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FINAL PROJECT REPORT

Power and Water-Saving Advanced Hybrid Air/Wet Cooling System

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Power and Water-Saving Advanced Hybrid Air/Wet Cooling System is the final report for the Power and Water-Saving Advanced Hybrid Air/Wet Cooling System (Contract Number EPC-16-012) conducted by Altex Technologies Corporation. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC website at www.energy.ca.gov/research/ .

ABSTRACT

Given reduced water supplies in arid regions of California, obtaining water permits for air conditioning and refrigeration condenser cooling use in commercial and industrial buildings is becoming a challenge. Water can be saved by driving users to dry-only cooling systems, but at a higher consumer cost. A hybrid system that operates dry most of the time and wet only when ambient air temperatures are high is one way to reduce water use and control capital costs since dry operation at low air temperatures requires a smaller condenser. However, with conventional heat exchanger technology, wet and dry operations require high air-fan power. An advanced hybrid heat exchanger (AHHEX) developed and tested meets the requirements of reduced water use and lower fan power. It operates efficiently when dry and only uses water for cooling at high temperatures. Under this project, a prototype hybrid condenser was designed, fabricated, and integrated with an available 10-ton chiller; performance data was collected over a range of ambient air temperatures. These test results were used to determine the power, water, greenhouse gas, pollutants, and cost-reduction benefits of AHHEX. Water and electric power reductions of up to 2.1 million gallons per year and 28,499 kilowatt hours per year would be expected for a 170-ton cooling system with a constant cooling load. Relative to the total potential California commercial and industrial markets, assuming a 20 percent market share, water and electric power savings from this technology would be 290 million gallons per year and 3.7 million kilowatt hours per year. Greenhouse gas emissions, methane emission and nitrogen oxides would be reduced by 994 tons, 30,316 pounds and 1,278 pounds per year, respectively. The AHHEX can also be applied to utility power systems and yield 25 times the benefit achieved for commercial and industrial systems.

Keywords: Condenser, heat exchanger, cooler, dry cooling, wet cooling, hybrid dry/wet cooling

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EXECUTIVE SUMMARY

Introduction

Dwindling water supplies in dry regions of California make it increasingly difficult to acquire water permits for air conditioning and refrigeration condenser cooling. Driving energy consumers to dry-only cooling systems saves water, but at higher cost because of cycle-efficiency losses. A hybrid system that operates dry most of the time and wet only when ambient air temperatures are high is one logical path for reducing water use. However, with conventional heat exchanger technology, both wet and dry operations require high air-fan power. Wet cooling system heat transfer is driven by lower wet bulb temperatures, which deliver better performance at high ambient air temperatures. However, these systems are designed to use water year-round and deliver relatively poor performance at low ambient-air temperatures when compared with dry systems that don’t require water. Besides eliminating water use and treatment costs, the power needed to pump and treat water would also be eliminated in dry operations; if the hybrid system improves wet and dry heat transfer and fan performance, then the overall hybrid performance itself is also improved. The advanced hybrid heat exchanger (AHHEX) developed and tested in this study meets this threshold requirement. It operates efficiently when dry and uses water only for cooling at high ambient air temperatures. In this project, a prototype AHHEX condenser was integrated with an available 10-ton Legacy Chiller Systems, Inc., (Legacy Chiller) unit, and performance data was collected over a range of ambient-air temperatures. These results then ultimately defined the power, water, greenhouse gas, other pollutant, and cost-reduction benefits of AHHEX.

Project Purpose

Given the timely energy and environmental potential of the AHHEX, this project’s goal was multi-faceted: (1) to leverage prior successful pilot-scale dry cooling and bench-scale wet cooling developments, test results and analyses; (2) to create an advanced hybrid air- and wet-cooling AHHEX test system; (3) to test the unit in an available 10-ton chiller unit to document the hybrid system benefits; and (4) to support the evaluation of those system benefits for commercial and industrial end users. Besides supporting commercial, and industrial cooling loads, this hybrid technology will also reduce power and water use for electric utilities that use Rankine power cycles (a model used to predict steam engine system performance). Specific project objectives were to:

- Integrate Altex Technologies Corporation (Altex) advanced dry and wet cooling systems into a hybrid cooling system that reduces water use by 2.4 million gallons per year and power by 17,420 kilowatt-hours per year, for a chiller with 170 tons of cooling capacity.
- Install AHHEX in a 10-ton chiller from Legacy Chiller for prototype testing.
- Prove the performance in the Altex test facility.

- Evaluate water savings, electricity savings, and reduced capital costs.
- Show AHHEX annual power, water, cost, and greenhouse gas emission savings of 8,371 megawatt-hours, 725 million gallons, $4.47 million, and 2,187 tons, respectively, for commercial and industrial markets.
- Determine production readiness and create a commercialization plan with manufacturing partners and Legacy Chillers.

Project Approach

The AHHEX advanced hybrid air/wet cooling test condenser was developed using prior experience and existing models to design high-performance dry cooling systems. While the most common AHHEX units are greater than 100 tons of cooling, a 10-ton cooling unit was chosen for testing for several factors including a market need in the small-to-medium commercial sector, the ability to be installed in parallel for scaling and to effectively test the system within the project budget. Process conditions for the AHHEX test system were defined with a commercial process analysis model. Heat exchanger product manufacturing experience was then applied to produce a prototype-scale AHHEX test condenser. Several manufacturing partners supported the AHHEX fabrication, a key verification that the hybrid technology would be accepted and work effectively for industrial and commercial end users. The unit was then outfitted with temperature, pressure, and flow instrumentation to measure and document performance. Day-and-night testing covered a range of ambient air temperatures. This test data was then compiled and analyzed over a 1-year period for both cool- and hot-climate locations in California. To identify pollution-reduction impacts, AHHEX and conventional condenser fan-power requirements were compared. The AHHEX reduced-fan-power requirement was then computed and translated into reduced-emission estimates at the power plant providing the electricity. The data then ultimately determined the AHHEX water-use reductions and cost savings.

Project Results

Operation of the AHHEX condenser, integrated in a 10-ton chiller, showed that the AHHEX could provide needed heat dissipation under dry ambient air conditions below 85^{o}F (29^{o}C). Above that temperature the AHHEX system shifted to wet/dry operation, where wet operation effectively drove the system back to dry operation, where residual water in the AHHEX continued to effectively cool the heat until the water was evaporated. At that point AHHEX wet operation was reinitiated. At an ambient air temperature above 89^{o}F (32^{o}C), the AHHEX shifted to continuous wet operation, which maximized cooling; wet operation was recorded for ambient air temperatures up to 95^{o}F (35^{o}C). These test results show that the AHHEX hybrid wet/dry system operated over a range of ambient air temperatures. While the chiller system pressure controls were set to activate wet operation at 85^{o}F (29^{o}C), the controls can adjust to wet/dry transition temperatures, providing additional flexibility to its operation.

Test data show that AHHEX reduced annual evaporative cooler water use by up to 98.7 percent for a 170-ton test cooling system in Oakland, California. The water savings per year for Oakland would, therefore, be 2.1 million gallons per year, which is within range of the project goal. In addition, the AHHEX fan-power reduction was estimated at 28,499 kilowatt-hours per year, exceeding the goal of reducing power by 17,240 kilowatt-hours. While the test-system capacity was approximately an order of magnitude smaller than targeted commercial and industrial markets, the AHHEX modular-panel approach increased capacity by duplicating the panels and connecting them in parallel with the larger chiller. The data from the AHHEX condenser can, therefore, be directly applied to full-scale commercial and industrial condensers.

Results of this study clearly show that the modular nature of the panels and their easy scaling can be applied to AHHEX systems of different sizes for a broad range of applications. The unit was operated so that, just beyond the water activation point, with the water on, AHHEX water activation would turn on and off according to much higher heat dissipation. If desired by the user, this cycling could be either limited or eliminated by controlling each water injector and the panel area being wetted. By controlling the amount of wet cooling, heat dissipation in the wet/dry transition zone could be better balanced, reducing or eliminating cycling. More study is required to further explore this balance.

Technology, Knowledge Transfer, and Market Adoption

At this stage of development there was little emphasis on technology transfer and market adoption. For commercial and industrial markets, discussions were held with Legacy Chillers, which manufactures chillers for a number of process industries. For utility markets, discussions were also held with manufacturers of utility dry-cooling systems. More study and analysis are required to develop and execute a technology- and knowledge-transfer plan.

Benefits to California

While AHHEX applies to a variety of condensing applications, the study example chosen was a typical and familiar system: a wet-cooling, 170-ton mechanical vapor compression chiller. To expand its potential energy and environmental benefits throughout California, the amount of wet cooling already in use in California had to first be determined. Even assuming a conservative 20 percent market penetration, AHHEX has the potential to replace 57,524 installed tons of cooling equipment throughout the state. Using the total market with utility costs, emissions factors, and water-related electricity savings, total savings in the commercial and industrial markets were calculated; the results are summarized in Table ES-1. AHHEX can additionally apply to investor-owned and other utilities. Theoretically considering the application of AHHEX to eight power plants, the power, water, greenhouse gas, pollutant reductions, and cost savings would be substantial when compared with a wet-only system, as shown in Table ES-1.

Table ES-1: AHHEX Projected Power, Water, Cost, and Pollutant Reductions

	Commercial	Industrial	Utility
Power (kWh/yr)	3,049,508	624,418	111,533,485
Water (MGal/yr	241	49	7,736
Power Cost ($K/yr)	477	73	13,105
Water Cost ($K/yr)	940	191	2,080
Total Cost ($K/yr)	1,417	264	15,186
GHG (lbs/yr)	1,650,587	337,975	62,910,418
CH4 (lbs/yr)	25,165	5,151	808,956
N2O (lbs/yr)	1,061	217	34,116

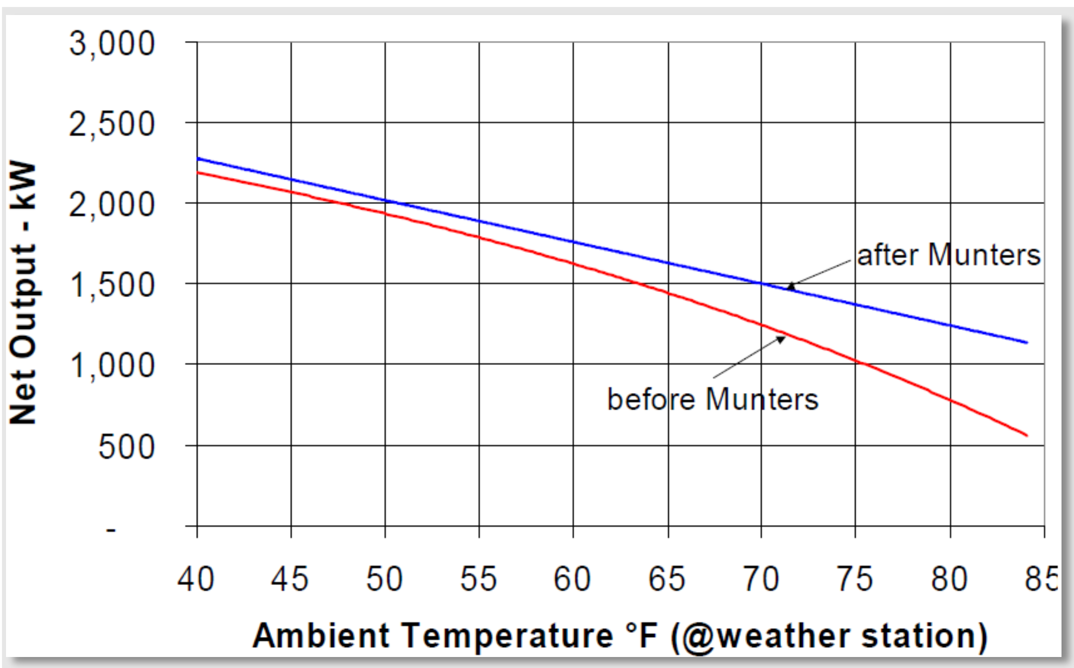
*** GHG reductions due to power savings. CH4 and N2O reductions are a result of reduced water consumption and the associated emissions during biological treatment of water.**

Source: Altex Technologies Corporation

CHAPTER 1: Introduction

Given the reduced availability of water in arid regions of California, acquiring water permits for air conditioning and refrigeration condenser cooling is increasingly difficult. Driving end-use customers to dry-only cooling systems does save water, but at a cost through losses in cycle efficiency. A hybrid system that operates dry most of the time and wet only when ambient air temperatures are high is another way to reduce water use. However, both wet and dry operation require more air-fan power. Wet cooling system heat transfer is driven by lower wet bulb temperatures that deliver performance advantages at high ambient air temperatures. However, as shown in Figure 1, these systems are designed to consume water all year, resulting in minimal performance improvement at low ambient air temperatures when compared with dry systems.

Figure 1: System Performance for Dry and Wet Cooling Versus Ambient Dry Bulb Temperature before and after installation of Munters Water Cooled System

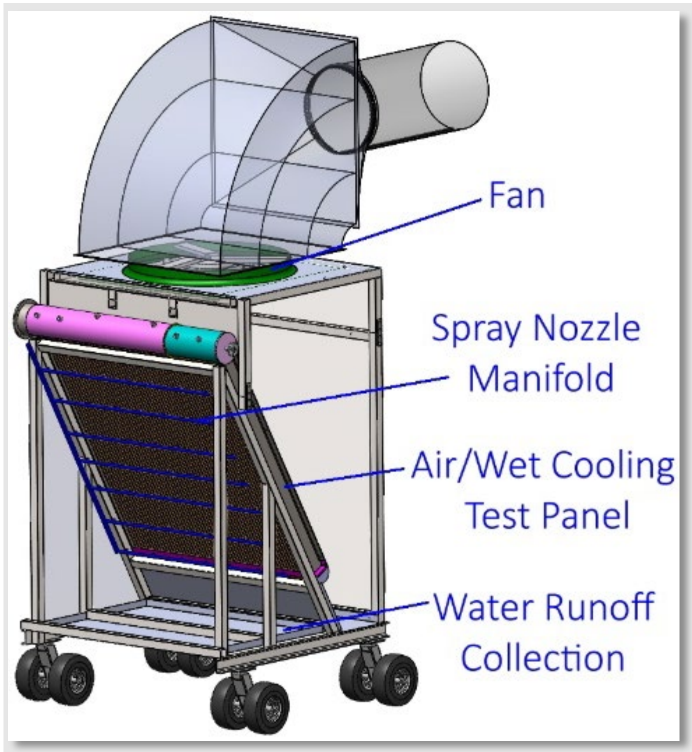


Unit 200 Performance Data

Source: Altex Technologies Corporation

Besides eliminating water use and treatment costs, the power needed to pump and treat water would be eliminated when operating a dry system. Furthermore, if the hybrid system improves both wet and dry heat transfer and fan performance, the hybrid system's performance overall would also improve. The AHHEX developed and tested in this report meets this requirement. It operates efficiently when dry and only uses water for cooling at high temperatures. During wet operation, water is sprayed on the porous air-side fins to activate evaporative cooling. The general AHHEX condenser configuration is illustrated in Figure 2, followed by its advantages over alternative hybrid cooling systems.

Figure 2: AHHEX Condenser General Configuration



Source: Altex Technologies Corporation

Several hybrid air/wet cooling technologies are under consideration for replacing wet or dry cooling systems. Table 1 lists these different approaches along with their respective advantages and disadvantages.

Table 1: Comparison of Hybrid Air/Wet Cooling System Approaches

No.	Approach	Pros	Cons
1	Air and wet units in series	Air handles desuperheating load	Cost of dual equipment, condensate temperature very limited
2	Air and wet units in parallel	Simple design improves approach to dry bulb	Condensate temperature limited by dry bulb
3	Air unit with evaporative media	Can achieve good approach to wet bulb on inlet air	Cost of media, high pressure drop and power
4	Air unit with water spray	Simple and low cost of nozzles, low pressure drop and power	Overspray and water waste, cost of treatment and mist eliminator, damage to finned tubes
5	Deluge of surface	Highest enhancement	Cost of water treatment and mist eliminator, protective coating

Source: Altex Technologies Corporation

A system that uses direct water contact on the tubes and fins (Number 5) has the best performance, but also has the most challenging water management, with water droplet carryover an issue. One hybrid system that limits droplet carryover is the Guntner ACS.[1] During high ambient air temperatures, a porous pad mounted ahead of the HEX panel is wetted to cool the air entering the dry heat exchanger (HEX). By using a wetted pad, water management challenges and carryover potential with the smooth HEX fins are avoided. However, as noted in Table 1, this approach is not as effective as the wetting of the tubes and fins approach that is applied in AHHEX. Furthermore, because of porous AHHEX fins, the HEX serves the multiple functions of managing water, droplet carryover and mass and heat transfer, thereby reducing costs relative to a separate wet and dry sections approach, such as the Guntner ACS. Also, AHHEX is simply implemented by integrating a water spray system to wet the tubes and porous fins when needed. As shown in Figure 2, the dry cooling test panel is fitted with water spray nozzles to create the AHHEX. The low pressure and low power nozzles direct a spray of water at the porous fins that capture the water due to their impingement/ demisting capabilities. The feasibility of this approach was shown by bench scale tests. This water layer then evaporates into the air as a result of the high mass transfer capability of the fins. Due to the capillary action of the porous fins, the water will not easily run off of the fins and be carried over into the downstream duct. The effective AHHEX advanced hybrid air/wet cooling system configuration, shown in Figure 2, has a layout similar to the Guntner hybrid system, but the AHHEX has the advantage of a single dual use dry/wet core matrix that yields the higher performance of the wetted tubes and fins approach.

[1] www.guntnerus.com/products/condensers/

Given the AHHEX potential, this project's goal was to leverage successful pilot-scale dry cooling and bench-scale wet cooling developments, test their results and analyses to create an advanced hybrid air/wet cooling AHHEX test system, then finally test the system in an available 10-ton Legacy Chillers unit to both validate the hybrid system and support the evaluation of system benefits for commercial and industrial applications. Besides supporting the commercial and industrial markets that ultimately also benefit ratepayers, this hybrid technology will also reduce power and water use for electric utilities that use Rankine-based power cycles.

Specific objectives were to:

- Integrate Altex advanced dry and wet cooling systems into a hybrid cooling system that reduces water use by 2.4 million gallons per year (MG/yr) and power by 17,420 kilowatt-hours (kWh)/yr for 170 tons cooling.
- Install AHHEX in a 10-ton chiller from Legacy Chiller for pilot-scale testing.
- Prove the performance in the Altex test facility and building.
- Evaluate the water savings, electricity savings, and reduced capital costs.
- Show AHHEX yearly power, water, costs, and greenhouse gas (GHG) reduction savings of 8,371 megawatt-hours (MWh), 725 million gallons (Mgal), $4.47 million and 2,187 tons, respectively, for commercial and industrial markets.
- Determine production readiness and create a plan by interacting with manufacturing partners and Legacy Chillers, a high-potential early adopter of the AHHEX.

CHAPTER 2: Project Approach

The AHHEX advanced hybrid air/wet cooling test condenser was designed using established experience and models from high-performance dry cooling systems. While AHHEX units of most interest are commonly greater than 100 tons of cooling, a 10-ton cooling unit was selected for several factors including a market need in the small-to-medium commercial sector, the ability to be installed in parallel for scaling and to effectively test the system within the project budget. Process conditions for the AHHEX test system were defined by a commercial process analysis model. Heat exchanger product manufacturing experience then produced a prototype-scale AHHEX test condenser. Several manufacturing partners supported the AHHEX fabrication. This unit was then outfitted with temperature, pressure, and flow instrumentation to determine its performance. Day-and-night testing covered a range of ambient air temperatures. Test data then defined the AHHEX performance over a one-year period for both cool- and hot-climate locations in California. To determine pollution-reduction impacts, the AHHEX fan-power needs were compared with conventional condenser fan-power needs. The AHHEX lower fan-power requirement was then translated into reduced emissions at the power plant providing the power. The test data were also used to determine both AHHEX water-use reductions and cost savings.

CHAPTER 3: Project Results

3.1 Chiller Process Analysis

AHHEX specifications were refined based on assessing refrigeration and chiller system markets and identifying anticipated customer benefits from the system. For systems operating under 2,000 hours per year, dry cooling systems are favored for capacities below approximately 200 tons refrigeration (Archibald et al., 2002). However, at 4,000 hours' operation, wet systems become attractive at 100 tons refrigeration (Archibald et al., 2002). Given this input, a 170-ton chiller unit was selected as the primary target for this effort. Table 2 provides summary information on the high-potential application that was used as a baseline for the test system's development.

Table 2: AHHEX Requirements for a Typical Chiller Application Air-Cooled Condenser for 170-Ton Cooling

	Air Side In	Air Side Out	Refrigerant Side In	Refrigerant Side Out
Pressure	0″ H_2O	–0.5″ H_2O	360 psi	359 psi
Temp (deg F)	95		198	120
Cond. Temp (deg F)	—	—	135	135
Enthalpy (Btu/lb)	30.5	26.9	203.06	119.04
Flow rate (cfm air, lb/hr ref)	188,500	188,500	34,000	34,000
Capacity (Btu/hr)	2,850,000	2,850,000	2,850,000	2,850,000

Btu/lb: British thermal units per pound; cfm: cubic feet per minute; lb/hr ref: pounds per hour of refrigerant flow on a mass basis; Btu/hr: British thermal units per hour.

Source: Altex Technologies Corporation

As shown in this table, the air side uses the 95 degrees Fahrenheit (°F) temperature [2] for calculating performance, with operating conditions ranging substantially below and above this level depending on location, time of year, time of day, and local weather conditions. For this chiller, a reference air flow is also provided. For advanced chiller systems, fan power can be saved by varying the air-flow rate when ambient air temperatures are lower and heat transfer improved. On the refrigerant side, the condenser pressure is 360 pounds per square inch, gauge (psig), and the entering temperature is 198°F, as listed in the table. The high entering temperature and low exit temperatures, when compared with the condensing temperature, indicate that the condenser fluid is superheated at the inlet and subcooled at the exit. These would be typical refrigerant operating conditions for both the full-scale and test unit wet/dry AHHEX condenser.

An available 10-ton cooling capacity chiller was used to demonstrate the performance of the AHHEX. A photograph of this Legacy Chiller unit is shown in Figure 3. The specifications for the unit are included in Table 3[3].

Figure 3: Legacy Chiller 10-Ton Cooling Unit

Source: Altex Technologies Corporation

Table 3: Legacy Chiller 10-Ton Cooling Unit

Specifications
• **Model PACT 120S3-T3-Z** • **Packaged, Air-cooled, Integrated Tank, 10-Ton Chiller** • **Rated at 45°F Fluid Temperature, and 95°F Ambient Air Temperature** • **Microprocessor-Based Controls** • **85" L X 34" W X 72" H, With a 30-Gallon Tank** • **1,300 Pounds**

Source: Altex Technologies Corporation

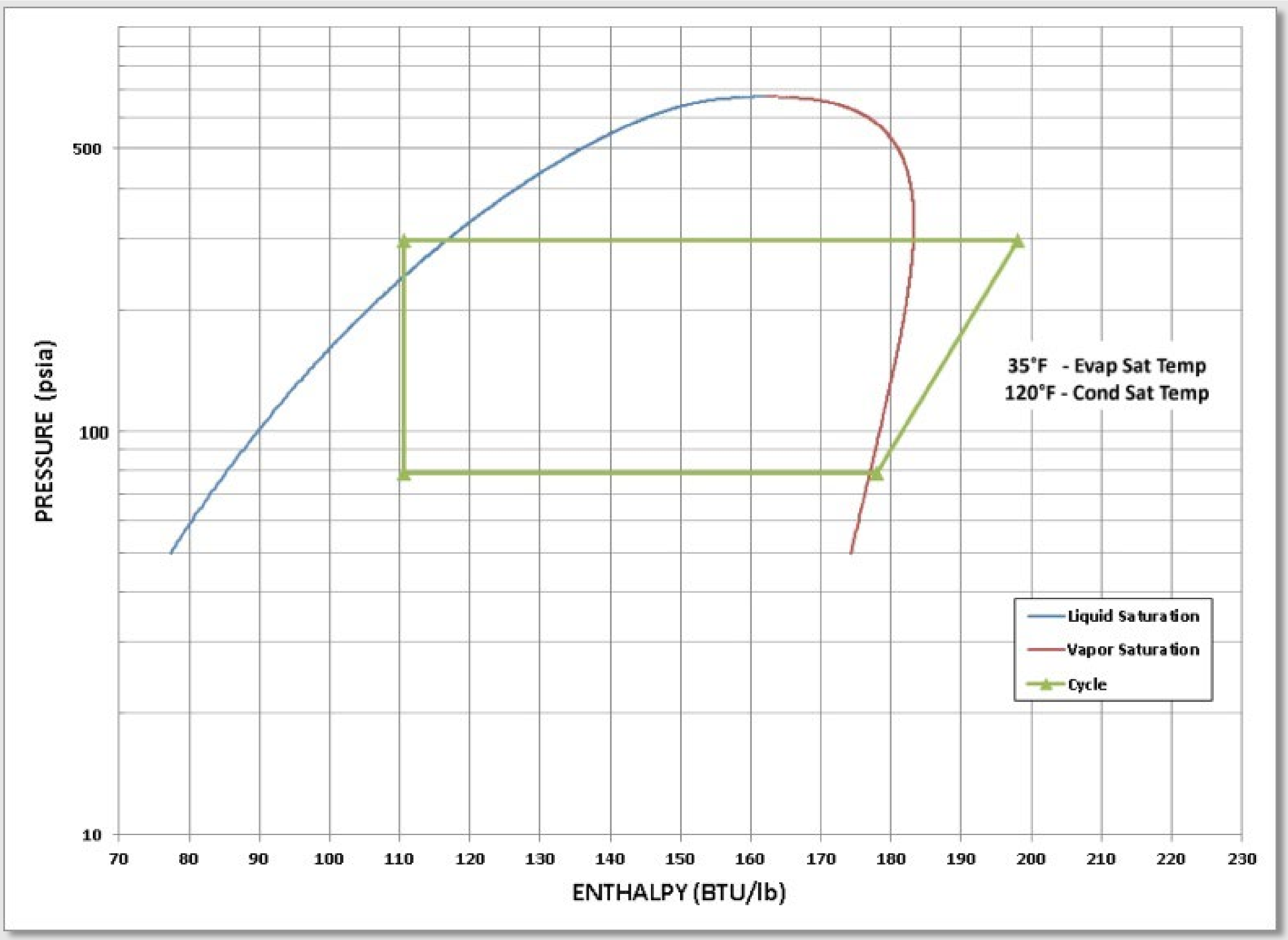
This is a commonly used chiller with similarities in performance and operation to larger chillers. Given that the AHHEX cooler is easily scaled up by simply using multiple panels and fans, AHHEX testing at the 10-ton cooling level will save testing costs while providing directly relevant results for larger systems. In addition, at this 10-ton, 35 kW cooling capacity, the fabrication method and materials will be the same as those used for larger-capacity units. Therefore, the condenser production process will be proven at pilot scale under this effort, and production cost estimates will be well supported.

A vapor cycle model has been created similar to the Altex 407C refrigerant chiller. The model includes compressor operating characteristics, including the compressor's efficiency. The model considers refrigerant superheating and sub-cooling, as shown in Figure 4. Relative to evaporator and condenser fan power efficiencies and requirements, these are not included in the cycle model, but are instead included in the overall system model, including the key condenser performance model. This system model is described here. The cycle model is able to take condenser data, and for a given ambient temperature and relative humidity, calculate both compressor power and chiller capacity. Based on this information, electrical and water operating costs can be calculated.

Figure 5 illustrates how the chiller's performance varies with the condenser saturation temperature (also the saturation pressure) that is related to ambient air temperature. In other words, as the ambient temperature increases, the condenser temperature (and pressure) will rise to meet the heat transfer requirements of the cycle.

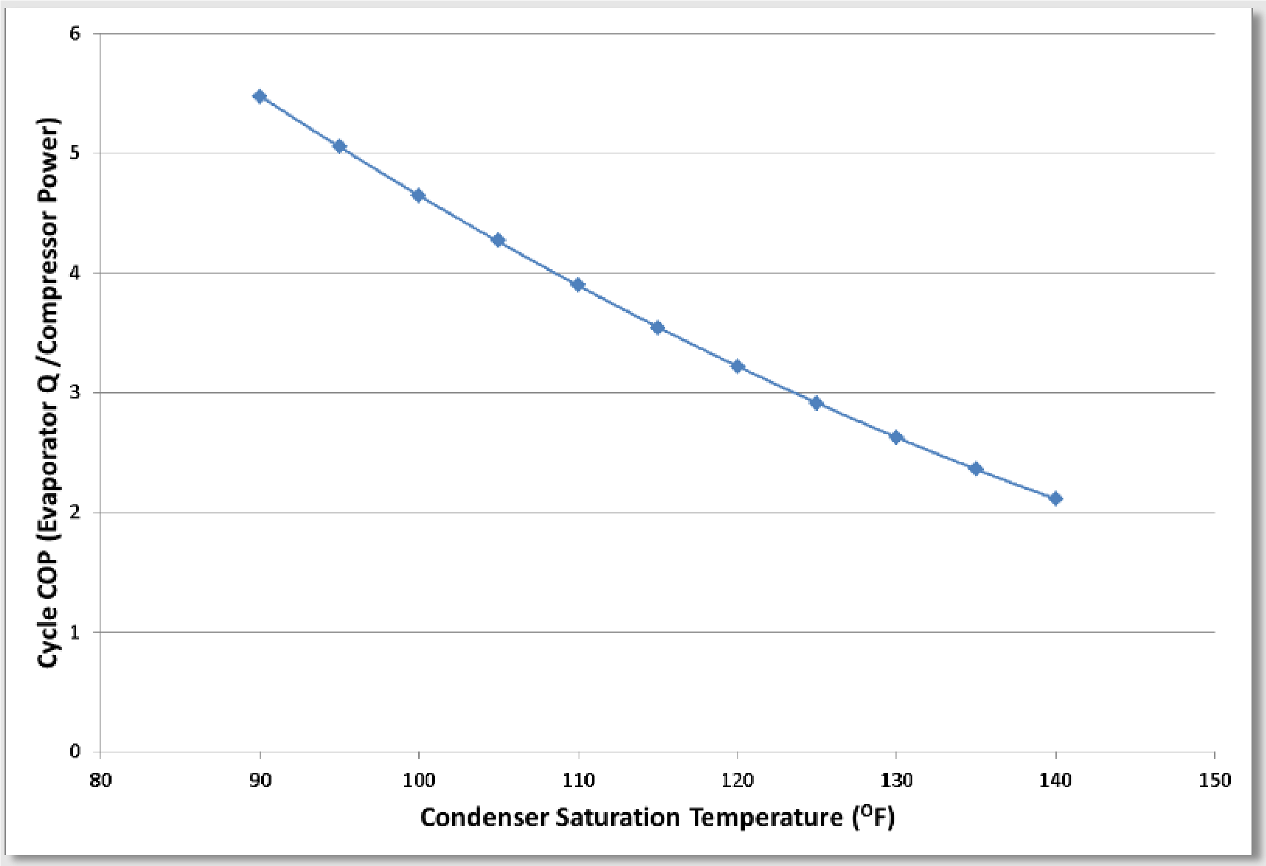
In this case, system performance, or the coefficient of performance (COP), will be reduced, as shown in Figure 5. An increase in fan speed, or air flow, will help maintain performance, but as the ambient temperature further increases, a limit will be reached where performance cannot be further maintained. However, for hot and dry conditions, water evaporation can boost heat transfer to maintain COP performance. It should be noted that the COP shown in Figure 5 pertains only to the cycle. The overall system COP includes evaporator and condenser fan power, so is therefore lower than the COP given in Figure 5.

Figure 4: 407C Vapor-Cycle Process Diagram



Source: Altex Technologies Corporation

Figure 5: Chiller Cycle Performance Versus Saturation Temperature



Source: Altex Technologies Corporation

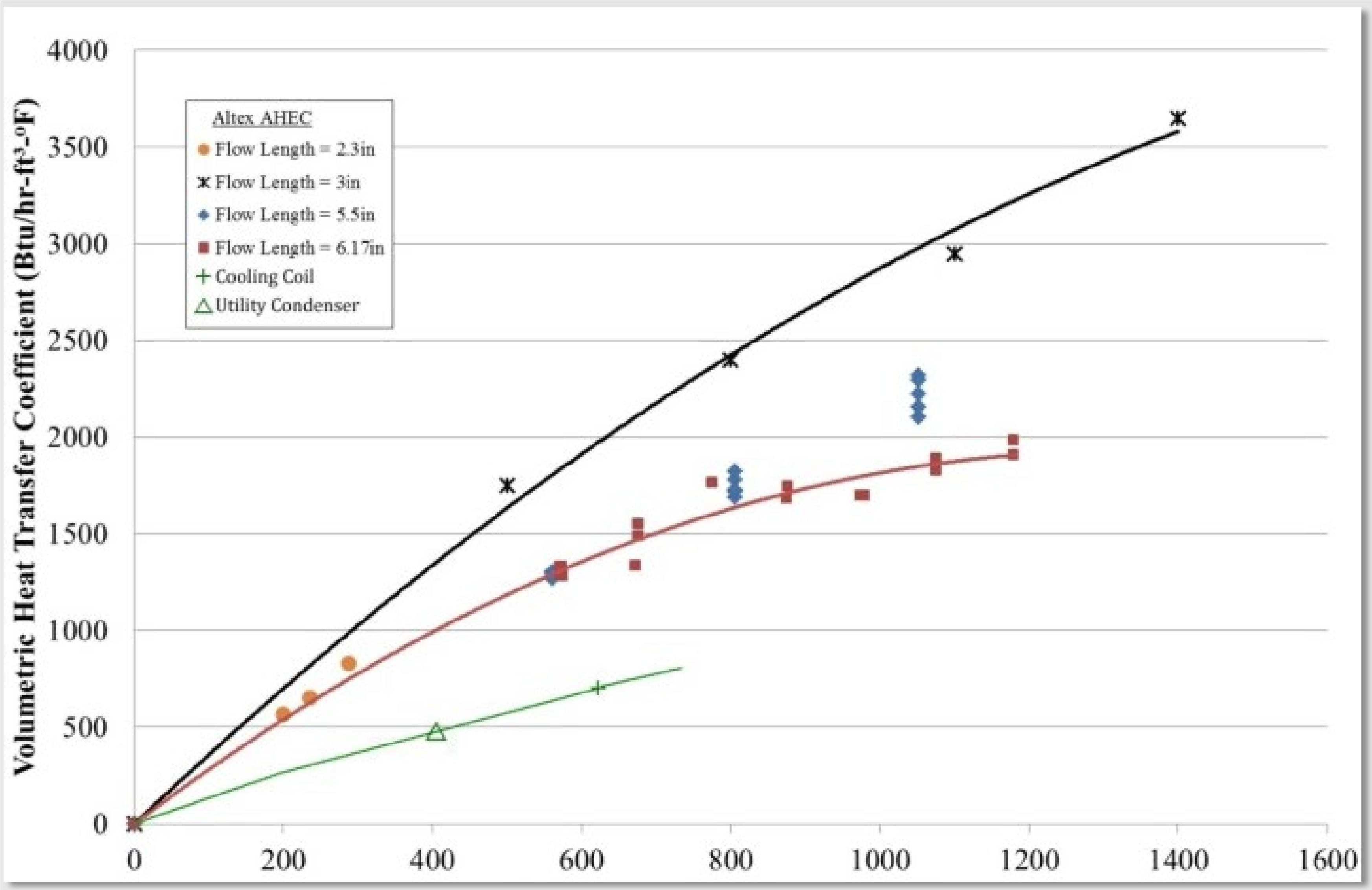
3.2 Condenser Dry Performance

The AHHEX is based on a successful utility-scale dry cooling condenser design that uses porous fins similar to those in the AHHEX design. This unit has been tested and shown superior to conventional condensers in both volumetric heat transfer coefficient and pressure drop. Utility dry cooling condensers use air to condense low-pressure steam exiting the turbine. Condensation-side operating pressures are in the range of 1 pound per square inch, absolute (psia) versus 375 psia for the chiller example shown in Table 2. This difference in fluid pressure and density creates the need for some difference in condenser-tube configuration. However, in both cases the air-side heat transfer is limiting and controls condensing performance. Furthermore, since the air fins represent around 80 percent of the air-side heat transfer surface area, fin performance then drives condenser performance for both the steam and refrigeration chiller systems. Therefore, the earlier steam condenser experience with the special high-performance fins is relevant to the chiller condenser performance, including both heat transfer and pressure drop. To easily compare the AHHEX to conventional condenser performance, the heat transfer data is converted to a volumetric heat transfer coefficient by dividing the heat transfer by the heat exchanger core volume and the initial temperature difference (ITD) (ITD=initial condenser temperature–initial air temperature). By reducing heat transfer data to a volumetric heat transfer coefficient, it is easier to compare heat exchangers of different volumes with different operating temperatures. Figure 6 provides volumetric heat transfer coefficient test results for condensing conditions, cooling coil conditions (the cold-water cooling of air) and vehicle radiator conditions (higher face velocity results) for heat exchanger core thicknesses, or flow lengths of 2.3 in, 3 in, 5.5 in and 6.17 in [4]. The 3-inch thickness case used a high-liquid flow rate that increased heat transfer versus the other cases.

Figure 6 shows that, over a range of face velocities and fluid types, flow rates and temperatures, the special fin design has double the volumetric heat transfer than a utility steam condenser [4] and Navy ship cooling coil [5]. This translates into 50 percent lower volume, and lower weight and cost, to achieve the same heat transfer.

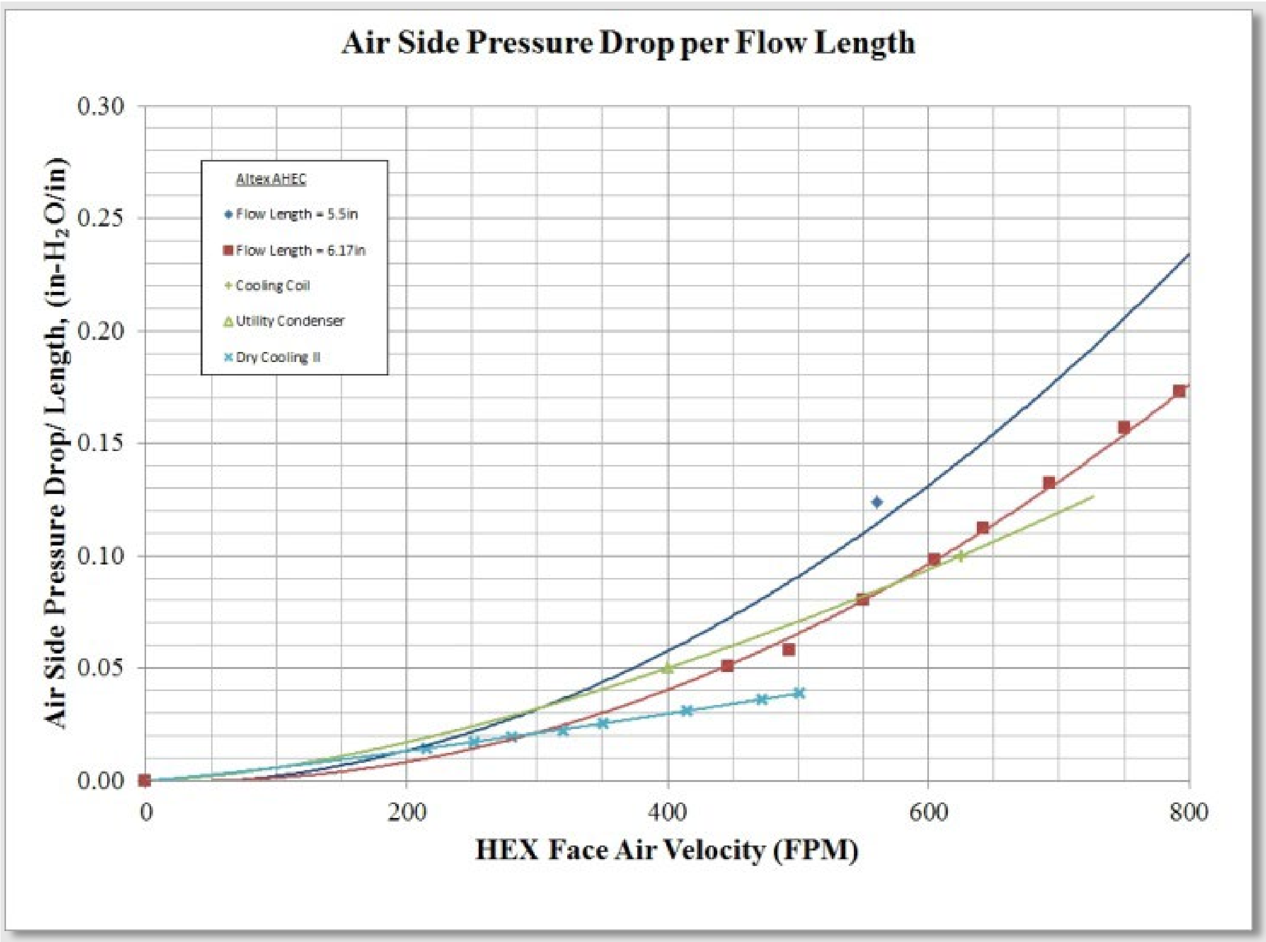
In addition, as shown in Figure 7, the pressure drop per unit length for the special design is 40 percent lower at a 400 feet per minute face velocity [4]. Since the AHHEX will be shorter in depth to meet the same heat transfer requirement as a conventional HEX, as illustrated in the prior volumetric heat transfer coefficient comparison, the AHHEX reduction in pressure drop will be even greater than 50 percent. This pressure drop reduction translates into lower fan power and operating cost. These results show the success of the special design under dry condensing operation.

Figure 6: Comparison of AHHEX and Conventional Condenser Volumetric Heat Transfer



Source: Altex Technologies Corporation

Figure 7: Comparison of AHHEX and Conventional Condenser Pressure Drop



Source: Altex Technologies Corporation

As illustrated in Figure 2, this beneficial dry operation will be leveraged in the hybrid dry-wet AHHEX by using water spray and evaporation to augment heat transfer when the air is hot and dry cooling is limited. In these cases, water distributed onto the porous fins would evaporate and add substantial cooling capacity as a result of the high latent heat of evaporation. Because of the porosity of the fins, the water would be retained on the fins and provide consistent evaporative heat transfer augmentation rather than quickly running off the fins. Given the importance of fin water retention and coating for wet performance, small-scale fin water management tests were carried out to support the AHHEX design. These results follow.

3.3 Water Management

The porous fins work well for dry cooling, as shown by test results for several heat exchanger configurations, and as noted in Figures 6 and 7 [4]. For wet operation, the heat transfer and pressure drop data for the porous fins do not exist. Consistent fin heat transfer performance under wet operation will be driven by the ability of the fin to retain an inventory of water on the surface and promote the evaporation of the water to extract heat. Water retention is influenced by surface characteristics, solid area, and pore size. For large pores, the water will not bridge the pore, and water retention would be limited to that on the surface. For the right size pore, the water will bridge the pore, with possibly maximum retention. For even smaller pores, the water may not be able to enter the pore and retention drops again. Given these complexities, fin sample materials with different pores were tested to define high potential fins for water retention and the avoidance of dry spots during evaporative operation of the condenser.

To characterize water retention on different porous fin materials, tests were run where squares of various porous fin materials were fully immersed vertically into a water bath and then removed. The weight after immersion versus the dry weight before immersion then defines water retention. A total of 14 fin samples was tested, consisting of three types of porous fins, with several different porosities and surface features. All tests used tap water at room temperature. Table 4 presents the water retention results for the 14 samples.

Table 4: Single Fin Layer Water Retention Results

			g	g	g	%	in^2	g/in^2
Sample #	Type	Orientation	Dry Weight	Wet Weight	Water weight	Open Area	Planar Area	Weight/PA
A1	Y	0°	1.3200	1.4700	0.1600	15.45%	2.86	0.0560
B1	Z	0°	0.5300	0.6600	0.1300	38.20%	2.86	0.0455
C1	Y	0°	0.8900	1.0100	0.1100	22.90%	2.86	0.0385
D1	Z	0°	1.1700	1.2500	0.0800	12.70%	2.86	0.0280
E1	Z	0°	0.4100	0.5400	0.1300	26.70%	2.86	0.0455
F1	X	45°	0.5391	0.6358	0.0967	36.00%	4.00	0.0242
G1	X	45°	0.3835	0.4409	0.0574	45.97%	4.00	0.0144
H1	X	45°	0.7106	0.7832	0.0726	33.64%	4.00	0.0182
I1	X	45°	0.3875	0.4545	0.0670	46.24%	4.00	0.0168
J1	X	45°	0.4970	0.5599	0.0629	45.70%	4.00	0.0157
K1	X	45°	0.6853	0.8002	0.1149	37.21%	4.00	0.0287
L1	X	45°	1.2469	1.3535	0.1066	30.91%	4.00	0.0267
M1	X	45°	1.5458	1.6700	0.1242	30.25%	4.00	0.0311
N1	X	45°	3.2034	3.4856	0.2822	19.36%	4.00	0.0706

Source: Altex Technologies Corporation

To account for the different sample sizes, the water retentions per planar area (that is, not considering open pores) are listed. As shown, the water retention per area varied by fin type and configuration. The minimum level was .0144 grams per square inch (G/in^2) and the maximum was 0.0706 gm/in^2, or a factor of 4.9 higher. Dividing the water weight gain by the solid surface area (that is, planar area minus pore area), the minimum retention was 0.028 G/in^2 and the maximum was .087 gm/in^2, or a factor of 3.2 higher. This indicates that the porosity plays some role, but a bigger factor is the type and configuration of the fin. Of the samples tested, fin type X and configuration N1 had the greatest water retention. Besides the single fin layer results in Table 4, two fin layers together were also tested. These results are given in Table 5.

As shown, the two-layer configuration substantially increased water retention per planar and solid area. The minimum to maximum ratios for planar and solid areas were 2.9 and 2.6, respectively. These ratios are substantially lower and closer together than the single layer results. This suggests that having two layers reduces the impact of fin type and configuration, as well as increases water retention.

Given the importance of gravity to water runoff, flat and non-flat fin samples were tested at different angles to the anticipated air flow direction in the core, including aligned, perpendicular and 45 degrees. Table 6 gives the weight gain results for these different angles. For the flat type fin of type Y, the weight gain is relatively constant at 30 percent, compared to the non-flat fin and type Y, where weight gain varied between 22 percent and 34 percent. From these results, it appears that, for the typical flat fin surfaces, weight gain is not strongly influenced by the angle to the flow.

Table 5: Two-Fin Layer Water Retention Results

			g	g	g	%	in^2	g/in^2
Sample #	Type	Orientation	Dry Weight	Wet Weight	Water weight	Open Area	Planar Area	Weight/PA
A2	Y	0°	2.6500	2.9200	0.2700	15.45%	2.86	0.0945
B2	Z	0°	1.0500	1.3500	0.3000	38.20%	2.86	0.1050
C2	Y	0°	1.8100	2.1400	0.3300	22.90%	2.86	0.1155
D2	Z	0°	2.3300	2.5900	0.2600	12.70%	2.86	0.0910
E2	Z	0°	0.8100	1.0300	0.2100	26.70%	2.86	0.0735
F2	X	45°	1.0658	1.4434	0.3776	36.00%	4.00	0.0944
G2	X	45°	0.7600	1.0705	0.3105	45.97%	4.00	0.0776
H2	X	45°	1.4211	1.8618	0.4407	33.64%	4.00	0.1102
I2	X	45°	0.7719	1.0376	0.2657	46.24%	4.00	0.0664
J2	X	45°	0.9896	1.3655	0.3759	45.70%	4.00	0.0940
K2	X	45°	1.3793	1.7648	0.3855	37.21%	4.00	0.0964
L2	X	45°	2.4726	2.8632	0.3906	30.91%	4.00	0.0977
M2	X	45°	3.1030	3.5340	0.4310	30.25%	4.00	0.1078
N2	X	45°	6.5431	7.3872	0.8441	19.36%	4.00	0.2110

Source: Altex Technologies Corporation

Table 6: Single-Fin Layer Flow Angle Impact on Water Retention

Air-flow "Direction"	Non-Flattened				Flattened			
	Metal Weight (g)	Dip Weight (g)	Water Weight (g)	Gain (%)	Metal Weight (g)	Dip Weight (g)	Water Weight (g)	Gain (%)
Longitudinal	1.9975	2.5462	0.5487	27.47%	1.9120	2.4828	0.5708	29.85%
Traverse	1.9975	2.6829	0.6854	34.31%	1.9120	2.4972	0.5852	30.61%
45°	1.9975	2.4428	0.4453	22.29%	1.9120	2.4961	0.5841	30.55%

Source: Altex Technologies Corporation

Besides type and orientation influencing water retention, how the fins are configured or oriented to each other also influences water retention. Table 7 illustrates how orientation and configuration impact water retention for porosities from 12.7 percent to 38.2 percent. As shown, the porosity effect has a smaller impact than the fin relative orientation effect. In addition, the use of three fins yields the most water retention as illustrated by fins A1A1W, B1B2W, C1C2W, D1D2W and E1E2W. These results show that if high levels of water retention are required, fin orientation to each other can be configured to yield an up to a factor-of-ten higher water retention. This is a very substantial increase, at the expense of a more complex fin arrangement.

Table 7: Multiple-Fin Layer Orientation Water Retention Results

Configuration	Type	Porosity [%]	Thickness [in]	Dry Weight [g]	Wet Weight [g]	Water Weight [g]	Mass Water/Plain Area [g/in^2]
A1	Y	15.45%	0.013	1.32	1.47	0.16	0.112
A2			0.028	2.65	2.92	0.27	0.1891
A3			0.071	3.87	5.26	1.39	0.9734
B1	Z	38.20%	0.011	0.53	0.66	0.13	0.091
B2			0.022	1.05	1.35	0.3	0.2101
B3			0.062	2.23	3.5	1.26	0.8823
C1	Y	22.90%	0.017	0.89	1.01	0.11	0.077
C2			0.034	1.81	2.14	0.33	0.2311
C3			0.068	2.99	4.63	1.65	1.1554
D1	Z	12.70%	0.013	1.17	1.25	0.08	0.056
D2			0.028	2.33	2.59	0.26	0.1821
D3			0.064	3.44	4.62	1.18	0.8263
E1	Z	26.70%	0.011	0.41	0.54	0.13	0.091
E2			0.023	0.81	1.03	0.21	0.1471
E3			0.059	2.02	3.54	1.52	1.0644

Source: Altex Technologies Corporation

Water retention provides an inventory of water on the fins that gives more consistent heat transfer during operation by avoiding local dry-out. Using a water retention amount of .05G/in^2 as a reference, the amount of water retained on 10-, 100-, 170-, 200-, 300- and 400-ton cooling AHHEX condensers can be estimated. These results are listed in Table 8. Dividing the evaporative cooling energy of the water by the heat transfer produced by the different condensers then gives an estimate of the cooling time provided by just the retained water. As shown in Table 8, the cooling time is on the order of 1.7 minutes, which is a substantial buffer time to avoid dry-out spots when spraying fresh water for evaporation to the fins.

Table 8: Water Retention Layer Evaporation Time

Refrigeration (tons)	Face Velocity (fpm)	Total Area (ft^2)	Number of Cells	Water Retention (g/in^2)	Water Inventory (pounds)	Cooling Time (minutes)
10	400	9	NA	0.050	4.31	1.72
100	400	93	4	0.050	43.12	1.72
170	400	157	7	0.050	73.30	1.72
200	400	185	8	0.050	86.23	1.72
300	400	278	12	0.050	129.35	1.72
400	400	370	16	0.050	172.47	1.72

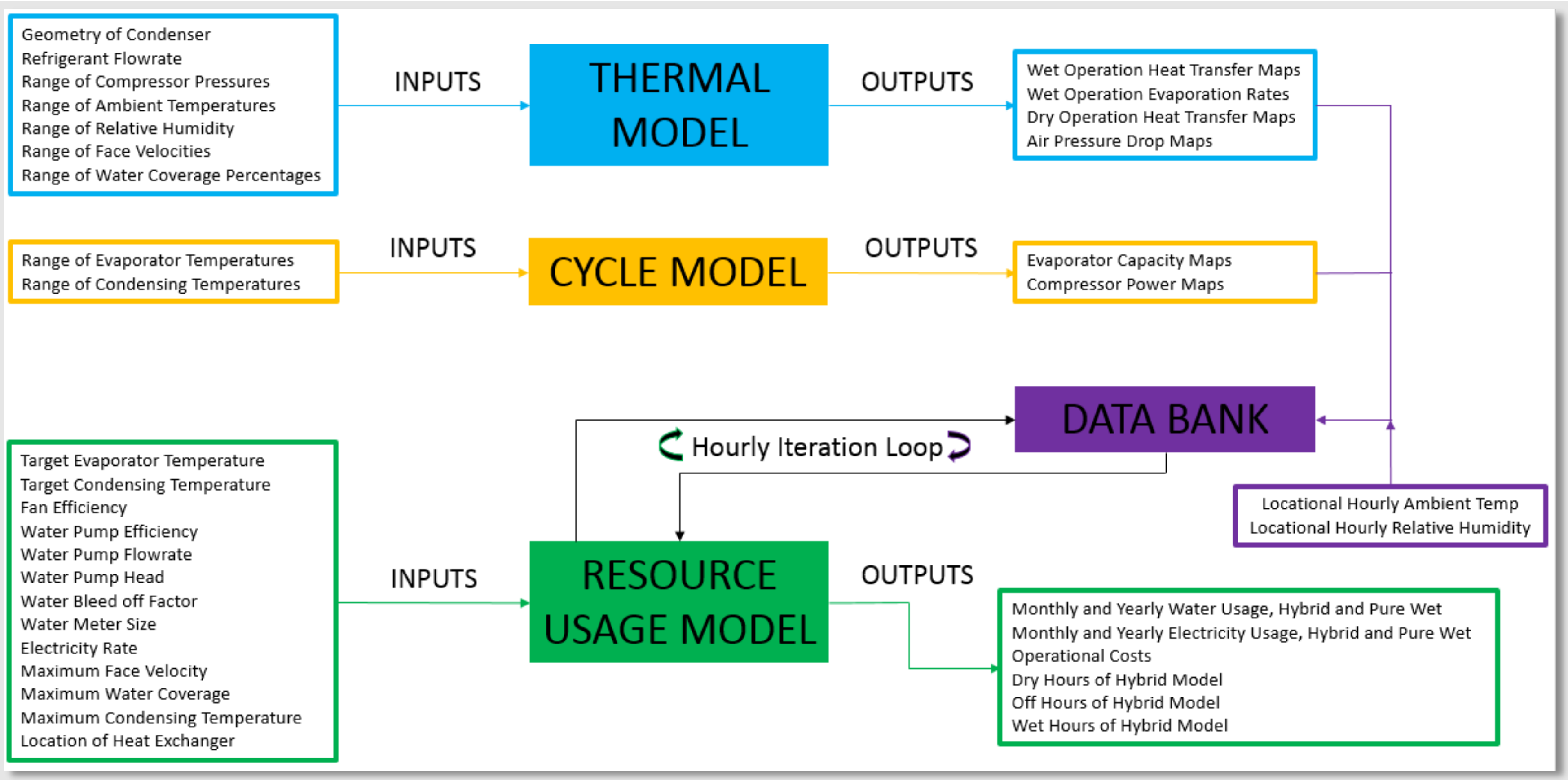
Source: Altex Technologies Corporation

Overall, these results show that water retention is substantial for many fin types and configurations, and this water can provide the needed buffer to make heat transfer consistent when adding fresh water to the fins. Therefore, water retention for the fins of interest tested is not limiting, and other criteria can be used to select the highest potential fin type and configuration for AHHEX.

3.4 Wet and Dry AHHEX Condenser Modeling

The AHHEX hybrid wet/dry cooling system efficiently uses water for evaporative cooling only during times when ambient temperatures are high and dry cooling alone would not be able to maintain system cooling capacity. Since ambient temperature varies substantially between day and night, as well as seasonally and according to weather conditions, the AHHEX system will have varying water use, as well as varying fan-power requirements. To evaluate AHHEX water and power use versus a conventional wet or dry cooling system, a performance model that considers operation over a year in selected California locations was developed. To construct this hybrid model, the dry cooling model developed in an earlier effort [4] was extended to consider water evaporation from wetted fins and tubes and the associated mass transfer of the vapor to the cooling air stream. Figure 8 illustrates the model process diagram that incorporates all of the needed refrigeration cycle and ambient condition inputs to predict condenser water use and power inputs over a time period of one year in selected locations in California.

Figure 8: AHHEX Hybrid Wet/Dry Model Processes



Source: Altex Technologies Corporation

As indicated in Figure 8, the system model includes the Thermal Model that covers dry and wet condenser performance, the Cycle Model that covers the chiller cycle performance, and the Resource Usage model that determines water and power usage to meet cooling needs. A weather data bank, from NSRDB (2005), was used to develop daily, monthly, and yearly water and power usage for comparison with alternative approaches. The Thermal Model uses a version of the Colburn factor (J) and friction factor (f) compact heat exchanger model described in Kays and London (1994). This model includes lumped parameter heat transfer and pressure drop sub-models based on correlations of data for classes of heat transfer surfaces and fins. In addition to these sub-models, the model includes energy and mass balances to calculate overall heat transfer. Using the turbulent flow analogy between heat and mass transfer coefficients, the mass transfer impact on evaporation is calculated for the wetted heat exchanger surface. Given that the analogy is not perfect, an experimentally based factor is used to adjust the mass transfer coefficient to fit the evaporation for the configuration. To calculate pressure drop, the model includes experimentally derived f factors for the frictional loss and incorporates simple entrance and exit and temperature change acceleration pressure losses to determine the total pressure loss.

As noted in Figure 8, the Thermal Model produces wet and dry operation heat transfer, evaporation and pressure drop maps that are used with the Cycle Model maps to determine the water and power use for a given AHHEX condenser design and weather. Examples of the Thermal Model maps for a given design and reference air face velocity of 400 feet per minute (fpm) and a condensing temperature of 90°F are given in Figure 9. Many new dry condenser systems offer variable speed fans in order to reduce electrical costs, especially at lower ambient temperature conditions. In order to capture these benefits, the dry heat transfer maps include face velocity as a variable. As shown, the maps define wet or dry heat transfer for a range of air temperatures and relative humidity, with the wet map including water coverage of the heat exchanger as another parameter. It should be noted that some regions of the maps have negative heat transfer. This is because the specified condenser temperature is below the ambient air temperature. This is obviously an unrealistic condition that is avoided during the model iterations with the weather data. Combining these Thermal Model and Cycle Model maps with the weather data for the location of interest then allows the calculation of water and power usage through the Resource Model.

Examples of weather data for Visalia, California, and San Jose, locations are given in Figure 10. These data are taken from NSRDB (2005) and cover the temperature and relative humidity on an hourly basis for an entire year. As shown, Visalia has a higher summer temperature that will trigger more condenser wet operation than the same unit in San Jose.

Figure 9: Example Thermal Model Maps

Wet Operation Heat Transfer Maps [btu/hr]

Condensing Temp [°F]	**90**					
Water Coverage	**0%**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	176933	168626	163401	159705	156985	154923
50	115978	110673	107211	104832	103091	101764
70	56759	54128	52485	51338	50576	50069
90	-1034	-1048	-1043	-1034	-1023	-1011
110	-57276	-55010	-53849	-53359	-53295	-53527
130	-111773	-108269	-107255	-107708	-109132	-111256
Water Coverage	**25%**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	242604	231041	223220	217223	212402	208379
50	185569	174878	166704	160041	154267	149060
70	130466	118369	108223	99072	90669	82723
90	76810	60384	45106	30484	16102	1723
110	24730	-1273	-27030	-53280	-80481	-108870
130	-25789	-69556	-115722	-165616	-219977	-279629

Wet Operation Evaporation Maps [gal/hr]

Condensing Temp [°F]	**90**					
Water Coverage	**0%**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	0.000	0.000	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.000
90	0.000	0.000	0.000	0.000	0.000	0.000
110	0.000	0.000	0.000	0.000	0.000	0.000
130	0.000	0.000	0.000	0.000	0.000	0.000
Water Coverage	**25%**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	9.062	8.571	8.189	7.857	7.558	7.282
50	9.587	8.804	8.133	7.531	6.970	6.434
70	10.140	8.796	7.609	6.502	5.452	4.435
90	10.693	8.400	6.290	4.285	2.321	0.360
110	11.247	7.336	3.646	-0.005	-3.724	-7.568
130	11.772	5.274	-1.175	-7.933	-15.188	-23.105

Dry Operation Heat Transfer Maps [btu/hr]

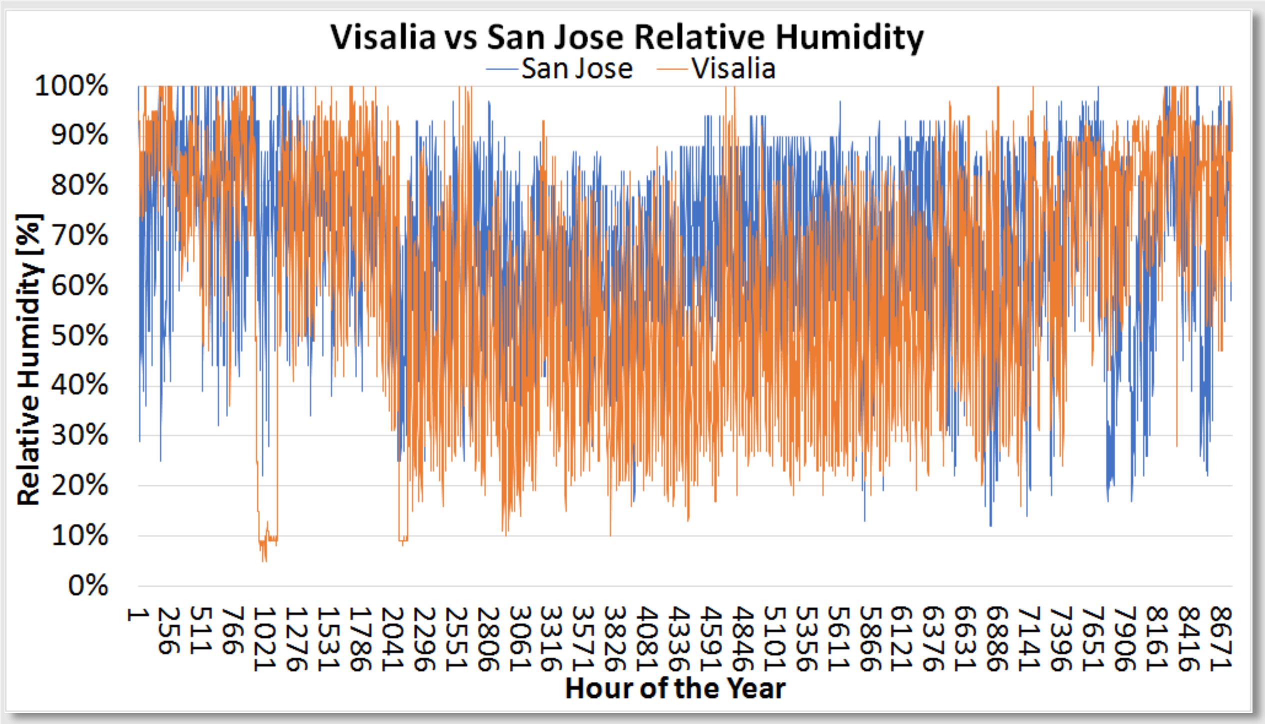
Condensing Temp [°F]	**90**					
Face Velocity	**400**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	127199	119080	114096	110879	108633	107024
50	82339	77229	74268	72389	71173	70399
70	39644	37367	36106	35405	35057	34950
90	-1027	-999	-974	-951	-935	-917
110	-39917	-38385	-38034	-38471	-39391	-40743
130	-77132	-75695	-77067	-80204	-84997	-91601
Face Velocity	**450**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	137807	129343	124008	120416	117878	116030
50	89393	83935	80620	78483	77113	76192
70	43127	40595	39170	38355	37894	37672
90	-1046	-1019	-999	-979	-960	-940
110	-43247	-41515	-40915	-40995	-41550	-42478
130	-83728	-81688	-82174	-84346	-87869	-92638

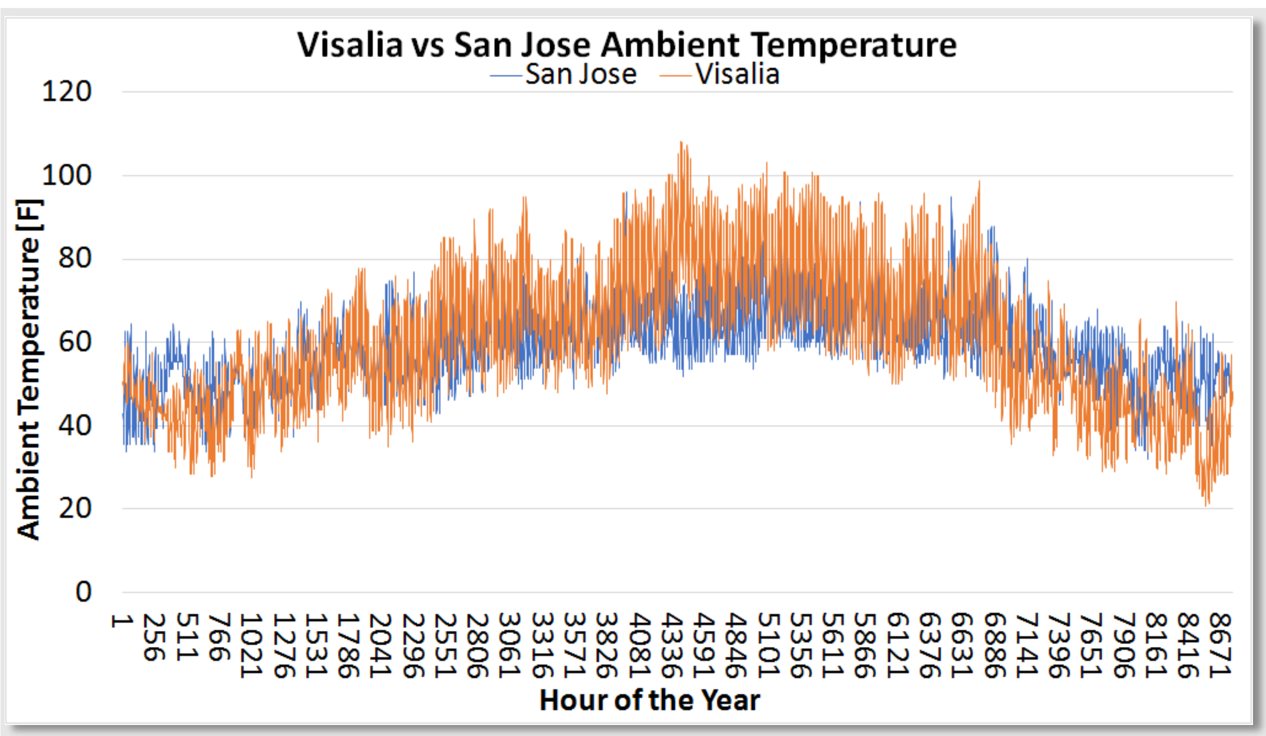
Dry Operation Airside Pressure Drop Maps [in-H2O]

Condensing Temp [°F]	**90**					
Face Velocity	**400**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	0.0559	0.0532	0.0511	0.0494	0.0481	0.0471
50	0.0553	0.0521	0.0496	0.0479	0.0466	0.0456
70	0.0546	0.0507	0.0482	0.0464	0.0451	0.0442
90	0.0532	0.0492	0.0467	0.0450	0.0437	0.0427
110	0.0518	0.0478	0.0453	0.0436	0.0422	0.0412
130	0.0505	0.0465	0.0439	0.0420	0.0406	0.0395
Face Velocity	**450**					
	%RH					
Amb Temp	0	0.2	0.4	0.6	0.8	1
30	0.0665	0.0634	0.0615	0.0601	0.0590	0.0580
50	0.0659	0.0628	0.0607	0.0589	0.0574	0.0562
70	0.0654	0.0621	0.0593	0.0572	0.0557	0.0545
90	0.0647	0.0607	0.0576	0.0555	0.0539	0.0527
110	0.0638	0.0590	0.0559	0.0537	0.0521	0.0508
130	0.0623	0.0574	0.0542	0.0519	0.0502	0.0488

Source: Altex Technologies Corporation

Figure 10: Weather Data for Visalia and San Jose, California





Source: Altex Technologies Corporation

Ahead of exercising the model for a given condenser design, the validities of model components were assessed. To verify the dry performance of the model, the geometry and conditions supplied by Greenheck were input [9]. These were for the condenser Coil C-1, heat exchanger model number CD58S04S140-36x36-RH. Table 9 presents the Greenheck parameters and the Altex model results. The Altex model pressure drop is 5 percent lower than Greenheck's reported result, which confirms good model accuracy. Matching the target inputs, and deriving other inputs, results of the model show a latent heat capacity that is only 0.52 percent lower than Greenheck's reported capacity, and the heat transfer is only 0.18 percent lower. Note that heat transfer accuracy is important, as it is the output that will be used in wet-dry performance assessments.

Table 9: Comparison of Greenheck Dry Cooling to Altex Performance Model Results

Tag	Units	Greenheck	Altex	Difference	Direct Input
Airflow	SCFM	5400	5400		**Derived**
Length	In	36	36		**Output**
Height	In	36	36		
Depth	In	5.2	5.2		
Refrigerant M-dot	lbm/hr	1760.7	1760.7		
Sub cooling	F	0	0		
Superheating	F	0	0		
Dry Bulb	F	95	95		
RH	%	unknown	0%		
Target Avg Condenser Temp	F	unknown	120.868		
Inlet Vapor Temp	F	125	125		
Vapor Velocity	Ft/s	13.36	13.153	–1.55%	
Q Latent "Capacity"	Btu/hr	117200	116595.5	–0.52%	
Air Temp Out	F	115	115.91	0.79%	
Pressure Drop	in-H2O	0.6	0.57	–5.00%	
Heat Transfer	Btu/hr	117200	116994	–0.18%	

SCFM: standard cubic feet per minute; lbm/hr: mass flow in pounds per hour; Ft/s: feet per second; H2O: water

Source: Altex Technologies Corporation

To illustrate the Thermal Model results, some example results for a given heat exchanger core design are shown in Table 10. In this case, the heat exchanger core is split into four sections and the results show three different configurations, where up to three sections are wet. There are also four different "xfer" values which represent the percentage of surface area that is wet in each section. Compared to dry operation, the results clearly show that operating wet significantly increases heat transfer performance. It also shows how important the percent coverage of the heat exchanger by water is in maximizing heat transfer and thereby reducing capital costs.

Table 10: Condenser Heat Transfer Versus Ambient Temperature and Humidity

Air Inlet	RH	Qdot Dry	Qdot, Water in Section 1				Qdot, Water in Sections 1, 2				Qdot, Water in Sections 1, 2, 3			
		xfer = 0.0	xfer = 0.25	xfer = 0.5	xfer = 0.75	xfer = 1.0	xfer = 0.25	xfer = 0.5	xfer = 0.75	xfer = 1.0	xfer = 0.25	xfer = 0.5	xfer = 0.75	xfer = 1.0
°F	%	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr
70	10	179090	292628	346434	375361	402959	398343	487017	529752	559116	488943	598635	647596	676221
70	30	169435	275848	325663	351644	364865	375710	457721	495924	513982	461138	562636	605985	625203
70	50	163680	263796	309915	333518	345544	358430	434599	469829	485581	439606	533937	573762	590423
70	70	160155	254501	297316	319107	329461	344262	405299	448082	461836	421557	509748	546871	543320
70	90	158035	246814	286741	306560	315446	332123	379043	428687	441036	405743	488520	522810	535878
90	10	109578	234223	289602	318239	332959	343130	432499	474122	493348	433236	542163	588482	608815
90	30	104448	217085	266288	290627	301906	316319	395603	431142	446119	398332	494702	534678	550183
90	50	101809	203246	246726	267437	276977	293722	364154	394304	407220	368431	453941	488516	502019
90	70	100618	191673	229784	247614	254680	273675	335793	362405	371919	341430	417603	447595	426082
90	90	100367	181199	214368	228944	235194	254852	309481	331949	340473	315813	383429	409177	418030
110	10	43477	178511	234997	262734	275579	289590	378502	417979	434706	377853	484153	527949	545015
110	30	41984	157195	203627	225012	233641	252027	325132	356183	367667	326959	414604	448953	461067
110	50	41585	137634	174963	191559	197301	217235	276728	300354	308674	279882	351370	378092	386766
110	70	41853	119601	148627	160352	164313	184352	230564	248489	253946	234925	290496	310846	316945
110	90	42581	101582	122736	130883	133409	151088	185563	197846	201070	189262	231039	245244	248802

Source: Altex Technologies Corporation

To illustrate the effect of fin design, the heat transfer performances under dry and wet operation were calculated for five different types of fins. The air-flow rate and pressure drop were held constant by adjusting the fins per inch. The heat exchanger envelope dimensions were held constant. Table 11 shows the heat transfer at various relative humidity and evaporation coefficients.

Table 11: Wet and Dry Heat Transfer Performance of Various Fin Configurations

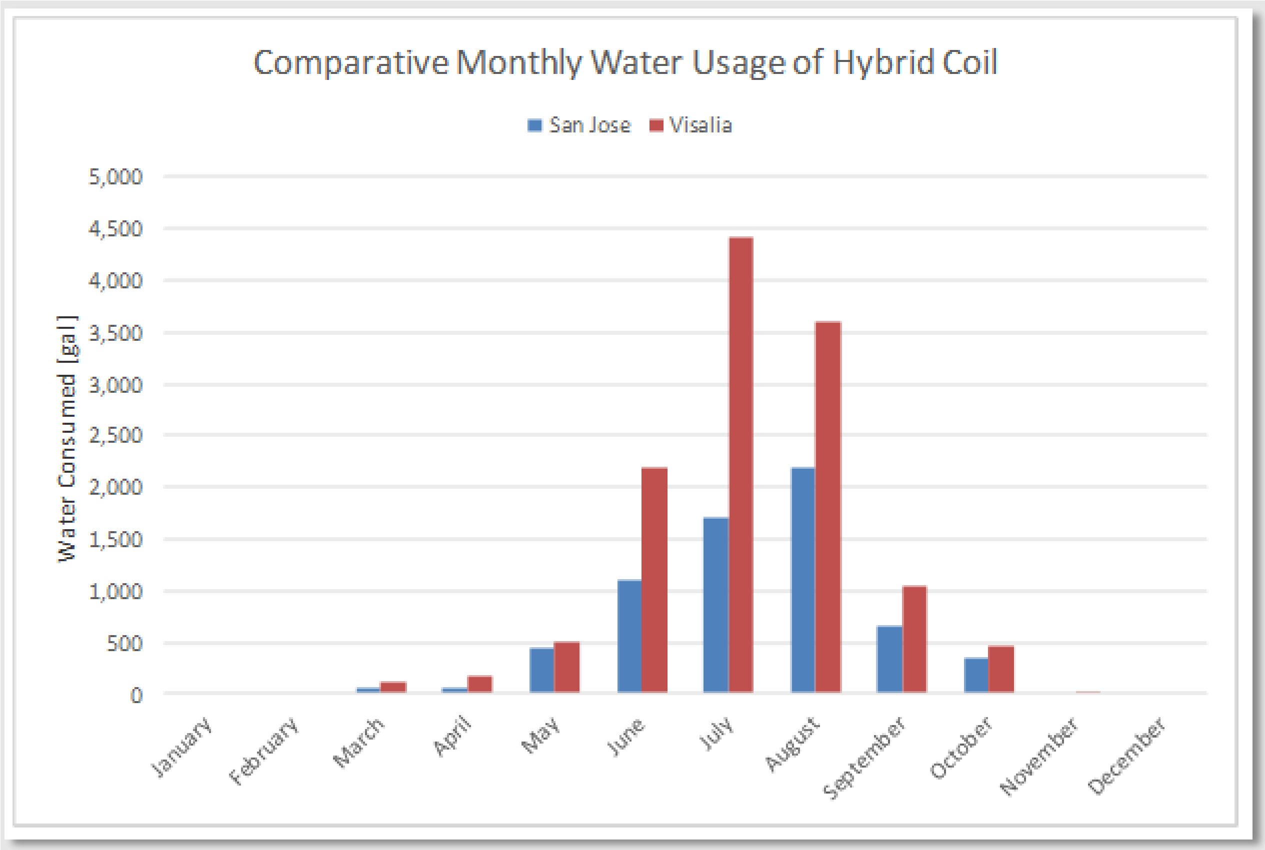
RH	Evap Coeff	High Performance Commercial Fin (Btu/hr)	Altex Enhanced Fins			
			A (Btu/hr)	B (Btu/hr)	C (Btu/hr)	D (Btu/hr)
25%	0	82,086	88,880	89,861	92,440	87,795
50%	0	79,698	86,124	87,405	89,313	84,776
75%	0	79,016	85,304	86,754	88,405	84,192
25%	0.2	279,413	309,740	321,205	341,769	303,888
50%	0.2	252,707	279,026	292,997	304,647	271,239
75%	0.2	229,036	251,506	265,491	272,541	246,469
25%	0.3	335,756	368,332	380,394	401,922	362,182
50%	0.3	300,989	329,675	344,466	356,731	321,308
75%	0.3	270,514	294,259	308,953	316,388	288,927
25%	0.4	377,497	410,270	422,007	443,319	404,134
50%	0.4	337,449	365,851	380,262	392,117	357,557
75%	0.4	301,146	325,254	339,295	346,605	319,911
25%	0.5	409,534	441,795	453,213	473,611	435,728
50%	0.5	364,970	392,508	405,784	416,672	384,649
75%	0.5	324,864	347,815	360,943	367,700	342,756

Source: Altex Technologies Corporation

An evaporation coefficient of zero represents dry operation while values greater than zero represent varying degrees of water coverage. The high-performance fin is used in industry in dry applications, while Altex enhancements A through D are unique fins that have shown high potential for this wet/dry application. Enhancement C shows the best performance while enhancement B is a close second. Compared with the high-performance fin in dry operation, enhancement C showed 12 percent greater heat transfer. Under wet conditions, the enhancement is 16 percent. This performance increase translates into either more dry operation and, therefore, water savings, or a reduction in heat exchanger size and cost.

Using the validated model for a 13.3-ton cooling system that uses a 16.7-ton AHHEX condenser, the power and water usage for the Visalia and San Jose, California, systems were calculated over a year. The Visalia location has higher ambient air temperatures than the San Jose location, as shown in Figure 10, and so should promote more water use for evaporation. Figure 11 shows this water use increase for Visalia over the year period.

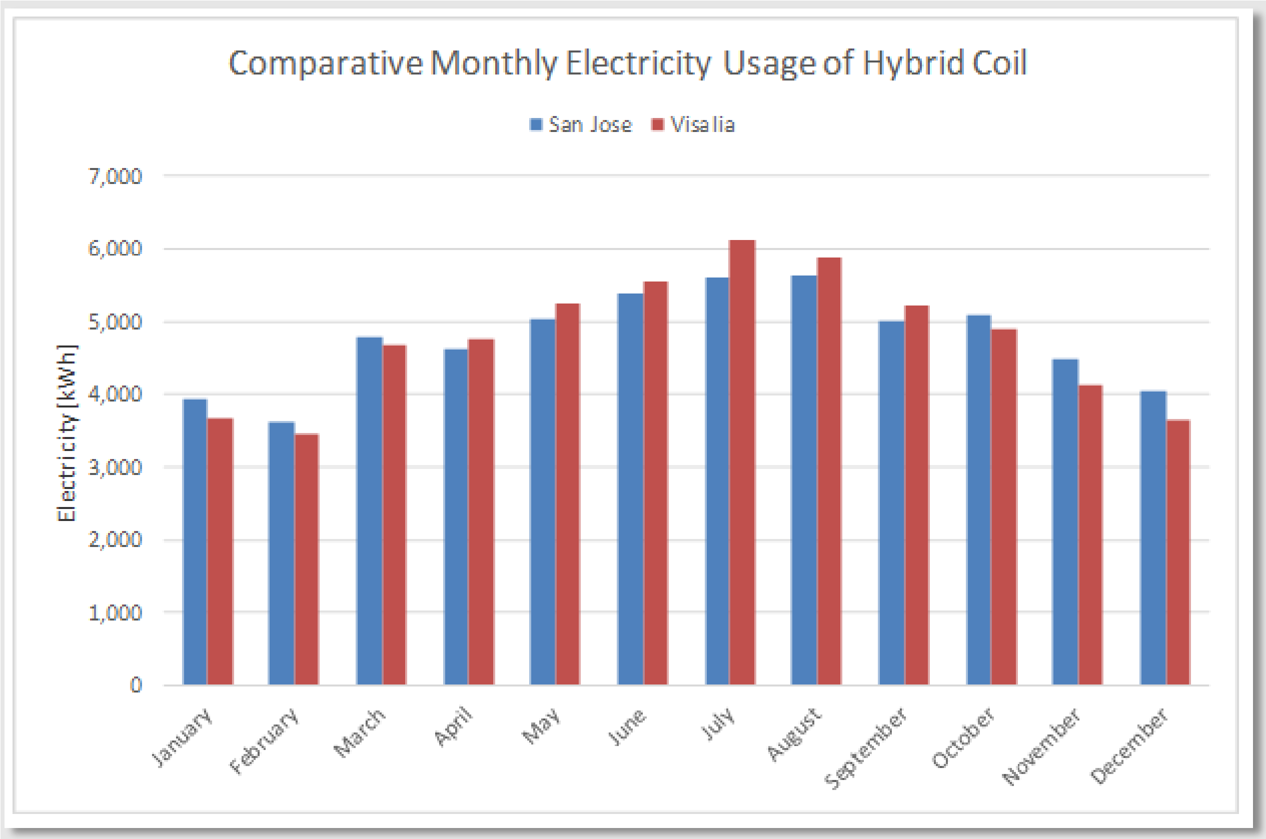
Figure 11: AHHEX Condenser Water Use in Visalia and San Jose, California



Source: Altex Technologies Corporation

Relative to power cost, Figure 12 presents the condenser fan-power usage in Visalia and San Jose over the one-year period for the same condenser design used in Figure 11. These results show greater power use in Visalia, which will increase operating costs.

Figure 12: AHHEX Condenser Fan-Power Usage in Visalia and San Jose, California



Source: Altex Technologies Corporation

To determine operating costs for the two locations, water and power use were combined along with expected maintenance, biocide, and other costs developed from Archibald et al. (2002). These results, for a 13.3-ton chiller in Visalia and San Jose, are included in Tables 12 and 13, respectively.

Table 12: AHHEX to Wet Condenser System Annual Cost Comparison–San Jose

Annual Cost Comparison		
Pure Wet System		**Hybrid System**
66,816	Total E Power (kWh)	57,229
$8,953.30	Total E Cost	$7,668.69
107957	Total Water Consumed (gal.)	6578
$227.45	Total Water Cost	$13.86
$33.29	Biocide	$2.03
$10.00	Chem Control	$10.00
$1,500.00	Cleaning Access	$1,500.00
$177.95	Chem System Maintenance	$177.95
$132.00	General Maintenance	$132.00
$11.72	Sewage Discharge Costs	$11.72
$11,033.99	TOTAL COST	$9,504.53

Source: Altex Technologies Corporation

Table 13: AHHEX to Wet Condenser System Annual Cost Comparison–Visalia

Annual Cost Comparison		
Pure Wet System		**Hybrid System**
80,142	Total E Power (kWh)	57,321
$10,739.05	Total E Cost	$7,680.96
141447	Total Water Consumed (gal.)	12517
$298.00	Total Water Cost	$26.37
$33.29	Biocide	$2.95
$10.00	Chem Control	$10.00
$1,500.00	Cleaning Access	$1,500.00
$177.95	Chem System Maintenance	$177.95
$132.00	General Maintenance	$132.00
$11.72	Sewage Discharge Costs	$11.72
$12,890.30	TOTAL COST	$9,530.23

Source: Altex Technologies Corporation

For comparison purposes, the evaporative (water only) cooling condenser results are also included in Tables 12 and 13. As shown in Table 12 for the San Jose location, the total power cost is higher for the wet-only system. As expected, water use is higher with the wet-only system, as well as water cost. For the other items, such as biocide, cleaning and maintenance, there could be some difference between the wet only and the AHHEX hybrid system, but to determine this difference requires real operating cost data for AHHEX. Therefore, at this stage these costs are assumed to be equal to the wet-only system. It should be noted that these costs are only 17 percent of the total cost. Comparing the total cost, Table 12 shows that the AHHEX annual cost is 14 percent lower than a wet-only system for operation in San Jose. Importantly, AHHEX has 94 percent lower water usage. A similar analysis was completed for Visalia. As shown in Table 13, AHHEX annual cost is 26 percent lower than the wet-only cost, and water use is reduced by 91 percent. This supports a greater cost advantage for AHHEX in higher ambient temperature locations. In addition to a greater cost advantage in Visalia versus San Jose, more water is saved in Visalia. In summary, model results for Visalia, a hot climate in the summer, and San Jose, show that AHHEX can save both operating costs and water usage versus a water evaporation only cooled condenser. While the model results are illustrative of the benefits of AHHEX, test results were required to confirm its advantages.

3.5 Full-Scale and Test Article AHHEX Design

Given the benefits shown by the modeling results, the AHHEX was designed for the 170-ton cooling application. Since the AHHEX capacity is related to the heat exchanger panel width for the same panel height, the design for the full-scale system can be used as a base for the planned test system by simply reducing the panel width. For example, the single panel width would be approximately 2.4 feet for the test system versus 21 feet for the 170-ton full-scale application, considering that the full-scale system would use two rows of panels. The capacity scale-up of the AHHEX test article data would then simply be the ratio of panel area, assuming the same face velocity. The measured pressure drop between the test panel and full-scale system would be about the same, and independent of capacity. This makes the translation of test article results to estimate full-scale system performance straightforward. Furthermore, if the materials and construction methods for the test article are the same as those that would be used in full-scale unit production, AHHEX results from this effort can be directly used to assess full-scale system durability, cleaning, corrosion, and cost. A significant challenge of this project was to manufacture an AHHEX panel made up of over 800 fins with soft tooling, rather than with the hard tooling that would be applied during actual production of AHHEX units. This was overcome by developing a novel soft tooling and applying the needed level of manual labor to successfully construct the AHHEX test unit. Based on modeling, analysis, supplier inputs, and test results, the top-level AHHEX design features were identified and are listed in Table 14. Relative to materials use, the wet portion will use stainless steel for good corrosion resistance, while the dry portion can use aluminum fins to save costs and reduce panel weight, which translates into reduced structural support weight and cost. When operating wet, water must be evenly distributed to the panels and water carryover to the exhaust minimized to limit downstream component corrosion and mist plumes that can wet surrounding areas and potentially promote Legionella and molds. To avoid misting, the water distribution system will use arrays of low-pressure water nozzles to create drops that will be of a small enough size to impinge on and coat the fins and tubes, but not small enough to create a mist that carries through to the exhaust. Also, to capture and return any water to the distribution systems, an impingement demister is located downstream of the wet portion of the panel. To control mineral deposits, sufficient water will be used during wet operation to prevent dry spots where scale can form. Also, in the water recirculation system, a small portion of the collected water is removed with time to prevent mineral concentration buildup in the water distribution system. To address Legionella, the system will dry out as operation shifts from wet to dry. This will help control potential Legionella growth. In addition, a proper level of biocide will be maintained in the reservoir to prevent Legionella from developing in that portion of the system.

Table 14: AHHEX Wet/Dry Condenser Design Features

Item	Features
Materials	Aluminum on always dry portion to control costs and stainless steel on wet/dry portion to control corrosion
Water distribution	Low pressure nozzles arranged in sections to control wetting and evaporation
Water mineral deposition control	Limit dry out region and perform regular washing and water discharge
Water Legionella control	Periodic dry out and biocide treatment when wet
Panel orientation and configuration	Near vertical rectangular panels, with less than 30 degrees from vertical
Tubes	Cylindrical horizontal tubes in standard staggered pattern
Manifolds	Cylindrical tubes of similar material
Fins	Porous high-performance fins with potential hydrophilic coating, pierced by tubes

Source: Altex Technologies Corporation

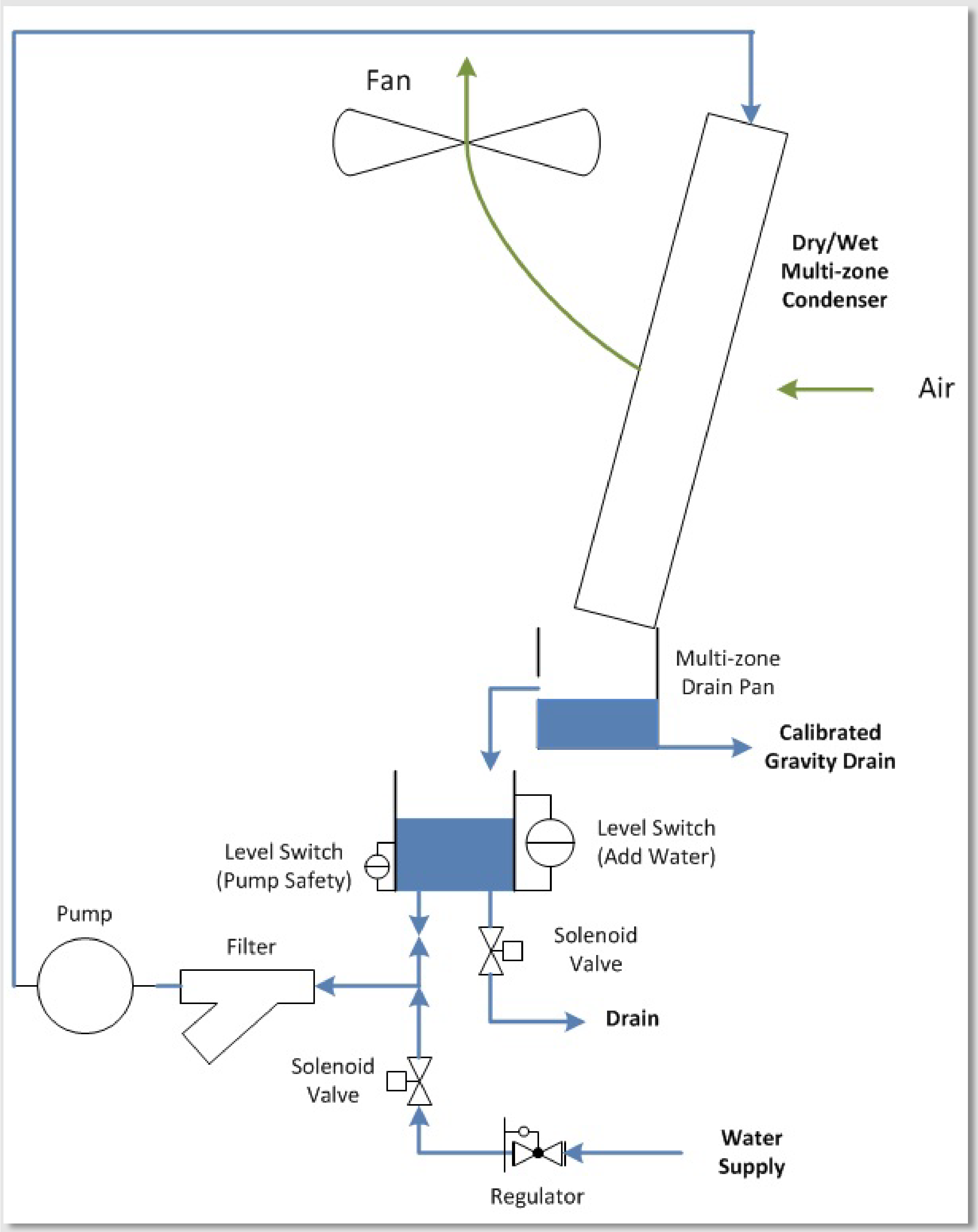
Relative to orientation, conventional dry condenser panels can be arranged in vertical, off-vertical, and horizontal orientations. For AHHEX wet operation, gravity will help the water distribute over the wet portion of the heat exchanger panels. Given the air flow through the panel, a forward leaning angle, as illustrated by the conventional dry condenser in Figure 13, would help to prevent water runoff from the back of the panel into the exhaust. The angle of the panel versus vertical would be less than 30 degrees, and an angle of 20 degrees would be a good balance between water running off the back of the panel versus running off the front of the panel. Refrigerant tubes for AHHEX will be sized for the proper refrigerant velocity to prevent lubricating oil excessive dropout, consistent with accepted practice, with manifolds also configured and sized to achieve the same objective at an acceptable pressure drop.

Figure 13: Example Conventional Dry-Cooling Condenser

Source: Altex Technologies Corporation

Fins for the panel are selected from those tested and modeled under both wet and dry conditions. These fins and their spacing will yield the needed heat-transfer performance at acceptable pressure drop. The control of AHHEX operation with water will be simple and an overlay of controls on top of the proven chiller control system. Figure 14 gives a piping and installation diagram (PI&D) illustration of the water distribution system, including sensors and actuations to maintain water levels and water distribution for wet operation. Water distribution on the wet portion of the core is by a low-pressure water shower that will avoid producing mist that could potentially carry over into the exhaust.

Figure 14: AHHEX Water Distribution PI&D



Source: Altex Technologies Corporation

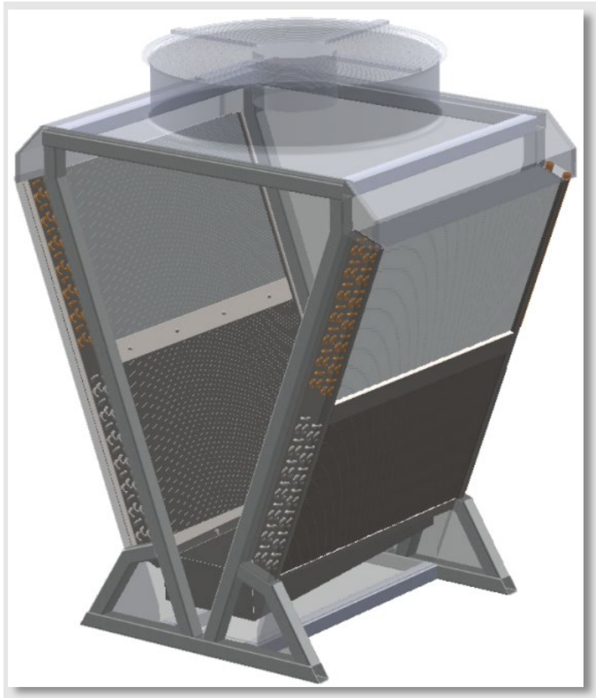
The fan speed will be controlled by a variable frequency drive to tailor the air flow to dry and wet operation, depending on the weather. This is currently a well-accepted practice and can save power costs over an annual period. Using the design features as shown, a full-scale AHHEX condenser cell with a single fan was designed. This unit, consistent with 28-tons refrigeration capacity, is illustrated in Figure 15. This system consists of two angled heat exchanger panels set in a frame that has a fan on top to draw the cooling air through the panels. By drawing rather than pushing air through the panels, air flow uniformity and heat transfer are improved.

Figure 15: AHHEX Hybrid Dry/Wet Condenser Cell

Source: Altex Technologies Corporation

This design has similarities to the conventional V-system illustrated in Figure 13, with the important difference being the special heat exchanger cores and fins. Figure 16 gives more detail on the AHHEX cores. The top core portion is constructed with aluminum fins and always operates dry, with the super-heated refrigerant vapor entering at the top of the core. At the bottom is located a wet/dry core that is plumbed in series with the top core. When operated wet, water is distributed to the top of this core and flows down the fins, with excess water collected at the bottom in a drain pan that is then recirculated to the water distribution manifold. Placed between the tops of the wet cores is a mesh-based impingement demister that would collect any water carried over from the core and recycle the water back to the water distribution system. By having these two cores in series, the dry and wet performance can operate at the lowest material cost when compared with a conventional condenser system.

Figure 16: AHHEX Hybrid Dry/Wet Cell Details



Source: Altex Technologies Corporation

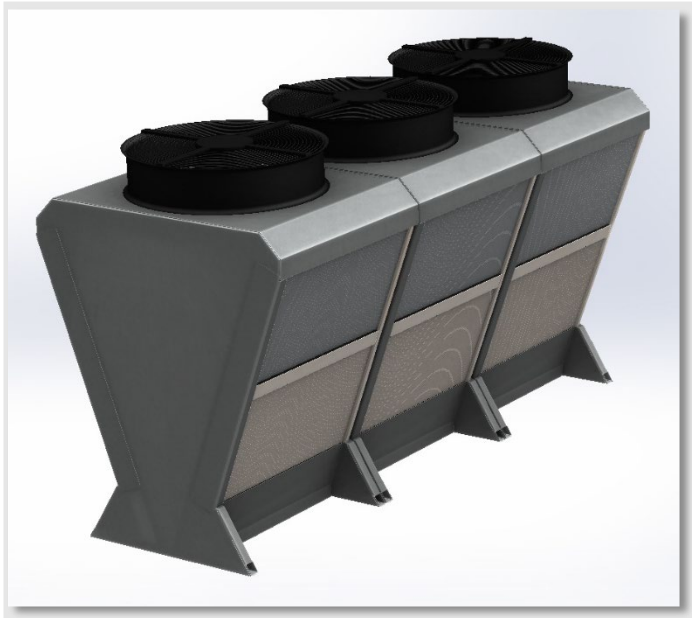
To achieve larger capacities, cells are added in parallel, as illustrated in Figure 17. Table 15 gives different capacity cooling systems and the number of AHHEX cells needed to cover those capacities. Depending on the available space at a site, the units could be arranged in a line, as shown in Figure 17, or as multiple rows to achieve the needed capacities. In all cases, the cells would be plumbed in parallel to yield a constant pressure drop and processing conditions for ease of AHHEX adoption to different capacity installations.

Table 15: AHHEX Cells to Cover Different Condenser Capacities

Refrigeration (tons)	Number of Cells	One Row Length (feet)	Two Rows Length (feet)	Three Rows Length (feet)
100	4	12	6	4
170	7	21	10	7
200	8	24	12	8
300	12	37	18	12
400	16	49	24	16

Source: Altex Technologies Corporation

Figure 17: Multiple Cell AHHEX Condenser System



Source: Altex Technologies Corporation

Figure 17 shows the design for full-scale AHHEX cells that can be grouped in parallel to address different capacity applications. For the 10-ton cooling test unit, a heat exchanger panel of the same height as the full-scale system will be used to directly simulate the full-scale processes, under carefully controlled test conditions. By simulating the full-scale processes, the test results from this effort will be easily scaled to full-scale capacities. For the 10-ton cooling test system, the width of the single panel will be 2.4 feet relative to a single cell width of 3 feet. Therefore, the scaling based on face area will be straightforward and data will be almost directly applicable. Refrigerant inlet and outlet manifolds for the test panel will be appropriately sized to maintain the required minimum flow velocity to avoid significant drop out and collection of compressor lubricant in the panel. Figure 18 gives an illustration of the test panel. To test this single panel, a frame will be constructed to hold the panel at the correct angle to the vertical, with a fan mounted on top of the frame to draw air through the panel, similar to the full-scale design illustrated in Figure 13.

Figure 18: AHHEX Test Article Panel

Source: Altex Technologies Corporation

Figure 19 shows the frame design and fan for the single-panel test system. A duct on the downstream end of the fan will be included to accurately measure air velocity and flow during performance characterization testing. This test system unit would be instrumented to measure flows, temperatures, and pressures. The unit would be hooked up to the 10-ton chiller (shown in Figure 3), in parallel with the conventional dry condenser. Using valves, chiller tests can be run with either the AHHEX wet/dry hybrid condenser or the conventional dry condenser.

Figure 19: AHHEX Test Panel in Frame

Source: Altex Technologies Corporation

3.6 Materials of Construction

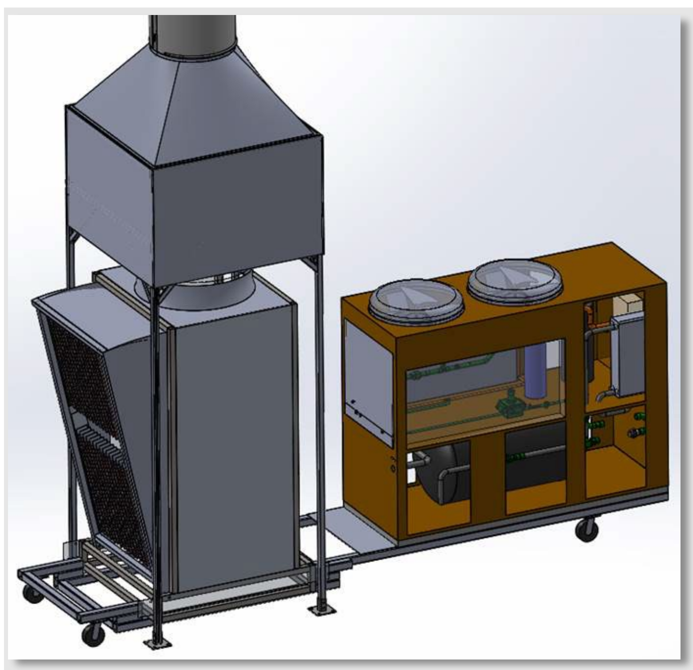
Heat exchanger corrosion from weather and air-borne contaminants must be controlled to yield long condenser lifetimes. Base materials play an important role, with aluminum or galvanized steel materials providing corrosion protection for dry cooling applications. For wet cooling applications, stainless steel provides good corrosion resistance, at some added cost when compared with galvanized steel. Besides using more corrosion-resistant base materials, coatings could be applied to reduce corrosion. One potential coating would be a thermosetting hybrid polymer coating. However, coatings can breach locally and, therefore, be subject to enhanced corrosion of the base material.

Common material options used in wet systems by manufacturers are hot-dip galvanized steel or 304 and 316 stainless steel. After further research, galvanizing is not a feasible option for the enhanced fins. Inadequate coating and/or filling of the enhancing surface features is anticipated, which would hinder performance. Stainless steel is the preferred option for maximum corrosion protection and heat exchanger life. In this case, no corrosion resistant coating is needed. However, the material is expensive, and the heat conductivity is one order of magnitude lower than for aluminum.

3.7 Chiller System

In support of testing, the AHHEX hybrid air/wet cooling system, an available Legacy Chillers 10-ton cooling chiller was modified to accept the advanced hybrid air/wet cooler test condenser. Another modification was the integration of two conventional fan-coil units that provided cooling to the Altex building during the test period. Figure 20 presents an illustration of the overall layout of the hybrid condenser (left lower), exhaust duct for the air heated by the condenser (left top) and the chiller (right). As shown, the hybrid condenser and chiller are mounted on a frame with casters for portability. For controlled conditions testing, an exhaust duct must be located within the test facility. In a typical industrial/commercial application, the condenser subsystem would be mounted on the building roof. For better control of environmental conditions during near-term performance testing, operation with an exhaust duct at the facility was used. Figure 21 shows the completed exhaust duct that is consistent with the test system illustration in Figure 20.

Figure 20: Overall Hybrid Condenser and Chiller Test System Layout



Source: Altex Technologies Corporation

Figure 21: Condenser Hot Air Exhaust Duct Installation at Altex Facility

Source: Altex Technologies Corporation

As shown in the picture of the chiller test unit, the chiller contains the compressor, conventional condenser panels, fans, reservoir, pumps, and associated plumbing and controls. The specifications for the unit are included in Table 3. This is a typical chiller design that has similarities in performance and operation to larger chillers of interest to this effort. Given that the AHHEX cooler is easily scaled up by just using multiple panels and fans, AHHEX testing at the 10-ton cooling level will save testing costs while providing directly relevant results for larger systems. In addition, at this 10-ton (35kW cooling) capacity, the fabrication method and materials will be the same as those used for the larger capacity units. Therefore, the condenser production process will be proven at pilot scale under this effort, and production cost estimates will be well supported.

In support of fully characterizing the hybrid condenser performance, chiller modifications were made, and the unit was instrumented to collect needed data. A NIST-calibrated flow meter was installed, and the copper plumbing rerouted to allow installation of the flow meter, as shown in Figure 22. The process water connections to and from the two fan-coil units were installed and are shown in Figure 23. The cam lock fittings allow the fan coils to be easily disconnected and connected, as needed. The valves not only allow the fan coils to be disconnected but also allow flow rate adjustability.

Figure 22: NIST-Calibrated Flow Meter Installed in Tube

Source: Altex Technologies Corporation

Figure 23: Chilled Process Water Connections for Fan-Coil Units

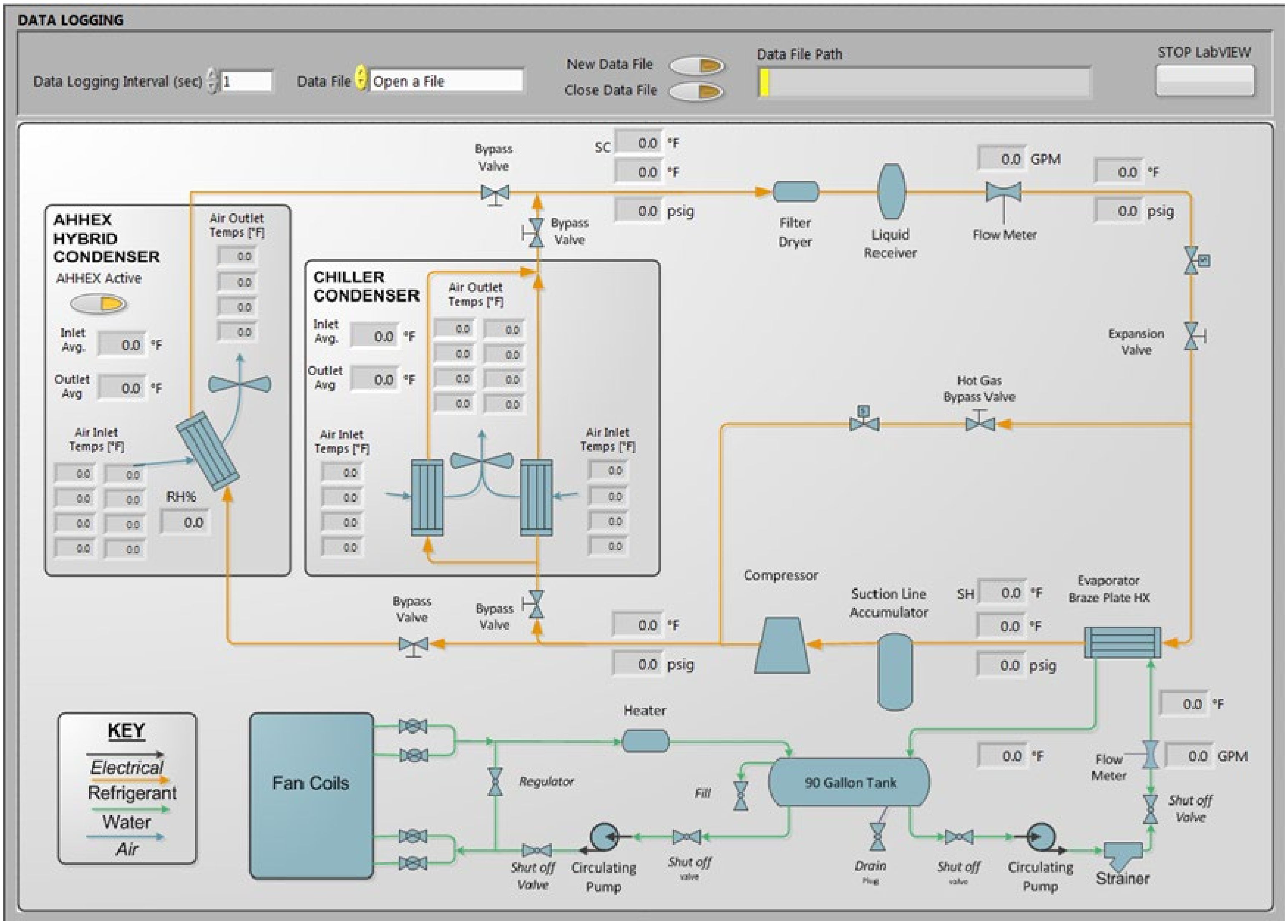
Source: Altex Technologies Corporation

In order to obtain accurate performance data, a given set of operating conditions must be maintained for a long enough time period to reach steady-state operation. One of the constant conditions is the water inlet temperature into the evaporator, which relates to the heat load. To ensure that a wide range of constant heat loads can be achieved, an electric immersion heater was installed in the water process loop. The chiller wiring was completed, and thermocouples installed, and a set of refrigeration gauges were connected to the compressor. The system was energized, and the compressor rotation and operation were confirmed. The circulating and process pumps were energized, and operation was confirmed. The system was also checked for leaks and found to be leak free.

3.8 Fan Coil Units

The chiller provides 10 tons of cooling to the circulating water loop. This cooling can be utilized for various purposes, including air conditioning. Two fan-coil air conditioning units were utilized to provide the needed 10-tons cooling load to operate the chiller and hybrid condenser. This fan coil cooling approach is consistent with larger systems installed in hotels where individual room temperature control is of interest. LabView, a system-design platform and development environment was used to monitor and record data for performance testing. The user interface is shown in Figure 24.

Figure 24: LabView Program User Interface for Test System



Source: Altex Technologies Corporation

The fan coil units were mounted onto dollies, as shown in Figure 25, to allow easy relocation to spaces that need cooling. This portability increases testing flexibility.

Figure 25: Fan Coil Units

Source: Altex Technologies Corporation

3.9 Hybrid Condenser Test Article Design

Conventional dry condenser panels can be arranged in vertical, off-vertical, and horizontal orientations. For AHHEX wet operation, gravity will help distribute water over the wet portion of the heat exchanger panels. Given the air flow through the panel, a forward leaning angle, as illustrated by the conventional dry condenser in Figure 13, would help prevent water runoff from the back of the panel into the exhaust. Figure 20 illustrates this angle orientation for the hybrid test system. An angle of 20 degrees is a good balance between water running off the back of the panel versus running off the front of the panel. Refrigerant tubes for AHHEX were sized for the proper refrigerant velocity to prevent excessive lubricating oil dropout, consistent with accepted practice, with manifolds also configured and sized to achieve the same objective at an acceptable pressure drop. The fan speed will be controlled by a variable frequency drive to tailor the air flow to dry and wet operation, depending on the weather. This is currently a well-accepted practice and can save power costs over an annual period.

The AHHEX unit, consistent with 28-ton refrigeration capacity, is illustrated in Figure 16. This system consists of two angled heat exchanger panels set in a frame that has a fan on top to draw the cooling air through the panels. This design has similarities to the conventional V-system illustrated in Figure 13, with the important difference of special heat exchanger cores and fins. Figure 16 shows details of the panel construction, which consists of horizontally-aligned refrigerant tubes that pierce multiple layers of flat fins aligned vertically for both the dry and dry/wet portions.

The top portion of the panel always operates dry while the bottom portion operates dry until weather conditions (high temperature) require activation of a water spray that provides extra cooling from the latent heat of evaporation. To test a single panel AHHEX, a frame was constructed to hold the panel at the correct angle to the vertical, with a fan mounted on top of the frame to draw air through the panel, as illustrated in Figure 1. For flexibility in testing, the angle of the frame to the vertical can be varied.

Figure 26 gives a picture of the horizontal refrigerant tubes that are circuited as shown in Figure 16 for both dry and wet portions of the AHHEX condenser. These hairpin-shaped tubes pierce a stack of special flat fins that provide the needed surface area and water retention capability to meet the advanced hybrid performance characteristics. Figure 27 provides an example of fin configuration where the tube layout is shown and collars are formed to yield the needed fins-per-inch distribution for optimal performance. For purposes of illustration, solid rather than actual fins are shown.

Figure 26: Refrigerant Tubes for Dry and Wet AHHEX Panels

Source: Altex Technologies Corporation

Figure 27: Example Fins With Formed Collars

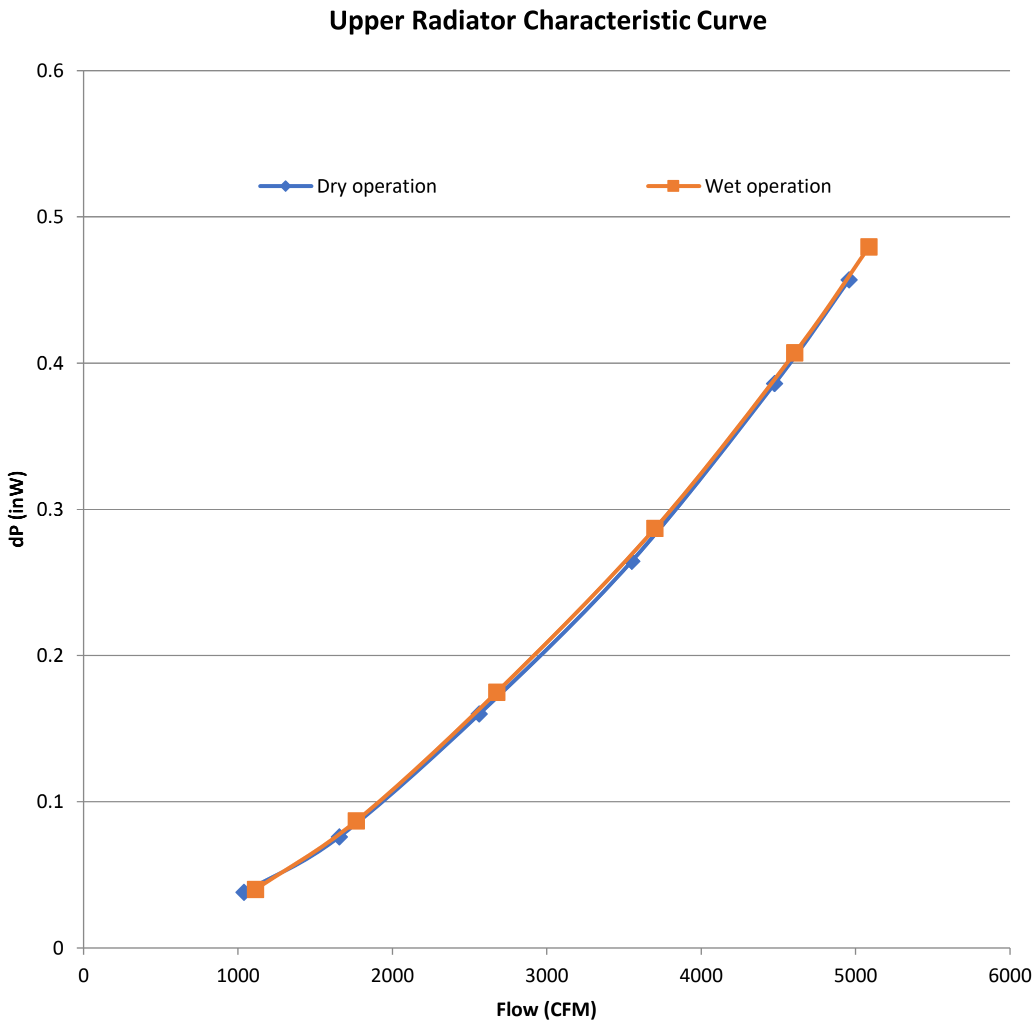
Source: Altex Technologies Corporation

3.10 Performance Test Results

Using the AHHEX condenser test setup previously described, tests were carried out to obtain the performance data that define water and power requirements for the AHHEX condenser. Testing was initiated with characterization of the air flow through the dry upper and wet/dry lower condenser panels. The upper and lower panels have different designs in terms of face area and fin arrangements. Therefore, air flow will distribute between the panels to achieve the same pressure drop for a given fan setting. Changes in air temperature will alter the total flow through the panels, but the split between panels is expected to be the same. These differences are limited for the range of temperature and heating rates so that the impacts can be analytically estimated. A larger impact on pressure drop is the impact of the water flow in the lower panel that increases pressure drop. Air flows through the panels were tested under dry and wet conditions to define air flow versus pressure drop. These results were then used to characterize AHHEX performance.

The air-flow tests used an array of 40 velocity measurements over the upper and lower panels to define zone velocities that were then converted into air flows through the panels. In addition, temperatures were measured in an array of 40 measurements to characterize the air densities ahead of the panels. The air velocities were then determined as a function of fan speed. In addition, using static pressure probes ahead of and after the panels, the pressure drops were also determined. Figure 28 gives the upper AHHEX panel pressure drop as a function of flow.

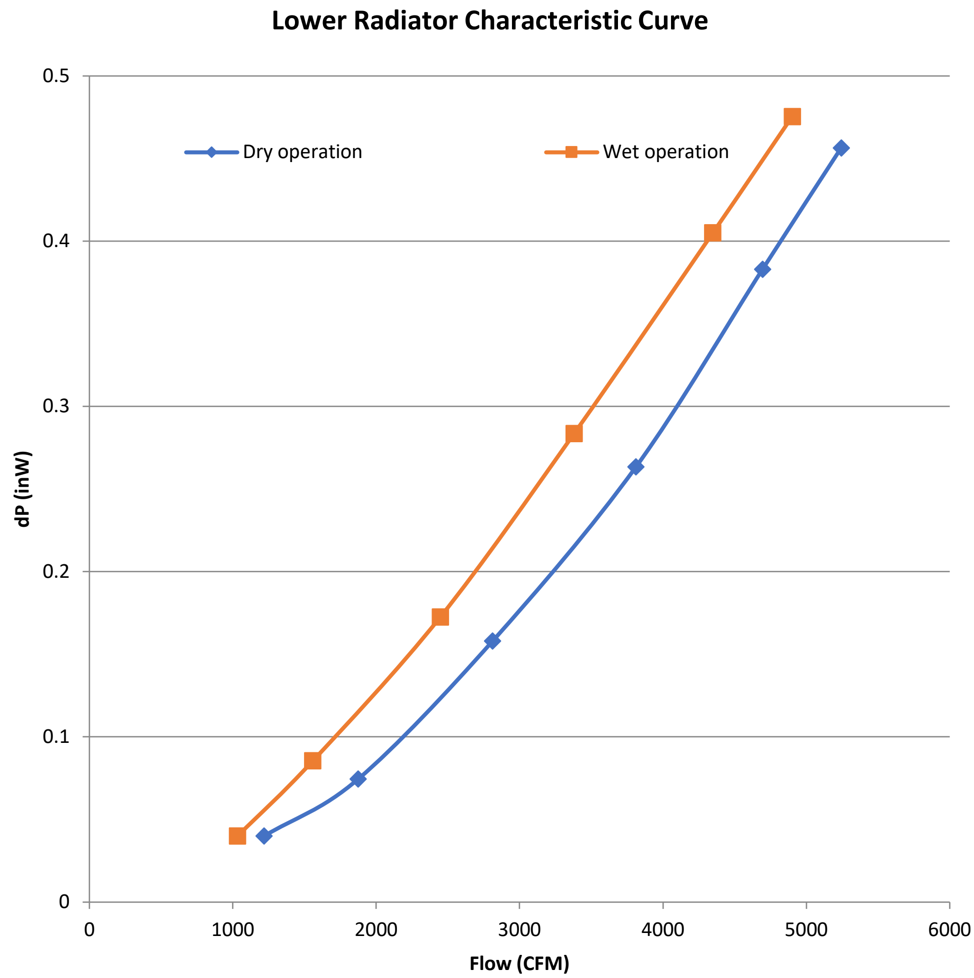
Figure 28: Upper Panel Pressure Drop Versus Air Flow



Source: Altex Technologies Corporation

The measured curve follows the expected behavior, and the pressure drop is limited for the flow rates (such as, 5,000 CFM). As noted, the upper panel operates without water deluge; therefore, as shown in the figure, the dry and wet operation of the AHHEX does not change the upper-panel pressure drop. Figure 29 gives the lower-panel pressure drop as a function of air flow. As shown in the figure, under dry conditions the pressure drop is lower, by over 0.05” H2O, versus the wet operation pressure drop. This is expected since the water deluge will block some of the flow area and add droplet form drag to the pressure drop. This will impede air flow and result in more pressure drop to achieve the same air flow as under dry conditions. These test results were used to convert pressure drop measurements to air flow during the chiller tests.

Figure 29: Lower Panel Pressure Drop Versus Air Flow



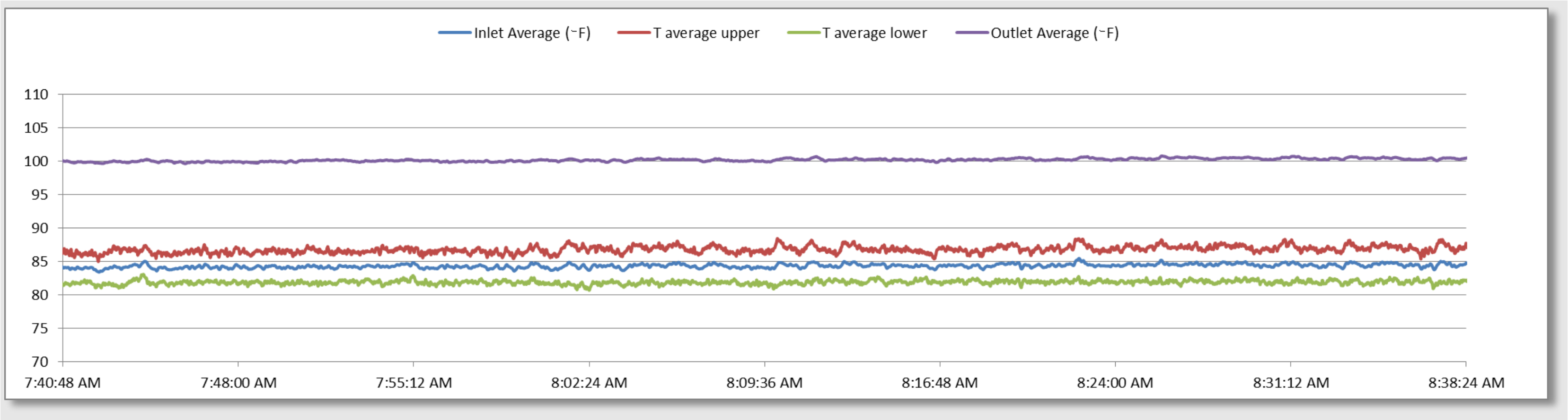
Source: Altex Technologies Corporation

As noted previously, water is sprayed on the AHHEX lower panel to provide evaporative cooling when ambient temperatures are high. The AHHEX condenser fan and water spray flow are controlled by the refrigerant compressor outlet pressure. With low ambient air temperature, the refrigerant expansion valve opens up to allow more refrigerant flow and cooling in this low ambient-air-temperature condition. The expansion valve action maintains the compressor suction-side superheat that prevents liquid refrigerant from entering and damaging the compressor. This action also reduces compressor exit pressure and power draw. As the ambient temperature increases, the compressor exit pressure increases. The AHHEX controls then ramp up the fan air flow to provide better heat dissipation in the AHHEX condenser. This offsets the impact of the rising ambient temperature. The current controls are set so that the minimum fan speed is achieved at 285 psig compressor pressure, with the maximum fan speed achieved at 300 psig. Once ambient air temperature has increased to a compressor exit pressure of 330 psig, the water spray to the lower panel is activated. This provides significantly increased cooling of the refrigerant, thereby opposing the increase of compressor pressure when the ambient air temperature increases. With these compressor-exit pressure set points, test results identified what ambient air temperatures correspond to the fan speed and water activation pressure set point controls.

Figure 30 is a time plot of the AHHEX condenser inlet and outlet air temperatures, which shows a fairly consistent temperature difference over the time tested. It should be noted that there is a difference between the upper and lower panel entering air temperature. This is a result of some heated air in the facility recirculating into the inlet. With the AHHEX unit mounted on a roof, this recirculation would be suppressed, or possibly even enhanced, depending on the speed and direction of the wind and the interaction of the fan exhaust with nearby obstacles. The design of the actual product and installation must consider these effects. Shrouds, including fan exhaust extensions, could better control exhaust air flow recirculation. Further work on product design, including installation factors, is needed to eliminate this effect. Including this recirculation effect produces roughly a 5°F increase in ambient temperature on the upper panel, or a 4 percent reduction in AHHEX heat transfer for the full panel. Therefore, the performance results reported here are conservative.

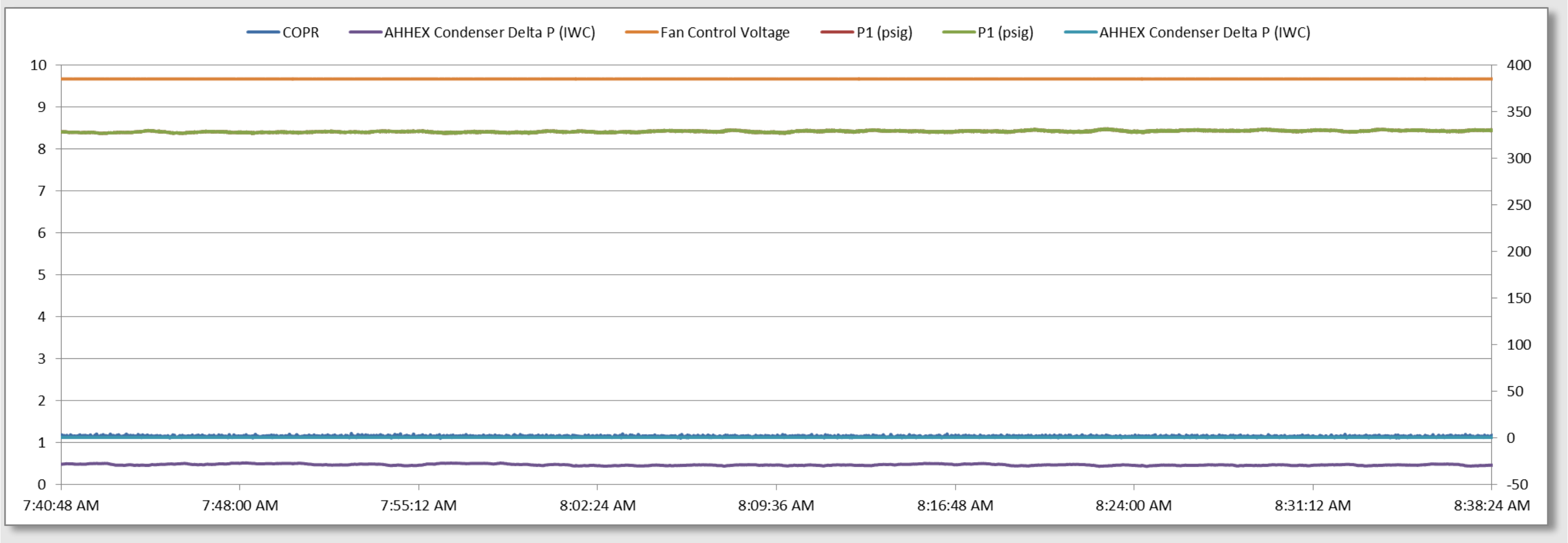
The average ambient air temperature for this case is approximately 84°F. Consistency of temperatures over time is also shown in Figure 31, in the fan-control voltage of 9.7 volts that is associated with the maximum fan speed. At an ambient air temperature of 84°F, the compressor exit pressure is 330 psig, which exceeds the maximum fan set-point pressure and is very close to the water spray activation pressure. Figure 32 shows what happens when the ambient air temperature reaches 85°F to 86°F. Under these conditions, there are 6-minute cycle fluctuations in the condenser exit temperature, with some evidence of recirculation of hot air to the condenser inlet that causes the air inlet temperature to cycle. As noted, this recirculation can be suppressed. Figure 33 indicates what causes the cycling. As shown, the compressor exit pressure has sharp drops from over 330 psig down to about 300 psig, which corresponds to the water flow. This supports that the water spray is so effective at cooling the AHHEX lower condenser panel that the pressure rapidly drops to the level where the water spray turns off. The pressure is even low enough for the fan to shift to low speed, as indicated in Figure 31. At this point, the residual water on the lower panel continues to evaporate and provides condenser cooling. As the cooling becomes more limited as the residual water is evaporated, the pressure rises, and the fan speed increases. As the pressure increases above 300 psig the fan again hits maximum voltage and speed. The expansion valve then opposes the increase in pressure until it reaches above 330 psig, at which point the cycle is repeated. The water-on period is approximately 45 seconds with the total cycle time of about 6 minutes.

Figure 30: AHHEX Upper- and Lower-Panel Inlet Air Temperature and Outlet Average Temperature – Dry Operation



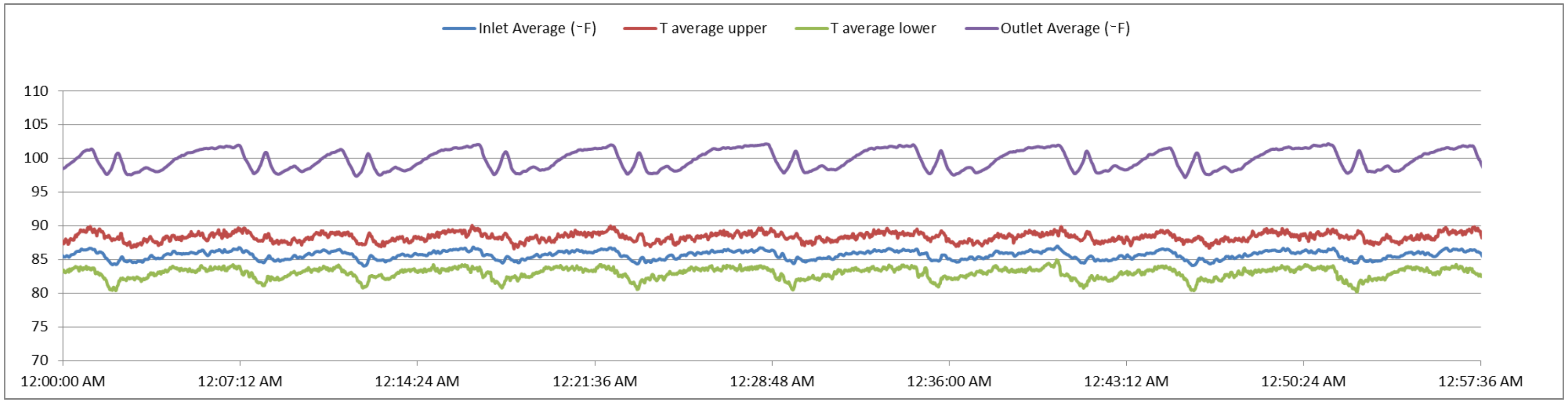
Source: Altex Technologies Corporation

Figure 31: AHHEX Pressure Drop, Compressor Pressure, Fan-Control Voltage and COP – Dry Operation



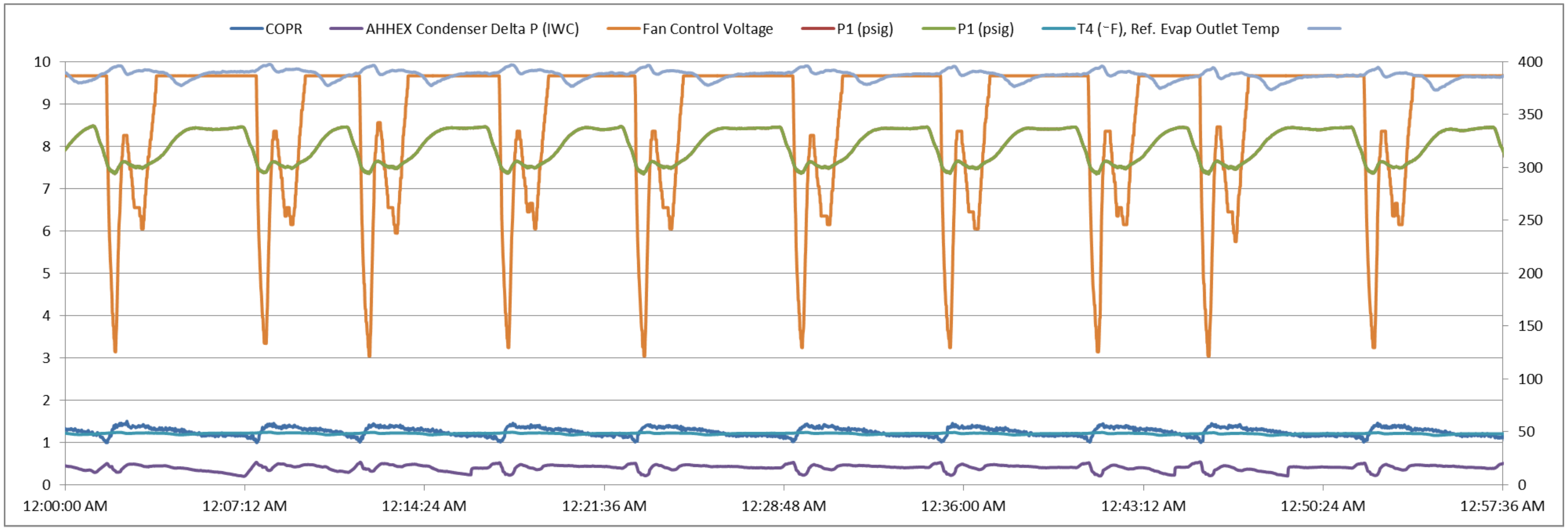
Source: Altex Technologies Corporation

Figure 32: AHHEX Upper- and Lower-Panel Inlet Air Temperature and Outlet Average Temperature – Wet/Dry Operation



Source: Altex Technologies Corporation

Figure 33: AHHEX Pressure Drop, Compressor Pressure, Fan-Control Voltage and COP – Wet/Dry Operation



Source: Altex Technologies Corporation

Results in Figure 33 also show that the COP increases by approximately 40 percent from the low point where the water spray is activated. This represents a significant reduction in power use versus the cooling achieved. As shown in Figure 33, the system cycles at an ambient air temperature of about 85°F to 86°F as a result of the sharp increase in condenser cooling when the water spray is activated. With higher ambient air temperatures, the water spray will stay on longer until the spray is always on. In this case, the operation will be steady, as experienced in the low ambient air temperature dry-operation case. Therefore, the unit operates steadily at low ambient air temperature, transitions to a deluge water on-off cycle at the compressor set point that activates the water spray, then back to steady operation at high ambient air temperatures, where the water spray is always active.

To fully characterize AHHEX and chiller performance, the test unit was operated both day and night. Air flow in the test facility was controlled so that high ambient temperatures could be achieved as a result of the recirculation of hot air. Also, the fan-coil units were operated either in the facility to limit air temperatures or placed outside the facility to maximize facility-heat input and air temperature. Even with the ambient temperature varying between 80°F to 95°F, the chiller and AHHEX water deluge controls managed to hold the cooling capacity nearly constant at 13 tons. As expected, the activation of water reduces the compressor pressure and increases COP, with the COP increasing by a significant amount. This shows the importance of water cooling. Operation with low constant compressor pressure is when the deluge water is activated. High-compressor pressure happens when the unit operates dry during the night when the ambient temperature drops. With the refrigerant flow control via the thermal expansion valve, the condenser refrigerant inlet and outlet temperatures remain relatively constant within the cycling band. Based on averages of the time-history data, performance parameters for the chiller and AHHEX condenser were calculated. This averaging approach was used to cover the fluctuations in conditions due to the cycling under wet/dry operation in ambient temperature ranges where the unit cycles. In either lower or higher temperatures, where operation is either all dry or all wet, conditions are steady.

Table 16 gives the performance test results with the first three rows representing conditions where the unit operates dry at ambient air temperatures between 80.4°F to 86.2°F. This covers dry-only operation up to incipient wet operation. The next two rows in Table 16 give the performance results when the unit is operating wet, at ambient temperatures of 89.9°F and 93.0°F. The lines below the first five in the table are continuations of the first five lines. The table provides temperatures and pressures, as presented in the PI&D for the chiller and AHHEX condenser provided in Figure 24. The condenser outlet sub-cooling and evaporator outlet superheat temperatures were low relative to typical practice where sub-cooling and superheat are between 8°F and 12°F. It is believed that the installation of a refrigerant flow meter, receiver, and filter for the testing has resulted in the chiller operating off of the design point, resulting in a lower overall performance. This is indicated by the 6.6 percent to 10 percent lower cooling capacity than the chiller manufacturer specifications for the operating conditions tested, as shown in Table 17. Given that the focus of this work was on the condenser performance rather than on the chiller performance, the shortfall in dry or wet chiller baseline performance of up to 10 percent was acceptable

Table 16: AHHEX Performance Over Range of Ambient Air Temperatures

T1 (°F), Ref. Cond. Inlet	T2 (°F), Ref. Cond Outlet	T3 (°F), Ref. Flow meter Outlet	T4 (°F), Ref. Evap Outlet Temp	T5 (°F), EGW Evap Inlet	T6 (°F), EGW Evap Outlet	T7 (°F), Water, Process Return	T8 (°F), Water, Process Supply	P1 (psig)	FM-1 Refrigeration Loop (GPM)	RH-1 Relative Humidity	FM-2 EGW Flow Meter	Fan Power (W)	Compressor Power (W)
190.8	119.2	117.9	44.4	45.1	41.1	53.5	44.0	312	5.0	49.9	60.6	2130.4	23265.7
192.8	120.7	119.4	42.5	43.4	39.5	51.6	42.4	319	4.9	47.0	60.5	2129.7	23622.4
198.7	124.4	123.1	44.9	45.6	41.7	53.8	44.6	334	5.1	46.6	60.5	2110.8	24305.1
192.2	118.0	116.8	47.0	47.3	43.2	55.8	46.4	308	5.0	54.0	60.7	2129.8	23130.6
195.1	120.7	119.4	47.5	47.7	43.7	56.2	46.8	319	5.1	56.5	60.6	2113.4	23599.0
Average inlet air T (F)	Average outlet air T (F)	Condenser Refrig. Heat Transf. (Btu/hr)	Evap. Refrig. Heat Transf. (Btu/hr)	Evap. EGW Heat Transf. (Btu/hr)	Comp. Refrig. Work (Btu/hr)	Fan Coil EGW heat transfer (Btu/hr)	Water Usage (gal/hr)	EER	COPr	tons cooling	Comp Power (kw)	Comp eff	
80.4	96.3	211,675	153,045	105,838	58,630	129,307	0	5.8	1.7	12.8	17.2	0.7	
82.7	98.3	207,717	148,564	102,944	59,154	125,799	0	5.55	1.63	12.4	17.3	0.7	
86.2	102.0	209,536	147,544	102,554	61,992	125,166	0	5.38	1.58	12.3	18.2	0.7	
89.9	100.3	216,556	157,479	107,430	59,077	129,463	8.976	6.00	1.76	13.1	17.3	0.7	
93.0	103.0	217,724	156,916	106,353	60,808	129,277	11.22	5.87	1.72	13.1	17.8	0.8	
Average inlet air T (F)	Average outlet air T (F)	RH-1 Relative Humidity	Average inlet air T (F)	Average outlet air T (F)	Enthalpy Inlet Air (B/lb)	Enthalpy Outlet Air (B/lb)	Air Side Heat Transfer (B/hr)	Inlet Air Grains/Lb Dry Air	Ratio Refrig/Air Side Heat Transfer	Outlet Air Grains/lb Dry Air			
80.4	96.3	49.9	80.4	96.3	31.6	35.8	185,348	79	1.14				
82.7	98.3	47.0	82.7	98.3	32	36.2	184,588	79	1.13				
86.2	102.0	46.6	86.2	102.0	34.4	38.6	183,379	88	1.14				
89.9	100.3	54.0	89.9	100.3	38.7	43.3	189,532	109	1.14	121.08			
93.0	103.0	56.5	93.0	103.0	42.6	47.7	208,969	130	1.04	145.10			

Source: Altex Technologies Corporation

Table 17: Comparison of Chiller Performance to Manufacturer Specifications

Average Inlet Air T (F)	AHHEX Evaporator Heat Transfer (B/hr)	Legacy Chiller Heat Transfer (B/hr)	Difference (%)
80.4	153,045	168,000	8.9%
82.7	148,564	159,000	6.6%
86.2	147,544	164,000	10.0%
89.9	157,479	168,000	6.3%
93.0	156,916	168,000	6.6%

Source: Altex Technologies Corporation

As shown in Table 16, the compressor pressure varied over the ambient air temperature range, as expected. For dry operating conditions, as the ambient temperature increased, the compressor pressure increased from 312.3 psig to 334.0 psig. This upper pressure level is close to where the deluge water is activated. Interestingly, as the ambient temperature increases to 90°F and above, the pressure is reduced by 7.8 percent versus the dry operating condition at a lower temperature. As described, the deluge water is effectively cooling the refrigerant, lowering the compressor pressure and increasing the COP by 12 percent, as shown in Table 16 for wet conditions. In addition, the use of water cooling increases the cooling capacity and EER by 6.7 percent. Without this extra cooling, the capacity and efficiency (COP and EER) would have continued to drop as ambient air temperature increased. Compressor power is also reduced with water cooling, which would be expected based on the drop in compressor pressure. Table 16 gives the compressor power and the decrease of 5 percent when deluge water is activated. As indicated in the table, fan and deluge water pump power are only a small fraction of the compressor power.

Using the refrigerant loop temperatures, pressures, and flow data, the AHHEX condenser heat transfer, evaporator heat transfer, and compressor flow power were calculated, as shown in Table 16. Above the ambient temperatures, with or without deluge water cooling, neither the compressor flow power nor the evaporator heat transfer varied significantly. This is because the chiller and deluge water controls adjust system characteristics to deliver a relatively consistent cooling load from the fan-coil units at the maximum cooling load of about 13 tons, as given in Table 16. This cooling capacity lines up approximately with the chiller manufacturer specifications, as shown in Table 17.

Table 16 gives the AHHEX condenser heat transfer for dry and wet conditions over the ambient air temperature conditions tested. As shown, the heat transfer only varies by 4.8 percent from the maximum to minimum results. Again, the chiller unit is controlling conditions to meet the needed cooling load capacity of the fan-coil units. Table 16 also gives the deluge makeup water flow that drives the extra heat transfer required for high ambient air temperatures. As shown, the flow rate of the makeup water that either supports evaporative cooling or is carried out of the fan exhaust, is limited. In fact, the change in Relative Humidity (RH) from air entry to air exhaust from evaporation is limited, as shown in Table 16. The air exhaust for AHHEX is far from saturated and, for the conditions tested, a water mist plume is not expected. Of course, for very high-inlet air RH, a water mist plume could be created.

Using measured air temperatures and flows, the AHHEX condenser air-side heat transfer can be calculated, and the results are shown in Table 18, along with the condenser heat transfer calculated from the refrigerant data. Given the other potential heat transfer mechanisms, such as heat transfer and dissipation in the structure and ducts, the refrigerant side heat transfer is expected to be higher than the air-side heat transfer. This is apparent in the data shown in Table 18, where the refrigerant-based heat transfer is from 4 percent to 14 percent higher than the calculated air-side heat transfer. Given comparable heat transfer levels, it can be concluded that the AHHEX heat transfer and water flow data can be used to estimate water, fan, and pump power use for AHHEX for comparison with conventional evaporative-cooled or dry-condenser results.

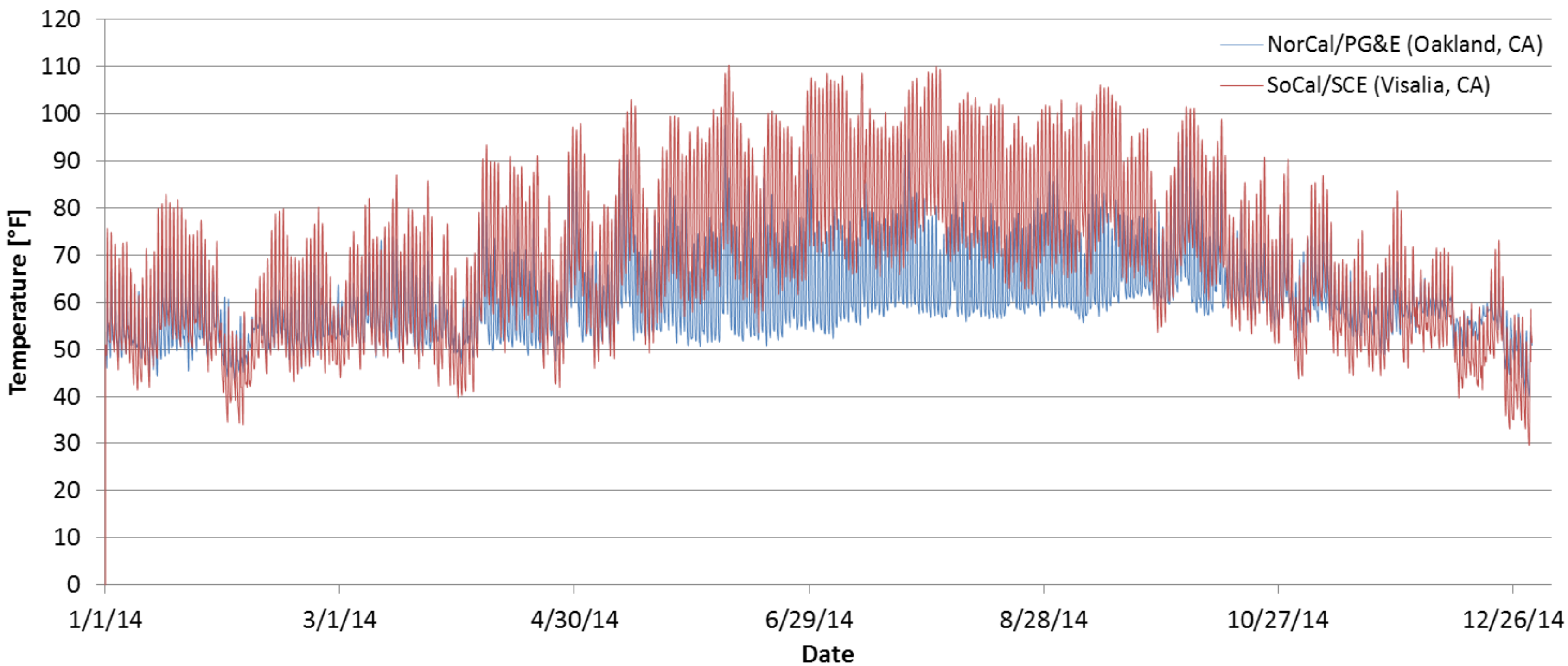
Table 18: Comparison of Heat Transfer

Average Inlet Air T (F)	Condenser Refrigerant Heat Transfer (Btu/hr)	Air Side Heat Transfer (B/hr)	Ratio Refrigerant/Air Side Heat Transfer
80.4	211,675	185,348	1.14
82.7	207,717	184,588	1.13
86.2	209,536	183,379	1.14
89.9	216,556	189,532	1.14
93.0	217,724	208,969	1.04

Source: Altex Technologies Corporation

When the air temperature is high, the AHHEX system uses water. According to the test results summarized in Table 16, that water use is between 0.69 and 0.86 gallons per ton-hour (gal/t-hr). This is lower than the water-use range of conventional evaporative coolers, which consume 1.3 to 3.5 gal/t-hr, as shown in Table 19 [10]. If a commercial or industrial cooling application is considered where the constant cooling load is 170 tons for most of the year, then hours of operation will be high when compared with air-conditioning applications. For a conventional system, hours of operation can be either a significant fraction of the year, or in the range of 4,000 hours per year, as shown in Table 19. This results in high water use in conventional evaporative coolers, as illustrated in the first two rows of the table. For the AHHEX-based system shown in subsequent rows for Oakland and Visalia in Table 19, the hours where deluge water is activated are comparatively limited. These hours of deluge water operation were computed from the ambient air temperature data in Figure 10 for both Oakland and Visalia in Figure 34.

Figure 34: 2014 Ambient Air Temperatures for two California Locations (National Renewable Energy Laboratory Data)



Source: Altex Technologies Corporation

As indicated in Table 19, the number of hours for deluge water operation for Oakland is much lower than the hours for the Visalia location; Visalia, in a hotter climate, required roughly ten times more water than Oakland.

Table 19: Comparison of AHHEX and Conventional Evaporative Cooler Water Use

	Water (gal/hr)	Water (gal/t-hr)	Cooling (tons)	Water (gal/hr)	Use Time (hr/yr)	Total Use (gal/yr)	Latent to Heat Transfer	Water Cost ($/1000gal)	Cost per Year ($/yr)
Evaporative	Low	1.3	170	221.0	4,000	884,000	0.98	3.9	$3,448
Evaporative	High	3.5	170	595.0	4,000	2,380,000	2.64	3.9	$9,282
Oakland	9	0.69	170	117.7	184	21,655	0.52	3.9	$84
Oakland	11.22	0.86	170	146.7	184	26,997	0.65	3.9	$105
Visalia	9	0.69	170	117.7	1,892	222,674	0.52	3.9	$868
Visalia	11.22	0.86	170	146.7	1,892	277,600	0.65	3.9	$1,083

Source: Altex Technologies Corporation

However, even with greater water use, AHHEX would reduce water use by 2.1 Mgal/yr in the worst-case scenario, or an 88 percent reduction. This is close to the project goal of reducing water use by 2.4 Mgal/yr. Relative to the Oakland location, where ambient air temperatures are lower, the water use reduction is 2.35 Mgal/yr, or a 98.7 percent reduction. These are important water-use reductions for both cooler and hot climates in California. Besides reduced water use, AHHEX will have lower pressure drop and fan power needs than conventional dry and wet systems, particularly when the air temperature is low and water is not utilized. This will provide power cost reduction benefits to California ratepayers. Relative to fan power use in conventional coolers, the test results from Figure 7 can be used to estimate the power reduction for AHHEX. At a 500 fpm face velocity and assuming similar core thicknesses, the pressure drop and flow power for AHHEX would be 28.6 percent lower than a conventional dry condenser. When operating wet, this advantage would be reduced, as indicated by the results in Figure 29. Relative to a conventional wet condenser, the AHHEX dry operation advantage of 28.6 percent would be offset by 16 percent and 8 percent for hot (Visalia) and cool (Oakland) areas in California, respectively. This is based on a comparison of conventional dry cooling and evaporative coolers given in Greencheck Fan Corporation (2011). This then gives the fan-power savings versus a wet system of 12.6 percent for Visalia and 20.6 percent for Oakland, respectively. Considering the same commercial and industrial year-round cooling-load requirement used in the water-reduction assessment, the conventional or AHHEX units are expected to operate 4,000 hours per year. Scaling the tested fan power need of 2.1 kW for the 13-ton cooling unit to the 170-ton example, the fan-power use would be 27.5 kW, and for the 4,000 hrs of operation, the AHHEX power use would be as shown in Table 20. Using the expected savings for AHHEX relative to an evaporative cooler, the energy savings per year are shown in Table 20. The maximum energy savings for Oakland of 28,499 kWh/yr exceeds the project goal of 17,240 kWh/yr.

In summary, for the Oakland and Visalia locations, the AHHEX water savings come close to meeting the project-savings goals for commercial and industrial applications, where the cooling load is relatively constant throughout the year. Furthermore, for this same application, the AHHEX electric energy savings exceed the project goal for the Oakland location and come to within 10 percent of the goal for the Visalia location. While these results indicate the savings potential of AHHEX for individual units, the total benefit to California must be calculated. These results are shown in Chapter 6.

Table 20: Comparison of AHHEX and Conventional Evaporative Cooler Electrical Energy Use

Location	Use (hr/yr)	Fan Power (kW)	AHHEX (kW-h/yr)	Conventional (kW-h/yr)	Difference (kW-h/yr)
Oakland	4000	2.1	109,846.2	138,345.3	28,499.1
Visalia	4000	2.1	109,846.2	125,682.1	15,835.9

Source: Altex Technologies Corporation

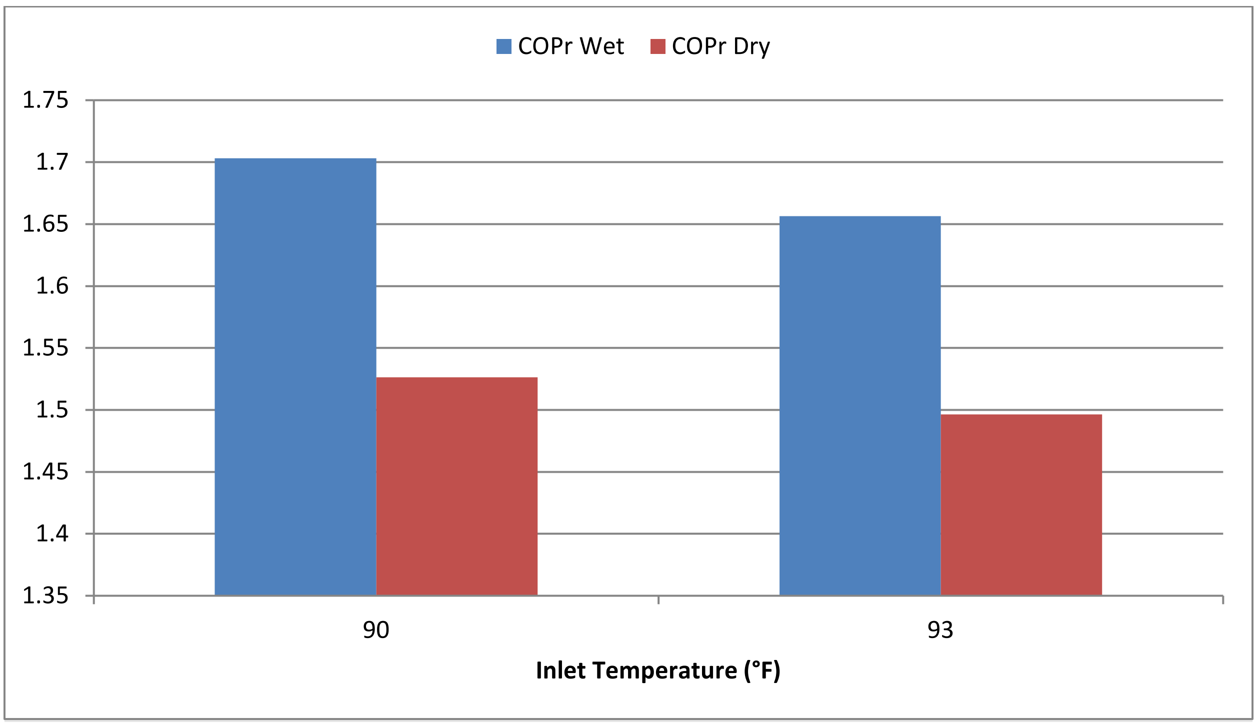
These results show the potential of the AHHEX relative to conventional evaporative wet condensers. The project also determined the benefit of wet AHHEX operation at high temperatures by deactivating the AHHEX deluge water feature. To demonstrate the benefits of wet operation, the water spray feature in AHHEX was deactivated and the unit was tested over a range of ambient air temperatures consistent with those listed in Table 16. The unit operated up to 95°F ambient air temperature. Above this temperature, the compressor pressure exceeded its operating limit and the unit shut down. This shutdown did not occur with wet/dry operation. Dry and wet/dry test system results were then directly compared to determine the benefits of wet operation, as shown in Table 21. The first two lines in the table illustrate dry operation. As shown in the table, under dry conditions the EER, COP, cooling, and power savings varied by only a small amount between the different test runs. This was expected and the closeness of the results shows the valid repeatability of the test results. In the last two rows, the advantages of AHHEX wet operation at higher temperatures are demonstrated. As shown, wet operation of the AHHEX increases EER and COP by a significant 17.1 percent to 17.5 percent, which is a significant increase. This is also illustrated in Figure 35, which shows the COP under dry and wet conditions at ambient air temperatures of 90°F and 93°F. In addition, the use of water cooling decreases the air outlet temperature, as shown in Figure 36. Also, as shown in Table 21, the cooling capacity increases with wet cooling, but by a smaller amount. These advantages are a result of the water-cooling reducing compressor pressure at the higher ambient air temperatures, versus dry cooling. This is also shown by the approximately 10 percent reductions in power use and power savings shown in the last column of Table 21. These advantages translate into benefits for California equipment users and ratepayers, which will be further described Chapter 6.

Table 21: Benefits of AHHEX Wet Operation

AHHEX EER Increase	AHHEX COP Increase	AHHEX Cooling Increase	Power savings
–2.0%	–2.0%	–1.4%	–0.6%
1.6%	1.6%	0.5%	1.1%
17.1%	17.1%	5.7%	9.7%
17.5%	17.5%	5.0%	10.7%

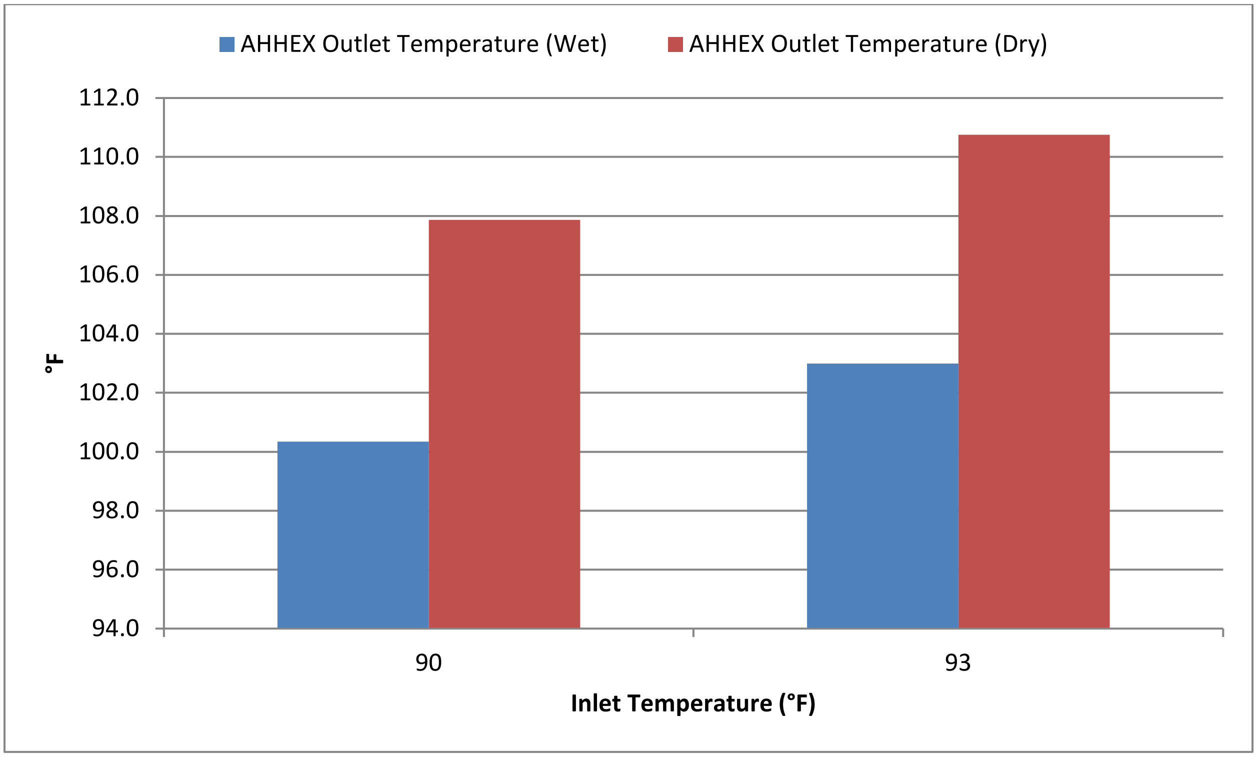
Source: Altex Technologies Corporation

Figure 35: Wet and Dry Operation COP



Source: Altex Technologies Corporation

Figure 36: Wet and Dry Air Outlet Temperature



Source: Altex Technologies Corporation

CHAPTER 4: Technology/Knowledge Transfer/Market Adoption

At this stage of development, limited effort was devoted to technology transfer and market adoption, though discussions were held with Legacy Chillers, a manufacturer of chillers for a number of commercial and industrial processes. It was noted that for the smaller chillers evaporative condensers are not favored because of their complexity, maintenance, and water treatment and Legionella issues. In these cases, the higher-cost dry coolers are favored. Much larger systems that would have more maintenance and water treatment support could benefit from an AHHEX hybrid system. More effort is required to develop relationships with manufacturers of larger chiller and air conditioning systems. For utility markets, discussions were held with manufacturers of utility dry cooling systems. These manufacturers are concerned about water permitting and have introduced dry coolers to replace evaporative-type systems where water use is constrained. A hybrid system, which can substantially reduce water use in regions where moderate water use is still permitted, could be an important option to limit capital cost increases relative to switching to dry cooling. More work is required to develop and execute a technology and knowledge transfer plan for commercial and industrial markets.

CHAPTER 5: Conclusions and Recommendations

A 170-ton chiller was selected as the appropriate vehicle for testing an advanced hybrid heat exchanger hybrid wet/dry condenser technology. With AHHEX wet/dry operation, water use is reduced, and power saved. Available data were studied and analyzed to confirm the superior heat transfer and pressure drop performances for AHHEX-type fins in dry conditions. Compared with conventional condensers, the AHHEX condenser has a 100 percent higher volumetric heat transfer coefficient and a 40 percent lower pressure drop per air-flow length. These metrics reduce heat exchanger volume, weight, and cost, and reduce fan-power cost. Project tests defined both the water management and retention characteristics of these fins for AHHEX wet operation. The water retention provided 1.7 minutes operating time without requiring additional water. This water inventory will help prevent local dry-out, areas of the coil that evaporate water faster then it is being applied and yield more consistent evaporative heat transfer. A low-pressure water distribution and recirculation system provided water application that minimizes water carry-over to either downstream components or surroundings. To compute cost, the AHHEX heat exchanger core was divided into dry and wet/dry sections constructed of aluminum fins and copper tubes. A full-scale AHHEX modular cell of 28 tons cooling capacity was designed. To meet other capacities, these factory-built modular cells were plumbed together in parallel to yield the same heat transfers and pressure drops for different cooling capacities. The cells can be further arranged in single or multiple rows to fit available site footprints. To ensure the relevance of the test data, the AHHEX test system had the same height and depth as the full-scale cell unit, but with a 20 percent shorter width. With this approach, the prototype-scale system's air pressure drop will be the same as a full-scale system and the capacity difference will simply be related to the face area ratio. Using computer aided design tools, the prototype-scale AHHEX for a 10-ton chiller was designed; commercially available components were assembled into an AHHEX wet/dry test condenser. The condenser was then integrated into an available 10-ton condenser for performance testing. This AHHEX condenser was mounted in a frame with a fan that simulated a full-scale system.

To determine the AHHEX condenser performance, the test unit was operated over a range of ambient air temperatures. The unit controls were set to activate water operation at 85°F, as driven by the compressor outlet pressure. Over the range of ambient temperatures, from 80°F up to 95°F, the AHHEX was able to maintain a constant cooling output from the chiller of 13 tons cooling, as would be required for industrial processes with constant cooling requirements. Using the test results extrapolated to a 170-ton cooling application, the AHHEX was found to reduce water use by up to 2.1Mgal/year and reduce energy use by 28,499 kWh/year. This water-use reduction is in the range of the project goal of 2.4 Mgal/year. Relative to the power-use reduction, the reduction of 28,499 kWh/year exceeds the project goal of 17,240 kWh/year. Besides these reductions for a 170 tons chiller application, the test results were combined with weather data to illustrate the benefits of AHHEX when applied to both cool and hot locations in California. If AHHEX were installed in only 20 percent of the commercial and industrial markets and only eight power plants in California, significant water, power, greenhouse gases and other pollutants would be reduced, as shown in the following table. These are significant benefits to commercial, industrial, utilities, industries, and, ultimately, to ratepayers.

Table 22: AHHEX Annual Projected Power, Water, Cost, and Pollutant Savings

	Commercial	Industrial	Utility
Power (kWh/yr)	3,049,508	624,418	111,533,485
Water (MGal/ yr	241	49	7,736
Power Cost ($K/yr)	477	73	13,105
Water Cost ($K/yr)	940	191	2,080
Total Cost ($K/yr)	1,417	264	15,186
GHG (lbs/yr)	1,650,587	337,975	62,910,418
CH4 (lbs/yr)*	25,165	5,151	808,956
N2O (lbs/yr)*	1,061	217	34,116

**GHG savings due to power reductions. CH4 and N2O savings due to reduced water consumption and the associated emissions during biological treatment of water. https://www.sciencedirect.com/science/article/abs/pii/S0958166918301265*

Source: Altex Technologies Corporation

CHAPTER 6: Benefits to Ratepayers

Using performance test data combined with the weather data, shown in Figure 34, the total water use for AHHEX through the year can be estimated. In addition, the water use for a wet-only system can be calculated and the results compared to determine the water-saving benefits of AHHEX for the Oakland and Visalia locations. These areas represent relatively cool and hot regions of California, respectively, and their results can be used to estimate the water-saving benefits of AHHEX throughout California. It should be noted that the water and electric energy savings described in Chapter 3 were for a commercial or industrial application of 170-ton cooling, where the cooling load is nearly constant throughout the year. To calculate the total AHHEX savings to California industries and ratepayers in general, air conditioning and refrigeration applications, where the cooling load varies throughout the year, were also considered. Even with fewer hours of AHHEX operation, water and electrical energy savings were still substantial.

To determine annual benefits to a California customer, the amount of time that AHHEX provides these benefits to the customer must be defined. To accomplish this, data on regional annual temperature was sourced from the National Renewable Energy Laboratory,[2] and two representative locations were selected for analysis: the Bay Area (Oakland), and the Central Valley (Visalia), both located in large investor-owned utility service territories. As shown in Figure 34, the temperatures in both locations meet the 82.5°F criteria during the year.

While AHHEX is applicable to a variety of condensing applications, a familiar and typical system was chosen as an example: a 170-ton MVC chiller, operating with wet cooling. The savings for a typical customer that converted this equipment to AHHEX (or replaced the unit with a new AHHEX-equipped model), is shown in Table 22. The savings are consistent with the water and electricity savings just described, as applied to the heat rejection requirements of a 170-ton chiller.

To determine the total potential benefit offered by AHHEX to all California electric ratepayers, the amount of wet cooling in use in California must be determined. As shown in Table 24, the electric consumption for all cooling end uses is 24,169.5 GWh/year. This is determined from Energy Commission data. For commercial buildings, the electrical consumption for cooling and refrigeration is well defined and represents 23.8 percent of the total commercial consumption. The Energy Commission's industrial

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[2] National Solar Radiation Database Data Viewer. National Renewable Energy Laboratory. https://mapsbeta.nrel.gov/. Accessed January 21, 2016.

data does not contain end-use breakdowns, so the same 23.8 percent percentage was applied to the total consumption for the industrial sectors likely to use the most cooling.

Commercial and industrial facilities use wet and dry cooling methods in equal proportion,[3] based on the number of installed units. The proportion of the market, on a GWh/yr basis, can then be easily determined by the relative power consumption of units using the two cooling methods. The COP of a dry-cooled chiller is typically 3-4, while the COP of a wet-cooled unit is 5-6. Table 25 uses these two COPs to estimate the installed capacities of each type. The exact COP's shown are based on typical chillers, both manufactured by the Carrier Corporation and of equal nominal capacity. The proportion of their COPs is then applied to the total electric consumption from Table 24, to determine installed wet-cooler equipment capacity, again using the chiller relationships for a 170-ton chiller. Even with a conservative 20 percent market penetration assumption, AHHEX has the potential to supplement roughly 57,000 installed tons of cooling equipment.

Table 23: Annual Savings for AHHEX—170-ton Chiller Savings Realized When Ambient Temperatures <82.5°F

	NorCal / PG&E	SoCal / SCE
% of time < 82.5°F Ambient	97.9%	78.4%
AHHEX Total Power Consumption (kWh/yr)	24,715	68,641
Wet Cooling Total Power Consumption (kWh/yr)	31,128	78,331
AHHEX Power Savings (kWh/yr)	6,412	9,869
Avoided Water Use (gal/yr)	508,503	1,205,734

Source: Altex Technologies Corporation

Table 24: Determination of Cooling Electrical Consumption by Sector

Commercial Consumption, 2012	
Total Consumption, All Commercial	84,339.7 GWh
Cooling, all Commercial Buildings	13,124.0 GWh
Refrigeration, all Commercial Buildings	6,937.7 GWh
Total Cooling/Refrigeration, Commercial	**20,061.7 GWh**
Cooling + Refrigeration, Percent of all Commercial Consumption	23.8%

[3] Frost & Sullivan, "North American Heat Exchangers and Cooling Towers Market", N848-10, April 2011

Industrial Consumption, 2015	
Total Consumption*	17,269.5 GWh
Assumed % of Total Consumption Used for Cooling and Refrigeration	23.8%
Total Cooling + Refrigeration, Industrial	**4,107.8 GWh**
Total Cooling Consumption, Commercial + Industrial	***24,169.5 GWh***

*** Food Processing; Food and Beverage; Pulp/Paper Mills; Paper Manufacturing; Chemical Manufacturing; Semiconductor Manufacturing; Computer/Electronics Manufacturing; Electrical Equip/Appliance Manufacturing; Misc. Manufacturing.**

Source:
California Energy Commission Energy Almanac: https://www.energy.ca.gov/data-reports/energy-almanac

Table 25: Cooling Consumption by Technology and Sector

Technology	COP	Market Share, by Electricity Consumption	Market Share, by System Type (GWh/yr)	AHHEX Market (20% Market Penetration) (GWh/yr)	AHHEX Market (20% Market Penetration) (tons cooling)
Typical Dry Cooling (e.g., Carrier AquaForce 30XA)[1]	3.14	63.3%	12699 (commercial)	N/A	N/A
			2602 (industrial)	N/A	N/A
Typical Wet Cooling (e.g., Carrier AquaForce 30XW)[2]	5.43	36.7%	7355 (commercial)	1471 (commercial)	47,747 (commercial)
			1506 (industrial)	301 (industrial)	9,777 (industrial)

[1] 30XA080-501 AquaForce® Fixed Speed Air-Cooled Liquid Chillers, 80 to 500 Nominal Tons (265 to 1740 Nominal kW). Carrier Corp. http://www.carrier.com/commercial/en/us/products/chillers/chillers/30xa/. Published 1/13/2016

[2] 30XW150-400 AquaForce® Water-Cooled Liquid Screw Chillers, 150 to 400 Nominal Tons (528 to 1407 kW). Carrier Corp. http://www.carrier.com/commercial/en/us/products/chillers/chillers/30xw/#tab-3. Published 8/21/2015

Source: Altex Technologies Corporation

The total benefit to California ratepayers is shown in Table 26. Using the AHHEX market share in Table 25, single-unit savings for a typical 170-ton chiller described in Table 23 were extrapolated to the total AHHEX market, assuming a conservative 20 percent market penetration. The utility costs and emissions factors used to calculate electricity-related savings are consistent with Energy Commission data. The water-related electricity savings and emissions reduction factors came directly from the "Agency-Info" section of the California Public Utility Commission's Water Energy Nexus Calculators (v.4B). It should be noted that, in addition to the power cost savings in Table 26, water cost savings of $788,430 and $161,439 per year for commercial and industrial markets, respectively, should also be included.

AHHEX technology is also applicable to utility-scale condensers such as those used in natural-gas-fired power plants. To determine the potential savings for this application, the water and electricity savings, on a per-ton basis, can be scaled to the heat-rejection requirements for a typical 500-MW power plant, which would have a typical 800-MW heat rejection requirement.[4] The resulting benefits, if the AHHEX hybrid technology were installed instead of wet cooling, at a single plant, are shown in the first row at the bottom of Table 26; these benefits assume the same Energy Commission industrial electricity rates and CPUC water rates as were used in the commercial and industrial results. If eight power plants were to adopt this technology, an even more substantial benefit to the state would accrue, as shown in the second row in the bottom of Table 26. As shown, power savings would be over $13 million per year, with water savings of 7.7 billion gallons per year and greenhouse gas reductions of 31,500 tons per year. Water cost savings of $30.2 million per year should also be included. These results for commercial, industrial and utility markets are summarized in Table 22.

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[4] Conservatively estimated an overall plant efficiency of 33% for Rankine steam cycles

Table 26: Estimated Benefits of AHHEX, Commercial, Industrial and Utility Sectors

	Water Savings				Electricity Savings	
Case	**Water Savings (mgal/yr)**	**Electricity Savings (kWh/yr)**	**CH4 Savings (lbs/yr)**	**N2O Savings (lbs/yr)**	**Electricity Savings (kWh/yr)**	**GHG Avoided (lbs/yr)**
Norcal / PG&E 170 ton, Commercial	0.508	1,810	53	2.24	6,412	4,681
Norcal / PG&E 170 ton, Industrial	0.508	1,810	53	2.24	6,412	4,681
Socal / SCE 170 ton, Commercial	1.205	4,293	126	5.31	9,689	7,073
Socal / SCE 170 ton, Industrial	1.205	4,293	126	5.31	9,689	7,073
California 170 ton, Avg Commercial	0.857	3,052	90	3.78	8,051	5,877
California 170 ton, Avg Industrial	0.857	3,052	90	3.78	8,051	5,877
Total CA Commercial	241	788,430	25,155	1,061	2,261,079	1,650,587
Total CA Industrial	49	161,439	5,151	217	462,979	337,975
Total CA Industrial / Commercial	290	949,869	30,306	1,278	2,724,058	1,988,562
	Water Savings				**Electricity Savings**	
Case	**Water Savings (mgal/yr)**	**Electricity Savings (kWh/yr)**	**CH4 Savings (lbs/yr)**	**N2O Savings (lbs/yr)**	**Electricity Savings (kWh/yr)**	**GHG Avoided (lbs/yr)**
500 MW Power Plant	967	3,169,351	101,120	4,264	10,772,332	7,863,802
4 GW Power Plant Capacity	7736	25,354,830	808,956	34,116	86,178,655	62,910,418

Total Savings					
Case	Total Electrical Savings (kWh/yr)	Operating Cost Savings ($/yr)	GHG Avoided (lbs/yr)	CH4 Savings (lbs/yr)	N2O Savings (lbs/yr)
Norcal / PG&E 170 ton, Commercial	8,222	$ 1,286	4,681	53	2.24
Norcal / PG&E 170 ton, Industrial	8,222	$ 966	4,681	53	2.24
Socal / SCE 170 ton, Commercial	13,982	$ 2,187	7,073	126	5.31
Socal / SCE 170 ton, Industrial	13,982	$ 1,643	7,073	126	5.31
California 170 ton, Avg Commercial	11,103	$ 1,736	5,877	90	3.78
California 170 ton, Avg Industrial	11,103	$ 1,304	5,877	90	3.78
Total CA Commercial	3,049,509	$ 476,973	1,650,587	25,155	1,061
Total CA Industrial	624,418	$ 97,665	337,975	5,151	217
Total CA Industrial / Commercial	3,673,927	$ 574,638	1,988,562	30,306	1,278
Total Savings					
Case	**Total Electrical Savings (kWh/yr)**	**Operating Cost Savings ($/yr)**	**GHG Avoided (lbs/yr)**	**CH4 Savings (lbs/yr)**	**N2O Savings (lbs/yr)**
500 MW Power Plant	13,941,686	$ 1,638,148	7,863,802	101,120	4,264
4 GW Power Plant Capacity	111,533,485	$ 13,105,185	62,910,418	808,956	34,116

Source: Altex Technologies Corporation

LIST OF ACRONYMS

Term	Definition
AHHEX	Advanced hybrid heat exchanger
Ambient Air Temperature	Current Air Temperature
Btu/hr	British thermal units per hour
Btu/lb	British thermal units per pound
CEC	California Energy Commission
cfm	Cubic feet per minute
Chiller	Refrigeration System that Dehumidifies Air In Commercial and Industrial Facilities
Condensing	Change from Vapor to a Liquid
Compressor Power	Device that Converts Power into Potential Energy Stored in Pressurized Air
COP	Coefficient of Performance
CPUC	California Public Utilities Commission
EPRI	Electric Power Research Institute
F	Degrees Fahrenheit
fpm	Feet per minute
Ft/s	Feet per second
gal/ton	Gallons per ton
gal/t-hr	Gallons per ton-hour
GHG	Greenhouse Gas
G/in^2	Grams per square inch
GWh/yr	Gigawatt hours per year
H2O	Water
HEX	Heat Exchanger
IOU	Investor-Owned Utility
ITD	Initial temperature difference
KW	kilowatts
kW-h/year	Kilowatt hours per year
lb/hr ref	Pounds per hour of refrigerant flow

MG/yr	Million gallons per year
Mgal	Million gallons
Microprocessor-Based	System Designed Using a Microprocessor as its central processing unit (CPU)
MVC	Mechanical vapor compression
MW	Megawatts
MW-h	Megawatt hour
NREL	National Renewable Energy Laboratory
P&ID	Piping and installation diagram
PG&E	Pacific Gas and Electric
PIER	Public Interest Energy Research
psia	Pounds per square inch, absolute
psig	Pounds per square inch, gauge
Rankine-Based Power Cycle	Thermodynamic Cycle of Heat Engine that Converts Heat into Mechanical Work While Undergoing Phase Change
RD&D	Research, development, and demonstration
RH	Relative humidity
SCE	Southern California Edison
SCFM	Standard cubic feet per minute
VFD	Variable frequency drive
Vapor Cycle Model	A Thermodynamic Cycle Operating as a Heat Engine or Heat Pump, where the Working Substance is in, or passes through, the vapor state
Wet/Dry System	Wet/Dry System is a Cooling Process Where a Water-Cooled Condenser Runs Parallel to an Air-Cooled Condenser

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