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FINAL PROJECT REPORT

INLET AIR SPRAY COOLING ENHANCEMENT FOR AIR-COOLED CONDENSERS

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PREFACE

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ABSTRACT

Given the state’s increasing demands for limited freshwater supplies, dry cooling systems that use an air-cooled condenser that directly rejects the heat from steam condensation to the atmosphere with no consumptive use of water use are an increasingly attractive choice for power plants. The primary limitation of this cooling technology is the inability to maintain desired turbine backpressure during the hottest periods of the year. Increasing turbine backpressure reduces the amount of energy the power plant can produce. Air-cooled condenser inlet spray cooling, consisting of spraying a fine mist of water into the air passing through the condenser, can reduce the capacity penalties associated with increased turbine back pressure during periods of high ambient temperatures and peak electricity demand. This study evaluated the results of field testing of spray enhancement on the 40-cell air-cooled condensers at the Bighorn Power Plant in Primm, Nevada. Flow visualization tests at the Crockett Cogeneration Plant and pilot-scale screening of spray nozzles and mist eliminators were conducted prior to performing the Bighorn Power Plant field tests.

The field tests measured the performance of inlet spray cooling under hot, dry conditions observed the effect of wind on spray behavior and determined the preferred location and arrangement of spray nozzles under windy conditions. Practical aspects of the system were also considered, including liquid rainback from the spray zone, wetting of the finned tube bundles and carryover of spray from the fan inlet zone. Design recommendations were proposed to minimize the problems.

The practical considerations of rainback and unit wetting will likely limit the cooling effect for typical air-cooled condenser designs to no more than 50 F. This is sufficient to significantly reduce the load reduction during the hottest 200 to 300 hours of the year in locations in the Southwestern United States.

Please use the following citation for this report:

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EXECUTIVE SUMMARY

Introduction

Concerns over increasing demands on limited freshwater supplies are resulting in many new power plants being built with dry cooling, both in California and around the world. Unlike many wet power plant cooling systems, which can use significant amounts of water to condense steam used in electricity generation, dry cooling directly rejects the heat from steam condensation to the atmosphere with no consumptive water use. As use of this cooling technology becomes more widespread, the importance of ensuring adequate, predictable power plant cooling performance becomes more critical to the efficient operation of the entire electric grid as well as to individual plants.

The most prevalent dry cooling system utilizes air-cooled condensers in which steam that has passed through the steam turbine is routed through a distribution manifold (pipe) to the top of a series of tubes with fins (to enhance heat transfer) arranged in parallel, inclined bundles forming an elevated A-frame shape. These inclined bundles are referred to as cells and the cells are arranged next to each other. A 500 megawatt (MW) combined cycle power plant might typically have 30 to 40 cells arranged in one of several rectangular layouts.

Steam enters the tubes at the top and as it flows down, heat is transferred through the condenser walls to the atmosphere, causing the steam to condense to water. The condensate continues to run down the tube until it reaches the bottom, where it is collected and returned to the power plant to be re-used. The air flow within the condenser is from the bottom up, with the heated air exiting the condenser at the top. To ensure sufficient air movement, air-cooled condensers rely on a series of large fans with one located beneath each cell to ensure adequate air movement up and through the condenser. The condensers are elevated well above the ground surface to ensure sufficient air flow into the bottom of the condenser.

One concern with air-cooled condenser technology is that it can impose a limitation on plant output during the hottest hours of the year, when power demand is at its peak. One approach to mitigating this concern is to use a small amount of water for a limited period to enhance air-cooled condenser performance at this critical time.

This can be implemented by cooling the inlet air with a fine mist of water sprayed into the inlet air stream. Spray enhancement has the benefit of having low capital costs and can be easily installed on existing air-cooled condensers. The disadvantages of spray enhancement are the relatively inefficient use of the spray water and potential corrosion or scaling of the finned surfaces of the air-cooled condensers. Such damage can lessen the heat transfer ability of the condenser.

Purpose

Previous tests of spray enhancement were conducted at the Crockett Cogeneration Plant. Observation of ad hoc (improvised) systems installed on existing air-cooled condensers by plant owners suggests that the approach is a promising one. Field tests at the Bighorn Power Plant in Primm, Nevada were undertaken with the objective of developing design and operating
guidelines which would address the two primary issues: water use inefficiency from “rainback” out of the spray zone and potential damage to the finned tube bundles.

Project Outcomes

Preliminary screening tests were carried out in preparation for the field tests. These included:

- Nozzles were evaluated to find ones that would produce a reasonably fine spray without requiring high pressures.
- Demisters (devices which remove water droplets from the air) were evaluated as a means of ensuring that the finned tube bundles would remain dry. Since demisters decreases airside pressures and lowers air flow, they were not used.
- Flow visualization tests were conducted at Crockett Co-Generation Plant and at the Big Horn plant to show air flow patterns within a cell. A water mist was sprayed inside the cells of the air-cooled condensers to show air flow patterns and to identify the most suitable location for the spray to target.

For the field test set-up, a single cell was selected and heavily instrumented with temperature probes on the fan bridge (a walkway) just above the fan and in the inlet plane of the finned tube bundles on both faces. The selected cell was an interior one, chosen to be less susceptible to recirculation (heated condenser exhaust air carried back into the bottom of the condenser) or degraded fan performance due to wind effects. Neighboring cells were lightly instrumented to detect carry over from the spray zone underneath the test cell. Spray nozzles were mounted on the structural elements surrounding the test cell at levels of 10, 20 and 30 feet below the fan inlet plane. In additions, four nozzles were suspended from the inlet screen which hangs underneath the fan. These nozzles could be adjusted to from 5 to 15 feet below the screen. Spray flow rate, supply pressure, wind speed and direction and ambient temperature were all continuously monitored.

Tests were conducted on 12 separate days between August 18 and September 16, 2005. Twenty-nine individual runs were recorded at a variety of ambient temperatures, wind conditions, nozzle locations and spray flow rates.

Conclusions and Recommendations

The present test program extended the work at Crockett with field tests at Bighorn by measuring performance under hot, dry atmospheric conditions, observing the effect of wind on spray patterns and documenting the severity of practical operating problems such as rainback, finned tube bundle wetting and wind losses due to spray carryover.

Conclusions from these efforts include:

- Air flows through each cell of an air-cooled condenser of the size used in power plants require the evaporation of approximately 3 gallons per minute of water for each degree of cooling effect. Therefore, spray rates of 15 to 25 gallons per minute per cell are necessary to achieve a significant air inlet temperature reduction of 5°F.
• Spray flow rates in excess of 12 to 15 gallons per minute are less efficient for utilizing the water because of the higher rainback. This upper limit would differ for fans of differing size and air flow and for differing temperature and humidity conditions.

• Flows and nozzles placements which reduce rainback and improve utilization also tend to minimize bundle wetting.

• Under summer weather conditions typical for the Western United States, and for a typical air-cooled condenser design, spray enhancement could be used for approximately 300 hours or more to offset generation reductions due to high temperatures. If the spray enhancement achieved a 5°F cooling effect, that would permit full load operation for nearly all of those hours with increased output of 1,000 to 2,000 megawatt-hours (MWh).

• This study shows that, with the proper choice of nozzle type, location and orientation and the provision of a suitable water treatment facility, acceptable water use efficiency can be achieved and the effects of rainback and the risk of bundle wetting can be kept to acceptable levels. However, the limitations on the extent and duration of tests did not allow us to demonstrate this on a full-scale, long term basis.

The following recommendations are based not only on the measurements and observations made during this study but on the results of previous work at Crockett and on observations at other installations made in the course of plant visits while evaluating possible test sites for this work.

1. Opportunities should be sought to work with plants wishing to try spray enhancement, to encourage them to follow the design recommendations in this report and to observe full scale operation over an extended time.

2. Variations on the approach taken in these tests should be explored. For example, the use of a larger number of smaller nozzles mounted inside the cells has been recommended by an air-cooled condenser vendor as a preferred approach.

3. A systematic comparison of the cost/benefits of spray enhancement with those of a supplementary wet cooling tower should be made for both new unit and retrofit situations.

**Benefits to California**

Given the state’s increasing demands for limited freshwater supplies, air-cooled condensers are an increasingly attractive choice for power plant cooling. By advancing knowledge of how to reduce the effects of high temperatures on air-cooled condenser performance, this research will facilitate greater acceptance of this cooling technology and lessen the effects of electricity generation on limited water supplies.
CHAPTER 1: Introduction

This report documents the conduct of and the results and conclusions drawn from tests of inlet air spray cooling on a full-scale, operating air-cooled condenser at a power plant in the southwestern United States.

Dry cooling of electric power plants is being used with increasing frequency in the United States and around the world. Table 1-1 lists existing and “under construction” ACC installations in the United States. This total generation capacity exceeds 8,500 MW.\(^1\) The first U. S. installation was at Neil Simpson I, a 20 MW coal-fired plant in Gillette, Wyoming, in 1968. Of the 73 existing units listed in Table 1-1, 29 of them have come on-line since 2000 and 57 since 1990.

As the use of dry cooling becomes more widespread, the importance of ensuring adequate, predictable cooling performance becomes more critical to the efficient operation of the plant and eventually to the network. A point of particular concern derives from the fact that air-cooled systems impose their greatest limitation on plant output during the hottest hours of the year, which is precisely the time at which power demand is at its peak. In hot, arid regions, summertime ambient temperatures can reach levels well above 100 °F for extended periods. In order to ensure acceptable performance at these elevated temperatures, either a very large, and hence costly, air-cooled condenser is required or else some means must be found to enhance the performance of a smaller and more economical design during the hot periods of the summer.

One approach to this is the use of supplementary wet cooling in which a small amount of water is used for a limited period to take some of the heat load off the ACC. One approach is the installation of a hybrid wet/dry system in which the heat load is carried by two separate cooling systems; one, a dry system which assumes all or most of the load during most of the year; the other, a parallel wet system to which a portion of the steam flow and hence the heat load is diverted during the hotter periods when the performance of the dry system is limited. While these systems can achieve significant water conservation on an annual basis and maintain acceptable performance through the hot periods, they can have high initial costs as a result of the need for two cooling systems, parallel circulating water loop components, more complex controls and other requirements associated with providing two, nearly independent cooling systems. Although there has been renewed interest in recent years, they have not been widely adopted to date.

An alternative approach, which is the subject of this study, is the enhancement of ACC performance by cooling of the inlet air with water sprayed into the inlet air stream. This approach has the benefit of being a low capital cost system which can be easily installed on conventional ACC’s. Its perceived disadvantages are relatively inefficient use of the spray water compared to a cooling tower component in a full hybrid system and the concern of

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\(^1\) Includes only the output from the steam turbine side of any combined-cycle plants (See Table 1-1)
potential corrosion damage or scaling of the finned surfaces of the ACC through repeated wetting and drying from the impingement of spray droplets on the surfaces. While to our knowledge, no ACC has included spray enhancement capability as part of an original design, many owner/operators have installed spray systems of varying degrees of sophistication on their units to get improved summertime performance.
CHAPTER 2: Basis for Spray Enhancement

This section develops the rationale, technical basis and potential benefits of inlet spray enhancement of air-cooled condensers at steam-electric power plants.

2.1 Power Plant Cooling

A brief review of the function and performance characteristics of power plant cooling systems is presented here for convenience of reference. The function of plant cooling systems is to condense the steam leaving the low-pressure turbine and, in so doing, to maintain the turbine exhaust pressure at an acceptably low level. This is required to maintain high plant efficiency. Figure 2-1 displays typical operating characteristics of turbine heat rate vs. turbine exhaust pressure. Three different turbine characteristics are shown. Curve A is for a so-called “conventional” turbine intended for use with wet cooling; Curve B is a “high backpressure” turbine originally used for dry cooling systems for which very high backpressure operation was expected; and Curve C is an “extended” backpressure design more typical of current designs intended for use with modern air-cooled condensers.

The significance of the turbine characteristics and their consequences for optimum cooling system design will be discussed in later paragraphs.

The turbine exhaust pressure is the saturation pressure of steam corresponding to the temperature at which condensation is taking place. Figure 2-2 displays the saturation line for steam relating the condensing pressure to the condensing temperature.

The condensing temperature is set by the performance of the cooling system at a given steam load (or heat duty) and the temperature (or in some cases the relative humidity) of the cooling medium, which can be air or water.
Figure 2-1: Turbine Heat Rate Characteristics

Turbine Heat Rate Curves

- Conventional
- High Backpressure
- Extended Backpressure

![Turbine Heat Rate Characteristics Graph](image)

Figure 2-2: Steam Saturation Line

Steam Saturation Line

\[ p = 2.369245E-08T^4 - 3.864467E-06T^3 + 4.922033E-04T^2 - 1.923475E-02T + 4.298425E-01 \]

![Steam Saturation Line Graph](image)
2.2 Cooling System Alternatives

Power plant cooling systems can be categorized as wet, dry or hybrid depending on whether the cooling medium is water, air or a combination of the two. Wet cooling systems can be further categorized as once-through or recirculating as described below.

2.2.1 Once-Through Cooling

Until the early 1970’s, most power plants in the U.S. operated with once-through cooling which is illustrated in Figure 2-3a. Steam from the low pressure turbine exhaust flows into a surface (usually shell-and-tube) condenser, where it is condensed on the outer surface of tubes with cooling water running through them. The condensed liquid is returned to the boiler to complete the power cycle.

The cooling water is drawn from some near-by water body (river, lake, ocean or bay) and pumped through the condenser tubes where it is warmed by the heat of condensation. The warmed water is then returned to the environment, usually the same water body from which it was withdrawn. Figure 2-3b shows the relationship of the steam and water temperatures and defines some nomenclature of cooling systems.

Figure 2-3a: Once-Through Cooling System Arrangement

Source: EPRI 2008
Typical operating points for once-through cooling systems are a cooling water flow rate of about 600 to 800 gallons per minute (gpm) per MW and a corresponding temperature rise ($T_{\text{discharge}} - T_{\text{inlet}}$; called the “Range”) of 12 to 18 °F. Condenser designs normally have terminal temperature differences (TTD) of 5 to 10°F.

Source water temperature obviously depends on the type, size and location of the water body. The greatest variability and highest peak temperatures are found in small rivers or shallow bays in southern states. However, peak source temperatures seldom exceed 80 to 85 °F. Therefore, assuming a condenser range of 15 °F and a TTD of 8 °F an 85 °F inlet water temperature would result in a condensing temperature of 108 °F and a corresponding backpressure of ~2.5 in Hga which is an acceptable operating point for conventional turbines. The problem in this instance might be the return of 100 °F discharge water to the source water body without exceeding thermal discharge limits.

During much of the year, source water temperatures are much lower. Source water at 65 °F, typical of coastal ocean water temperature in much of the country would provide a 1.3 in Hga backpressure. Indeed, many turbines at older plants, intended for use with once-through cooling, had design backpressures of 1.0 to 2.0 in Hga. Under some conditions, the recirculating water flow might be lowered to reduce the withdrawal and perhaps reduce the environmental effects of impingement or entrainment while still maintaining an acceptable backpressure.

### 2.2.2 Recirculated Wet Cooling

Recirculated wet cooling is similar to once-through cooling with the exception that the warm condenser discharge flow is not returned directly to the environment but rather is sent to a cooling tower (or pond or canal) where it is cooled through heat rejection to the atmosphere, primarily by evaporation, and then recirculated to the condenser inlet. A small amount of make-up water is added to the system to replace water lost by evaporation and drift and by blowdown. The blowdown is water discharged from the system to control the buildup of
dissolved and suspended solids which are concentrated above the levels in the make-up by the evaporation.

The system arrangement is shown in Figure 2-4a. Recirculated wet cooling systems optimize at lower circulating water flows and higher ranges than once-through cooling systems. A more typical range would be from 15 to 25 °F. Typical approach temperatures, defined as the difference between the cold water temperature leaving the cooling tower and the ambient wet bulb temperature range from 6 to 10 °F for a mechanical-draft cooling tower in warm, humid environments.

The highest wet bulb temperature in hot, humid areas seldom exceeds 80 °F. For a 20 °F range, a 7 °F TTD and an 8 °F approach, the condensing temperature is 115 °F with a corresponding turbine exhaust pressure of ~ 3.0 in Hg. During most of the year, when the ambient wet bulb is lower, reduced backpressure can be achieved although for a fixed tower the approach increases with reduced wet bulb.

**Figure 2-4a: Recirculated Wet Cooling System**

![](image)

**NOTE:** illustrated as a cross-flow tower although most current designs are counterflow

**Source:** EPRI 1989
The important point with regard to both once-through and recirculated wet cooling systems is that the systems can be economically designed to achieve low (<3 in Hg) backpressures at the most demanding environmental conditions. Even if the system design were based on a lower source water or ambient wet bulb temperature, as for example, a summer average value, the variation in these temperatures from a summer average to a 1 percent maximum is relatively small and would result in a modest operating penalties for a few hours per year.

2.2.3 Dry Cooling Systems

Dry cooling systems are most commonly configured as direct, mechanical draft air-cooled condensers. The designation “direct” means that the steam is ducted directly to the air-cooled condenser where it condenses inside finned tubes which are cooled by the passage of ambient air over the external, finned tube surfaces. The arrangement, typical temperature conditions and the nomenclature are illustrated in Figure 2-5a.
Figure 2-5a: Dry Cooling System

Source: EPRI 1989

Figure 2-5b: Dry Cooling System Operating Temperatures
The critical design characteristics for an air-cooled condenser are the Initial Temperature Difference (ITD) and the selected design ambient temperature. Typical choices are the summer average temperature and an ITD of 40 to 45 °F. For a hot, arid site, typical of many for which dry cooling is selected, a summer average temperature of 80 °F and a design ITD of 45 °F give a condensing temperature of 125 °F and a corresponding turbine exhaust pressure of 4. in Hga. However, the variability of dry bulb temperature is much greater than the variability of wet bulb or source water temperature and peak temperatures at hot, arid sites can exceed 110 °F with a corresponding condensing condition of approximately 150 to 155 °F and 7.5 to 8.5 in Hga. Such turbine exhaust pressures approach or exceed the limit of turbine operation (“trip” point). Larger ACC’s with lower ITD’s can be installed. For example, a 30 °F ITD/80 °F ambient design point would maintain the backpressure below 6 in Hga at 110 °F but at significantly higher cost.

2.2.4 Hybrid or Wet/Dry Systems

An obvious alternative to either all-dry or all-wet cooling systems is a hybrid system with both wet and dry components which can operate with significantly lower annual water consumption than a wet system while using some water during the hotter periods of the year to avoid the high backpressure operation of all-dry systems. The potential exists to achieve water conservation, and acceptable hot day performance at moderate cost. There are a number of ways to implement the wet/dry concept. Two of them, a hybrid (full combined ACC/wet tower) system and a spray enhanced ACC are described below.

2.2.5 Hybrid Cooling

Figure 2-6 illustrates schematically a hybrid system in which steam can be condensed in both an ACC and a wet surface condenser/cooling tower. In operation, the system is run dry with the wet tower fans and circulating water pumps shut off until such time as the ambient temperature and the condensing pressure rise beyond desired limits. At that time, the wet system pumps and fans are turned on and a portion of the steam flows naturally to the cold surfaces in the shell-and-tube condenser. The reduction in steam flow to the ACC reduces the condensing temperature in accordance with the approximate relationship that

\[ \text{ITD/Heat Duty} \sim \text{constant} \]

The system is self-balancing at a lower backpressure. A more detailed discussion of hybrid system design optimization and operation is given an EPRI report on cooling system comparisons. At the time of this writing, relatively few hybrid systems are installed and operating. The largest system is at the Tucuman plant, a 450 MW gas-fired, combined-cycle plant, located in Argentina. A 750 MW coal-fired steam plant in Pueblo, Colorado is in the planning and design phase and is expected to use such a system.
2.2.5.1 Spray Enhancement

Spray enhancement, illustrated schematically in Figure 2-7 works by reducing the temperature of the inlet air to the ACC. At an essentially constant ITD, this results in a corresponding reduction in condensing temperature and backpressure. Many owner/operators of existing ACC’s have installed *ad-hoc* retrofits to obtain better hot weather performance. A few of these installations are illustrated in Figures 2-8a through 2-8d.
Figure 2-7: Spray Enhancement System

Source: Maulbetsch 2004

Figure 2-8a: Sprays in Operation at Chinese Station

Figure 2-8b: Spray Nozzle on El Dorado Energy Center ACC
Figure 2-8c: Interior Spray Nozzles in Operation at Crockett Co-Generation
In some cases, such as Chinese Station, the use of the sprays has become routine operation for many years. In others, such as El Dorado, the use of sprays, although effective in reducing hot day backpressure, has been discontinued for a variety of reasons ranging from concern over incipient corrosion or scaling of the finned tube surface to water supply limitations. To my knowledge, no designs for new ACC’s have incorporated this feature.

An extensive pilot study of spray enhancement of a single, air-cooled heat exchanger (not a condenser cell) at the Crockett Co-Generation plant was conducted in 2001 and reported in several references. 2,3,5

Figure 2-9 shows the test spray rig in operation. Figure 2-10 shows performance data from a single test day demonstrating an inlet cooling effect of about 10 ºF or approximately 70 percent of the ambient wet bulb depression (T_{amb} - T_{amb\ wet\ bulb}) . Finally, Figure 2-11 shows a correlation of the data in the form of the cooling effect vs. the spray flow rate times the wet bulb depression.
Figure 2-9: Crockett Spray Tests

Figure 2-10: Spray system Performance at Crockett; September 9, 2001

Average DB Temperature Profiles
Crockett Single-Cell Spray Testing

- Deck DB
- Fan Outlet DB
- S Exch DB
- Glycol
- Deck WB
- Fan Outlet WB
In general, the spray enhancement approach has the advantage of low capital cost compared to a full hybrid system. The disadvantages, however, are the less efficient use of water and potential scaling and corrosion problems. Therefore, the spray enhancement system may be favored for applications where the enhancement would be required for only a few (<100 to 200) hours per year. The full hybrid system would be favored when longer duration enhancement periods (100 to 200 hours) are anticipated. A more detailed consideration of how the breakeven point would be determined more accurately is found in Section 6.

2.3 Current Study

The pilot work at Crockett indicated the range of cooling effect that might be expected, but the results had limitations on their usefulness in guiding the design of a full-scale system. Specifically,

- The ambient conditions at the site during the test period were cooler and more humid than would be expected at a good candidate site for spray enhancement.
- The test rig was deliberately protected from wind effects to obtain a reasonably reliable heat balance for test purposes.
- The nozzles were smaller with low flow (~ 0.1 to 0.4 gpm/nozzle) requiring a large (~100) number of nozzles per cell with attendant likely O&M problems.
- No attempt was made to determine the amount of liquid spray impingement on the finned tube bundles.
Therefore, to develop a body of information for the purpose of designing an optimized full-scale spray enhancement system, tests were planned and conducted on a modern, full-scale operating ACC located at hot, arid site.

2.4 Test Site Description----Bighorn Power Plant and ACC

To this end, a spray enhancement test system was designed, installed and operated on the ACC at Reliant’s Bighorn Power Plant. Figure 2-12 shows an aerial view of Bighorn. It is located in Primm, Nevada just East of Interstate Highway, I-15, on the Nevada side of the California/Nevada line (35.61N/115.39W) at an elevation of 2,800 feet above sea level. The plant is 540 MW gas-fired, combined cycle (2 x 1 configuration) plant which came on-line in 2004.

![Figure 2-12: Aerial View of Bighorn Power Plant](source)

The ACC is a 40 cell unit designed and installed by Hamon (now owned by SPX-Marley). The cells are arranged in two 20 cell clusters each with four streets with five cells (4 condensing cells/1 reflux cell) in each street. Figure 2-13 shows the general layout of the Bighorn ACC as seen looking West from the catwalk near the top of the stack on HRSG #1 (closest to the ACC). It shows the steam duct and risers in the space between the north and south clusters. The
general configuration and the identification of cell location is shown schematically in Figure 2-14. The fans are seven blade, 34 foot diameter Howden fans. The ACC is designed to maintain a 3.79 in Hg turbine exhaust pressure at an ambient temperature of 96 F with a design fan power of 5,190 kW.

Figure 2-13: Steam Duct and Windwall Arrangement at Bighorn
The unit has a porous screen running below the fans at locations identified in Figure 2-14 and shown photographically in Figure 2-15. Windwalls surround the A-frame heat exchanger bundles. The west windwall is extended as narrow wings from grade level to the top of the windwall on the north and south ends. (See Figures 2-13 and 2-14) While the porous screen and the wind wings were installed for cosmetic purposes and not as wind control devices, they obviously affect the flow of the wind under and around the ACC.
Figure 2-15: Porous Screen Beneath ACC Cells
The meteorological conditions are typical of the Southwester US in the Las Vegas area. Complete meteorological data is given in Appendix A. The temperatures exceed 90 F for approximately 1,200 hours per year with median extreme highs of 112 F. The site temperature duration curve and wind rose are shown in Figures 2-16a and 2-16b. The summer winds are primarily from the South/Southwest frequently exceeding 15 to 20 miles per hour.

Figure 2-16a: Temperature Duration Curve at Bighorn

![Temperature Duration Curve at Bighorn](image)

Source: National Climate Data Center 2000
With reference to Figure 2-12, it is seen that the ACC is aligned essentially North/South with the evaporation pond on the West. The other plant structures are all to the East of the ACC. The HRSG’s off the Southeast wall of the ACC are the tallest obstructions. The combustion turbine buildings and other plant structures to the North and further to the East of the HRSG’s are lower and provide less obstruction. Wind from the South, West or North is unobstructed in its approach to the ACC. The low structure at the North end of the ACC is an air-cooled auxiliary heat exchanger with the potential for discharging hot air into the ACC inlet when winds come from the North.

### 2.5 Test Objectives

The intent of the tests was to

- Determine cooling performance of spray enhancement under hot, dry conditions
- Explore nozzle type, nozzle arrangement and orientation to maximize the efficiency of water utilization by reducing rainback or the falling out of spray droplets from the inlet air stream
- Determine the effect of wind on the preferred nozzle type, arrangement and orientation
- Explore the possibility of using demisters to capture spray liquid that would otherwise wet the finned tube bundle
• Consider the costs and benefits of water treatment alternatives which would eliminate or minimize the risk of danger to the ACC finned tube bundles in the event of tube bundle wetting.

• In addition, several preliminary tests were carried out in preparation for the field tests
CHAPTER 3: Preliminary Testing and Field Test Set-up

This section presents the preliminary screening and flow modeling work which supported the design of the spray enhancement field testing and then describes the spray test apparatus and instrumentation installed and operated at Bighorn.

The preliminary tests, carried out in preparation for the field tests, included

- Nozzle screening and selection
- Demister screening
- Flow/spray visualization inside ACC cells at the Crockett Co-Generation plant
- Flow/spray visualization under windy conditions beneath the Bighorn ACC.

3.1 Nozzle Screening

The pilot spray tests at Crockett [EPRI, California Energy Commission, et al. 2003 #10] had been conducted with small (1/4" NPT; 0.1 to 0.4 gpm) nozzles of several different designs. However, achieving a cooling effect of 10 to 15 ºF in an air stream of 1.0 to 1.5 million acfm (typical of full-scale ACC 10-meter fans) requires evaporating up to 25 gpm per fan, thus requiring 60 to 250 of the small nozzles per fan. This is clearly unacceptable from an O&M standpoint, so nozzles were sought which would produce a reasonably fine spray at supply pressures of 250 to 400 psi while delivering to 5 gpm.

A series of simple test runs were performed on a test stand at EnviroCare, International in American Canyon, California. Figure 3-1 shows the test stand in operation. The nozzles were evaluated qualitatively based on visual observations and “feeling” the spray by hand. This technique, when carried out by experienced observers such as the technical staff at EnviroCare gives a good indication of droplet size and uniformity. In addition the behavior of the plume in wind currents was observed. A balance was sought between a spray of very fine droplets which would evaporate quickly but be blown around uncontrollably by the wind and droplets so coarse that they would not evaporate before hitting ACC structural members or the finned tube bundles.

In addition, nozzles producing varying spray cone angles from a flat spray (180 º cone angle—See Figure 3-1) which simply “lays the spray out” in a layer below the fan to a directed spray (30 to 60º cone angle—See Figure 3-2) which could point the spray at a selected portion of the fan inlet or orient it with respect to the wind direction. Nozzle types varied from internal swirl nozzles (Figure 3-3a) to a “pigtail” nozzle (Figure 3-3b).
Figure 3-1: Flat Spray Nozzle (180° Cone Angle)

Figure 3-2: Directed Spray Nozzle (30 to 60° Cone Angle)
The nozzles chosen for the flow visualization and field testing are listed in Table 3.1.
Table 3-1: Test Nozzles

<table>
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<tr>
<th>Nozzle Type/Designation</th>
<th>Spray pattern</th>
<th>Flow, gpm (@300 psig)</th>
<th>Drop Size, μ (Sauter mean diameter)*</th>
<th>Test location</th>
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<tr>
<td>Internal swirl/HM WL-30° (FC)</td>
<td>30° full cone</td>
<td>2.5</td>
<td>50</td>
<td>On structural elements</td>
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<tr>
<td>Spiral/SM 3-FHC</td>
<td>Radial spray</td>
<td>3.5</td>
<td>70</td>
<td>Below fans</td>
</tr>
</tbody>
</table>

* Sauter mean diameter is defined as the diameter of a sphere that has the same surface area to volume ratio as a particle of interest.

3.2 Demister Screening

One of the important concerns over the use of inlet air spray cooling for air-cooled condenser (ACC) performance enhancement is the potential for corrosion or scaling of the finned tube bundles. This may result if unevaporated spray reaches the tube bundles and wets the surfaces. Repeated wetting and drying can lead to deposition of dissolved or suspended solids in the spray droplets or to corrosion for certain combinations of water chemistry and surface material.

This problem might be addressed in several ways including ensuring complete evaporation of the drops before they reach the tube bundles, exercising careful control over spray water quality or intercepting the droplets before they reach the tube bundles.

Ensuring complete evaporation is difficult. It requires producing a very fine mist and providing a long residence time between the nozzle and the tube bundles. Production of a fine mist typically requires high pressure (~1,000 psi or higher) and low-flow (less than 0.1 gpm per nozzle) nozzles both of which lead to high system cost and pumping power requirements.

Long residence times can be achieved through proper placement of the nozzles but this may result in losing spray to air that never enters the cells or to impingement on ACC structure. In either case, the cooling benefit of some portion of the spray is lost.

Water quality control requires the use of treatment equipment such as reverse osmosis or deionization which adds to the cost and power requirements for the system and produce waste steam which must be disposed of at further cost.

The approach of intercepting any unevaporated droplets just before they reach the tube bundles might be achieved with the installation of demister panels on the inlet face of the tube bundles, as shown in Figure 3-4.
This approach has some attractive features and some important drawbacks. The advantages include:

Relatively coarse spray from a few low-pressure (200 to 400 psi), high flow (1 to 5 gpm) nozzles could be used enabling a low capital cost system.

The nozzles could be located above (downstream) of the fans for easy installation and maintenance.

Within reason, low quality water could be used so long as any serious maintenance problems on the demister panels themselves were avoided.

All of these attributes would reduce the cost and power requirements of the spray enhancement system. On the other hand, the permanent installation of demister panels at the tube bundle inlet plane has disadvantages.

- Each cell has nominally 3,000 to 4,000 square feet of tube bundle frontal area. The purchase and installation would be a significant cost, particularly in a retrofit situation where no provision for attaching the panels would have been made in the original design.
• The presence of the panels would add to the air-side pressure drop and required fan power. Again, in a retrofit situation, the fan selection and heat exchanger design would not have been optimized for this additional pressure drop and the resulting performance and power penalties would likely be higher than if the approach had been included in the original design. It is a further drawback that this pressure drop/fan power penalty exists for every hour of operation throughout the year even though the spray system might only be used for a small portion of the year.

• The presence of demister panels will introduce maintenance requirements and may make the routine cleaning of the finned tube bundles more difficult.

Preliminary tests were conducted at EnviroCare facilities in American Canyon, California to screen a number of candidate demister panels and to evaluate the potential for their use in a full scale system. The test facility for the screening tests is shown in Figures 3-5 and 3-6. The essential information to be obtained from the tests included:

1. Assurance that the panels would prevent droplets from reaching the tube bundle over the range of air velocities and water loadings expected for a spray-enhanced ACC.

2. Evidence that rainback from the front surfaces of the demister panels would be minimal.

3. Evidence that the collected water would be drained internally through the panels to a central collection point for recycle.

4. An estimate of the pressure drop and fan power added by the presence of a demister panel.
Figure 3-5: Photograph of Demister Test Rig

Figure 3-6: Photograph of Demister Panel Mounted in Test Rig
The complete report of the screening testing is included as Appendix B. The conclusions and recommendation are repeated here for convenience of reference.

It would be possible to select a demister which could be mounted at the inlet plane of the ACC tube bundles that would provide satisfactory protection to the finned tubes against repeated wetting and drying. This would permit the use of low quality water and coarser spray nozzles while eliminating the risk of corrosion or scaling.

It is likely that a satisfactory drainable and collection arrangement could be designed which would maintain acceptably dry conditions in the interior of the A-frame and recover the water for reuse.

The disadvantages would be

1. An increase in fan power over the entire year of about 10 percent. We assumed that the demisters would stay in place all year long because it would be costly to remove and re-install them every year.

2. A significant increase in the cost of an inlet spray enhancement system for retrofit situations. For a plausible installed material cost of $3.00 to $5.00 per square foot, the cost for a 30 cell ACC would exceed $240,000 to $400,000 plus a high installation cost to mount the panels in an existing cell. (If a new unit were so equipped, the installation cost would likely be substantially reduced.)

The use of demisters as part of a spray enhancement system would appear to be a “solution of last resort”. For the purposes of this study, attention was turned to minimizing the cost of any necessary water treatment system and optimizing the choice and location of nozzles to minimize surface wetting. However, if it should be necessary, the use of demisters has been shown to be technically feasible if the benefits of spray enhancement are sufficiently high to warrant it.

### 3.3 Flow Visualization---Crockett Co-Generation Plant

Flow visualization tests were conducted inside a cell at the Crockett Co-Generation plant using a hand-held spray wand. Spray was injected into the airflow from the fan-bridge at various locations and orientations. Some example flow patterns are shown in Figures 3-7 and 3-8. A vortex flow pattern was observed and is shown schematically in Figure 3-9.
Figure 3-7: Spray Flow Visualization at Crockett ACC (Flow Turning Down)

Figure 3-8: Spray Flow Visualization at Crockett ACC (Flow Turning Up)
A complete report on these flow visualization tests is included as Appendix C. The essential conclusions are repeated here for convenience of reference.

- Water sprayed from a single hand-held nozzle is a useful means for flow visualization.
- The injection of spray into the air flow above the fan at varying locations along the fan bridge, at varying heights above and below the fan bridge and at varying angles allowed a consistent picture of the flow pattern inside the ACC cell to be determined. (See Figures 3-7 and 3-8)
- The fan rotates in a clock-wise direction (looking down from the top) and imparts a general swirl flow to the air passing through the cell. The flow is highly unsteady but is generally ordered as follows:
  - in the lower part of the cell the flow rotates in a toroidal pattern with a secondary (also clockwise looking in the direction of the primary swirl) rotation;
  - in the upper part of the cell (above the cross structural members) the flow is primarily upward and turns outward toward the upper portion of the tube bundles. The resulting pattern is shown schematically in Figure 3-9.
This flow pattern can be exploited to obtain both longer residence times for spray droplets and to minimize the amount of unevaporated liquid impinging on the finned tube bundles.

3.4 Flow Visualization---Bighorn ACC

A similar flow visualization approach was used at Bighorn both inside and underneath the cells.

3.4.1 Interior Sprays

A few tests were attempted within the cells. The Bighorn fans, which were higher speed and had simple straight blades as opposed to the low speed, highly twisted and pitched blades on the very low noise fans at Crockett imparted less swirl to the flow and the trapped vortex with the toroidal flow pattern was not detectable. Spray injected into the air stream from the fan bridge at Bighorn was immediately entrained and flowed essentially straight up and out toward the finned tube bundles as shown in Figure 3-10a. As a result there was no opportunity to “sequester” the spray in a trapped vortex to extend the residence time as was possible at Crockett. Therefore, the decision was made to place all of the nozzles for the test program outside of and underneath the fan deck as shown in Figure 3-10b.
Figure 3-10a: Spraying Inside Cell 2I at Bighorn
3.5 Field Test Apparatus

3.5.1 Test Cell Location

The field testing of the spray enhancement system was conducted at Reliant’s Bighorn Power Plant in Primm, Nevada described in Section 2.4. The primary test cell is Cell 2I in Street 2 (1st street East of the screen) and Row I (2nd row in from the South end). Figure 3-11 reproduces the schematic layout of the ACC (from Figure 2-14 and shown here for convenience of reference) showing the location of Cell 2I.

Cell 2I was selected for several reasons.

1. It is an interior cell and therefore less susceptible to hot plume recirculation and degradation of fan performance due to winds. As a result, the cell performance is expected to have steadier short term behavior.

2. It is near the end of the South cluster and exposed to the prevailing southerly winds during the test period. This is important to observe the effect of wind on spray pattern distribution.
3. The fan operating protocol at the plant operates the “I row” at full speed more consistently than the neighboring “H row” or “J-row”.

4. Cell 2I is more conveniently located to the entrance of the MCC building for the South cluster where the data acquisition computer could be located.

**Figure 3-11: Schematic of ACC and Cell 2I Location**

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**3.5.2 Spray Delivery System**

Reverse osmosis permeate was taken from the plant’s water treatment plant and stored in two 28,000 gallon storage tanks (See Figure 3-12) leased for the duration of the tests. Water was pumped from the tanks with a 5 HP Grundfus centrifugal pump and delivered to the spray system through flexible high pressure hoses. (See Figure 3-13) The hoses were run up each of the structural columns at the four corners of Cell 2I. Banks of valves at the base of each column were used to turn on nozzles at different levels below the fan and on different sides of the cell. (See Figure 3-14)
Figure 3-12: Water Storage Tanks

Figure 3-13: Spray Pump and Hoses
3.5.3 Nozzle Locations

The general arrangement of the structural columns and beams supporting the ACC cells can be seen in Figures 2-15 and 3-10. The fan deck is 60 feet above grade. The intermediate horizontal beams are at 40 feet and 20 feet above grade. Between each of the levels there are sets of diagonal braces running from the intersection of the vertical columns and the horizontal beams up to the mid-point of the horizontal beam at the next level.

Twenty-four nozzles, eight at each of three levels,

- Level 1---60 feet (horizontal beam at the fan deck)
- Level 2---50 feet (mid-point of diagonal beams between 40’ and 60’ horizontal beams)
- Level 3---40 feet (horizontal beam at 40’ level)

are located at horizontal positions approximately 1/3 and 2/3 of the column spacing. These positions are shown in Figure 3-15. The nozzles could be turned on two at a time at any of the three levels on each of the four sides.
Four additional nozzles were suspended from the small beams supporting the bird screen below the fan as shown in Figure 3-16. The supporting pipes were segmented so that the nozzles could be set a 5, 10 or 15 feet below the screen. All of the four “under fan” nozzles were controlled with a single valve and had to be on or off together.
3.5.4 Instrumentation and Measurements

Instrumentation was deployed on and around the ACC to determine the amount of cooling in Cell 2I, the fate of spray that was blown to other cells, the occurrence and pattern of wetting of the finned tube surfaces in Cell 2I and the ambient temperature, wet bulb, wind speed and wind direction. The spray flow rate and nozzle supply pressure were also measured.

Ambient Conditions

The locations of the ambient measurement points are shown in Figure 3-11. Far-field temperature and wet bulb measurements were made with dry and wet-bulb aspirating psychrometers mounted on the plant boundary fence approximately 200 feet south of the ACC. The psychrometers were approximately five feet above grade and positioned in three locations, southwest, south and southeast of the south end of the ACC.

Wind speed and direction were measured at the boundary fence, approximately 20 feet above grade, roughly in line with the west side of the ACC. The North-south axis of measurement was aligned with “Plant North” and coincided with the street direction of the ACC.
Figure 3-17: Perimeter Strings for Inlet Temperature Measurements
Twelve additional ambient (or ACC inlet) temperature measurements were made at three levels at each of four positions on the perimeter of the ACC. These positions are shown schematically in Figure 3-11 and photographically in Figure 3-17.

Cell 2I Temperatures

Cell 2I was heavily instrumented to obtain a detailed picture of the cooling effect, its variation around the cell and the distribution of liquid spray across the fan opening and on the finned tube bundle inlet planes. A total of the 26 measurement points were monitored.

- Four unshielded temperature probes were fastened to the side of the fan bridge at the walkway level, approximately five feet above the fan deck. They were positioned on opposite sides of the walkway, approximately 2/3's of the way from the hub of the fan blade to the tip on both North and South of the fan center, as shown in Figure 3-18a.

- Four additional probes, shielded in aspirating psychrometers, were fastened to the upper handrail of the fan bridge, approximately 4 feet above the walkway, as shown in Figure 3-18b. This was an attempt to protect the probes from liquid impingement of spray droplets. (Note that wetted probes read the local wet bulb temperature rather than the local air temperature.)

- Eighteen probes were located in 3 x 3 arrays centered on each face of the cell. They were positioned by being pushed through the finned passages from the outside so that the probe tip protruded approximately 2 inches beyond the inlet plane of the finned tube bundles. The locations on the East and West faces are shown in Figures 3-19a and -19b.
Figure 3-18a: Unshielded Probe Locations in Cell 2I

Psychrometer & Probe Locations – Plan View
ACC Cell 2I, Big Horn
Figure 3-18b: Shielded Probe Locations in Cell 2I

Psychrometer & Probe Locations - Elevation
ACC Cell 2I, Big Horn

Figure 3-19a: Finned Tube Bundle Face Probes---East Face
Adjoining Cells

A single, unshielded probe was installed on the side of the fan bridge at the walkway level in each of the cells surrounding Cell 2I; namely Cells 1H, 1I, 1J, 2H, 2J, 3H, 3I and 3J, as shown in Figure 3-18. Each was positioned on the West side of the fan bridge approximately 2/3s of the way from the hub to the tip of the fan blades in the South half of the cells.

Spray Conditions

The spray flow rate and nozzle spray pressure were measured at the outlet of the spray pump as seen in Figure 3-13.
CHAPTER 4:
Test Results

The following section provides a description of the tests that were run and results obtained.

4.1 Test Runs

The spray tests were conducted between August 18 and September 16, 2005 on 12 separate days. Typically two or three distinct runs were conducted on each day for a total of 29 runs. Whenever possible the tests were conducted at times when all the ACC fans (or at least all the fans in the cells neighboring Cell 2I) were running at full speed. A test run is defined as a given selection of nozzles running at a constant flow rate. The duration of a run, typically 45 to 60 minutes, was determined by the length of time required to reach a “steady state”.

“Steady state” is a subjective determination, based on the following considerations. Prior to the start of a run, the interior of Cell 2I and the surrounding structural members were dry. Exceptions were occasional puddles of water on the fan deck inside Cell 2I, typically in the Northeast and sometime the Southwest corners. The cell floor is an essentially stagnant region allowing small puddles to persist for an hour or more after sprays are turned off. The amount of water, however, is negligibly small (less than 5 gallons) compared to the total water sprayed during a test run and has no effect on the performance.

After the spray is turned on, droplets impinge on the structure, both inside and below Cell 2I and some of the neighboring cells. As water builds up on the wetted surfaces, the processes of evaporation, re-entrainment and drainage increase until a dynamic equilibrium is attained. At this time, the amount of evaporation contributing to the cooling of the air was considered to have reached an equilibrium condition. This condition was identified by qualitative observation of the liquid accumulation on the ACC structural members and the amount of water falling back to the ground, equipment and buildings under the sprayed region of the ACC.

During some runs, there was significant and persistent change in the wind conditions (as opposed to minute-to-minute variability which was always the case) which altered the spray trajectories and the build-up patterns. In these instances, the data from the test period was segmented into two or more sub-runs to see if obvious wind effects could be detected.

Table 4-1 lists each of the runs by date and time, the spray flow rate and pressure, the nozzles that were turned on during each run and a qualitative assessment of the wind conditions.
### Table 4-1: Test Conditions Summary (Continued)

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<th>Date</th>
<th>Test #</th>
<th>Start Time</th>
<th>Stop Time</th>
<th>Duration</th>
<th>Flow Rate @ Fan Press</th>
<th>Temp</th>
<th>Average Wind Speed, mph</th>
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### Table 4-1: Test Conditions Summary

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<th>Date</th>
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<th>Temp</th>
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<td>14.30</td>
<td>NE</td>
<td>14.00</td>
</tr>
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</table>

### Notes:
1. Below-fan nozzles were changed from ___ to ___.
2. 13:30- fans 3A, 3B, 3C, 3D, 3E at full speed.
3. 14:50 - data logger was not operating.
4. Flow ranged from ___ to ___.
5. Flow rate was not calculated because data logger was not operating.
6. This test run was plagued with more detail.
7. Wind direction and/or wind speed data not available.
8. Wind direction and/or wind speed data not available.

---

### Table 4-1: Test Conditions Summary (Continued)

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<th>Date</th>
<th>Test #</th>
<th>Start Time</th>
<th>Stop Time</th>
<th>Duration</th>
<th>Flow Rate @ Fan Press</th>
<th>Temp</th>
<th>Average Wind Speed, mph</th>
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### Notes:
1. Below-fan nozzles were changed from ___ to ___.
2. 13:30 - fans 3A, 3B, 3C, 3D, 3E at full speed.
3. 14:50 - data logger was not operating.
4. Flow ranged from ___ to ___.
5. Flow rate was not calculated because data logger was not operating.
6. This test run was plagued with more detail.
7. Wind direction and/or wind speed data not available.
8. Wind direction and/or wind speed data not available.
4.2 Test Measurements

As described in detail in Section 3, project test measurements were made of ambient conditions including wind speed and direction and ambient dry- and wet-bulb temperature and of air temperatures at several locations in test cell 2I and in the eight neighboring cells. In addition weather and plant operating data were obtained throughout the test periods from the plant data acquisition systems.

Table 4-2 gives an example of the project test data printouts for a 15 minute period on August 19, 2005. Tables 4-3 and 4-4 display the plant met and operating data respectively for the corresponding period. Field observations were also recorded for each test period. Examples are given in Table 4-5.

In addition, both still photographs and video footage were taken of spray operating conditions, primarily wind driven spray patterns and evidence of rainback from the spray zone, at different times during the tests. The video is accompanied by a running narrative of conditions and observations. Some of the photographs will be used in later sections as part of the data analysis discussion. A complete set of all data is available in CD/DVD format from the California Energy Commission or this report’s authors upon request.
### Table 4-2: Project Test Data

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54
### Table 4-3: Data from Plant Meteorological Tower

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Plus status report on all fans (0-off; 2-half speed; 4-full speed)
### Table 4-4: Plant Operating Data

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<th>Steam to LP Turbine Flow k#/hr</th>
<th>Bypass Flow k#/hr</th>
<th>LP Sprhtr Flow k#/hr</th>
<th>Amb Air Temp-ACC F</th>
<th>Amb Air Temp-Adm F</th>
<th>ACC BP *Hg</th>
<th>Status</th>
<th>Test Fan</th>
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### 4.3 Inlet Temperature Measurements

In order to determine the cooling effect of the spray, it is necessary to define an appropriate “unsprayed” inlet temperature or the temperature of the inlet air upstream of the spray zone. The total cooling effect for most test conditions is only 5 to 10 F. Therefore, a small inconsistency or variability in the determination of this base temperature leads to significant uncertainty in the calculation of the cooling effect. A consistent measurement of the pre-spray inlet air temperature proved to be problematic.

Temperature measurements were taken at several locations external to and inside of Cell 2I in an attempt to define the appropriate “cell inlet temperature” from which to measure the cooling effect of the spray. Figure 4-1 plots these temperatures taken for a brief period on August 25, 2005 before the sprays were turned on. The differences and trends exhibited during this period are representative of “non-spray” measurements made throughout the test period. The location of the measurement points external to Cell 2I are shown in Figure 3-11; those inside Cell 2I are shown in Figures 3-18 and 3-19.
Figure 4-1: Ambient/inlet temperature measurements Tests

August 25, 2005--Inlet Temperatures

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<th>Time</th>
<th>Temperature, F</th>
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</tr>
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<td>94</td>
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Table 4-5: Example Field Notes for Spray

Field test notes: August 19, 2005

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<th>Pressure psi</th>
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<th>SW Col</th>
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<td>330</td>
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<td>M</td>
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<td>---</td>
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<td>Strong</td>
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<td>330</td>
<td>U</td>
<td>M &amp; L</td>
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<td>---</td>
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<td>South</td>
<td>Strong</td>
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</tbody>
</table>

Test 1 Narrative.....
Getting lots of rainback.
Mid sprays are most utilized.
Low spray is being drawn to 2H.
Uppers sprays also being drawn into 2I (like mid sprays).
Rainback progressively more - mostly on MCC.

Test 2 Narrative.....
Upper sprays by wind screen being drawn into fan.
Some of the spray being blown toward 1H & 2H.
As time proceeds, rainback increases as iron gets wet.
Slight shift in wind - upper SW wetting wind curtain.
JSM thinks 98% of spray evaporating - I think 90-95%.
Standing water on floor in 2I plenum. HX walls wet in areas.
Can feel mist in 2H, but handrails are dry.

................
The following observations are relevant.

- The “plant met data” were 5 minute averages taken at Bighorn’s weather tower. The tower is located several hundred yards west of the ACC (not shown in Figure 3-11) in an open area with no obstructions to wind flow. The temperature sensor is 10 meters above grade and well shielded from solar radiation. The readings are consistently 0.5 to 1.0°F lower than the lowest readings taken on or in the ACC.

- The “Fence” points were taken with aspirating psychrometers mounted on the plant fence about 5 feet above grade. The ground covering at the base of the fence is a thick layer of grey rock (1 to 2” gravel) which is essentially a black body to incoming radiation. The surface gets very hot in direct sunlight and produces high readings near the ground. The “fence” readings were consistently 2 to 3°F above the highest readings on or in the ACC and 5 to 7°F above the “plant met data”.

- Readings were taken with aspirating psychrometers at four positions (denoted as W, SW, SE and E in Figure 3-11) on the perimeter of the South end of the ACC at three levels (10, 30 and 50 feet above grade) at each position for a total of 12 measurements. The “10 foot elevation” readings are consistently higher than the others for the same reasons as were discussed above for the “fence” readings. They are lower than the “fence” readings both because of being higher above grade and because the rock layer around the edge of the ACC is frequently shaded by neighboring buildings or the ACC itself.

- The remaining readings from the perimeter probes at the 30 and 50 foot elevations and from the shielded and unshielded probes inside Cell 2I are all clustered in a range of approximately +/- 0.5°F.

- The lowest readings and those showing the least point-to-point variability are from the aspirating psychrometer probes inside Cell 2I. Of all the probes, they are the least affected by radiation effects either from solar radiation or from the hot tube bundles on the sides of the cells.

The points plotted in Figure 4-2 are the temperatures of each of the four shielded probes inside Cell 2I along with the average of the four readings.

- The maximum difference among the four probes is about 0.5 to 0.7°F and the greatest deviation from the average is less than 0.4°F.

- The two probes in the North half of the cell are consistently warmer by about 0.4°F than the two probes in the South half. There is no immediately obvious explanation for this difference.

Figure 4-3 is the corresponding plot (the four individual temperatures plus the average) for the unshielded probes inside Cell 2I. The temperature, the variability and the probe-to-probe differences are all slightly higher for the unshielded probes. The Southeast probe shows the most deviation from the average.
Figure 4-4 compares the averages of the shielded and the unshielded probes. The shielded probe readings are steadier and less variable. This is due presumably to the sampling of a greater air volume by the aspirating psychrometers and the resultant smoothing out of very localized temperature variations.

Figure 4-2: Shielded Probe Measurements Inside Cell 2I

Figure 4-3: Unshielded Probe Measurements Inside Cell 2I

Figure 4-4: Comparison of Shielded and Unshielded Probe Averages
Figure 4-5 plots readings from each of the eight cells neighboring Cell 2I along with the averages of the Cell 2I unshielded probes.

Each measurement from the neighboring cells is from a single, unshielded probe. Most of the interior cells cluster within a range of approximately +/- 1.0 F of the Cell 2I average. The cells on the south end of the ACC (Row J) are most susceptible to recirculation or interference with fan performance from winds blowing from the South.
The greatest excursions, particularly in Cells 1J and 2J, appear to be associated with periods of higher wind speed, particularly when the wind is from slightly West of South, as shown by comparing Figures 4-5 and 4-6.

Cell 1H on the East side of the ACC also appears to have recirculation and hence higher inlet temperature when the wind moves slightly West of South. From this direction the wind would be most likely to create a wake zone and downdraft on the East side.

As a result of the recirculation to the edge and corner cells, the average temperature of the neighboring cell inlet air streams is sometimes significantly (2.5 to 3.5 °F) higher than the average of the shielded probes inside Cell 2I as shown in Figure 4-7.

Figure 4-6: Wind Conditions During Non-Spray Period

Wind Conditions

Figure 4-6: Wind Conditions During Non-Spray Period

Wind Conditions

- Wind speed
- Wind direction
Additional temperature measurements were taken tight at the inlet plane of the finned tube bundles. Nine temperature probes on each face were pushed through the finned tube bundles with the tip penetrating 2 to 3” beyond the bundle inlet plane. The probes were arranged as shown in Figures 3-19a and 3-19b. Figures 4-8 and 4-9 display the individual temperature readings on the West and East faces respectively.
Several points are noteworthy.

- On the West face (Figure 4-8) three temperature readings are significantly different from the other six. This was found to be the result of probe slippage under the weight of the probe wire on the outside of the tube bundle. The probe tip would be pulled back into the bundle between the fins and read a higher temperature. Three elevated reading were omitted from the calculation of the averages displayed in Figure 4-10. The remaining six readings were tightly clustered within ~ +/- 0.5 F.

- On the East face (Figure 4-9), there is more variation but with obvious outliers with the possible exception of E7.

- The East face average temperature is slightly (~ 0.5F) lower than the West face average as shown in Figure 4-10. Both compare reasonable well with the average of the four shielded probes at the fan bridge level but show significantly more variability with peak-to-valley swings of 0.5 to 1.0 F.
On the basis of these comparisons, the best choice for a consistent steady base inlet temperature would be the average readings of the shielded probes in Cell 2I. However, they cannot be used to measure ambient inlet air temperature during the spray periods since they are downstream of the spray nozzles and will be subject to at least a fraction of the cooling effect when the spray is on.

An alternative approach is based on the following reasoning. The tests are run, as described in Section 4.1, with periods of spray separated by drying out periods. It is possible to create reasonable extrapolations of the shielded inlet temperature readings from the preceding dry period to the succeeding dry period and, in so doing to bridge the spray period with an accurate estimate of what the cell 2I inlet temperature would be if the sprays were not operating. This is illustrated schematically in Figure 4-11.
4.4 Cooling Effect Determination

Determination of the spray cooling effect requires a measurement of the air temperature downstream of the spray zone as it approaches the inlet of the finned tube heat exchangers. Probes in or downstream of spray zone are subject to wetting by unevaporated droplets. Under these conditions they read the local wet bulb temperature which is lower that the local dry bulb temperature of the most air and is not a measure of the cooling effect.

The probes most likely to remain dry are those shielded in the aspirating psychrometers, and they are used to measure the cooled air temperature. The four shielded probes mounted at the fan bridge handrail level in Cell 2I are averaged to estimate the cooled air temperature at that location. The cooling effect is then calculated as the difference in temperature between the pre-spray inlet air and the average of the four shielded probes during the spray period.

As discussed in the previous section and illustrated schematically in Figure 4-11, the pre-spray air temperature is estimated by extrapolation across the spray period of the shielded probe readings taken before and after the spray period.
Figure 4-12 illustrates this with actual data from Run #14, Test #1, a 55 minute test on September 7, 2005 from 11:15 am to 12:10 pm. The average cooling effect, as defined by Figure 4-12, is displayed in Figure 4-13.

The conditions during the test period were the following:

- Nozzle arrangement:
- “Below screen” umbrella nozzles located 5 feet below the screen (See Figure 3-16)
- Spray flow rate: 12.5 gpm
- Spray pump pressure: 340 psig

The wind speed and direction during the test run are displayed in Figure 4-14. Figure 4-15 plots the cooling effect for each of the four shielded probes separately.

Figure 4-12: Extrapolated Cell 2I Inlet Temperatures (September 7, Run #14, Test #1)
Figure 4-13: Cell 2I Average Cooling Effect (September 7, Run #14, Test #1)

Spray Testing 09/07/2005
Big Horn, Primm, NV

![Graph showing Cell 2I Cooling Effect with maximum effect at 12.5 gpm and average effect during steady state spray period.]

Figure 4-14: Ambient Wind Speed and Direction (September 7, Run #14, Test #1)

Spray Testing - 09/07/2005
Big Horn, Primm, NV

![Graph showing wind direction and speed with different wind directions marked.]

Cell 2I Cooling Effect, F

Maximum cooling effect at 12.5 gpm
Average cooling effect during steady state spray period
Figure 4-13 indicates that for the given test conditions an average cooling effect of 3.2 F out of a maximum cooling effect of 4.8 F was achieved. This corresponds to a spray cooling effect of about 67 percent. This maximum cooling effect is determined by assuming that all of the spray flow is evaporated and entirely contained in the air stream entering Cell 2I. Neither of these situations normally pertains. The greatest cooling effects, achieved temporarily from about 11:50 am to noon, momentarily exceeded 4.0 F, corresponding to a spray efficiency of over 80 percent. This performance appeared to coincide with a period of very low wind speed coming almost directly from the South to South-southeast.

4.5 Dispersal of Spray to Neighboring Cells

Under windy conditions, some portion of the spray can be blown out of the immediate spray zone above the nozzles and transported into downwind cells. The degree of dispersal depends on the strength of the wind and the location of the nozzles. For purposes of enhancing ACC performance it makes little difference which cell the spray enters since the average inlet temperature is still cooled by the same amount. If the nozzles are located near the downwind edge of the ACC, the spray might be blown out from under the ACC and would then be of no benefit for performance enhancement.

To determine the magnitude of this effect and to identify conditions and nozzle arrangements under which a significant amount of spray dispersal might occur, inlet temperature measurements were made at the fan bridge level in all eight of the cells in closest proximity to Cell 2I, as described in Section 3.5.4.3. These measurements were made with a single unshielded probe per cell.
Figure 4-16 shows the temperature profiles of Cell 2I and the neighboring cells for test run #11 (September 2, 2005; Test #1).

During this test, the wind was moderately strong (10 to 13 mph) and from the South-southeast. (See Table 4-1) The transport of spray into Cells 2H and 3H, which are North and Northwest of the spray zone respectively, is entirely consistent with those wind conditions. Because the probes in the neighboring cells are bare, unshielded probes they are occasionally wetted and, in this instance, record lower temperatures than the shielded probes in Cell 2I. This should not be taken as a quantitative indication of the relative amount of cooling in the two cells, but rather as a qualitative indication that a substantial amount of spray is being carried into adjacent cells.

4.6 Measurements at Finned Tube Bundle Inlet Plane

As discussed in Section 3.5.4, nine unshielded probes were located on each face of Cell 2I in the finned tube bundle inlet plane. These measurements were intended to address two features of the test. First, since the interior of the cell is filled with liquid droplets during the spray period, it is clear that additional evaporation and cooling can take place in the air stream as it passes from the inlet area near the fan bridge on toward the heat exchangers. This additional cooling would not be detected on the basis of readings from the shielded probes at the fan bridge. Second, the probes can be used to detect the presence of remaining liquid in the air as it enters the tube bundles and serve as a qualitative indicator of whether or not the tube bundles are being wetted by the spray. Clearly these two objectives are in conflict since a wet probe does
not give an indication of the dry-bulb temperature of the local air stream but rather reads the local wet-bulb temperature.

Figure 4-17 and 4-18 shows the readings from the West and East face temperature probes for Run #15 (September 7, 2005; Test #2). It is apparent that even on under hot, dry conditions (ambient temperature = ~93°F; relative humidity = 15 to 20 percent) and with a very low spray flow rate (5 to 6 gpm), there is still wetting of the finned tube bundle inlets at many, though not all, locations. These results will be discussed in more detail in Section 5.

Figure 4-17: Temperature Probes on West Face

Figure 4-18: Temperature Probes on East Face
CHAPTER 5:
Data Analysis and Interpretation

The following section will analyze the data obtained and interpret the results in terms relevant to selecting a preferred spray enhancement system for full-scale application. The primary areas of interest are:

- the cooling effect and the major influences on it
- the relationship between wind conditions and the appropriate choice of nozzle arrangement
- the degree to which system design can minimize both the wetting of the finned tube surfaces and rainback.

5.1 Cooling Effect

The measurements used to determine the cooling effect are described in detail in Sections 4.2 and 4.3. In addition the theoretical “maximum cooling effect” is defined as the amount that the full, well-mixed air stream into the single test cell would be cooled by the evaporation of the entire spray flow. Table 5.1 lists, for each of the 29 test runs, the average cooling effect during the test, the maximum cooling effect and the ratio of the two expressed as a “percent of maximum cooling achieved”. Figure 5.1 displays the data as cooling effect vs. spray flow rate. Figure 5.2 identifies for each Run Number the measured cooling effect as a percentage of the “maximum cooling” effect. Most of the runs lay between 65 and 85 percent of the maximum cooling effect.

This fraction of the spray that is evaporated is reasonably consistent with the results obtained in earlier tests at Crockett (Maulbetsch, 2004). It had been expected that the evaporated fraction would be higher in these tests that it had been at Crockett given the hotter, drier conditions at Bighorn. However, there are a number of reasons for this less-than-expected evaporation rate.

- The nozzles at Crockett were much smaller (~0.2 to 0.4 gpm per nozzle) than those used at Bighorn (2. to 3. gpm per nozzle) and produced a much finer spray and hence more rapid evaporation.
- The test cell at Crockett was protected from wind effects by a windscreen especially installed for the tests. Therefore, nearly all the spray was entrained into the test cell and contributed to the measured cooling effect. At Bighorn, under nearly all wind conditions, at least some portion of the spray was blown away from the test cell to be entrained into other cells.
- The higher inlet air velocity and differences in the air flow patterns within the cells, as was discussed in Section 3.3.3.1, may result in a shorter droplet residence time at Bighorn than was the case at Crockett.
Table 5-1: Cooling Effect for Each Test Run

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<td>0.27</td>
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<td>13:15</td>
<td>13:55</td>
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<td>12</td>
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<td>1.99</td>
<td>0.48</td>
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<td>3.08</td>
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<td>4.53</td>
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<tr>
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<td>15:40</td>
<td>4</td>
<td>13</td>
<td>4.71</td>
<td>0.85</td>
</tr>
<tr>
<td>24</td>
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<td>13:30</td>
<td>14:15</td>
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<td>13</td>
<td>4.71</td>
<td>0.95</td>
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<td>12</td>
<td>4.35</td>
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<tr>
<td>26</td>
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<td>15:20</td>
<td>16:25</td>
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<td>17</td>
<td>6.16</td>
<td>1.01</td>
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<td>0.59</td>
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<td>28</td>
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</tr>
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<td>15:20</td>
<td>3.89</td>
<td>12.5</td>
<td>4.53</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Figure 5-1: Cooling Effect Versus Spray Flow Rate for Each Test Run

Cooling Effect vs. Flow Rate

- **Cooling Effect**
- 50% Efficiency
- 75% Efficiency
- Linear (Theoretical Maximum)
- Linear (50% Efficiency)
- Linear (75% Efficiency)

Maximum Cooling effect = 0.3625 degrees F/gpm
The runs with the lowest cooling effects as a fraction of the maximum possible cooling are (in ascending order as shown in Figure 5-2) Run #’s 19, 18, 8, 10 and 11, all less than 30 percent. All of these points have nozzle arrangements where most of the spray is delivered from the mower or mid-level nozzles in moderate to strong winds.

In Run 19, eight of the ten active nozzles were in the mid- or lower levels. The winds averaged 10 to 20 mph from the South. As a result, a significant amount of spray was blown out of the Cell 2I inlet region and was entrained in other cells, primarily Cell 2H and, to a lesser extent, in Cell 1H as shown in Figure 5.3. The cells in Street 3 (3H and 3I) are blocked from the spray by the screen which runs between Streets 2 and 3. (See Figure 3-11). The shielded probes in Cell 2I indicate an average cooling effect of less than 2. F compared to the theoretical maximum of 7.6 F. Cell 2H, just North of Cell 2I, shows significant cooling during the entire run. Since the probes in all the neighboring cells are unshielded and subject to intermittent wetting, the appropriate comparison is with the unshielded probes in Cell 2I.
Run 18 shows a similar pattern with the bulk of the carryover entering Cell 2H, as seen in Figure 5-4. In comparison to Run 19, the wind was directed more from the Southwest with the result that less of the spray entered Cell 1H.

In Run 11, one-third of the spray was coming from the lower level of nozzles. Although the nozzles were on the South face, the wind from South was strong and the lower sprays were carried clear of the Cell 2I inlet zone. Similar observations during Run 11 show carryover and significant cooling in Cell 2H and 3H, the cells downwind from Cell 2I during this run when the winds were from the Southeast.

The runs with the highest cooling effects as a fraction of the maximum possible cooling are (in descending order as shown in Figure 5-2) are run numbers 26, 24 and 6. Runs 26 and 24 in particular have measured cooling effects of over 95 percent of the maximum. This seems inconsistent with visual observations of rainback and of the deposition of liquid drops on the finned tube bundles and on the walls, floor and fan bridge of Cell 2I.
Two explanations are plausible.
1. The maximum cooling effect is based on the assumption that all of the sprayed water is fully evaporated and mixed with all the air. Since the spray is not uniformly distributed over the air stream, it is possible that some regions of the air flow will entrain more than their proportional amount of spray and, hence, will be cooled more than the average.

2. The four shielded probes are located in the inner region of the inlet area as are the spray nozzles and some local overcooling is possible. Although shielded in aspirating psychrometers, one or more of the temperature probes might have been wetted by spray droplets entrained in the psychrometer inlet air. Figures 5.5 and 5.6 illustrate these points.

During Run #26, none of the local shielded temperature readings approached the wet bulb, suggesting that probe wetting, if any, was minimal. The Southwest probe appears to be in a region where the cooling is greater than average and, in fact exceeds the theoretical maximum cooling. This suggests a region of higher than average spray concentration and resultant greater than average cooling locally. Runs 24 and 6 exhibit similar patterns.

Run #4, although having a cooling effect of less than 80 percent, operated at a very high spray rate of 33 gpm corresponding to a maximum cooling effect of nearly 12 F. As seen in Figure 5.5, the Southwest probe (SW) approached the local wet bulb temperature for most of the run indication that it was wetted and giving an erroneously low reading. The Northeast probe (NE), while not quite at the wet bulb temperature, nonetheless gave an anomalously high
cooling effect suggesting intermittent wetting. It is, therefore, unclear what the real cooling effect was for this run.

The reasons for why these runs had spray maldistribution or wetted probes are not well understood. In some cases the flow rates were higher than most runs (Runs 26 and 4) and most of the flow was delivered from the higher level nozzles (Runs 24 and 6), conditions which might be expected to result in spray patterns that were still unmixed by the time the spray reached the level of the fan bridge. However, other runs with the same flows, the same nozzle arrangements, and the same wind speed and direction did not exhibit this behavior. For example, Run 10, with no apparent probe wetting or serious maldistribution and a very low cooling fraction of less than 30 percent is essentially identical to Run 26. While it may be that very subtle differences in wind direction may interact with the screen bordering the West side of Street 2 where the test cell is located have substantial effects on the spray distribution, no conclusions can be drawn on the basis of current data or observations.

**Figure 5-7: Local Cooling in Cell 2I During Run #4**

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5.2 Wetting of Finned Tube Bundles

A major concern for the use of spray augmentation is the possibility that intermittent wetting and drying of the finned tube surfaces might lead to scaling or corrosion damage. As discussed in Section 3.5.4.2, temperature probes were placed at the inlet plane of the finned tube bundles on both the East and West faces of Cell 2I. Figures 5.7 through 5.11 show the response of these probes for a series of runs at increasing spray flow rates.
Figures 5.7a and 5.7b (Run 15) which represent the lowest spray rates of 5.0 to 6.0 gpm, show that most, but not all, areas of the bundles remain dry. The active spray nozzles are at the upper levels of the North and South faces. The wind was predominantly from the South, somewhat variable but shifting gradually from Southwesterly to the Southeasterly during the run. This is consistent with the general patterns of Figure 5.7a and 5.7b where the East face shows more wetting early in the run and the West face starts relatively dry and becomes wetter near the end of the run.

On the West face, only bottom and middle areas at the North end approach the wet bulb temperature, suggesting nearly continuous wetting later in the run. On the East face, the North mid-point is continuously wetted throughout the run with the center-top area occasionally approaching the wet-bulb temperature. However, even though the majority of the probes were well above the wet bulb temperature, many of them were frequently cooled well below the fully mixed, fully evaporated cooling effect of 2 F, indicating frequent intermittent wetting by unevaporated spray. The essential point is that, even at this very low flow rate, the finned tube surfaces do not remain dry in all areas. The situation becomes more pronounced as the spray flow rate increases.

Figure 5-8a: Tube Bundle Inlet Plane Temperatures---East Face; Run 15
Figures 5.8a and 5.8b (Run 21) are for a spray flow rate of 12.5 gpm from nozzles located at all three levels on the South face with strong winds from the Southwest. As would be expected, the East face receives more wetting than the West face with several areas on the East face (the mid-levels across the entire face and the bottom level in the center of the face) at or close to the wet bulb temperature throughout the run.

On the West face, the South end of the face at all levels would occasionally experience complete wetting. During periods when the wind shifted more to the Southwest, as it did momentarily around 13:30h and 13:40h, the wetted areas would experience less wetting and partially dry.

Figures 5.9a and 5.9b (Run 6) display a case with a spray flow of 17 gpm from nozzles on all four sides of Cell 2I and all at the upper level. The winds during the run were moderate (5 to 15 mph) and from the North/Northwest, an unusual direction for the period of spray testing at Bighorn.
Figure 5-9a: Tube Bundle Inlet Plane Temperatures---East Face; Run 21

Spray Testing - Cell 2I East Exchanger Panels - 09/09/05
Bighorn, Primm, NV

Figure 5-9b: Tube Bundle Inlet Plane Temperatures---West Face; Run 21

Spray Testing - Cell 2I West Exchanger Panels - 09/09/05
Bighorn, Primm, NV
At this flow rate, most of the face areas on both the East and West faces are being almost continually wetted with probe temperatures in all areas at or near the wet bulb temperature. On both faces, there are a few locations which are drier. On the East face, the bottom regions at both the North and South ends as well as the top area at the South end appear to get little wetting. On the West face, the bottom areas at the North end and top area at the South end experience the least wetting. In general, the temperature of the air though the less wetted regions is lower on the West face than on the East face. There is no obvious explanation for this from current information.

Figures 5.10a and 5.10b (Run 20) are for a spray flow rate of 23 gpm from nozzles at all levels on the South face and from the four “below fan” nozzles located 5 feet below the fan inlet. The winds were strong (15 to 20 mph) and predominantly from the Southwest. Most areas on both faces were continuously wetted and the probes were reading near the wet bulb temperatures. On the West face, the entire face experienced a brief drying period at about 16:15h when the wind shifted momentarily to slightly East of South carrying the spray away from the West side of the cell. All levels at the South end of the East face experienced periodic drying periods (16:10 to 16:20h; 16:25 to 16:30h; and 16:40 to 16:45h) which were not obviously related to any aspects of the wind behavior and hence not fully understood. Nonetheless, at this spray rate, most of the finned tube bundle inlet areas are wet most of the time.

Figure 5-10a: Tube Bundle Inlet Plane Temperatures---East Face; Run 6

![Figure 5-10a: Tube Bundle Inlet Plane Temperatures---East Face; Run 6](image-url)
The same conditions pertain during Run 4 with a very high flow rate of 33 gpm from “below fan” nozzles located 10 feet below the fan inlet with moderate (10 to 15 mph) winds from the West/Southwest.

On the West face, winds from the WSW might be expected to drive the spray away from the NE corner of the cell with a drying of the North end at the bottom and this is observed. The drier character of the Center and South top areas and the Center mid-level area on the East face is not easily explainable. Again, however, at this spray rate most areas of both faces are continually wetted throughout the test.
Spray Testing - Cell 2I West Exchanger Panels - 09/08/05
Bighorn, Primm, NV

Figure 5-12a: Tube Bundle Inlet Plane Temperatures---East Face; Run 4

Spray Testing - Cell 2I East Exchanger Panels - 08/25/05
Bighorn, Primm, NV

Spray Testing - Cell 2I West Exchanger Panels - 09/08/05
Bighorn, Primm, NV

Figure 5-12a: Tube Bundle Inlet Plane Temperatures---East Face; Run 4
5.3 Rainback

Some of the sprayed water is lost to the process when it collects on structural and other non-heat transfer surfaces of the ACC, builds up and eventually falls back to the ground as droplets too large to be re-entrained and evaporated. Although this rainback eventually evaporates, it does so at ground level and contributes little or nothing to performance enhancement of the ACC. Figures 5.12 and 5.13 are photographs of wetted areas beneath Cell 2I taken during Runs 16 and 17.

Figure 5-13: Rainback on Ground Beneath Sprayed Cell
Figure 5-14: Rainback on Wall of Motor Control Center Building

Figure 5-15: Rainback on Top of Motor Control Center Building
The rainback, in addition to reducing the efficiency of water use in the spray enhancement process, has two additional drawbacks. First, in some jurisdictions, environmental permits may be required if “process water” is “discharged” onto the ground. For occasional, intermittent discharges of small quantities of reasonable quality water, obtaining the permit would likely be straightforward, but the issue should be considered in advance.

Second, the rainback on buildings, walkways, vehicles and equipment located or stored under the ACC may present an undesirable nuisance or maintenance problem. The amount of rainback is difficult to estimate. The data discussed in Section 5.1 suggests that approximately 65 to 85 percent of the sprayed water is evaporated under most circumstances by the time the entrained spray reaches the fan bridge level. Additional evaporation will take place in the cell volume above the fan bridge and on the hot finned tube surfaces. Therefore, it is unlikely that the rainback could exceed 2 to 5 percent of the sprayed water flow rate. Assuming a nominal system design flow rate of 15 gpm per cell, the rainback from a 40-fan ACC would be 2 to 5 percent of 600 gpm or 12 to 30 gpm. This amount of rainback, if distributed over the plan area of the ACC, would be equivalent to approximately 1/5 to ½ inch of rain per hour during the period of spraying. Whether or not this is acceptable would depend on the individual preferences and opinions of the pant staff, but it should be recognized that there is essentially no way to eliminate rainback entirely.

### 5.4 Results Summary

Table 5-2 lists each of the runs in descending order of water use efficiency, expressed as “Cooling effect, percent”; that is, the amount of cooling measured inside Cell 2I at the fan bridge divided by the maximum amount of cooling that could be achieved if all the spray flow were evaporated and mixed with the full airflow to Cell 2I. The table contains data for spray flow rate, cooling effect, wind speed and direction. It also describes the location of the active nozzles for each run. In addition the amounts of spray carryover to neighboring cells, rainback and tube bundle wetting are described qualitatively based either on related temperature measurements or visual observations. The following paragraphs will discuss the cooling effectiveness and the operational characteristics of bundle wetting and rainback as a function of nozzle arrangement and wind conditions. The three runs at the bottom of the table (Runs 3, 25 and 28) have no quantitative data as a result of data logger power interruptions during these test runs.

#### 5.4.1 Cooling Effect and Carryover to Neighboring Cells

In an operating system, spray from any nozzle or group of nozzles can be dispersed by the wind and eventually be entrained with air that can enter any of several cells. From the point of view of enhancing the performance of the ACC, it makes no difference which cell it cools. However, for these test results, the cooling effect is defined as the cooling of the air entering Cell 2I. The entire array of nozzles was located under Cell 2I, and only Cell 2I was heavily instrumented. The eight neighboring cells were instrumented with a single, unshielded temperature probe in each at the fan bridge level to detect qualitatively the spray carryover into surrounding cells.
Table 5-2 shows a strong inverse correlation between the water use efficiency as determined by the cooling effect in Cell 2I and the degree of carryover to neighboring cells. All of the runs in the upper half of the chart, with one exception (Run 9), had carryover described as “none”, very low or light. Similarly, all of the runs in the lower half of the table, here with two exceptions (Runs 12 and 22), are rated as “moderate” or “heavy”.

### Table 5-2: Spray Test Run Descriptions

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<tr>
<th>Run</th>
<th>Spray Flow, gpm</th>
<th>Cooling Effect</th>
<th>Carryover to Neighboring Cells</th>
<th>Tube Surface Wetting (% of face probes uncovered as East/West/Total)</th>
<th>Rainback</th>
<th>Wind Conditions</th>
<th>Nozzle Location</th>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed, mph</td>
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<td>5 - 10+</td>
<td>SW to NW</td>
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<td>SW to N</td>
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<td>N-NW</td>
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<td>85.8%</td>
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<td>NW - SW</td>
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<td>moderate to heavy 15 - 20</td>
<td>S - SW</td>
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<td>4</td>
<td>84.9%</td>
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<td>15 - 25+</td>
<td>SW - W</td>
</tr>
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<td>BF-10'</td>
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<td>SE - SW</td>
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<td>2.58</td>
<td>84.7%</td>
<td>very slight to 2H 91/93/91</td>
<td>light 7 - 15</td>
<td>SE - SW</td>
<td>M-S, S &amp; E faces</td>
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<td>S</td>
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<td>95.9%</td>
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<td>light 5 - 15</td>
<td>S to S to W (highly variable)</td>
<td>BF-10'</td>
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<td>2.56</td>
<td>96.5%</td>
<td>moderate to heavy neutral 70/79/79</td>
<td>light 5 - 20+</td>
<td>S - SE</td>
<td>BF-5'</td>
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<td>12</td>
<td>2.4</td>
<td>95.2%</td>
<td>occasional spike intro 2H 89/93/95</td>
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<td>NW to NE</td>
<td>U-NE &amp; NW cols; M-North face</td>
</tr>
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<td>12</td>
<td>2.24</td>
<td>91.5%</td>
<td>moderate to heavy intro 62/52/58</td>
<td>7 - 15 (not recorded in notes)</td>
<td>S-SW</td>
<td>U-NW &amp; S cols; M-South face</td>
</tr>
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<td>12</td>
<td>12</td>
<td>2.16</td>
<td>90.7%</td>
<td>moderate 73/74/75</td>
<td>light 10 - 15+</td>
<td>S to SW/S</td>
<td>U-SE &amp; S cols; M-South face</td>
</tr>
<tr>
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<td>0.96</td>
<td>48.2%</td>
<td>moderate 9/13/95</td>
<td>light 14 - 20</td>
<td>SE-SW</td>
<td>U-North and South faces</td>
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<td>2</td>
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<td>44.4%</td>
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<td>moderate 10 - 15</td>
<td>S</td>
<td>U-SE col; ML-SW col</td>
</tr>
<tr>
<td>17</td>
<td>17.5</td>
<td>2.41</td>
<td>38.6%</td>
<td>moderate to heavy intro 2H 74/86/88</td>
<td>moderate 12 - 20</td>
<td>S</td>
<td>ULM-North and South faces</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>2.93</td>
<td>35.1%</td>
<td>moderate to heavy intro 2H and 1H 59/87/72</td>
<td>moderate to heavy 10 - 20 (variable)</td>
<td>S - SW</td>
<td>ULM-South face; BF-5'</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>1.52</td>
<td>34.9%</td>
<td>moderate in 2H 86/86/86</td>
<td>moderate 10 - 15</td>
<td>S</td>
<td>U-SE col; M-SW col</td>
</tr>
<tr>
<td>22</td>
<td>11</td>
<td>1.2</td>
<td>30.1%</td>
<td>light to 2H; moderate to 1H 58/99/91</td>
<td>moderate to heavy 15 - 20</td>
<td>S</td>
<td>S - SW</td>
</tr>
<tr>
<td>11</td>
<td>23</td>
<td>2.28</td>
<td>27.3%</td>
<td>moderate to light into 2H and 1H 64/67/72</td>
<td>light 7 - 15</td>
<td>S - SE</td>
<td>U-SE &amp; S cols; M-South face</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>1.67</td>
<td>27.1%</td>
<td>moderate 68/98/80</td>
<td>light 5 - 15</td>
<td>6 to S to SW (highly variable)</td>
<td>M-all columns</td>
</tr>
<tr>
<td>18</td>
<td>12.5</td>
<td>1.22</td>
<td>28.6%</td>
<td>heavy 2H 83/79/74</td>
<td>light 10 - 20</td>
<td>SE - S</td>
<td>ULM-South face</td>
</tr>
<tr>
<td>8</td>
<td>17</td>
<td>1.64</td>
<td>26.6%</td>
<td>occasional spike intro 2H 95/87/87</td>
<td>light to moderate 5 - 10</td>
<td>NW to E (highly variable)</td>
<td>M-all columns</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>1.77</td>
<td>23.3%</td>
<td>heavy into 2H and 1H 81/87/89</td>
<td>moderate 15 - 20</td>
<td>S</td>
<td>S - SW</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>No data</td>
<td>No data</td>
<td>moderate</td>
<td>No data</td>
<td>No data</td>
<td>U-all columns</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>No data</td>
<td>No data</td>
<td>moderate</td>
<td>No data</td>
<td>No data</td>
<td>ULM-South face</td>
</tr>
<tr>
<td>28</td>
<td>12.5</td>
<td>No data</td>
<td>No data</td>
<td>light to moderate</td>
<td>No data</td>
<td>No data</td>
<td>ULM-South face</td>
</tr>
</tbody>
</table>

Run 9 introduced the spray directly below the fan (“Below fan, 10’”), and the rainback was described as “light”. The winds were relatively light and variable and enough spray was retained in the fan inlet zones to produce efficient cooling in Cell 2I while still dispersing spray to neighboring cells. The cooling effect for the entire ACC would, therefore, be quite high.

Runs 12 and 22 exhibit relatively low cooling efficiencies even though there is little carryover to neighboring cells. In this case the winds were reasonably strong, and all of the active nozzles were at the mid-level, 20 feet below the fan inlet. Therefore, the rainback was heavy. Run 12 had little carryover or rainback, yet still had a low cooling efficiency. It is hypothesized that the
wind was sufficiently strong to both disperse the spray to a wider range of neighboring cells so that no single cell indicated noticeable cooling and that the rainback was spread out over a wide area and appeared to be lighter than it actually was. It was noted that during Run 12 the wind screen was occasionally wet which was unusual for most of the test runs. Water on the windscreen would be evaporated and not be observed as rainback. The cooled air would also be widely dispersed to many cells.

5.4.2 Nozzle Location

In general, the most effective choice of nozzle location is up close to the fan inlet as would be expected and as was indicated in the pre-test flow visualization tests discussed in Section 3.4. The most effective arrangements were either the “below fan nozzles at the 5 foot level or the upper level on the structure. These nozzle locations were usually associated with light or moderate rainback and little carryover to neighboring cells. See Runs 24, 6, 23, 4, 16, 27 9 and 14. The cases where the bulk of the spray was delivered from nozzles at the mid- and lower levels on the structure tended to have higher rainback and more carryover. See Runs 19, 10, 22, 1 and 2.

Exceptions do exist. Run 26, with all the spray delivered from the mid-level nozzles had a high cooling efficiency, no carryover and only moderate rainback. In this case, the winds were light, variable in direction and coming predominantly from the west where the screen would have sheltered the spray zone. It should be noted that for this run the cooling efficiency is unrealistically high and in fact slightly exceeds 100 percent. As discussed in Section 5.1 and illustrated in Figure 5-5, this is due to a wetting of one of the shielded probes in Cell 2I causing the probe to read the wet bulb temperature.

5.4.3 Rainback

It is desirable to minimize rainback to the maximum extent possible both to improve the efficiency of water utilization and to eliminate any possible nuisance and maintenance problems. Fortunately, the nozzle locations associated with lighter rainback are those also associated with the higher cooling efficiencies and reduced carryover. With only ??? exceptions, all of the runs with “light” rainback are those with “Below fan nozzles” or with most of the spray coming from the upper level nozzles on the structure. (Runs 6, 9, 14, 7, 12, 15 and 11) Exceptions are Runs 13 and 10, where mid-level sprays gave light rainback, and Run 18 where sprays at all three levels (UML) also gave light rainback. For Runs 13 and 10 the winds were relatively light which improves the chances for the fan inlet stream to entrain the spray. For Run 18, the reasons for the light rainback are unclear. Runs 4 and 16 are case in which the “Below fan” nozzles resulted in heavy or moderate rainback. Run 4 is an anomalous case in which the nozzles were 10 feet below the fan inlet and the flow rate was very high (33 gpm). This is simply more flow that the air stream can entrain and the bundle wetting, the rainback, the carryover and the cooling effect are all very high. Run 16 had relatively high winds, but the explanation for the higher rainback is also unclear.
5.4.4 Bundle Wetting

The degree of bundle wetting was represented by the number of inlet plane temperature probes which were at the wet bulb temperature vs. those which were at a higher temperature suggesting that they were either dry or only intermittently wetted. This was determined for the East and West faces separately. Table 5-3 shows the percentage of the probes which were not at the wet bulb temperature for both faces, for both faces combined and the ratio of the percentages for the two faces.

The degree of bundle wetting correlates reasonably well with the percent water use efficiency. All of the heavy wetting runs are in the top half of the listing in Table 5-2. All but two (Runs 21 and 13) of the light wetting runs are in the lower half. The moderate wetting runs are scattered throughout the list. For Run 13, the flow is quite low as is the wind speed. The nozzles are well distributed across the inlet area of the fan. This combination of circumstances could lead to high entrainment of the spray into Cell 21 and the low flow rate could be largely evaporated before reaching the finned tube bundle inlet planes. Run 21, by comparison to other runs, should be expected to exhibit a higher degree of bundle wetting, but does not. No obvious explanation is apparent based on existing information.

In some instances, the two faces were wetted approximately equally (See Runs 2, 1 14, 13 and 10); in others, one face was much wetter than the other. (See Runs 26, 24, 8, 5, 20, 29 and 21)

5.4.5 General Guidance

The primary objectives for the design of a preferred spray enhancement system are to maximize the water use efficiency while reducing tube bundle wetting and rainback. It should be noted that only rainback reduces the water use efficiency. The spray which reaches and wets the tube bundles evaporates on or near the bundle heat transfer surfaces and contributes to the ACC performance enhancement equally as well as the spray which is evaporated in the incoming air stream. The requirement of minimizing bundle wetting is related to the potential risk of scaling or corrosion of the heat exchangers.

The data discussed in the preceding sections provides the following general guidance.

- Spray flow rates in excess of 12 to 15 gpm are less efficient for utilizing the water because of the higher rainback. The upper limit would differ for fans of differing size and air flow and for differing atmospheric temperature and humidity.

- Nozzle placement either below the fan at the 5 foot level or on the surrounding structural beams at the upper (10 feet below the fan) level gave the best utilization and the least rainback.

- Flows and nozzles placements which reduce rainback and improve utilization also tend to minimize bundle wetting.

- The “Below fan” locations using the radial spray nozzles appeared to provide a more uniform distribution over the fan inlet area, although comparisons from Table 5-2 show
no systematic advantages over the 30° hollow cone nozzles located at the upper level on the beams with the spray directed generally toward the middle of the fan inlet area.

The degree of carryover to neighboring cells is of less importance unless carryover from edge cells carries the spray outside of the ACC boundaries where it then evaporates uselessly in the surrounding atmosphere. Many sites have meteorological characteristics that give dominant wind directions during periods of highest temperature. Figure 5.15 shows that at the Bighorn site, the highest temperatures (above 95°F) are associated with winds primarily from the South to Southeast.

### Table 5-3: Bundle Wetting

<table>
<thead>
<tr>
<th>Run</th>
<th>% Probes not wet</th>
<th>Ratio E/W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>West</td>
</tr>
<tr>
<td>1</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>3</td>
<td>No data</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>83</td>
<td>52</td>
</tr>
<tr>
<td>6</td>
<td>85</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>88</td>
<td>82</td>
</tr>
<tr>
<td>8</td>
<td>95</td>
<td>57</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>10</td>
<td>79</td>
<td>80</td>
</tr>
<tr>
<td>11</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>12</td>
<td>73</td>
<td>83</td>
</tr>
<tr>
<td>13</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>15</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>55</td>
<td>69</td>
</tr>
<tr>
<td>17</td>
<td>74</td>
<td>98</td>
</tr>
<tr>
<td>18</td>
<td>82</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>81</td>
<td>97</td>
</tr>
<tr>
<td>20</td>
<td>58</td>
<td>85</td>
</tr>
<tr>
<td>21</td>
<td>72</td>
<td>98</td>
</tr>
<tr>
<td>22</td>
<td>83</td>
<td>99</td>
</tr>
<tr>
<td>23</td>
<td>67</td>
<td>75</td>
</tr>
<tr>
<td>24</td>
<td>76</td>
<td>45</td>
</tr>
<tr>
<td>25</td>
<td>No data</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>72</td>
<td>24</td>
</tr>
<tr>
<td>27</td>
<td>65</td>
<td>74</td>
</tr>
<tr>
<td>28</td>
<td>No data</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>64</td>
<td>90</td>
</tr>
</tbody>
</table>
This suggests that carryover completely out of the ACC would be expected primarily at the Southwest corner (Cells 4I and 4J) during periods when spray enhancement would be used. The effect of southerly winds on the north row of cells would be dissipated by the ACC structure and the intake of the intervening fans. Cells other than 4I and 4J could be operated at somewhat higher spray flow rates with carryover to adjoining cells, although at the risk of additional rainback.
CHAPTER 6:  
Full Scale System Design Recommendations

The attractiveness of a spray enhancement system is predicated on the notion that a small amount of water, utilized for a relatively short time using a relatively simple, low capital cost system can mitigate one of the serious disadvantages of dry cooling with air-cooled condensers; that is, the limitation on plant output during the hottest hours of the year.

6.1 Economic and Operating Assumptions

The economic benefit of such a system depends strongly on the site meteorology, the price of power during hot day periods of peak demand, the heat rate characteristics of the plant and the design capability of the ACC.

Assuming the following plant and ACC characteristics:

- ACC design ITD: 42°F
- Turbine trip point: 8 in Hga
- Turbine alarm point: 7.5 in Hga
- Turbine heat rate slope: ~3%/in Hga (@6 to 7 in Hga)

Prudent operation would attempt to hold the back pressure at or below 7 in Hga, particularly if high temperatures are accompanied by gusty wind conditions. This corresponds to a condensing temperature of 147°F, which for an ITD = 42°F, corresponds to an inlet temperature of 105°F. Assuming a 2°F re-circulation allowance, this implies an ambient temperature of 103°F, which is exceeded in the Las Vegas area, where many ACC’s are located, for about 300 hours per year. A spray system with a cooling effect of 5°F would maintain a 103°F inlet temperature up to an ambient temperature of 108°F, which is exceeded for only about 40 hours per year. At the mean extreme maximum temperature of 112°F, the inlet temperature would be 109°F implying a condensing temperature of 151°F or 7.7 in Hga, just above the alarm point.

To reduce the backpressure from 7.7 in Hga to 7.0 in Hga by lowering load would require a reduction of approximately 2.5 percent at a turbine heat rate characteristic slope of 3%/in Hga. For the steam turbine at a typical 2 x 1 gas-fired, 500 MW combined-cycle plant with full duct burning, the steam turbine output is approximately 250 MW. Therefore, a 2.5 percent reduction amounts to a loss of just over 5 MW. The cost of this reduction to the generating company depends on their power-purchase agreements, the availability of alternate power and the required demand as a function of peak regional capacity. The value may be as low as $50/MWh and has, in the recent past, gone as high as several hundred dollars per MWh. Assuming a plausible value of $100/MWh, a loss of 5.25 MW over a 300 hour period represents potential lost revenue of approximately $160,000 per year.
6.2 Spray System Design Recommendations

Section 5.3.3 gives some general guidance for the design of spray enhancement systems. Design costs have been developed a spray system sized for both a 40-cell and a 30-cell ACC. The basic configuration is

- Spray rate: 15 gpm/cell
- Nozzle arrangement: 4 radial flow nozzles 5 feet below fan inlet
- Nozzle pressure: 350 psig
- Water treatment: Reverse osmosis

6.3 Design Basis Summary

The system consists of four basic component groups including

- Spray system
- Reverse osmosis system and feed system
- Treated water (RO permeate) storage
- Brine (RO reject) disposal

The RO system is sized to operate 24 hours per day to support the spray system operating only 6 hours per day. The RO system will feed a storage tank sized to store a 6 hour supply of treated water for the spray system. It is assumed that the site is in a zero liquid discharge (ZLD) region, and the RO reject stream will be discharged to an evaporation pond.

6.3.1 Cost Development Assumptions

The spray delivery system itself (pumps, piping, valves, nozzles, controls, and so forth) is a smaller fraction of the total system cost than are the water treatment, storage and disposal components.

6.3.1.1 RO System

The cost for the RO system including the feed system is taken from actual project cost information on comparably sized systems on similar feedwater. To this are added estimates for a programmable logic controller (PLC), a large storage tank and miscellaneous assembly parts. Installation is factored at 50 percent of the equipment cost. Finally a 35 percent contingency is applied.
### Table 6-1: Spray Enhancement System Design Basis

<table>
<thead>
<tr>
<th>Design Basis.....</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray Rate, gpm/cell</td>
<td>15</td>
</tr>
<tr>
<td>Cells</td>
<td>40</td>
</tr>
<tr>
<td>Total Spray Rate, gpm</td>
<td>600</td>
</tr>
<tr>
<td>Total Spray Time, hours</td>
<td>300 (during summer months - June to Sept - equivalent to spraying 40% of summer days)</td>
</tr>
<tr>
<td>RO Recovery</td>
<td>75%</td>
</tr>
<tr>
<td>Equiv RO Feed Rate, gpm</td>
<td>800</td>
</tr>
</tbody>
</table>

#### RO Feed System.....(Note 1)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RO Transfer Pumps</td>
<td>2 (100% capacity)</td>
</tr>
<tr>
<td>RO Transfer Pump Feed Rate, gpm</td>
<td>200</td>
</tr>
<tr>
<td>RO Transfer Pump Feed Pressure, psi</td>
<td>50</td>
</tr>
<tr>
<td>RO Transfer Pump Power, HP</td>
<td>8.3 (70% efficiency)</td>
</tr>
</tbody>
</table>

#### RO System.....

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray Duration, hours/day</td>
<td>6.0</td>
</tr>
<tr>
<td>RO Feed Flow, gpm</td>
<td>200 (continuous operation)</td>
</tr>
<tr>
<td>RO Permeate Flow, gpm</td>
<td>150</td>
</tr>
<tr>
<td>RO Reject Flow, gpm</td>
<td>50 (to waste)</td>
</tr>
<tr>
<td>Annualized RO Reject Flow Rate, gpm</td>
<td>6.85</td>
</tr>
<tr>
<td>RO Feed Pressure, psi</td>
<td>200</td>
</tr>
<tr>
<td>RO Feed Pump Power, HP</td>
<td>33.3 (70% efficiency)</td>
</tr>
</tbody>
</table>

#### Permeate Storage.....

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RO Permeate Tank Volume, hours</td>
<td>6 (permeate)</td>
</tr>
<tr>
<td>RO Permeate Tank Volume, gallons</td>
<td>216,000 (working volume)</td>
</tr>
</tbody>
</table>

#### Evap Pond Requirement.....

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A Pan Evap Rate, inches/year</td>
<td>120 (Southwest US)</td>
</tr>
<tr>
<td>Salinity Adjustment Factor</td>
<td>0.7</td>
</tr>
<tr>
<td>Geometry Adjustment Factor</td>
<td>0.7</td>
</tr>
<tr>
<td>Adjusted Evap Rate, inches/year</td>
<td>58.8</td>
</tr>
<tr>
<td>Additional Evap Pond Reqmt, acres</td>
<td>2.25</td>
</tr>
</tbody>
</table>

#### Notes.....

1. Use existing raw water tank for RO feed storage.

### 6.3.1.2 Spray System

The spray system was laid out for a 40-cell ACC arranged in two 4 x 5 clusters as at Bighorn and a 30-cell 5 x 6 arrangement as at El Dorado. Costs for pumps, piping, fittings (elbows, couplings, tee’s, and so forth) were assembled by Adair Engineering, a local engineering contractor with recent project experience utilizing similar equipment and materials. Nozzle costs were obtained from EnviroCare, International, the supplier of the nozzles for the spray testing. Layout, design and installation levels of effort were estimated by the authors based on experience with various field projects. The labor category costs were obtained from an engineering contractor in Southern Nevada.

Finally, a 35 percent contingency was applied. Table 6-2 summarizes the results.
Table 6-2: Summary of Spray Enhancement System Costs

40-cell Cost Summary.....

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO System &amp; Evap Pond</td>
<td>$1,970,000</td>
</tr>
<tr>
<td>40-Cell Spray System</td>
<td>$470,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,440,000</strong></td>
</tr>
</tbody>
</table>

Additional Evap Pond NOT Required.....

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO System and Permeate storage tank</td>
<td>$1,360,000</td>
</tr>
<tr>
<td>40-Cell Spray System</td>
<td>$470,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,830,000</strong></td>
</tr>
</tbody>
</table>

Additional Evap Pond NOT Required & RO Permeate Tank NOT Required.....

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO System (w/o permeate storage tank)</td>
<td>$720,000</td>
</tr>
<tr>
<td>40-Cell Spray System</td>
<td>$470,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,190,000</strong></td>
</tr>
</tbody>
</table>

Figure 6-1: Comparison of Spray System Costs

6.4 Breakeven Costs and Benefits

A simple cost/benefit analysis is based on comparing the annualized cost of the spray system to the annual revenue which could be produced from the sale of the additional plant output.
6.4.1 Annualized Cost

The annualized cost is the sum of the amortized capital cost, the cost of water and power for operating the system and an O&M charge. The capital costs given in Table 6-2 are amortized at an annual rate of 7 percent; the annual O&M charge is assumed to be 2 percent of the capital cost; and the cost of water and power will be taken as $2.00 per thousand gallons and $0.10/kWh respectively. The costs are tabulated and summed in Table 6-3.

Table 6-3: Annualized Spray System Costs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td>$2,440,000</td>
<td>$170,800</td>
<td>48,800</td>
<td>14,400</td>
<td>$28,800</td>
<td>180</td>
<td>$5,400</td>
<td>$253,800</td>
</tr>
<tr>
<td>No evaporation pond</td>
<td>$1,830,000</td>
<td>$128,100</td>
<td>36,600</td>
<td>14,400</td>
<td>$28,800</td>
<td>180</td>
<td>$5,400</td>
<td>$196,900</td>
</tr>
<tr>
<td>No evaporator pond or storage tank</td>
<td>$1,190,000</td>
<td>$83,300</td>
<td>23,800</td>
<td>14,400</td>
<td>$28,800</td>
<td>180</td>
<td>$5,400</td>
<td>$141,300</td>
</tr>
</tbody>
</table>

6.4.2 Annual Benefits

The annual revenue benefit will be calculated as described in Section 6.1. Figure 6-2 shows the revenue benefit as a function of peak power price. The intersection with the annualized system costs for each of the three system configurations gives the peal power price at which the use of the system breakeven for the assumptions given above.

Figure 6-2: Breakeven Points

Figure 6-3 taken from the California Independent System Operator (CalISO) Website shows the peak price on an hourly basis for a recent month during hot weather indicating that peak prices frequently rise into and above the $100 to $190/kWh range needed to breakeven.
Figure 6-3: Peak Power Prices in California, June 2006 (From Cal-ISO Website)
CHAPTER 7: Summary, Conclusions and Recommendations

7.1 Summary

Air-cooled condensers can experience performance shortfalls during periods of hot weather. Spray inlet cooling, in which a small amount of water is used for brief periods to reduce the inlet temperature to the ACC below the ambient air temperature, has long been considered as an economical means for mitigating these hot day penalties. Single cell tests, conducted by the authors at Crockett Co-Generation in 2001 established that substantial cooling effects could be achieved with reasonable water use efficiency.

The present test program extended the work at Crockett with field tests at Bighorn by measuring performance under hot, dry atmospheric conditions, observing the effect of wind on spray patterns and documenting the severity of practical operating problems such as rainback, finned tube bundle wetting and windage losses due to spray carryover. Recommendations for nozzle selection, location, arrangement and orientation to minimize these problems were developed. Ancillary work included flow visualization tests at Crockett and Bighorn and demister and nozzle screening tests.

7.2 Conclusions

Test results and observations yielded the following important conclusions.

- Air flows through each cell of modern ACC’s of the size used in power plants require the evaporation of approximately 3 gallons per minute of water for each 1 F of cooling effect. Therefore, spray rates of 15 to 25 gallons per minute per cell are necessary to achieve significant air inlet temperature reduction.

- Nozzle screening tests indicate that, for a supply pressure of 300 to 400 psi, nozzles in a size range of 2 to 5 gpm per nozzle produce mean droplet sizes of 50 to 100 microns. To obtain finer mist or to significantly reduce the “large drop” fraction requires either much higher supply pressure or much smaller nozzles, both of which results in significantly higher costs or high maintenance. Therefore, the system must operate acceptably with the larger droplet sizes.

- For the drop size distributions and spray patterns achievable with either hollow cone or radial flow nozzles in the 2 to 5 gpm size at 350 psi, the spray is essentially fully entrained by the fan if the nozzles are located within 5 to 10 feet below the fan inlet plane. However, at flow rates above 15 gpm, the rainback is heavy and the finned tube bundles are completely wet, no matter what nozzle location/orientation is used. Therefore, the cooling effect is limited, for all practical purposes, to about 5 F.

- For ACC’s with design ITD’s of 40 to 45 F and for summer weather conditions typical of the Southwestern US, mandatory load reductions to avoid steam turbine alarm/trip conditions would be expected to occur for about 300 hours per year. A 5 F cooling effect
would permit full load operation for nearly all of those hours with increased output of 1,000 to 2,000 MWh.

- A spray system designed to provide a 5°F cooling effect on a 40-cell ACC is estimated to cost approximately $0.5 million installed.
- A water treatment system, assumed to be reverse osmosis, is required at a cost of $0.7 to $2.0 million. The high end of this wide range assumes that both a 250,000 gallon storage tank and an additional 2.5 acres of evaporation pond must be provided. If neither is required because of adequate storage and excess pond capacity already at the site, the lower cost pertains.
- At peak power prices within the currently expected range of up to $400 per MWh, the use of spray enhancements can result in increased revenue from the increased power output. The breakeven power prices for the range of system costs vary from approximately $100/MWh for the lowest cost spray system to just under $200/MWh for the highest cost system.
- The authors believe that, at sites where high temperatures perhaps accompanied by gusty winds might be expected to curtail plant output for a few hundred hours, a spray enhancement system would be an economical choice for performance enhancement assuming that an adequate amount of water is available.
- The authors conclude that, with the proper choice of nozzle type, location and orientation and the provision of a suitable water treatment facility, an acceptable water use efficiency can be achieved and effects of rainback and the risk of bundle wetting can be kept to acceptable levels. However, the limitations on the extent and duration of tests did not allow us to demonstrate this on a full-scale, long term basis.

7.3 Recommendations

The following recommendations are based not only on the measurements and observations made during this study but on the results of previous work at Crockett and on observations at other installations made in the course of plant visits while evaluating possible test sites for this work.

1. Many owners of ACC’s have experimented with spray enhancement to boost summer performance using systems developed on a largely ad-hoc basis. Some of those owners have abandoned the use of their sprays for a variety of reasons but their need for summer enhancement remains. Future ACC owners are likely to want to try spray as well. Opportunities should be sought to work with plants who wish to try spray enhancement, to encourage them to follow the design recommendations in this report and to observe full scale operation over an extended time.

2. Variations on the approach taken in these tests should be explored. For example, the use of a larger number of smaller nozzles mounted inside the cells has been recommended
by an ACC vendor as a preferred approach. This was not tested in this study due to limitations of funding and schedule.

3. A systematic comparison of the cost/benefits of spray enhancement with those of a supplementary wet cooling tower should be made for both new unit and retrofit situations. We expect that the supplementary, hybrid design will be preferred for conditions where sufficient water is available to allow operation for a much longer time than the 300 hours used in this analysis. In addition, the fraction of the heat load taken by the supplementary wet tower could be a much larger effect on ACC operation and backpressure than an air inlet temperature reduction on an all-dry stem limited to 5 F. The major benefit of the hybrid system, however, will presumably accrue to new plants rather than retrofits because of the ability to design the combined system with a significantly smaller, and hence less expensive, ACC. This comparison is necessary to establish the limits of applicability of spray enhancement with confidence.
REFERENCES


Appendix A: 
Meteorological Data for Bighorn

### LAS VEGAS/MCCARRAN NV

| Latitude | 36.08 N |
| Longitude | 115.10 W |
| Elevation | 2179 feet |

| Period of Record | 1973 to 1996 |
| Average Pressure | 27.67 inches Hg |

#### Design Criteria Data

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<th>Mean Coincident (Average) Values</th>
<th>Wet Bulb Temperature (°F)</th>
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#### Other Site Data

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*Note: Temperatures at greater depths can be estimated by adding 1.5°F per 100 feet additional depth.*
Caution: This summary reflects the typical distribution of temperature in a typical year. It does not reflect the typical moisture distribution. Because wet bulb temperatures are averaged, this summary understates the annual moisture load. For accurate moisture load data, see the long-term humidity summary and the ventilation and infiltration load pages in this manual.
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Caution: This summary reflects the typical distribution of temperature in a typical year. It does not reflect the typical moisture distribution. Because wet bulb temperatures are averaged, this summary understates the annual moisture load. For accurate moisture load data, see the long-term humidity summary and the ventilation and infiltration load pages in this manual.
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Caution: This summary reflects the typical distribution of temperature in a typical year. It does not reflect the typical moisture distribution. Because wet bulb temperatures are averaged, this summary understates the annual moisture load. For accurate moisture load data, see the long-term humidity summary and the ventilation and infiltration load pages in this manual.
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<tr>
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<td>0</td>
<td>0</td>
<td>9.9</td>
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<tr>
<td>5 / 9</td>
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Caution: This summary reflects the typical distribution of temperature in a typical year. It does not reflect the typical moisture distribution. Because wet bulb temperatures are averaged, this summary understates the annual moisture load. For accurate moisture load data, see the long-term humidity summary and the ventilation and infiltration load pages in this manual.
## Dry-Bulb Temperature Hours For An Average Year (Sheet 5 of 5)

Period of Record = 1973 to 1996

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<th>Obs (°F)</th>
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<tr>
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<td>0</td>
<td>2</td>
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<td>0</td>
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<td>0</td>
<td>6.0</td>
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</table>

**Caution:** This summary reflects the typical distribution of temperature in a typical year. It does not reflect the typical moisture distribution. Because wet bulb temperatures are averaged, this summary understates the annual moisture load. For accurate moisture load data, see the long-term humidity summary and the ventilation and infiltration load pages in this manual.
Annual Summary of Temperatures

Temperature (°F)

1.0% Dry Bulb Temp  MCWB (1% Dry Bulb)  Mean Max Temp  Mean Min Temp  99% Min Dry Bulb Temp
Wind Summary - December, January, and February

Labels of Percent Frequency on North Axis

Percent Calm = 5.72

Wind Summary - March, April, and May

Labels of Percent Frequency on North Axis

Percent Calm = 2.37
Wind Summary - June, July, and August

Labels of Percent Frequency on North Axis

Percent Calm = 2.06

Wind Summary - September, October, and November

Labels of Percent Frequency on North Axis

Percent Calm = 4.21
APPENDIX B:

Testing Of Demister Panels For Applicability To Inlet Air Spray Cooling On Air-Cooled Condensers
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EXECUTIVE SUMMARY

Introduction

One of the important concerns over the use of inlet air spray cooling for air-cooled condenser (ACC) performance enhancement is the potential for corrosion or scaling of the finned tube bundles. This may result if unevaporated spray reaches the tube bundles and wets the surfaces. Repeated wetting and drying can lead to deposition of dissolved or suspended solids in the spray droplets or to corrosion for certain combinations of water chemistry and surface material.

This problem might be addressed in several ways including ensuring complete evaporation of the drops before they reach the tube bundles, exercising careful control over spray water quality or intercepting the droplets before they reach the tube bundles.

Ensuring complete evaporation is difficult. It requires producing a very fine mist and providing a long residence time between the nozzle and the tube bundles. Production of a fine mist typically requires high pressure (~1,000 psi or higher) and low-flow (less than 0.1 gpm per nozzle) nozzles both of which lead to high system cost and pumping power requirements.

Long residence times can be achieved through proper placement of the nozzles but this may result in losing spray to air that never enters the cells or to impingement on ACC structure. In either case, the cooling benefit of some portion of the spray is lost.

Water quality control requires the use of treatment equipment such as reverse osmosis or deionization which adds to the cost and power requirements for the system and produce waste steam which must be disposed of at further cost.

The approach of intercepting any unevaporated droplets just before they reach the tube bundles might be achieved with the installation of demister panels on the inlet face of the tube bundles, as shown in Figure 1.
This approach has some attractive feature and some important drawbacks. The advantages include

- Relatively coarse spray from a few low-pressure (200 to 400 psi), high flow (1 to 5 gpm) nozzles could be used enabling a low capital cost system
- The nozzles could be located above (downstream) of the fans for easy installation and maintenance.
- Within reason, low quality water could be used so long as any serious maintenance problems on the demister panels themselves were avoided.

All of these attributes would reduce the cost and power requirements of the spray enhancement system.

On the other hand, the permanent installation of demister panels at the tube bundle inlet plane has disadvantages.

- Each cell has nominally 3,000 to 4,000 square feet of tube bundle frontal area. The purchase and installation would be a significant cost, particularly in a retrofit situation where no provision for attaching the panels would have been made in the original design.
• The presence of the panels would add to the air-side pressure drop and required fan power. Again, in a retrofit situation, the fan selection and heat exchanger design would not have been optimized for this additional pressure drop and the resulting performance and power penalties would likely be higher than if the approach had been included in the original design. It is a further drawback that this pressure drop/fan power penalty exists for every hour of operation throughout the year even though the spray system might only be used for a small portion of the year.

• The presence of demister panels will introduce maintenance requirements and may make the routine cleaning of the finned tube bundles more difficult.

Prior experience

Preliminary tests with demister panels were run as part of the original spray enhancement testing at Crockett in the summer of 2001. In these tests, originally reported in the final report of that project, demister panels using a Brentwood CF 1900 counter-flow cooling tower fill, shown in Figure 2, were installed below (upstream) of the fan as seen in Figure 3.

Figure 2: Brentwood CF 1900 fill panels used in Crockett testing
The results were mixed. The spray droplet removal efficiency of the cooling tower fill panels was excellent. There was no detectable unevaporated liquid above (downstream of) the fan for any spray flow rate or nozzle location. The cooling effect for the system as a function of spray rate and ambient conditions was consistent with the other tests run without the panels. However, because these tests were run at the end of the testing period in early November, the ambient conditions (temperature below 70 °F; wet bulb depression less than 10 °F) were very unfavorable for spray cooling. As a result the cooling effect was low (~ 1 to 2 °F) and difficult to measure accurately.

The unevaporated liquid captured by the demisters drained directly back into the area below the cell creating an operating and maintenance problem. In addition, the geometry of the panels distorted the inlet air flow to the fan in such a way as to introduce severe asymmetry into the flow with an adverse effect on both fan and heat exchanger performance.

It was concluded on the basis of these brief tests that

1. the preferred location for any demister panels would be above (downstream of) the fans
2. the panels themselves would need to have provision for internal drainage paths so that some sort of collection system for removal and recycle of the unevaporated liquid could be devised
3. droplet removal, drainage capability and pressure drop data were required on a few candidate demister designs before any conclusion on the merit of this approach could be made.

The remainder of this report describes a brief demister test program which addressed these questions.
CHAPTER 1: Test Plan

1.1 General

The essential information to be obtained from the tests included:

1. Assurance that the panels would prevent droplets from reaching the tube bundle over the range of air velocities and water loadings expected for a spray-enhanced ACC.

2. Evidence that rainback from the front surfaces of the demister panels would be minimal.

3. Evidence that the collected water would be drained internally through the panels to a central collection point for recycle.

4. An estimate of the pressure drop and fan power added by the presence of a demister panel.

1.1.1 Droplet collection

The presence or absence of droplets downstream of the drift eliminators was determined qualitatively through visual observation and by standing in the exit air stream for several minutes while attempting to feel any drops. While this is an admittedly crude test, we believe that any droplets too small to feel or to see as a mist would, if present, evaporate in the thermal boundary layer on the finned tube surfaces before wetting the surfaces. The range of operating conditions was determined as follows:

**Airflow:** Nominal air velocity at ACC bundles (based on El Dorado specs).

- Bundle area (per cell): ~2,750 sq. ft.
- Fan flow (per cell): 1.33 x 10^6 acfm
- Superficial velocity: ~485 ft./min.

For 25 sq. ft. array, nominal flow = ~12,200 acfm

**Water flow:**

- Maximum: 40 gpm per cell @ 75 percent evaporation
  - Droplet flow = 10 gpm
  - Droplet flux = 0.0036 gpm/sq. ft.
- Nominal: 20 gpm per cell @ 80 percent evaporation
  - Droplet flow = 4 gpm
  - Droplet flux = 0.0015 gpm/sq. ft.
For 25 sq. ft. array, spray rate = 0.035 to 0.09 gpm

1.1.2 Rainback
The severity of rainback from the front face of the demisters was determined visually through the viewports on the sides of the wind tunnel.

1.1.3 Drainage
Drainage flow was collected at two drain ports at the lower corners of the panel support frame. This flow rate was compared to the spray flow rate. The difference could be attributed to three sources.

1. Rainback
2. Evaporation in the air stream or from the surfaces of the demister after collection. The amount of evaporation could be calculated from the inlet and outlet dry and we bulb temperature measurements and the air flow rate. Evaporation was shown to be negligible for the residence time in the air steam and for the ambient conditions during the testing periods.
3. Droplet impingement on the walls of the tunnel prior to reaching the demister panel inlet plane. This loss appeared to be small. Furthermore, it is essentially independent of which demister panel is in place. Therefore, any differences among the panels could be attributed to different rainback characteristics.

1.1.4 Pressure drop and fan power
Pressure drop across the demister panel was measured directly as was the air velocity at the panel exit. Calculations of the total air flow and fan power are straightforward.
CHAPTER 2: Test Facility

A test facility was designed, built and instrumented to allow data to be obtained over the range of variables defined in the previous section.

2.1 Wind tunnel

A wind tunnel to deliver an air stream and entrained water droplets to the test demister panels was assembled. Drawings of the three elevation views are shown in Figures 4, 5 and 6. A photograph of the completed apparatus on the grounds of EnviroCare, Inc. in American Canyon, California where the tests were performed is shown in Figure 7.

Figure 4: Side View of Wind Tunel

Demister Test Stand – Elevation 1
Figure 5: View of Test Rig from Opposite Side

Demister Test Stand – Elevation 2
Figure 6: End View of Test Rig

Demister Test Stand – End Elevation

Axial Fan (36.5" Dia)
50% Diffuser Plate
Spray Port, Lance & Pressure Gage
Straightening Vanes
Drain Port
60.5" x 60.5" Demister Support Frame

DiFilippo 09/18/2003
The rig was designed so that the demister panels are at the same inclination to the vertical as the tube bundles in a typical ACC. (See a typical installation in Figure 8. This was done to simulate the orientation of the internal drainage paths and to obtain data on the effectiveness of each test panel for collecting the unevaporated liquid captured by the demister for recycling.
Figure 9 shows the drainage port in the lower right hand corner of the frame holding the test panels. Another symmetrically located port is installed in the lower left hand corner.
2.2 Instrumentation

The facility was instrumented to obtain all of the data needed as described in the previous section. This included

- Aspirating psychrometers for dry- and wet-bulb temperature measurements of the inlet (ambient) and exit air streams. (Figure 10)

- Pressure gauge on the spray nozzle inlet. (Figure 11) Spray flow rates vs., pressure for each nozzle were determined externally using a graduated container and stopwatch.

- Drainage flow rates were also measured at both drainage ports (Figure 9) again with a graduated container and stopwatch.

- An inclined manometer (Figure 12) for pressure drop across the demister panels.

- A variable speed motor drive could be set from the control panel (Figure 13) to vary the fan speed and air flow.

- The absolute air flow was determined from a nine-point velocity traverse taken with a hand-held anemometer. (Figure 14)

Visual inspection of the spray pattern at the nozzle exit and the quantity of rainback from the leading edges of the demister panels (representing uncollected liquid hence unavailable for recycling) could be observed qualitatively through viewing ports on the sides of the test rig. (Figures 4, 5 and 6)
Figure 10: Aspirating Psychrometers
Figure 11: Pressure Gauge on Spray Nozzle Inlet
Figure 12: Inclined Manometer for Panel Pressure Drop
Figure 13: Fan Motor Control Panel
Figure 14: Hand-held Anemometer
CHAPTER 3: Tests

3.1 Demister panels

### Table 1: Candidate Demister Panels

<table>
<thead>
<tr>
<th>Panel Identification</th>
<th>Shown in Figure...</th>
<th>Tested</th>
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<td>Marley Plastic Matrix: TU12-XF Eliminator</td>
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<tr>
<td>Marley Hi-V Eliminator</td>
<td>Figures 18 and 19</td>
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<td></td>
<td>(Also Figures 8 and 14)</td>
<td></td>
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<tr>
<td>Brentwood Blade Type Drift Eliminator DE-080</td>
<td>Dwg.---Figure 20</td>
<td>No</td>
</tr>
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<td>Brentwood Blade Type Drift Eliminator DE-120</td>
<td>Dwg.---Figure 21</td>
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<td></td>
<td>Photos---Figure 22 and 23</td>
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<tr>
<td>C. E. Shepherd</td>
<td>24 and 25</td>
<td>Yes</td>
</tr>
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</table>
Figure 15: Marley Matrix Eliminator Front Face
Figure 16: Marley Matrix Panel Showing Drainage Collection Passages
Figure 18: Marley Hi-V Panel Section Front Face
Figure 19: Marley Hi-V Panels End View with Mounting Frame
Figure 20: Drawing of Brentwood DE-080 Blade Type Drift Eliminator

Figure 21: Drawing of Brentwood DE-120 Blade Type Drift Eliminator
Figure 22: Brentwood DE-120 Installed
Figure 23: Brentwood DE-120 Close-up
Figure 24: C.E. Shepherd Panel from Bottom
3.2 Nozzles

Table 2 lists the several nozzles used in the tests. All tests were run at a nozzle supply pressure of 60 psig. At this pressure, the spray flow rates varied from nozzle to nozzle from 0.08 to 0.23 gpm. The differing spray patterns provided different coverage patterns on the demister inlet plane and there were slight differences in droplet size distribution. On balance, however, the nozzle-to-nozzle differences, other than flow rate, were not important to the tests.
## Table 2: Spray Nozzles for Demister Tests

<table>
<thead>
<tr>
<th>Designation</th>
<th>Spray pattern</th>
<th>Flow rate, gpm (@ 60 psig)</th>
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</thead>
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<tr>
<td>WDB 8</td>
<td>~70° FHC™</td>
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<tr>
<td>PJ 24</td>
<td>~90° HC</td>
<td>0.12</td>
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<tr>
<td>WDB 14</td>
<td>~80° FHC™</td>
<td>0.18</td>
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<tr>
<td>PJ 28</td>
<td>~90° HC</td>
<td>0.16</td>
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<td>PJ 32</td>
<td>~90° HC</td>
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<tr>
<td>WDB 18</td>
<td>~80° FHC™</td>
<td>0.24</td>
</tr>
</tbody>
</table>

WDB = Delavan Body; PJ = Bete Body; HC = Hollow Cone; FHC™ = Fuzzy Hollow Cone
CHAPTER 4:  
Test Results

Tests were run to calibrate the test rig and to obtain data on four of the five demister panels. The schedule of the tests is shown in Table 3. Raw and reduced data for all tests are included in Appendix A.

Table 3: Schedule of Tests

<table>
<thead>
<tr>
<th>Date</th>
<th>Tests Performed</th>
<th>Nozzles</th>
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<td>WDB 8; WDB 14; WDB 18; PJ 24</td>
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<tr>
<td>9/5/2003</td>
<td>Evaporation tests; fan calibration; Marley matrix</td>
<td>PJ 24</td>
</tr>
<tr>
<td>9/9/2003</td>
<td>Marley Hi-V</td>
<td>WDB 18</td>
</tr>
<tr>
<td>9/16/2003</td>
<td>Marley Hi-V; Brentwood DE-120</td>
<td>WDB 8; WDB 14; WDB 18; PJ 24</td>
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<tr>
<td>9/17/2003</td>
<td>Brentwood DE-120</td>
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<tr>
<td>12/22/2003</td>
<td>C.E. Shepard</td>
<td>?</td>
</tr>
</tbody>
</table>

The Brentwood DE-80 panel was not tested. The DE-80 design is identical to the DE-120 except for a closer blade spacing which would be expected to improve the droplet collection at the expense of higher pressure drop. Since the droplet collection efficiency with the DE-120 was already adequate there was no reason for incurring a higher pressure drop and fan power.

4.1 Calibration tests

4.1.1 Air flow tests

A linear relationship was established between the fan motor drive frequency and the air flow expressed as the average exit air velocity. The correlation curve is shown in Figure 26 based on data in Table A-1 in Appendix A. Stable operation could be maintained between 20 and 60 Hz corresponding to face velocities of 250 to 775 feet per minute. This provides a good range below and above the “nominal” ACC operating point of 485 ft/min established in the Test Plan earlier.
4.1.2 Evaporation rate

A few tests were run to determine whether spray evaporation was an important factor in the mass balance. Measurements of the wet- and dry-bulb temperature were taken at the fan inlet and at the panel exit. Calculations of the specific humidity (lb. moisture/lb. dry air) were made using the “Psychrometrics” feature of the CTI Toolkit. For several reasons, the evaporation rate would be expected to be very low and difficult to measure precisely.

1. Ambient conditions on all of the test days were relatively cool with a low wet bulb depression.

2. The nozzle supply pressure was only 60 psig which is low for the production of a fine mist.

3. The residence time was only about 1 second (~ 8 foot travel at 485 ft./min/).

Consequently, data in Appendix A, Table A-2 indicate a high degree of uncertainty and scatter in the measurements. In several instances, the net evaporation was measured as negative.

Uncertainty in the temperature measurements of a fraction of a degree Fahrenheit has a large influence on the result. In one set of auxiliary measurement, all four psychrometers operating dry were placed close together and read simultaneously over a one hour period. Table 4 shows the results with differences among them sufficiently large to obscure any systematic evaporation measurements. We concluded that the evaporation rate was at or below the limit of detection with our instrumentation. It was not considered further.
### Table 4: Comparison of Temperature Readings

<table>
<thead>
<tr>
<th>Time</th>
<th>9:15</th>
<th>9:30</th>
<th>9:48</th>
<th>10:15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometer</td>
<td>Temperature, °F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>61.00</td>
<td>61.80</td>
<td>62.00</td>
<td>62.70</td>
</tr>
<tr>
<td>2</td>
<td>61.40</td>
<td>62.00</td>
<td>62.30</td>
<td>62.70</td>
</tr>
<tr>
<td>3</td>
<td>61.20</td>
<td>61.80</td>
<td>63.00</td>
<td>63.00</td>
</tr>
<tr>
<td>4</td>
<td>61.20</td>
<td>61.90</td>
<td>63.00</td>
<td>63.60</td>
</tr>
<tr>
<td>Average</td>
<td>61.20</td>
<td>61.88</td>
<td>62.58</td>
<td>63.00</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.163</td>
<td>0.096</td>
<td>0.506</td>
<td>0.424</td>
</tr>
</tbody>
</table>

#### 4.2 Demister performance

Test results for the four demister panels tested are summarized below.

**4.2.1 Marley matrix panel**

Data for the Marley matrix panels are found in Appendix A, Tables A-3 and A-4 and are summarized in Table 5.
4.2.2 Marley Hi-V panel

Data for the Marley Hi-V panels are found in Appendix A, Table A-5 and are summarized in Table 6.

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Vel'y</th>
<th>Spray Rate</th>
<th>Drainage</th>
<th>Fraction Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>9/4--1</td>
<td>256</td>
<td>0.11</td>
<td>0.063</td>
<td>57.3%</td>
</tr>
<tr>
<td>9/4--2</td>
<td>256</td>
<td>0.11</td>
<td>0.073</td>
<td>66.4%</td>
</tr>
<tr>
<td>9/5--1</td>
<td>640</td>
<td>0.12</td>
<td>0.088</td>
<td>73.3%</td>
</tr>
<tr>
<td>9/5--2</td>
<td>640</td>
<td>0.12</td>
<td>0.092</td>
<td>76.7%</td>
</tr>
<tr>
<td>9/5--3</td>
<td>512</td>
<td>0.15</td>
<td>0.097</td>
<td>64.7%</td>
</tr>
<tr>
<td>9/5--4</td>
<td>512</td>
<td>0.15</td>
<td>0.097</td>
<td>64.7%</td>
</tr>
<tr>
<td>9/5--5</td>
<td>512</td>
<td>0.23</td>
<td>0.162</td>
<td>70.4%</td>
</tr>
</tbody>
</table>

4.2.3 Brentwood DE-120 panel

Data for the Brentwood DE-120 panels are found in Appendix A, Table A-6 and are summarized in Table 7
Table 7: Test Data from Brentwood DE-120 Demister Panel

### Pressure Drop

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Vel'y</th>
<th>Delta p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fpm</td>
<td>in H2O</td>
</tr>
<tr>
<td>Spray on</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/9--1p</td>
<td>512</td>
<td>.03-.04</td>
</tr>
<tr>
<td>9/9--2p</td>
<td>640</td>
<td>.04-.05</td>
</tr>
<tr>
<td>9/9--3p</td>
<td>384</td>
<td>.02-.03</td>
</tr>
<tr>
<td>9/9--4p</td>
<td>256</td>
<td>.01-.02</td>
</tr>
<tr>
<td>Spray off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/9--5p</td>
<td>256</td>
<td>0.015</td>
</tr>
<tr>
<td>9/9--6p</td>
<td>384</td>
<td>0.019</td>
</tr>
<tr>
<td>9/9--7p</td>
<td>512</td>
<td>0.025</td>
</tr>
<tr>
<td>9/9--8p</td>
<td>640</td>
<td>0.033</td>
</tr>
</tbody>
</table>

### Drainage

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Vel'y</th>
<th>Spray Rate</th>
<th>Drainage</th>
<th>Fraction Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/9--1</td>
<td>512</td>
<td>0.08</td>
<td>0.035</td>
<td>43.8%</td>
</tr>
<tr>
<td>9/9--2</td>
<td>640</td>
<td>0.23</td>
<td>0.039</td>
<td>17.0%</td>
</tr>
<tr>
<td>9/9--3</td>
<td>640</td>
<td>0.23</td>
<td>0.023</td>
<td>10.0%</td>
</tr>
<tr>
<td>9/9--4</td>
<td>512</td>
<td>0.23</td>
<td>0.01</td>
<td>4.3%</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/9--5</td>
<td>512</td>
<td>0.23</td>
<td>0.072</td>
<td>31.3%</td>
</tr>
<tr>
<td>9/9--6</td>
<td>640</td>
<td>0.23</td>
<td>0.137</td>
<td>59.6%</td>
</tr>
</tbody>
</table>

#### 4.2.4 C. E. Shepherd panel

Data for the C. E. Shepherd panels are found in Appendix A, Table A-7 and are summarized in Table 8
4.3 Performance comparisons

4.3.1 Droplet collection

All four panels demonstrated satisfactory droplet removal performance. Over the full range of air flows and droplet loadings tested. As noted previously, a “typical” face velocity for a full-scale ACC is approximately 500 fpm. The test conditions ranged from 256 fpm to 640 fpm with most of the tests at 512 fpm or 640 fpm. The droplet loading is more difficult to select a simulation for. If a full-scale ACC were outfitted with inlet spray enhancement, a likely maximum spray rate would be about 25 gpm per cell for an inlet air temperature reduction of about 10 °F. If there were no evaporation, the superficial liquid loading for a 2,750 ft.² bundle frontal area would be 0.0091 gpm/ ft.². For the test rig with a 25 ft.² frontal area, this would be simulated with a spray rate of 0.23 gpm which was the case in several of the tests. However, spray enhancement on an operating ACC would be expected to evaporate at least 75 to 80 percent of the delivered spray, reducing the droplet loading at the bundle inlet plane to at least 0.0018 to 0.0023 gpm/ ft.² corresponding to a spray rate on the test rig of 0.045 to 0.058 gpm. The lowest spray rate tested was 0.08 gpm and that in only one test. Therefore, the droplet loadings in the tests were significantly higher than would be expected in practice. This should represent a more severe test of the droplet removal and internal drainage performance and is considered appropriate for the test program.

4.3.2 Rainback/Internal drainage

The rainback performance varied considerably from one panel to another. Both the Marley HI-V and C. E. Shepherd had unacceptably high levels of rainback as shown in Figures 27 and 28. The Marley matrix had the least rainback, and, consequently, the highest “collected fraction” through internal drainage. The collected fraction ranged from 57 percent to 77 percent with the lowest value at an air velocity of only 256 fpm which would be expected to allow more droplet fallout prior to the demister inlet. The Brentwood DE-120 gave reasonable drainage collection.
(up to 60 percent in the vertical orientation but unacceptably low values (4 percent to 17 percent) at the higher droplet loadings and only 44 percent at the lowest (0.08 gpm) spray rate.

**Figure 27: Rainback from Marley Hi-V Panel**
4.3.3 Pressure drop

Measurements of pressure drop vs. air flow were made on three of the four panels. In the case of the Brentwood DE-120, measurements were made both with the spray on and the spray off. The Marley HI-V panel was not tested for pressure drop since the rainback was observed to be so high as to preclude any further interest. It would be expected to have pressure drop comparable to the C. E. Shepherd panel, however, because of the similar geometry.

The pressure drop results are shown in Figure 29.
Two items are noteworthy.

1. For the case of the Brentwood DE-120, the pressure drop is higher for the same air flow for the Spray On condition than for the Spray Off condition. This is presumably due both to some degree of blockage from the water held up in the demister passages and to higher surface drag from the uneven wavy water surface.

2. The C. E. shepherd pressure drop is significantly higher than the other panels, due presumably to the blunt leading edges of the blades. This same geometry contributes to the high degree of droplet impingement, capture and subsequent rainback from the blunt leading edges in both the C. E. shepherd and the Marley HI-V panel.

3. The pressure drop at the “design” air velocity of 485 fpm with spray on ranges from .04 in H2O (Brentwood DE-120) to .06 in H2O (Marley matrix). This compares to an ACC fan static pressure rise of about 0.5 in H2O or an increase of 10 percent in the pressure drop and fan power. For a full scale ACC this would represent several hundred kilowatts additional operating power.
CHAPTER 5: Conclusions

The demister testing leads to the following conclusions.

1. It would be possible to select a demister which could be mounted at the inlet plane of the ACC tube bundles that would provide satisfactory protection to the finned tubes against repeated wetting and drying. This would permit the use of low quality water and courser spray nozzles while eliminating the risk of corrosion or scaling.

2. It is likely that a satisfactory drainable and collection arrangement could be designed which would maintain acceptably dry conditions in the interior of the A-frame and recover the water for reuse.

3. The disadvantages would be
   
   a. There is an increase in fan power over the entire year of about 10 percent. We assumed that the demisters would stay in place all year long because it would be costly to remove and re-install them every year.
   
   b. There is a significant increase in the cost of an inlet spray enhancement system for retrofit situations. For a plausible installed material cost of $3.00 to $5.00 per square foot, the cost for a 30 cell ACC would exceed $240,000 to $400,000 plus a high installation cost to mount the panels in an existing cell. (If a new unit were so equipped, the installation cost would likely be substantially reduced.)
CHAPTER 6: Recommendation

The use of demisters as part of a spray enhancement system would appear to be a “solution of last resort”. For the immediate future of the demonstration program, attention will be turned to minimizing the cost of any necessary water treatment system and optimizing the choice and location of nozzles to minimize surface wetting. However, if it should be necessary, the use of demisters has been shown to be technically feasible if the benefits of spray enhancement are sufficiently high to warrant it.
## APPENDIX A: Demister Test Data Sheets

### Table A-1: Airflow Calibration Data

<table>
<thead>
<tr>
<th>Position</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
<th>Position</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>385</td>
<td>533</td>
<td>668</td>
<td>528.7</td>
<td>Top</td>
<td>475</td>
<td>635</td>
<td>840</td>
<td>650.0</td>
</tr>
<tr>
<td>Middle</td>
<td>399</td>
<td>512</td>
<td>608</td>
<td>506.3</td>
<td>Middle</td>
<td>510</td>
<td>620</td>
<td>740</td>
<td>623.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>601</td>
<td>475</td>
<td>529</td>
<td>535.0</td>
<td>Bottom</td>
<td>576</td>
<td>645</td>
<td>670</td>
<td>630.3</td>
</tr>
<tr>
<td>Average</td>
<td>461.7</td>
<td>506.7</td>
<td>601.7</td>
<td>523.3</td>
<td>Average</td>
<td>520.3</td>
<td>633.3</td>
<td>750.0</td>
<td>634.6</td>
</tr>
</tbody>
</table>

Repeated points (highlighted)

<table>
<thead>
<tr>
<th>Position</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>385</td>
<td>533</td>
<td>701</td>
<td>539.7</td>
</tr>
<tr>
<td>Middle</td>
<td>399</td>
<td>512</td>
<td>608</td>
<td>506.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>465</td>
<td>475</td>
<td>529</td>
<td>489.7</td>
</tr>
<tr>
<td>Average</td>
<td>416.3</td>
<td>506.7</td>
<td>612.7</td>
<td>511.9</td>
</tr>
</tbody>
</table>

### Table A-2: Evaporation Rate Measurements

Evaporation Calculations:

<table>
<thead>
<tr>
<th>Run Date/Time</th>
<th>Fan Frequency</th>
<th>Spray Rate</th>
<th>Inlet T</th>
<th>Inlet WB</th>
<th>Inlet Humidity</th>
<th>Exit T</th>
<th>Exit WB</th>
<th>Exit Humidity</th>
<th>Water In</th>
<th>Water Out</th>
<th>Evap Rate</th>
<th>Fraction Evaporated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 4/Afternoon</td>
<td>20</td>
<td>0.11</td>
<td>78.9</td>
<td>65.5</td>
<td>0.01050</td>
<td>76.8</td>
<td>67.0</td>
<td>0.00856</td>
<td>76.6</td>
<td>64.0</td>
<td>0.01026</td>
<td>0.01000</td>
</tr>
<tr>
<td>Sep. 4/Afternoon</td>
<td>20</td>
<td>0.11</td>
<td>76.9</td>
<td>65.2</td>
<td>0.01062</td>
<td>76.0</td>
<td>66.2</td>
<td>0.00122</td>
<td>67.8</td>
<td>61.6</td>
<td>0.00934</td>
<td>0.00900</td>
</tr>
<tr>
<td>Sep. 5/11:15 AM</td>
<td>50.00</td>
<td>0.12</td>
<td>68.2</td>
<td>60.4</td>
<td>0.009945</td>
<td>67.8</td>
<td>59.5</td>
<td>0.009021</td>
<td>76.7</td>
<td>64.3</td>
<td>0.00921</td>
<td>0.00950</td>
</tr>
<tr>
<td>Sep. 5/11:25 AM</td>
<td>50.00</td>
<td>0.12</td>
<td>69.6</td>
<td>61.2</td>
<td>0.009996</td>
<td>69.5</td>
<td>60.0</td>
<td>0.008890</td>
<td>69.8</td>
<td>61.2</td>
<td>0.00905</td>
<td>0.00890</td>
</tr>
<tr>
<td>Sep. 5/12:35 PM</td>
<td>50.00</td>
<td>0.13</td>
<td>69.0</td>
<td>62.2</td>
<td>0.009966</td>
<td>69.0</td>
<td>60.0</td>
<td>0.008833</td>
<td>69.4</td>
<td>61.3</td>
<td>0.00902</td>
<td>0.00883</td>
</tr>
<tr>
<td>Sep. 5/13:45 PM</td>
<td>50.00</td>
<td>0.13</td>
<td>72.7</td>
<td>61.9</td>
<td>0.009338</td>
<td>72.6</td>
<td>62.6</td>
<td>0.009239</td>
<td>72.5</td>
<td>64.4</td>
<td>0.00999</td>
<td>0.00999</td>
</tr>
<tr>
<td>Sep. 5/3:12 PM</td>
<td>40.00</td>
<td>0.15</td>
<td>77.9</td>
<td>66.7</td>
<td>0.011934</td>
<td>77.6</td>
<td>64.7</td>
<td>8.7</td>
<td>0.068</td>
<td>12</td>
<td>0.094</td>
<td></td>
</tr>
</tbody>
</table>

Airflow:
- **Air density @ 70 F lb/cu ft**: 0.075
- **Average Veloc, fpm**: 512
- **Vol flow, cu. ft./min**: 12,798
- **Mass flow, lb/min**: 960

**Summary Averages**

<table>
<thead>
<tr>
<th>Summary Averages</th>
<th>Drive, Hz</th>
<th>Vel, fpm</th>
<th>Flow, acfm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>40</td>
<td>517.6</td>
<td>12,940</td>
</tr>
<tr>
<td>Middle</td>
<td>50</td>
<td>634.6</td>
<td>15,865</td>
</tr>
<tr>
<td>Bottom</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Evaporation Rate**

| Sep. 4/Afternoon | Neg. evap |
| Sep. 5/11:15 AM | Neg. evap |
| Sep. 5/11:25 AM | Neg. evap |
| Sep. 5/12:35 PM | Neg. evap |
| Sep. 5/13:45 PM | Neg. evap |
| Sep. 5/3:12 PM  | Neg. evap |

---

*Note: Data measured with EXTECh Heavy Duty Vane Thermo-Anemometer; Model 407112.*
### Table A-3: Marley Matrix Data

Demister Tests—EnviroCare Test Rig—Spetmeber, 2003

September 4, 2003 (Thursday)

Demister Type: Marley Stacked Matrix (first installed)

Nozzle: WDB8

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Pressure</th>
<th>Nozzle Flow</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
<th>Fraction collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hz</td>
<td>psig</td>
<td>oz/min</td>
<td>F</td>
<td>F</td>
<td>oz/min</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>Afternoon #1</td>
<td>20</td>
<td>60</td>
<td>14</td>
<td>0.11</td>
<td>78.0</td>
<td>65.5</td>
<td>76.0</td>
<td>67.0</td>
<td>3.75</td>
<td>4.25</td>
<td>0.029</td>
</tr>
<tr>
<td>Afternoon #2</td>
<td>20</td>
<td>60</td>
<td>14</td>
<td>0.11</td>
<td>76.9</td>
<td>65.2</td>
<td>76.0</td>
<td>66.2</td>
<td>4</td>
<td>5.375</td>
<td>0.042</td>
</tr>
</tbody>
</table>

### Table A-4: Marley Matrix Data

Demister Tests—EnviroCare Test Rig—Spetmeber, 2003

September 5, 2003 (Friday)

Demister Type: Marley Stacked Matrix (first installed)

Nozzle: PJ24

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Pressure</th>
<th>Nozzle Flow</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
<th>Fraction collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hz</td>
<td>psig</td>
<td>oz/min</td>
<td>F</td>
<td>F</td>
<td>oz/min</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>11:15</td>
<td>50</td>
<td>60</td>
<td>15.6</td>
<td>0.12</td>
<td>68.2</td>
<td>60.4</td>
<td>67.6</td>
<td>65.8</td>
<td>4.15</td>
<td>7.15</td>
<td>0.032</td>
</tr>
<tr>
<td>11:25</td>
<td>50</td>
<td>60</td>
<td>15.6</td>
<td>0.12</td>
<td>69.6</td>
<td>61.2</td>
<td>69.5</td>
<td>60.0</td>
<td>4.5</td>
<td>7.25</td>
<td>0.035</td>
</tr>
<tr>
<td>11:35</td>
<td>50</td>
<td>60</td>
<td>16.6</td>
<td>0.13</td>
<td>69.8</td>
<td>61.2</td>
<td>69.8</td>
<td>60.0</td>
<td>4.5</td>
<td>7.25</td>
<td>0.035</td>
</tr>
<tr>
<td>~12:15</td>
<td>50</td>
<td>60</td>
<td>16.6</td>
<td>0.13</td>
<td>72.7</td>
<td>61.9</td>
<td>72.6</td>
<td>61.6</td>
<td>4.5</td>
<td>7.25</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Nozzle: WDB14

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Pressure</th>
<th>Nozzle Flow</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
<th>Fraction collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hz</td>
<td>psig</td>
<td>oz/min</td>
<td>F</td>
<td>F</td>
<td>oz/min</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>2:10</td>
<td>40</td>
<td>60</td>
<td>19.5</td>
<td>0.15</td>
<td>77.6</td>
<td>65.7</td>
<td>75.6</td>
<td>64.5</td>
<td>5</td>
<td>7.4</td>
<td>0.039</td>
</tr>
<tr>
<td>2:35</td>
<td>40</td>
<td>60</td>
<td>19.5</td>
<td>0.15</td>
<td>76.5</td>
<td>65.6</td>
<td>75.6</td>
<td>63.8</td>
<td>5.2</td>
<td>7.2</td>
<td>0.041</td>
</tr>
<tr>
<td>2:45</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>77.9</td>
<td>66.7</td>
<td>78.3</td>
<td>64.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Nozzle: WDB18

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Pressure</th>
<th>Nozzle Flow</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
<th>Fraction collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hz</td>
<td>psig</td>
<td>oz/min</td>
<td>F</td>
<td>F</td>
<td>oz/min</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>gpm</td>
<td>%</td>
</tr>
<tr>
<td>3:30</td>
<td>40</td>
<td>60</td>
<td>29</td>
<td>0.23</td>
<td>78</td>
<td>63.9</td>
<td>75.6</td>
<td>64.7</td>
<td>8.7</td>
<td>12</td>
<td>0.068</td>
</tr>
</tbody>
</table>

### Pressure Drop Across Demister

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Delta p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hz</td>
<td>in H2O</td>
</tr>
<tr>
<td>3:00</td>
<td>40</td>
<td>3.05 to 0.06</td>
</tr>
<tr>
<td>3:05</td>
<td>50</td>
<td>0.07</td>
</tr>
</tbody>
</table>

0.07/0.055 = 1.27
50/40 = 1.25; (50/40)**2 = 1.56
Table A-5: Marley Hi-V Data

Demister Tests—EnviroCare Test Rig—Spetmeber, 2003

September 9, 2003 (Tuesday)

Demister Type: Marley Hi-V

Nozzle: WDB18

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Pressure</th>
<th>Nozzle Flow</th>
<th>Temp F</th>
<th>Wet Bulb F</th>
<th>Left oz/min</th>
<th>Right oz/min</th>
<th>Total oz/min</th>
<th>Drain flow</th>
<th>Fraction collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:40</td>
<td>40</td>
<td>60</td>
<td>not meas</td>
<td>0.24</td>
<td>not measured</td>
<td>0</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>45.6</td>
</tr>
</tbody>
</table>

Airflow Measurements (Readings in ft/min)

(Measured with EXTECh Heavy Duty Vane Thermo-Anemometer; Model 407112)

Superficial area, sq. ft.: 25.42
Fan Drive at 50Hz

<table>
<thead>
<tr>
<th>Position</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>315</td>
<td>330</td>
<td>353</td>
<td>332.7</td>
<td>990</td>
<td>784</td>
<td>780</td>
<td>851.3</td>
</tr>
<tr>
<td>Middle</td>
<td>441</td>
<td>455</td>
<td>439</td>
<td>445.0</td>
<td>607</td>
<td>453</td>
<td>560</td>
<td>540.0</td>
</tr>
<tr>
<td>Bottom</td>
<td>611</td>
<td>421</td>
<td>512</td>
<td>514.7</td>
<td>333</td>
<td>298</td>
<td>260</td>
<td>297.0</td>
</tr>
</tbody>
</table>

Average: 455.7 | 402.0 | 434.7 | 430.8

Repeated points (in green)

<table>
<thead>
<tr>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>315</td>
<td>330</td>
<td>353</td>
</tr>
<tr>
<td>Middle</td>
<td>441</td>
<td>455</td>
<td>439</td>
</tr>
<tr>
<td>Bottom</td>
<td>558</td>
<td>421</td>
<td>512</td>
</tr>
</tbody>
</table>

Average: 438.0 | 402.0 | 434.7 | 424.9
### Table A-6: Brentwood DE-120 Data

#### Demister Tests—EnviroCare Test Rig—Spetmeber, 2003

September 16 & 17, 2003 (Tuesday & Wednesday)

Demister Type: Brentwood DE-120

#### Nozzle: WDB8

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Delta p in H2O</th>
<th>Pressure</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left oz/min</th>
<th>Right oz/min</th>
<th>Total oz/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:40</td>
<td>40</td>
<td>30</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>40.5</td>
<td>30</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>0</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Sep. 17**

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Delta p in H2O</th>
<th>Pressure</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left oz/min</th>
<th>Right oz/min</th>
<th>Total oz/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>30</td>
<td>1</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>1</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>1</td>
<td>60</td>
<td>10.5</td>
<td>0.082</td>
<td>not measured</td>
<td>0</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Airflow Measurements** (Readings in ft/min)

(Measured with EXTECH Heavy Duty Vane Thermo-Anemometer; Model 407112)

<table>
<thead>
<tr>
<th>Superficial area, sq. ft.: 25.42</th>
<th>Measured at outer face of eliminator pack (60.5&quot; x 60.5&quot;)</th>
<th>Fan Drive at 40Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>343 378 378 366.3</td>
<td>1048 825 904 925.7</td>
</tr>
<tr>
<td>Middle</td>
<td>430 486 509 472.0</td>
<td>611 474 644 576.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>717 755 649 707.0</td>
<td>292 390 322 334.7</td>
</tr>
<tr>
<td>Average</td>
<td>496.7 539.7 509.0 515.1</td>
<td>Average 650.3 563.0 623.3</td>
</tr>
<tr>
<td>Inlet Air</td>
<td>Exit Air</td>
<td></td>
</tr>
<tr>
<td>Nozzle Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Air</td>
<td>Exit Air</td>
<td></td>
</tr>
<tr>
<td>Nozzle Flow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Liquid Drain Measurements**

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Delta p in H2O</th>
<th>Pressure</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left oz/min</th>
<th>Right oz/min</th>
<th>Total oz/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:40</td>
<td>40.0</td>
<td>60</td>
<td>10.5</td>
<td>0.08</td>
<td>not measured</td>
<td>0</td>
<td>0.035</td>
<td>4.5</td>
<td>0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Sep. 17 WDB18**

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive</th>
<th>Delta p in H2O</th>
<th>Pressure</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Temp</th>
<th>Wet Bulb</th>
<th>Left oz/min</th>
<th>Right oz/min</th>
<th>Total oz/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>60</td>
<td>0.23</td>
<td>5</td>
<td>0.039</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0.039</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>0.23</td>
<td>3</td>
<td>0.023</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0.023</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>0.23</td>
<td>1.3</td>
<td>0.010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.3</td>
<td>0.010</td>
<td>0</td>
</tr>
</tbody>
</table>

---

**B-48**
Table A-7: C. E. Shepherd Data

Demister Tests—EnviroCare Test Rig—December, 2003

December 22, 2003 (Monday)

Demister Type: C. E. Shepherd

Nozzle: WDB 18 (?)

<table>
<thead>
<tr>
<th>Run Time</th>
<th>Fan Drive Hz</th>
<th>Delta p in H2O</th>
<th>Nozzle Pressure psig</th>
<th>Nozzle Flow oz/min</th>
<th>Inlet Air Temp F</th>
<th>Wet Bulb F</th>
<th>Exit Air Temp F</th>
<th>Wet Bulb F</th>
<th>Left Drain flow oz/min gpm</th>
<th>Right Drain flow oz/min gpm</th>
<th>T F</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:30</td>
<td>30</td>
<td>.08/.07</td>
<td>No spray</td>
<td>not measured</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td></td>
<td>nm</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>11:12</td>
<td>50</td>
<td>nm</td>
<td>60</td>
<td>0.24</td>
<td>53.2</td>
<td>not measured</td>
<td>0</td>
<td>0</td>
<td>7.0</td>
<td>0.05</td>
<td>24</td>
</tr>
</tbody>
</table>

Airflow Measurements (Readings in ft/min)
(Measured with EXTECh Heavy Duty Vane Thermo-Anemometer; Model 407112)

Measured at outer face of eliminator pack (60.5” x 60.5”)
Superficial area, sq. ft.: 25.42

Fan Drive at 50 Hz

<table>
<thead>
<tr>
<th>Position</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>562</td>
<td>561</td>
<td>602</td>
<td>575.0</td>
</tr>
<tr>
<td>Middle</td>
<td>628</td>
<td>642</td>
<td>642</td>
<td>651.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>646</td>
<td>634</td>
<td>634</td>
<td>643.3</td>
</tr>
<tr>
<td>Average</td>
<td>612.0</td>
<td>631.7</td>
<td>626.0</td>
<td>623.2</td>
</tr>
</tbody>
</table>
APPENDIX C
Crockett Flow Pattern Observations
Introduction

During the hottest periods of the year, air-cooled condensers are often limited in their ability to maintain desired turbine backpressure. Inlet spray cooling is a potential approach to mitigating this problem.

This paper presents the results from field tests conducted August 27, 2003 on one of the auxiliary cooling cells on the air-cooled condenser auxiliary heat exchanger at the Crockett Cogeneration plant. Sprays were mounted on a movable rack hung below the fan. Tests were carried out to establish the effect of droplet size (as affected by nozzle choice and nozzle supply pressure), droplet residence time, ambient conditions, spray flow rate and nozzle location on the inlet cooling effect and the efficiency of water utilization.

Background

Crockett desires a supplementary spray enhancement capability to operate for a limited number (25 to 50) of hours per year in order to maintain 240 MW output on the hottest hours or at times when the co-gen host is not accepting the normal steam load.

They have installed a pump (and delivery piping to one cell) capable of 144 gpm or 12 gpm per ACC cell. Some trial nozzles were installed in Cell ACC-I, as shown in Figure 3. It remains to be determined the best way to introduce 12 gpm of spray into the air stream inside each cell at a location above the fan that will

- maximize the fraction of spray evaporated and
- minimize the amount of unevaporated water impinging upon the finned tube bundle surfaces.

Information on ambient conditions during the test period, test cells and nozzles follow.

Ambient conditions

Ambient temperature: 75 to 80°F

Relative humidity: Not reported (wet bulb temperature probably between 65 to 70°F based on 2001 experience)

Wind: Moderate and reasonably steady from the West (based on wind sock observation near ground off SW corner of the ACC)
Test cell

Primary cell Cell #ACC-I; Cell adjacent to ACE “C” cell (cell at west end of south row)

Secondary cell Cell # ACC-J; Next cell to the east. Brief confirmatory observations were made to see if major differences were seen.

Nozzles

2.6 gpm high momentum nozzle; 30° full cone

5.25 gpm 60° hollow cone (pigtail design)

Initial Tests, August 27, 2003

A 2.6 gpm spray stream was sprayed into the air at several locations along the catwalk. Figure 1 shows the positions of the several spray injection locations and defines the nomenclature for the following description of the observed flow patterns.

The spray lance was typically held at the height of the catwalk top rail (approximately 3 1/2 feet above the catwalk floor level and could be pointed in different directions (up, down, or horizontally and at different angles relative to the catwalk). In a few instances, the lance was lowered to the catwalk floor level or held to a level of 8 to 10 feet above the catwalk floor.

Figure 2 provides a sketch of the general airflow pattern inside the cell. The fan rotates in a clock-wise direction (looking down from the top) and imparts a general swirl flow to the air passing through the cell. The flow is highly unsteady and is generally ordered as follows:

- in the lower part of the cell the flow rotates in a toroidal pattern with a secondary (also clockwise looking in the direction of the primary swirl) rotation; (See Figure 4)
- in the upper part of the cell (above the cross structural members) the flow is primarily upward and turns outward toward the upper portion of the tube bundles.

Observed Spray Patterns – Cell I

Location: L – left side of catwalk, facing east; R – right side of catwalk, facing east

L-1 (north-east corner; outside perimeter of fan shroud):

Flow turns vertically upward exiting through tube bundles near top of A-frame; substantial liquid impingement on east cell wall.

L-2: (over fan blades; one-third of distance from tip to hub):

Majority of flow turns upward; some flow entrained and flows both over and under the catwalk over to the south side of the cell (into the R-1/R-2 area); liquid impingement on east wall much reduced

L-3: (over fan blades; two-thirds of distance from tip to hub):
Similar to L-2; more of the flow entrained into the clockwise swirl over to south side of the cell; no more impingement on east wall; most of the entrained flow now goes under the catwalk; little accumulation on structural surfaces high up on north side; additional accumulation on south side in R-1/R-2 areas.

L-4: (over fan centerline):

With nozzle pointed down, the spray goes straight down and hits the hub; when pointed horizontally the full flow is entrained and goes mostly under the catwalk; droplets can be felt in the R-5 to R-7 areas.

L-5: (over fan blades; one-third of distance from hub to tip):

Spray directed horizontally and perpendicular to catwalk; tube bundles wetted opposite spray position but majority of flow is entrained and carried around under the catwalk; injection lance turned 45° (toward the east end in the direction of the swirl) results in much reduced wetting of the tube bundles and additional entrainment into the clockwise swirl pattern; when turned 45° (toward the west end facing into the swirl direction) result is increased wetting of the tube bundles; still good entrainment of much of the flow.

There appears to be a critical angle at which the penetration of the spray toward the tube bundles is suddenly reduced as the entrainment into the swirl flow suddenly increases. This angle is about 45° but is somewhat dependent on droplet size and momentum and, therefore, a function of which nozzle is used.

L-6: (over fan blades; two-thirds of distance from hub to tip):

Similar behavior to L-5 with less wetting of the tube bundle surfaces and more entrainment into the swirl flow under similar injection locations and directions;

The injection level was lowered from the top rail to the catwalk floor level. This resulted in more upflow and increased wetting of the bundle surfaces.

L-7: (north-west corner; outside perimeter of fan shroud):

Similar behavior of L-1; flow goes pretty much straight up, wets the bundles and exits the cell at the top of the bundles; little wetting of the west wall.

R-1: (south-east corner; outside of fan shroud) and R-2: (over fan blades; one-third of distance from tip to hub):

Brief observations were made as a “symmetry check” expecting behavior similar to the L-6/L-7 behavior.

Symmetry was essentially confirmed although the downdraft entrainment appeared to be slightly weaker with a corresponding slight increase in the amount of wetting of the tube bundles.
Since the cell doors (open between Cell I and the ACE Cell C; closed between Cell I and Cell J) introduced some asymmetry, observations were made with both doors open and both doors closed. No significant differences were observed.

**Observed Spray Patterns – Cell J**

“L-6” (west end, left hand side of catwalk; two-thirds of the way from hub to tip):

Brief observations were made in the next cell to the east at a location corresponding to L-6; the pattern and degree of bundle surface wetting was comparable in appearance. Any differences, had they been observed, would presumably have been attributable to differing effects of wind on the two cells. Since the wind was moderate, westerly and steady, this was not a particularly severe test of cell-to-cell comparability.

**5.2 gpm Nozzle**

Since two of the four corners appeared to be the preferred spray locations, a spray flow at each location of 5 to 6 gpm would be required to supply the desired 10 to 12 gpm to the cell. Tests were run with the larger nozzle to determine whether this much flow could be adequately dispersed from one location.

L-6 and R-2: Very similar patterns were observed at the higher flow rate. The degree of wetting of the tube bundle was higher but could be minimized with adjustment of the injection angle (60 to 70 degrees from perpendicular). Higher volumes of water were deposited on the structural surfaces. There will always be some amount of unevaporated liquid sequestered on the structural surfaces; it is to be expected that the amount will decrease as the ambient temperature increases and the evaporation rate increases.

**Other Observations**

There was relatively little loss of unevaporated liquid out the bottom of the cell. It was not possible to judge this from the wetting of the floor beneath the cell, since a bypass flow to protect the pump was continuously being discharged from the ACC walkway and wetting the floor beneath Cells I and J. However, there was very little liquid observed on the inside of the fan shroud indicating that very little liquid impinged on the fan blades. This is in distinction to observations made during our tests with the spray introduced below the fan where substantial liquid was intercepted by the fan blades and thrown to the shroud resulting in a constant dripping from the bottom edge of the shroud onto the floor.

**Additional Testing, August 29, 2003**

Additional tests were conducted on Friday, August 29, 2003 to obtain confirmatory information in three areas in order to

1. observe any wind effects inside the cell with the fan turned off,
2. confirm the existence of a the secondary toroidal flow and
3. determine the benefit of corner injection in the L1 and R7 areas to obtain more and complete coverage of the airflow into the bundles.
Fan-off Operation

The upward airflow at the eastern end of the catwalk was consistently stronger than that at the western end throughout the test period on August 27. This was true for all cells in the south row. It was hypothesized that this might be the result of the wind patterns with the prevailing winds from the west. To explore this further, the fan was turned off for a period of 10 to 15 minutes to see if wind currents could be felt inside the cell at preferred locations. For conditions prevailing at 10:30 to 10:45 am on August 29, there was no observable air motion within the cell that could be attributed to the wind. Therefore, no conclusions could be drawn about the effect of wind on the flow patterns within the cell.

Secondary Toroidal Flow

Injection at 2.6 gpm at several locations and in differing angles relative to the horizontal and to the catwalk confirmed the existence of a clock-wise toroidal circulation (See Figures 5 and 6). This flow pattern can be exploited to obtain both longer residence times for spray droplets and to minimize the amount of unevaporated liquid impinging on the finned tube bundles.

Corner Injection

At location L1 and R7, spray introduced into the airflow outboard of the fan circumference turns immediately upward and is not entrained in the clockwise circulating flow pattern characteristic of the lower portion of the cell (See Figure 7). Therefore, spray at that location gives improved coverage of bundle areas in the northeast (L1) and southwest corners particularly in the upper portion of the cell.

Recommendations

In order to provide a spray rate of 12 gpm in a single cell, the recommended arrangement is the following:

1. Two spray nozzles of approximately 5 gpm each should be located at the L-6 and R-2 positions at a level near the top of the catwalk railing. Nozzles of the hollow cone type with cone angles of 60 to 90° directed horizontally at a 45 to 60° angle from the perpendicular to the catwalk in the direction of the primary, clockwise swirl.
2. Two nozzles with capacities of approximately 1 gpm each should be located at the L-1 and R-7 positions at a level near the top of the catwalk railing. These nozzles, also of the hollow cone type with cone angle of 60 to 90°, should be directed vertically.
Figure 1

Location of Spray Insertion Points
Figure 2

Schematic of Observed Flow Pattern
Figure 3

Trial Installation

(Note “split” cone; outer cone ~ 170° angle; inner cone ~ 60° angle)
Figure 4

Spray Entrainment in Clockwise Swirl Flow in Lower Part of Cell
Figure 5
Toroidal Flow Pattern---Downflow at Hub
Figure 6
Toroidal Flow Pattern—Down Near Hub; Up Near Bundles
Figure 7

Upflow in Northeast Corner (Location L-1)