Design and Implementation of a Night Roof-Spray Storage Cooling System

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This paper describes the energy analysis, design, and construction of a night roof-spray storage cooling system installed on a new 27,500 ft^2 office building in Los Angeles. The system operates a water spray system on the roof at night, cooling the water by evaporation and radiation to the cool night sky. Cooled water returns via the roof drain system to a 15,000 gallon underground tank. One of the two spray pumps circulates water through 6000 lineal feet of underfloor tubing enroute to the spray heads, using the floor mass to augment tank storage. Tank water is pumped on thermostat demand to return-side cooling coils located at four large rooftop heat pumps, augmenting passive cooling delivery from the cool floor. System installation was completed between September 1995 and January 1996.

The building was designed for the California Economic Development Department(EDD). Full year hourly simulations indicated night roof spray system benefits to include a 25 ton reduction in required cooling capacity and approximately 21,000 kWh (47%) reduction in annual cooling use. Considering cooling capacity and demand savings, the system's $10,100 incremental cost was projected to generate a 6.1 benefit/cost ratio based on a 30-year life cycle analysis.

INTRODUCTION

Background

In climates with clear summer nights such as predominate in the southwestern U.S., the cold night sky offers major opportunities for reducing building cooling costs and energy consumption. Water sprayed on low mass surfaces facing the night sky can be cooled below wet bulb temperature in a combined radiative/evaporative cooling process. Flat or low slope commercial building roofs are ideal surfaces for such night spray systems. In addition to the water chilling function, sprayed water cleans the roof, thus reducing day-time roof temperatures and ceiling heat gains. This feature is particularly valuable in clear dry climates where lack of summer rainfall otherwise allows white roofs to be darkened by windblown dirt which is captured by early morning dew and baked on by the afternoon sun.

Since cooling loads in dry climates are often lowest when night spray cooling rates are highest, thermal storage is required to derive economic value from such systems. Where adequate thermal storage is provided, heat rejection rates exceeding 300 Btu/ft^2 per night in peak cooling weather are sufficient to satisfy 40 to 100% of typical California commercial building cooling loads. The authors have evaluated several thermal storage location options for night roof spray systems including rooftop water, ground mass, and water tanks both above and below ground.

Prior papers have documented a water-ballasted roof technology with floating insulation panels with an impressive performance record and favorable economics in California climates (Bourne & Hoeschele 1992; Bourne & Rainer 1992). The water-ballasted technology offers superior roof membrane protection, but requires ''dead-level'' roof construction and causes structural loading concerns. These two factors combine to require significant advance planning for integration of water-ballasted roof systems.

Off-roof storage can typically be integrated later in the building design process, or can be retrofitted to existing buildings. Like the water-ballasted system, off-roof thermal storage systems have very favorable economics when they allow downsizing or elimination of the conventional cooling system. Thus, retrofit systems are most cost-effective if installed concurrently with HVAC system replacement. Maximizing peak cooling demand reduction requires ''next-day'' control of night storage cooling delivery. Water tanks coupled with cooling coils maximize control, as this configuration permits storage cooling delivery to be delayed and modulated to minimize peak auxiliary demand. Use of floor and underfloor mass for thermal storage limits control because the cooled floor acts as a passive cooling surface whose delivery cannot be concentrated in afternoon peak cooling hours.

Scope

This paper describes the energy analysis, system design, and construction of a night roof-spray storage cooling system installed on a new 27,500 ft^2 office building in Los Angeles. The building was designed for occupancy by the California Economic Development Department (EDD).

The system includes an underground tank and two spray pumps; one circulates filtered tank water through underfloor tubing enroute to the west side spray heads, using the floor mass in combination with tank storage. The other pump circulates filtered tank water directly to the east side spray heads and, on thermostat demand, to cooling coils located at four rooftop heat pumps, augmenting passive cooling delivery from the floor. System installation was completed between September 1995 and January 1996.

METHODOLOGY

Analysis

In an initial project completed for the project developer while final construction documents were being completed, we analyzed ten potential energy-efficiency measures (EEM's) which could be incorporated without major design changes, including a WhiteCap™ night roof spray thermal storage system (marketed by Roof Science Corporation of Davis, CA). This paper evaluates only the night roof spray cooling system.

Performance and economic studies which justified WhiteCap selection were described in a summary report by Davis Energy Group to the developer. We completed the analyses using the research version of the MICROPAS full year hourly building energy simulation program (marketed by Enercomp of Sacramento, CA) in conjunction with a Long Beach ETMY hourly weather file. The program models all envelope components, building schedule impacts (both thermostats and internal gains), and hourly climate influences on building space conditioning. The building is scheduled for 8 AM to 6 PM weekday-only occupancy. Assumed peak-hour building occupancy was 160 persons. We assumed thermostat setpoints of 76°F for cooling and 70°F for heating, and 2.0 watt/ft^2 internal gains from lighting and equipment. An external hourly simulation model calibrated from prior demonstration project monitoring data was used to project WhiteCap performance. The model considered only the thermal storage provided in the buried water tank, ignoring the additional thermal storage provided in the floor mass.

For economic studies, we selected a preferred rate from the local electric utility options, and applied a 2% real discount rate against future savings to compute net present values and benefit cost ratio's (BCR's) over the 30 year study period. Cost streams included estimated incremental first costs plus discounted future operation, maintenance, and replacement costs.

Design

After the developer's tentative approval of recommended EEM's including WhiteCap, we prepared preliminary drawings and specifications for incorporating the system into the nearly-completed building design. We reviewed preliminary designs with Los Angeles building officials and modified the drawings as necessary for approval. We also recommended 50% downsizing of the four- 10 ton rooftop ''package heat pumps'' serving the lobby and open office areas, and five ton total reduction in smaller heat pumps serving rooms along the west side, based on projected delivery capacity of the WhiteCap system. Designs included detailed controls drawings specifying how WhiteCap system controls integrate with heat pump cooling delivery.

Construction and Commissioning

After completion of design, we assisted the developer and general contractor to determine how the WhiteCap installation tasks would be carried out by the subcontractor trades. Since many of the tasks were unfamiliar, we reviewed each task with the appropriate subcontractor, and assisted with several tasks to streamline installation. We also installed the WhiteCap controls and commissioned the system to verify proper operation of all components in all operating modes.

Operation and Monitoring

After completion of commissioning, we completed the operations and maintenance (O&M) manual and reviewed system operation with the occupant's building manager. We also developed a monitoring plan based on an electronic datalogger with telephone modem for remote data collection. The monitoring system was designed to measure Btu's delivered to the cooling coils and floor tubing based on measured flows and temperature differentials, to verify system energy savings; and to monitor electrical use for the four large heat pumps, to verify system demand reduction. Installation of the monitoring system was awaiting funding approval as of May 1996.

RESULTS

Analysis

The preliminary analyses indicated that WhiteCap would save almost 21,000 kWh annually, or about 47% of the base case cooling load. The actual savings percentage is expected to be higher because the floor storage mass was ignored in the analyses due to modelling limations. Fig. 1 shows projected energy savings by month, and Fig. 2 compares base case and WhiteCap cooling demand profiles on the 98°F peak day. WhiteCap was projected to save approximately 14% of overall building base case energy use. However, the system should cause a 19% reduction ($3400/year) in the projected annual energy bill, by significantly reducing demand charges.

Figure 1. Project Monthly Cooling Energy Use

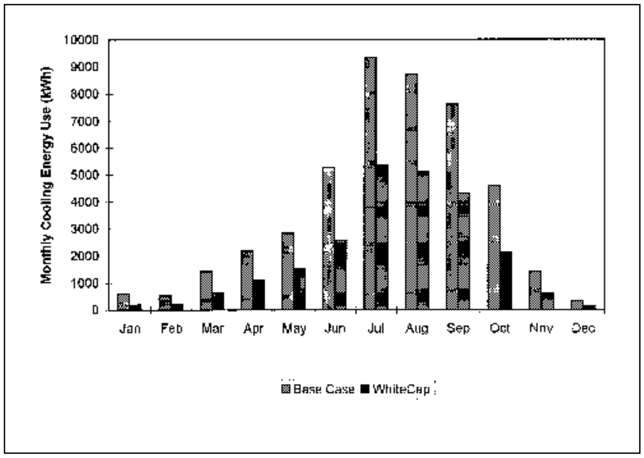
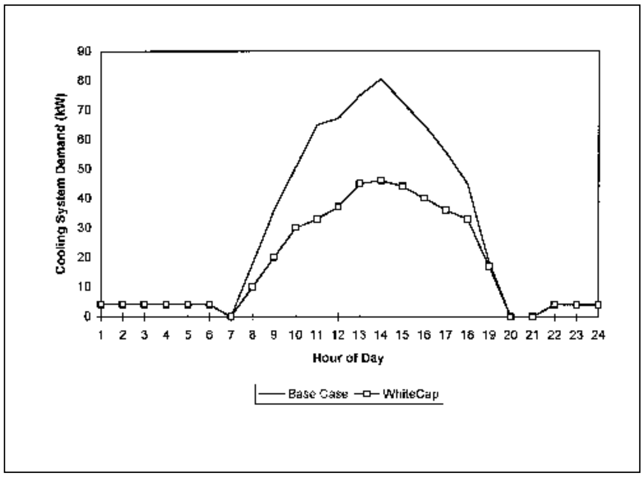


Figure 2. Projected Peak Day Cooling Demand



Water cost was not explicitly considered in the study, but was found to be inconsequential in several prior evaluations. Monitored WhiteCap water use is 0.15 to 0.20 gallons/kBtu cooling delivered. The 40,000 gallon projected annual make-up water for the EDD building will cost $159 at the $2.98/100CF ''high season'' rate.

Design

WhiteCap system designs were completed for the following components:

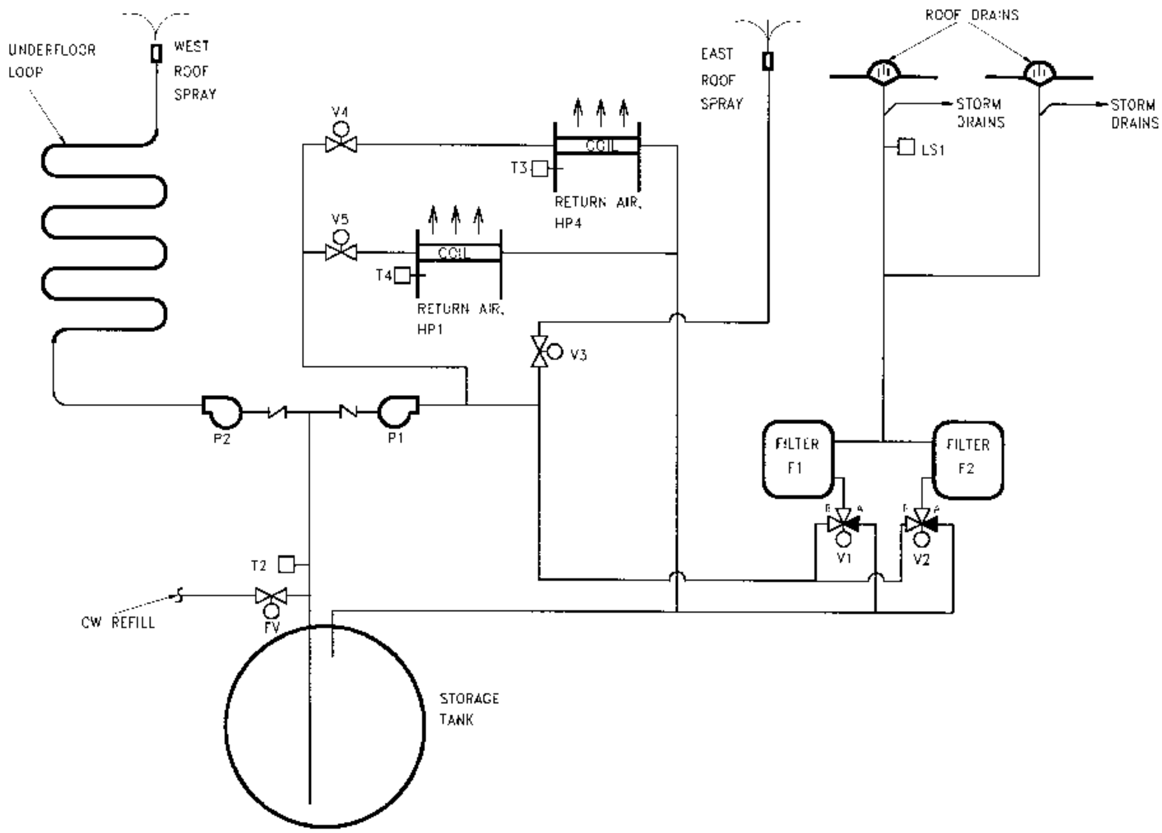
- pumps, connecting piping, and roof-mounted spray heads
- special drain assemblies to return collected water to the thermal storage location(s)
- water filters to remove dirt washed from the roof surface
- motorized valves and piping for automatic filter back-wash
- water tank and/or tubing in floor mass for thermal storage
- floor mass and/or cooling coils for cooling delivery
- a microprocessor-based control system to optimize WhiteCap operation

We began WhiteCap system design for the EDD project with development of preliminary drawings based on the schematic layout shown in Fig. 3, proposed after reviewing several alternatives in the energy analysis stage. The low-slope (1/4 inch per foot) building roof has a north-south ridge, with an east roof area of approximately 17,000 ft^2 and a west roof area of approximately 12,000 ft^2; roof area exceeds floor area due to overhangs. We specified separate roof spray pumps for the two roof areas, with a shared filtration system and 15,000 gallon storage tank under the north side parking lot. Spray water collected at the drains returns through a parallel pair of low pressure drop sand filters into the storage tank. In the schematic design, flow from west side spray pump P2 passes through high density polyethylene tubing arranged in an L-shaped pattern under the floor slab. The flow schematic for east side pump P1 includes a diverter valve for chilled water delivery to cooling coils in the open office and lobby areas. Fig. 4 shows major components, including the underfloor tubing, in plan view.

We devised a unique cooling delivery strategy to maximize WhiteCap cost-effectiveness in the context of the original HVAC design and high utility demand charges. Seventeen rooftop heat pumps had been specified, including four ten ton units serving the open office and lobby areas, and thirteen smaller units with 39 tons total capacity, providing zoned comfort to conference rooms, offices, and service rooms along the south and west exterior walls. We projected the highest cooling loads in the high occupancy open areas served by the four large heat pumps. Due to the expected expense of piping and many small pre-cooling coils at the small heat pumps, we concentrated on reducing demand by applying WhiteCap cooling in the large open spaces served by the four large heat pumps.

In the original design, tubing was to be placed in a C-shaped configuration under all west and south perimeter rooms, and across the lobby floor. In this way, the high occupancy lobby would be WhiteCap-cooled from below (passively) by the floor and from above by the chilled water coils. However, several factors including restroom plumbing and exhaust air flow, an outside deck at the southwest corner, and unconditioned south side storage rooms conspired to eliminate the south side tubing. The tubing design called for placement

Figure 3. EDD Los Angeles—WhiteCap System Schematic



of 3/4'' high density polyethylene tubing in twelve parallel circuits at the bottom of an under-slab sand layer, to maximize the time lag between ''cool charging'' of the underfloor mass and delivery of cooling to occupied space above.

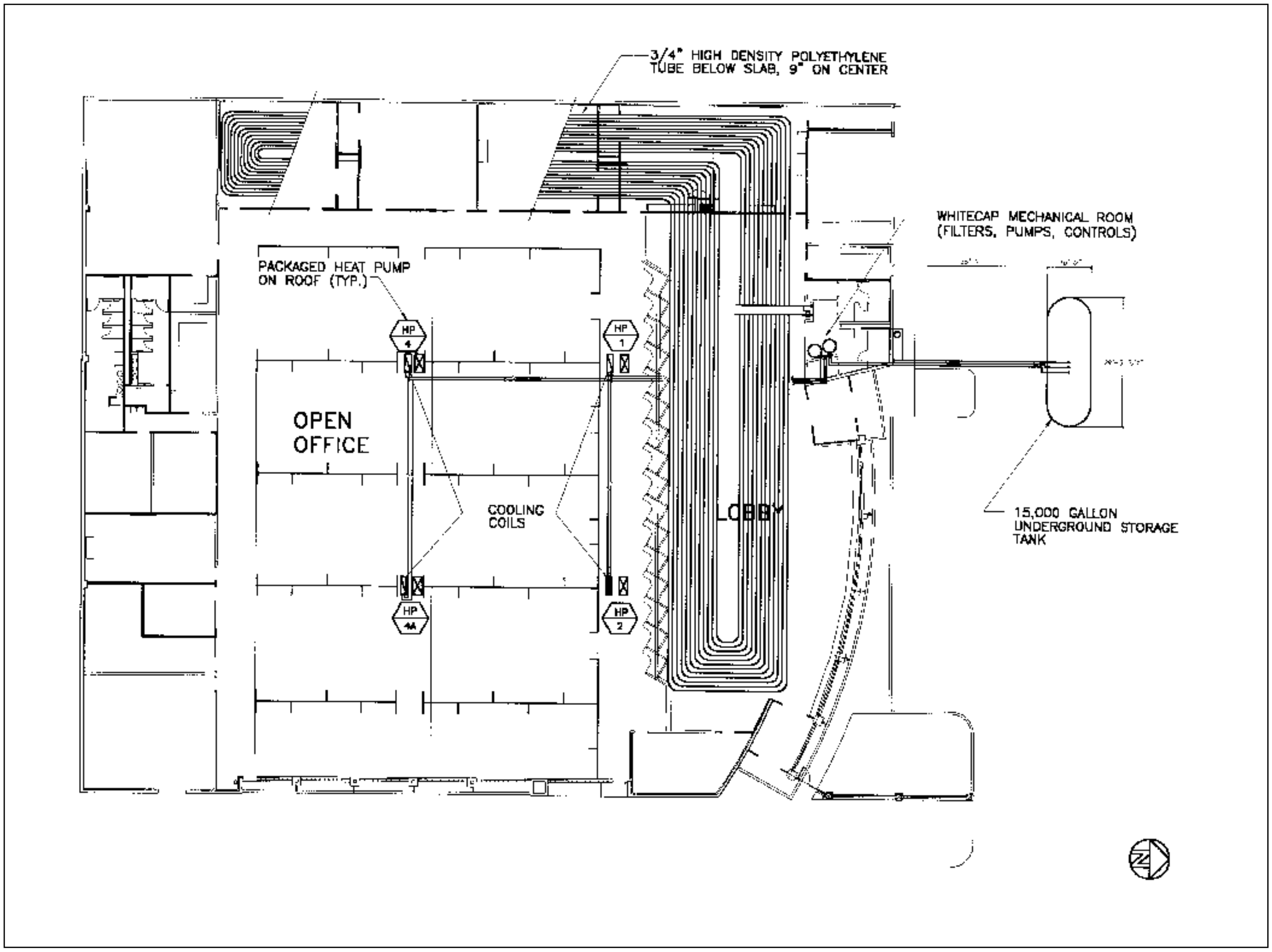
Fig. 3 also shows: 1) the backwash flow pattern in which water from the east side pump P1 flows in reverse through the two filter tanks, carrying collected dirt up through the drain lines to spill over into the storm drains; and 2) the refill valve and backflow preventer through which makeup water is added to compensate for evaporative loss during the spray cycle. Rainfall also refills the system; when drain lines are filled by rain, the drain design causes excess water to overflow into the storm leaders.

The building ventilation design pressurizes the building; outdoor ventilation air is drawn in at the rooftop heat pump units and indoor air can escape through a single central exhaust port. Since the ''makeup air'' is often warmer than indoor air in cooling season, we generally prefer to place pre-cooling coils just upstream of the refrigerant cooling coils, in the ''mixed air'' stream. However, the heat pumps could not accommodate an additional coil in this location. Therefore, the four affected return plenums were redesigned by the mechanical contractor for addition of the WhiteCap chilled water coils.

Control Design

The microprocessor controller is programmed to maximize efficiency and prevent overcooling. The controller operates both spray pumps together in response to a storage tank target temperature and recent weather. The target is set lower in hotter weather. Late in the evening, the algorithm estimates required spray time based on the difference between current and target tank temperatures. Starting time is then computed to achieve the target temperature at 6 AM. As the spray cycle proceeds, the controller monitors tank temperature and turns off the spray either when the target is achieved or at 7 AM if the target has not been achieved. Separate cooling delivery controls activate pump P1 to deliver chilled tank water to zoned cooling coils at the large heat pumps. No WhiteCap controller action was required to activate the heat pump supply fans, which operate continuously. We

Figure 4. *WhiteCap Plan*



specified return air temperature sensors to activate the chilled water flow when air temperature rises to a value below the heat pump thermostat settings. Thus, the WhiteCap coils act as ‘‘Stage 1’’ cooling, but heat pump and WhiteCap cooling settings must be manually synchronized.

Code Approval Issues

We encountered several unexpected setbacks which compromised WhiteCap cost-effectiveness (but not performance) before approval of final designs by the Los Angeles Building Department. The project developer and mechanical engineer decided not to downsize the originally-specified heat pumps to ensure full cooling output in the event of WhiteCap system problems, eliminating a key WhiteCap economic advantage. Later, the Building Department required placement of a heavy membrane barrier under the floor tubing array to drain any leakage and prevent building damage from heaving of wet clay below. When our proposed controller-based leakage detection strategies were rejected by the City, we developed a design, subsequently approved by the City, for a 20 mil vinyl liner system and drain tiles connected to the storm drainage system under the full tubing array.

Construction and Commissioning

Construction of the EDD building began in late September 1995 and was completed in late January 1996. Major WhiteCap system installation items were, in sequential order:

- underslab drainage membrane, tubing and manifolds
- underground storage tank
- spray system, cooling coils, and connecting piping
- filters, pumps, valves, and mechanical room piping
- wiring and controls

A general contractor and all subcontractors for EDD construction had been selected prior to completion of the WhiteCap design. Therefore, addition of WhiteCap components was largely accomplished through change orders. However, since most of the installation work was in the plumbing category, two plumbing bids were solicited for the WhiteCap additions. We reviewed the designs and installation tasks with the general and plumbing contractors before change order cost budgets were finalized. The contractor previously selected for conventional plumbing tasks was the low bidder for the WhiteCap additions.

The plumber was unfamiliar with both the drainage membrane and underfloor tubing installation tasks, but with preparatory coaching and onsite assistance completed both in approximately 50% of their original time budgets. The tubing was covered with and protected by the sand layer, and then was pressurized during the slab pour as a leak detection strategy. The pour proceeded smoothly without tubing damage. Installation of the fiberglass storage tank and connecting piping was completed by a specialty contractor.

Cooling coils were added by the mechanical contractor to return plenums at the four- 10 ton heat pumps. Access doors were also added to allow coil cleaning, since the coils were upstream of the air filters located in the heat pump units. Plumbing lines in the ceiling cavity for both drainage return lines and supply/return lines to the cooling coils were of Type M copper. One difficulty caused by WhiteCap addition to the EDD project resulted from choice of a single central location for the filters in a small mechanical room centered near the front of the building. Despite design calculations based on scaled drawings indicating adequate space, the installers could not achieve the required 1/32 inch per foot drainage slope between the roof drains and the mechanical room, so the 10’ ceiling height was lowered by 4″. The need to filter the drain water before any ‘‘trap’’ (to prevent clogging from dirt accumulation) prompted the design, but separating the filters so that each shared a pair of drains along east and west walls, respectively, would have eliminated the problem as well as the cost of the long copper drain lines.

The plumber installed the roof spray system consisting of surface-mounted copper piping and brass irrigation sprinkler heads secured and supported using rectangular plastic tube supports to prevent roof damage. Full, half, and quarter spray heads were strategically placed to avoid water spray onto rooftop equipment and components. Fig. 5 shows the completed roof spray system.

The plumber also installed WhiteCap components in the mechanical room. The WhiteCap supplier provided a prefabricated piping assembly which included valves V1, V2, and V3 (see Fig. 3) and union connections to the filters. Additional manual valves (not shown on Fig. 3) close the roof return lines to allow installation and/or service work in the mechanical room. Piping is Type M copper in wall and ceiling cavities and schedule 40 PVC in the mechanical room.

The system control panel including the microprocessor unit and control relays was provided by the WhiteCap supplier. The electrical subcontractor ran power wiring to the control panel and the two pumps, and control wiring from the control panel to the outdoor sensor and the two fan coil return temperature sensors. WhiteCap personnel placed other system temperature sensors and completed final connections between the controller, sensors, and low voltage valve components.

System commissioning was performed upon completion of installation work. We first tested all control valves for proper open and closed positions. We then manually operated each pump in spray mode, checked for leaks, adjusted spray patterns to minimize overspray and eliminate direct spray on rooftop equipment. We also verified proper return drainage through the filters to the tank. Next, we operated pump P1 in cooling delivery mode on both low and high speed and checked for leaks. In the final manual tests we operated backwash and refill modes and verified proper operation. After the manual testing, we calibrated all sensors and tested automatic operation. We checked all controller modes including spray, cooling, backwash, refill, and ‘‘fire’’ mode. In the latter mode, the building fire alarm system activates roof water spray.

Operation and Monitoring

After commissioning, a training session was held for the building manager and staff. The operation and maintenance manual was used as a reference during the session. Routine operation was scheduled to begin with installation of the monitoring system in May 1996. Performance monitoring results were not yet available at the submittal deadline for this paper.

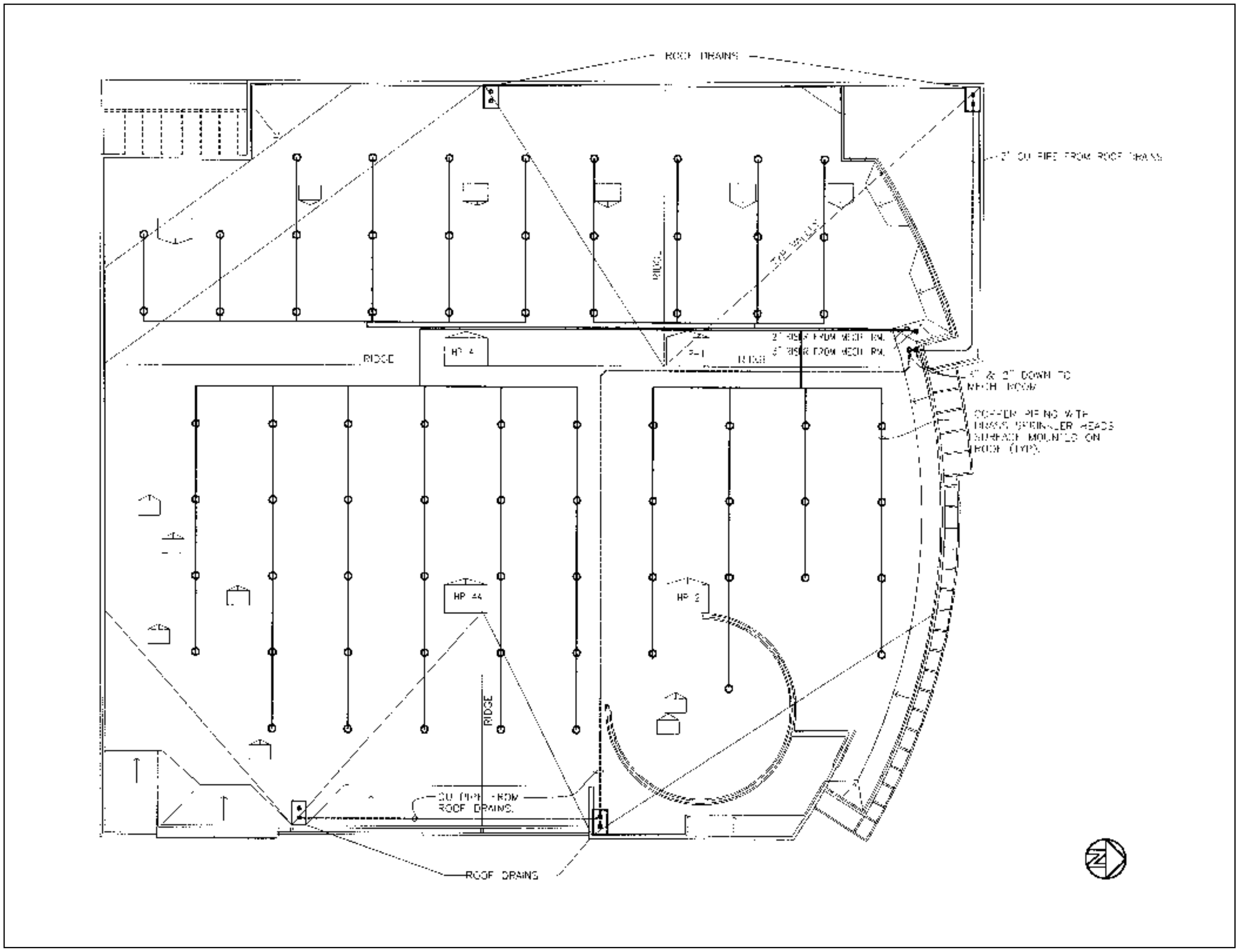
CONCLUSIONS

The following conclusions are drawn from experience through the commissioning phase with the WhiteCap system on the EDD building:

(1) A night roof spray storage cooling system can be added quite late in the design stage for a new construction project without major difficulties.

(2) System economics are enhanced by downsizing of the conventional cooling system.

Figure 5. *WhiteCap Roof Plan*



(3) System components may conveniently be installed by conventional subcontractors, without requiring an additional contractor on-site.

(4) Long sloping system drain lines can interfere with ceilings when a single central mechanical room is used. Exterior filters located near the roof drains would eliminate this problem.

ACKNOWLEDGEMENTS

We appreciate the considerable support provided by Ian Ekholm of the California Office of Real Estate Development Services for initiating the EDD WhiteCap project, and the enthusiastic response of Kevin Brunk of 5401 Associates, L.P. Without Mr. Brunk's willingness to add the WhiteCap system at a relatively advanced state of design, and his continuing ''Why not?'' response to participants expressing that they couldn't make small changes in their piece of the design to accommodate the system, the project and this paper would not have been possible. We also appreciate support of the California Energy Commission in providing partial funding for the original WhiteCap development, and full funding for performance monitoring work.

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