# WATER TREATMENT AND MANAGEMENT FOR EVAPORATIVELY COOLED CONDENSERS

*ET07SCE1091*

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*October 29, 2012*

## Acknowledgements

Western Cooling Efficiency Center at the University of California, Davis, conducted this project under contract for Southern California Edison's Design & Engineering Services (DES) group. Beutler Corporation donated an evaporatively cooled condensing unit for testing. The project was funded by Southern California Edison's Emerging Technologies Program under internal project number ET07SCE1091. DES project manager John Lutton managed this technology evaluation for SCE with overall guidance and management from Paul Delaney. For more information on this project, contact John.Lutton@sce.com.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| Btu | British thermal unit |
| Ca | Calcium |
| $Ca^{2+}$ | Calcium ion |
| $CaCO_3$ | Calcium carbonate |
| $Ca_2SiO_4$ | Dicalcium silicate |
| $C_{ca}$ | Calcium concentration |
| $CO_2$ | Carbon dioxide |
| $CO_3^{2-}$ | Carbonate |
| cfm | Cubic feet per minute |
| $C_{mg}$ | Magnesium concentration |
| dB | Dry bulb temperature |
| ECCU | Evaporative condensing unit |
| EE | Energy efficiency |
| EER | Energy efficiency ratio |
| EER* | Energy efficiency ratio, condensing unit power only included |
| EPA | Environmental Protection Agency |
| FW | Formula weight |
| gpm | Gallons per minute |
| gph | Gallons per hour |
| $HCO^{3-}$ | Bicarbonate |
| $H_2O$ | Water |
| Hr | Hour |
| L | Liter |
| lb | Pound |
| $Me^{2+}$ | Metal ion |
| Mg | Magnesium |
| $Mg^{2+}$ | Magnesium ion |

| | |
|---|---|
| $MgCO_3$ | Magnesium carbonate |
| $MgSO_4$ | Magnesium sulfate |
| mL | milliLiter |
| mM | milliMolar |
| mS | Millisiemens |
| mol | Moles |
| P* | Power for ECCU (compressor, sump pump, condenser fan) |
| pH | Measure of hydrogen ion concentration |
| ppm | Parts per million |
| RTD | Resistance temperature detector |
| SCE | Southern California Edison |
| Si | Silicon |
| $SO_4$ | Sulfate |
| SR | Saturation ratio |
| µm | Micron |
| WB | Wet bulb temperature |
| WCEC | Western Cooling Efficiency Center |

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# EXECUTIVE SUMMARY

Residential air conditioning is a challenging and costly peak load for utilities to meet. The load factor, defined as the average annual demand divided by peak demand, is only 7%[1]. In California, only 8% of air conditioning units surveyed in single family homes were evaporative coolers[2], even though evaporative systems have a large potential to reduce both the peak electricity demand and the energy use associated with cooling. Water management of evaporative cooling units is essential and particular care must be taken to reduce the effects of hard water on the system. Evaporative processes lead to the concentration of minerals in the cooling water reservoir which eventually precipitate out of solution, scaling the condensing coil, pumps, piping, and other surfaces.

The primary goal of this investigation was to provide long term laboratory test data to assess the longevity of an evaporatively-cooled condensing unit (ECCU) and to provide recommendations for operation and maintenance of the system to maintain performance and energy efficiency. A secondary objective was to evaluate water management strategies to minimize the use of bleed water and reduce the water consumption of the system.

The first step toward completing the objective was to run a full scale ECCU to “failure”, defined for the purposes of this project as a loss of efficiency of 25% or more. This accelerated test was accomplished by operating the 3-ton ECCU for 2,000 hours with no water treatment or bleed, which is against the manufacturer’s recommendation. Based on the water supply in Davis, CA the manufacturer recommends that the bleed be set such that 40% more water (over and above the amount of water evaporated) be supplied to the ECCU. This test identified modes of failure for the ECCU and the rate of performance and efficiency degradation. At the end of the “full-scale to failure” test, the power use increased 19%, the capacity decreased 9%, the total efficiency decreased 26%, and large amounts of scale were on the coil, inside the nozzles, in the sump, and on the drift eliminator. The weight of scale on the coil was estimated at 27.7 lb by weighing the removed coil and estimating its initial weight from the length of copper tubing. Efforts to restore the system performance by cleaning the sump, drift eliminator, and water delivery system were largely unsuccessful, increasing system efficiency only slightly (Figure 1).

Small scale testing of an evaporatively cooled hot water coil at approximately 1/20 scale of the ECCU was used to evaluate three water management strategies (two different bleeds and one water treatment) simultaneously in comparison to a no bleed control. The results showed that the higher-bleed-rate system (40% additional water use) was more effective at maintaining initial capacity, with no loss in capacity over the course of the experiment, as compared to the lower-bleed-rate system (8% additional water use), which had a 12% reduction in cooling capacity by the end of the experiment. In comparison to the no bleed system with six pump failures, the low bleed system had only one pump failure, and the system with permanent-magnet water treatment and no bleed had two pump failures. Significant scale in the magnetic treatment system reduced the coil capacity by 20%. The results of the small-scale testing suggested that implementing a low bleed strategy in the field could save water compared to the current practice of bleeding 40% or more of the evaporated water in high hardness areas, while maintaining adequate performance.

As seen in Figure 1, implementing the low bleed (17% additional water use) in a full-scale system test significantly reduced the loss of efficiency after 2,000 hours of testing to 8.6%. In addition, the low bleed eliminated pump failures, reduced cleaning requirements, and drastically reduced scale formation on the copper coil to 0.7 lb (versus 27.7 lb for the no-bleed test). The efficiency of the low bleed system was almost completely restored by cleaning the cabinet and drift eliminator, a quick and easy process taking less than 15 minutes. Note that the initial efficiency of the ECCU system in Test 2 was lower than in Test 1. This is due to a change in the condenser coil design by the manufacturer prior to replacement of the coil between Test 1 and Test 2. The replacement coil was more compact, with 10% less length and surface area. Therefore, percentage changes in performance are compared as opposed to absolute changes.

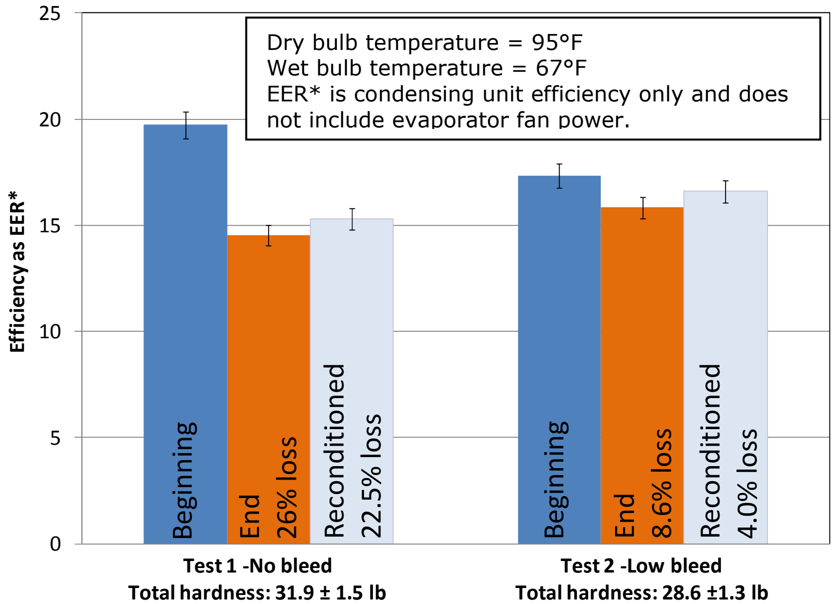


**FIGURE 1. BEGINNING AND REFURBISHED PERFORMANCE OF A 3-TON ECCU IN TEST 1 AND TEST 2**

Using the data produced in this study, an analytical model was developed and an optimized bleed rate was calculated for nine of the largest water districts in SCE service territory. In each water district, the optimal bleed rate for an ECCU was calculated, and the resulting scale deposited was estimated. The analysis demonstrates that in most cases, introducing a bleed is helpful initially, but that a substantial bleed (e.g., >15%) is counterproductive in most cases. The model results were well correlated to the small scale tests; however the model significantly over-estimated the amount of scale formed on the coil in the low bleed test of the full size ECCU. This discrepancy will be investigated by future research. One theory is that vibrations from the condenser fan and compressor shake loose scale from the condenser coil whereas these components are not present in the small scale tests.

The model was used to predict the longevity of a system operating at 15% bleed rate in the nine water districts in SCE service territory relative to the ECCU tested in the Davis laboratory. The model results show that all but one water district should expect as good or better performance of ECCUs as compared to the 2,000-hour Test 2 performed in the Davis laboratory. This equates to an efficiency decrease of 4% or less after 2,000 hours of operation. WCEC recommends adoption of the technology into the Energy Efficiency (EE) program where water guidelines are met, which is true for 8 of the 9 water districts studied. To assure optimum performance and energy efficiency, a water quality report should be obtained prior to installation. A maintenance program should be considered as a requirement for inclusion in the EE program.

WCEC has proposed to undertake additional research to further validate and expand upon the model presented here. Additional research is needed to understand the differences in modeling the small scale systems and the full-size ECCU. The model will be expanded to assess the impacts of pH, non-carbonate alkalinity (e.g., sulfate, phosphate), calcium, magnesium, and silicon. Although no benefit was seen from the static magnets, WCEC is planning to re-test them in combination with a low-bleed. In addition, future testing will include an electro-magnetic pulsing device and a vortex device, both in combination with low bleed. Those results should be available as a future appendix to this report.

# INTRODUCTION

Residential air conditioning is a challenging and costly peak load for utilities to meet. The load factor, defined as the average annual demand divided by peak demand, is only 7%1. In California, only 8% of air conditioning units surveyed in single family homes by the California Residential Appliance Saturation Survey were evaporative coolers2, even though evaporative systems have a large potential to reduce both the peak electricity demand and the energy use associated with residential and light-commercial cooling.

Typically, the condenser in a compressor-based system is air-cooled, which results in a decrease in the efficiency of the cooling process as the outdoor air temperature increases. An alternative is a condenser cooled with air and water in an evaporative process. In this case, the air temperature passing over the condenser coil approaches the outdoor wet bulb temperature, which in dry climate zones may be 30-35°F cooler than the dry bulb temperature at conditions of peak electrical demand. The result is that a compressor based cooling system with an evaporatively cooled condenser can operate at a lower temperature differential and thus have a higher efficiency.

In 2009, Southern California Edison (SCE) completed lab testing of a production ECCU[3]. The Energy Efficiency Ratio (EER), which include indoor fan energy use, was reported as 14.6 in mild conditions (84°F outdoor dry bulb, 67°F wet bulb) and 13.1 in hot-dry conditions (115°F outdoor dry bulb, 74°F wet bulb). The laboratory study at SCE did not evaluate the long term performance of the system.

Water management of evaporative cooling units is essential to their longevity and to protecting return on investment; particular care must be taken to reduce the effects of hard water on the system. Evaporative processes lead to the concentration of minerals in the cooling water reservoir which eventually precipitate out of solution, fouling the condensing coil, pumps, piping, and any other surfaces in contact with the liquid. Fouling of heat transfer surfaces and mechanical elements like pumps leads to a loss of heat transfer capacity and degradation of system efficiency, requiring greater energy input for the same cooling performance.

It should be noted that water hardness can vary drastically based on geography. For example, the city of Davis, CA, which relies on ground water supplies, has relatively hard water with an average hardness of approximately 360 ppm. Just 10 miles away, in West Sacramento, CA, which relies on surface river water, the average hardness is approximately 80 PPM. A simple calculation would suggest that an ECCU located in West Sacramento could operate four times longer before the efficiency would degrade to that of the same unit in Davis. In conducting a longevity test of an evaporative condenser using municipal water in Davis, CA, the water chemistry was closely monitored so that the results could be applied to units operating in Southern California Edison territory using analytical models.

Numerous water treatment technologies and water management strategies have been developed to increase evaporative cooling equipment product life by reducing or modifying scale formation while attempting to minimize water consumption. These methods range from water bleed strategies to chemical and physical water treatment. The sheer number of technologies, and diverse technology types, may lead to confusion about the best application for water-cooled equipment. This project required development of a methodology for testing the effectiveness of various water treatment and management strategies to estimate the impact that each would have when applied to evaporative coolers. Results for the impacts of multiple bleed rates and static magnets are reported.

# BACKGROUND

Evaporative cooling technologies have a large potential to reduce both the peak electricity demand and the energy use associated with residential and light-commercial cooling in hot and dry climates, such as in inland California. One particular residential technology that has seen a surge in interest recently is an ECCU, which uses a combination of air and water to remove heat from the condenser coil. This research evaluated water management and treatment strategies for evaporative cooling systems, and analyzed their impact on the ECCU.

## ECCU

The ECCU utilizes an evaporatively cooled condenser that takes advantage of the latent heat of vaporization of water to evaporatively reject waste heat. Similar to a cooling tower, the copper tube refrigerant coils are showered with water to facilitate cooling the coil (Figure 2). The primary benefit of this method of heat rejection in dry climates is that the cooling efficiency is less sensitive to ambient dry bulb temperature and more dependent on the wet bulb temperature, which may be 30-35°F cooler than the dry bulb temperature during a peak day in hot and dry climates. The ECCU tested used copper tubing 0.37” outer diameter and 0.31”inner diameter.

FIGURE 2. ECCU CONDENSER COIL

## WATER MANAGEMENT AND TREATMENT

In residential scale evaporative cooling systems, water management and treatment is essential to the longevity of the equipment. Several types of physical treatment technologies are commercially available; however peer-reviewed literature investigating their performance shows mixed results. No studies were found regarding water management and treatment strategies in evaporative cooling systems.

Historically, bleed strategies have been successfully used at the expense of increased water consumption of the system. There is little guidance available to determine the most appropriate strategy of employing bleeds. The following methods were studied and compared to gain a better understanding of the most promising solution. Additional methods, such as purging of sump water, chemical water treatment, and other methods of physical water treatment in addition to those described may be evaluated in future research.

### BLEED

Bleeding of a system is defined as the rejection of a portion of the cooling water in the system either continuously or at regular intervals during operation. The volume removed is replaced with fresh tap water. Assuming constant tap water characteristics, the percentage of the cooling water removed from the system per unit time, or bleed rate, defines the steady state hardness in the cooling water. In theory, a higher bleed rate leads to a lower concentration and therefore fewer precipitates fouling the system, at the cost of increased water usage. This cost can be significant and a balance between equipment maintenance and water costs must be found for any given combination of cooling equipment and available water supply. Important factors to consider include tap water chemical characteristics, the type of appliance installed, and the intensity of use.

### PHYSICAL

In a review of literature on physical water treatment technologies, it became immediately apparent that a moderate amount of previous work had been done and that the results were mixed. There are many forms of physical water treatment that are available in the market. Most of them rely on permanent magnets, electro-magnets, and electrostatic units. These units claim to cause water constituents to bind together in solution, and ultimately to cause aragonite to precipitate rather than calcite. Aragonite and calcite are both calcium carbonate minerals (CaCO3), however their crystalline structure varies. Aragonite is preferable, from a scale fouling perspective, because it is less likely to stick to a heat exchanger and is more easily removed if it does stick. Other less common physical water treatment approaches include crystallization sites and proprietary vortexes, which also claim to form aragonite crystals.

Low Calcium (Ca) concentrations are theoretically best treated by electrostatic units, while high concentrations are reportedly better treated with permanent or electro magnets[4]. Case studies of applied magnetic treatments for scale reduction have demonstrated positive effects at both preventing scale deposition and removing existing deposited scale4. In other cases, application of magnetic treatment has resulted in no effect[5], though this could be due to either incorrect installation of the treatment device, interference within the aqueous matrix (iron, silicon), or high voltage in the local environment5. Previous research has focused on calcium carbonate scale.

### AQUEOUS CHEMISTRY

Select manufacturers have based bleed recommendations based on water quality considerations that typically include hardness and/or alkalinity. Hardness is the summation of all freely dissolved multivalent cations in water. Among most environmental and drinking water, Ca and Mg are the primary components of hardness, however other elements can also contribute (e.g., copper, zinc, and aluminum ions). As hardness is comprised of several constituents, the contributions are normalized and expressed on a single basis; the basis that is often used is "mg/L as $CaCO_3$," where the following equations are used to convert mass based constituent concentrations (i.e., mg/L of constituent Ca and Mg) into the common hardness basis (i.e., mg/L as $CaCO_3$).

**EQUATION 1. HARDNESS CALCULATION**

$$Hardness \frac{mg}{L} as\ CaCO_3 = \left(C_{Ca} \times \frac{FW_{CaCO_3}}{FW_{Ca}}\right) + \left(C_{Mg} \times \frac{FW_{CaCO_3}}{FW_{Mg}}\right)$$

$$Hardness \frac{mg}{L} as\ CaCO_3 = \left(C_{Ca} \times \frac{100.1}{40.1}\right) + \left(C_{Mg} \times \frac{100.1}{24.3}\right)$$

Where $C_{Ca}$ and $C_{Mg}$ are freely dissolved concentrations of calcium and magnesium, respectively, expressed as mg/L, and FW is the formula weight of the specified constituent (also called atomic weight in the case of Ca or Mg). Bleed rates based on hardness and alkalinity are likely based on the assumption that $CaCO_3$ and $MgCO_3$ are major components in the formation of mineral scale in evaporative condensers.  Bleed rates based on hardness (expressed as mg/L as $CaCO_3$) are a first step in using water quality considerations to inform evaporative condenser water management, however evaluations based on hardness do not reflect the different characteristics of the hardness components, namely that calcium is substantially less soluble than magnesium.

The formation of mineral scale in an evaporative condenser will be driven by the solubility limitations. The principals of precipitation reactions are discussed elsewhere[6], and a simplified solubility equation for a carbonate solid is shown below.

**EQUATION 2. HARDNESS SOLUBILITY**

$$K_{sp} = [Me^{2+}][CO_3^{2-}]$$

Where $K_{sp}$ is the unitless solubility product, $[Me^{2+}]$ is the cation concentration (e.g., calcium or magnesium ions expressed as a molar concentration (mols/L) and $[CO_3^{2-}]$ is the molar carbonate concentration.

If the product of the cation and the carbonate concentrations exceeds $K_{sp}$, then formation of a solid is expected. If the product is less than $K_{sp}$, then no solid is expected. Via this relationship, it can be seen that both the cation and the carbonate concentrations play a critical role in the precipitation reaction. The carbonate concentration is influenced by atmospheric $CO_2$ concentrations, carbonate solid precipitation reactions, and solution pH.

The solution pH plays a critical role in determining the concentration of carbonate available for a precipitation reaction. When in equilibrium with atmospheric $CO_2$, pH controls how much of total carbonates are in solution, and the speciation among the carbonates (i.e., distribution among carbonate, bicarbonate, and carbonic acid). The solubility limit for calcite (a form of calcium carbonate) is 3.36 E-9 at 25°C, while the solubility limits for magnesium carbonates range from 2.38E-6 to 6.82E-6 at 25°C indicating that calcium is 1,000-times less soluble than magnesium[7]. This means that for a given pH (and therefore $CO_3^{2-}$ concentration), calcium will precipitate at much lower concentrations than magnesium. An additional challenge exists in that calcium carbonate is inversely soluble, meaning that its solubility decreases as the temperature increases (i.e., precipitation is more likely to occur at elevated temperature).

# SCOPE

The scope of this project includes three phases:

1. Testing a full scale ECCU system to “failure”, defined as a loss of efficiency of 25% or more.
2. Evaluating three water management strategies against a no bleed strategy in small scale test setup.
3. Selecting the most promising water management strategy and repeating the full scale test with the same run time.

# ASSESSMENT OBJECTIVES

The primary goal of this investigation is to provide long term laboratory test data to assess the longevity of the ECCU and to provide recommendations for operation and maintenance of the system to maintain performance and energy efficiency. A secondary objective is to evaluate water management strategies in order to minimize the use of bleed water and reduce water consumption of the system.

The first objective was to run a full scale ECCU to “failure”, defined as a loss of efficiency of 25% or more. This accelerated test was accomplished by operating the ECCU for 2,000 hours with no water treatment or bleed, which is contrary to the manufacturer’s recommendation. Based on the water supply in Davis, CA the manufacturer recommends a 40% bleed rate. The test results identified modes of failure and the rate of performance and efficiency degradation.

The second objective was to evaluate the relative performance of the water management and treatment strategies studied in small scale tests. Small scale tests, intended to simulate a system similar to the ECCU on a smaller scale, were conducted in parallel in order to directly compare the performance degradation over time associated with each water management strategy. Aqueous chemistry assays were conducted to better understand the changes in mineral hardness and production of precipitates.

The small scale apparatus was designed to run up to four tests simultaneously. The strategies applied were low bleed, high bleed, and static magnets, which were all compared to a baseline no bleed system. The most promising strategy was then applied to the full scale ECCU, which had been completely refurbished, to validate the water management strategy over another 2,000 hours of operation.

# TECHNOLOGY/PRODUCT EVALUATION

The technology evaluated in this study is the ECCU. In order to accelerate longevity results, all testing was done in a controlled laboratory environment. Approximately 500 hours of run-time were achieved per month in the laboratory; this could take an entire summer in the field. In addition, the laboratory provided for high quality measurements and control of incoming air dry bulb temperature to 95°F.

The water management strategies tested included two bleed rates. Bleeding sump water during operation is the manufacturer recommended water management strategy for the ECCU. The manufacturer recommended bleed rate differs according to water hardness and alkalinity. Since increased bleed rates result in higher water consumption for the unit, the goal was to determine a reasonable bleed rate that would minimize water consumption while reducing scale build-up.

The water treatment technology tested was limited to permanent magnets. This treatment technology was chosen due to its claimed effectiveness on reducing hard water deposits, low maintenance requirements, and ease of installation. Three strontium ferrite permanent ceramic magnets with strength of 0.4 Tesla each were applied in series on the re-circulating water hose.

# TECHNICAL APPROACH/TEST METHODOLOGY

Laboratory tests were conducted to measure the performance degradation of an ECCU with and without water management. Each test monitored the cooling capacity, power, and efficiency of the condenser over 2,000 hours of runtime. In addition, a series of small-scale tests were run to evaluate three water treatment and management methods. The most promising of these strategies was subsequently applied to the ECCU to measure the impact that the most promising method had on performance over time. Experimentation was conducted in WCEC's laboratory space, in Davis, California.

## ECCU TEST PLAN

An overall system schematic is shown in Figure 3 and details of all the instrumentation are provided in Table 1. A picture of the laboratory during system construction is shown in Figure 4. The test apparatus consists of the following sub-systems: condenser-air conditioning, condenser air flow, refrigerant circuit, closed water loop ("evaporator" load), power supply, and water supply. The sub-systems are described below with instrument numbers referring to both the detailed diagram in Figure 5 and Table 1.

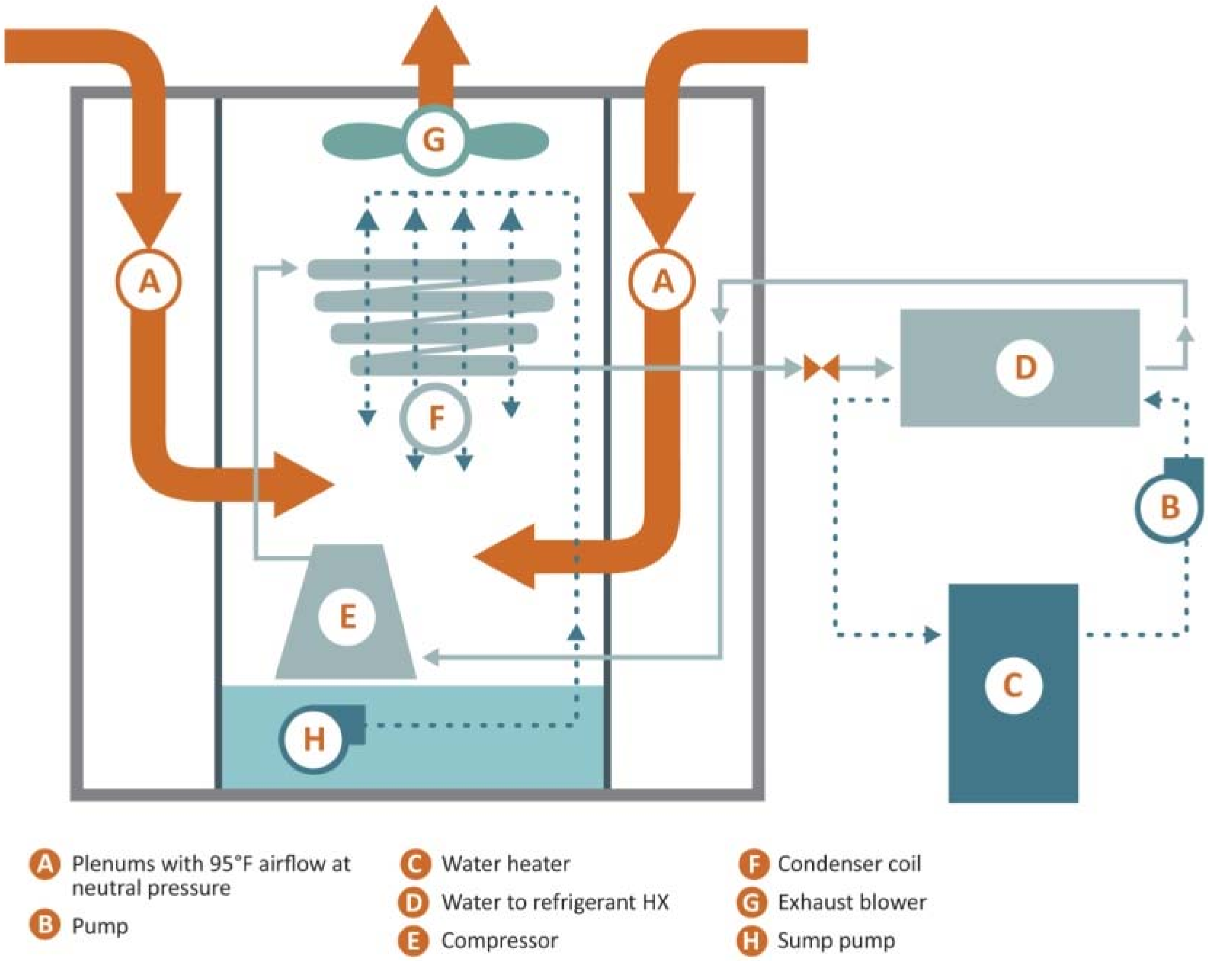


**FIGURE 3. SYSTEM SCHEMATIC OF ECCU TEST CONFIGURATION**

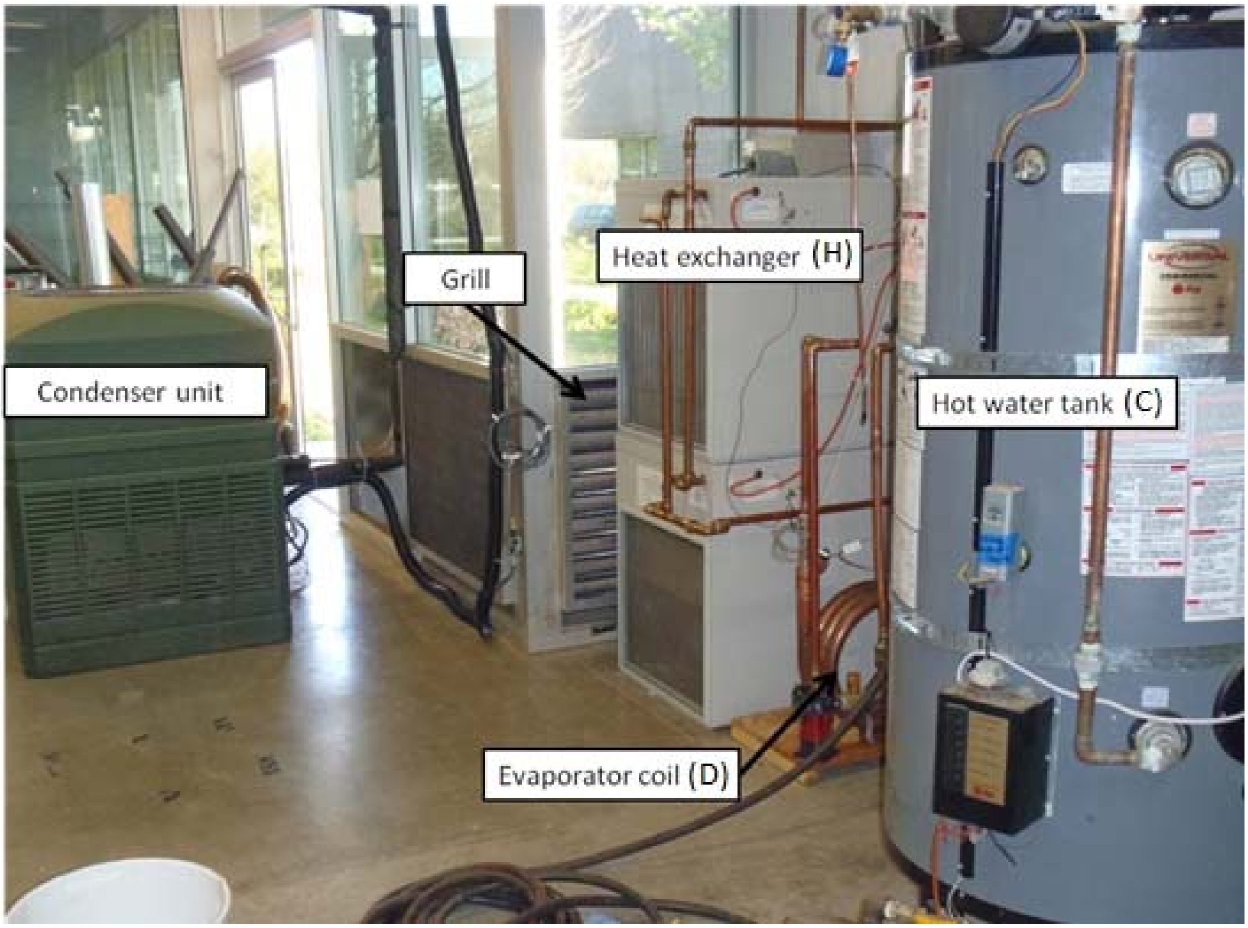


FIGURE 4. ACTUAL ECCU TEST CONFIGURATION

### CONDENSER-AIR CONDITIONING

The air supplied to the condenser was heated using two water-to-air heat exchangers. The water side of the heat exchangers was supplied by a 200 kBtu hot water heater. The target dry bulb temperature for the conditioned air was 95°F. The conditioned air was ducted through four - 12” round ducts of equal length into the plenum surrounding the condenser air intake. The dry bulb temperature of each of the four air streams was monitored to ensure the 95°F target was maintained with sufficient uniformity (Instruments #3-6 shown in Figure 5).

The dry bulb temperature was maintained at 95°F through a PID control using LabVIEW which continuously adjusted the flow rate of hot water through the heat exchangers used to heat the ambient air (Instrument #25, Figure 5). If ambient weather conditions during the summer exceeded 95°F, testing was paused until the outdoor air temperature returned to the operating condition. Relative humidity of the incoming air was measured but not controlled (Instruments #1-2, Figure 5). Wet bulb temperature was calculated from temperature and relative humidity and was observed to fluctuate between 60-72°F (mean over all operating hours of 66°F), depending on the ambient weather conditions. Because the wet bulb temperature has a significant effect on system efficiency, caution must be exercised when comparing results. System efficiency at the beginning and end of the test were compared at the same dry bulb/wet bulb conditions. As long as comparisons of system performance are made at similar wet bulb temperatures, the changing wet bulb temperature over the course of the experiment is not expected to impact the result.

### CONDENSER-AIR FLOW

The experimental apparatus, which consists of air-to-water heat exchangers to condition the condenser air, ducting, a plenum, and a flow measurement device at the condenser exhaust, added significant flow resistance to the existing condenser. Two additional variable speed fans, working in parallel with a combined maximum airflow of 4,000 CFM, were commissioned to offset this additional resistance (Instruments #26-#27, Figure 5). The fans were located at the outdoor air intake to provide airflow in series with the condenser fan.

The device used to measure the airflow at the condenser exit was a custom sized Fan-E airflow measurement station (Table 1), which is essentially an averaging pitot tube designed to measure the flow in a round duct. The accuracy of the device is 2% of the reading.

The following procedure was developed to determine the speed of the variable speed fans needed to offset the additional flow resistance of the ducting and test chamber:

1. Measure the differential static pressure across the condenser inlet grill (Instrument #13, Figure 5) while the ECCU fan is on without experimental apparatus or airflow measurement device in the airstream. This pressure differential is a function of the airflow rate only.
2. Measure the differential static pressure across the condenser inlet grill (Instrument #13, Figure 5) while the ECCU fan is on with experimental apparatus in the airstream. Adjust variable speed blowers until pressure matches that measured in step 1. This step returns the flow rate to the unimpeded flow of the ECCU.
3. Measure and report the flow rate using the airflow measurement station (Instrument #12, Figure 5).

### REFRIGERANT CIRCUIT

Pressures and temperatures of the refrigerant circuit were monitored for reference, including the compressor input and output temperatures and pressures, as well as the condenser output temperature (Instruments #19-23, Figure 5). This data was not used to determine the coefficient of performance (COP) of the system, but was instead used as additional insight into system performance. For example, as the system degrades it may be difficult for the condenser to meet the required load, potentially tripping the ECCU's high pressure switch on the refrigerant circuit. The refrigerant flow rate was not measured and therefore loads were not calculated from the refrigerant data.

### CLOSED WATER LOOP ("EVAPORATOR" LOAD)

The refrigerant loop absorbed heat from a refrigerant-to-water heat exchanger sized appropriately for the 3-ton ECCU. The incoming water temperature was held between 77-83°F (average 80°F) using a dedicated water heater and a thermostatic mixing valve. The flow rate was fixed at approximately 3.6 GPM using a single speed pump. The capacity of the heat absorbed from the water is defined as a function of the water temperature differential across the heat exchanger, the water flow rate, and the specific heat of water. The temperature differential was measured with resistive temperature devices (RTDs) submerged in line with the water flow (Instruments #16-17, Figure 5). A paddle wheel type flow meter was used to measure flow rate (Instrument #18, Figure 5).

### POWER SUPPLY

Two power measurements were recorded. The compressor power was measured to determine the power input to the refrigeration cycle and the system power was measured to use in calculating the total condenser system COP (Instruments #10-11, Figure 5). A digitally controlled relay turned the ECCU on and off (Instrument #24, Figure 5).

### WATER SUPPLY

The makeup water supply rate was monitored with a paddle wheel type flow sensor (Instrument #7, Figure 5). In-line conductivity and pH sensors continually provided water quality data (Instruments #8-9, Figure 5). Periodic water samples were taken to measure total hardness and to correlate the continuous conductivity measurement to the total hardness.

### BLEED RATE

In the first longevity test of the ECCU no water was bled from the system. In the low bleed trial of the ECCU, in which a low bleed water management strategy was implemented, the bleed rate was measured and recorded. The bleed rate was manually set in the condensing unit by adjusting an aperture through which water returning from the cooling coil dripped; this allowed water to bleed only while the system was running. The bleed water was collected and the volume was measured periodically using a calibrated peristaltic pump with the data acquisition system tracking the "on" time of the pump.

### SYSTEM OPERATION

The ECCU was operated cyclically with the system on for 60 minutes followed by 30 minutes off. The off period allowed the coil to dry so that scale was more likely to adhere as in typical use. The external blowers continued to run conditioned air over the coil during the 30 minute off period to facilitate drying.

### ECCU INSTRUMENTATION PLAN

Figure 5 is a schematic of the experimental apparatus and instrumentation locations. Details of the instrumentation are shown in Table 1.

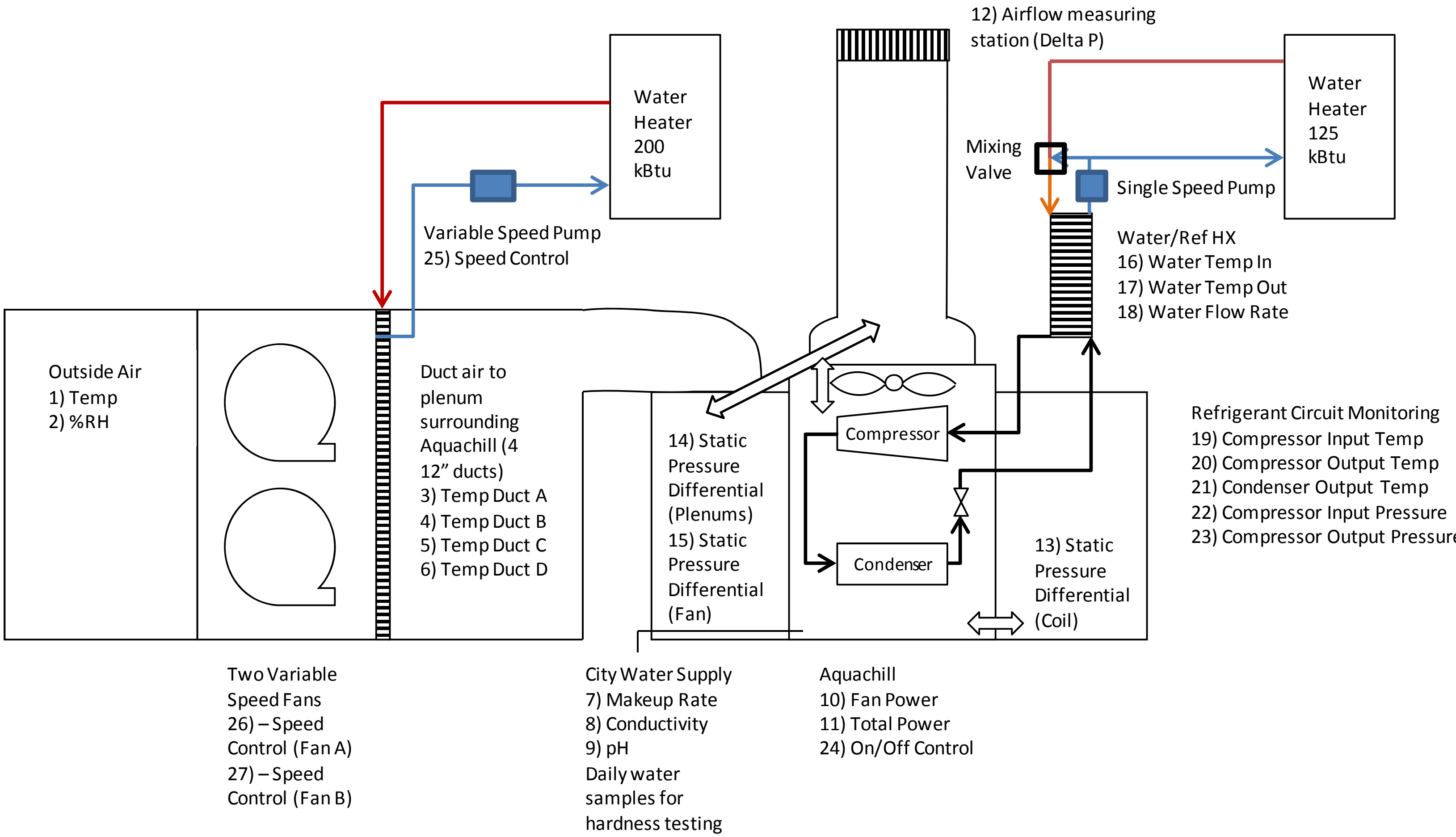


**FIGURE 5. SYSTEM SCHEMATIC INCLUDING MECHANICAL COMPONENTS AND INSTRUMENTATION**

TABLE 1. ECCU INSTRUMENTATION

| ITEM # | MEASUREMENT TYPE | MANUFACTURER MODEL # | TARGET RANGE | RANGE | ACCURACY | DAQ CARD |
|---|---|---|---|---|---|---|
| 1 | Inlet Air Temperature | Vaisala HMD-70Y | 100 °F | -4 + 176°F | 0.1°F | NI 9201 |
| 2 | Inlet Air RH | Vaisala HMD-70Y | 30% RH | 0-90% RH | 2% RH | NI 9201 |
| 3 | Duct Air Temperature | Omega RTD-806 | 100 °F | -328-302°F | 0.4 °F | NI 9217 |
| 4 | Duct Air Temperature | Omega RTD-806 | 100 °F | -328-302°F | 0.4 °F | NI 9217 |
| 5 | Duct Air Temperature | Omega RTD-806 | 100 °F | -328-302°F | 0.4 °F | NI 9217 |
| 6 | Duct Air Temperature | Omega RTD-806 | 100 °F | -328-302°F | 0.4 °F | NI 9217 |
| 7 | Water Supply Flow Rate | Omega FTB601B-T | 0.1 gpm | .03-0.53 gpm | 3% of reading | NI 9401 |
| 8 | Water Supply Conductivity | CDTX-300, CDE-300 | 1 mS/cm | 0-10 ms | 0.2 ms | NI 9201 |
| 9 | Water Supply pH | PHE-7351-15 | 8 | 0-14 | 0.07 | NI 9201 |
| 10 | Condenser Fan Power | WattNode WNB-3D-240-P | 300W | 2-20A | 0.5% of reading | NI 9401 |
| 11 | ECCU Total Power | WattNode WNB-3D-240-P | 3kW | .5-5A | 0.5% of reading | NI 9401 |
| 12 | Fan-E Airflow measuring station | Custom/DG-500 | 2000 CFM | 0-5600 CFM | 2% of reading | SERIAL |
| 13 | Delta P Static (Coil) | DG-500 | 30 Pa | 0-1250 Pa | 1% of reading | SERIAL |
| 14 | Delta P Static (Plenum) | DG-500 | 10 Pa | 0-1250 Pa | 1% of reading | SERIAL |
| 15 | Delta P Static (Fan) | DG-501 | 40 Pa | 0-1250 Pa | 1% of reading | SERIAL |
| 16 | Evap In Water Temp | Omega RTD-NPT-72-E | 82 °F | -328-302°F | 0.4 °F | NI 9217 |
| 17 | Evap Out Water Temp | Omega RTD-NPT-72-E | 62 °F | -328-302°F | 0.4 °F | NI 9217 |
| 18 | Evap Water Flow Rate | Omega FTB-4607 | 3.6 gpm | 0.88-20 gpm | 1% of reading | NI 9401 |
| 19 | Compressor In - Temp | Omega RTD-NPT-72-E | 62 °F | -328-302°F | 0.4 °F | NI 9217 |
| 20 | Compressor Out - Temp | Omega RTD-NPT-72-E | 145 °F | -328-302°F | 0.4 °F | NI 9217 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 21 | Condenser Out - Temp | Omega RTD-NPT-72-E | 85 °F | -328-302°F | 0.4 °F | NI 9217 |
| 22 | Pressure - Compressor In | Climacheck 200-100 | 150 psi | 0-500 psi | 3.5 psi | NI 9201 |
| 23 | Pressure - Compressor Out | Climacheck 200-100 | 350 psi | 0-500 psi | 3.5 psi | NI 92016 |
| 24 | Relay out on/off (call for cooling) | Solid state relay | Normally Open | NA | NA | NI 94015 |
| 25 | Set Pump Speed | Grundfos UP26-96F/VS 1/6 HP Re-circulator Pump | 0-10 VDC | 0-10 VDC | 0.01 VDC | NI 9263 |
| 26 | Fan A Control | Atkinson Electronics, Ins. VPM1 0-10VDC to 85Hz PWM | 0-10 VDC | 0-10 VDC | 0.01 VDC | NI 9263 |
| 27 | Fan B Control | Atkinson Electronics, Inc. VPM1 0-10V to 85Hz PWM | 0-10 VDC | 0-10 VDC | 0.01 VDC | NI 9263 |

Data was collected using LabVIEW 2010 in conjunction with the various digital and analog data acquisition and output devices listed in the DAQ Channel column of Table 1 and pictured in Figure 6. Data was collected by LabVIEW every second, then averaged and written to a text file every 60 seconds.


**FIGURE 6. DATA ACQUISITION HARDWARE**

## WATER MANAGEMENT TEST PLAN

To determine the effects of different water management techniques, the experimental setup shown in Figure 7 was developed to test three water management strategies and one control in parallel. The experimental apparatus was designed to emulate an evaporatively cooled condenser on approximately a 1/20 scale. Water management strategies compared the performance of a no bleed system to a system with a low bleed rate, a system with a high bleed rate, and a system with no bleed and a magnetic water treatment device installed.

Each parallel system consisted of a copper coil supplied with hot water from a water heater to simulate a hot condenser coil (Figure 8). A pump was used to spray the coil with water from a sump in the bottom of the chamber. The air flow was supplied by a fan upstream and controlled to approximately 50 cfm for each chamber by a constant air flow damper. Evaporated water was replaced using a peristaltic metering pump controlled by a float switch.

**FIGURE 7. WATER TREATMENT PARALLEL TESTING EXPERIMENTAL SETUP**

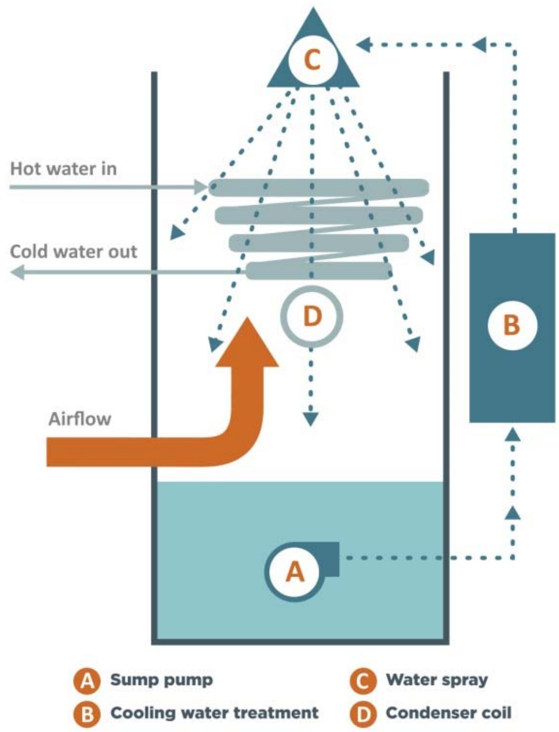


FIGURE 8. SYSTEM SCHEMATIC OF SINGLE SMALL-SCALE TEST CHAMBER

## AIRFLOW

The fan speed was set by an analog dial on the side of the fan housing. Air leaving the fan passed through four 1.4 kW heaters to bring the temperature up to 95°F±2°F as controlled by the data acquisition system. When ambient conditions prevented proper conditioning of the air, the experiment was paused until the 95°F±2°F target could be achieved.

Once conditioned, the warmed air entered a 10 inch round by 54 inch long manifold where the flow was then separated into four 6 inch flexible round ducts, one for each test chamber. Sensors monitored the pressure at the entrance to each of the four ducts while the temperature and humidity measurements were taken at the center of the manifold, 42 inches from the inlet.

Each air stream was then passed through an American Aldes constant airflow regulator model CAR-IIA which limited the flow to a nominal 50 cfm. A calibration with a Duct Blaster, manufactured by Energy Conservatory and last calibrated on 2/8/2011, performed prior to beginning the experiment showed the actual flows to be 55±2 cfm for pressures across the regulator between 100 and 220 Pa (Figure 9). The fan speed was initially set to provide a resulting pressure drop of 200 Pa. As hard-water scale accumulated downstream from the regulators, the dampers opened to maintain the airflow which in turn, reduced the pressure drop across the regulator. The fan speed was then increased periodically to raise and maintain the desired pressure drop. The air flow was then routed through a 6” flexible duct where it entered the chamber, passed over the coil and carried heat and water vapor out the exhaust.

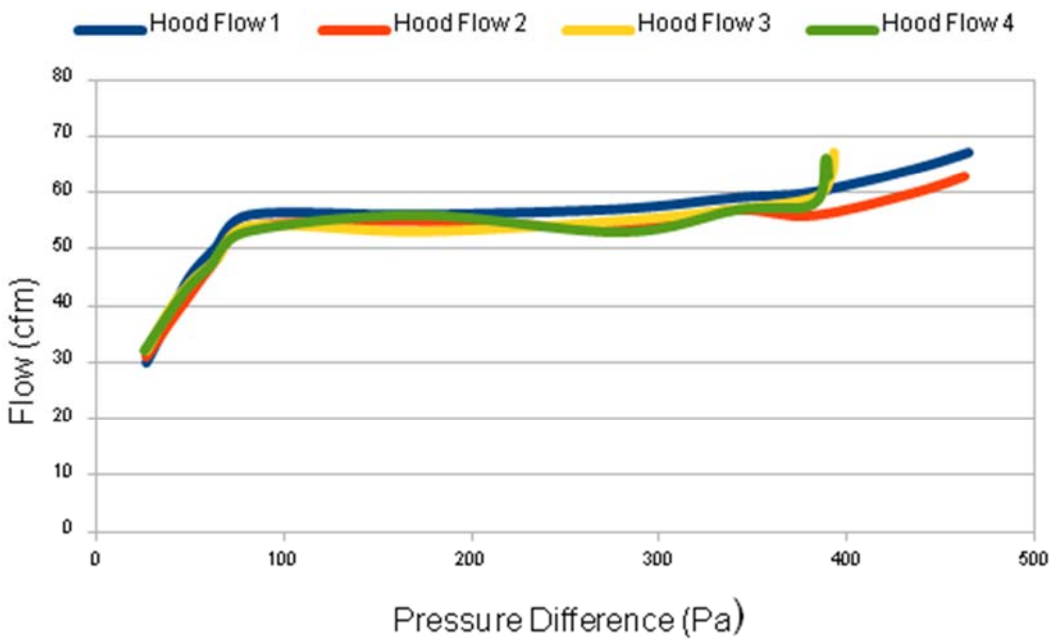


**FIGURE 9. HOOD FLOW PER CHAMBER AS A FUNCTION OF PRESSURE DIFFERENTIAL ACROSS THE REGULATOR**

### HOT WATER FLOW

To simulate hot refrigerant coils, a constant speed pump circulated hot water through the small-scale coils constructed of ¼″ outer diameter copper tube with 0.03″ wall. The flow of hot water supplied to the coils originated in a 100 US gallon, 125kBtuh water heater (Figure 10). The flow exiting the water heater passed through a 50 micron filter before entering a thermostatic mixing valve used to blend incoming hot water with cooler water returned from the coils. The valve automatically varied the mix to supply a constant temperature (122.6°F±2°F) output stream. Water temperature was measured using a resistive temperature device (RTD) before being split into four streams, one for each test chamber. The flow rate for each system was measured using an Omega FTB2001 paddle wheel flow sensor before the inlet of each copper coil. Finally, the temperature of the water leaving each coil was recorded using RTDs.

The coils were wound by hand using a conical mold. They were measured by weight before installation to ensure consistency between tests (coil weights ranged from 754-776 grams). In addition, the coils were measured after testing to determine the total amount of scale deposited on each coil.

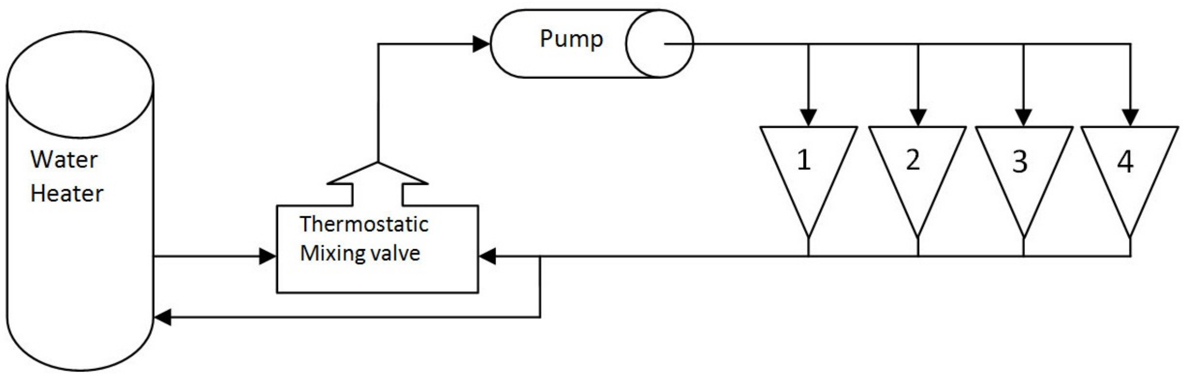


FIGURE 10. HOT WATER FLOW BLOCK DIAGRAM SHOWING THE FLOUR INDIVIDUAL COIL UNITS

### COOLING WATER FLOW

The cooling water was re-circulated from sumps under the test chambers. Each test chamber had an individual sump reservoir which held the cooling water and contained a sump pump used to supply cooling water to the respective spray nozzle. To ensure consistency among the four chambers, the initial performance of each pump and nozzle system was measured and found to have a flow rate of 0.58±0.02 gallons per minute (gpm). The flow rate of each system was checked periodically and it generally decreased over time due to scale build up in the hose and nozzle. However, the hoses and nozzles were left undisturbed throughout the course of the experiment. Pumps were replaced if complete failure occurred.

The spray nozzles used were the same as those sold in the commercial ECCU. They provided a wide aperture with a hollow cone spray pattern. They produced large droplets which minimized drift loss into the airstream. The water leaving the spray nozzle wetted the heat exchange coil where approximately 1% evaporated and the remainder fell back into the sump reservoir. One nozzle was used per chamber.

The sump level was controlled using a float switch that actuated an individual peristaltic pump, model Mightyflex 907, for each test chamber. Each pump was individually calibrated on-site by measuring the amount of water pumped by mass in three minutes. The calibration was checked periodically every 6 weeks to assure consistency and no significant changes were recorded. During the experiment, the on-time of each pump was recorded by the data acquisition system and the water replacement rate was calculated. In the system with no bleed, the water replacement rate is equal to the evaporation rate plus any water carried out by the air stream (drift). In the systems with a bleed, the water replacement rate is the sum of the evaporation rate, drift rate, and the bleed rate.

The conductivity and pH of the municipal water at the inlet to the lab were measured continuously. Periodic water samples were taken and total hardness was measured in the laboratory in order to correlate the continuous conductivity measurement to total hardness.

Within each sump chamber was an Omega CDE 1202 conductivity sensor connected to either an Omega CDTX 1201 or Omega CDTX 1202 series controller. The CDTX 1201 controller, with a range of 0-199.9 mS/cm, was used in the sump reservoirs without bleed while the CDTX 1202, with a range of 0-19.99 mS/cm, was used on those with controlled bleed. The hardness of the sump water was measured periodically.

Total hardness was tested using the Hach 8213 method[8]. For expected concentrations above 4,000 ppm, samples were diluted to below 4,000 ppm before titration.

### WATER MANAGEMENT INSTRUMENTATION

The instrumentation corresponding to the experimental setup described in the previous section is shown in Figure 11 and specifications are listed in Table 2.

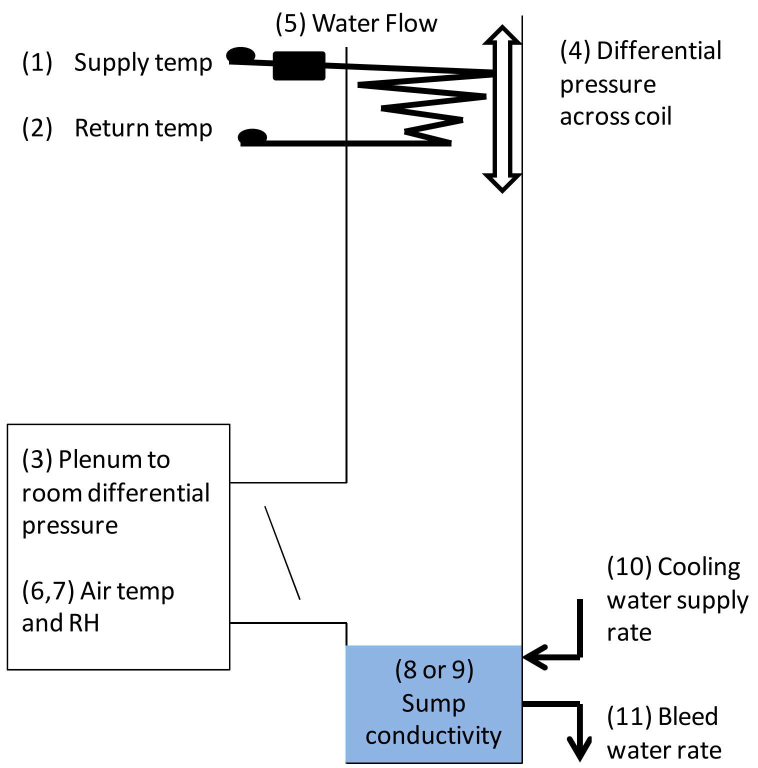


FIGURE 11. LOCATION OF INSTRUMENTATION IN SMALL-SCALE TEST

TABLE 2. SMALL-SCALE TEST INSTRUMENTATION PLAN

| ITEM # | MEASUREMENT TYPE | QUANTITY | MANUFACTURER MODEL # | TARGET RANGE | RANGE | ACCURACY | DAQ |
|---|---|---|---|---|---|---|---|
| 1 | Hot water return temperature | 4 | Omega RTD-NPT-72-E | 90 °F | To 445 °F | 0.63 °F | NI 9217 |
| 2 | Hot water supply temperature | 1 | Omega RTD-NPT-72-E | 125 °F | To 445 °F | 0.63 °F | |
| 3 | Differential air pressure (plenum to room) | 4 | APT | 125 Pa | 0-1000 Pa | 1% | Energy conservatory APT |
| 4 | Differential air pressure across each coil | 4 | APT | 2 Pa | 0-1000 Pa | 1% | Energy conservatory APT |

| Item # | Measurement Type | Quantity | Manufacturer Model # | Target Range | Range | Accuracy | DAQ |
|---|---|---|---|---|---|---|---|
| 5 | Water flow through each coil | 4 | Omega FTB-2001 | 0.25 gpm | 0.13-1.3 gpm | 3% | NI PCI 6321 |
| 6 | Air temperature in plenum | 1 | Vaisala HMD60Y | 95 °F | -4 + 176°F | 0.1°F | NI 9203 |
| 7 | RH in plenum | 1 | Vaisala HMD60Y | 15-20% | 0-90% RH | 2% | NI 9203 |
| 8 | Water conductivity in sump 1 and 3 | 2 | Omega CDE-1202 | 2-10 mS | 0-19.99 mS | 2% | NI 9203 |
| 9 | Water conductivity in sump 1 and 3 | 2 | Omega CDE-1202 | 2-10 mS | 0-199.9 mS | 2% | NI 9203 |
| 10 | Cooling water supply rate | 4 | MightyFlex 907 | 0.01 GPM | 0-0.06 GPM | 3% | NI PCI 6321 |
| 11 | Bleed water rate | 2 | MightyFlex 907 | 0.003 GPM | 0-0.06 GPM | 1% | NI PCI 6321 |

## WATER MANAGEMENT TECHNOLOGIES TESTED

Cooling water treatment varied between the four chambers. An untreated control was compared to the following techniques: a high bleed rate, a low bleed rate, and static magnets.

### BLEEDS

Two of the sump chambers, numbers one and three, were fitted with a second peristaltic pump which controlled the bleed rate of cooling water from the sump reservoir. In units with bleed water management regimens, sump water was removed near the top of the water column to avoid inadvertently removing solids. The flow rate for these pumps was calibrated and the duty cycle for each was controlled by LabVIEW to achieve the desired bleed rate. To investigate the impact bleed rates have on performance degradation, two different rates were considered. The bleed rate for the lower bleed system was set at 0.029 gal/hr (approximately 8% additional water use above what was measured for evaporation/drift in the no bleed control) and the bleed rate for the higher bleed system was set at 0.143 gal/hr (approximately 40% additional water use above evaporation/drift). The higher bleed rate is consistent with a typical manufacturer's suggested bleed rate for the ECCU based on the municipal supply water quality of Davis, CA.

### MAGNETIC WATER TREATMENT

For the system with magnetic water treatment, three strontium ferrite permanent ceramic magnet units were installed on the rubber hose between the sump pump and the nozzles (Figure 12). According to manufacturer documentation, each magnet supplies 0.4 Tesla over about 4 inches of tubing length. The test chamber with magnetic water treatment had no bleed applied.

FIGURE 12. MAGNETIC TREATMENT ON COOLING WATER LINE

## AQUEOUS CHEMISTRY TEST PLAN

Samples from each small-scale sump were collected weekly and analyzed for pH and metals, including calcium and magnesium hardness. pH was analyzed with a Hach HQ40d meter and a Hach Intelical PHC301 probe (0.01 pH unit resolution). The meter and probe were calibrated daily before use per manufacturer's instruction using standard pH solutions. Metals were measured for both total and "dissolved" metals, where the latter was operationally defined as the hardness of the water passing through a 0.2 µm PVDF filter. All data discussed in this report are based on the dissolved concentrations. Metals analysis was completed using an inductively coupled plasma mass spectrometer (ICP-MS; Agilent 7500i, Ar plasma at 1350 W) on dilute acid extracted samples according to EPA method 6020[9]. This instrument is sensitive for concentrations across seven orders of magnitude. The limit of detection for calcium and magnesium was <0.1 mg/L, which is far less than the concentrations observed in any of the samples.

# RESULTS

## FULL SCALE TEST WITHOUT WATER MANAGEMENT

In the first phase of experimentation, the ECCU was run for 2,074 hours over a period of seven months in an accelerated laboratory experiment. During the test 11,059 gallons of water was evaporated and no water management or treatment strategy was applied. The result showed a 25% decrease in efficiency of the condensing unit.

## DATA ANALYSIS METHODS

The efficiency of the condensing unit was evaluated based on the EER* [Btu/hr/W]. The EER*, as opposed to a traditional EER, includes all power for the condenser but does not include the power for an evaporator fan and is calculated as follows (Equation 3):

**EQUATION 3. ECCU EER***

$$EER^* = \frac{Cooling\ Capacity}{P^*}$$

where P* is the total power for the compressor, sump pump, and condenser fan [W]. Pump power for the water-to-refrigerant heat exchanger is not included. The cooling load was measured at the water-to-refrigerant heat exchanger coil, where the refrigerant-to-water heat exchanger is a piece of test equipment simulating an evaporator of a typical split system air conditioner. The cooling load of the system in Btu/hr is as follows (Equation 4):

**EQUATION 4. ECCU COOLING LOAD**

$$Cooling\ Load\ [\frac{BTU}{hr}] = \mathrm{Q_{evap}} \times \rho \times C_p \times (T_{evap\_OUT} - T_{evap\_IN}) \times 60$$

where $Q_{evap}$ is the evaporator water flow rate [gpm], ρ is the density of water [lb/gal], Cp is the specific heat of water [Btu/(lb°F)], 60 is a conversion factor from minutes to hours, and $T_{evap\_OUT}$ and $T_{evap\_IN}$ are the outlet and inlet water temperatures of the heat exchanger [°F]. The cooling capacity on the water side is the total cooling capacity provided by the refrigerant system and was not cross checked with the refrigerant side capacity, since the refrigerant flow rate was not measured.

The measurement uncertainty for the capacity and efficiency of the system, as calculated using sensor accuracies as the inputs and applying error propagation methods[10], is approximately 3.2% (Figure 14). The measurement uncertainty for the power is approximately 0.5%.

The quantity of minerals introduced in the cooling water is expected to have the primary impact on any reduction in unit performance. Additionally, supply water mineral content can vary significantly between different water districts. For this reason, the ECCU performance was analyzed with respect to mineral mass added to the system through the water supply. The total added hardness is calculated for each cycle using Equation 5:

**EQUATION 5. HARDNESS ADDED**

$$\mathrm{HD}_{added} = [(C_{tap} \times K) + b] \times \mathrm{W}_{in} \times t_{flow}$$

where $C_{tap}$ is the conductivity of supply water [mS], K and b are the experimentally derived slope and offset relating hardness to conductivity (K=0.63 mg/mS·L and b=-220.8 mg/L, Figure 13), $W_{in}$ is the supply water flow rate [L/s], and $t_{flow}$ is the duration of flow [s]. The data shown in Figure 13 were obtained periodically over the course of the entire experiment. The measurement uncertainty for the total hardness added to the system, as calculated using error propagation methods, is approximately 4.2% (Figure 14).

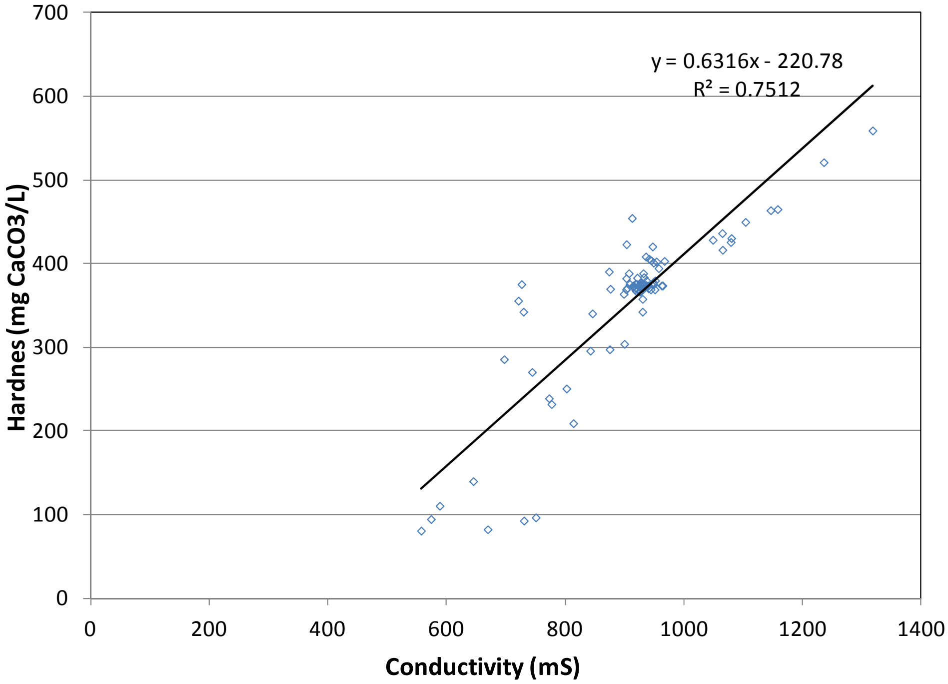


**FIGURE 13. LINEAR REGRESSION FOR HARDNESS TO CONDUCTIVITY RELATIONSHIP DATA.**

$$Capacity = C_p \times W \times \rho \times (T_{OUT} - T_{IN})$$

| Independent variable | Average value | Sensitivity Index, Θ | Instrument error (%) | Uncertainty , u (±) |
|---|---|---|---|---|
| x1 = T_out (F) | 61 | -1712.7 | 0.65% | 0.4 |
| x2 = T_in (F) | 80 | 1712.7 | 0.50% | 0.4 |
| x3 = volumetric flow rate (gph) | 208.86 | -153.5 | 1.00% | 2.089 |
| Average capacity | -32061 | | | 1020.5 |
| Uncertainty (%) | | | | 3.18% |

$$COP = \frac{\text{capacity}}{P * 3.412}$$

| Independent variable | Average value | Sensitivity Index, Θ | Instrument error (%) | Uncertainty , u (±) |
|---|---|---|---|---|
| x1 = capacity | 32620 | 0.00014 | 3.18% | 1038.3 |
| x2 = Power | 2158 | -0.00205 | 0.50% | 10.8 |
| Average COP | 4.43 | | | 0.1 |
| Uncertainty (%) | | | | 3.22% |

$$EER = COP \times 3.412$$

| Independent variable | Average value | Sensitivity Index, Θ | uncertainty (%) | Uncertainty , u (±) |
|---|---|---|---|---|
| x1 = COP | 61 | 3.4 | 3.22% | 2.0 |
| Average capacity | 209 | | | 6.7 |
| Uncertainty (%) | | | | 3.22% |

$$CaCO_{3\_added} = C_{tap} \times K \times Q_{in}$$

| Independent variable | Average value | Sensitivity Index, Θ | Instrument error (%) | Uncertainty , u (±) |
|---|---|---|---|---|
| x1 = avg hard | 353 | 41635.0 | 3.00% | 10.590 |
| x2 = Water volume | 41635 | 353.0 | 3.00% | 1249.050 |
| Average Hardness added | 14697155 | | | 623547.5 |
| Uncertainty (%) | | | | 4.24% |

FIGURE 14. UNCERTAINTY ANALYSIS FOR FULL SCALE TEST CALCULATIONS.

## PERFORMANCE DEGRADATION

Performance data for the ECCU over time includes EER*, total power, and condenser airflow. This data was aggregated into minute averages and further into cycle averages throughout the test. The performance of the system is plotted in Figure 15 and Figure 16 against the total hardness added to the system.

Figure 15 shows a 26% reduction in efficiency of the ECCU over the 2,074 hour test period with no water management or treatment strategy applied. It should be noted that an initial failure point showing a 25% reduction in efficiency was observed after 10lb of mineral hardness were introduced to the system. This was caused by the pump filter basket clogging and is discussed further below. This failure, which is easily fixable by the homeowner, was remedied and the test continued. Figure 16 illustrates the two components of efficiency, system power consumption and cooling capacity, which together result in the total efficiency loss. Figure 17 illustrates the ECCU exhaust air flow rate over the duration of the test with no water management strategy. In each figure, the hourly data is plotted with symbols and the moving average on a daily basis is shown with the solid black line. The missing efficiency and capacity data in Figure 15 and Figure 16 is due to a failed temperature sensor in the water side of the refrigerant to water heat exchanger. The system was run for a short time with the bad sensor. The sensor was replaced as soon as the failure was discovered.

The initial steep reduction and significant variation in efficiency (Figure 15) were found to be a problem with the pump filter basket clogging and starving the sump pump of water. The variation of the data points is due to a diurnal fluctuation, which was caused by the municipal water pressure dropping at night enough to reduce the sump water level and the resulting flow to the pump. On several occasions, the lack of water flow reduced the heat rejection capacity of the condenser sufficiently to trip the refrigerant high pressure shut-off switch. Once this problem was identified, the filter basket was cleaned and there was an immediate increase in efficiency of the unit. The diurnal sump water height fluctuation does not affect efficiency of the system when the basket is clean.

Condenser airflow reduction due to scale build-up in the unit also had an impact on performance. During the test, the airflow dropped approximately 27% from 1,100 cfm to 800 cfm.

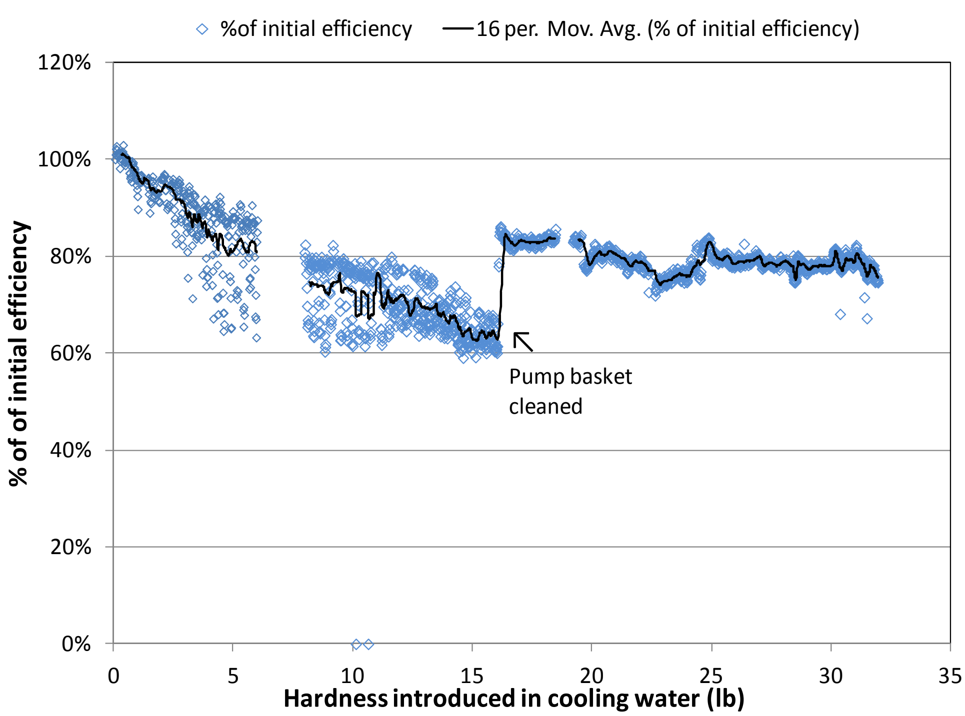


**FIGURE 15. 3-TON ECCU EFFICIENCY (±3.2%) WITHOUT WATER MANAGEMENT VS. MINERAL MASS ADDED.**

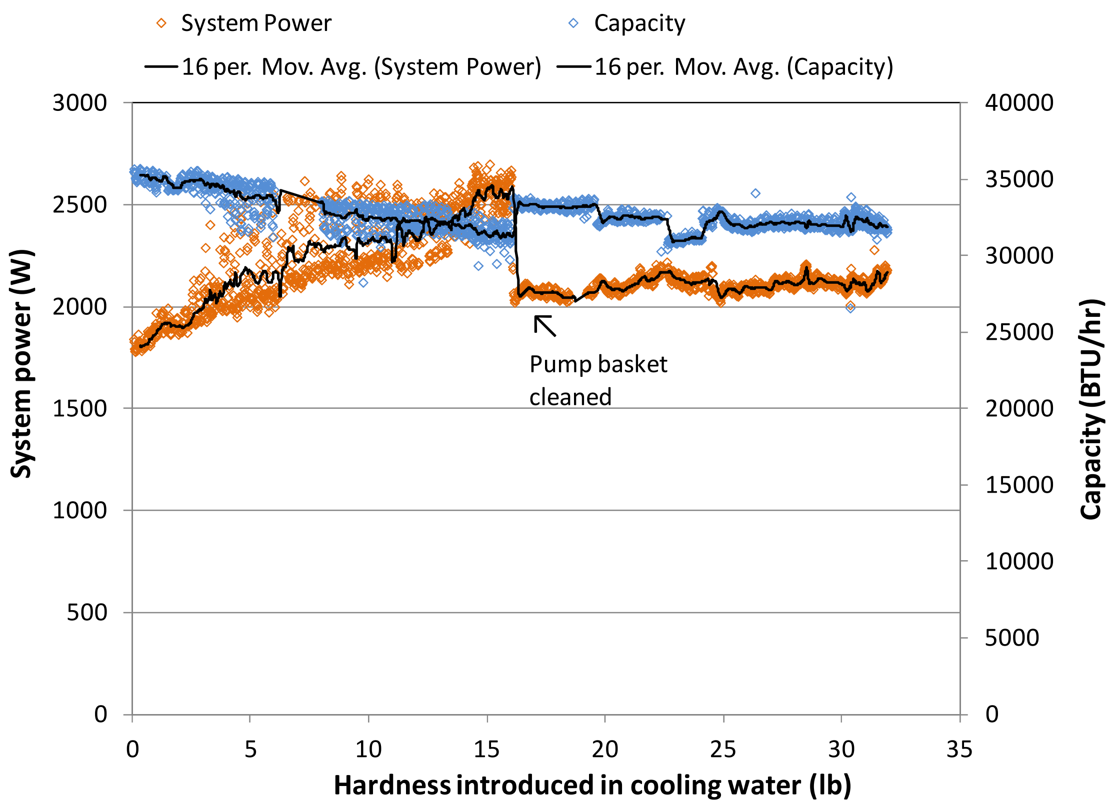


**FIGURE 16. CAPACITY (±3.2%) AND POWER (±0.5%) FOR A 3-TON ECCU WITHOUT WATER MANAGEMENT.**

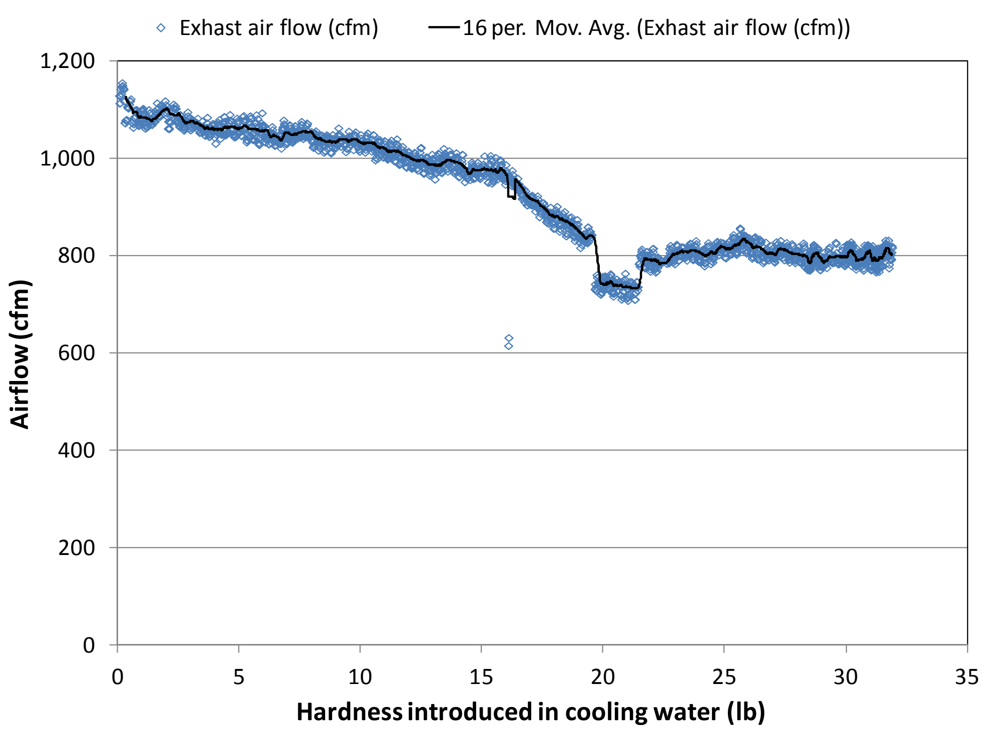


**FIGURE 17. 3-TON ECCU EXHAUST AIR FLOW WITH NO WATER MANAGEMENT (±2%).**

## SCALE FORMATION ANALYSIS

Aqueous chemistry principals were applied to improve understanding of scale formation in the evaporative cooling unit. Chemical equilibrium modeling of municipal supply water demonstrated that pH plays a critical role in the extent of scale formation. When aqueous pH values are less than 8, very little scale is expected to form until the water constituents are highly concentrated. By contrast, at aqueous pH values greater than 8.5, virtually 100% of the hardness is expected to precipitate out (at equilibrium conditions).

Over the 2,000 hour long experiment, the average water hardness, expressed as units of carbonate hardness, was 362 mg/L as $CaCO_3$, resulting in an estimated 33 lbs of potential scale forming constituents added to the system. When the coil was removed for replacement, it weighed 63.8 lb (Figure 18). No initial weight was available as the coil came factory installed. For comparison, the new coil weighed 32.5lb, and was estimated to be 10% smaller than the first coil. The resultant estimate of the weight change of the first coil is 27.7lb; similar to (but less than) the value of the estimated weight of total applied hardness as $CaCO_3$. Additional scale was found in the sump, drift eliminator, and on the walls of the system.

FIGURE 18. ECCU COOLING COIL FOULING. ENTIRE COIL (LEFT) MAGNIFIED SECTION (RIGHT)

Scale and water samples were collected from various locations within the evaporative cooling unit, and elemental distributions were highly dependent on sampling location. The sump water contained very high concentrations of salts, such as sodium (Na) and chlorine (Cl), which is expected due to their high solubility. Magnesium (Mg) and calcium (Ca), hardness constituents, were present in low concentrations in the sump water. However, Mg and Ca were both found in the solid precipitates, though their precipitate elemental composition varied with sampling location. Ca, in the form of calcite ($CaCO_3$), was anticipated to be the major scale forming component; the results of this study indicate that $CaCO_3$ likely plays a significant role, but that there are several other scale contributors that warrant investigation, particularly magnesium.

### PHYSICAL FAILURES

Reduction in efficiency is a combined effect, involving reduced heat transfer at the condenser coil, reduced water flow, and reduced exhaust airflow. In addition to scale formation on the heat exchanger, several other potential failure points were identified including clogging of the water distribution system, pump failures, and clogging of the pump filter basket.

### CONDUIT/NOZZLE CLOGGING

At the end of the test, inspection of the system showed a number of clogged nozzles, resulting in a 30% reduction in total water flow (from 8.2gpm to 5.8gpm). Eight of the twenty nozzles were 100% clogged and five of these were located in the corner farthest away from the pump, preventing an entire section of the coil from being wetted. Design of the spray bar is such that the water does not drain completely upon shutoff. This caused scale to form in the tube. When the water was turned back on, the scale in the tube was pushed into the back corner, eventually clogging the nozzles. As a result of this research, The manufacturer implemented a small design change to tilt the spray bar at a slight angle, increasing water drainage to reduce this problem. The manufacturer is also considering a straight nozzle as opposed to a right angle nozzle which would also increase drainage.

FIGURE 19. ECCU WITH NO BLEED NOZZLE CLOGGING.

### PUMP FAILURE

There were two pump failures over the duration of experiment: one at 1,177 hours of testing and the other at the 1,736 hours. The specific cause of the failure has not been identified. It is expected that scale clogging the pump basket starved the pump of water resulting in failure due to overheating. A refinement in the design to address the problem of basket clogging is expected to mitigate pump failures.

### BASKET CLOGGING

The cooling water pump, which is submerged in the sump reservoir, was protected from large pieces of debris by a plastic basket constructed of two layers of mesh. The finer (interior) mesh perforations were approximately 1/8 inch. The basket was susceptible to scale deposition causing blockage and reduced cooling water flow to the cooling water pump (Figure 20). This was later determined to be the cause for the initial steep reduction in efficiency of the unit. When the basket was cleaned, the efficiency immediately improved. The clogged pump basket had an effect on both cooling capacity and compressor power consumption due to the reduced heat transfer at the condenser coil. Increasing the mesh size could potentially decrease this problem; this design change is under consideration by the manufacturer. The manufacturer has also added a float switch inside the basket to assure that the pump is receives adequate water; when the float switch trips, operation of the system ceases. Cleaning the pump basket screen is an important maintenance activity that can be easily undertaken by the homeowner or by a service technician.

FIGURE 20. ECCU COOLING WATER PUMP BASKET FOULING

### RECONDITIONING

To determine the impact that simple reconditioning methods had on the performance of the ECCU, various components of the unit were cleaned and the performance was subsequently measured. Reconditioning consisted of cleaning the sump, the pump basket, and the scale off the air intake grill on the cabinet, and replacing the water piping and nozzles to restore water flow. Table 3 summarizes the efficiency improvements associated with reconditioning of the unit.

Cleaning the nozzles and restoring water flow to the coil did not yield a significant improvement in performance, increasing the EER* by 5% to 15.3.

TABLE 3. EFFECTS OF STEPS IN RECONDITIONING PROCESS

| | Capacity (kBtu/hr) | Power* (kW) | EER* (kBtu/hr/kW) |
|---|---|---|---|
| Test Start | 34.9 | 1.80 | 19.7 |
| Test End (% Change from Start) | 31.8 (-9%) | 2.15 (+19%) | 14.5 (-26%) |
| Test End + Cleaning (% Change from Start) | 31.7 (-9%) | 2.07 (+15%) | 15.3 (-22%) |

# SMALL SCALE TESTING OF MANAGEMENT TECHNOLOGIES

To test water treatment and management strategies directly, each small scale test was operated in parallel to reduce the variability in test conditions. The four parallel small scale units were run for more than 1,000 hours, with exception of the control unit which had no bleed or other treatment. The control unit developed sufficient scale to cause frequent pump failures by 690 hours; therefore the test was terminated.

## DATA ANALYSIS METHODS

Performance was measured as coil heat rejection capacity, or the ability of the system to reject heat from the coil. Since each system had slightly varying performance when new, the percent reduction in performance over time was compared between chambers.

Equation 6 was used to calculate the capacity of each small scale system in Btu/hr:

**EQUATION 6. SMALL SCALE CAPACITY**

$$Capacity = W_{coil} \times \rho \times C_p \times \left(T_{coil\_OUT} - T_{coil\_IN}\right) \times 60$$

where $W_{coil}$ is the evaporator water flow rate [gpm], ρ is the density of water [lb/gal], $C_p$ is the specific heat of water [Btu/(lb*°F)], 60 is a conversion factor from minutes to hours, and $T_{coil\_OUT}$ and $T_{coil\_IN}$ are the outlet and inlet water temperatures of the small scale coil [°F]. The measurement uncertainty for the capacity of the system, as calculated using error propagation methods, is approximately 4.7%[10]. The small scale system performance was analyzed with respect to the number of cycles the system was operated, where one cycle is one hour with the water on followed by a half hour with the water off.

| $Capacity = C_p \times W \times \rho \times (T_{OUT} - T_{IN})$ | | | | |
|---|---|---|---|---|
| Independent variable | Average value | Sensitivity Index, Θ | Instrument error (%) | Uncertainty, u (±) |
| x1 = T_out (F) | 88 | -2.2 | 0.63% | 0.6 |
| x2 = T_in (F) | 112 | 2.2 | 0.63% | 0.7 |
| x3 = volumetric flow rate (gpm) | 0.274 | -200.9 | 3.00% | 0.0 |
| Average capacity | -55 | | | 2.6 |
| Uncertainty (%) | | | | 4.73% |

FIGURE 21. UNCERTAINTY ANALYSIS FOR CAPACITY OF THE SMALL-SCALE TEST

## PERFORMANCE DEGRADATION

Figure 22 shows the capacity of each test unit relative to the high bleed unit that was observed to have no measureable capacity loss over the 1,000 hour test. The results are normalized in comparison to the high bleed unit to help minimize performance fluctuations due to humidity variations of incoming air. The data in Figure 22 is filtered to show only data points with humidity conditions between 10-15% relative humidity. The control unit failed relatively quickly compared to the low bleed, high bleed, and static magnet water management methods, indicating that water treatment or management is successful at extending the life of evaporative equipment. The control unit had six pump failures over the 700 hour operating period. The magnetic water treatment method ultimately had similar capacity losses after 1,000 hours of operation, but only needed two pump replacements.

The units where a bleed strategy was implemented had the best performance. The bleed rate for the lower bleed system was set at 0.029 gal/hr (approximately 8% additional water use above evaporation) and the bleed rate for the higher bleed system was set at 0.143 gal/hr (approximately 40% additional water use above evaporation). Over the duration of the test the low bleed rate unit experienced a 12% reduction in capacity and had one pump failure in comparison to the high bleed unit that had no reduction in capacity and no pump failures. However, the low bleed system bled 80% less water than the high bleed system, suggesting significant water savings may be achievable for relatively small losses in performance.

Failure of the sump pumps was also tracked as a useful measure of the impact that a particular water management or treatment strategy has on water-cooled equipment. Note that the pumps in the small scale tests were not protected by a filter. The high bleed system had no pump failures, the low bleed system had one failure (749 hours), the magnetic system had two pump failures (403 and 713 hours), and the no bleed system had six pump failures (166, 402, 483, 656, 687, and 700 hours). It is worth pointing out that the magnetic system successfully reduced pump failures even though the ability to reduce coil heat transfer degradation was minimal. It should also be noted that biological growth in the water occurred approximately halfway through the experiment in the no treatment chamber and approximately three quarters of the way through the experiment in the low bleed chamber. The biological material did not significantly affect the water properties and did not impact pump performance

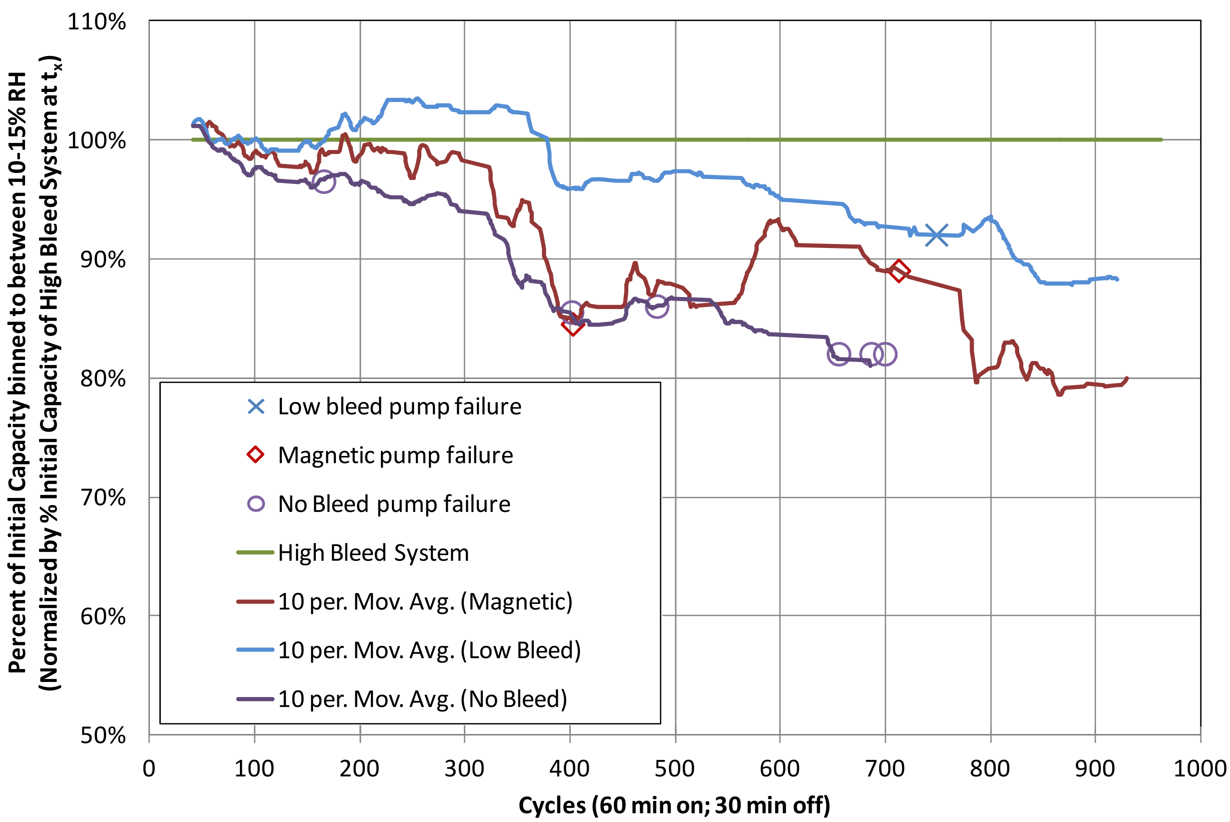


**FIGURE 22. WATER TREATMENTS % OF INITIAL COOLING CAPACITY VS TOTAL CYCLES OF OPERATION**

### AQUEOUS CHEMISTRY ANALYSIS

In an evaporative condenser, there are a number of factors that contribute to conditions that are favorable for precipitation reactions. Evaporation removes only water, therefore the concentration of soluble minerals is increased. This means that for a given carbonate concentration, evaporation will increase the cation concentration and may cause the solution to exceed the solubility limit. However, there are also other factors involved. When water evaporates it not only concentrates the minerals, it also concentrates the carbonate species, which creates a carbonate-system super-saturated solution. To rectify this, the solution can reduce the total carbonates by removing them via a precipitation reaction (removal of a base) or by returning them to the atmosphere as $CO_2$ (removal of an acid). Due to the quantity of water being evaporated, the latter is the dominant path.

As $CO_2$ (aqueous) concentrations are reduced by releasing $CO_2$ (gas) into the atmosphere, concentrations of bicarbonates and carbonates increase. In the redistribution process, hydrogen ions (protons) are consumed and the pH increases. This results in an increase in the solution pH, and this shift corresponds to an increase in $CO_3^{2-}$. As the pH increases, more total carbonates are present in the system and the speciation (division among the three forms) shifts toward the scale forming species ($CO_3^{2-}$ ).

Average pH in tap water measured over the course of the experiment was 8.2, while in the four small scale systems, pH was observed to be: low bleed (9.2), high bleed (9.0), magnets (9.6), and control (9.5). The elevated pH in all treatment systems, compared to tap water, demonstrates the effects of evaporation. The formation of calcium carbonate ($CaCO_3$) scale, both calcite and aragonite phases, is also promoted by elevated temperatures because $CaCO_3$ solubility decreases with increasing temperature. This temperature dependence is responsible for the formation of $CaCO_3$ scale in water heaters. In evaporative condensers, both elevated temperatures and evaporation leading to elevated cation concentrations and pH values encourage the formation of carbonate mineral scale.

Table 4 shows the results of solution and mineral scale analysis for the small scale test units. As previously mentioned, in all cases, the sump pH was higher than the tap water and this is due to the "off gassing" of $CO_2$. In the no-bleed cases, the sump water pH is higher because there is less tap water being provided. As previously highlighted, the sump pH is a major factor for carbonate-based precipitation reactions, and the observed elevated pH values will contribute to scale formation.

Calcium was observed to be largely or entirely precipitated in all systems. In the two no-bleed systems, calcium was not detected in the sump water indicating that it had entirely precipitated (100% precipitation). In the low and high bleed systems, the sump concentrations of calcium were actually lower than that of the tap water. The calcium concentration in the low bleed sump was 0.40 mM, the high bleed sump was 0.21 mM, and the tap water was 0.85 mM. Therefore, increasing the bleed rate actually increases the total amount of calcium available to the system. Conversely, sump concentrations of magnesium were higher than that of tap water. The magnesium concentration in the low bleed sump was 14.4 mM, the high bleed sump was 7.6 mM, and the tap water was 2.0 mM. Therefore, increasing the bleed rate reduced the total amount of magnesium available to the system.

In the high and low bleed systems, the mass of precipitated calcium compared to the no bleed system increased (~4% increase for the low bleed and ~14% increase for the high bleed) and the mass of precipitated magnesium compared to the no bleed system decreased (~100% decrease for the low bleed and ~52% decrease for the high bleed). These results indicate that increasing the bleed rate may actually contribute to calcium-based scale formation. By increasing the bleed rate, more makeup water is required, and therefore a greater amount of calcium is supplied to the system. Because of its low solubility, a majority of the calcium is then converted into mineral scale. This indicates that in supply waters with elevated calcium concentrations, an increased bleed rate may increase the total mass of scale formed (i.e., the increased bleed maybe be more detrimental than beneficial).

Magnesium has a different solubility and precipitates differently than calcium. Under no-bleed conditions, a vast majority of the magnesium precipitated out; however, when a bleed was introduced the mass and percentage of magnesium precipitated dropped off quickly. At the high bleed condition, magnesium was not found to contribute to mineral scale. The difference in the behavior is due to the differences in solubility limits and the effect of the increased bleed on the solution pH. This indicates that, unlike calcium-based scale, the bleed is an effective approach for controlling magnesium-based scale.

For the two no-bleed cases, the final coil scale mass of the magnetic system had 1.5-times the scale of the control system. There are two possible contributing factors to this observed effect. The first, and most significant factor, is that the four systems were not all run for the same number of cycles. To enable a fair comparison, normalized coil scale (mg/cycle) was calculated and is presented as follows: control-no bleed (217 mg/cycle), magnets – no bleed (222 mg/cycle), low bleed (132 mg/cycle), and high bleed (111 mg/cycle) (Table 4). The second factor that possibly contributes to the magnetic system retaining more scale than the control system is the alteration in the mineral phase due to the presence of the magnetic field. As the x-ray diffraction analysis shows, in the control system, the mineral scale did not present an identifiable mineral phase (e.g., amorphous). By contrast, the magnet no-bleed system presented a spectra that indicated the presence of dicalcium silicate ($Ca_2SiO_4$), aragonite ($CaCO_3$), and magnesium sulfate ($MgSO_4$) which indicates that non-carbonate species (i.e., silicates and sulfates) also contribute to mineral scale.

**TABLE 4. AQUEOUS CHEMISTRY RESULTS**

| SYSTEM | PH | CALCIUM | | | MAGNESIUM | | | Coil scale mass (g)[d] | Normalized coil scale mass (mg/cycle) | Mineral phase |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Sump (mM)[a] | Precipitated (mols)[b] | Precipitated (%)[c] | Sump (mM)[a] | Precipitated (mols)[b] | Precipitated (%)[c] | | | |
| Influent (tap) | 8.11 | 0.85 | - | - | 1.97 | - | - | - | - | - |
| Control - no bleed | 9.46 | 0 | 1.13 | 100 | 11.04 | 2.57 | 98.4 | 150.0 | 217 | none identified |
| Magnets - no bleed | 9.56 | 0 | 1.13 | 100 | 8.73 | 2.58 | 98.7 | 224.6 | 222 | Ca2SiO$_4$; $CaCO_3$ (arag); $MgSO_4$ |
| Low bleed | 9.19 | 0.40 | 1.17 | 95.4 | 14.41 | 1.23 | 43.4 | 142.2 | 132 | $MgCO_3$ |
| High bleed | 8.99 | 0.21 | 1.29 | 81.1 | 7.64 | 0.00 | 0.0 | 119.5 | 111 | $CaCO_3$ (arag) |

[a] Average steady state sump concentration (mM=milimolar)
[b] Calculated based on a mass balance approach for steady state conditions for 1,000 cycles (mols is similar to a unit of mass)
[c] Calculated based on a mass balance approach for steady state conditions; unprecipitated component is in sump
[d] Determined by difference between initial unused coil mass and final coil+scale mass
[e] X-ray diffraction was used to assess mineral phase; these results are preliminary

# FULL SCALE TEST WITH LOW BLEED RATE APPLIED

The third phase of testing consisted of running the ECCU for 2,027 hours with an average bleed rate of 0.92 gal/hr. The bleed water was collected by an aperture as the water dripped down off the condenser coil. It was measured but not controlled. Based on data collected during the no bleed test, this resulted in an additional 15-23% water use above that evaporated and/or lost through drift (Figure 23). This bleed rate is between the 8% and 40% bleed rates tested in the small scale systems.

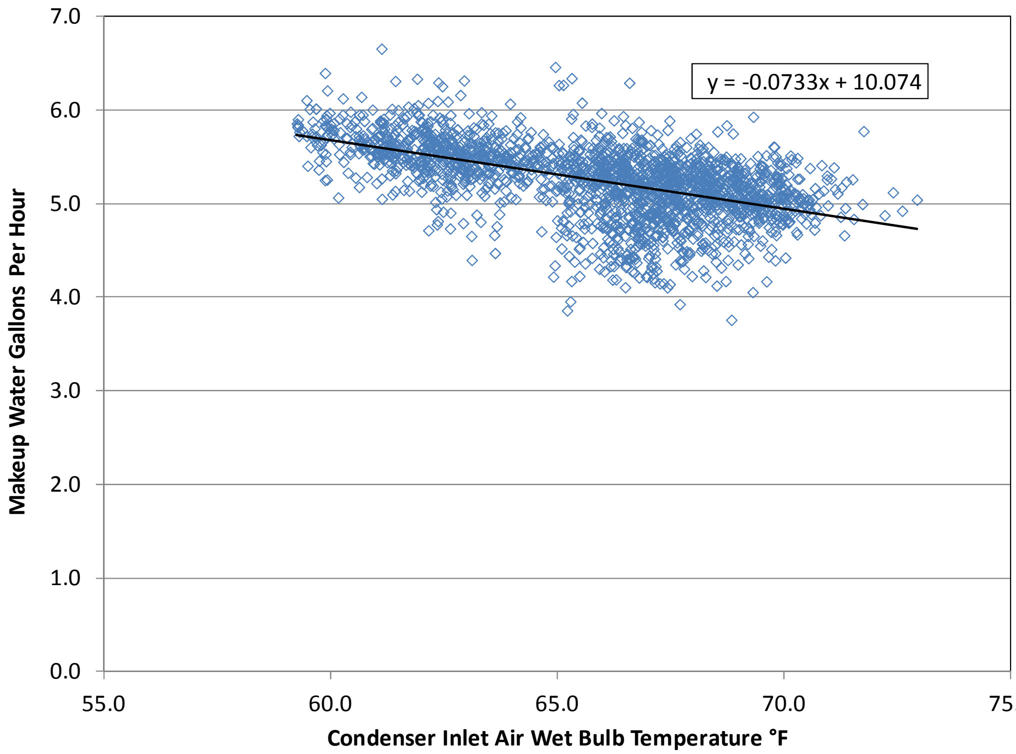


FIGURE 23. MAKEUP WATER VERSUS CONDENSER INLET AIR WET BULB TEMPERATURE FOR NO BLEED TEST

## PERFORMANCE LOSS

Performance was calculated similarly to the first full scale test using Equation 3 through Equation 5. The results are presented in Figure 24, Figure 25, and Figure 26. Each hourly data point is shown with the solid line representing a daily moving average. The low bleed strategy successfully reduced the efficiency degradation of the ECCU unit compared to the first test with no water management strategy applied (Figure 24). This is an encouraging result since the bleed rate was significantly lower than the manufacturer's recommended rate based on local water hardness. During the test, the efficiency dropped by about 10%, compared to 25% in Test 1 (with no bleed) over 2,000 hours of operation. The capacity of the system was minimally affected and the efficiency change was mainly due to increased power consumption (Figure 25). The capacity in Test 2 (with low bleed) started lower than in Test 1 by about 14%. This is due to a change in the condenser coil design upon manufacturer replacement of the coil between Test 1 and Test 2. The replacement coil was more compact and of 10% less surface area. Therefore, percentage changes in performance are compared as opposed to absolute changes.

The accumulated mineral hardness of the system was less than that of Test 1, 28.5 pounds versus 33.0 pounds. It was expected that due to the increased water usage that the total mineral hardness added to the system would be more. However, since the average hardness of the water supply decreased to 254 mg/L (from 362 mg/L in Test 1) the end result was a reduction in total accumulated mineral hardness.

Condenser airflow reduction due to scale build-up in the unit also has an impact on performance. Figure 26 illustrates the ECCU exhaust air flow rate over the duration of the low bleed test. During the test, the airflow dropped by about 33% from 1,050 cfm to 700 cfm. The gap in the data is due to a communication error with the instrument used for monitoring exhaust airflow.

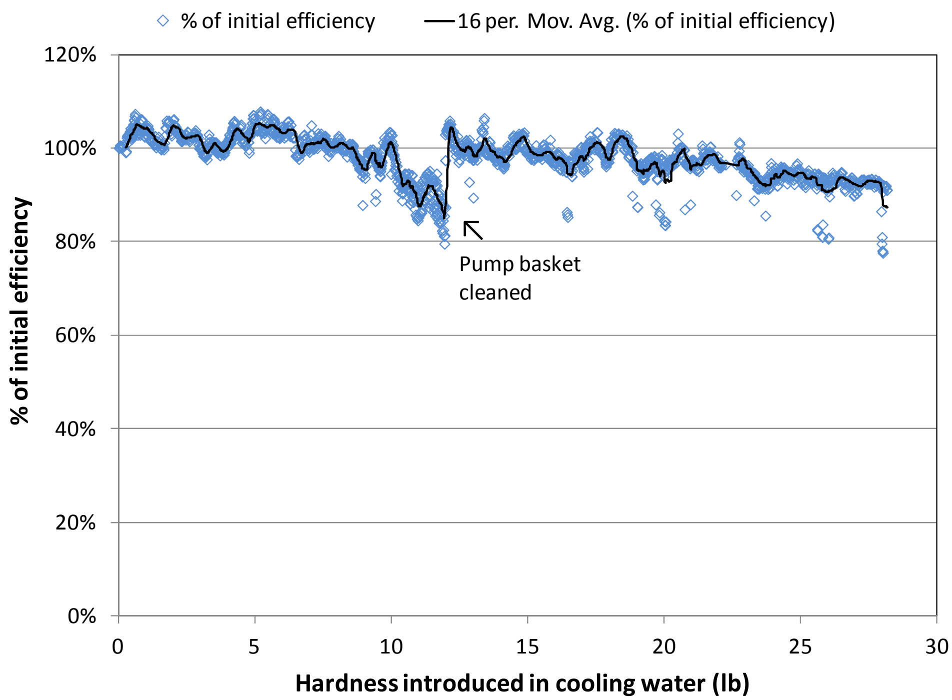


FIGURE 24. 3-TON ECCU EFFICIENCY (±3.2%) WITH LOW BLEED VS MINERAL MASS ADDED.

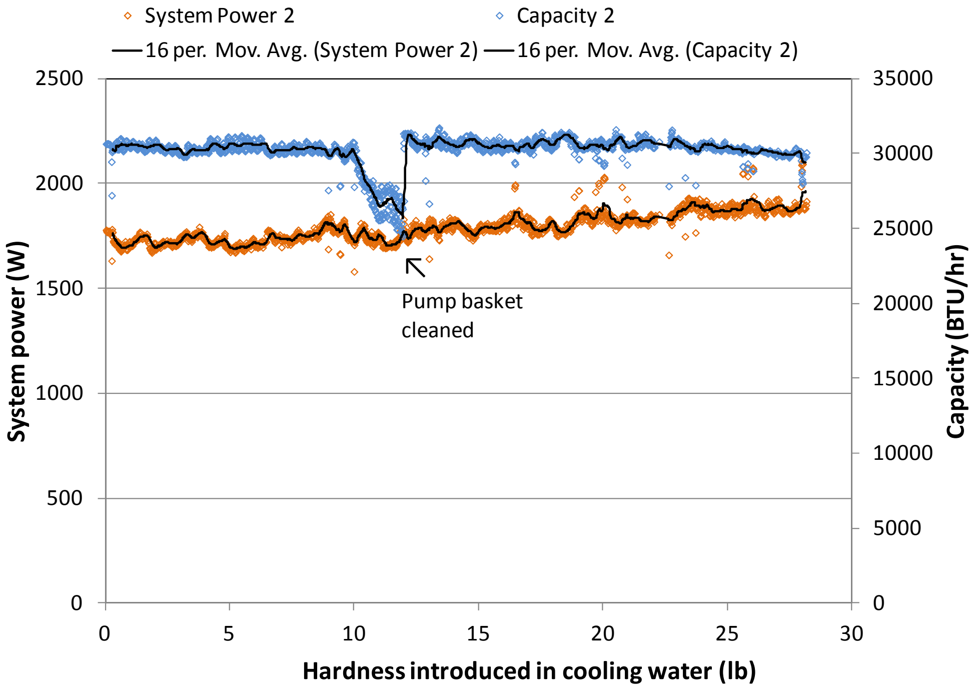


**FIGURE 25. 3-TON ECCU POWER CONSUMPTION (±0.5%) AND CAPACITY (±3.2%).**

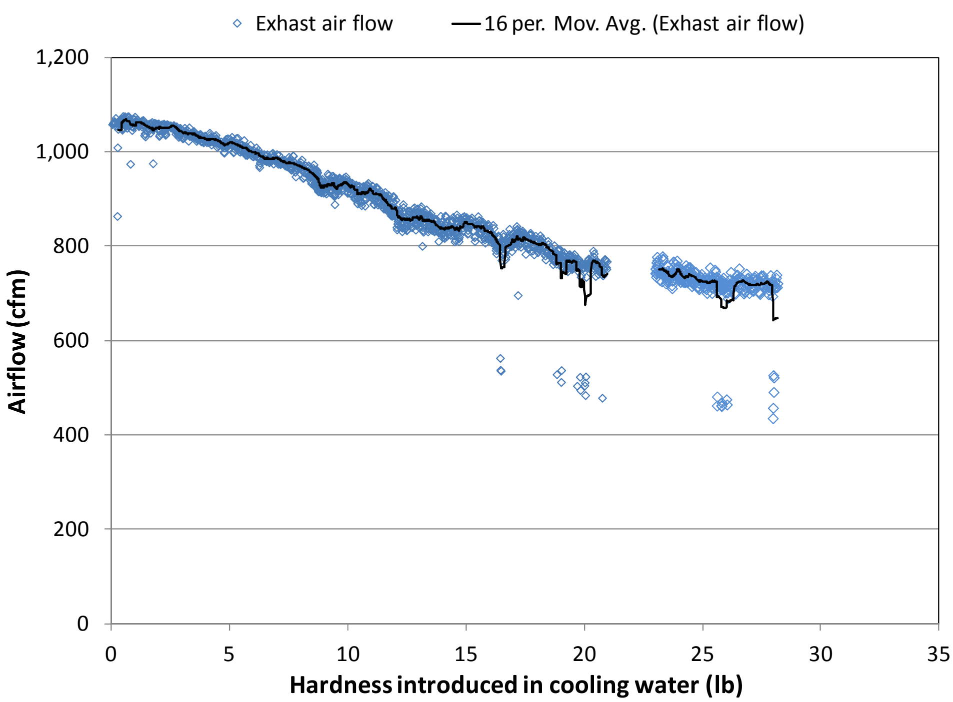


**FIGURE 26. 3-TON ECCU EXHAUST AIR FLOW WITH LOW BLEED ( ±2% ).**

### PHYSICAL FAILURES

Upon inspection at the end of the test, minimal scale was found on the coil. A before and after weight measurement determined that 0.7 lb of scale was on the coil, compared to approximately 31 lb in the no bleed test. However, scale buildup was found on the nozzles, on the pump basket, and on the drift eliminator.

### CONDUIT/NOZZLE CLOGGING

While total scale formation at the end of the low bleed test was significantly less than in the no bleed test, there was still nozzle clogging, as can be seen in Figure 27. Overall, cooling water flow was not reduced over the duration of the test, but the spray pattern was reduced or non-existent in approximately 50% of the nozzles. The spray pattern is shown in Figure 28.

FIGURE 27. ECCU WITH LOW BLEED NOZZLE CLOGGING.

FIGURE 28. ECCU WITH LOW BLEED SPRAY PATTERN.

### PUMP FAILURE

There were no pump failures over the duration of 2,027 hours of experimentation.

### BASKET CLOGGING

The basket became clogged once after 1,300 cycles, after which it was cleaned again preemptively after 1,800 cycles.

### DRIFT ELIMINATOR CLOGGING

Unlike the no bleed test, where scale buildup on the coil was significant enough to impede air flow through the ECCU, in the low bleed test there was little additional air flow resistance in the coil. Airflow reduction in the low bleed test was caused by scale buildup on the drift eliminator above the spray manifold and on the inlet vents on the sides of the ECCU (Figure 29).

FIGURE 29. ECCU WITH LOW BLEED –SCALE FORMATION ON DRIFT ELIMINATOR

## RECONDITIONING

At the end of 2,027 hours, the drift eliminator was cleaned and the system was run for 14 cycles. Then the inlet vents on the sides of the ECCU were cleaned and the system was run for another 14 cycles. The combination of these two cleaning operations had a significant effect on the EER*, bringing it back to 96% of the initial efficiency (Table 5).

TABLE 5. ECCU LOW BLEED: EFFECTS OF RECONDITIONING

| | Capacity (kBtu/hr) | Power* (kW) | EER* (kBtu/hr/kW) |
|---|---|---|---|
| Test Start | 30.7 | 1.77 | 17.3 |
| Test End (% Change from Start) | 29.7 (-3.3%) | 1.88 (+6.2%) | 15.8 (-8.7%) |
| Test End + Cleaning (% Change from Start) | 30.7 (0%) | 1.85 (+4.5%) | 16.6 (-4.0%) |

# Long-Term Performance in SCE Territory

Laboratory testing of the evaporative condenser occurred with municipal water in Davis, CA and under two conditions (no bleed, and bleed=0.92 gal/hr, which is equivalent to an average 17% bleed). An analytical model is required to extrapolate the results to SCE territory in order to determine an optimal bleed rate and relative lifetime of the condenser compared to a base-case ECCU operating in Davis, CA. In the laboratory experiment, it was shown that the chemical composition of the scale was dependent on the employed bleed rate. In summary, when no bleed was employed both Ca and Mg precipitated extensively (> 98%). In the presence of a bleed, Ca was still largely precipitated, while Mg was removed by the bleed. In the small scale testing, increasing the bleed rate reduced the total Mg precipitate but increased the total Ca precipitate.

Given a long enough time line, precipitation will occur any time the solution exceeds the solubility limit. The Ca solubility limit depends on the pH, salinity, and temperature; Mg solubility will similarly depend on pH and salinity, but temperature has only a minimal effect. If precipitation is predicted (based on solubility limits), then reaction rates become important. Behavior in the low bleed case indicates that the reactions occur fast enough for both Ca and Mg precipitates to form in the system. Precipitation is not expected when sump concentrations are below the solubility limit.

Observed sump concentrations of dissolved calcium (Figure 30) and dissolved magnesium (Figure 31) were compared to their thermodynamic equilibrium concentrations. The equilibrium concentration for Ca and Mg with their respective carbonate solids ($CaCO_3$ or $MgCO_3$) is dependent on pH, temperature, and salinity. The lines in the figure represent equilibrium (i.e. saturation) concentrations as a function of pH for different salinity/temperature combinations. The region above a given curve indicates a super-saturated solution and the region below a curve indicates an unsaturated solution. Six theoretical equilibrium lines are shown in Figure 30 and Figure 31, which are meant to demonstrate a range of conditions associated with three salinity values (negligible salinity, salinity similar to the low bleed and salinity similar to the high bleed conditions) and two temperatures (similar to those in the sump, 25ºC, and at the coil surface, 60ºC). The predicted dissolved concentrations were determined using the thermodynamic equilibrium modeling software, MINEQL+, with a system consisting of water, carbonates, and either Ca or Mg. The total dissolved concentration was the sum of the appropriate dissolved species of Ca or Mg.

Figure 30 and Figure 31 also show the measured "dissolved" calcium and magnesium concentrations in the sumps of the small scale tests illustrated by the symbols. In this discussion, dissolved concentration is operationally defined as the solution passing through a 0.22 μm filter (i.e., it is a measured value for a collected sample; it is not based on computer modeling). The dissolved concentration data points all fall in the supersaturated region. This solution is expected to contain freely dissolved metals (i.e., $Ca^{2+}$, $Mg^{2+}$), inorganic complexes (e.g., calcium hydroxide), and may also contain colloids (i.e., very small suspended solids); the analytical methods employed in this study cannot quantify freely dissolved constituents. Non-equilibrium conditions were numerically analyzed using a saturation ratio (SR) calculated as follows:

**Equation 7. Saturation Ratio**

$$SR = \frac{measured\ total\ dissolved\ concentration\ [\frac{mols}{L}]}{predicted\ total\ dissolved\ concentration\ at\ measured\ pH\ [\frac{mols}{L}]}$$

For the aqueous chemical conditions present in these experiments, both calcium carbonate and magnesium carbonate have been identified as the thermodynamically most favorable calcium and magnesium solids, and therefore are the solids that would be expected to form in the system at equilibrium conditions. Saturation ratios for Ca were ~55 for the low bleed and were ~27 for the high bleed case, indicating that the solutions either contain colloidal precipitate and/or are super saturated in Ca. Saturation ratios for Mg were an order of magnitude greater (~300 for low bleed and ~170 for high bleed). These saturation ratio values, which are noticeably greater than one, indicate that there were likely kinetic hindrances to the precipitation reactions. For example, actual reaction times may be greater than the time that the reactants remain in the system before they are removed by the bleed, particularly for Mg. The residence time, meaning the average length of time from when dissolved solids enter the system with the supply water to when they leave the system in the bleed water, is 34 hours in the low bleed system and is 7 hours in the high bleed system.

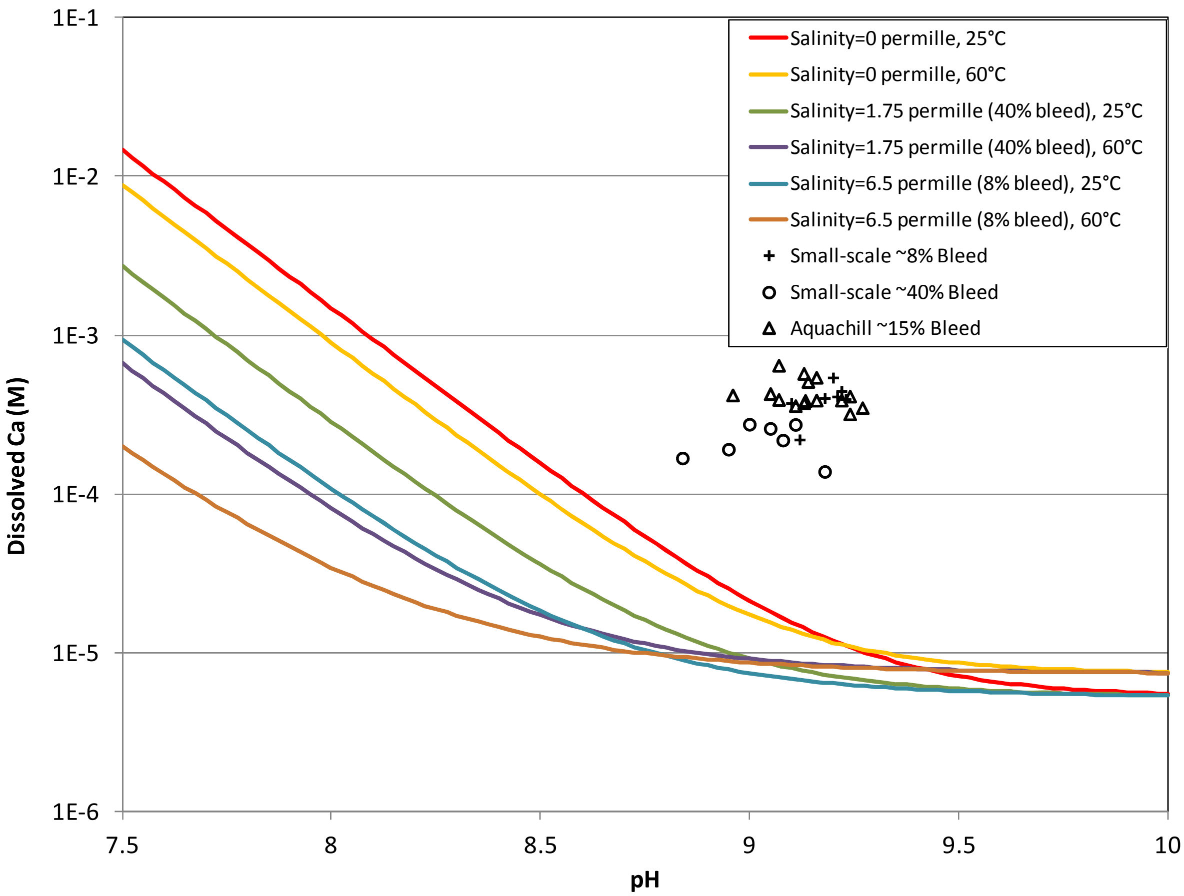


**FIGURE 30. COMPARISON OF SUMP CALCIUM CONCENTRATIONS TO EQUILIBRIUM CONCENTRATIONS**

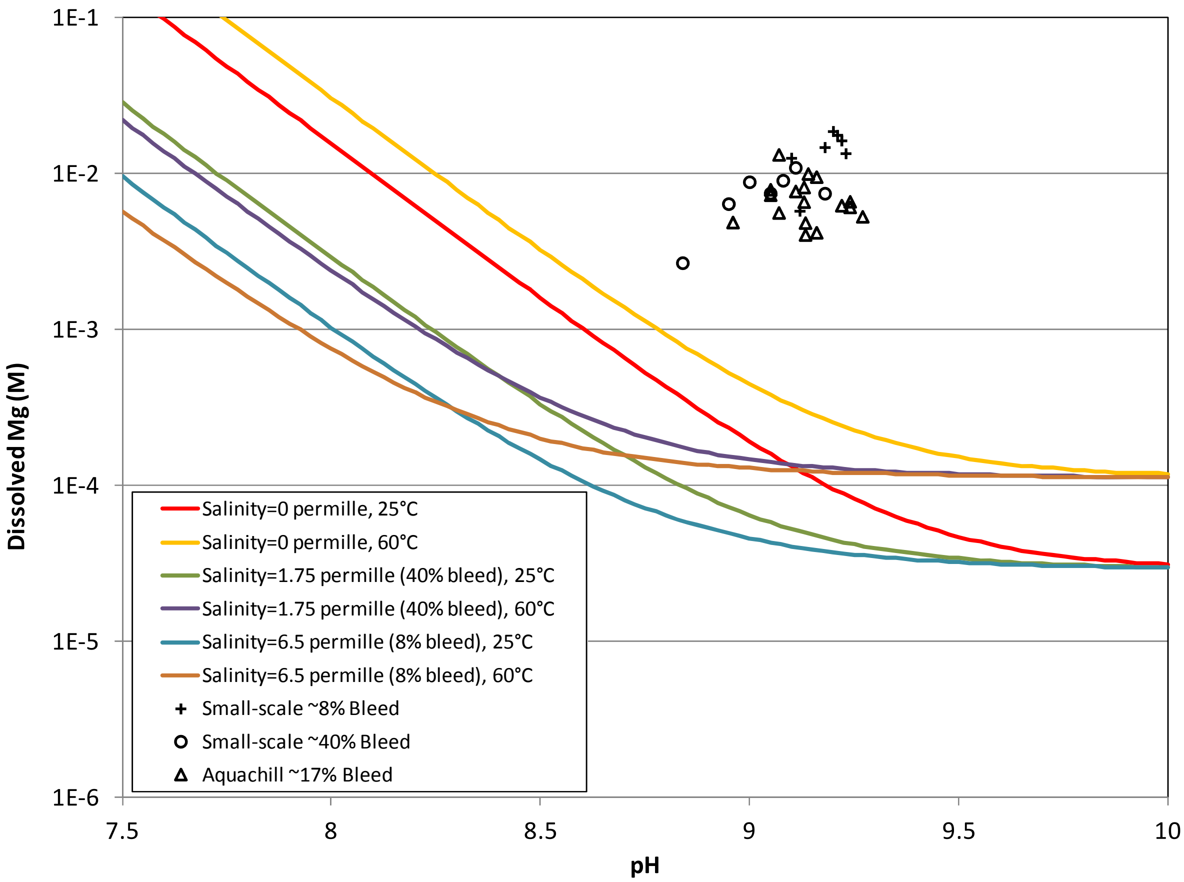


**FIGURE 31. COMPARISON OF SUMP MAGNESIUM CONCENTRATIONS TO EQUILIBRIUM CONCENTRATIONS**

Using the data produced in this study and the principles of precipitation reactions described above, an analytical model was developed and an optimized bleed rate was calculated for nine of the largest water districts in SCE service territory including Anaheim, Eastern, Irvine, Long Beach, Oxnard, Riverside, Santa Ana, El Centro, and Ventura. Municipal calcium concentrations were between 50-96 mg/L while magnesium concentrations were between 10-35 mg/L. For comparison, the 2011 Davis water quality report states that the calcium concentration is 33 mg/L and the magnesium concentration is 53 mg/L.

A mass balance approach was employed to predict the coil scale accumulation using the mineral concentrations of the incoming tap water and the exiting concentrations in the bleed water; the remainder forms a precipitate in the system. An unknown portion of the precipitate sticks to the coil and the remainder sticks to the walls, falls into the sump, adheres to pumps, nozzles, etc, or is expelled from the system in the air stream.

The assumptions behind this model and optimization were based on a limited number of data points; they should be regarded as displaying a trend, rather than as absolute values, and therefore should be used with care. Some of these assumptions are estimates that reflect our best scientific guess. Additional research is anticipated to refine the model and provide improved confidence. The assumptions that were applied to the optimization, based upon the experimental data presented in this report, were as follows:

1. The number of run hours per year for the evaporative condenser was determined from an E-Quest simulation of a residential home with construction typical to Southern California. The climate zone for the water district studied was simulated.
2. Ca precipitates as $CaCO_3$ (Molecular Weight (MW)=100 g/mol)
3. Mg precipitates as $MgCO_3$-1.5$H_2O$ (MW=111 g/mol)
4. Non-carbonate solids are not considered
5. Several parameters were determined to be dependent on the bleed rate and were evaluated as a function of bleed rate. The variable used is the percent increase in water used for bleed (%) = bleed volume/evaporation volume. Additional parameters for the model are:
    a. pH is a function of the %bleed as follows: pH = 0.1258*ln(1/%Bleed +1) + 8.8466. This relationship was developed from a fit of experimental data of measured sump water from the no bleed, low bleed, and high bleed experiments. Maximum pH allowed was 9.6 which was the observed pH in one of the no bleed experiments (Table 4).
    b. Non-equilibrium conditions, which are most likely due to kinetic limitations, were included in the model through the employment of saturation ratios
    c. Ca saturation ratio is a function of %bleed and is based on measured data for sump water from small scale testing, with the function 2.824*(1/%Bleed +1) + 17.33.
    d. Mg saturation ratio is a function of % Bleed and is based on measured data for sump water from small scale testing, with the function 13.190*(1/%Bleed +1) + 69.40.
6. Precipitations are based on the solubility calculated with the salinity (S) equal to 6.5 parts per thousand (permille) and the calculated saturation ratio. The model assumes a fixed salinity regardless of bleed rate, and applies the salinity observed in the low bleed case of the small scale testing. Salinity is acknowledged to affect carbonate speciation; however the makeup water salinity will also vary by source. The model could be improved in the future to reflect makeup water salinity and the effect of the bleed on the sump salinity.
7. Precipitation is based on solubility at T=25$^{o}$C and the calculated saturation ratio.
8. Iterations, which could possibly improve this fit, were not included

Employing the above assumptions, the effect of increasing bleed, as a percent of evaporated water use, on mineral-scale formation is shown in Figure 32. The analysis demonstrates that it is likely that some scale will form in all locations, regardless of bleed rate. This is due to evaporation producing increased concentrations of hardness components (Mg and Ca) and other salts (increased salinity), as well as increased pH (which reduces the solubility of those hardness components). More importantly, the analysis demonstrates that in most cases, a small bleed is helpful initially (e.g., increasing from no bleed to 5%), but that a substantial bleed (e.g., >15%) is counterproductive in most cases. In most of the locations analyzed in Southern California, increasing the bleed rate reduces the scale formation rate until an inflection point is reached at 5-15% percent water use for bleed. At that point, bleeding additional water increases scale formation rate. In Oxnard and Riverside (Figure 32), the model predicts that inclusion of any bleed will increase the amount of formed scale; however this does not account for changes in sump salinity that will occur with bleed. For example, the model predicts that in Oxnard, CA, following the manufacturer's recommended bleed rate of 40% would reduce the ECCU lifespan by 20% compared to using a more conservative bleed rate of 15%.

The model predicts that in Davis and El Centro, CA where more magnesium is present, higher bleed rates of 78% and 36% respectively will achieve minimum scale formation. Davis is a location with high magnesium concentrations, and for this reason, the higher bleed rate was more effective in controlling scale for the lab experiments in this study. Most water districts in California, and more specifically all those evaluated in SCE territory, contain more Ca than Mg, so better performance at high bleed rates is not common. Since it would be most practical to have one bleed rate recommendation for Southern California, a 15% bleed rate was chosen because it is within the optimized range and it is the closest to current recommended practice. Current recommendations for ECCU installations specify 12-40% bleed, where the higher bleed is recommended in hard water areas.

In addition to providing a model for bleed rate optimization, the model was used to predict total estimated scale formation on the copper coil. The model results were well correlated to the small scale tests; however the model significantly over-estimated the amount of scale formed on the coil in the low bleed test of the full size ECCU. This discrepancy will be investigated by future research. One theory is that vibrations from the condenser fan and compressor shake loose scale from the condenser coil whereas these components are not present in the small scale tests. Because the model could not accurately predict the condenser coil scale formation in full size ECCUs, it was instead used to predict how a full size ECCU would operate in SCE locations relative to the 2,000 hour full scale laboratory test in Davis, CA.

The relative lifetime of the condenser in SCE service territory compared to the ECCU tested in Davis, CA was calculated based on the water characteristics and the expected number of run hours per year in the climate zone in which it is operating (Table 6). The number of annual operating hours was modeled with eQUEST building energy simulation software (Table 6, column 5). The simulation was performed for a two story 1,768 square foot residential home. The air conditioning unit for the model home was a 3.5-ton split system with a seasonal energy efficiency ratio of 13. In practice an evaporative condenser is may have reduced run times relative to the unit modeled, due to higher capacity at higher ambient temperatures.

Table 6 presents the normalized lifespan predicted by the model, as compared to a base-case ECCU operating in Davis, CA, in which the ECCU operated in the laboratory for 2,000 hours with 4% loss of efficiency. The results indicate that some locations in Southern California are better suited for evaporative condensers than are other locations. For example, Long Beach is a prime location, while evaporative condensers in Oxnard will last less than half as long as those in Long Beach and/or require more maintenance. Although it appears that an ECCU lasts 7 times longer in Oxnard as compared to El Centro, it should be noted that unit longevity as measured by cooling provided is about the same in both places.

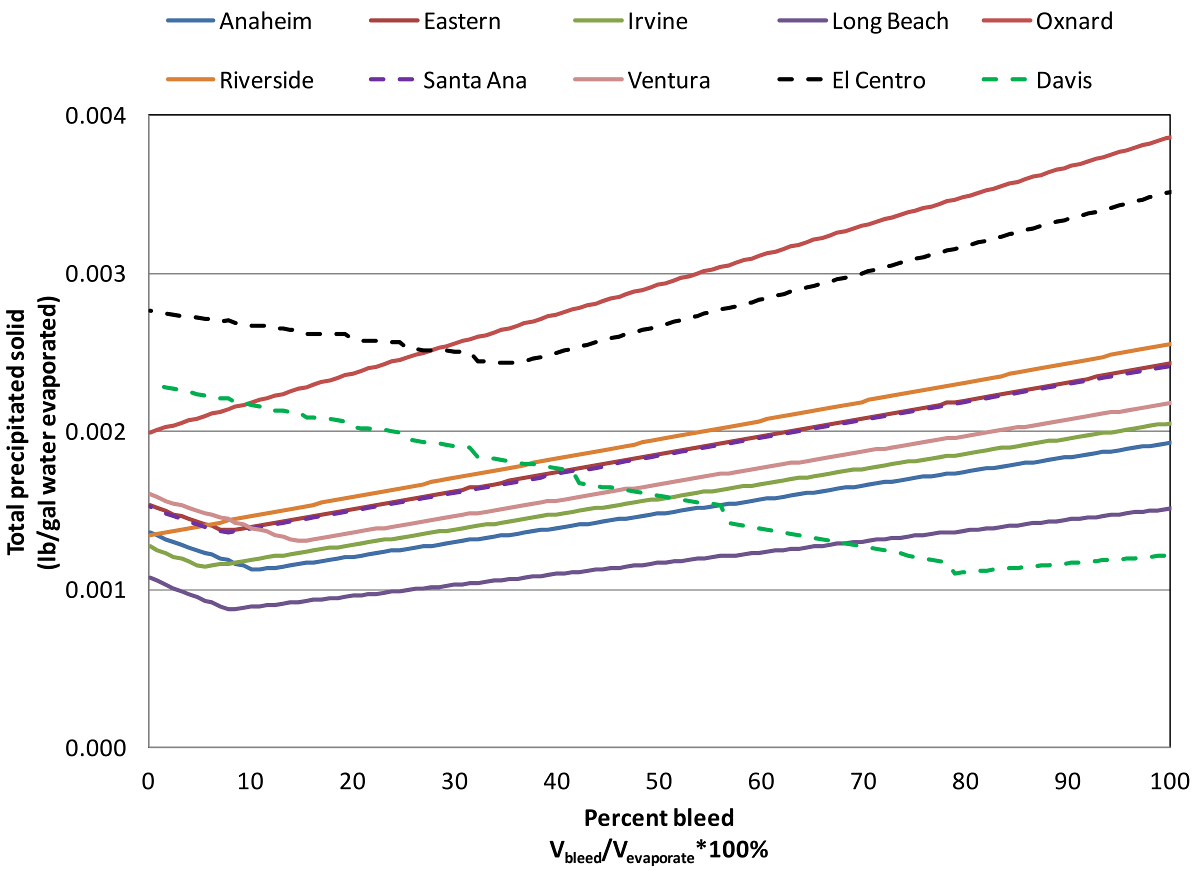


**FIGURE 32. THE EFFECT OF TOTAL DEPOSITED SCALE VERSUS PERCENT BLEED BY LOCATION**

**TABLE 6. MODELED LIFETIME OF AN EVAPORATIVE CONDENSER IN NINE LOCATIONS IN SCE TERRITORY AND DAVIS, CA**

| Location | Climate Zone | Mg (mg/L) | Ca (mg/L) | Est. Hours Per Yr | Lifespan Relative to Davis at 15% bleed |
|---|---|---|---|---|---|
| Anaheim | 8 | 19.0 | 50.0 | 733 | 2.0 |
| Eastern (Temecula, Hemet) | 10 | 17.0 | 62.0 | 1,039 | 1.1 |
| Irvine | 8 | 15.0 | 53.0 | 733 | 1.9 |
| Long Beach | 6 | 17.0 | 40.0 | 372 | 4.9 |
| Oxnard | 6 | 10.1 | 96.4 | 372 | 2.0 |
| Riverside | 10 | 10.0 | 65.0 | 1,039 | 1.1 |
| Santa Ana | 8 | 16.8 | 61.7 | 733 | 1.6 |
| Ventura | 6 | 22.0 | 56.0 | 372 | 3.5 |
| El Centro | 15 | 35.0 | 88.0 | 2,545 | 0.3 |
| Davis (High Mg) | 12 | 53.0 | 33.0 | 796 | 1.0 |

# DISCUSSION

The test of a water cooled condenser without any water management or treatment strategy showed a 26% reduction in efficiency after operating for 2,074 hours. Approximately ~27.7lb of scale precipitated out solution and deposited on the condenser refrigerant coil and a substantial amount of solids were also found in the sump. The only maintenance performed during the experiment was to clean the pump filter basket to prevent clogging. Without a functioning filter basket the water circulation pump can become starved of water and result in failure of the unit much earlier than presented in this paper. Deposition of minerals on the refrigerant coil reduced the heat transfer effectiveness, as well as the condenser airflow, which led to an overall decrease in performance.

Small scale testing of a similar system design was also conducted to analyze the performance of multiple water management and treatment strategies directly. This parallel study analyzed the impact of two different water bleed rates and static magnets as a treatment device against a control with no water management or treatment strategy applied. The capacity of each system was measured and compared to determine the total impact that each strategy had on performance. The lower bleed rate system had a capacity decrease of 12% over the course of the experiment, compared to 0% in the high-bleed system. The water savings of the low bleed system compared to the high bleed system made this an interesting treatment to pursue in the second round of ECCU testing. In addition, the low bleed rate significantly reduced the number of pump failures from six to one as compared to the no-bleed case.

Although the change in capacity over time was a useful result, a mass balance of the minerals precipitated from the sump water quality data provided more detailed information on the chemistry of scale formation. Because of its low solubility, calcium was observed to be largely precipitated in all systems in all bleed rates tested. This indicates that in supply water with elevated calcium concentrations, an increased bleed rate may be counterproductive and increase the total mass of scale formed. However, magnesium, with solubility ~1,000 times greater than calcium, was more effectively removed by the bleed. Under no bleed conditions, a vast majority of the magnesium precipitated out, but when a bleed was introduced, the mass and percentage of magnesium precipitated dropped off quickly. At the high bleed condition, magnesium was not found to contribute to mineral scale.

As seen in Figure 33, implementing the low bleed (17%) in the full scale tests reduced the loss of efficiency from 26.0% to 8.7% after 31.9 lb and 28.6 lb of mineral hardness were added to the 3-ton system in each case (due to 2,074 hours of operation in the no-bleed test and 2,027 hours of operation in low-bleed test). In addition, the low bleed eliminated pump failures, reduced basket cleaning requirements, and drastically reduced scale formation on the copper coil from an estimated 27.7lb to 0.7lb. Efforts to recondition the ECCU after running 2,000 hours without a bleed led to no significant improvement (Figure 33). Although the water delivery components could be restored, over 27lb of scale could not be removed from the coil. In contrast, the efficiency of the low bleed system was nearly restored by cleaning the cabinet and drift eliminator, a quick and easy process taking less than 15 minutes (Figure 33). The performance degradation observed in the laboratory tests may vary based on the diameter and relative length of the condenser coil; therefore, scale buildup on an ECCU with a different size coil would not necessarily have the same impact on efficiency of the unit.

Combining the results obtained in the experiments conducted in Davis, CA, a water chemistry model, and water data obtained from municipalities around Southern California resulted in a practical analysis for optimizing the bleed rate and predicting the relative lifetime of evaporative condensers in Southern California. This analysis provides some interesting insights into the influence of bleed rate on scale formation in evaporative condensers. However, this is a preliminary model and more research is needed to improve the model and the optimized bleed rates. Further research is needed to understand the type of crystal structure of formed scale, the pH and salinity of steady state sump water in ECCUs, and the percentage of precipitate that adheres to the condenser coil. Furthermore, additional testing of physical water treatment devices may provide another resource for reducing scale formation. In this study, no benefit was observed from the magnetic treatment device operating on a no bleed system. However, WCEC plans to retest this device with a low bleed employed as it may be more effective when there is the possibility for minerals to be removed from the system.

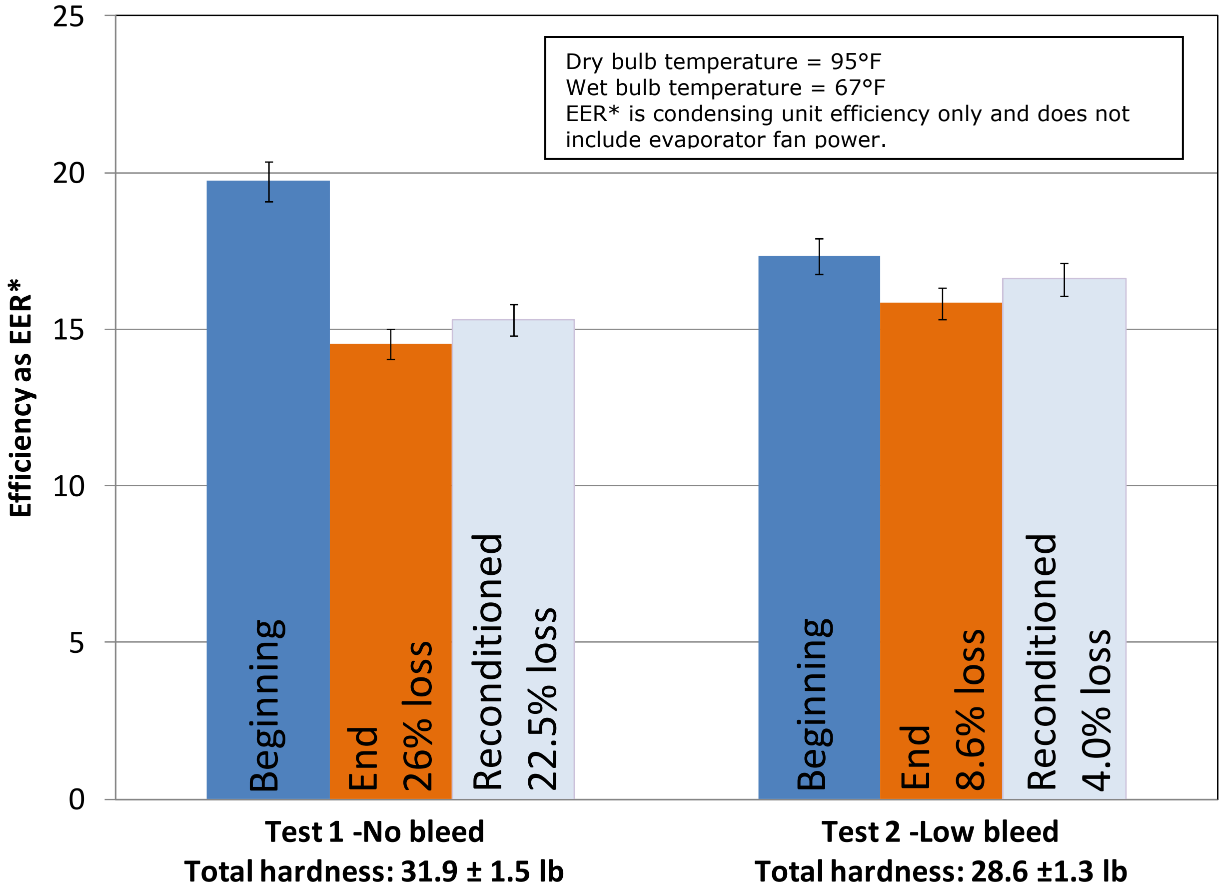


**FIGURE 33. BEGINNING, ENDING, AND REFURBISHED PERFORMANCE OF THE 3-TON ECCU IN TEST 1 AND TEST 2**

# CONCLUSIONS

Testing has found that the ECCU is a robust technology, running at high efficiency even when driven to 25% loss of performance at the end of the no bleed test. Even in the degraded state, the EER is estimated at 12.9 at outdoor conditions 95/66 (°F DB/°F WB) when including an estimated 438 watts for evaporator fan power. In the low bleed case, which used a bleed rate approximately 50% below the manufacturer recommended rate for local tap water hardness, the unit was returned to 96% of original performance with simple cleaning after more than 2,000 hours of use. An analytical model was developed that indicated that ECCUs with a 15% bleed rate are expected to perform as good as or better than the low-bleed laboratory unit in most locations in SCE territory. A higher bleed rate of 36% is the theoretical optimization in the Eastern Water District, however a 15% bleed rate is expected to yield as good or better than the low-bleed laboratory unit. The research confirmed that water management of ECCUs is required, but that the bleed rate may not need to be as high as previously thought, leading to a potential reduction in water use compared to existing manufacturer recommendations.

Perhaps the most significant finding was scale formation's dependence on the specific metals contributing to hardness, which vary with every water source. The rates of precipitation are driven by the varying solubility limits of calcium and magnesium, and while low bleed rates are sufficient to remove most magnesium, there is a spectrum over which increasing the bleed rate appears to actually increase calcium deposition. Further research is required to more fully understand this phenomenon and quantify ideal bleed rates based on water hardness constituents. An analytical model based on existing data demonstrates a wide range of relative ECCU lifetimes.

Several conclusions were drawn specific to the ECCU design and improvements which could lead to a greater operating life span. The first was to increase the perforation size in the protective pump basket. The rationale for having a basket is to reduce the amount of debris, either flakes of scale or organic matter like leaves, which enter the pump and are pushed through the manifold to where they could block nozzles. However, the first cause of failure in both of the ECCU tests was basket clogging, where scale precipitation on the basket constricts cooling water availability to the pump. Larger holes would increase the time before blockage would occur. The second improvement would be to design the spray manifold such that it would more thoroughly drain between cooling cycles. In the current implementation cooling water is left to stand in the manifold causing scale to develop, which then is forced into the nozzles with the next use.

# RECOMMENDATIONS

The documented energy savings potential and the robustness of the ECCU technology support the adoption of this technology into the Energy Efficiency program in Southern California, perhaps with some water district limitations. However, to assure optimum performance and energy efficiency, a maintenance program should be considered as a requirement. In addition to the manufacturer's recommended startup maintenance, which includes sump and basket cleaning and cleaning air intake grills, the following should be completed:

1. Inspection of the water delivery system while the water is on to assure adequate water delivery through the manifold and nozzles. If clogged, the manifold should be cleaned or replaced. Replacement is likely the more economical option.
2. Inspection and cleaning of the drift eliminator to remove scale.

It is estimated that this additional maintenance will take less than 15 minutes, although it should be done by a professional as it involves disconnecting the fan from the system and manually starting the water pump.

This research has potentially uncovered a paradigm-shifting result in that increasing bleed water may increase calcium scale formation while reducing magnesium scale formation. Furthering understanding of the potential scale forming components in the water may play a critical role to optimizing bleed rates in the future.

Although additional research is important and will optimize evaporative cooling water use in Southern California Edison's service territory, the need for this research should not impede the adoption of the ECCU technology. The system is remarkably robust, operating with a reasonable efficiency even when run completely outside of the manufacturer's recommendation with no bleed for 2,000 hours of operation.

For units deployed in SCE territory, we are recommending a 15% bleed rate, a single value that represents a compromise that is consistent with the level of knowledge that we currently possess. It was chosen to be on the high side of the range of optimums because that is the least drastic change from the manufacturer's current practice of using bleed rates of 40% when hardness is greater than 300ppm . Relative to current practice, this bleed rate should improve long-term evaporative-condenser performance in areas with low to moderate magnesium concentrations (Mg<20 mg/L; most of SCE territory). It should also be acknowledged that certain locations, based on their water containing high concentrations of both Ca and Mg, are much less amenable to evaporative condensers. Using the 15% bleed protocol is a promising water management strategy for Mg concentrations less than 20 mg/L and calcium concentrations less than 65 mg/L. Following this recommendation should result in performance as good as or better than the result seen in the Davis laboratory, with minimal loss of efficiency over 2,000 hrs of operation. Relative to current practice, decreased water consumption is a benefit of this recommended bleed rate.

WCEC has proposed to undertake additional research to further validate and expand upon the model presented here. Water quality parameters to be assessed will include: pH, non-carbonate alkalinity (e.g., sulfate, phosphate), calcium, magnesium, and silicon. Although no major benefit was seen from the static magnets, WCEC is planning to re-test them in combination with a low bleed scenario. In addition, future testing will include an electro-magnetic pulsing device and a vortex device, both in combination with low bleed. Those results will be available as a future appendix to this report.

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