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ADVANCEMENTS IN COOLING TECHNOLOGY

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Advancements in Cooling Technology is the final report for the Advancing Efficient Cooling in California project (contract number 500-07-011), conducted by the Western Cooling Efficiency Center at the University of California, Davis. The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

The Western Cooling Efficiency Center (WCEC), a research unit of the University of California, Davis, was formed in 2007 to pursue air-conditioning technologies that are designed for hot, dry western climates. By partnering with technology developers, manufacturers, end users, utilities, and public policy organizations, the WCEC helps to move technologies through a series of progressive stages from concept, through technology research, development, demonstration and utility programs and ultimately, to the market and into codes and standards.

The California Energy Commission's Public Interest Energy Research program has provided significant support to the WCEC by funding individual research projects as well as a comprehensive cooling technology advancement programs. This report summarizes the research and development program outcomes. It includes results from the following projects, which were all focused on advancing climate-optimized air-conditioning technologies:

- Best Practices for Evaporative Water-Based Cooling Systems: Scoping Study
- Energy Efficient Opportunities for Packaged Rooftop Cooling Units
- Energy Efficiency Opportunities for Residential Cooling
- Condenser Mist Cooling
- Technology Demonstration: DualCool Installation, Climate-Mat Installation
- Emerging Cooling Technologies
- Website and Technology Catalog

The project benefits California's residential and commercial ratepayers directly by helping bring more efficient cooling technologies to market and thereby reducing electricity use and peak demand.

Keywords: Cooling, peak demand, residential cooling, non-residential cooling, air-conditioning technologies

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EXECUTIVE SUMMARY

Cooling is generally considered to be the "worst load" by electric power utilities in the western United States, because it creates very large peak electrical power demand, during high air temperature and low humidity in the West. This condition is in contrast to the eastern United States, where air conditioners tend to run all day and night to control indoor temperature and humidity. One way to look at cooling is in terms of load factor, which is the ratio of average electricity demand to peak electricity demand. In the case of residential air conditioning, the load factor is seven percent. The load factor roughly means that a utility needs to construct a power plant that is effectively operated only seven percent of the time, which would be a very poor use of resources. Anything that can be done to reduce the air conditioner energy consumption will have a direct benefit in reducing electricity usage and peak demand.

Though conventional air-cooled, vapor-compression cooling technologies can operate under almost any temperature and humidity condition, these technologies do not run efficiently in dry (low humidity) climates. Opportunities exist in the West's low wet-bulb temperatures and large day to night temperature swings to use significantly less energy than a standard system. Technologies designed specifically for the West could save energy and reduce peak demand.

In 2007, the Western Cooling Efficiency Center (WCEC) was contracted by the California Energy Commission's Public Interest Energy Research Program to identify the status, research needs and potential for the following advanced climate-optimized air-conditioning technologies:

- Best Practices for Evaporative Water-Based Cooling Systems: Scoping Study
- Energy-Efficient Opportunities for Packaged Rooftop Cooling Units
- Energy Efficiency Opportunities for Residential Cooling
- Condenser Mist Cooling
- Technology Demonstration: DualCool Installation, Climate-Mat Installation
- Emerging Technologies

As part of the contract, WCEC also developed a Website and Technology Catalog to discuss outreach efforts and inform the public and researchers regarding the status of various cooling technologies. The following summarizes the results from this contract:

Best Practices for Evaporative Water-Based Cooling Systems: Scoping Study

The purpose of this project was to prepare a scoping study that describes the evaporative water based cooling system technology and benefits, issues and barriers to installing evaporative cooling and some ways to manage these issues, especially water management and maintenance.

Water-based cooling technologies use dramatically less energy than conventional air-based vapor-compression systems. Since water-based cooling technologies are most effective in dry climates, they have been essentially overlooked as a significant solution for cooling nationwide,

which experiences higher humidity levels than the western climates. Water-based cooling systems are very well adapted for western climates and can contribute significantly to achieving greenhouse gas and peak demand reduction goals and to achieving net-zero energy buildings. Water-based cooling technologies can reduce energy and peak demand, lower energy costs, and improve air quality and comfort. Unfortunately, except for cooling towers and direct evaporative "swamp coolers," water-based cooling technologies have not achieved significant penetration in either the residential or commercial markets.

The scoping study results indicated that there was potential for evaporative cooling in meeting peak demand and greenhouse gas reduction goals in the western US, but there are many barriers to successful evaporative cooling implementation. Some of these barriers are perception, rather than reality. For example, historic experience with evaporative cooling indicates that it creates conditions that make it prone to failure (scaling and corrosion), while non-evaporative systems do not have these problems. There are valid concerns that must be addressed to enhance market prospects of evaporative cooling systems. This report outlines these concerns and identifies some solutions, such as using a water purge, dry-out, and fill cycle to mitigate health and maintenance concerns. There is still much work to be done to provide guidance to equipment manufacturers and owners, to ensure that the systems will perform adequately year after year, provide energy and demand savings, and maintain or improve comfort without burdensome maintenance requirements. The WCEC is beginning accelerated life-cycle testing of water management strategies and developing evaluation tools that can assist product developers, systems engineers, and owners to identify optimal operation and maintenance strategies to optimize energy, water, and maintenance resources.

Energy-Efficient Opportunities for Packaged Rooftop Cooling Units

It is estimated that 70 percent of California commercial building cooling is provided by rooftop packaged units (RTUs). Commercial RTUs create a large peak cooling load demand and represents a 22 percent load factor in California. RTUs on commercial buildings range in cooling capacities from 36,000 Btu/h (3 tons) to 600,000 Btu/h (50 tons). This report summarizes opportunities for efficiency and peak-demand improvements for rooftop packaged units and outlines current WCEC projects addressing rooftop units. This report provides information on the following areas:

- New rating system for rooftop units, Peak Energy Efficiency Ratio Sensible (PEERS); Evaporative accessories; and
- Western Cooling Challenge.

Peak Energy Efficiency Ratio Sensible

RTUs currently use energy efficiency rating scales and standards based on the RTU's total (sensible and latent) cooling capacity. California's hot-dry climates, however, mainly rely on sensible cooling and not total cooling. Thus the existing standards ratings do not accurately characterize RTU efficiencies in the hot, dry California climates.

A PIER-funded project conducted by Southern California Edison developed a new rating standard called Peak Energy Efficiency Ratio Sensible (PEERS) for Hot Dry Air Conditioners

which provides a better energy performance indicator by residential air-conditioners and light-commercial rooftop packaged units in California. This rating, appropriate for rooftop packaged units installed on new buildings or as replacement equipment, requires RTUs to meet two conditions:

1. Hot Dry 115° outdoor dry bulb/80° indoor dry bulb/63° indoor wet bulb: gross sensible capacity must be at least 75% of the gross total capacity from ARI Test A (95/80/67) and the PEERS rating must be at least 8 Btu/Watt (W)
2. Hot Medium 115°/80°/67°: gross sensible capacity must be at least 65% of the gross total capacity from ARI Test A and the PEERS rating must be at least 6.8 Btu/W

WCEC tested four units for PEERS qualification in this study, three 5-ton units and one 20-ton unit. Two of the 5-ton units did not pass the qualification test because the units failed to meet the PEERS rating criteria in Condition #1. The remaining two units passed both conditions. Stakeholders suggested eliminating Condition #1 for simplicity, which would allow more units to meet the PEERS criteria.

Evaporative Accessories for RTUs

The RTU load factor increases when the temperature and flow rate of the warm air entering the RTU increases, which lowers its efficiency. The cooler the air entering the RTU, the less energy the RTU has to use to cool the conditioned space. Two evaporative technology accessories that can be applied either as a retrofit or original equipment to improve energy efficiency and peak electricity demand are: 1) precooling the air passing through the condenser coil by water evaporation, and 2) indirect evaporative cooling of outdoor ventilation air. Although it is possible to build a "hybrid" rooftop packaged unit that comes off the assembly line with both vapor compression and evaporative cooling integrated into one box, the present practice applies evaporative components to "standard" equipment either in a custom product shop or at the point of installation.

The first evaporative cooling accessory is condenser coil air precooling, which can improve the cooling efficiency by 1-2 percent per degree F of precooling. The equipment efficiency can increase 10-40 percent for a 10-20°F temperature difference between dry-bulb and wet-bulb temperatures. The issues with evaporative precooling in the past have occurred due to poorly designed precooling devices, which have resulted in corrosion and/or scaling that restricts airflow to the condenser coil. Flushing the cooling media can minimize the corrosion and scaling,

The second accessory is an indirect evaporative cooler for ventilation air. In this application, outdoor air is evaporatively cooled and then passed through a heat exchanger with "dry" outdoor air that is cooled convectively and do not add any moisture to the ventilation air, hence the term "indirect evaporative cooler". With these indirect systems, the outdoor air temperature can be reduced to lessen the cooling load on the RTU. The trade-off is between cooler temperatures and increased electricity consumption for the fans moving the air through the heat exchangers.

A number of manufacturers produce compressor-less RTUs that use indirect (or a combination of indirect and direct evaporative cooling) for all of the cooling provided. These RTUs are sometimes used to provide the required ventilation air to the conditioned space, allowing other RTUs to operate in recirculation-only mode. Open-loop, multistage units (compressor-less) supply 100 percent of the required outdoor air, provide all of the required cooling, and have the added advantage of exhausting all internally generated pollutants. They also pressurize the space; therefore, eliminating any infiltration loads.

Western Cooling Challenge

The Western Cooling Efficiency Center issued a formal announcement for the Western Cooling Challenge (WCC) at the Retailer Energy Alliance Supplier Summit on June 5, 2008, in Denver, Colorado. The Western Cooling Challenge goal was to have manufacturers sell rooftop packaged units that used 40 percent less energy, and have 40 percent less peak electricity demand by January 2011. For this challenge, a set of test conditions was developed for annual consumption and peak performance. The challenge was developed in conjunction with the center's retailer affiliates and Pacific Gas and Electric, Sempra Energy, Southern California Edison, and the Sacramento Municipal Utility District. The WCC goal was to challenge manufacturers to modify existing equipment and not necessarily redesign a system to meet the WCC criteria.

Energy Efficiency Opportunities for Residential Cooling

Residential cooling energy use and demand can be reduced in many ways and is highly dependent upon equipment, distribution system, and electrical and thermal storage. This report focuses primarily on the equipment. This project discusses the various equipment technologies for residential cooling that are applicable to both new construction and retrofit/replacement applications and their limitations. Equipment analysis was provided on:

- Hot, dry air conditioners
- Water cooled condensers
- Indirect/direct evaporative cooling systems
- Hybrid direct expansion/evaporative systems
- Swimming pool heat sink systems
- Refrigerant desuperheaters (that give off heat from the refrigerant to heat water for domestic uses)
- Subcoolers

Another important consideration in residential cooling is electrical and thermal storage. These technologies reduce the large peak demand currently associated with residential cooling. Electrical storage systems in this application address the timing mismatch between renewable energy sources (such as wind and solar) and peak cooling needs. Thermal storage systems address the large range in western cooling energy demand more generally, using any available electricity during off-peak times to produce "coolness," such as ice, that can be released during peak-demand periods. The options on the thermal storage side include a nighttime, ice-production technology sized for the residential and light commercial markets. Other thermal

storage technologies for residential cooling include swimming pools and ground-source heat pumps that essentially use the ground for thermal storage.

Condenser Mist Cooling

This project discusses the state-of-the-art of this precooling technology and recommends future activities to assess and advance its commercialization potential. The report identifies three basic strategies for evaporative precooling of air-conditioning condenser air:

- Spraying water on the condenser coil
- Distributing water on evaporative material ahead of the condenser coil
- Creating a fog or mist of precooled air entering the coil.

The first strategy is easy to implement but is not recommended due to its many liabilities including excessive use of water, scale buildup (in hard water areas) that restricts airflow, and coil damage from water droplets corroding the surfaces. The second strategy is widely used for evaporative precooling and is not susceptible, when properly applied, to the liabilities of direct spray on the coils. Installation costs of the evaporative material and its (usually stainless steel) framework can discourage application, however.

The third (fog/mist) or "flash evaporative" strategy is appealing for its potential to combine the low cost of the first strategy with the reduced liabilities of the second strategy. Among the three strategies, fog/mist systems may also use the lowest possible amount of water.

The report identifies recommendations to advance the potential for significant penetration of flash evaporative technology into California's cooling marketplace, such as:

- Continue to support test installations and provide: 1) impartial review and reporting of project results and 2) recommendations for system improvements considering both maintenance and performance issues.
- Develop a funded project that systematically evaluates energy use versus micron water particle size of alternate misting strategies.
- Survey the range of available pressurization pumps and, if necessary, develop required cost/performance specifications. Then solicit development of small pump/water treatment packages suitable for single-family home applications.
- Determine the water particle size, if any, at which minerals in "misted" untreated water will pass through typical condenser coils.
- If research results are favorable, prepare and issue a "product opportunity" paper that summarizes the business potential for misting systems that precool condenser air.

Technology Demonstration: DualCool Installation, Climate-Mat Installation

This report documents project activities and results from analytical assistance provided by the Western Cooling Efficiency Center to Walmart, a major retailer and an affiliate that conducted

its own demonstration projects with the goal of reducing compressor and blower energy consumption. Walmart installed and monitored:

- The "DualCool" system that precools both condenser and ventilation air entering rooftop cooling units through evaporation.
- The "Climate-Mat" in-slab radiant cooling system.

DualCool

DualCool units were installed on two Munters 30-ton dedicated outdoor air supply rooftop units at the Walmart store in Dixon, California, in September 2007. The DualCool units use a direct evaporative assembly to precool condenser air. Water from the evaporative sumps is circulated through radiator coils at the ventilation air intake to indirectly precool ventilation air. After installation, both the modified units and a third (unmodified) Munters unit were monitored to assess DualCool performance.

This report provides a preliminary assessment of DualCool's potential for this application. The monitoring results confirm that DualCool technology offers significant value in this application, principally for its ability to increase capacity, thus reducing capacity required for nonventilation air rooftop units. Installed costs are expected to vary significantly depending on whether DualCool components are factory installed or field-installed. When factory-installed, DualCool will likely generate an immediate payback, with energy cost savings in addition. When field-installed at $12,500 per unit, a two-year payback appears likely.

Based on results, the Western Cooling Efficiency Center recommends the following:

- *Monitoring:* Monitor to assess persistence of savings and maintainability. Improve monitoring to better assess DualCool effects on refrigeration efficiency and capacity.
- *Modeling:* Develop an hourly simulation program calibrated with monitoring results that can project energy savings and demand reduction in any simulated climate.
- *Economics:* Based on bid data and solicited quotations, determine DualCool incremental costs for both factory- and field-installed scenarios.
- *Barriers:* Reduce DualCool water use on future applications by recapturing condensate and supporting the Center's campaign to remove the California requirement that rooftop unit condensate be directly piped to a drainage system.

Climate-Mat

Circulating cool water through floor slab tubing can save energy by cooling without a compressor, thereby reducing blower energy use and eliminating unnecessary dehumidification. In most California locations, these benefits can combine to generate more than 50 percent annual electrical savings for heating, ventilation, and air-conditioning (HVAC). Walmart has pursued radiant floor cooling as an energy efficiency measure, and in 2005 it installed large radiant floor systems in two experimental stores. However, slab tubing is expensive if installed using materials and processes common to the radiant floor heating industry and the $6-$7 per square foot installed cost precluded further use in prototype or production stores.

A team including the UC Davis Western Cooling Efficiency Center, the Davis Energy Group, and tubing manufacturer Viega have worked with Walmart to develop a lower-cost radiant floor cooling system. The concept uses large prefabricated "roll-up" tubing arrays that can be deployed quickly and do not interfere with concrete placement. In February 2007, the team installed a 12,500 sq ft. test array in the new Walmart store in West Sacramento. The test focused on the capability of installing it with Walmart's well-developed "green slab" technology. Walmart and Viega developed several system improvements and in August 2007 installed the modified system throughout the 110,000 square foot general merchandise area of a new Supercenter in Las Vegas. The installed cost for the Las Vegas radiant floor tubing was reported to be less than $2 per square foot. Since completion of that project, Viega has applied the "Climate-Mat" product name to this system, and Walmart has specified the system for installation in additional projects.

The low-cost "Climate-Mat" radiant floor-cooling system has reduced the installed cost of radiant floor tubing and manifolds by at least 65 percent, and thus has clearly improved the cost-effectiveness of radiant floor cooling. The Western Cooling Efficiency Center/Walmart/Viega team plans to work on further cost-reduction strategies to improve the marketability of the technology. The ultimate goal is to reduce the installed cost to roughly $1 per square foot. This goal appears achievable through a combination of system refinements and increasing volume. If this goal can be achieved, the technology should become compelling enough to mandate its installation in most new nonresidential cooling applications.

Emerging Technologies

This project addresses the shortage of regionally perfected cooling systems in the hot dry-climate marketplace. Innovative products typically enter this market through smaller firms, while the major manufacturers focus on mass marketing and cost-reduction for established products. One of the project purposes was to provide business and market support to entrepreneurial firms committed to developing, producing, and marketing viable energy-efficient cooling products designed for hot, dry climates. With partial support from the UC Davis Graduate School of Management, the center supported selected firms trying to significantly influence the California cooling marketplace. The center used its connections with utilities, local developers, and business expertise to support the business development and future success of the following affiliates of the Center:

- Beutler Corporation, with the following two concepts:
    - AquaChill, a residential evaporative condenser
    - FlashCool, a multiple-unit flash evaporative technology for precooling condenser inlet air
- Delphi Corporation and Coolerado, manufacturers of the HMX indirect evaporative cooling modules
- Speakman Company, manufacturer of the OASys two-stage evaporative cooler
- Ice Energy, manufacturer of Ice Bear thermal storage products

- Integrated Comfort, manufacturer of the DualCool evaporative precooling system
- Novatorque, developer of advanced electric motors
- Seeley, Australian manufacturer of innovative evaporative cooling products
- Cooling Corp., an entity interested in commercializing the center's "WicKool" passive condensate evaporator concept

This report summarizes Center activities and status of these business support efforts. The support activities include both a range of activities that are necessary and underway to support emerging technology firms in the HVAC arena, and addressing the many barriers and hurdles that slow progress. These activities are making progress in the center's mission of accelerating new technology implementation. The affiliate support activities are essential to improving the cooling processes for California buildings.

Website and Technology Catalog

The Western Cooling Efficiency Center has a website, (http://wcec.ucdavis.edu) that provides information about the center, how to contact it, what activities the center is engaged in, and center projects. The web site includes:

- "Research" menu with information about specific projects. Information is available about the Center's education activities, including posting for seminars that the center will provide through the UC Extension.
- Quarterly newsletter including archives of past newsletters.
- Links to new affiliates.
- Press coverage about the center.
- Documents on hot, dry air conditioning generated from PIER-funded research.
- Information about the Western Cooling Challenge, including requirements, links to news releases, and a list of participants.
- Presentations that the center uses to introduce itself to the industry

In addition, the Western Cooling Efficiency Center has a catalog of information and sources about energy-efficient cooling systems, including evaporative, radiant, vapor-compression, and hybrid systems. This information, developed in conjunction with the Southwest Energy Efficiency Project, includes basic descriptions of the technologies, contact information for manufacturers, and incentives. Images of most of these items are included in this report.

Benefits to California

The projects conducted by the Western Cooling Efficiency Center are aimed at producing benefits for California's residential and commercial ratepayers directly by helping to bring more efficient cooling technologies to the market and thereby lowering their energy costs. Compared to conventional air conditioning systems, these higher efficiency technologies also help reduce peak electricity demand in California and the need to have expensive surplus energy supply for

peak periods. These new cooling technologies also stimulate California's green economy with jobs in research and development, manufacturing, and installation.

CHAPTER 1:
Best Practices for Evaporative Water-Based Cooling Systems: Scoping Study

1.1 Introduction

Evaporative cooling has been used for thousands of years to provide cooling by blowing dry air past wet surfaces. Air becomes cooler as it absorbs water. Evaporative cooling technologies can use dramatically less energy than conventional air-based vapor-compression systems, in appropriate applications. Since they are most effective in dry climates, they have been essentially overlooked as a significant solution for cooling nationwide. However, they are very well adapted for western climates, and are essential to achieving greenhouse gas and peak demand reduction goals and approaching net zero energy buildings in hot dry climates. Cooling is a direct contributor to utility peak demands. The unique climate of hot-dry regions is such that cooling loads are very localized to peak days and peak hours (in contrast to more humid climates, where cooling loads are more uniform). In some western U.S. climates, residential air conditioners are used for only a few hours on only the few hottest days of the year. Thus air-conditioning is sometimes described by electric utilities as the "load from hell." Innovative cooling technologies can and should play a pivotal role in utility peak reduction efforts.

Unfortunately, except for cooling towers and direct evaporative "swamp coolers", water-based cooling technologies have not achieved significant penetration in either the residential or the commercial markets. One of the barriers to their success has been the "swamp cooler" image as a poor man's substitute for "real" air conditioning. It is also perceived as more complicated, primarily because it is water based. It is likely that any system that involves an open water cycle can collect and accumulate minerals and debris, and may inherently require more attention. On the other hand, while a conventional split-system air conditioner can operate year after year with little or no maintenance, its efficiency will drop over. There are common precedents for maintaining water based systems: for example, swimming pools, boilers, cooling towers. Since the water used in these systems is not in direct contact with ventilation air, it can be treated with chemicals that would not be advisable for direct evaporative cooling systems. There are non-chemical methods of treating water that can effectively manage water quality over time. An appropriate goal is to find optimal solutions that minimize the requirement for frequent maintenance and reduce treatment and maintenance costs.

Conservation of water resources is also a rapidly growing concern, particularly in the west; thus the water consumed by evaporative cooling systems must be considered carefully. Evaporative cooling systems consume more water than air-based systems. They typically use up to 5 gallons/ton-hour at peak operating conditions. Since water is as scarce a resource as energy in many locations, the tradeoff between water and energy must be carefully considered. It is important to evaluate not only water consumed at the site, but also water consumed at the electricity generation plant, and the energy that is used to treat and transport water to the site.

An optimized solution should be possible, although the best solution may vary from location to location.

These and other practical issues must be addressed before evaporative water-based cooling technologies can be successful in the marketplace and have significant impact on the energy situation in the west.

1.1.1 Best Practices for Evaporative Cooling Systems

The purpose of this research is to:

- Describe some of the key water-related issues for evaporative cooling systems, and identifies some of the best practices in addressing these issues.
- Identify the benefits of evaporative cooling and the barriers to installation and ways to confront these barriers.
- Describe the leading technologies for evaporative cooling, with a particular emphasis on the use of water and ways to manage water use in these systems, operation and maintenance strategies, reuse of waste water, and water treatment.
- Describe how water quality information can be used to evaluate appropriate strategies for managing water use, including a description of the requirements for an evaluation tool to provide guidance on best practices for application of evaporative cooling technologies and for water management strategies.

There are many elements of water management that have become rules-of-thumb over the years, or are based on unsupported assumptions. There are several key unknowns that must be better understood to develop a recommended optimal water management strategy. Some of these unknowns are the basis for open research questions, which the WCEC will attempt to shed light on over the course of its work. These items are highlighted in a blue box in this document.

1.2 Evaporative Cooling Benefits

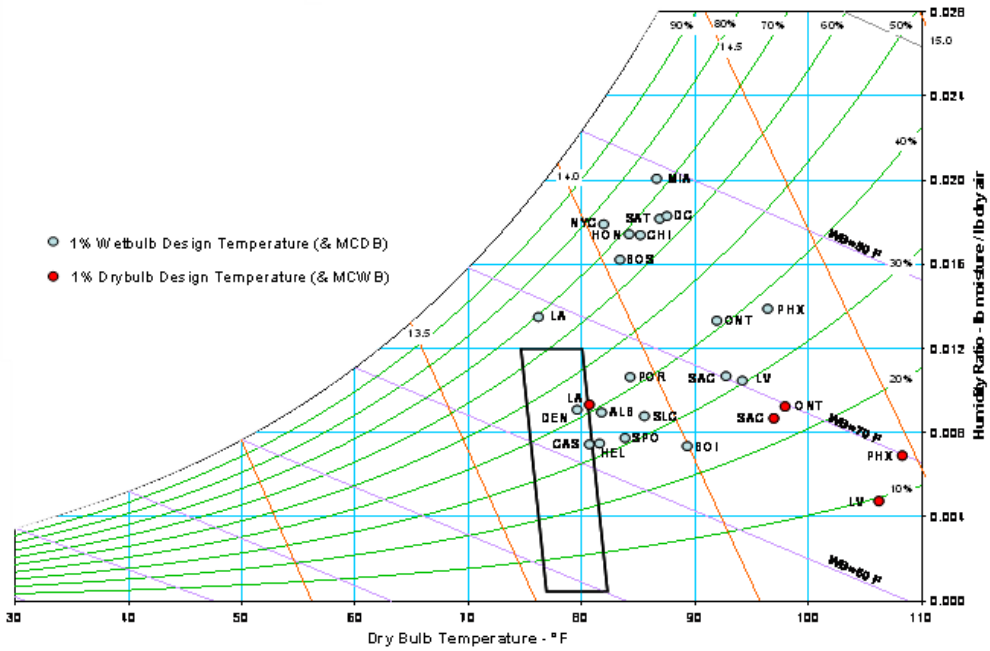
The following sections discuss key benefits offered by evaporative cooling systems.

1.2.1 Evaporative Cooling Can Reduce Energy Use and Peak Demand

The primary benefit of evaporative cooling is that it will reduce energy use. Water is a much better heat transfer fluid than air—in comparison, water's heat-carrying capacity is many times greater. Therefore, it takes much less energy to move 1 BTU using water than to move 1 BTU using air.

It is particularly beneficial to take advantage of evaporative cooling in the hot and dry climates of the Western United States, where humidity is low. Cooling provided by an evaporative cooler is limited by the wet bulb (or dew point, for some systems) depression (the difference between the dry bulb and the wet bulb temperatures). In humid climates, there is very little room for evaporative cooling. For example, in New York City, the wet bulb design temperature is 76° F and the mean-coincident dry bulb is 82° F, and the wet bulb depression is only 6° F. Figure 1 and Table 1show the wet bulb design temperatures and wet bulb depressions for several major cities.

Figure 1: Design Conditions for Selected Cities



Design Conditions for Selected Cities: 1 percent Design Wet bulb/Dry bulb Temperatures, and Mean-Coincident Dry bulb/Wet bulb Temperatures

All things being equal, a water-based cooling system can provide 30-50 percent savings over any conventional air-cooled vapor compression cooling system. The WCEC has organized a portfolio of advanced cooling technologies into four classes, with a wide range of annual energy efficiency (annual cooling Btus delivered divided by kWh used).

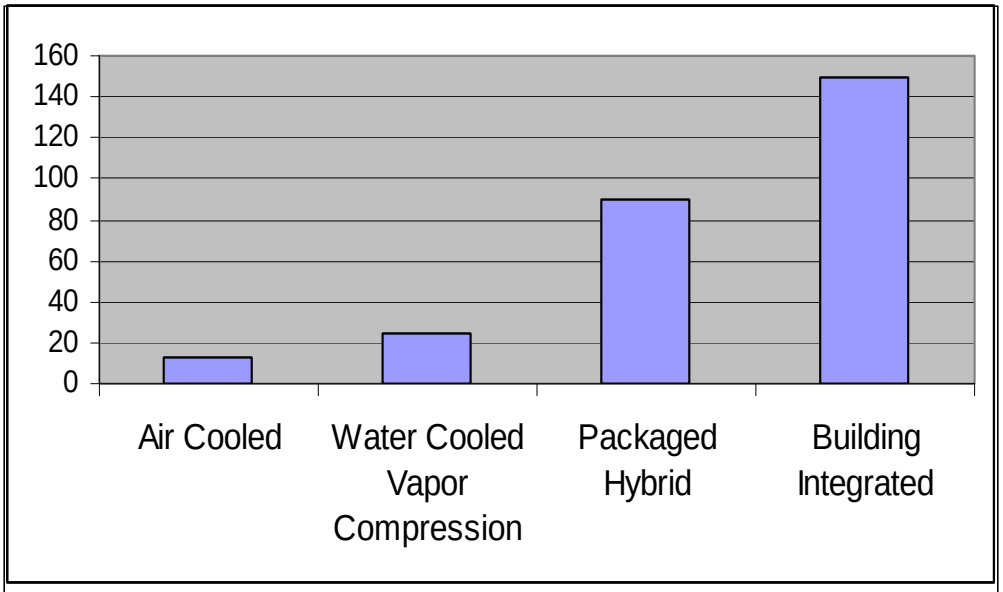
Figure 2 illustrates the maximum efficiency practically possible for different types of cooling systems. It should be possible, with existing and emerging water-based technologies, to cut cooling energy for new buildings in western climates in half by the year 2030, and to cut cooling energy for existing buildings by 25 percent.

Table 1: Evaporative Design Temperatures for Selected Cities

	City	1% WB (F)	MCDB (F)	WB Dep			City	1% WB (F)	MCDB (F)	WB Dep
NYC	New York, NY	75.8	81.9	6.1		ALB	Albuquerque, NM	64.4	81.7	17.3
LA	Los Angeles, CA	68.9	76.2	7.3		ONT	Ontario, CA	73.2	91.9	18.7
MIA	Miami, FL	79.3	86.6	7.3		CAS	Caper, WY	61.8	80.7	18.9
HON	Honolulu, HI	75.9	84.2	8.3		HEL	Helena, MT	62.2	81.5	19.3
BOS	Boston, MA	74.3	83.4	9.1		SLC	Salt Lake City, UT	65.4	85.5	20.1
CHI	Chicago, IL	76.1	85.2	9.1		SPO	Spokane, WA	63.3	83.8	20.5
SAT	San Antonio, TX	77.4	86.7	9.3		PHX	Phoenix, AZ	75.1	96.3	21.2
DC	Washington, DC	77.6	87.4	9.8		SAC	Sacramento, CA	70.4	93.1	22.7
DEN	Denver, CO	63.9	79.6	15.7		LV	Las Vegas, NV	70.3	94.1	23.8
POR	Portland, OR	67.6	84.2	16.6		BOI	Boise, ID	64.6	89.2	24.6

1 percent Design **Wet bulb** Temperatures, Mean Coincident Dry-Bulb temperatures, and **Wet bulb** Depressions (MCDB-WB)

Figure 2: Annual Energy Efficiency Ratios for Different Cooling Technologies (Annual average kWh/BTU)



Air Cooled:

- Residential Split System (11-14)
- Packaged RTU (9-13)
- Thermal Energy Storage (7-13)

Water Cooled Vapor Compression:

- Evaporative Condenser (17-25)
- Ground Source Heat Pump (13-20)

Packaged Hybrid:

- Indirect/Direct Evaporative Cooling (30-90)
- Solar Desiccant/Indirect Evaporative (20-90)
- Direct Evaporative (30-50)
- RTU Dual Evaporative Precooler(11-17)
- Hybrid Hydronic Rooftop Units(15-25)

Building Integrated:

- Night Sky-residential (80-150)
- Night Sky-roof spray (40-150)
- Radiant Floor or Ceiling(15-30)

Because of the potential for nighttime cooling and storage (enabled by the large diurnal temperature swings typical in hot dry climates), water-based cooling technologies can save even more on peak demand. With existing and emerging technologies, it should be possible to cut the peak demand for existing buildings in half by 2030, and, with some on-site renewable electricity generation, it would be possible to completely eliminate on-peak energy use for new buildings.

1.2.2 Evaporative Cooling Can Reduce Energy Costs

Energy savings result in cost savings. These energy savings are particularly valuable, since they primarily occur during utility peak periods. Since cooling system operation causes the utility peaks, reducing cooling energy during peak periods can directly reduce the need for new electrical generators. For this reason, cooling demand savings should be valued at the marginal "peaker" power plant level. If they were, many more emerging evaporative cooling technologies would be cost-effective.

1.2.3 Evaporative Cooling Can Provide Improved Air Quality and Comfort

Both direct and two-stage evaporative cooling add moisture to the ventilation air in the building, and so must deliver 100 percent outside air into the building (continual evaporation of moisture to indoor air would drive up humidity, causing occupant discomfort and ultimately eliminating further cooling potential). Supplying 100 percent outside air is quite advantageous for air quality. There are many applications where a large amount of outdoor air is required; for example laboratory buildings and schools. With conventional systems, high ventilation rates come at a cost as more energy is used to condition the larger volume of air. With high ventilation rates, it is also possible in cooling season to provide more ventilation of the building under low humidity conditions, so evaporative cooling can provide superior control of building humidity.

1.3 Water Concerns

Despite significant advantages, the market penetration of evaporative cooling is quite low. This is due partly to low awareness, but also partly to a number of concerns that building owners have about employing water-based technologies in historically air-based applications. Some of these concerns are baseless. Others are based upon earlier experience with more primitive technologies. Still others are valid concerns, and must be addressed by technology promoters to achieve a more significant penetration.

1.3.1 Concern That Evaporative Cooling is Unreliable

Because evaporative cooling systems have components that use water, they are perceived to be more complicated than a conventional air conditioning device. This perception is actually not the case. Both devices can include fans and pumps and heat exchangers. It is true that water-based systems have the potential to leak water, causing equipment or building material damage. Vapor-compression devices can also have leaks. When refrigerant is leaked, there is no local damage, but more significant environmental damage occurs.

The most significant difference is that evaporative cooling has open system circulation: the water that is circulated is open to the environment, and therefore it can pick up contaminants from the environment. Since the water evaporates, any contaminants in the water will become more and more concentrated. Scaling and microbial growth are the biggest concerns. Either deposit type might degrade the heat transfer effectiveness of the evaporative media, and might cause fouling of water lines, fittings, and nozzles. If effective water management schemes (described in more detail in the Water Management Strategies) are employed, this fouling can be minimized.

Another water-based concern is corrosion. If the water becomes too corrosive, it can cause any metal parts or fittings to degrade. The most important factor in avoiding corrosion may be the avoidance of the use of corrodible materials in the evaporative cooling unit itself. Stainless steel, brass or PVC fittings and a fiberglass or other non-metallic housing can help to avoid corrosion. Since corrosion is the opposite of scale build up, controlling the equipment corrodibility will allow the unit to be more tolerant of nonscaling water chemistries.

Because of these tendencies, evaporative cooling devices do in fact require more maintenance than a conventional air conditioner to stay operating over the years, although conventional air conditioners do require more maintenance than they typically receive and their performance also can tend to degrade. The maintenance required to keep them running is described in the Water Use and Maintenance section of Chapter 1.

1.3.2 Concern That Humidity Will Be Too High

In direct evaporative coolers, all the moisture that is evaporated is added to the occupied space. In extremely dry climates, this is humidity is a welcome addition. However, in many cases, the humidity will be excessive. This can cause discomfort and health effects, and can contribute to mold growth. Whether the amount of humidity added will be excessive depends upon the air flow, the outside air humidity, and the effectiveness of the evaporative media.

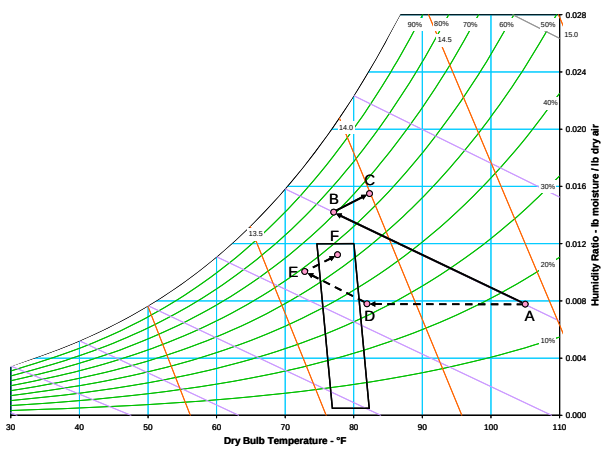
The ASHRAE Standard 55 Comfort Zones (ASHRAE, 2005) define the upper and lower limits of acceptable indoor temperature and humidity for summer (see Figure 3) and for winter. The upper humidity limit (humidity ratio of 12 lb. water/1000 lb. dry air) is actually based upon concern about materials damage from mold growth, rather than human comfort. Extremely high humidity, however, is not comfortable.

The greatest concern for comfort is with direct evaporative cooling, which introduces the greatest fraction of humidity to the air. In order to meet the cooling load throughout the summer, direct evaporative cooling can typically only create comfort in on design days in locations with a design wet-bulb of about 68ºF or less. For example, it could be used on a design day in Salt Lake City, where the design wet-bulb is 65ºF, but not in Sacramento, where the design wet-bulb is 70ºF. Of course, even in climates like Sacramento, it can be used for many hours throughout the cooling season. The solid line from A to B in Figure 3 shows a direct evaporative process. (The lines from B to C and from E to F represent the room loads that warm the air from its inlet to its outlet conditions).

Indirect or two stage evaporative cooling can be used in much more humid climates than direct. The dashed line from A to D in Figure 3 illustrates an indirect stage, and the dashed line from D to E illustrates a direct stage, in a two-stage evaporative process. At least one study looked at the indoor conditions in an advanced two-stage evaporatively cooled home. The Davis Energy Group found that during the monsoon season (brief period of high humidity, when daytime wet bulbs can exceed 80 ºF) in the southern desert area of California, direct/indirect evaporative cooling alone was not sufficient to not maintain comfort (DEG 2008). They state that in climates with less extreme cooling loads and design wet bulb temperatures of around 70 °F, advanced two-stage evaporative coolers have great potential.

Evaporative condensers do not affect comfort or the humidity of the incoming air (unless their use allows an undersized unit to have enough capacity to meet loads and provide comfort).

Figure 3: Evaporative Processes on a Psychometric Chart



1.3.3 Concern That Evaporative Cooling Will Cause Health Problems

Another unique attribute of water is its ability to support the growth of microbes. There is a valid concern that an evaporative cooler might tend to become contaminated with algae, mold, and even Legionella and other bacteria. These life forms are abundant in the air and soil surrounding the unit, and one cannot control their entrance into the cooler. However, one can control the conditions under which they grow, and make it inhospitable.

Algae growth is unsightly and can foul the lines and nozzles in the evaporative cooler. It can be effectively controlled by eliminating one of the resources that it requires to sustain life: direct sunlight. If the evaporative cooler designer makes sure that the sump is shaded, algae will not be a problem.

Mold is more difficult to control, since it does not require sunlight. The best way to control mold is to interrupt its life cycle with a periodic dry-out cycle. Dry-out cycles probably contribute to scale build up, so an optimum combination of wetting and drying must be found. This optimum combination is not well understood currently. Biocides have also been used to prevent mold growth, but there is a health concern when ventilation air comes in contact with chemically treated water.

Bacteria are another concern, including Legionnaire's Disease, which is a special concern for HVAC professionals, because of its deadly history. Legionella pneumophilia will grow in water between 68 ºF and 115 ºF. Evaporative condensers and cooling towers operate in this dangerous range, so this is an important concern. Evaporative coolers typically run below 65, so it is less of a concern, although if they are left idle for any period of time, the temperatures will rise and bacterial growth will be a concern. The best way to prevent bacterial growth is to prevent the build-up of dirt, scale, corrosion by-products, slime, algae, and foreign matter that can serve as a breeding ground for Legionella and other bacteria, through periodic cleaning.

Bacteria could be prevented with oxidizing or non-oxidizing biocides. These are harmful to evaporative media, however, and may cause health concerns, and thus are not typically used for this application. Ozone treatment is less toxic to humans and easier on the evaporative media, and has potential for use in evaporative cooling systems. Care must be taken to not introduce too much ozone, as it will cause the water to become corrosive.

Future Research: What is the optimum combination of wetting and drying of the evaporative media, to simultaneously control scale and microbe growth?

1.3.4 Concern That Evaporative Coolers Will Be Too Difficult to Maintain

To prevent the issues described above, an evaporative cooler should be periodically maintained. This service need not be difficult. The primary service required is to inspect and clean the unit. The inspection is to see if any of the fittings appear fouled, and look on the evaporative media for evidence of scale or microbe buildup. If any such a buildup is evident, the unit should be cleaned thoroughly, and the water management strategy should be reevaluated. Even if no excessive buildup is evident, the unit should be periodically hosed off and cleaned. If the media is excessively scaled, it should be replaced, although the degree of scaling required to degrade the performance of the unit is unknown. Since both mold and scale buildup can be prevented with increased supply of fresh water, there will be an optimum solution that minimizes both maintenance required and water use.

Most maintenance of evaporative coolers can be performed by an owner (either residential or commercial). It is probably not realistic, however, to assume that the owner will carry out this maintenance faithfully. Programs to educate owners on the importance of maintenance and the maintenance measures themselves and to remind owners when maintenance is required may be helpful, but they may not be 100 percent effective. Maintenance can be provided by the equipment distributor, in a part of a service contract. Integrated Comfort, Inc., for example, has implemented this type of service: they bundle a two-year service contract with all sales.

It is possible that in the future, onboard diagnostics can substitute to some extent for frequent service calls. By monitoring variables such as the water chemistry, the differential pressure across the evaporative media, and the energy use, and setting alarms to identify when the system seems to be malfunctioning, it might be possible to reduce the frequency of service calls. It will probably always be necessary to make service calls periodically.

Future Research:

- *What is the relationship between scale growth and degradation of performance? What is an optimum maintenance regime?*
- *What is an effective service model for evaporative cooling equipment?*
- *What variables can be monitored to identify when an evaporative unit performance is beginning to degrade or is malfunctioning? How is this best annunciated, and to whom?*

1.3.5 Concern That Evaporative Cooling Will Consume Too Much Water

Evaporative cooling systems consume less energy than air-cooled systems. This comes at the cost of additional water consumption. Whether or not it is a good tradeoff will depend on the relative energy-efficiencies of the systems, the relative water-efficiencies, and the costs for energy and water. This tradeoff will have to be made on a case-by-case basis.

While the water use will increase, it need not increase dramatically. The water use is a combination of water used for evaporation and the water used to flush away excess minerals. The amount of water used can be reduced by minimizing the water that is evaporated using these strategies:

- In indirect evaporative heat exchangers, using building exhaust air instead of outdoor air in the wet section
- Reducing air flow in the wet section of the heat exchanger
- Rejecting heat to the night sky in combination with thermal storage

The purchased "bleed" or "purge" water used to remove excess minerals can also be minimized by:

- Capturing rain water to blend with purchased water
- Using non-chemical water treatment
- Applying regular maintenance to assure proper bleed or purge operation
- Reusing bleed or purge water for landscaping
- Optimizing bleed or purge cycles

Making use of rainwater is an excellent way to reduce the amount of water that must be delivered to the site. Rainwater has very different chemical properties from groundwater: its low mineral content makes it very soft, although this lack of minerals makes it "mineral-hungry", and corrosive. It is often beneficial to combine rainwater with recirculated water to obtain blended water with suitable characteristics. Unfortunately, the availability of

precipitation does not typically coincide with peak cooling periods in dry climates. Multiplying the annual rainfall by the rooftop area (and adjusting units) suggests the available water quantity, but water storage container costs typically preclude storage of all seasonal rain water.

Another way to reduce the water consumed is to combine evaporative cooling with other water-consuming applications. For example, discharged evaporative cooling water can be applied to landscape irrigation. Using this strategy, several buildings currently under design will have a "green roof" irrigated by the discharge from a set of cooling towers. The allowable chemistry has not been well studied. This adds a further complexity to the optimization of water use, energy use, and maintenance: it is possible that the optimal bleed rate will depend more on the requirements for landscape irrigation than on requirements for evaporative cooling system operation.

Looking at on-site water use is really only half the picture, however. Water is also used to produce the electricity consumed by an air conditioning unit, so reductions in energy will also reduce water use at the power plant. The amount of water used to generate electricity depends on the source of the electricity. Water is evaporated in the cooling towers of thermal electric power plants (nuclear and fossil fuels), and about one-half gallon is used for each kWh produced (Torcellini et al, 2004). Reservoirs evaporate a great deal more water than the rivers they replaced, and their average water consumption for hydropower is about 18 gallons per kWh. Specific evaporation rates vary from location to location, and across the year and the day. Torcellini estimated the average consumption for each state of the US, based on the annual average generation mix. These values, for western states, are shown in Table 2.

Table 2: Average Annual Water Consumed in Electricity Generation in the United States and Western States

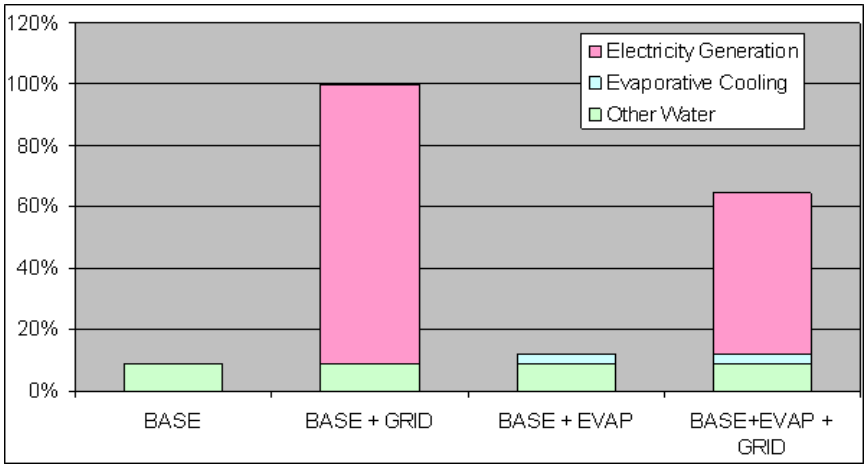
Region/State	Water (gal/kWh)	Region/State	Water (gal/kWh)
NATIONAL	2.0	New Mexico	1.1
Arizona	7.9	Nevada	7.3
California	4.6	Oklahoma	8.4
Colorado	1.2	Texas	0.43
Kansas	0.58	Utah	3.05

Source: Torcellini, 2004

When an analysis of the impact of evaporative cooling is expanded to include water used at the electricity generation station, the picture looks much different. Figure 4 shows a qualitative analysis done for the design of a large chain retail facility in Nevada. Evaporative cooling was projected to increase the on-site water use (the difference between bars 1 and 2). When the water used for electricity generation is added, however, the base case air-cooled building's

consumption increased dramatically. With evaporative cooling, the consumption actually decreases, although this will have to be evaluated on a case by case basis. There is a need for data and evaluation tools that can consider electricity generation at a finer grain (looking at time of year and time of day differences in the generation mix) to further optimize the water use. For example, the water-reducing impact of avoiding a peak kW may be quite different from the impact of avoiding an average kWh, depending on the resource mix at the peak and the marginal generation source.

Figure 4: Effect of Water for Electricity Production on Site Water Use



Future Research:

- *What are the practical issues encountered when reusing discharge evaporative cooling water for landscaping? What are the limits on allowable discharge water quality? Are there plant species that are particularly tolerant of mineral-rich irrigation water?*
- *What data are required to develop estimates of the water used by electricity generation for different seasons and different times of the day? What kinds of tools could make use of this information?*

1.3.6 Concern That Water Used Will Cost Too Much

Aside from the global and local resource issues, an increase in on-site water consumption will cost the building owner more. Water rates vary widely. It should be recognized, however, that water tends to be an undervalued resource, and the current rates often do not cover the cost of supplying water in the intricate system of reservoirs in the west, let alone cover the significant costs that will be borne as the water-supply reservoirs in the west approach the end of their useful lives. Most reservoirs were designed for a useful life of from 50 to 100 years, and were built in the 1930's. They have limited life because silt that enters the reservoir from streams

tends to settle in the slow-moving reservoir (Reiser, 1986). One can anticipate that the cost of water will go up over time. Still, it is difficult to imagine that the cost of providing water for evaporative cooling will outweigh the reduction in energy costs.

Since a large fraction of the water used in an evaporative cooling system is evaporated and never makes its way into the sanitary sewer, it is possible to have sewer charges adjusted in many jurisdictions to reflect "use without sewage." In some large facilities, the sewer is separately metered, so these impacts can be measured directly. If the sewer is not separately metered, it is often possible to negotiate a discount with the water utility.

1.4 Characteristics of Cooling Technologies

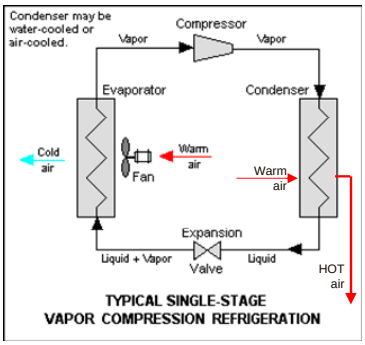
Before considering water management strategies, it is important to understand how vapor-compression, evaporative, and night-radiative cooling systems work, and whether/how they use water.

1.4.1 How Cooling Works

1.4.1.1 Vapor Compression Cooling

The most common residential and non-residential cooling systems use a compressor, two heat exchangers, an orifice, and a refrigerant in a closed cycle to move heat from indoors to outdoors. The compressor sends a compressed hot refrigerant gas to the outdoor heat exchanger where it gives up heat to the outdoors and condenses the refrigerant to a liquid; hence the outdoor heat exchanger is called the "condenser." The high-pressure condensed liquid then passes through the orifice, which exerts a pressure drop such that the refrigerant quickly expands in the downstream, low-pressure zone. The refrigerant enters the indoor heat exchanger immediately after the orifice; the expanding refrigerant cools rapidly as it flashes to a vapor; hence the indoor heat exchanger is called the "evaporator." From the evaporator, the low-pressure refrigerant gas enters the compressor, which re-pressurizes the refrigerant. The work of compression also heats the refrigerant, which leaves the compressor as a hot, high pressure gas (see Figure 5).

Figure 5: Standard Vapor Compression Cycle



Most conventional packaged air conditioning systems use "air-source" indoor heat exchangers and "air-cooled" outdoor heat exchangers. Two types of residential designs are common. Window and through-wall units have all components in a single package, while "split-system" central air conditioning systems have the indoor and outdoor heat exchangers joined by refrigerant lines, allowing the heat exchangers to be widely separated. The outdoor section is called the condensing unit and includes the compressor, the outdoor heat exchanger (the "condenser coil") and a fan that moves outdoor air across the coil. The indoor section includes the indoor heat exchanger (the "evaporator coil"), the orifice, and a blower that moves air across the evaporator into supply ductwork.

The most common non-residential cooling units are like through-wall residential units; all components are contained in a single box. They are designed for placement on roofs and hence are commonly known as rooftop units or RTU's. All of these common equipment types are capable, if properly sized, of satisfying cooling loads in buildings virtually anywhere on earth. Their efficiency depends on the temperature difference between indoor and outdoor air; the greater the difference (the warmer the outdoors) the lower the efficiency. Therefore, they typically operate more efficiently in humid climates than they do in dry climates, for two reasons:

1. Peak outdoor temperatures are typically lower in humid climates than in dry climates because moisture in the air tends to moderate temperatures,
2. The evaporator coils condense more moisture from the indoor air in humid climates than in dry climates, and this "phase-change" cooling is quite efficient.

Condensing moisture from the indoor air ("dehumidification") occurs in almost all conventional cooling systems because the evaporator temperature frequently drops below the dew-point temperature of the indoor air. However, one liability of typical units designed to operate in any climate is that in dry climates they often dehumidify unnecessarily. In California climates, conventional systems use 10-20 percent of their energy extracting moisture that doesn't need to be removed.

1.4.1.2 Evaporative Cooling

Evaporative cooling takes advantage of the air's ability to hold moisture, one of the most convenient characteristics of the earth's atmosphere. (Imagine the inconvenience of water spills or wet clothes that never dry.) Dry air can absorb a great deal of moisture, and wet air can only absorb a little, so "how dry is the air?" is the vital question affecting efficiency and viability in evaporative cooling evaluations. Just as vaporizing water by boiling in a saucepan removes heat from an electric burner, water vaporizing in air removes heat from (such as cools) the air and/or the surface from which it evaporates. This heat exchange process is at the heart of all evaporative cooling systems, which in dry climates are 3 to 5 times more efficient than compressor-based cooling systems.

The engineering of evaporative cooling systems requires an understanding of "psychrometrics," a science dealing with the state of air/water mixtures. Air in our environment ranges between 0 percent relative humidity (a rare state in which air contains no water vapor) and 100 percent

relative humidity (ready to rain). Crucial measures for evaporative cooling are the "dry bulb" and "wet bulb" temperatures. Dry bulb temperatures are the widely reported values accurately obtained with a high quality thermometer. The wet bulb temperature depends on the amount of moisture in the air. For air at less than 100 percent relative humidity, the wet bulb temperature is always cooler than the dry bulb temperature; the wet bulb reading can never exceed the dry bulb reading. The wet bulb is the lowest temperature that can be achieved in a direct (one-stage) evaporative air cooling process. The greater the difference between dry and wet bulb temperatures, the greater the temperature drop in an evaporative cooling system. For example, during a typical dry summer day when outdoor dry and wet bulb temperatures are 95ºF and 65ºF, a "perfect" direct evaporative cooler would deliver 65 ºF air.

1.4.1.3 Night Radiative Cooling

The night sky is the coldest available above-ground "heat sink" in the outdoor summer environment. As a radiative receiver, the sky falls below freezing during some portion of most summer nights in dry temperate climates. The cold, clear night sky is the reason for the large daily temperature ranges in dry climates. All surfaces facing a clear sky radiate heat into space more quickly during the night time than during the day time. The cooling rate is highest when humidity is low, since moisture in the air raises the apparent sky temperature and impedes heat discharge to the sky. Radiation is a powerful heat transfer mechanism, and in fact is proportional to the difference of the fourth powers of the absolute temperatures of the emitting and receiving surfaces.

There are multiple ways to discharge heat to the sky at night. Roof surfaces naturally cool by radiation, such that most roofs collect dew by morning. Condensation occurs because the roof surface cools to below the "dew point" temperature of the outdoor air. The dew point is lower than the wet bulb temperature, so night radiative systems have the potential for lower temperatures than are economically achievable with evaporative systems. At typical night outdoor temperatures when the dry and wet bulb temperatures are 66 ºF and 58 ºF, respectively, the dew point temperature is 53 ºF and the sky temperature is 20-25 ºF. But because of their mass and contact with the warmer outdoor air and condensing "dew", roof surfaces do not typically fall below the dew point temperature.

Thermal storage is required to maximize the potential for cooling discharge to the night sky, since the cooling process occurs at night when cooling loads are typically lowest. Water, rocks, concrete, and soil are the most economical storage media but "phase-change" media such as eutectic salts may also be used to reduce the storage media space requirement. While air may be used in a night sky-radiative system, the best performing systems to date distribute water in an "open system" on the roof, combining evaporative and radiative cooling mechanisms. (Of course, if the water is circulated at night, when there are lower air temperatures, there will be lower evaporative losses). Circulating water in closed panels without water consumption is also a possibility, but the high cost of the panels is a deterrent to project economics. This study focuses on the water consumption of open water-based night roof radiative systems.

1.4.2 Cooling Technology Descriptions

1.4.2.1 Direct Evaporative Cooling

Evaporative cooling occurs when moisture is added to air whose relative humidity is less than 100 percent. The lower the relative humidity, the greater the temperature drop when moisture is added. Evaporative cooling is the original and most natural process for human comfort cooling, since it is evaporation of perspiration which allows humans to withstand summer temperatures (but not always in perfect comfort). Wet fabrics to mop a brow, or to intercept a warm breeze through an open window, are simple applications of evaporative cooling dating to prehistory.

Direct evaporative cooling is the term applied to comfort cooling applications that simply add moisture to a moving air stream to cool the air while increasing its humidity. This process only works for a moving air stream because adding moisture to a fixed body of air will increase humidity to 100 percent, preventing further evaporation. Thus, direct evaporative cooling requires a source of air drier than that in the space to be cooled. Outdoor air is not always in such a condition, especially in humid climates.

In most direct evaporative cooling applications, moisture is added to a moving stream of outdoor air delivered to the indoors; an equal quantity of indoor air must leave the building for the process to continue. Even the direct evaporative "mist" systems used for cooling desert outdoor plazas require air movement, which they automatically create; the cooled air falls, sucking more dry air into the nozzle path to continue the process.

Air that reaches 100 percent relative humidity in an evaporative process emerges at the wet bulb temperature, the theoretical limit for direct evaporative cooling. The "effectiveness" of such a (rare) cooler would be 100 percent; effectiveness is a percentage measure of relative progress from dry bulb to wet bulb temperature. Achieving more than 90 percent effectiveness in a direct ("one-stage") cooler is difficult, requiring very thorough mixing of water and air particles. Most evaporative air coolers operate with 70 to 90 percent effectiveness using wetted fibrous or corrugated pads or "media." These "wet surface" direct evaporative coolers typically use pumped re-circulating water systems to keep the media wet. (Another direct evaporative approach known as "flash evaporative technology" (FET) forces highly pressurized water through small nozzles to create a fine mist that is injected into a dry air stream, thus eliminating evaporative media.)

Figure 6: Direct Evaporative Cooler

Photo credit: Seeley International

In a typical direct evaporative cooler (Figure 6) air flows horizontally through the vertical media as water from a sump is pumped and distributed along the top of the media. The media absorbs water by capillary action and maximizes contact between the air stream and wet fibers or corrugated paper. To ensure that all surfaces are wet, more water is usually pumped than can be evaporated, and excess water drains from the bottom of the media into the sump. An automatic refill system replaces evaporated water.

Fibers from Aspen trees woven into a pad 1-2" thick have traditionally served as the evaporative media. These pads are still widely used in inexpensive evaporative "swamp" coolers. They typically achieve 70 percent effectiveness and last 1 to 2 years in service. The "CELdek" and GLASdek" rigid media introduced by Munters Corporation in the late 1960's have facilitated longer life modern evaporative cooling unit designs. Pads of treated paper have gradually been replacing aspen pads as more modern evaporative air cooler designs have emerged in the last 20 years. Many new models use "rigid media" fabricated from corrugated paper or fiberglass into rectangular blocks 4" to 12" thick. (The "Oasis" series manufactured by Des Champs Laboratories of Buena Vista, VA integrates heat pipe indirect evaporative cooling with optional direct evaporative and compressor-based cooling in a large rooftop cooling unit.) The rigid media typically achieve 80-90 percent effectiveness and also have longer operating lives compared to woven pads. Air follows a contorted path through the media, facilitating the higher effectiveness.

Direct evaporative cooling may be applied to air that is supplied into a building, or to air (either outdoor or building exhaust) that is used to cool the condenser of a compressor-based cooling system. The moisture added in the direct evaporative process increases the humidity of air supplied to a building, but has little impact when applied to the condenser unless moisture droplets hit and erode fins on the coil. When the highly-recommended "rigid" direct evaporative media is used, droplets will not leave the media unless the airflow velocity exceeds 400 feet per minute. Evaporative pre-coolers and evaporative condensers are both technologies

that are applied to a compressor-based system condenser rather than to air entering a building air.

1.4.2.2 *Hybrid Evaporative Cooling*

Evaporative pre-coolers are virtually identical to direct evaporative coolers in their use of a vertical evaporative media, but with air pulled through the media (and then the condenser coil) by the condenser fan(s) instead of through the evaporator coil by a supply blower prior to being supplied into the building. Using 8" rigid media, pre-coolers typically achieve 80-85 percent effectiveness, so that with dry bulb temperature at 100F and wet bulb temperature at 70F, air will enter the condenser coil at 75 ºF instead of 100 ºF. On a newly-introduced high efficiency rooftop unit series, this 25 ºF reduction in condenser inlet air temperature increases capacity by 13 percent and energy efficiency ratio (EER) by 53 percent. Pre-coolers are more widely used on commercial rooftop units than on residential cooling systems.

Evaporative condensers typically evaporate water right on the condenser surface, rather than in an evaporative media to cool air entering the condenser. A few low-production evaporative condenser products are available in both residential and non-residential size categories. Water issues are similar to other direct evaporative systems, although hardness mineral buildup may be more likely when water with high mineral content is applied directly on the warm condenser surfaces.

1.4.2.3 Indirect Evaporative Cooling

Indirect evaporative cooling systems cool air without adding moisture. They are usually more expensive than direct systems, but have many applications.

In non-evaporative heat exchange processes, when two materials at different temperatures come in contact, the warmer one cools and the cooler one warms up as they try to reach a common temperature. In contrast, when dry air contacts slightly warmer water, the evaporative process magically cools both the air *and the water*. This characteristic facilitates many interesting indirect evaporative cooling systems. Indirect systems use a direct evaporative process to cool air and/or water on one side of an impermeable heat exchange surface, such as a thin plastic plate or tube. The wet side cools the dry side without adding moisture. Spraying water on a hot roof, for example, evaporates water at the roof surface, cooling the roof deck that in turn cools indoor space below, without increasing indoor humidity.

A schematic diagram of a typical indirect evaporative air cooler is shown in Figure 7. The essential element is a heat exchanger in which dry air to be supplied to a building contacts heat exchange surfaces whose "other sides" are cooled evaporatively by a water spray or drip system. "Primary" outdoor air enters the horizontal flow passages and is cooled by contact with the heat exchanger surfaces, which may be parallel plates or tubes. The wet passages are evaporatively cooled as water sprayed or dripped from the top of the passages meets dry air entering at the bottom. Air in this vertical "secondary" path, usually also drawn from the outdoors, is cooled too, but is highly humidified and usually discharged back to the outdoors.

Figure 7: Schematic of a Typical Indirect Evaporative Air Cooler

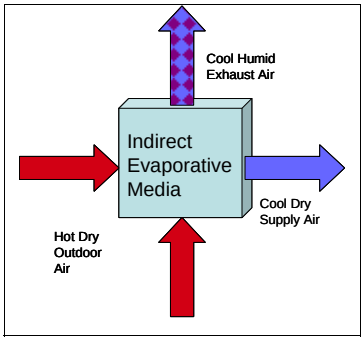
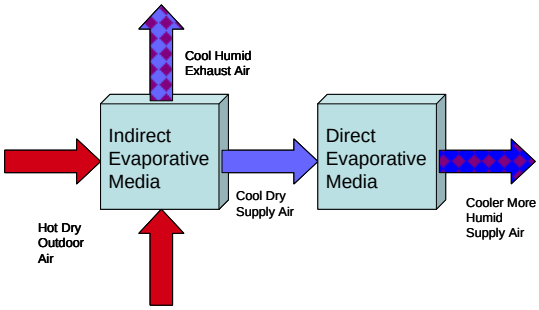


Figure 8: Schematic of a Typical Two-Stage Evaporative Air Cooler



Indirect evaporative heat exchangers were typically fabricated of aluminum or stainless steel until, in the 1970's and 1980's, plastic models were introduced to reduce costs. The plastic heat exchangers have slightly poorer heat exchange but have had market success due to their lighter weight, ease of fabrication, and corrosion resistance. Uniform moisture distribution (hence evaporation) over the full surface improves heat transfer, so the wet side of indirect heat exchanger materials is often "flocked" or textured to prevent beading of water droplets.

While indirect systems are often configured in a "cross-flow" heat exchange design with a vertical secondary air path, heat pipes may be used to allow counter flow, side-by-side air flow which is particularly useful for large rooftop applications. Heat pipes contain a refrigerant that evaporates at the pipe's warmer end and condenses at the cooler end. With one end in a dry air stream (such as summer ventilation air entering a building) and the other in an evaporatively-cooled stream of building exhaust air, heat pipes can efficiently cool the ventilation air without adding moisture.

Other indirect strategies use evaporatively cooled water rather than air to cool a building or supplement compressor-based cooling. In these cases, the evaporative cooler may be located

remotely from the air stream being cooled. Cooling towers, for example, evaporatively cool water used for efficient discharge of the heat removed by compressor-based air conditioning systems, with the cooling tower sometimes far from the chiller. Cooling tower outlet water is increasingly used in dry climates to directly cool air in heat exchange coils, or in radiant cooling applications using hydronic circuits in the floor or ceiling. These indirect evaporative cooling strategies, though often used to cool ventilation air, do not require that an outdoor air stream pass through the building.

There are also two-stage systems that combine a direct stage with an indirect stage, as illustrated in Figure 8.

1.4.2.4 Roof Night Radiative Cooling Systems

Night-radiative cooling of water on roofs has been demonstrated on a variety of projects in the western U.S. All installed systems have used spray arrays to distribute water uniformly on the roof surface. Radiant roof cooling systems operating through an 8 hour night cycle discharge 150- 600 BTU/sq. ft. of roof per night, depending on weather conditions, starting water temperature, water storage volume, and tank stratification design. In R&D efforts from 1988-91, Davis Energy Group (DEG) developed a water spray rate "rule-of-thumb" (ROT) of one gallon per minute (gpm) per 100 square feet of roof surface. This flow rate was determined partly from design flow rates for typical irrigation spray heads, and partly by a desire to cool water to the lowest possible temperature. In the hottest outdoor conditions and lowest heat discharge rate, the ROT flow rate results in only a 4 ºF water temperature drop across the roof; this relatively small drop means the system, at the expense of pumping power, is cooling water to a relatively low temperature for the outdoor conditions. Experience and analysis suggest that significant evaporative cooling occurs in the early part of the night cycle when the water temperature is above the wet bulb, but that in the nearer-dawn hours cooling largely radiative, since the sprayed water is near or below the outdoor wet bulb temperature. While the evaporative component uses water, the radiative component does not.

Another night radiative cooling option is "sheet flow" distribution of water instead of spray arrays. On a typical large retail roof with a 350-foot one-way slope, the average water flow depth under a sheet flow scenario will vary with water flow velocity. Velocity will vary with roof slope, surface characteristics, and wind. Tests conducted in 2008 determined whether water depth in "sheet flow" is adequate to spread water uniformly sideways and fully cover the roof surface. If steady sheet flow does not achieve full coverage, flow could be sequenced, applying the full flow to one area and then another. In addition to insuring full coverage of the section served, this strategy could reduce pumping power and allow the unserved roof section to pre-cool by radiation in preparation for its next flow sequence, increasing net cooling efficiency. Sheet flow systems are in early development, but are expected to reduce water consumption by minimizing the evaporative cooling component.

1.5 Water Management Strategies: Best Practices

The most effective water management strategy for persistent site energy performance and reducing maintenance costs would be once-through operation: fresh water is always provided

to the evaporative medium and any water that is not evaporated is discharged, taking away dissolved minerals, microbes, and solids. This would result in very few water quality issues and minimize maintenance. However, water consumption would be excessive, which would be expensive and inappropriate from a total resource point of view. Therefore, the challenge in water management is to identify optimal means of reusing the non-evaporated water so that it minimizes the potential to degrade performance and cause operational or health problems. In this optimization, we try to minimize water use, energy use, and maintenance, and the optimal combination may differ from application to application. Little work has been done to investigate optimal water management strategies for evaporative cooling processes. The WCEC will conduct accelerated life-cycle laboratory tests, to identify effective and ineffective strategies, and identify methods to optimize strategies for a particular application. What follows is a description of what is known about some of the strategies that are employed or proposed.

1.5.1 Unit Operation and Maintenance

"Makeup" water is typically added to a system to replace water that is evaporated or that is discharged from the system through continuous bleeds or periodic purges that are used to reduce the concentration of hardness minerals.

1.5.1.1 Bleeds

If a cooling unit is operated continually without recycling the water, water evaporates, leaving behind the contaminants it had contained. The longer the unit is operated, the more concentrated these contaminants become. The terms "concentration ratio" and "cycles of concentration" are commonly used to describe the concentration of contaminants in proportion to the concentration of contaminants in the original fresh water. For example, when the concentration of contaminants in recycled water is twice as high as in the fresh water, it has a concentration ratio of 2, and it is said to have 2 "cycles of concentration." When the concentration of particular contaminants reaches the saturation point, they come out of solution, and are either deposited on the equipment, or settle into the bottom of the sump. This is how scale is formed, and is the source of the "sludge" that is often found in sumps.

Of course, in a real system, as water evaporates, the amount of water in the system will fall, and it is necessary to supply fresh makeup water to keep the water in the sump at a constant level. The concentration of the fresh water, the volume of water in the system (including the sump, the evaporative media, and all connecting piping) and the evaporation rate all combine to determine whether the steady-state concentration of water will be unacceptably high.

If the concentration is too high, it is common to continually bleed off some of the concentrated water and replace it with an additional amount of makeup water. The bleed rate is one of the major variables that can be optimized in an effective water management strategy.

There are two ways to control the bleed rate: a constant value, and varying to maintain a constant concentration. A constant bleed is the simplest to implement, but it may result in too much or too little fresh water at different levels of operation. The contractor can set the bleed rate at a reasonable level. The owner should be informed about how to reset this level if there is evidence of scale buildup or if the owner wishes to reduce water consumption. The bleed must

be configured so that it does not operate when the unit is not operating. In this case, however, some other means is necessary to ensure that microbes do not have the opportunity to grow in the standing water. Because of concern about water use, California Title 24 does not allow evaporative coolers that utilize a bleed system.

An improvement on this is to control the bleed rate to maintain a constant concentration. This is typically based upon measuring the conductivity of the water, which correlates to the Total Dissolved Solids. The conductivity of the sump water, taken together with the conductivity of the makeup water, provides a good approximation for the cycles of concentration. The sensor must be accurate, calibrated, well-placed, and maintained in good condition and the set point should be set carefully, either by the manufacturer, the contractor or the owner. Again, the owner should be informed about how to reset the set point if there is evidence of scale buildup or if the owner wishes to reduce water consumption.

Future Research: How should an owner be advised about resetting the bleed rate (either a constant rate or a conductivity set point)?

1.5.1.2 Purges

Another way to remove mineral-laden water and replace it with fresh water is to periodically purge the system: discharging all the water, and adding fresh water. This can be done after a preset number of hours of operation, or based upon a measurement of conductivity.

This conductivity might be set at the same set point as for a constant bleed, (resulting in a lower average concentration of water, but the same peak), or at some higher level (resulting in the same average concentration, but a higher peak). WCEC personnel do not yet know which would represent the best compromise between water use and scale reduction.

Bleeds have a disadvantage in that they may allow contaminants to deposit in stagnant areas of the sump, unless the system drainage is very carefully designed. One advantage of a system purge is that the higher instantaneous flow rates can result in a more thorough flush of the system, minimizing the potential for stagnant spots. Another advantage is that the media is periodically rinsed with unconcentrated water. WCEC personnel do not yet know whether this would help to reduce scale deposition.

Future Research:

- *Should a bleed and purge have the same conductivity set points? (Is the scale deposition more driven by the average concentration or by the peak?)*
- *How can an optimal purge frequency or bleed rate be set by the contractor or owner? What process should be used for empirically determining the best value at a given site?*
- *Does the flushing action of a purge make it superior to a steady bleed?*
- *Is there a difference in scale deposition between a constant concentration and a concentration that cycles from fresh water to some peak value?*

1.5.1.3 Dry-Out cycle

In conjunction with either a bleed or a system purge, some systems include or recommend a dry-out cycle, in which air is forced through the media after the pump has stopped.

Dry-out cycles interrupt the life-cycles of microbial agents that may be growing on the media, but probably also provide more opportunity for scale to deposit.

Future Research: Does a dry-out cycle dramatically increase the rate of scale deposition?

1.5.1.4 Maintenance

To some extent, providing adequate maintenance of evaporatively cooled equipment might substitute for excess flushing. There are several spots on the unit where scale and microbial growth will occur. It can occur on the evaporative media itself, in the sump, or in fittings, tubing, and nozzles. WCEC personnel do not currently know either which locations are the most prone to scale buildup or the effect on performance or operation if scale builds in various locations.

Scale buildup in the sump might be removable in a maintenance intervention. The design of the system will determine how difficult this is to do. Scale buildup in the media, fittings and pipes may be difficult to remove. But in most systems the media can be replaced (at obvious expense) when its performance becomes compromised. Table 3 provides examples of manufacturers recommended maintenance requirements.

Future Research:

- *Where within the evaporatively cooled equipment is scale most likely to occur? Where is it most likely to create problems?*
- *Are there locations where scale can be effectively removed?*
- *How can the design of the unit facilitate or discourage maintenance?*
- *How much can water concentration be increased if equipment is maintained more frequently? What type of maintenance must be provided to allow for this increase?*
- *Are there locations where scale can be effectively removed?*

Table 3: Examples of Manufacturer's Recommendations on Water Management

OASys

- "Purge Cycle: If the OASys has not started for 4 hours the Dump Pump will come on for 4 minutes which will empty out the sump to prevent biological growth. The 4 hour automatic setting can be changed in steps of 2 hours from 2-12 hours. When this Purge Cycle starts the inlet valve will close and remain closed till the OASys is restarted to provide cooling."
- "Dry Out Cycle: When the Set Temperature is achieved the Circulation Pump will stop while the fan will continue to run for four minutes at medium speed. This will dry out both the indirect and direct media and will prevent bacteriological growth."
- "Clean Out cycle: Periodically the OASys will refresh the circulation water to prevent the build-up of hardness minerals that can degrade the effectiveness of the evaporative media. During this mode the Dump Pump will automatically empty the unit while the Fill Valve is open and the Circulation Pump is on. This will "wash" the evaporative media and will purge accumulated dirt and minerals. This mode will last for 4 minutes. The period when this mode turns on can be programmed. Please consult your HVAC contractor to determine the optimal Clean out frequency. The more often the unit goes into the Clean out cycle, the longer the indirect and direct media will last before they require replacement. However, frequent clean out cycle use will consume more water. The highest setting is only required in areas that have high mineralization of the water supply."
- Maintenance or Seasonal Changeovers: Annual visual inspection, Winter: drain, dry, cover
- External Water Treatment: Biocides if necessary

Freus

- Flush Pump will automatically change out water after approximately 6 hours run time
- Twice per year: Rinse out the base to remove debris and minerals, check that drain cap is firmly seated and not leaking, check water level and make sure the unit is mounted level, check that the flush pump works if not install a replacement flush pump, turn thermostat lower to turn on unit and note that the fan, pump, and compressor all come on within a few minutes, if not call for professional service.
- Expected life of parts: 3-5 years: hoses, valves, gaskets; 6-10 years: anodes, timers, motors, grilles…; 11-20 years: compressor, nozzles, coils, switches…; >30 years: cabinet.
- External Water Treatment: Chemical water treatment not recommended

1.5.2 Reuse of Wastewater

Water discharged from an evaporative cooling unit with mineral concentrations that are too high for continued evaporative cooling use might still be used for other purposes such as landscaping. If the mineral concentrations are too high for irrigation, the discharged water can be blended with locally stored rainwater. Under this strategy, the optimal mineral concentration limit might be based upon the requirements for reuse of water, rather than the requirements of the cooling equipment.

Future Site-Specific Research Needs:

- *What is the coincidence of the discharge water availability and the requirements for irrigation?*
- *What is the maximum allowable concentration of minerals for reuse of water? What are the practical limitations on using recycled water from evaporative cooling units for landscaping? Are there impacts on irrigation systems or on plant health that would limit this use?*

1.5.3 Use of Stored Rainwater

Stored rainwater can be used in an evaporative cooling system. Because of the need for onsite storage and filtering, this solution may not be cost-effective in many situations, although careful system design might bring the cost into a useful range. Rainwater has low mineral content, although it is slightly acidic. Rainwater is pure and thus "hungry" for minerals and aggressively corrosive. Rainwater can dissolve heavy metals and other impurities from materials of the catchment and storage tank. When rainwater is blended with mineral-laden water, corrosion will not likely be a problem.

1.5.4 Water Treatment

The amount of water used by an evaporative cooling system can be reduced if there is some mechanism (chemical or non-chemical) to remove minerals and microbes from the water.

1.5.4.1 Chemical

Chemical water treatment in small evaporative cooling systems has some significant differences from chemical treatment in large cooling systems. The most significant difference is that the air that is in contact with the water is (or may be) introduced into the building. This is particularly of concern for direct evaporative systems, where all of the air that is in contact with the water enters the building. Thus, there are human health concerns with chemicals added to the water. Most evaporative cooling manufacturers are hesitant to recommend chemical water treatment, although there is little research into the effects of these chemicals on human health in the home. The other significant difference is often the economy of scale: it will often not be cost effective to utilize conventional chemical treatment strategies in small evaporative coolers.

Future Research: What is the health impact of chemical water treatment in direct or indirect evaporative cooling systems?

1.5.4.2 Magnetic, Electromagnetic, Catalytic, and Mechanical

There are several other water treatment options, including magnetic, electromagnetic, catalytic, and mechanical. There is considerable controversy over magnetic and electromagnetic water

treatment technologies. Some work very well for very large systems, although they would not be cost effective for smaller systems. Others may hold promise only for smaller evaporative cooling systems, particularly those that have small diameter pipes, low flow rates through the water treatment device, and recirculate the water through the treatment device frequently. While manufacturers' claims and satisfied customers abound, there is little hard evidence and few technical studies of their effectiveness. Much more research is needed in this area, since many of these technologies do hold promise.

Future Research: What is the effectiveness of non-chemical water treatment technologies?

1.6 Water Use and Maintenance in Cooling Technologies

Different evaporative cooling technologies use water differently. The amount of water used, and the most effective strategies for minimizing water use, must be considered on a technology-specific basis.

1.6.1 Direct Evaporative Cooling

All direct media types are subject to water maintenance issues. Hard mineral deposits can build up in and on the media if they become too concentrated during the evaporative process. Hard mineral buildup has two negative impacts: it reduces the air flow rate, and it shortens media life. Most low-cost direct evaporative coolers continuously "bleed" water to a drain when hardness mineral is present in the supply water, to limit mineral concentration. The bleed process wastes water; at a typical operating condition allowing "three times" concentration, the bleed rate increases total system water use by 50 percent. Direct media are also subject to biogrowth, particularly if they remain continuously damp and are exposed to direct sunlight. A common control strategy to combat biogrowth is to design the sump and control systems to completely purge and dry the sump on a regular interval, such as daily. Systems equipped with a purge capability often use this feature more frequently if necessary, instead of a bleed, to limit hardness mineral concentration. Purge cycles are more common to commercial and higher quality residential units.

1.6.2 Indirect Evaporative Cooling

While calculating water use in direct evaporative cooling systems is a simple process, the same is not true for indirect systems. The WCEC has evaluated expected water use for various packaged indirect evaporative technologies. Several key variables have notable effect on the results. Here are some design issues that affect both performance and water use:

1. Choice of air source for wet passages: can be outdoor air or building exhaust air
2. Wet/dry air flow ratio: wet flow is typically 80-100 percent of dry flow, but can be lower
3. Flow configuration: possibilities, and existing product examples are:
    a. Crossflow (AdobeAir, Spec Air)
    b. Quasicounterflow (OASys)
    c. Multi-stage (Coolerado)

Heat exchange plate surface treatments, spacing, size, and "aspect ratio" also affect performance and water use. Water quality also plays a role, as hard water requires bleed, purge, or water treatment, or a combination of these to maintain performance and minimize maintenance. This WCEC study only evaluated the water required for evaporation to accomplish the required cooling. If hard water requires excess water to limit mineral concentration, then water use will increase. For instance, limiting "cycles of concentration" to 3 increases total water use by 50 percent.

Estimating water use for indirect evaporative cooling first requires a calculation of the dry air stream's enthalpy decrease. Following the law of conservation of energy, the enthalpy of the wet air stream must increase by an equal amount. If dry and wet mass flows are equal, the enthalpy changes per pound of flowing air must also be equal. On the psychrometric chart, the dry air moves horizontally to the left along a line of constant moisture content, since moisture is neither added nor removed. The wet air stream, instead of following a constant wet bulb line, moves upward at a steeper angle to accomplish the required enthalpy increase. While the leaving point for the wet stream must be on the enthalpy line required for energy balance, its actual path is more interesting. Typically, the dry air entering the wet passages evaporatively cools nearly to its entering wet bulb temperature, and then begins to warm back up as it flows toward the exit, absorbing moisture from the wet surfaces and heat from the warmer dry air across the heat exchanger walls.

The WCEC study assumes that air leaving the wet passages is saturated. While this may not always be true in practice, it is the conservative assumption with respect to water consumption. If the leaving air is not saturated but is on the required enthalpy line, it must be warmer and have lower moisture content per pound than if it were saturated. One of the challenges of indirect heat exchanger design is to maximize the leaving temperature of the wet air stream. The hourly water use is computed based on the change in moisture content per pound through the wet passages, times the pounds per hour of air flow.

The analysis considers high performance "90 percent evaporative effectiveness" indirect heat exchangers, but the conclusions likely extend to lower-performance units as well. The study sought the required water per ton-hour in the following scenarios, for outdoor air at 100°F DB, 70°F WB, and indoor air at 76°F DB, 63°F WB:

1. Dry and wet flows are equal and outdoor air is the wet passage source
2. Dry and wet flows are equal and indoor air is the wet passage source
3. Outdoor air is the source, but dry flow is twice wet flow
4. Indoor air is the source, but dry flow is twice wet flow

Results of the study are tabulated in Table 4.

Table 4: Indirect Evaporative Cooling Study Results

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Required gallons per ton-hr	2.18	1.35	1.57	1.16
Energy Savings vs. Case 1	N/A	38%	28%	47%

The two key conclusions are:

1. Water use is lower if building exhaust air is used in the wet passages (Scenario 4).
2. Water use is lower as the exhaust flow rate is reduced, assuming 90 percent effectiveness can be maintained.

The first conclusion fits well with the prior WCEC conclusion that using building exhaust air, rather than outdoor air, in the wet passages improves performance, with the greatest benefit occurring in the hottest outdoor conditions. This strategy also contributes to balanced building pressures in many applications. Based on Conclusion #1, the WCEC recommends that developers of indirect evaporative heat exchangers apply building exhaust air in wet passages whenever possible.

The second conclusion is more surprising, since halving the wet side flow rate requires twice the climb up the saturation line for equivalent enthalpy increase. There are also performance benefits from this strategy, since reducing the exhaust air rate lowers exhaust side fan power, and may allow a more compact heat exchanger with narrower exhaust passages. But why doesn't the movement further "up the chart" toward higher enthalpy per pound result in greater water use, since the saturation line is steeper as it moves upward? The answer emerges from the chart. Whether the wet side source is outdoor or indoor air, the first increment of water addition is associated with saturating the entering air at its original wet bulb condition (to clarify: climbing leftward up the wet bulb line without increasing enthalpy). There is no cooling benefit associated with this water use. But the next increment of water addition increases enthalpy and has value. Within a reasonable range, the higher one goes, the less impact results from the water use increment associated with climbing the original wet bulb line. When the wet side flow rate is decreased and performance requires higher leaving enthalpy, required water use per pound increases due to the steeper curve, but the lower mass flow rate allows the total enthalpy increase to occur with lower water consumption.

Based on Conclusion #2, the WCEC recommends that developers of indirect evaporative heat exchangers explore the limits of reduced wet side air flow.

1.6.3 Roof Night Radiative Cooling

Water use by spray-type night radiative cooling systems has been monitored for several past projects with both on-roof and off-roof water storage. A brief paper by Davis Energy Group in 1993 reviewed water use on the original 6300 sq. ft. "Cool Roof" prototype installed at the California Office of State Publishing (OSP) in 1991. This project, with a 30 foot high roof on a Sacramento site, showed evidence of substantial wind losses on many nights, but still used

approximately 50 percent less water per cooling unit delivered compared to a typical cooling tower. A Davis, California home with night spray radiative cooling uses about 800 gallons annually and is estimated to deliver 1700 ton-hours of cooling. The resulting water use rate of 0.47 gal/ton-hr is far lower per ton-hour in comparison with evaporative cooling systems. If the 2000 gallon storage for this project were increased by 50 percent, it could perform well throughout the summer with refill only from seasonal rainfall. Sheet flow systems are expected to show even lower water use in comparison with evaporative systems.

Night-radiative systems have shown no need for water dilution to control hardness minerals. This benefit is attributed largely to the large water storage volumes and reduced evaporation rates, such that annual rainwater refill keeps mineral concentration to a low level. At a Vacaville, California project with particularly hard refill water, several large "coupons" of dark metal roofing were placed in the spray array to assess whether they would be discolored by mineral deposits. After a full summer of exposure, there were no visible deposits. However, these systems do require filtration because they wash the roof during operation. The filters require periodic cleaning, and use more or less water depending on filter type. At the home discussed in the paragraph above, the filter cartridge is washed annually with consumption of less than 50 gallons. Backwashing filters weekly may have higher gal/ton-hr. water usage rates than those that do not backwash.

The WCEC is considering the potential for using night-roof radiative surfaces to collect water from the air, gathering dew that accumulates on the roof. If this potential can be realized, it will significantly affect the cooling/water equation.

1.7 Water Evaluation

It should be clear by this point that the selection of a system and the optimal choice of operating strategies to minimize energy and water use depend on multiple factors. The principal factor is the quality of incoming water. This varies dramatically from locality to locality, and even over time, and it has a large impact on the operation of the evaporative cooling system. Other important factors include type of system, location, energy costs, water costs, and service costs. This section describes information used in an evaluation, and different evaluation approaches.

1.7.1 Water Quality Factors

In typical evaporative applications, the chemistry of water does not affect the evaporative process. It has a major effect, however, on the condition of the evaporative media and the equipment, over time, and the ability of the system to perform efficiently or at all. Contaminants in the water will concentrate over time, as pure water evaporates and replacement water is added. Identifying the maximum allowable number of cycles before the water is too concentrated requires identifying the mineral content of the replacement water. The primary variables that affect the operation of an evaporative cooler are hardness minerals, pH, alkalinity, total dissolved solids, and silicates.

1.7.1.1 Hardness Minerals

The most important water quality variable is the hardness, or the concentration of minerals such as calcium and magnesium. These minerals inhibit soap from forming foam. These minerals also contribute to the scale buildup on the evaporative media and equipment.

Calcium and magnesium are present in low concentrations in rainwater but, as the water is exposed to earth minerals, the concentrations increase. Surface water (as in rivers, lakes, and reservoirs) tends to be harder than rainwater, and groundwater (as in aquifers feeding wells) tends to be harder still. Since a typical municipality may blend water from a combination of sources, the hardness at a site must be determined by the water provider, or through water testing.

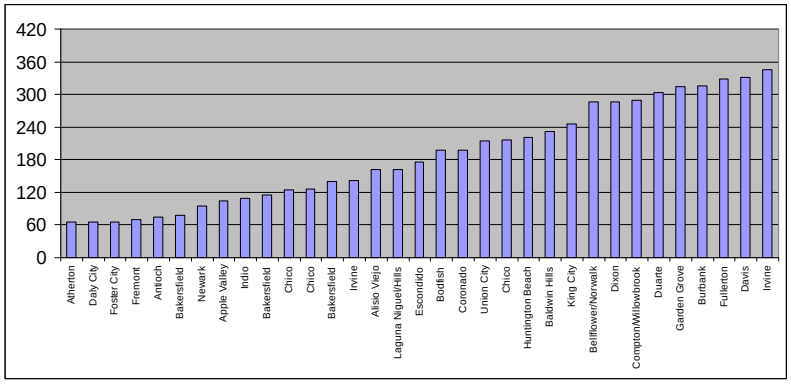
Because different minerals have different tendencies to react or deposit, their reported concentrations are normalized to the molecular weight of calcium carbonate (CaCO3). Hence, it is important to identify if a reported value is "as such", indicating that it is the actual concentration in parts per million or grains per gallon, or it is "as CaCO3." If all the concentrations are reported as CaCO3, they can be summed to determine the "total hardness," in parts per million (ppm). Table 5 describes the different hardness levels.

Table 5: Qualitative Descriptions of Quantitative Hardness Levels

Quantitative Total Hardness (ppm as CaCO3)	Qualitative Hardness
< 17.1	Soft
17.1 – 60	Slightly hard
60 – 120	Moderately hard
120 – 180	Hard
> 180	Very hard

Figure 9 illustrates the hardness reported by several California cities. It can be seen that all are at least moderately hard, and about half are considered very hard. Hardness is included in most water quality reports, although it is typically best to take an actual sample of the supply water for a site and have it analyzed. It is generally recommended that water hardness be controlled so that it does not exceed 350 ppm.

Figure 9: Total Hardness Reported for Selected California Cities (Parts Per Million as CaCO3)



1.7.1.2 Water pH

Another very important factor in water chemistry is pH which is a measure of water's acidity or alkalinity. pH is defined as the concentration of hydrogen ions expressed as the logarithm of its reciprocal:

$$[pH] = \log 1/[H^+] = -\log [H^+]$$

If the pH is 7, the water is neutral. If it is less than 7, it is acidic, and if it is greater than 7 it is alkaline. Acidic water (low pH) tends to corrode, and alkaline water (high pH) has a tendency to produce scale. All the other water quality variables are affected by the pH of the water, and the reproduction of bacteria is also affected by pH. Table 6 identifies the pH of some familiar liquids. The generally-recommended pH of water in evaporative cooling systems is above 6.5.

Table 6: Illustration of pH Levels in Common Substances

Range	pH	H+ Concentration	OH- Concentration	Example
Acidic	0	1	0.00000000000001	
	1	0.1	0.0000000000001	Battery acid
	2	0.01	0.000000000001	Lemon juice
	3	0.001	0.00000000001	Vinegar
	4	0.0001	0.0000000001	Orange juice
	5	0.00001	0.000000001	Coffee
	6	0.000001	0.00000001	Normal rain water
Neutral	7	0.0000001	0.0000001	Distilled water
Alkaline	8	0.00000001	0.000001	Milk
	9	0.000000001	0.00001	Salt brine
	10	0.0000000001	0.0001	Baking soda
	11	0.00000000001	0.001	Milk of magnesia
	12	0.000000000001	0.01	Ammonia
	13	0.0000000000001	0.1	Chlorine bleach
	14	0.00000000000001	1	Lye

1.7.1.3 Alkalinity

Alkalinity is the capacity of a solution to neutralize acids. It is related to pH but is not quite the same thing. It is often reported as total or "M" alkalinity, in parts per million (often reported "as CaCO3"). Alkalinity is an important factor in controlling pH. Total alkalinity should be controlled to be less than 250 ppm (as CaCO3).

1.7.1.4 Total Dissolved Solids and Conductivity

When solids are dissolved in water, they form positive and negative ions in solution. Since ions are conductive, the conductivity of the water is a good measure of the concentration of ions. Total Dissolved Solids (TDS) is often reported as CaCO3 and measured in ppm (see Table 7 for TDS levels of common water types). The easiest way to estimate TDS is by measuring conductivity, in mmho/cm. The conversion factor is 1 ppm TDS ≈ 1.6 mmho/cm conductivity. To reduce the chances of corrosion, TDS should be limited to 2,250 ppm which corresponds to a conductivity of about 3,500 mmho/cm.

Table 7: Typical Total Dissolved Solids in Different Types of Water

Water Type	TDS(ppm)
Fresh water	0 – 1,000
Brackish water	1,000 – 10,000
Saline water	10,000 – 100,000
Brines	> 100,000

1.7.1.5 Silica

Magnesium ions easily combine with dissolved silicates to produce a form of scaling that is very difficult to remove. In some cases, silica is the limiting factor in a water management scheme. Since it cannot be removed from the water, silica concentrations continue to increase even when other minerals have been taken out of solution in some way. Silica concentration starts to become a problem at about 150 ppm.

1.7.2 Water Quality Indices

It is impossible to point to one variable as the key for evaluating water quality, and the interrelationships between variables are very difficult to evaluate. Several water quality indices have been developed that try to combine the different variables into a single number that predicts the likelihood of forming scale or corrosion. The Langelier, Ryznar, and Puckorius Indices have all been used for different applications. Many people recommend using the Puckorius Scaling Index (PSI) for assessing water used for evaporative cooling evaluation.

It is defined by the following equations:

$$PSI = 2\ (pHs) - pHeq$$

Where:

$$pHeq = 1.465 \times \log10[Alkalinity] + 4.54$$

$$pHs = (9.3 + A + B) - (C + D)$$

Where:

$$A = (\mathrm{Log10}[TDS] - 1)/10 = 0.15$$

$$B = -13.12 \times \log10(^{o}C + 273) + 34.55 = 2.09 \text{ at } 25°C \text{ and } 1.09 \text{ at } 82°C$$

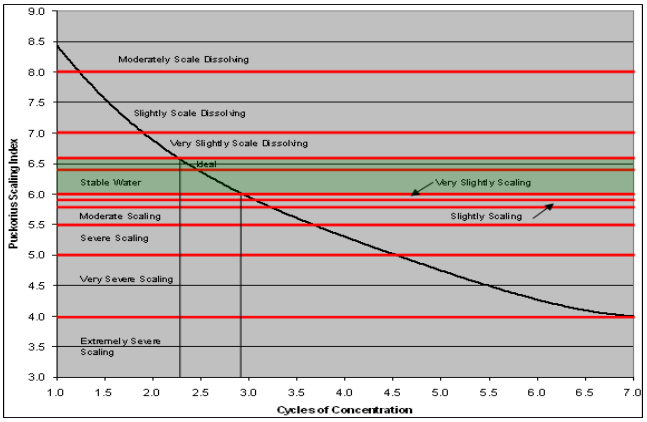
$$C = \log10[Ca2+ \text{ as } CaCO3] - 0.4 = 1.78$$

$$D = \log10[\text{alkalinity as } CaCO3] = 1.53$$

The earlier Langelier Saturation Index, which accounts for fewer factors, has also had good results. It is more conservative, and consistently predicts a higher probability of scaling than the other indices.

Figure 10 illustrates the interpretation of the PSI. This shows the PSI for water from Las Vegas, NV, from their 2007 Water Quality Report, as a function of the number of cycles of concentration. This figure shows that water goes scale dissolving to scaling very quickly. Note that as the water goes from a cycle of concentration (CC) of 2.25 to 2.95 it goes from "Very Slightly Scale Dissolving" to "Very Slightly Scaling," and by the time it reaches 3.6 it will cause "Severe Scaling." There is not a lot of room for error.

Figure 10: Example of Puckorius Scaling Index (PSI)



PSI for water from Las Vegas, NV in 2007, as a function of the Cycles of Concentration. Water goes from scale dissolving to scaling very quickly.

1.8 Sources of Water Data

Water quality information is available from a number of sources. The best approach for a particular project is to test the actual supply (makeup) water. It is simple to collect a sample of the water. The sample can be taken to a local water quality lab for analysis. The testing should provide analysis of calcium, silicates, pH, alkalinity, chlorides, TDS, and hardness.

Short of taking samples for laboratory analysis, the local water district can provide most necessary data. It should be remembered that districts sometimes use water from multiple sources, and it is important to obtain data reflecting the mix, which can vary over time. Water quality districts are required to issue annual reports showing measurements of certain health-related factors. They also typically report other factors, which are not mandatory. Reporting is not mandatory for most of the variables required for evaporative cooling analysis, although these variables are commonly provided. As described earlier, it is important to understand the units that are reported, either in a laboratory analysis, or in a water district annual quality report.

1.9 Using Water Quality Data in Calculations

Many water quality consultants and service providers have their own spreadsheets to evaluate water quality for evaporative cooling processes. These models can be quite sophisticated in estimating the quality of water after any number of cycles of concentration, and for different blends of water. There are also models and software available for purchase.

It is not difficult to do a simple spreadsheet-based calculation to estimate water use, as a function of makeup water hardness.

Figure 11 shows a sample calculation, and Figure shows the resulting water use from this example. But water quality is a function of many more variables than hardness, and there will be cases where these calculations under- or over-estimate the required water.

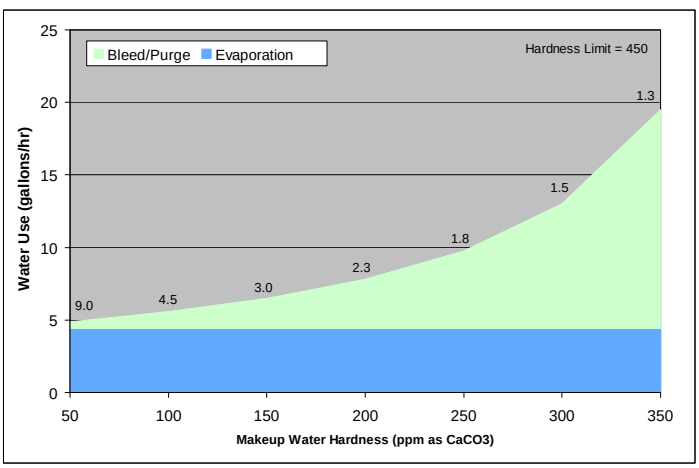
Future research by the WCEC will test evaporative coolers and identifying promising water management techniques in a laboratory-like setting.

Figure 11: Simple Water Use Calculation

	A	B	C	D	E
1	**Inputs**				
2	Wet-Bulb Depression	degrees	30		
3	Evaporative Effectiveness	percent	80		
4	Airflow	cfm	1,800		
5	Density of Air	cuft/lb	14.5		
6	Humidity Ratio	lb H2O/lb air	0.006		
7	Sump Area	sq ft	4.0		
8	Sump Depth	ft	0.5		
9	Makeup Water Hardness	ppm (as CaCO3)	250		
10	Hardness Limit	ppm (as CaCO3)	450		
11					
12	**Calculated Values**				*Formula*
13	Cycles of Concentration	-	1.8		MAX(1.1,C10/C9)
14	Airflow	lb air/min	124		C4/C5
15	Evaporation Rate	lb/min	0.6		C14*C6*C3/100
16	Evaporation Rate	gal/hr	4.3		C15*60/8.25
17	Sump Volume	gallons	15.0		C8*C7*7.5
18					
19	**Dump Option**				
20	Dump Frequency	hours	2.8		(C17/C16)*(C13-1)
21	Total Water Use per Dump (evap + dump)	gallons	27.0		C17+(C20*C16)
22	Total Water Use (evap + dump)	gal/hr	**9.8**		C21/C20
23					
24	**Bleed Option**				
25	Bleed Rate	gal/hr	5.4		C16/(C13-1)
26	Bleed Rate	gal/min	0.09		C25/60
27	Total Water Use (evap + bleed)	gal/hr	**9.8**		C16+C25
28					

Example of a simple spreadsheet calculation to estimate a required dump frequency bleed-rate for given makeup water hardness.

Figure 12: Effect of Makeup Water Hardness on Water Use



Result of example calculation. Cycles of Concentration also shown.

1.10 Recommended Development of an Advanced Tool

WCEC staff is not aware of any complete models designed to optimize water use and energy savings in evaporative cooling systems. Building or system simulation programs (such as DOE2, Energy Plus, etc.) do not report water used by evaporative cooling systems. They can be used to calculate the cooling load-hours provided by an evaporative cooler, which can be used in an estimation of water use. There is a need for a tool that can look at annual performance, rather than simply peak period consumption, and can look more thoughtfully at water quality. In future research, WCEC will develop a tool to help estimate water quality and use. It will be useful to design engineers, attempting to optimize a system for a particular application, as well as evaporative cooling manufacturers developing recommendations to contractors and owners. The tool will estimate water use, energy use, and costs with different technologies and options. While different users may have different objectives (minimizing overall costs, minimizing water use, or minimizing maintenance time or costs), the tool will allow optimization based upon the user's objectives.

This tool will be developed over time, based upon findings from lab and field testing, and information gathered in other elements of the WCEC Water Initiative. When completed, the tool will be used to conduct parametric runs for different applications, locations and or strategies, and will generate charts and graphs summarizing the results. For example, appropriate performance variables can be reported as a function of operating parameters for different locations or water quality or objectives. The emphasis will be on findings that are useful for operating current equipment and applying current systems.

1.10.1 Tool Requirements

Although the tool has not yet been designed, the following lists the requirements:

- The user can derive a cursory answer with the use of defaults, or can dive deeper and derive a more detailed result.
- The user can provide inputs parameters such as location, energy rates, water rates, service rates, hourly cooling loads, water quality data, system type.
- The user can select a water management strategy (chemical, non-chemical, bleed, purge, and so forth)
- The tool will have two modes:
    - The user provides operating parameters (for example, bleed rate, purge frequency), and the tool determines resulting performance (for example, water use and cost, maintenance time and cost, energy use and cost, overall costs)
    - The user provides performance objectives (minimize overall costs, minimize water use, or minimize maintenance time or costs) and the tool determines the optimum operating parameters
- The inputs will include climatic factors, evaporative cooling loads (calculated within the tool, imported from other sources, or estimated from simple lookups), water costs,

energy costs, maintenance costs, and water characteristics (either entered by the user or lookup from water database).

- The results will either be performance (energy use, demand, energy costs, maintenance costs, water use, water costs, overall costs) as a function of operating parameters, or operating parameters (cycles of concentration, purge frequency, bleed rate, maintenance frequency) as a function of performance objectives.

1.11 Conclusions and Recommendations

The WCEC recognizes the potential for evaporative cooling in meeting peak demand and greenhouse gas reduction goals in the western US, and is committed to helping to remove the barriers to its successful implementation. Some of these barriers are perception, rather than reality. For example, historic experience with evaporative cooling indicates that it creates sticky conditions and is prone to failure, while modern systems need not have these problems. There are, however, very valid concerns about comfort, health, water consumption, and maintenance requirements that must be addressed to enhance market prospects. This report outlines these concerns, and identifies some of the solutions. There is still much work to be done to provide reliable guidance to equipment manufacturers and to owners, to ensure that the systems will be perform adequately year after year, and will continue to provide energy and demand savings, while maintaining or improving comfort, without burdensome maintenance requirements. There are still many unanswered questions, summarized in Table 8.

Many of these questions will be addressed by the WCEC in subsequent phases of its Water Initiative. In particular, the WCEC is beginning accelerated life-cycle testing of water management strategies, and the development of evaluation tools that can assist product developers, systems engineers, and owners to identify optimal operation and maintenance strategies to optimize energy, water, and maintenance resources.

Although there are many unanswered questions, most current generation evaporative cooling technologies are effective and energy efficient, and deserve support through efficiency and peak reduction programs. Most water management strategies and operational recommendations can be implemented in existing equipment. The findings of subsequent phases of the WCEC's research should provide valuable additional guidance.

Table 8: Unanswered Questions in Water-Based Cooling Systems

What is the optimum combination of wetting and drying of the evaporative media, to simultaneously control scale and microbe growth?
What is the relationship between scale growth and degradation of performance? What is an optimum maintenance regime?
What is an effective service model for evaporative cooling equipment?
What variables can be monitored to identify when an evaporative unit performance is beginning to degrade or is malfunctioning? How is this best annunciated, and to whom?
What are the practical issues encountered when reusing discharge evaporative cooling water for landscaping? What are the limits on allowable discharge water quality? Are there plant species that are particularly tolerant of mineral-rich irrigation water?
What data are required to develop estimates of the water used by electricity generation for different seasons and different times of the day? What kinds of tools could make use of this information?
How should an owner be advised about resetting the bleed rate (either a constant rate or a conductivity set point)?
Should a bleed and purge have the same conductivity set points? (Is the scale deposition more driven by the average concentration or by the peak?)
How can an optimal purge frequency or bleed rate be set by the contractor or owner? What process should be used for empirically determining the best value at a given site?
Does the flushing action of a purge make it superior to a steady bleed?
Is there a difference in scale deposition between a constant concentration and a concentration that cycles from fresh water to some peak value?
Does a dry-out cycle dramatically increase the rate of scale deposition?
Where within the evaporatively cooled equipment is scale most likely to occur? Where is it most likely to create problems?
Are there locations where scale can be effectively removed?
How can the design of the unit facilitate or discourage maintenance?
How much can water concentration be increased if equipment is maintained more frequently? What type of maintenance must be provided to allow for this increase?
Are there locations where scale can be effectively removed?
What is the coincidence of the discharge water availability and the requirements for irrigation?
What is the maximum allowable concentration of minerals for reuse of water? What are the practical limitations on using recycled water from evaporative cooling units for landscaping? Are there impacts on irrigation systems or on plant health that would limit this use?
What is the health impact of chemical water treatment in direct or indirect evaporative cooling systems?
What is the effectiveness of magnetic and electromagnetic water treatment?

CHAPTER 2:
Energy Efficiency Opportunities for Packaged Rooftop Cooling Units

2.1 Introduction

It is estimated that 70 percent of the cooling in California commercial buildings is provided by Roof-Top packaged Units (RTUs). It is for this reason that the Western Cooling Efficiency Center (WCEC) was formed to pursue climate-responsive cooling, with a particular focus on RTUs. Like residential cooling, the RTUs cooling commercial buildings create large peak electrical power demands. The load factor for commercial air conditioning, which is the ratio of average electricity demand to peak electricity demand, is 22 percent in California. This makes commercial cooling an unfavorable load for California electric utilities, although it is less than the load for residential cooling. The goal of this document is to summarize opportunities for efficiency and peak-demand improvements for RTUs, and to summarize current WCEC projects related to this issue.

2.2 Background[1]

Commercial rooftop packaged units (RTUs) are manufactured in capacities ranging from 36,000 BTU/h (3 tons) to over 600,000 BTU/h (50 tons). Below 65,000 BTU/h, the units are usually rated with the residential metric SEER (Seasonal Energy Efficiency Ratio), and larger units are usually rated by EER at 95°F. Table 9 is a summary of units in the market as of March 2008, based upon the California Energy Commission (Energy Commission) appliance database. The figure also includes three standards from the US Department of Energy (USDOE), the American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) and the Energy Commission.[2] Table 9 compares the various EER95 standards as of March 2008.

Table 9: Summary of EER 95 Standards (as of March 2008)

Roof Top Unit		EER95 Standards				
Unit Capacity/Class	Nominal Cooling Tons	Current DOE Minimum	ASHRAE 90.1 2004	CEC T-20 Pending 2010 or Exemption	Joint Stakeholders Proposal for 2010	Congressional USDOE for 2010
65k to 135k with Heating	5 to 10	8.9	10.1	11.0	11.0	11.0
135k to 240k with Heating	12 to 20	8.5	9.7	10.8	10.8	10.8
over 240K	over 20	none	9.5	10.8	10.8	9.8

There are however some additional considerations. The standards in Figure 13 are for total cooling, both sensible and latent, and do not include outside ventilation air. In the hot, dry

1 The information in this section was current when the report was written in March 2008 .

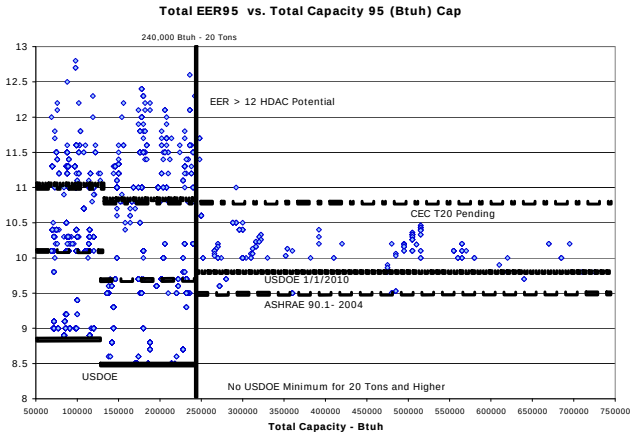
2 The USDOE standards changed in 2010 after this report was written.

climates of California, it is not total cooling performance, but rather sensible-only performance, that is important, and 95°F is not a representative temperature for the hot weather associated with peak electricity demand for cooling. In addition, the impact of outside ventilation air is important. For example, for an RTU serving 400 square feet of office per ton of capacity at an outside air requirement of 0.25 cfm/ft^2, 100 cfm/ton, or 25 percent of total airflow is outside ventilation air. When the equipment is operated in this manner, the outside air increases the load that the system must handle, but also increases sensible capacity in hot, dry California climates.

One other issue with the current rating procedures for RTUs is the effective duct resistance used in the tests, which ranges from 0.2 to 0.75 inches water column (IWC), depending upon the cooling capacity of the equipment (5 tons to over 42 tons). This range needs to be compared with the 0.7 IWC used by a major retailer for specifying their 5-25 ton equipment. To put this in perspective, a 20-ton unit moving 7000 cfm against the minimum rating-standard test pressure of 0.4 IWC needs a fan with 2.9 brake horsepower (HP), while at 0.7 IWC that same unit needs 3.68 HP. The electricity demand difference, assuming a combined efficiency of 73 percent for the motor and belt drive, is 790 W. If the space is occupied 14 hours a day, then the fan operates for 5110 hours per year, resulting in an additional 4050 kWh of electricity consumption per year, which corresponds to roughly 10 percent of that 20-ton unit's annual electricity consumption.

At steady-state EER95 conditions, efficiency increases for air cooled equipment are generally achieved by using better compressors, more efficient refrigerants, larger condenser heat exchangers, more efficient condenser fans, and premium-efficiency blower motors with no-slip belt drives. It is also possible to locate the blower motor outside of the air stream to increase efficiency, however this is not done due to the space constraints of most RTUs. The weight and cost increases for more efficient units are approximately 20 percent, which is generally paid back in the form of annual energy savings. About 50 of the >2400 units listed have EERs of 12 and higher, with the highest being 12.8, while EERs as low as 8.5 are allowed by regulation.

Figure 13: Energy Efficiency Ratios for RTUs With Capacities Larger Than 65,000 BTU/h



Blue dots represent individual units on the market, and black lines represent three different standards, US DOE - 2010, ASHRAE 90.1-2004, and Energy Commission T-20 (pending).
Source: California Energy Commission

2.3 Current RTU Activities at WCEC

The Western Cooling Efficiency Center's (WCEC) current activities addressing RTU efficiency are focused in three areas: 1) Hot Dry Air Conditioner (HDAC) specifications, 2) evaporative pre-cooling for condensers and ventilation air, and 3) the Western Cooling Challenge (WCC).

2.3.1 Hot Dry Air Conditioner (HDAC) RTUs – New Construction and Replacement

A large PIER-funded project conducted by Southern California Edison developed a new rating called Peak Energy Efficiency Ratio Sensible (PEERS) for Hot Dry Air Conditioners (HDAC). The purpose was to provide a better indication of residential air conditioner and light-commercial RTU energy performance in California. This rating, appropriate for RTUs installed on new buildings or as replacement equipment, is summarized in Table 10.

Table 10: Hot Dry Air Conditioner Criteria

Condition #1	**Hot Dry 115°/80°/63°**
Gross Sensible Capacity (sensible BTU/h)	At least 75% of the gross total capacity from ARI test A (95/80/67)
Sensible Peak Energy Efficiency Rating (PEERS)	At least 8 BTU/watt
Condition #2	**Hot Medium 115°/80°/67°**
Gross Sensible Capacity (sensible BTU/h)	At least 65% of the gross total capacity from ARI test A (95/80/67)
Sensible Peak Energy Efficiency Rating (PEERS)	At least 6.8 BTU/watt

To meet the PEERS specification, an RTU must meet two conditions:

- Condition #1 is for a room-air relative humidity of about 45 percent and is representative of return temperatures from a high-ceiling space with room temperatures of 75°F at the thermostat.
- Condition #2 uses the maximum- operating-condition test point from the ARI 340/360 – 2007 standard. This condition is a required test point in the ARI, and therefore does not require the use of manufacturers' expanded data tables, however manufacturers report that energy use data is often not taken at this test point. Currently there no neutral, third party listing of the 115°F test point data exists.

Calculation of the PEERS rating numbers is set up in a spreadsheet on the WCEC website. This spreadsheet is based upon the PIER/Southern California Edison HDAC report and is used to calculate the PEERS rating from manufacturers' literature. Table 11 shows the results associated with applying that procedure to a sample of RTUs.

Table 11: Example PEERS Calculations for High-Efficiency RTUs

	ARI Rated Capacity	**5 ton**			**20 Ton**
	Manufacturer	**1**	**2**	**3**	**2**
Test	**SEER**	15	15.5	15	
Condition	**EER**		12.8		12.6
ARI	Total Capacity [kBTU/h]	62.4	63.0	63.49	248.9
95/80/67	Sensible Heat Ratio[-]		0.73		0.75
	Sensible Capacity [kBTU/h]	45.9	46.0	47.3	186.7
	HDAC Capacity (75% of ARI) [kBTU/h]	34.4	34.5	35.5	140.0
HDAC #1	Total Capacity [kBTU/h]	51.8	53.5	52.5	212.4
	Sensible Heat Ratio[-]		1		1
115/80/63	Sensible Capacity [kBTU/h]	50.5	53.5	49.4	212.4
	Comp Motor [kW]	5.08	4.86	5.1	19.6
	Blower [brake HP]	0.83	1.09	0.64	4.07
	Conversion Constant [kW/bhp]	0.75	0.75	0.75	0.75
400 cfm/ton	Motor Efficiency [-]	0.80	0.80	0.80	0.80
	Blower [kW]	0.77	1.02	0.60	3.80
0.65 IWC	Blower [kBTU/h]	2.64	3.47	2.04	12.95
Static	Condenser Fan [kW]	0.25	0.32	0.32	1.9
Pressure	Condenser Fan [kBTU/h]	0.85	1.09	1.09	6.48
	PEERs numerator [kBTU/h]	47.9	50.0	47.4	199.4
	PEERs denominator [kW]	6.08	5.93	6.17	22.25
	PEERs Value [BTU/h/W]	7.9	8.4	7.7	9.0
	HDAC Target [BTU/h/W]	8	8	8	8
HDAC #2	Total Capacity [kBTU/h]	55.8	55.1	54.36	222.1
	Sensible Heat Ratio[-]		0.81	N/A	0.8
115/80/67	Gross Sensible Capacity [kBTU/h]	43.2	44.6	43.32	177.7
	HDAC 65% of ARI	29.8	29.9	30.8	121.3
400	Comp Motor [kW]	5.07	4.9	5	19.71
cfm/ton	Blower [brake HP]	0.83	1.09	0.64	4.07
0.65 IWC	Motor Efficiency [-]	0.80	0.80	0.80	0.80

	ARI Rated Capacity	5 ton			20 Ton
	Manufacturer	**1**	**2**	**3**	**2**
Static Pressure	Conversion Constant [kW/bhp]	0.75	0.75	0.75	0.75
	Blower [kW]	0.77	1.02	0.60	3.80
	Blower [kBTU/h]	2.6	3.5	2.0	13.0
	Condenser Fan [kW]	0.25	0.32	0.32	1.9
	Condenser Fan [kBTU/h]	0.85	1.09	1.09	6.48
	PEERs numerator [kBTU/h]	40.6	41.2	41.3	164.7
	PEERs denominator [kW]	6.07	5.97	6.07	22.36
	PEERs Value [BTU/h/W]	6.7	6.9	6.8	7.4
	HDAC Target [BTU/h/W]	6.8	6.8	6.8	6.8
	Passes HDAC Criteria	**No**	**Yes**	**No**	**Yes**

Some stakeholders have proposed eliminating Condition #1 for simplicity, which would mean that 3 of the 4 example units would pass, and the fourth would barely miss. Sensitivity analyses suggest that reducing the evaporator flow to 350 cfm/ton would also cause all four units to pass. Unfortunately, some of the required data for the calculations in Table 11 was not available from the manufacturers' published data, and thus had to be estimated. This could be a problem, as current plans are that for a piece of equipment to be on the HDAC list for IOU incentives, all estimates would need to be replaced by information from the manufacturer. In general, it appears that equipment with an ARI EER95 of 12 or higher has a chance of being HDAC compliant.

2.3.2 Evaporative Accessories for RTUs – New Construction and Retrofit

Evaporative accessories can improve both energy efficiency and peak electricity demand for RTUs. Two technologies that can be applied on either a retrofit or as original equipment basis are: 1) pre-cooling the air passing through the condenser coil by water evaporation, and 2) indirect evaporative cooling of outdoor ventilation air. While it is possible to build a "hybrid" RTU that comes off the assembly line with both vapor compression and evaporative cooling integrated into one box, the present practice is the apply evaporative components to "standard" equipment either in a custom product shop or at the RTU installation.

2.3.2.1 Evaporative Precooling

Using evaporation to cool the air entering condenser coils has been used for many years and is generically referred to as pre-cooling. A history of poorly engineered and/or poorly installed pre-cooling devices has resulted in the perception that pre-coolers damage equipment. The damage occurs when water droplets in the pre-cooled air are deposited on the coil, resulting in corrosion and/or scaling. Damage also occurs when clogged pre-cooler media restricts airflow enough to damage the condenser fans and compressor. Reports of clogged pre-cooler media

being taken off equipment and left piled on the roof circulate among HVAC maintenance technicians as proof that pre-coolers do not work.

Pre-coolers that work, are quality engineered, constructed of long lasting materials, operate to minimize maintenance, and are easy to maintain. The most common system uses a rigid media (6 to 12 inches thick) mounted in a stainless steel frame. A stainless steel sump located underneath the media allows water to wash through the media minimizing the deposition of minerals. A small pump that circulates the sump water is turned on with the compressor. As the circulated water evaporates, the original concentration of minerals increases to a point where it needs to be diluted or flushed and replaced with clean water to avoid scaling on the media.

The efficiency gained by pre-cooling condenser air is roughly 1-2 percent per °F of pre-cooling. The 1 percent figure roughly corresponds to equipment using R-22 refrigerant, whereas the 2 percent figure is for R-410A systems. Thus, if the pre-cooled air temperature is brought down to the wet-bulb temperature, the equipment efficiency would be increased by 10-40 percent for a 10-20°F wet-bulb depression (for example, temperature difference between wet-bulb and dry-bulb temperature).

2.3.2.2 Indirect-Evaporative Ventilation-Air Cooling

The second evaporative cooling accessory is an indirect evaporative cooler for ventilation air. In this application, outdoor air is evaporatively cooled and then passed through a heat exchanger with "dry" outdoor air that is cooled convectively and then introduced into the building for ventilation purposes. These accessories do not add any moisture to the ventilation air, hence the term "indirect evaporative cooler". With these indirect systems, the outdoor air temperature can be reduced to below the wet-bulb temperatures by using multiple indirect cooling stages (such as introducing water into the indirectly cooled outside air, which has a much lower wet-bulb temperature than the original outdoor air). The theoretical limit is the dew-point temperature of the outdoor air. The trade-off is between cooler temperatures and increased electricity consumption for the fans moving the air through the heat exchangers.

A number of manufacturers produce RTUs that do not contain compressors, but that use indirect (or a combination of indirect and direct cooling) for all of the cooling provided. These RTUs are sometimes used to provide all of the required ventilation air to the space, allowing other RTUs to operate in re-circulation-only mode. In other cases, multi-stage units (non-compressor) are used as open-loop systems (100 percent outdoor air) to provide all of the required cooling. These units have the added advantage of exhausting all internally generated pollutants, and because they pressurize the space, they eliminate any infiltration loads.

2.3.2.3 Combined Condenser Precooling and Indirect-Evaporative Ventilation-Air Cooling

Some manufacturers produce equipment/accessories that combine condenser pre-cooling and indirect ventilation-air cooling. This is generally performed by pumping the cool sump water below the condenser pre-cooler media through a coil mounted in the ventilation air intake prior to returning it to the top of the media. As most RTUs are run during occupied hours to simultaneous provide cooling and ventilation to interior spaces, this combination can provide

even larger fractional savings than either of two individual accessories. In addition to the efficiency improvement, such a system can reduce the total amount of air that needs to be moved for cooling. Reducing air flow improves annual performance by reducing fan power (which scales with the cube of the flow rate), especially for RTUs with constant-speed blowers. Such combination technologies are available for new equipment or as retrofits for existing equipment. In general retrofits are recommended for equipment that is less than 10 years old. Though older equipment may have enough remaining useful life, its efficiency is often so low that complete replacement is more cost effective.

2.3.3 Western Cooling Challenge RTU – New Construction and Replacement

The WCEC issued a press release and formal announcement for the Western Cooling Challenge (WCC) at the Retailer Energy Alliance Supplier Summit on June 5, 2008 in Denver. The Western Cooling Challenge goal was to have manufacturers begin selling RTUs that use 40 percent less energy, and have 40 percent less peak electricity demand, by January 2011 or before.[3] For this first challenge, a set of test conditions was developed for two test points (one to represent annual consumption, and the other to represent peak performance). The challenge was developed in conjunction with the WCEC's retailer affiliates, and Pacific Gas and Electric, Sempra Energy, Southern California Edison, and the Sacramento Municipal Utility District. The details of the challenge are presented in Appendix A and the schedule is summarized in Table 12.

Table 12: Western Cooling Challenge Schedule of Events

Date	Milestone/Event
January 2009	Begin laboratory testing of WCC entries
June 2009	Begin field testing of WCC entries
January 2010	Begin shipments of WCC compliant products
January 2010	Shipments of production products

To establish the WCC performance points, the philosophy was to assure that a major manufacturer could produce an RTU that meets the Challenge without having to go to a complete re-design, but rather could meet the challenge using accessories and modest re-manufacturing (for example, changing in a more-efficient fan motor). The targets were set using manufacturers' data for a high-efficiency RTU, combined with an evaporative pre-cooler with indirect ventilation air cooling (see Figure 14). The WCC is technology neutral, allowing participating manufacturers/teams to develop their own system designs, including designing a new system from scratch. The WCEC has identified other system configurations that exceed the performance of the system analyzed and can do so at lower initial cost.

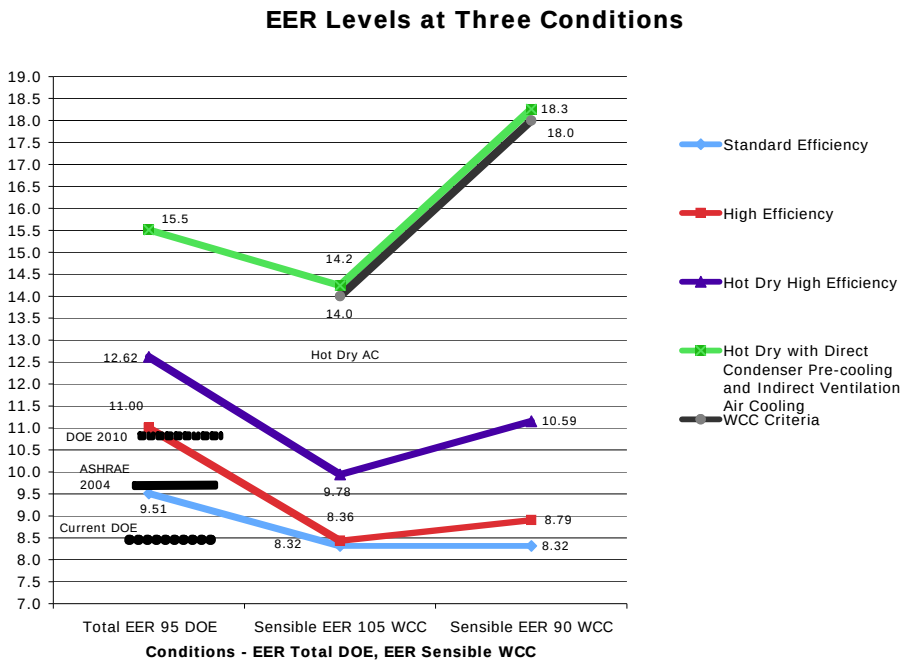
[3] The winning unit in this first challenge was Coolerado and the unit is now commercially available.

Figure 14 includes equipment performance values at three different rating points (the standard ARI test conditions, and the two test conditions for the WCC), all for four representative RTUs. In addition to the particular equipment values, the figure also includes horizontal lines representing three different target values for the ARI test results, the lowest being the current minimum DOE Standard, next the ASHRAE 90.1-2004 value, and then the approved DOE level for 2010.

The second column of test results is for the first WCC test point, which is meant to represent the performance of the equipment at peak cooling conditions. The third column of results is for the performance at the second WCC test point, meant to represent typical western cooling conditions.

Information on the current WCC can be found at: http://wcec.ucdavis.edu/programs/western-cooling-challenge/.

Figure 14: Performance of Different Types of Equipment at ARI and WCEC Test Conditions



2.4 Future Opportunities

In the future, annual simulation advancements being made in the Energy Plus program by LBNL, NREL and others are expected to facilitate analyses based on laboratory testing to predict both the peak demand and annual savings of RTUs that make use of advanced components and design strategies. The WCEC plans to work closely with both LBNL and NREL on this effort.

Existing and new RTUs would benefit from thorough commissioning and fault detection diagnostics but rarely receive either. New, high efficiency RTUs have on-board diagnostics built into control boards and many communicate with energy management systems. It is still uncommon to have these advances used to allow monitoring of performance by someone who can get personnel to the site to repair or maintain the RTU. The need for persistent savings becomes even more important when utility supply planners need to rely on them to minimize the need for new power plants, transmission lines and distribution infrastructure.

It is possible to retrofit RTU fans so that they can vary speed in response to loads. Condenser fans are below one horsepower and can be driven by permanent magnet brushless motors. Controls that allow reduced airflow through the condenser coil can save significant fan energy. Moreover, combining condenser-fan speed control with evaporative pre-cooling can reduce the water consumption. Additional energy can be saved with the installation variable speed drives on the blowers.

Research by the New Buildings Institute has found that for decades the control strategy associated with the dominant economizer controls does not facilitate or optimize ventilation cooling. A clear definition of economizer performance needs to be developed, followed by testing of available economizer controls both existing and proposed control algorithms.

CHAPTER 3:
Energy Efficiency Opportunities for Residential Cooling

3.1 Introduction

Residential cooling is generally considered to be the "worst load" by electric power utilities in the west. This is due to the fact that residential cooling creates very large peak electrical power demands, in large part due to the large temperature swings and lack of steady latent cooling loads in the west (air conditioners tend to run all day and all night long in the east to control indoor humidity). One way to look at residential cooling is in terms of load factor, which is the ratio of average electricity demand to peak electricity demand, which in the case of residential air conditioning is 7 percent. This means that a utility needs to construct a power plant that is effectively operated only 7 percent of the time, which is a very poor use of resources. To put this in perspective, the fans for toilet/kitchen exhausts in an apartment building or hotel essentially draw the same current all the time (making their load factors roughly 100 percent). Thus, from a pure return on investment perspective, electricity used for residential air conditioning should be very expensive (the costs for building and maintaining many KW of power generation capacity spread over relatively few kWh of consumption).

Residential cooling energy use and demand can be reduced in many different ways. These include:

- Improvements to cooling equipment for dry western climates such as California. The equipment technologies covered include those applicable to both new construction and retrofit/replacement applications. The equipment technologies discussed include: Hot Dry Air Conditioners (HDAC), water-cooled condensers, indirect/direct evaporative (IDEC) systems, hybrid DX/evaporative systems, swimming-pool heat-sink systems, and refrigerant de-super-heaters and sub-coolers.
- Improvements to envelope, orientation, and ventilation/infiltration measure that could impact cooling loads. Despite the importance of these measures, particularly when trying to achieve Zero Net Energy buildings, they are beyond the scope of this particular document.
- Improvements to the distribution of cooling around the home. Almost all residential cooling systems currently accomplish this function by moving cooled air around using a fan. One of the issues with these systems is duct leakage, which is particularly important during peak cooling demand periods (for example, attic air drawn in due to duct leaks is hottest during peak demand periods). Short-term efforts in the existing-home arena should be focused on enforcement of existing duct leakage requirements in Title-24, and on tightening of the minimum leakage requirements. Two new-construction technologies for residential cooling distribution that can have large impacts on both energy use and demand are 1) the location of ductwork inside the conditioned space, and 2) radiant cooling systems. Radiant cooling systems address not only the thermal

losses associated with cooling distribution, but also dramatically reduce the energy required to transport that cooling (such as. pump versus fan power), and impact the efficiency of the cooling equipment (as the refrigerant does not need to be as cool for a radiant system). Once again, a detailed discussion of these technologies is beyond the scope of this document.

- Incorporation of electrical and thermal storage. The purpose of these technologies is to reduce the large peak demand currently associated with residential cooling. Electrical storage systems in this application are geared towards addressing the timing mismatch between renewable energy sources (for example, wind and solar), and peak cooling needs. Thermal storage systems address the large variance in western cooling energy demand more generally, utilizing any available electricity during off-peak times to produce cooling that can be employed during peak-demand periods. The technology options on the thermal storage side include a turn-key night-time-ice-production technology that is sized for the residential and light commercial markets. Other thermal storage technologies for residential cooling include ground-source heat pumps (which essentially use the ground for thermal storage), and residential swimming pools (which are discussed in more detail later).

3.2 Residential Equipment Improvements

3.2.1 Hot, Dry Air Conditioners

Residential unitary air conditioning equipment sold in the U.S. and manufactured after January 23, 2006 must achieve SEER 13 or higher efficiency. A seasonal energy efficiency ratio (SEER) of 13 was fought over starting 10 years prior to 2006. The process and schedule is complicated by the 2007 Energy Independence and Security Act which gives USDOE the regulatory authority to set one national and two regional air conditioner standards. Efficiency advocates generally support regional standards, one for the Hot Humid Southeast, and one for the Hot Dry West. Industry advocates are on record as wanting just one national standard. California efficiency programs, PIER projects and emerging technology programs have fostered the development of residential air conditioning systems for the Hot Dry West that work with quality installation practices to maximize efficiency and peak reduction. A new rating called PEERS (Peak Energy Efficiency Ratio Sensible) for Hot Dry Air Conditioner (HDAC) came out of that work. Table 13 shows the effect that the PEERS rating would have for three example systems.

Only one of the three example systems meets the HDAC PEERS criteria even though all have EER95 values of 12 or better. It should be noted that EER95 is total (sensible plus latent) EER and PEERS is a “sensible-only” metric. Each of the example models used are equipped with a single two-speed compressor. To operate in high and low modes requires the use of a variable speed blower furnace. Major manufacturers can supply HDAC split systems that meet the PEERS rating by carefully matching the condenser with the coil and blower, however a simple SEER/EER pair is not a reliable indication of compliance with the PEERS HDAC criteria.

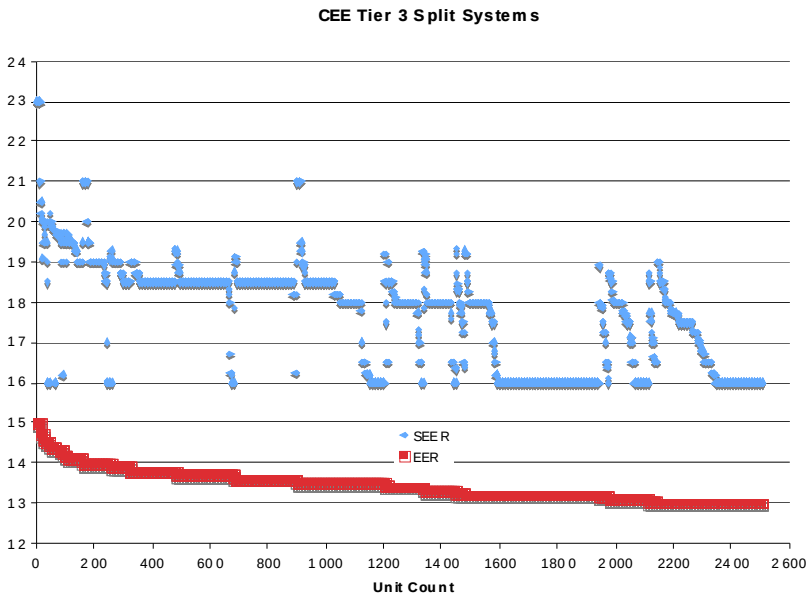
Table 13: Example HDAC PEERS Values for High-Efficiency Split Systems

Test Condition	Equipment	3 Ton, 2 Speed Compressor, Variable Speed Up-Flow Furnace Blower		
	Model	1	2	3
	SEER (ARI)	16.0	16.0	14.0
ARI 95/80/67	EER (ARI)	12.3	12.0	12.0
	Gross Capacity [kBtu/h]	35.2	35.2	36.0
	Sensible Heat Ratio	0.75	0.75	0.72
	Gross Sensible Capacity [kBtu/h]	26.4	26.4	25.8
HDAC #1 115/80/63 400 cfm/ton 0.65" Static Pressure	HDAC #1 Capacity = 75% of ARI [kBtu/h]	19.8	19.8	19.3
	Gross Capacity [kBtu/h]	26.7	28	29.8
	SHR	0.83	0.9	0.97
	Gross Sensible Capacity [kBtu/h]	22.2	27.5	28.8
	Comp Motor [kW]	2.7	2.5	3.2
	Blower [kW]	0.30	0.43	0.4
	Blower [kBtu/h]	1.0	1.5	1.4
	PEERS Capacity (numerator) [kBtu/h]	21.2	26.0	27.4
	PEERS Power Draw(denominator) [kW]	3.4	3.2	4.0
	PEERS	6.2	8.1	6.9
	HDAC #1 PEERS Value	8	8	8
HDAC #2 115/80/67 400 cfm/ton 0.65" Static Pressure	Gross Capacity [kBtu/h]	31.3	32	31.9
	SHR	0.74	0.8	0.76
	Gross Sensible Capacity [kBtu/h]	23.1	25.6	24.3
	HDAC #2 Capacity = 65% of ARI [kBtu/h]	17.2	17.2	16.7
	Comp Motor [kW]	2.8	2.6	3.3
	Blower [kW]	0.3	0.43	0.4
	Blower [kBtu/h]	1.0	1.5	1.4
	PEERS Capacity	22.1	24.1	22.9

Test	Equipment	3 Ton, 2 Speed Compressor, Variable Speed Up-Flow Furnace Blower		
	(numerator) [kBtu/h]			
	PEERS Power Draw(denominator) [kW]	3.5	3.3	4.0
	PEERS	6.3	7.3	5.7
	HDAC #2 PEERS Value	6.8	6.8	6.8
	Passes	**No**	**Yes**	**No**

A statewide HDAC program has been proposed that lists compliant systems using manufacturer data. Every split system is composed of three components: 1) a condenser (including a fan, a compressor and a coil); 2) an evaporator coil; and 3) a blower that circulates indoor air through the evaporator coil (typically part of a furnace or a heat-pump air handler). Inserting catalog data into a spreadsheet shows that listings could be created based upon this data; however additional quality control steps will need to be implemented before publishing such a listing. The chart in Figure 15 illustrates the challenge for the Consortium for Energy Efficiency's Tier-3 equipment. The over 2500 systems represented in that figure have a well behaved plot line for EER but an erratic scatter of points for SEER. Some scatter is due to two-speed versus single-speed compressors, but most of the scatter is due to the large variety of coil-compressor combinations that are available.

Figure 15: Manufacturers' Listed EER and SEER Combinations for 2500 Condenser/Evaporator-Coil Combinations



3.2.1.1 Original Equipment Manufacturer (OEM) Systems Listing

The ratings from the Original Equipment Manufacturers (OEMs) are calculated using USDOE approved Alterative Rating Method (ARM) computer programs. According to this approval process, the system with the highest national sales volume is tested and the results of those tests are used, along with individual component characteristics, in the ARM. ARM programs are proprietary and cannot be accessed by WCEC. The research team proposes starting with the following procedures, and then revising them as needed based upon testing and calculations that are part of a more complete HDAC program.

3.2.1.2 Preliminary OEM HDAC Listing Procedure

1. Each manufacturer completes a calculation spreadsheet with an example model from their catalogue.
2. Missing data are noted.
3. Data derived from other published data based on standard engineering assumptions are highlighted and accompanied by a listing of the assumptions.
4. Manufacturers are asked to submit a procedure for supplying the necessary data to WCEC technical staff.

5. Manufacturers submit their candidate-system data for technical review and HDAC-criteria calculations by the WCEC.
6. A list of HDAC-compliant models is developed by the WCEC using the data provided by the manufacturers.
7. This list (along with calculations) is sent to the manufacturer for review and comment.
8. Models not on the list are reviewed with the manufacturer and added to the list if additional or revised data shows that they qualify for HDAC.

3.2.1.3 Independent Coil Manufacturer Listing

The SEER and EER95 ratings of systems using components from independent coil manufacturers are currently calculated using DOE-approved ARM calculations. In the PG&E program that used SEER/EER pairs, when EERs were not being provided by ARI, independent coil manufacturer ratings for a particular system were requested and received via facsimile. An ARI number was provided and the turnaround time was one day. Thus, it may be possible to follow the proposed OEM HDAC procedures for systems using components from independent coil manufacturers. However, this may be controversial, in the same way that the current practice for SEER and EER95 ratings is controversial, namely that no one entity is responsible for the entire system. It is potentially important to address independent-coil systems. Supply, demand, cost, and performance issues drive the practice of using non-OEM coils, as independent manufacturers are generally more responsive, and can produce coils to match a customer's needs. The recent emphasis on SEER/EER ratings coupled with energy efficiency incentives has encouraged the use of coils that have larger heat exchange areas with reduced static pressure drop, and both OEMs and independents are making systems and components that meet this challenge. However, given the controversy noted above, there will need to be an HDAC steering committee that establishes the protocols for listing non-OEM systems.

3.2.2 Water-Cooled Condensers

Another type of residential HDAC system is one that uses evaporation at the condenser to improve efficiency. Large-capacity unitary equipment has for years offered water cooled condensers, where a built-in evaporative cooling tower produces water that cools the hot high-pressure gas coming from the compressor. In the last decade, a succession of residential water-cooled split-system condensers have been developed, tested and installed by one small manufacturer. Recently a second water-cooled-condenser has been developed by another small manufacturer. With two manufacturers in the market, consumers will be better served and utility incentive programs can support competition. However, for the mature market price to be achieved, sales in the California market will need to increase to thousands of units per year. On the bright side, laboratory and field testing of the currently available water cooled condenser systems have been providing good results. For these types of systems, refrigerant charging is performed using a sight glass, the condensers need to have a water supply line, and a drain is needed for purge water (preferably used for irrigating plants). All residential A/C systems require commissioning, however in the case of water cooled condensers it is particularly important to make sure that the water supply, drain, and controls are functioning properly. In

addition, maintenance is needed at the beginning and end of each cooling season. Although a homeowner can do the maintenance, it is generally a good idea to have a professional regularly check the status of all system components, as water quality with a timed purge cycle needs to be maintained without excessive water use. It is possible that once there is more widespread experience in the field, and the potential for water cooled condensers is better established, major manufacturers will become involved, bringing with them mass production and distribution, and thereby lowering unit costs.

3.2.3 Hybrid DX and Two-Stage Evaporative Cooling

There already exists in the marketplace a number of advanced evaporative coolers, including indirect-only, and two-stage indirect-direct equipment for residential applications. A positive feature of evaporative cooling is that the indoor air is not re-circulated and the fresh outdoor air supplied is filtered. They can function as whole house fans with the water turned off as well as be controlled by advanced thermostats. Moreover, evaporative cooling systems are considerably more energy efficient than conventional air conditioning systems, including HDAC systems and evaporative condensers, however their applicability has been limited due to issues with meeting load during hot periods with higher than usual outdoor humidity. Some indirect systems address this problem. We know of at least one development project underway to add a downsized DX (Direct-Expansion) system to an existing two-stage evaporative cooler that has consistently done well in laboratory and field testing. Adding a small compressor, condenser and evaporator to the system is designed to expand the applicability of evaporative coolers. The hybrid system is being developed in response to the need for a system that handles even the worst weather was well as the standard air conditioner but with twice the efficiency and less than half the annual operating cost.

Like evaporative condensers, all evaporative coolers require supply water and water drain capabilities, and somewhat more maintenance as compared to conventional residential air conditioners.

3.2.4 Desuperheaters and Subcoolers

Geothermal water source heat pumps cool the output of their compressor with water that is cooled by circulating it through pipes in the ground. A common factory-installed accessory for these systems is a de-super-heater that heats water for domestic uses with hot refrigerant before that refrigerant is cooled in the heat pump's refrigerant-to-water condensing heat exchanger. The main benefit of these systems is the "free" domestic water heating provided, however in the cooling mode, a de-super-heater generally improves cooling efficiency. At ARI rating conditions the EER can be increased by more than one point with a de-super-heater, however seasonal savings are expected to be less (particularly in California, where most water heating is done with gas). A standard air-cooled condensing unit can be retrofitted with a de-super-heater, however this requires recovering the refrigerant, brazing in the de-super-heater, running water lines to and from the water heater, and then charging the system correctly to account for the added components. This is not often cost effective in residential applications.

Along the same lines, sub-coolers are mounted in the refrigerant piping after the condenser coil and before the expansion device feeding the evaporator coil. A few custom-made systems that

sub-cool with swimming pool water have been installed. These systems increase EER by reducing the temperature of the returning liquid refrigerant, and also provide heating for the pool. About 10 percent of California single family homes have swimming pools so that there is a potential for a market impact in existing homes. Sub-coolers can be installed when a condensing unit is installed either in new construction or in an existing home.

3.2.5 Swimming-Pool Heat-Sink Systems

One residential system concept that is under investigation at the WCEC is the use of residential swimming pools as heat sinks for residential air conditioners. The basic concept is that the pool is cooler than outdoor air temperature during residential air conditioning periods, particularly during peak times, and that a water-to-refrigerant heat exchanger reduces the hot refrigerant temperature even further. The result is reduced electricity consumption, potentially up to 50 percent during peak demand periods. In addition, the rejected heat from the pool serves to heat the pool, reducing natural-gas or solar heating requirements for the pool. One of the issues associated with these types of systems is the match between the heat that needs to be rejected from the house, and the capacity of the pool to absorb that heat and remain within its desired operating temperature range. Although this type of cooling system has been successfully employed in a number of homes, it has not seen widespread application. WCEC efforts are geared towards providing the technical analyses and tools (potentially including technological advances) needed to make such systems easy to apply on a widespread basis.

CHAPTER 4:
Condenser Mist Cooling

4.1 Introduction

Evaporative pre-cooling of air-conditioning condenser air offers major efficiency benefits in hot dry climates. Three basic strategies are available:

1. spraying water on the condenser coil,
2. distributing water on evaporative media upstream of the condenser coil,
3. without "media", creating a fog or mist of pre-cooled air entering the coil.

The first strategy is easy to implement but is not recommended because of its many liabilities including:

1. excessive use of water,
2. scale buildup (in hard water areas) that restricts airflow,
3. coil damage from water droplets impinging the surfaces.

The second strategy is widely used for evaporative pre-cooling, and is not susceptible, when properly applied, to the liabilities of direct spray on the coils. However, installed costs of the evaporative media and its (usually stainless steel) framework can discourage application. Appendix B provides a more detailed discussion of how media-based systems can best deal with hardness minerals. The third (fog/mist) strategy is appealing for its potential to combine the low cost of the first strategy with the reduced liabilities of the second strategy. Among the three strategies, fog/mist systems may also offer the lowest possible water use. This report discusses the state-of-the-art of this "flash evaporative" pre-cooling technology, and recommends future activities to assess and advance its commercialization potential.

4.2 Flash Evaporative Technology (FET)

Flash Evaporative Technologies (FETs) are distinguished from spray systems by their much smaller water droplet size. The goal in applying FET to condenser coils is to minimize water droplet size to prevent damage to coils, and to assure that any hardness minerals in the water are carried through the coil by the airstream rather than depositing on the coil surfaces. This potential ability of FET to carry hardness minerals through the coil is a second major advantage (in addition to lower cost) compared to media-based systems, which, to prevent reduction in airflow area, must waste water to wash hardness minerals from media surfaces (see Appendix B). If proven, this "mineral carry-through" feature promises reduced water use per Btu of evaporative cooling delivered, since no water need be wasted for mineral control.

4.2.1 Available Products

FET is most frequently applied in grocery store fresh food areas, and (in hot weather) at outdoor restaurants and on the sidelines in "large stadium" sporting events. In these systems, water is

typically pumped at ~1000 psi through misting nozzles that create droplets as small as 5 microns in diameter. These drops are small enough to evaporate in a short distance. But several low-cost FET systems are marketed that operate at city water pressure, such as the Arizona Mist Systems by Orbit.[4] The Thomas Register lists more than 20 manufacturers of mist cooling systems; of the 20, at least five have these "line pressure" systems available. While these low pressure systems can be purchased as kits for around $50, high pressure systems that minimize droplet size start at about $1,500. FET currently is seldom applied to pre-cool condenser coils, possibly due to potential coil damage, but on the internet at least three firms market such kits for residential condenser pre-cooling. For non-residential applications, only one manufacturer, Micro-Cool, clearly advertises mist application for rooftop air-conditioning units. Their system requires the custom design and fabrication of a trellis on which high-pressure spray nozzles are mounted to create a cool fog around the rooftop unit's condensing coil(s).[5]

4.2.2 California Developments

4.2.2.1 Residential

The Beutler Corporation of Sacramento, with support from the WCEC and affiliate member Davis Energy Group, has attempted development of marketable FET products for both residential and non-residential applications. In the residential arena, Beutler worked with the Davis Energy Group in 2006-7 to evaluate the potential for a line-pressure mist accessory that could be retrofitted to a wide range of home condensing units. The two firms implemented a lab test program that assessed the performance and maintainability of this system, but results in both categories were below expectations. Beutler decided to postpone further R&D work on the system, preferring to focus their residential efforts on their emerging Aqua-Chill product. (Aqua-Chill is a replacement evaporative condenser similar to the Freus product that has been available in various forms since 1999.) .

4.2.2.2 Nonresidential

The first California participant in the non-residential FET market is Micro-Cool, briefly discussed above. Beutler Corporation is evaluating the CoolTec system. The initial CoolTec product uses a medium pressure pump/filter/water treatment center that can deliver ~200 psi water to about 175 tons of AC capacity.[6] . The system includes screened "surrounds" that hold the spray heads for each rooftop unit connected to the system. A unique control system minimizes water use. WCEC staff has reviewed a proprietary report on a test CoolTec system installed in Ft. Myers, Florida. The project showed economic viability even in the very humid Florida climate.

In related work, the WCEC evaluated in early 2007 a "roto-fogger" accessory designed to evaporate condensate from rooftop unit cooling coils into the condenser airstream. This device, developed in China, drips condensate onto a spinning disc that "slices" the droplet against a

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http://www.orbitonline.com/index.cfm/arizonamist

5 http://www.microcool.com/cooling/precooling.shtml

6 Gregg Steinriede of Beutler Corporation advocates 175-200 psi as the "sweet spot" for nozzle-based condenser cooling.

mating surface, spinning out small droplets in the 500 micron mil range- about the same as achievable with nozzles at ~50 psi (city) pressure. Since it requires electricity and line-pressure nozzles, the technology appears to have little value for large-scale condenser air pre-cooling.

4.3 Discussion: Finding a "Sweet Spot"?

Experience to date suggests that nozzle-based FET systems operating at city water pressure are unlikely to be maintainable. Coil plugging and water damage will shorten life and/or increase maintenance costs, thus limiting economic viability. These liabilities result from the "too large" droplets, which can impinge and deposit on the coil. Impingement can erode the coil, and deposits can significantly reduce necessary airflow.

It may be possible to find a "non-nozzle" strategy to mist water into "small-enough" particles. Ultrasonic misting technologies are widely used for small humidifiers and more recently, a portable humidifier/cooler.[7] Larger ultrasonic misters[8] promise very small water particles (5 microns or .0002") but consume about 700 watts per ton of cooling from the misted water, at a list price higher than a conventional air conditioner.

Additional research is warranted to assess whether a less-energy intensive ultrasonic process can generate ~50 micron water particles at costs (both equipment and energy) that are competitive with pressurized nozzle-based systems. However, such a system, if identified, might be limited to residential applications unless the misting equipment can be much less expensive. In comparison, a pressurized, nozzle-based system (whether 200 or 1000 psi), can apply a single hardware station to supply pressurized water to a large array of rooftop units. It is not practical to apply a single large mist-maker and then duct the mist to such an array.

At present the most promising direction appears to be the ~200 psi nozzle-based design being pursued by Beutler. By comparison, high pressure (~1000 psi) systems require significantly more energy to generate mist and they are also much more prone to nozzle clogging because of their smaller orifices. [9]

How widely applicable is this technology? If it works, it is currently limited by project size. There currently is only one field-proven, reliable pump in the 200 psi range, and it is large enough to drive a 175 ton system- which is too large for individual residences.[10] Of course, this unit could be applied to multi-family projects, but the owner would probably pay for the pump's operation while his tenants would reap the rewards. Development of an efficient, reliable, and economical 200 psi mini-pump is necessary to extend this technology to single-family homes.

3http://tallstou.manufacturer.globalsources.com/si/6008800064191/pdtl/Air-cooler/1003314362/Ultrasonic-Misting-Cooler.htm

4http://www.mainlandmart.com/humidify.html

9 Gregg Steinriede, Beutler Corporation.

10 Gregg Steinreide, Beutler Corporation

4.4 Recommendations

The following ongoing activities are recommended to advance the potential for significant FET impact on California's cooling marketplace:

1. Continue to support test installations, and provide: a) impartial review and reporting of project results and b) recommendations for system improvements considering both maintenance and performance issues.
2. Develop a funded project that systematically evaluates alternate misting strategies, tabulating energy use versus micron water particle size.
3. Survey the range of available pressurization pumps and, if necessary, develop required cost/performance specifications, then solicit development of small pump/water treatment packages suited for single family residential applications.
4. Determine the water particle size, if any, at which hardness minerals in "misted" untreated water will pass through typical condenser coils.
5. If research results are favorable, prepare and issue a "product opportunity" paper that summarizes the business potential for misting systems that precool condenser air.

CHAPTER 5:
DualCool Installation

5.1 Introduction

DualCool units were installed on two Munters 30-ton Dedicated Outdoor Air Supply (DOAS) rooftop units (RTUs) at the Walmart store in Dixon, California in September, 2007. The DualCool units use a direct evaporative assembly to pre-cool condenser air. Water from the evaporative sumps is circulated through radiator coils at the ventilation air intake to indirectly pre-cool ventilation air. After installation, both the modified units and a third (unmodified) Munters unit were monitored to assess DualCool performance. This chapter provides a preliminary assessment of DualCool potential for this application based on the monitoring results.

5.2 Installation

DualCool manufacturer Integrated Comfort, Inc. (ICI) of Vacaville CA installed the units under a turnkey agreement. Installation required placing the condenser and ventilation air components, piping between these two components, adding water supply lines, and modifying controls for preferred DualCool operation. ICI fabricated DualCool components to fit the existing Munters units. This was the first DualCool application to Munters rooftop HVAC units. Installation generally proceeded smoothly, though several issues needed resolution before completion. Photos below show the completed installations.

Figure 16: Ventilation Coil and Piping

Photo credit: Larry Poellnitz

Figure 17: Condenser Precooler, Piping, and Wiring

Photo credit: Larry Poellnitz

The most significant installation issue involved the ventilation coils, which were initially fabricated for piping connections at top and bottom on the right side. In this configuration the connecting piping interfered with an access door on the RTU, requiring the DualCool supplier to remove and modify the coils (moving the inlet and outlet to bottom and top, respectively) to prevent interference with the access door and to minimize turns in the piping. Water leakage at one of the pump connections also needed correction after initial startup, and one DualCool pump stopped functioning after the first day of operation. ICI replaced the pump and could not determine a cause for the failure, but a similar event at another relatively new DualCool site has prompted ICI's decision to change to air-cooled (versus "wet rotor") close-coupled pumps.

5.3 Control

Each DOAS RTU was originally installed with 3 condenser air movers: one 5 hp centrifugal blower and two 1.5 hp prop fans. A perforated plate separates the blower inlet from the condenser leaving air plenum served directly by the two prop fans. The base case control sequence activated the centrifugal fan and one prop fan as first stage, and the second prop fan as second stage. On the two DOAS RTU's with DualCool, installation personnel disabled the blower and added a parallel control relay to activate the Stage 1 prop fan whenever the DualCool pump operated. No changes were made to original controls for the base case RTU. Each DualCool unit operated whenever its sump water level was above a lower limit and outdoor temperature was above a limit setting (both were set at 70°F).

5.4 Monitoring

Davis Energy Group (DEG) was contracted to develop a monitoring plan, install and calibrate monitoring equipment, and log data for evaluation of DualCool operation at the site. The essence of the monitoring plan was as follows:

1. Install "self-logging" power monitors on all three Munters DOAS units
2. Install a DataTaker50 logging unit to record data from the following sensor points:
    a. Shielded outdoor temperature and relative humidity (one for the site)
    b. Pre-cooled condenser air inlet temperatures for both DualCool media arrays (five-point thermocouple stalks)
    c. Pre-cooled vent air inlet temperatures for both DualCool units (one central location)
    d. DualCool pump power transducer, both units
    e. DualCool water consumption, both units
3. To limit required site visits, a cell phone modem was specified for data transmission to the DEG office. However, in 2007 this component did not operate properly. As a result, DEG personnel manually downloaded data in 2007. DEG ordered a replacement modem that was installed for the 2008 season.

5.5 Operation

DEG personnel completed setup and calibration of monitoring equipment on in September 2007. Based on typical weather conditions, project participants expected at least a few daily high temperatures approaching 100F before the end of the cooling season. Unfortunately for the project, cool weather prevented evaluation of DualCool performance under peak cooling conditions. The hottest day after calibration of the monitoring equipment was the first full day of recorded data (September 27) with a high temperature of 90.7°F. Thereafter, the highest 2007 temperature was 81°F, and few days had highs above 75°F. As a result, little DualCool operation occurred. Operational reviews in the early summer of 2008 showed that cooling loads were seldom experienced on one of the DualCool AHU's, which was located near the refrigeration area; and AHU-3, without DualCool, was the busiest of the three. Based on this observation, ICI moved one DualCool to AHU-3. Monitoring results presented here include short term data from 2007 and longer term data from 2008.

5.6 2007 Results

Appendix C shows partial results for DualCool Unit #1, in 15 minute time steps, on the warmest 2007 day. After the "time" column, the next two columns show outdoor dry bulb and wet bulb temperatures. The outdoor dry bulb temperature peaked at 90.7°F (with 63.3°F concurrent wet bulb temperature) at 4 PM.

5.6.1 Condenser Air Precooling Effectiveness

The next two columns show the temperature of precooled air entering the condenser and the resulting evaporative effectiveness as a percentage of wet bulb depression (WBD). At the 4 PM peak condition, the measured outdoor air WBD was 26.4°F and the corresponding effectiveness was 88 percent. Results in the effectiveness column indicate that direct evaporative

effectiveness, which averages about 86 percent of WBD, is highest when outdoor air is warmest. This result is unexpected and, if correct, suggests that DualCool economic value increases in warmer conditions.

5.6.2 Vent Air Precooling Effectiveness

The next two columns show the temperature of precooled air entering the evaporator coil, and the resulting indirect evaporative effectiveness as a percentage of the difference between outdoor dry bulb temperature and assumed sump water temperature. The latter is assumed, based on prior monitoring, to average 5°F above the outdoor wet bulb temperature. Results again indicate that evaporative effectiveness (in this case indirect) is highest when outdoor air is warmest. This result is also unexpected and suggests that DualCool economic value increases in warmer conditions. Prior economic analyses for Walmart have assumed 50 percent ventilation air pre-cooling effectiveness with sump temperature 5°F above wet bulb in all conditions; 50 percent or greater effectiveness was measured about 66 percent of the time on the featured day. The average indirect effectiveness was about 50 percent for the featured 8 hour period.

5.6.3 Parasitic Energy

The DualCool system imposes three potential parasitic penalties on system performance:

1. Energy use for the DualCool pump
2. Higher main blower energy use due to pressure drop in the vent air coil
3. Higher condenser fan energy use due to pressure drop in the condenser precooling media

The second-to-last column in Appendix C shows pump energy use, which averaged 141 watts for the 8 hour featured period. This value is well below the 300 watt value used in the most recent DualCool economic projection for Walmart. Regarding main blower energy use, Munters personnel adjusted supply air delivery to 5000 cfm for all three DOAS RTU's after DualCool installation. Blower power readings taken after these adjustments indicated a 455 watt penalty for the vent air coil. This penalty should reduce to 232 watts when larger coils (equal to evaporator face area) are used. As in prior DualCool installations, condenser fan energy is substantially lower with DualCool, because an air mover is disabled in recognition of the cooler condenser inlet air. Additional work is needed to identify optimal condenser air flow rates with DualCool, but it is unlikely that a condenser fan energy penalty will be the result.

5.6.4 Water Use

The last column in Appendix C shows water use in gallons. The unit used 185 gallons during the 8 hour period, averaging 0.77 gallons per ton-hour rating for the 30 ton unit. A 2002 DualCool monitoring report established a linear water use relationship versus peak daily temperature that indicates 7.9 gallons per ton-day for a 90°F peak temperature when the DualCool threshold operating temperature is 70F. On September 27, 2007, including 17 gallons used before the 8 hour period, the water use was 6.7 gallons per ton-day, 15 percent below the prior estimate.

5.6.5 Controls

The on/off temperatures set in the DualCool control circuit do not match recorded outdoor temperatures. The DualCool pump, set at 70°F, activates in the 74°-79°F range as recorded by the monitoring system's calibrated outdoor temperature sensor. The DualCool sensors, in a shaded location near the sump, apparently read "low."

5.6.6 Overall RTU Power

Total RTU power for the 8 hour featured time period on September 27, 2007 was 35 percent lower (29.1 kWh versus 44.6 kWh) for Unit #1 in comparison with the base case unit. Due to inconsistencies in measurement of the (post-evaporator) supply air temperatures, additional work is necessary to assess the relative cooling delivery of DualCool and base case units.

5.7 2008 Results

Figures 18 through 21 were developed by Davis Energy Group based on 2008 operation of AHU-3 with and without DualCool. Figures 18 and 19 show daily AHU-3 kWh energy use, versus average and peak outdoor temperatures, respectively. Results show significant daily energy savings at high temperatures. The least-square lines suggest DualCool benefits on days with average temperature above 72°F and peak temperature above 87°F.

Figure 18: DualCool and Base Case Daily Energy Use Versus Average Outdoor Temperature

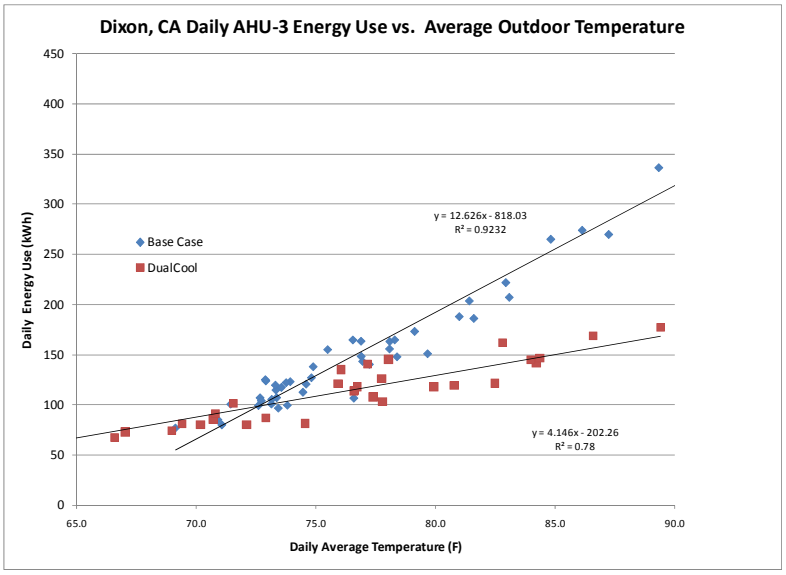


Figure 19: DualCool and Base Case Daily Energy Use Versus Outdoor Maximum Temperature

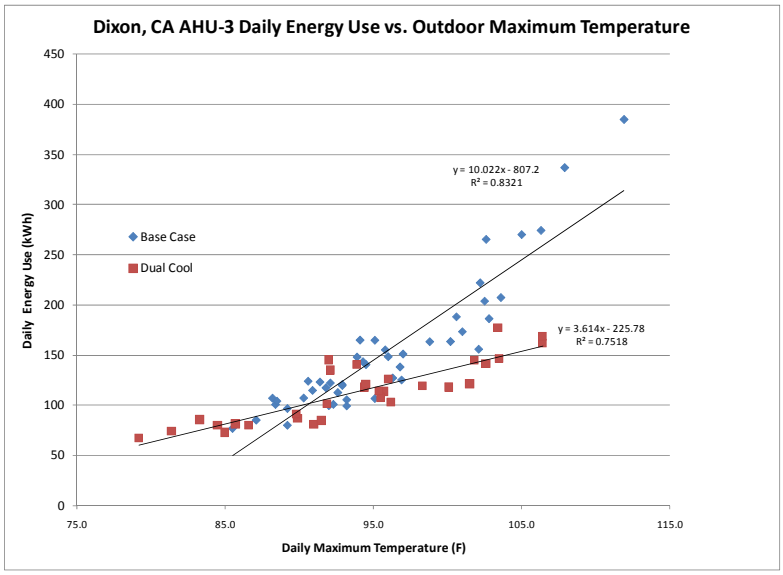
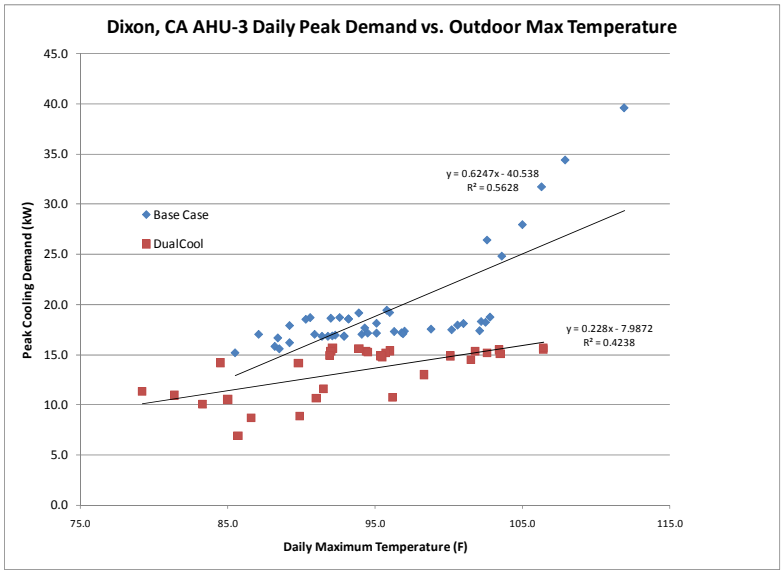


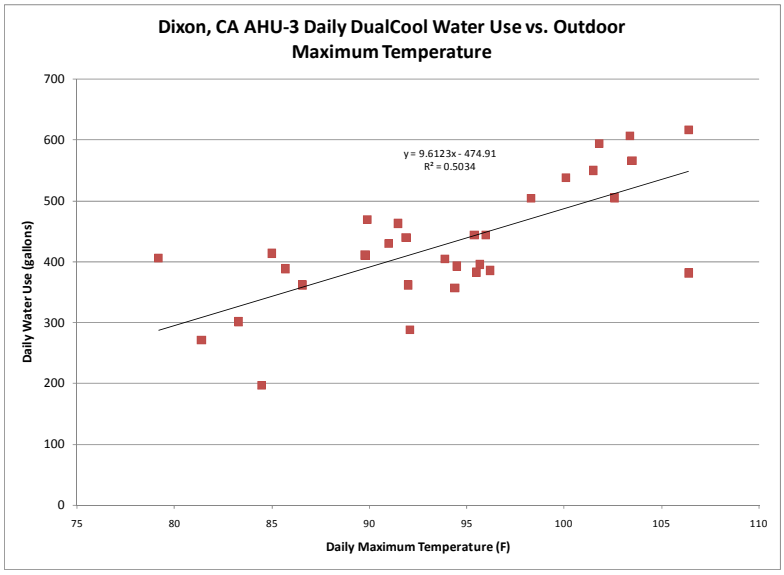
Figure 20: DualCool and Base Case Daily Peak Demand Versus Outdoor Maximum Temperature



Due to the limited number of data points in the very hot regime, the "base case" least-squares line for the above plot does not fully reflect the significant demand rise shown by the specific points in very hot conditions. But even based on the linear fits, DualCool shows 36 percent lower peak demand at 105°F.

Figure 21 shows AHU-3 daily water use versus outdoor temperature. At approximately 1.4 gal/ton-hour, the 2008 water use rate was more than double that reported for the short term data in 2007. Additional review is warranted to investigate the cause of the higher water use.

Figure 21: DualCool and Base Case Daily Water Use versus Outdoor Maximum Temperature



5.7.1 Revised Projection

The WCEC revised, based on monitoring data reported here, the DualCool value projection dated June 9, 2007. The revised projection is attached as Appendix D. The changes from the prior projection are:

1. Revised net vent air kWh/yr-ton savings (323 versus 268) based on lower cfm (5000 versus 6000), lower fan penalty watts (assuming interior coil, 234 versus 390), higher coil effectiveness (assuming interior coil, 0.6 versus 0.5), lower pump watts (141 versus 300).
2. Revised tons capacity credit (12.2 versus 9.2) based on higher direct evaporative effectiveness and more accurate projection of condensing temperature impact. Vent coil

changes were also considered, but the higher assumed vent coil effectiveness (with larger interior-mount coil) and lower cfm had exactly balanced impacts.

These changes result in an improved projection in which the 40 percent increased DOA unit capacity, valued at $800/ton in displacing RTU capacity, more than covers the $9,000 assumed incremental cost of the DualCool unit, while generating $1,700/year in net annual energy cost savings (water and maintenance savings must also be considered). However, the $9,000 installed cost has not yet been achieved for field installations. With reasonable volume, $12,500/unit appears more likely, which would generate a payback of about 8 years if savings projections hold up and (water + maintenance) costs do not exceed $350/unit per year.

Comment [v1]: How was this determined…earlier the net annual savings was $1,700/year. This results in a simple payback of over 7 years?

5.8 Conclusions

These results confirm that DualCool technology offers significant value in this DOAS application, principally for its ability to increase capacity, thus reducing capacity required for non-ventilation air RTU's. But installed costs are expected to vary significantly depending on whether DualCool components are included in units shipped by Munters, as opposed to field-installed. When factory-shipped, DualCool will likely generate an immediate payback, with energy cost savings in addition. When field-installed at $12,500 per unit, an eight-year payback appears likely.

Based on results so far, the WCEC recommends the following next steps:

1. *Monitoring*: Continue monitoring to assess persistence of savings and maintainability. Improve monitoring by resolving supply air temperature issue, recording sump water temperatures, and recording condensing and evaporating temperatures to better assess DualCool impact on refrigeration efficiency and capacity.
2. *Modeling*: Develop an hourly simulation program calibrated with monitoring results that can project energy savings and demand reduction in any simulated climate for the DOAS application.
3. *Economics*: Based on bid data and solicited quotations, determine DualCool incremental costs for both factory- and field-installed scenarios. Pending projected economics within Walmart guidelines.
4. *Barriers*: Reduce DualCool water use on future applications by recapturing condensate, and support the WCEC campaign to remove the California requirement that RTU condensate be directly piped to a drainage system.

CHAPTER 6:
Climate Mat Installation

6.1 Introduction

Circulating cool water through slab tubing can save energy by facilitating cooling from non-compressor sources, and by reducing energy use for blowers and unnecessary dehumidification. In most California locations, these benefits can combine to generate more than 50 percent annual HVAC electrical savings. Slab tubing is expensive if installed using materials and processes common to the radiant floor heating industry. Walmart has pursued radiant floor cooling as an energy efficiency measure, and in 2005 they installed large radiant floor systems in two experimental stores. However, the $6-7 per sq ft. installed cost precluded further use in prototype or production stores.

Since mid-2006 a team including the WCEC, the Davis Energy Group (DEG), and the tubing manufacturer Viega, have worked with Walmart to develop a lower-cost radiant floor cooling system. The concept uses large pre-fabricated "roll-up" tubing arrays that can be deployed quickly and do not interfere with concrete placement. In February 2007, the team installed a 12,500 sq ft. test array in the new Walmart store in West Sacramento. The test focused on the ease of installation with Walmart's well-developed "green slab" technology. Walmart and Viega developed several system improvements and in August, 2007 installed the modified system in the 110,000 sq. ft. general merchandise area of a new Supercenter in Las Vegas. The installed cost for the Las Vegas store's radiant floor tubing was reportedly less than $2 per sq ft. Since that project, Viega has applied the "Climate-Mat" product name to this system, and Walmart has specified the system for installation in additional projects.

6.2 Unique System Features

Climate-Mat achieves major cost-reduction compared to prior radiant floor systems by using high-density polyethylene (HDPE) instead of cross-inked polyethylene (PEX) as the tubing material. HDPE is approximately half the cost of PEX, and it can be thermally fused together, which PEX cannot. HDPE also has a lower "continuous duty" temperature limit, at 140°F versus 180°F for PEX (both at 100 psi pressure). But 140°F is no problem for cooling applications, and even for chain retail heating applications. Since it is fusible, HDPE can be configured into large arrays with fused header/manifolds buried in the slab. By comparison, PEX must use mechanical joints between circuits and headers. These joints are not advisable for in-slab placement. Thus, PEX requires much more field labor and many more access panels for tubing connections.

Walmart uses a unique 4 inch slab design without reinforcing steel, except for selected high load areas. For Walmart applications, Climate-Mat is configured in 10 foot wide, roll-out arrays 130 foot long, so that each mat covers 1300 square feet of floor area. Each mat includes 10 circuits of 260 foot long tubing, with circuits arranged as parallel "out and back" pairs on a 6 inch spacing pattern. Thus, each mat includes 2600 linear feet of ½ inch nominal tubing. The 10

foot long supply and return manifolds are together at one end of the array. The tubing lies at the bottom of the slab, and is held in place by the weight of the concrete.

6.3 Installations

The West Sacramento prototype system used 3" diameter headers that required significant excavation to bury them below the bottom of the slab, and then required time-consuming fusing of the large pipes before they are buried. Joining sections underground also limits access if a circuit leaks. Figure 22 shows the test pour, with tubing arrays partially deployed. Each roll has spacer bars every 10 feet along the 130 foot roll length to maintain the desired 6 inch spacing between circuit tubes. The large white apparatus at left is the laser screed that levels the concrete. The screed moves from left to right, working a slab section about 15 foot by 20 foot wide before it must be relocated for the next pass. In this test application, the tubing unrolled under the screed boom, which interfered with movement of the screed.

Figure 22: Climate-Mat West Sacramento Test Pour

The test was deemed successful, but the following lessons were applied to the subsequent Las Vegas, Nevada project:

1. Reduce header size: The decision to join the individual roll-out sections at ceiling level instead of under the floor reduces excavation and fusion time, as well as header cost. Though it likely increases piping and joining costs, this change also enhances accessibility for repairs.

2. Improve spacer design: The original spacers were 1 inch high plastic channels whose liabilities included high cost, possible weakening of the slab due to their height, and spacing too wide to hold tubing accurately when impacted by the concrete mix. Viega subsequently developed a lower-cost, low profile spacer bar system and reduced their spacing (along the 130 feet length) from 10 feet to 4 feet.
3. Change Rollout: Transverse rollout eliminated interference with screed movement.

Figure 23 shows a comparable photo from the Las Vegas, Nevada project. With the transverse rollout strategy, three 5 foot sections (1-1/2 Climate Mat rolls) are fully deployed from side-to-side. This format allows both the concrete truck and the laser screed to move closer to the pour zone, and does not endanger the rolls. Figure 23 also shows the lower profile with more frequent spacer bars in the redesigned system.

Figure 23: Climate-Mat Rollout in Las Vegas, Nevada

6.4 Conclusions

This technology has reduced the installed cost of radiant floor tubing and manifolds by at least 65 percent, and thus has clearly improved the cost-effectiveness of radiant floor cooling for Walmart. Further improvements are possible to reduce , cost. The ultimate goal is to reduce installed cost to approximately $1/sq. ft. This goal appears achievable through a combination of system refinements and increasing volume. If this goal can be achieved, the technology should become compelling enough to mandate its installation in most new non-residential cooling applications.

CHAPTER 7:
Emerging Cooling Technologies

7.1 Introduction

Innovative or "disruptive" products typically enter the cooling market through smaller firms, while the major manufacturers focus on mass marketing and cost-reduction for established products. The WCEC provides business and market support to assist entrepreneurial firms committed to developing, producing, and marketing viable energy-efficient cooling products optimized for hot, dry climates. With partial support from the UC Davis Graduate School of Management (GSM), WCEC work supported selected firms trying to significantly influence the California cooling marketplace. The WCEC used its connections with utilities, local developers, and business expertise to support the business development and future success of the following WCEC Affiliates:

1. Beutler Corporation, with the following two concepts:
    a. AquaChill, a residential evaporative condenser
    b. FlashCool, a multiple-unit "flash evaporative" technology for pre-cooling condenser inlet air
2. Delphi Corporation and Coolerado, manufacturers of the "HMX" indirect evaporative cooling modules
3. Speakman Company, manufacturer of the OaSys two-stage evaporative cooler
4. Ice Energy- manufacturer of Ice Bear thermal storage products
5. Integrated Comfort, manufacturer of the DualCool evaporative pre-cooling system
6. Novatorque – developer of advanced electric motors
7. Seeley- Australian manufacturer of innovative evaporative cooling products
8. Cooling Corp., an unofficial entity interested in commercializing the WCEC's "WicKool" passive condensate evaporator concept

7.2 Results

7.2.1 Beutler: AquaChill

AquaChill is a residential evaporative condenser concept that can replace current air-cooled condensing units used in almost all residential air conditioning systems in the Western U.S. AquaChill is similar to the Freus product that has been available in various forms since about 2000. Both can reduce cooling energy consumption by 25 to 35 percent in peak cooling weather. When Beutler first joined the WCEC in 2007, they were in negotiations with Freus to serve as both manufacturer and installer for the Freus product line. However, when they were unable to come to a mutually acceptable agreement, Beutler management decided to develop and market

their own product to compete with Freus. The WCEC initially supported this effort by finding a China-based HVAC manufacturer interested in producing the new product line for Beutler. This Chinese firm subsequently produced and tested several prototype units, and the WCEC helped Beutler work with the Davis Energy Group (also a WCEC affiliate member) for Northern-California testing of the prototype units. In the extensive 2007 tests, Beutler completed a series of parametric runs to optimize the sizing of AquaChill heat exchange components.

In 2008 Beutler decided to manufacture AquaChill in their own facilities, and worked with SMUD (also a WCEC affiliate) to field test a group of pre-production units. Beutler installed 31 units in the SMUD tests, of which SMUD monitored 25. Minor problems occurred with some of these field test units, particularly with the Chinese-made cases, condenser coils, and fan motors. Beutler has since made component changes on the product, and retrofitted the field units with these new parts. Beutler has worked with a local firm to develop a rotationally-molded plastic case that should resolve a quality problem while also reducing cost. ARI has approved the AquaChill units and the product qualifies for the SMUD water-cooled condenser rebate. AquaChill is currently commercially available.

7.2.2 Beutler: FlashCool

FlashCool is a non-residential product designed to enhance the performance of existing rooftop cooling units. Developed by Gregg Steinriede of Beutler, FlashCool will deliver treated, high pressure water to spray nozzles that generate an evaporative mist to cool air entering the condenser coils of rooftop cooling units. The water droplet size is presumably small enough that remaining hardness minerals in the water supply can pass through the coil without depositing. Each system comprises a water treatment center, connecting piping, spray nozzles, and screens that contain the "fog" to ensure maximum application to the coil. The water treatment center, which includes a pressurization pump, a water treatment device, and a buffer tank, can supply pressurized water for approximately 250 tons of cooling in California conditions. This quantity can assist the cooling necessary for approximately 100,000 sq. ft. of typical retail space, and so is applicable to a large retail store, a strip mall, or other facility that utilizes multiple roof-top packaged units. The WCEC plans to work with Walmart and others to demonstrate the FlashCool.

7.2.3 Delphi and Coolerado: HMX Modules

Delphi Corporation, former division of General Motors, has traditionally produced heat transfer products and accessories for automobiles. Delphi in 2005 negotiated production rights for the Coolerado "HMX" indirect evaporative heat exchanger, a unique product that appears to have the highest performance in its class. In their agreement, Coolerado reserved marketing rights for "small HVAC system" applications of the HMX, and Delphi intended to focus on high volume manufacturing for delivery to Coolerado and to manufacturers of large HVAC systems. Early Delphi HMX modules were delivered to Desert Aire for incorporation in "Desert Cool Aire" prototype 5-ton rooftop units. These prototypes were installed and field-tested with support from SMUD and the Northwest Energy Efficiency Alliance (NEEA) beginning in 2006.

Delphi joined the WCEC as a "Charter Affiliate" in 2007, and the WCEC networked with SMUD and Delphi in attempts to accelerate market development. The process broke down after SMUD

tests revealed mold contamination in the HMX units. Delphi replaced the heat exchangers, but subsequent testing indicated that after some use, mold was present in the replacements as well. The WCEC worked with Delphi to understand and resolve this problem, but before resolution, communications broke down between Coolerado and Delphi, with both sides pursuing legal actions.

The WCEC chaired the "Emerging HVAC Technologies" workshop/technical session in December 2008 that introduced Coolerado to developers of the UC Davis West Village project. We hope to continue to assist this promising technology.

7.2.4 Speakman Company: OaSys Cooler

Speakman has licensed technology from the Davis Energy Group to produce the patented OaSys two-stage evaporative cooler. OaSys combines a unique indirect evaporative heat exchanger with a direct evaporative stage and a multi-speed blower in a high-effectiveness cooling product. The WCEC has provided technical support for Speakman's marketing efforts. In 2008, the WCEC secured funding from Southern California Edison for testing OaSys reliability and water use. The WCEC also secured a contract with SMUD for development and testing of a "hybrid" OaSys unit that adds a third, vapor-compression stage to the standard OaSys unit. The WCEC supported field testing of a prototype unit in 2009, and results are promising; the WCEC also arranged for Speakman to present OaSys at the 2008 West Village Emerging HVAC Technologies workshop.

7.2.5 Ice Energy: Ice Bear

Ice Bear is a packaged thermal-storage cooling system designed to shift cooling electricity demand. Ice Bear units use a vapor-compression system at night and during off-peak hours to build a large block of ice that is melted to cool the building. One key to the product is that it produces ice with relatively warm refrigerant temperatures. The product has been available for several years and appeals to a national market- particularly where electric utilities face increasing needs for new generation.

7.2.6 Integrated Comfort: DualCool

DualCool is a dual evaporative pre-cooling system for package rooftop cooling units. The product pre-cools condenser inlet air using a direct evaporative process, and indirectly cools the ventilation airstream by pumping water from the condenser pre-cooler sump through an indirect cooling coil in the intake air path. In 2007 and 2008 the WCEC participated in a PG&E-supported "third party contract" administered by Energy Solution of Oakland. This "Big Box Cool and Light Program" offered incentives for chain retailers to install DualCool on their existing stores. The WCEC roles were to assist with creation of a retail alliance and to oversee an effort that would assure proper maintenance of installed units. Unfortunately, the program developed slowly and only twelve DualCool units serving about 240 tons of rooftop units were installed on two Target stores. However, based on WCEC help that has identified their most cost-effective applications, Target remains interested in additional DualCool installations.

The WCEC also helped Walmart with evaluations of the DualCool installation in Dixon, California, and has assisted Walmart with negotiating a license for Munters to produce DualCool units for Walmart under license to Integrated Comfort.

7.2.7 Novatorque: High-Efficiency Motors

Novatorque, a Sacramento-based start-up firm, has developed a proprietary high efficiency electric motor whose prototype test results show superior performance compared to today's best electrically commutated motors. The Novatorque motor uses a unique winding pattern and process. Novatorque motors occupy less space and create less heat than current motors; these characteristics are particularly advantage in HVAC blower and fan applications. The WCEC has introduced the technology both to its utility members and to manufacturing partners. Novatorque is listed as a component supplier in the WCEC's Western Cooling Challenge.

7.2.8 Seeley International: Indirect Evaporative Coolers

Seeley is an Australian manufacturer of innovative evaporative cooling products. Lab tests for their new indirect evaporative module show very impressive results. The WCEC has introduced Seeley technology to its US-based HVAC manufacturing affiliates. Seeley has applied to participate as both a system manufacturer and a component supplier in the WCEC's Western Cooling Challenge. The WCEC also presented Seeley product information at the 2008 West Village Emerging HVAC Technologies workshop.

7.2.9 "Cooling Corp": WicKool

Cooling Corp. is an unofficial entity interested in commercializing the WCEC's "WicKool" passive condensate-evaporator concept. With support from the UC Energy Efficiency Center (EEC) and WCEC, Siva Gunda presented the WicKool concept in the UC Davis GSM's "Little Bang" and "Big Bang" business plan competitions. WicKool won first place in the energy division at the Little Bang, which encouraged further support from the EEC. After expressions of interest, the WCEC installed prototype WicKool units on local Target and Walmart stores in 2008. These units were partially successful, and promising enough that WCEC and EEC have invested additional development time toward a more robust design that can evaporate all condensate in worst-case Sacramento summer conditions.

Based on WicKool's promise and the Gunda business plan, several local business people were nearing an official formation of "Cooling Corp" by the end of 2008. The WCEC expects to support further WicKool development with installation of improved prototypes for Target and Walmart.

7.3 Conclusions

These support activities indicate both the range of activities that are necessary and underway to support emerging technology firms in the HVAC arena, and the many barriers and hurdles that slow progress. However, it is clear that these activities are making progress in the WCEC mission of accelerating new technology implementation. Continuing these affiliate support activities is essential to changing and improving the processes by which California buildings are cooled.

GLOSSARY

ARM	Alternative rating method
BERG	Building Energy Research Grant
DEG	Davis Energy Group
DGS	Department of General Services (California)
DOAS	Dedicated outdoor air supply
DX	Direct expansion
EEC	UC Energy Efficiency Center
EER	Energy efficiency ratio
FET	Flash evaporative technology
GSM	Graduate School of Management (UC Davis)
HDAC	Hot, dry air conditioners
HDPE	High-density polyethylene
HP	Horsepower
HVAC	Heating, ventilating, and air conditioning
ICI	Integrated Comfort, Inc.
IDEC	Indirect/direct evaporative cooling
MOU	Memorandum of understanding
NEEA	Northwest Energy Efficiency Alliance
OEM	Original equipment manufacturer
OSP	Office of State Publishing (California)
PEERS	Peak Energy Efficiency Ratio Sensible
PEX	Cross-linked polyethylene
PSI	Puckorius Scaling Index
ROT	Rule of thumb
RTU	Rooftop packaged unit
SEER	Seasonal Energy Efficiency Ratio
USDOE	U.S. Department of Energy
WBD	Wet bulb depression
WCC	Western Cooling Challenge
WCEC	Western Cooling Efficiency Center

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APPENDIX A:
Western Cooling Challenge Requirements and Performance Metrics

Revised 9/27/08

Requirements

1. Roof-top package unit (RTU) systems
2. Capacity (ARI 340/360 Standard Rating Conditions - Cooling Test), tons: 3 – 30
3. An entry need not be part of a model line that spans the entire capacity range
4. Demonstrated minimum production capacity: 500 units per year
5. Test results for one capacity will not necessarily qualify units with other capacities
6. Testing can be performed under observation and data analysis by University of California Davis Western Cooling Efficiency Center (WCEC) representative, at manufacturer's location or at a third-party facility
7. No use of R-22
8. WCEC-covered observation and data analysis costs may be limited to one unit per manufacturer, and/or a total of three units
9. WCEC will not cover the costs for observation and data analysis on a unit that fails to meet all Challenge requirements
10. Unit shall have under-voltage protection that prevents grid connection in a stalled condition
11. On-board electronics shall have the capability to communicate significant performance degradation
12. Heating capability is recommended for marketing purposes but is not required to meet the challenge

Performance Metrics

1. **Three Tests Required**
   a. ARI 340/360 Standard Rating Conditions (0% outdoor-air basis, standard external resistance)[11]
   b. WCC Nominal Peak Performance
   c. WCC Surrogate Annual Average
2. **Protocols for WCC Tests**

5For units that cannot be ARI Listed with 0% outdoor air, rated capacity will be determined at ARI indoor and outdoor temperature conditions in the operating configuration used for the WCC nominal peak performance test. Rated sensible capacity shall be calculated based on the temperature difference between indoor air and supply air.

a. Indoor/Return Air: 78 db/64 wb
b. External Resistance: fixed orifice with 0.7″ H_2O pressure drop at 350 cfm/ton
c. Filtration (Internal): MERV 7 or higher
d. Outdoor Air Flowrate: 120 cfm/rated-ton or higher (flows above 120 cfm/ton are not credited for cooling air from outdoor to indoor conditions, only for cooling beyond indoor conditions)
e. Max Supply Humidity Ratio: 0.0092

3. **Nominal Peak Performance Test**
   a. Test Condition: full-capacity operation
   b. Surroundings/Outdoor Air: 105 db/73 wb
   c. Minimum Sensible EER[12]: 14.0
   d. Minimum Sensible Capacity: 95% of rated sensible capacity
4. **WCC Surrogate Annual Average Test**
   a. Test Condition: full-capacity operation plus one optional test mode[13]
   b. Surroundings/Outdoor Air: 90 db/64 wb
   c. Minimum Sensible EER[2]: 17.0, delivering at least 80% of rated sensible capacity
   d. Maximum Water Use: 4 gal/ton-hour with hardness of 200 ppm (as $CaCO_3$)

6Including all parasitic loads, e.g., blowers, fans, pumps, controls (EER= sensible capacity/total kW)

[13]7anufacturer may specify full-capacity operation or a two-point test with a) full-capacity operation, and b) continuous partial-capacity operation, delivering not less than 120 cfm outdoor air per rated ton, and between 70% and 85% of ARI rated sensible capacity. Annual average test results will be either a) full-capacity operation results or b) a linear interpolation or extrapolation to 80% of rated sensible capacity based upon the two test points.

APPENDIX B:
Water Quality Control with Media-Based Precooling Systems

A single pass system without a sump and circulating pump is not recommended because, adjusted correctly, little if any water comes off the bottom of the media to be drained away. All of the minerals in the water that is evaporated are deposited on the media and become scale. To mitigate this, the flow is increased and water is wasted to flush the media. A recirculating system is best and most commonly in use for evaporative coolers. Water is pumped from a sump to the top of the media where it is distributed to evenly wet the media as it flows back to the sump. Minerals concentrate in the water but the flow keeps them from depositing on the media. Water quality is maintained by either bleeding water at a constant rate from the sump or by emptying the sump after a preset period of operation. Air leaving the media has been filtered, is at 20 degrees or more cooler that it started, and is at around 80 percent relative humidity. A few systems sense the conductivity of the sump water and empty when conductivity reaches a level indicative of high concentration. The goal is to get cycles of concentration up to the three- to six- level. Even for the worst water source the discharge water can still be used to irrigate vegetation.

Evaporative media restricts airflow as it filters the air but this is generally not a problem if the media is large so that air velocity is below 300 feet per minute. The airflow can be impacted when scale builds up and clogs the media. This is a common occurrence in direct evaporative coolers that are supplied water but have no outlet for water removal.

Cooling the air entering a residential condenser can improve performance but is not common because of cost and maintenance concerns. In contrast to commercial systems, residential systems do not provide continuous ventilation and have many fewer hours of operation. Pre-cooler systems must be much less expensive and require less maintenance. Media based pre-coolers were tried by a Texas-based company and replaced by a water-cooled condenser unit technology. The original approach was to surround an air-cooled condenser with a media-type direct evaporative cooler. The wide variety of condensers limited application of the system since one size does not fit all units. The problems encountered were restrictive airflow, water droplet drift and inadequate maintenance. The normal practice of providing little or no maintenance meant that the simple direct evaporative cooler soon became “scaled up”

APPENDIX C: DualCool 2007 Results

DualCool - Dixon Walmart "Hottest Day" Results- Unit #1

Time	Dry Bulb	Wet Bulb	Direct T	Dir Eff	Indirect T	Ind Eff	Pump kW	Gallons
11:45:00	78.5	59.2	63.3	0.79	72.4	43%	0.134	5
12:00:00	80.3	59.6	63.4	0.82	73.3	45%	0.148	5
12:15:00	81.2	59.9	63.7	0.82	74.1	43%	0.131	7
12:30:00	82.2	60.1	63.8	0.83	74.5	45%	0.141	5
12:45:00	83.5	60.5	64.0	0.85	75.4	45%	0.137	6
13:00:00	84.3	60.5	64.3	0.84	76	44%	0.140	5
13:15:00	85.2	60.8	64.6	0.84	76.5	45%	0.138	6
13:30:00	86.3	61.0	64.7	0.85	77.1	45%	0.149	5
13:45:00	87.5	60.9	64.3	0.87	76.8	50%	0.142	6
14:00:00	88.5	61.7	65.0	0.88	77.5	50%	0.137	6
14:15:00	88.8	61.6	65.5	0.86	78.1	48%	0.150	6
14:30:00	89.6	62.2	65.1	0.89	77.6	54%	0.135	6
14:45:00	89.4	62.2	65.4	0.88	78	51%	0.147	6
15:00:00	89.5	62.4	65.5	0.88	77.9	52%	0.140	6
15:15:00	89.9	62.9	66.0	0.88	78.2	53%	0.148	8
15:30:00	90.1	63.2	66.4	0.88	78.3	54%	0.142	6
15:45:00	90.4	63.2	66.5	0.88	78.6	53%	0.142	6
16:00:00	90.7	63.3	66.6	0.88	78.7	54%	0.140	6
16:15:00	90.6	63.1	66.5	0.88	78.8	52%	0.136	6
16:30:00	90.3	62.9	66.3	0.87	78.6	52%	0.140	6
16:45:00	90.0	62.8	66.2	0.88	78.4	52%	0.146	6
17:00:00	89.6	62.9	66.2	0.88	78.2	52%	0.144	6
17:15:00	89.3	62.8	66.1	0.88	78	53%	0.143	5
17:30:00	88.8	62.7	66.0	0.87	77.7	53%	0.132	6
17:45:00	87.9	62.3	65.7	0.87	77.3	51%	0.140	6
18:00:00	87.2	62.1	65.4	0.87	76.7	52%	0.140	6
18:15:00	86.3	61.9	65.5	0.85	76.6	50%	0.146	7
18:30:00	85.0	61.3	65.1	0.84	75.4	51%	0.150	6
18:45:00	83.7	61.2	65.0	0.83	74.8	51%	0.145	5
19:00:00	82.1	60.4	64.4	0.82	74	49%	0.127	5
19:15:00	80.1	60.4	63.9	0.82	72.5	52%	0.145	5
19:30:00	78.2	59.5	63.2	0.80	71.7	48%	0.137	4
8:00:00	86.4	61.6	65.1	0.86	76.5	0.50	1.13	185

APPENDIX D:
DualCool Revised Projection

DualCool Valuation for 30 ton AHU's				**Sacramento**	
Compressor savings:				Vent Savings est.	
	tons	30			
	kWh/yr-ton	150		hours/yr	4000
	kWh/yr	4500		avg WBD	12
Vent Air savings:				avg sump rise	2
	tons	30		delta t	10
	kWh/yr-ton	323		cfm	5000
	kWh/yr	9681		coil eff	0.6
Total kWh Saved		14181		kBtu cooling	129600
Value				EER saved	11
	$/kW	0.12		kWh saved	11782
	savings/yr	$1,702		pump kW	0.141
				pump kWh	564
Costs				add fan kWh	1536
	DualCool	$9,000		net savings	9681
Capacity Credit				kWh/yr-ton	323
	tons vent	7.6			
	tons compr	4.6		Capacity Value	
	total	12.2		ODB	105
	$/ton	$800		OWB	72
	credit	$9,726		peak WDB	33
				peak sump rise	5
Incremental Cost		$(726)		air delta-T	28
				temp drop	16.8
Years Direct Payback		(0.43)		kBtuh	90720
				tons vent	7.56
fan kWh	coil delta-P	0.015		evap eff	0.88
	add bhp	0.273		new cond air	75.96
	add kW	0.234		new evap air	88.2
	add kWh	1536		% cap boost	15.3%