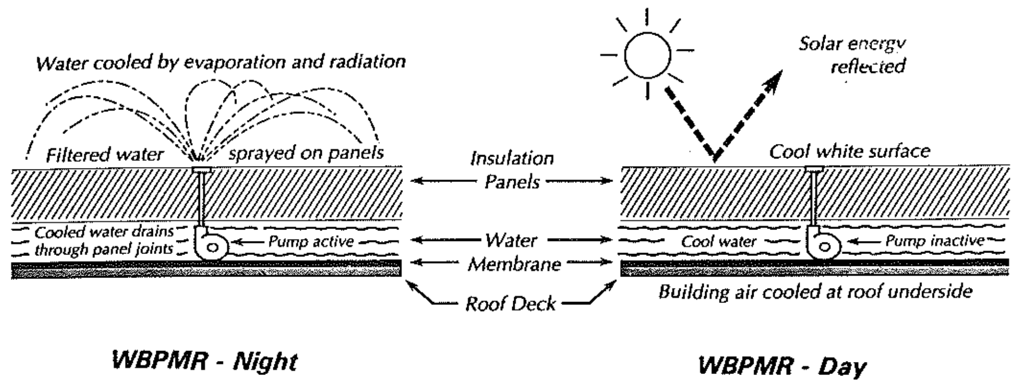

Figure 1 *Conventional roof and WBPMR exposure comparison.*

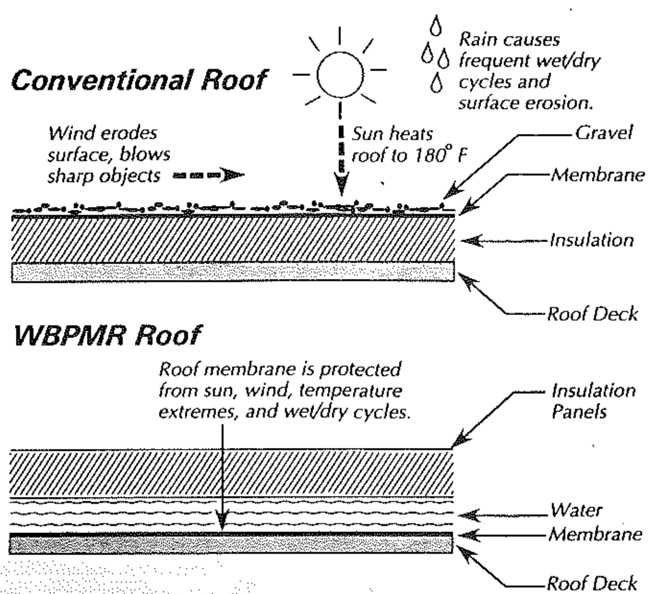

Figure 2 *WBPMR night and day condition comparison.*

sion on marketability issues is available in the ETAP final report (Bourne et al. 1992).

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 (by minimizing refrigerant use in vapor-compression cooling equipment) and global warming (by minimizing electrical energy consumption for cooling).

The ETAP project 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 nonresidential building types in California. A prior paper (Bourne and Hoeschele 1992) reported on demonstration project construction, monitoring, and model calibration. This paper presents results of WBPMR performance and economic projections for California.

Objectives

The objectives of the work discussed in this paper were

1. to incorporate a calibrated heat rejection algorithm into the WBPMR hourly simulation model,
2. to simulate WBPMR performance on five nonresidential building types in six California climatic zones, and
3. to estimate WBPMR economic value based on simulation results and detailed cost estimates.

Demonstration Project Summary

After completion of WBPMR prototype design and testing, a 6500 ft² demonstration project was constructed on an existing, previously uncooled warehouse building at the California Office of State Printing in Sacramento. On-roof demonstration project components include a perimeter "curb" system; an EPDM singe-ply roofing membrane placed over a gypsum board separator on a concrete deck topped with 2-inch fiberboard insulation; distribution piping placed on the roof membrane; 3-inch-thick, 4-foot-by-8-foot interlocking extruded polystyrene panels (with a three-coat white elastomeric coating); spray heads premounted in the panels on 12-foot centers, connected to distribution piping below; a hardware module including pump, filter, and automatic valves; and controls to regulate pump and valve operation. A large custom fan coil was installed below the roof with piping for cooling delivery from the WBPMR.

The demonstration WBPMR has worked reliably and substantially improved comfort in the previously uncooled occupied space (with uninsulated concrete walls) below the system (Bourne and Hoeschele 1992). Comfort benefits derive from cool air delivery and reduced ceiling temperature. Detailed monitoring results indicate very effective system performance. The spray cooling cycle has operated efficiently, typically cooling water 5°F to 10°F below the night dry-bulb minimum temperature. Measured "full night" spray cycle EERs ranged from 58 to 95 kBtu/kWh; smart controls that delay and shorten mild weather spray cycles should improve system EERs. The "minimum service" design strategy based on clogproof drains, self-cleaning surface, and automatic filter backwash appears sound and maintains adequate water quality based on initial system operation and water tests.

Calibration Summary

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-squared "total cooling" differences for a representative five-day calibration period. Constants for the three terms were adjusted to achieve a best fit. The final calibrated algorithm is presented in Bourne and Hoeschele (1992).

METHODOLOGY

Overview

A multi-zone hourly building energy simulation program was modified to include the spray cooling performance algorithm and other features needed for accurate WBPMR performance modeling. After model development and calibration, parametric studies were completed to evaluate performance impacts of (and optimize, if possible) key system design features.

Five different building types with "base case" conventional HVAC systems and up to three different WBPMR cooling delivery options (direct contact, plenum, and fan coil) were developed. Each prototype configuration was simulated in six California locations selected for a range of anticipated cooling loads and utility rates. Energy savings estimates from the simulations were combined with WBPMR incremental cost estimates to project simple payback periods under two roof life assumptions (equal conventional and WBPMR and 30-year WBPMR vs. 15-year conventional).

Model Development

A research version of an hourly building energy simulation program was modified for detailed WBPMR modeling. The program includes all necessary ventilation, schedule, and HVAC routines needed for nonresidential building modeling, assuming packaged air-cooled equipment. In the multi-zone model, the WBPMR was defined as a zone located above conditioned space. Custom algorithms were added to model the following WBPMR features:

- night spray cooling based on demonstration project monitoring results;
- WBPMR system spray pump energy use;
- roof deck and WBPMR conductive/convective heat transfer;
- plenum and fan coil delivery system heat flow and energy use;
- intelligent controls that vary water target temperature and spray "start hour" with anticipated cooling load to minimize overcooling and maximize efficiency.

Parametric Studies

The calibrated model was first used to perform a set of parametric runs to optimize WBPMR design parameters, including water depth, top panel insulation thickness, roof deck thermal conductivity, target water temperature, cooling start time, plenum fan size and temperature differential, and fan coil size and operating schedule. Optimization considerations and limits are described below.

Water Depth: Added weight probably limits practical depth (for new buildings properly designed for WBPMR) to six inches. Parametric runs were performed for two-, three-and-a-half-, and six-inch depths.

Insulation Thickness: Floating insulation panels must be strong enough to support occasional foot traffic. For strength, minimum thickness appears to be approximately three inches, though narrower panels or use of intermediate panel supports might reduce this minimum. Parametric runs were performed for two-, three-, four-, and five-inch insulation panel thickness. Panels must be extruded polystyrene to resist moisture absorption and be of a type intended for PMR application.

Roof Deck R-Value: Roof deck thermal conductance significantly affects cooling performance in direct cooling configurations if the roof deck underside is the only heat transfer surface. Both plywood and metal deck roof construction systems were investigated. Assumed deck conductances were 0.72 Btu/h·ft^2·°F for plywood and 1.64 Btu/h·ft^2·°F for metal.

Target Water Temperature: Lower "end-of-spray-cycle" water temperatures increase potential cooling delivery but may cause morning heating loads in mild weather, especially for direct cooling WBPMR systems. Options for a weather-variable target water temperature (for early spray-cycle termination if attained) were evaluated with the objective of minimizing annual (cooling + heating) energy costs. These evaluations were performed for one building type/location combination and results were applied to other types and locations. Therefore, results may not be fully optimized for many combinations.

Target temperatures were selected based on prior day peak dry-bulb temperature and statistical "load vs. prior day peak temperature" studies for a simulated prototype building. Several relationships between "target WBPMR water" and "prior day peak dry-bulb" temperatures were evaluated for direct contact, plenum, and fan coil cooling delivery strategies.

Cooling Start Time: Cooling cycle duration can vary with cooling needs. In mild weather, the night spray cycle may operate relatively briefly to achieve the target water temperature. Starting the spray cycle later can improve efficiency because the outdoor environment becomes progressively cooler from evening until sunrise. Simulated controls were configured to compute a start time by deducting required run time (based on target water, current water, and current dry-bulb air temperatures, and average spray cooling rate) from an assumed 5 a.m. cycle completion time.

Plenum System: The plenum cooling delivery system was assumed to be installed in parallel with the auxiliary (conventional) cooling system, with fan energy charged to WBPMR operation. Plenum air volume and on-off temperature differentials between plenum and conditioned space were varied to minimize operating costs.

Fan Coil System: Pumped loop hydronic cooling coils were assumed to be located in existing forced-air distribution systems with continuous air delivery. Chilled-water circulation pump energy to deliver WBPMR water to the cooling coils was charged to WBPMR operation but fan energy was not. Parametric runs were completed with 25%, 50%, and 75% cooling coil effectiveness values (Kayes and London 1958).

The fan coil and, to a lesser extent, plenum systems may be capable of additional peak demand reduction by delaying WBPMR cooling delivery. Auxiliary cooling could be applied earlier in peak weather, using WBPMR chilled water in a strategy designed to level auxiliary cooling demand. However, investigation of such strategies was beyond the scope of this project. In all cases, WBPMR cooling was assumed to be applied first, with remaining loads satisfied by conventional cooling.

Prototype Buildings

Five prototype buildings were selected and/or developed from previous nonresidential prototypes including several developed for the California nonresidential building standards (Huang et al. 1991; Akbari et al. 1989). All floor areas were normalized to 50,000 ft² and geometry was simplified for orientation independence. Table 1 identifies the five building types and WBPMR cooling delivery options considered for each.

Except for the uncooled warehouse prototype, all buildings were assumed to be conditioned by rooftop package units with 9.5 cooling EER and 0.65 heating SE

TABLE 1
Prototype Cooling Options

Building Type	Base Case	WBPMR Direct	Plenum	Fan Coil
Retail	√	√	√	√
Office	√		√	√
School	√	√		√
Warehouse	√	√		
Industrial	√	√		√

efficiencies. Economizers were assumed with all cooling systems. Base-case roof assumptions included 0.7 absorptivity (typical for gravel-ballasted roofs) and R-19 insulation. All WBPMR configurations were modeled with 3.5-inch water depth, 3-inch insulation panel thickness, and 0.75-inch plywood roof deck.

Direct, plenum, and fan coil WBPMR cooling delivery options were modeled. Direct systems assumed neither insulation nor dropped ceiling (hence no plenum) between roof membrane and occupied space below. The direct cooling option was not simulated for the office due to assumed marketability constraints and to potential direct cooling application only to the top floor of the two-story building. However, the direct option was selected over the plenum option for school, warehouse, and industrial buildings.

Plenum systems were modeled without insulation under the roof membrane; fans (using 0.07 W/cfm) and grilles were assumed to supply cooled air to the space below. For fan coil systems, R-6 insulation was assumed between roof membrane and occupied space. The assumed fan coil water delivery rate was 500 gpm via a 2 kW pump. The fan coil option was not considered for warehouse buildings for cost reasons. The plenum option for the two-story office building represented a "plenum up/fan coil down" combination.

Occupancy and schedule assumptions were varied widely among the five buildings. Seven-day operation was assumed for the retail and industrial prototypes, with five-day operation for the other three. "Morning only" school occupancy was assumed in summer. All buildings were one story except the two-story office. No conventional cooling was assumed for the warehouse; warehouse performance results identified WBPMR impacts on indoor temperature rather than economics.

Three-shift (24 hours a day) operation was assumed for the industrial building to allow assessment of schedule impacts on WBPMR economics, particularly by comparison with the much shorter school occupancy schedule.

Performance Simulations

Fifteen hourly performance simulations were completed per location (see Table 1). Key simulations outputs included

- hourly and total auxiliary cooling energy use and demand,
- hourly and total WBPMR parasitic energy use and demand, and
- heating fuel use.

Energy use outputs were used with utility rates and incremental WBPMR cost estimates to evaluate system economics. Cooling seasonal energy efficiency ratios (SEERs) were also calculated for each WBPMR simulation case. SEERs were computed as conventional cooling energy saved (representing WBPMR cooling energy delivered) divided by WBPMR parasitic energy consumption.

WBPMR Incremental Installed Costs

Incremental WBPMR construction costs, compared to new construction base-case assumptions described above, including labor, materials, and 20% overhead and profit, are summarized in Table 2. Cost estimates assume "mature market" conditions; initial WBPMR incremental costs will be higher to cover perceived risks for the new technology.

Incremental costs were grouped into "roof," "hardware and controls," "cooling system," and "structural" categories. The roof category includes incremental roof membrane and insulation costs. A single-ply EPDM membrane was assumed for both base-case and WBPMR systems; for the WBPMR system, added costs are required for water containment and special drains. The insulation cost includes fabrication, coating, and placement of the splined panels less a credit for conventional roof insulation.

Hardware and controls costs include all piping, spray heads, valves, filter, pump, and controls. Cooling system costs include credits for reduced conventional equipment capacity due to WBPMR impact on peak cooling load and added costs for WBPMR cooling delivery components in plenum and fan coil systems. Cooling components include plenum fans and grilles and fan coil loop pump and piping. Cooling coil costs for the fan coil delivery option were estimated per ton of cooling displaced.

Net structural cost increases due to increased vertical loads were estimated based on a structural engineer's report (Bourne et al. 1992). Cost increases were found to be modest for two reasons. First, live loads cannot exceed water loads (which are no more than typical design live loads) because added weight on the floating panels simply forces water down the drains (assuming distribution piping is located within the panel layer rather than in the ballast water). Second, foundation cost increases to accommodate "continuous" live loads (which are removable, not connected to the structure but not intermittent) may be largely offset by decreases due to "dead level" construction, such as elimination of warps and crickets and reduced wall and

TABLE 2
Summary of WBPMR Incremental Costs

Cost	Roof System Direct	Plenum	Fan
Membrane ($/ft²)	0.17	0.17	0.17
Insulation ($/ft²)	1.03	1.03	1.27
Spray System ($/ft²)	0.40	0.40	0.40
AC Equipment ($/ton)	1000	1000	1000
Other Equipment ($/ft²)	0	0.22	0.09
Structural ($/ft²)	0.18	0.18	0.18
Roof Replacement ($/ft²)	2	2	2
Fan Coil ($/ton)	0	0	144

column heights. Costs were also estimated for future removal and replacement of the base case roof.

Economic Analyses

Current electric utility nonresidential "demand rates" (summarized in Table 3) and commercial natural gas rates were combined with performance results to estimate annual HVAC energy costs. WBPMR results were then compared with base-case results to estimate WBPMR energy cost savings. Estimated WBPMR installed incremental costs were divided by estimated annual energy cost savings to compute simple paybacks with and without roof replacement credits.

RESULTS

Parametric Runs

Water depth: As expected, both thermal performance and structural costs were found to increase with water depth. Annual energy savings were found to decrease by 8% and increase by 3% for 2-inch and 6-inch, respectively, vs. 3.5-inch depth.

Insulation panel thickness: Optimization runs for the retail prototype building in Sacramento (considering both cooling and heating impacts) indicated 14- and 24-year paybacks for increasing insulation panel thickness from 2 inches to 3 inches and from 3 inches to 4 inches, respectively. Three-inch thickness was selected for future projects to maintain panel structural strength.

Roof deck conductivity: Parametric runs indicated that a metal deck, by improving water-to-space heat transfer, would increase energy savings by 33% compared to the base-case plywood deck for the Sacramento retail "direct contact" application. The plywood deck was conservatively assumed for all economic runs.

Target temperature: For the "direct only" configuration, minimum target water temperatures between 55°F and 60°F (depending on climate, building, and utility rates) were found to minimize projected energy costs. For plenum and fan coil configurations, optimal target temperatures were below typically achievable values; 50°F minimum target temperature was assumed for all runs.

Plenum system: Cooling energy savings were maximized with equal plenum and supply airflow rates. Larger plenum fans failed to increase projected savings due to roof deck heat transfer limitations. (In future studies, larger fans should be evaluated in conjunction with metal roof deck.) The optimal plenum fan temperature differential was found to be 5°F.

Fan coil: Fifty percent fan coil effectiveness was found to be optimal. Larger coils were projected to deliver more cooling but would be more costly and would deplete storage

TABLE 3
Utility Summer Peak Rates

Utility	Rate	On Peak Energy Charge ($/kWh)	On Peak Demand Charge ($/kW)
Pacific Gas & Electric	A-11	0.113	11.60
Southern California Edison	TOU-8	0.113	15.20
San Diego Gas & Electric	AL-TOU	0.085	17.54
Sacramento Municipal Utility District	47	0.058	8.60

earlier, reducing on-peak demand savings. Smarter controls to delay WBPMR cooling delivery might improve the economics of higher effectiveness cooling coils.

Energy and Demand Savings

Table 4 summarizes projected WBPMR electrical energy and demand savings ranges for the four air-conditioned building types, six climatic zones, and three cooling delivery alternatives. (Warehouse results, which are not presented here, showed indoor temperature reductions in lieu of energy savings.) Projected savings percentages were highest for schools due to a shorter operating schedule and lowest loads; industrial savings percentages were lowest due to a longer occupancy schedule and highest loads. Projected retail and office savings percentages were between school and industrial values, with office slighter higher than retail due to a relatively shorter occupancy schedule.

Projected savings of direct, plenum, and fan coil WBPMR cooling alternatives varied significantly with building type and climatic zone. Table 5 summarizes projected WBPMR energy and demand savings by delivery alternative averaged across all six climatic zones for the four air-conditioned building types. Direct cooling was projected to outperform the fan coil for schools because the shorter schedule and higher cooling setpoint (78°F) are more compatible with passive cooling delivery. For industrial applications, projected direct and fan coil savings were comparable. For retail applications, the fan coil option was projected to slightly outperform the plenum option, with both active strategies significantly better than direct cooling. Despite its lower parasitic energy requirement, direct cooling fared poorly due to higher target water temperatures; lower targets would cause heating loads on many summer mornings. Additional optimization work might improve projected direct cooling performance.

A modest demand savings advantage projected for fan coil vs. plenum delivery on retail buildings reversed for offices. (Results were complicated by the necessary assumption of fan coil lower floor cooling on the two-story prototype office building.) The higher and less controlled plenum cooling delivery rate was typically more compatible with the office schedule; on higher cooling load retail buildings, plenum WBPMR cooling would be exhausted earlier. The slower fan coil delivery system would have more remaining cooling capacity during afternoon peak load periods.

Cooling Efficiency

Table 6 summarizes projected WBPMR cooling SEER ranges and averages by cooling delivery method for all locations and building types. Projected SEERs were highest for direct cooling, which requires no parasitic delivery energy consumption. Projected plenum and fan coil SEERs were comparable. SEERs were generally projected to be highest in climatic zones with high summer temperatures and large diurnal temperature swings (Santa Rosa, Riverside, and Sacramento) and in buildings with larger cooling loads (industrial over schools, retail over offices).

Projected SEERs were higher for the WBPMR system than for comparable indirect evaporative "sensible cooling." For plenum and fan coil delivery alternatives, the WBPMR advantage results from a combination of radiative heat

TABLE 4
Savings Percentages vs. Base Case by Building Type

Building Type	Energy Savings (%) Range	Energy Savings (%) Average	Demand Savings (%) Range	Demand Savings (%) Average
Retail	30 - 62	46	19 - 36	27
Office	43 - 62	55	33 - 46	38
School	50 - 74	66	46 - 65	56
Industrial	15 - 37	32	22 - 33	27

TABLE 5
Savings Percentages vs. Base Case by Cooling Method

Cooling Method	Energy Savings (%) Range	Energy Savings (%) Average	Demand Savings (%) Range	Demand Savings (%) Average
Direct	27 - 74	46	21 - 65	35
Plenum	43 - 62	54	19 - 46	32
Fan Coil	15 - 69	50	22 - 62	38

TABLE 6
SEER by Cooling Method

Cooling Method	SEER Range	SEER Average
Direct	51 - 135	93
Plenum	45 - 64	56
Fan Coil	19 - 75	52

transfer to the night sky and reversal of typical summer daytime heat flow direction. Direct WBPMR systems have the added advantages of off-peak operation and much lower parasitic energy use compared to indirect evaporative cooling.

Energy Cost Savings

Projected annual WBPMR energy cost savings varied from \$0.12/ ft² for fan coil cooling on an Oakland school to \$0.76 \$/ft² for a plenum-cooled office building in Riverside. Figure 3 summarizes annual energy cost savings projections for the retail and office building types. School and industrial building results are summarized in the final project report (Bourne et al. 1992).

Projected annual energy cost savings averaged 25% higher for office buildings than for retail buildings despite larger projected retail energy savings; larger office demand savings made the difference. Figure 3 indicates the importance of utility rates in determining WBPMR value. Annual cooling loads are comparable in Riverside and Sacramento, but projected cost savings were much higher in Riverside due to higher rates.

Projected energy cost savings by cooling delivery type were most influenced by demand savings. For offices (modeled as combined "plenum upper/fan coil lower" systems), projected plenum demand and overall cost savings were highest. For retail, highest demand and overall cost savings were projected for the fan coil systems.

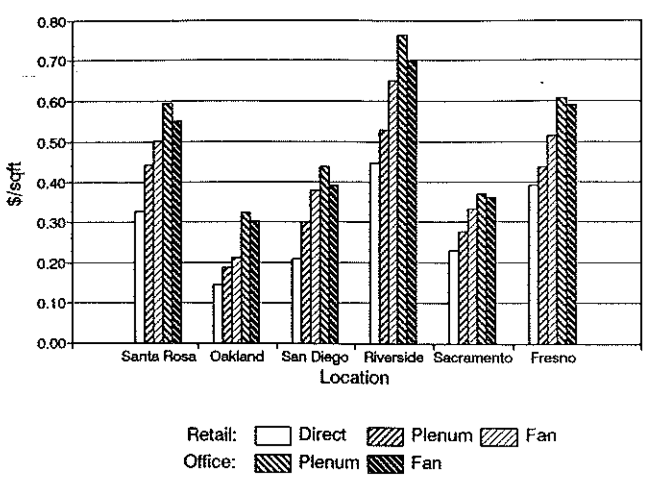

Figure 3 *Projected WBPMR annual energy cost savings vs. base case.*

Overall Economics

Example Table 7 provides an overall economic projection summary for the 50,000 ft² Fresno retail prototype building with fan coil WBPMR cooling. Annual electrical energy, electrical demand, and heating fuel costs are shown for both base-case and WBPMR systems. Projected heating fuel savings were modest (less than 1% of total savings); electrical energy cost savings were almost twice demand cost savings. Projected net incremental installed costs (NIICs) included more than \$2.00/ft² for WBPMR components and added structural costs. However, the net cooling system credit, computed by adding estimated cooling coil and circulating pump costs to savings from reducing air-conditioning capacity (by 86 tons), reduced the NIIC to approximately \$0.90/ft². The WBPMR projected simple payback was less than two years for the Fresno/retail/fan coil example without roof replacement credit.

The roof replacement present worth reflects the 30-year expected WBPMR roof life vs. 15 years for the "budget" conventional roof assumed in cost studies. The WBPMR assumption appears conservative considering membrane test results for EPDM in high-temperature continuous water containment applications (Youngberg 1983). For the Fresno retail example, projected roof replacement present worth more than offset WBPMR incremental cost, generating immediate value without energy savings. Added fire protection value (burn-through from either above or below would require boiling off all ballast water, a very difficult task; the fire-resistant coating and spray activation prevent panel burning) and utility demand-side management incentives would further improve WBPMR economics. Significantly reduced conventional cooling operating times would generate maintenance and replacement cost savings, offsetting WBPMR maintenance costs.

Net Incremental Installed Costs

WBPMR NIICs varied with cooling delivery type and auxiliary cooling capacity savings. Figure 4 summarizes estimated NIICs for the same location, building type, and WBPMR set previously shown in Figure 3. Estimated NIICs were inversely related to peak load reduction and were highest in mild locations such as Oakland and San Diego where WBPMRs would displace the least conventional cooling capacity. Of the 24 displayed combinations, only three (all in Oakland and San Diego) showed NIICs greater than \$1.50/ft²; five were below \$0.50/ft². Direct cooling NIICs were always lower than plenum NIICs, which were almost always lower than fan coil NIICs.

NIICs were based on demonstration project experience and "learning curve" improvements typical for "mature" technologies. Prefabricated, solvent-weld PVC piping trees

TABLE 7
Economic Projections for Fresno 50,000 ft Retail Fan Coil Prototype

	Base Case	Fan Coil	Net Cost
Anual Utility Cost:			
Energy	$35,912	$19,032	
Demand	$32,405	$23,639	
Fuel	$6,713	$6,597	
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Total	$75,030	$49,269	($25,761)
HVAC System Size (tons)	266	180	-86
Incremental Installation Costs:			
Membrane			$72,000
Hardware and Controls			$19,800
Cooling System			($55,980)
Structural			$9,000

Total Cost			$44,820
Simple Payback			1.74 years
Roof Replacement Present Worth @ 5% real discount rate			($48,102)

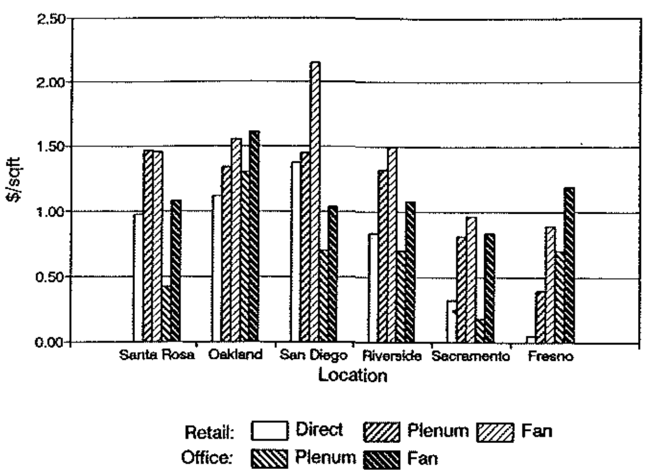

Figure 4 *Projected WBPMR incremental costs vs. base case.*

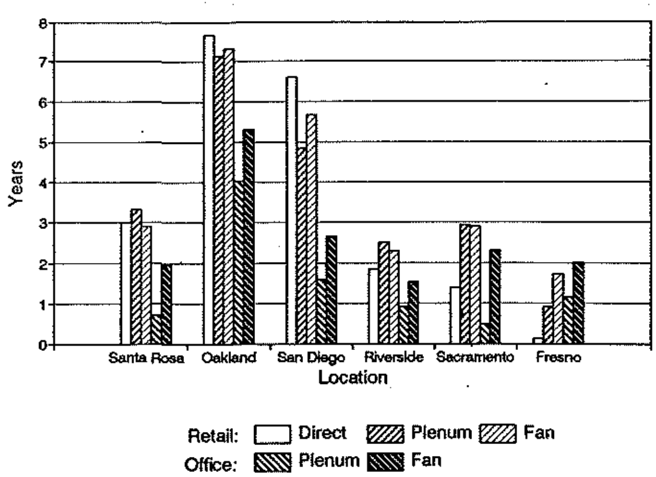

Figure 5 *Projected WBPMR simple paybacks vs. base case w/o roof replacement credits.*

were assumed, which minimize site labor and potential membrane damage during piping installation. The panel-on--water WBPMR configuration virtually eliminates membrane damage from service personnel working and walking on the roof.

Simple Paybacks

Figure 5 shows estimated paybacks in years, without WBPMR roof replacement credit, for cases shown previously in Figures 3 and 4. Estimated simple paybacks were three years or less for all but one case in locations excluding Oakland and San Diego. In those two locations, estimated San Diego office paybacks were less than three years, but paybacks for other cases were all longer than four years. Offices generally showed better WBPMR economics than retail buildings, probably because the two-story office imposed higher cooling loads per roof ft² yet showed greater WBPMR capacity reduction per roof ft² compared to retail cases.

For retail applications in the four most viable locations, direct cooling showed the most favorable economics, due to lower incremental costs, despite lower annual savings compared to plenum and fan coil cooling alternatives. WBPMR direct cooling economics would be even more favorable if higher cooling thermostat settings had been modeled to recognize improved comfort from lower ceiling temperatures. Comparable paybacks were projected for plenum and fan coil alternatives in retail applications, but the "plenum up/fan coil down" office configuration (labeled "plenum") showed approximately one year shorter paybacks than fan coil only, for all cases shown. The plenum advantage resulted chiefly from lower plenum system incremental costs.

When roof replacement savings were considered (not shown), immediate paybacks were projected for 12 of the 30 cases. Of the remaining 18 cases, projected paybacks were two years or less for all but 3, and the longest was 3.1 years.

For school and industrial buildings, projected paybacks showed greater variation compared to office and retail applications. In all locations, direct cooling showed a significant economic advantage over fan coil cooling, and schools showed slightly better projected paybacks than industrial buildings. With roof replacement credits, projected paybacks were less than six months in 12 of 24 cases and more than four years in only three cases. Utility demand-side management credits and fire insurance savings could further improve WBPMR economics.

CONCLUSIONS

The following significant conclusions were drawn, based on full-year calibrated simulations and detailed cost estimates, regarding expected WBPMR performance and economics in California nonresidential applications.

1. In preferred applications, WBPMR systems will reduce cooling energy consumption by 50% to 75% and peak cooling demand by 25% to 50% compared to conventional roof/HVAC combinations.
2. WBPMR cooling seasonal energy efficiency ratios (SEERs) should range from 50 to 75 Btu/W for plenum and fan coil systems and from 90 to 135 Btu/W for direct systems.
3. In preferred applications at current utility rates, WBPMR systems will reduce annual energy costs by \$0.30 to \$0.70 per roof ft^2. Sixty to sixty-five percent of savings will typically derive from reduced energy consumption and the remainder from reduced demand.
4. WBPMR incremental installed costs will vary significantly with cooling capacity savings, from a high of approximately \$2.00 per roof ft^2 to a low near zero. Improved WBPMR control could further reduce auxiliary cooling capacity and net incremental installed WBPMR cost.
5. Based on incremental costs and utility savings, projected WBPMR simple paybacks should be less than three years in locations with significant cooling loads. When roof replacement credits are applied to recognize extended WBPMR service, paybacks should be less than a year in most cases.
6. Economics are slightly more favorable for direct cooling than for active (plenum or fan coil) cooling on retail, school, and industrial buildings. For offices, where direct cooling was not considered, economics are slightly more favorable for plenum cooling than for fan coil cooling.
7. Economics are most favorable under the combination of high electric rates and high annual cooling loads typical of inland locations served by large private utilities.

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